XIV. Why Things Don't Work

or

Why *S/N* Theory Often Seems to be Irrelevant

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),

  and

- self-oscillation
  (circuit provides feedback path that causes sustained oscillation due to a portion of the output reaching the input)

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 here, 50 Hz in Europe, Japan)

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

Diagnostics:

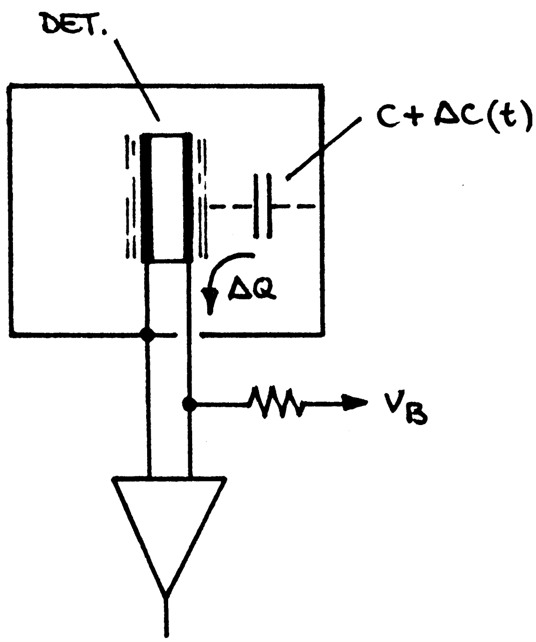
a) inspect signal output with oscilloscope set to trigger mode “line”. Look for stationary structure on baseline

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 it)

2. 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.

a) additional 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

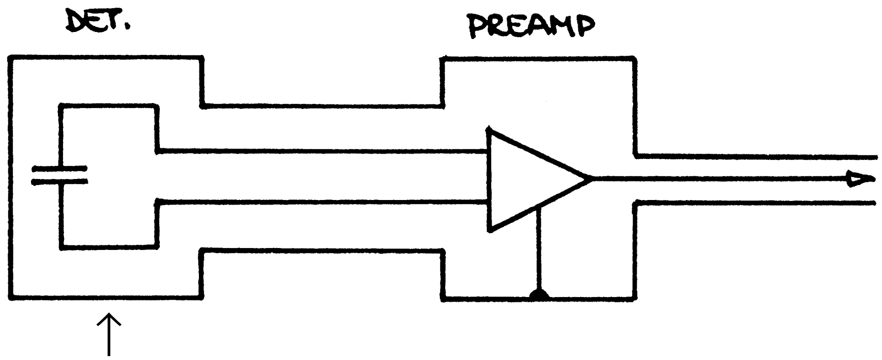
This is a very sensitive technique.

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



contiguous shield

Conducting shield attenuates an incident electromagnetic wave because of

a) reflection of the incident wave

$$E_{0r} = E_0 \left(1 - \frac{Z_{shield}}{Z_0} \right)$$

where

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}} = 377\ \Omega$$

is the impedance of free space.

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

b) attenuation of the absorbed wave

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

The net current decreases 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

$$\delta = \frac{c}{\sqrt{2\pi\mu\sigma\omega}}$$

is the penetration depth or “skin depth”. μ and σ are the permeability and conductivity of the conductor and ω is the frequency of the incident wave.

For an alternating current flowing in a conductor the current flow is confined to a surface layer of order δ. The resistance presented to the alternating current by a conductor of width w and length l is

$$R_{AC} = \frac{\delta\, w\, l}{\sigma}$$

i.e. the resistance is not determined by the geometric thickness of the conductor, but by the penetration depth.

In a round conductor, the resistance is determined by the outer cylindrical “skin” of thickness δ.

The skin depth decreases with the square root of the frequency and the conductivity.

Translating the expression for the skin depth from gaussian to technical units yields

$$\delta = \sqrt{\frac{2}{\mu\,\sigma\,\omega}} = \sqrt{\frac{1}{\pi\,\mu\,\sigma\,f}} = \sqrt{\frac{\rho}{\pi\,\mu\,f}}$$

and introducing the relative permeability $\mu_r = \mu/\mu_0$

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

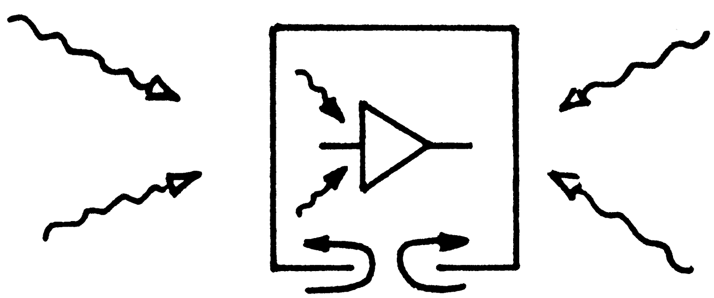
In aluminum, $\rho = 2.8\ \mu\Omega\cdot\mathrm{cm}$ and $\mu_r = 1$, so

at $f = 1$ MHz the skin depth $\delta = 84\ \mu\mathrm{m} \approx 100\ \mu\mathrm{m}$.

note: The wavelength in a conductor is also reduced to $\lambda = 2\pi\delta$.

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 > $\lambda/1000$ (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!), input lines must have good shield connections, shield coverage of coax or other cables >90%.
Connectors must maintain the integrity of the shield connection.

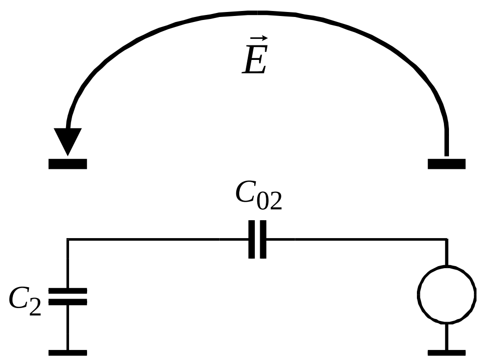
b) “Field Line Pinning”

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

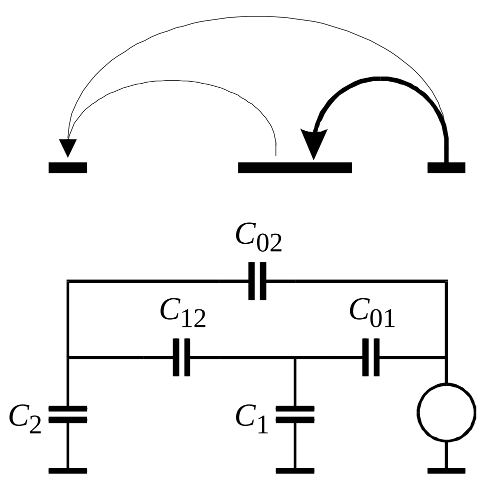
Rather than preventing interference currents from entering the detector system, it is often more practical to reduce the coupling of the interference to the critical nodes.

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.



“Field line pinning” is the operative mechanism of “Faraday shields”.

“Self-Shielding” Structures

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

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

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

Example: Si, ε_r = 11.9

⇒ 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 ε_r = 1, 50% of the field lines originating from electrode set 2 terminate on set 1.

⇒ high dielectric constant reduces coupling of electrode sets 2 and 3 to external sources.

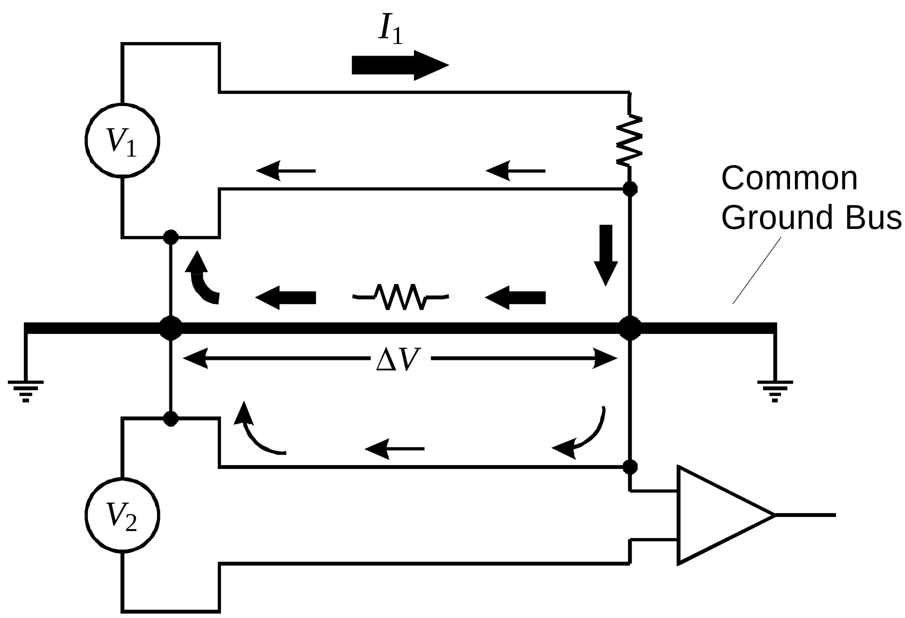
If the interference source is represented by electrode set 1 and sets 2 and 3 represent a detector

⇒ Si detector is 6.5 times less sensitive to capacitive pickup then a detector with ε_r = 1
(e.g. a gas chamber with the same geometry)

4. Shared Current Paths ("ground loops")

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.

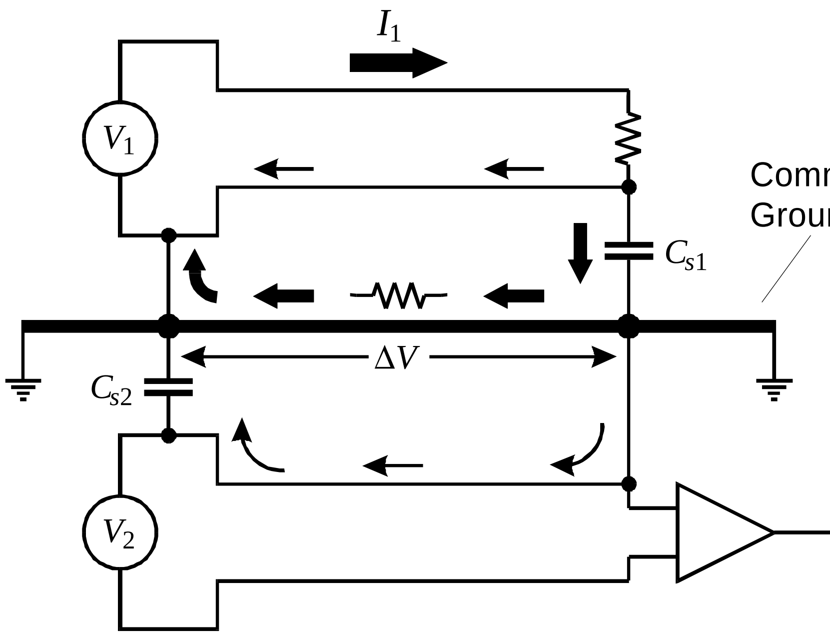
> Although the circuit associated with generator V_1 has a dedicated current return, the current seeks the past of least resistance, which is the massive ground bus.

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.

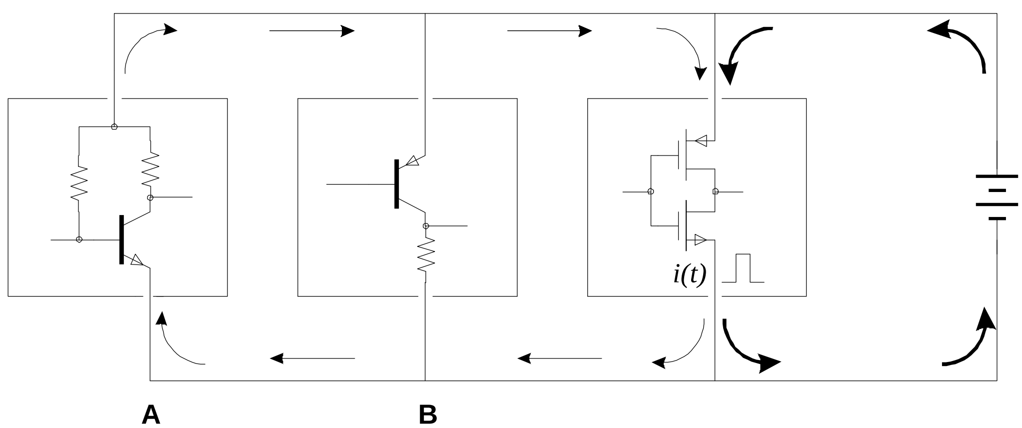
Interference does not cross-couple by voltage alone, but also via current injection.

Current spikes originating in logic circuitry, for example, propagate through the bussing system as in 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 and propagates primarily towards power supply

↓



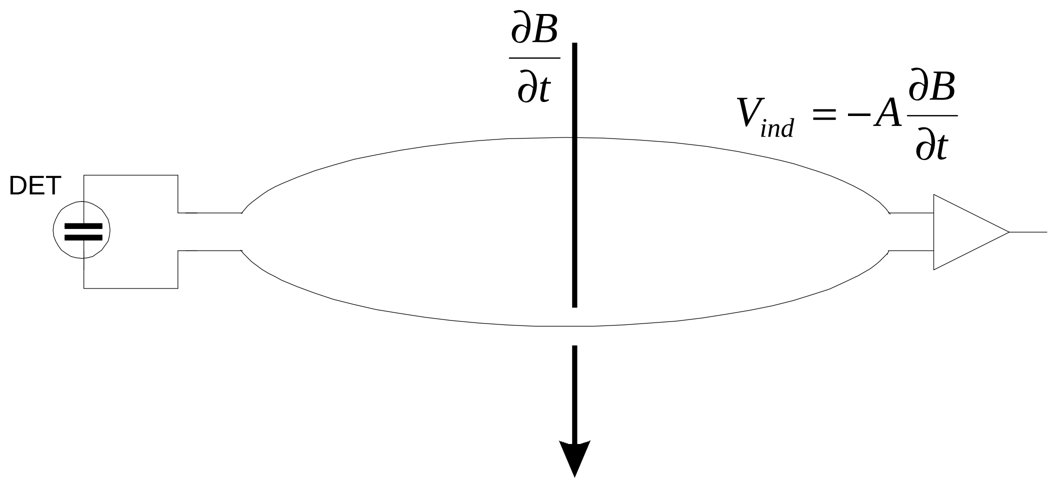
↑

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

↑

but not into high impedance node B

Another mechanism, beside common conduction paths, is induction:



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.

Remedial Techniques

1. Reduce impedance of the common path

   ⇒ Copper Braid Syndrome

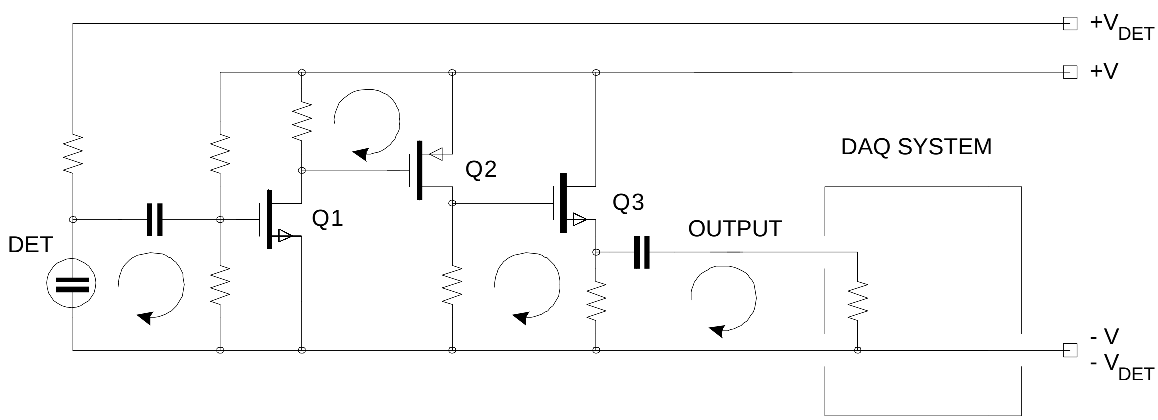
   Colloquially called "improving ground".

   (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!



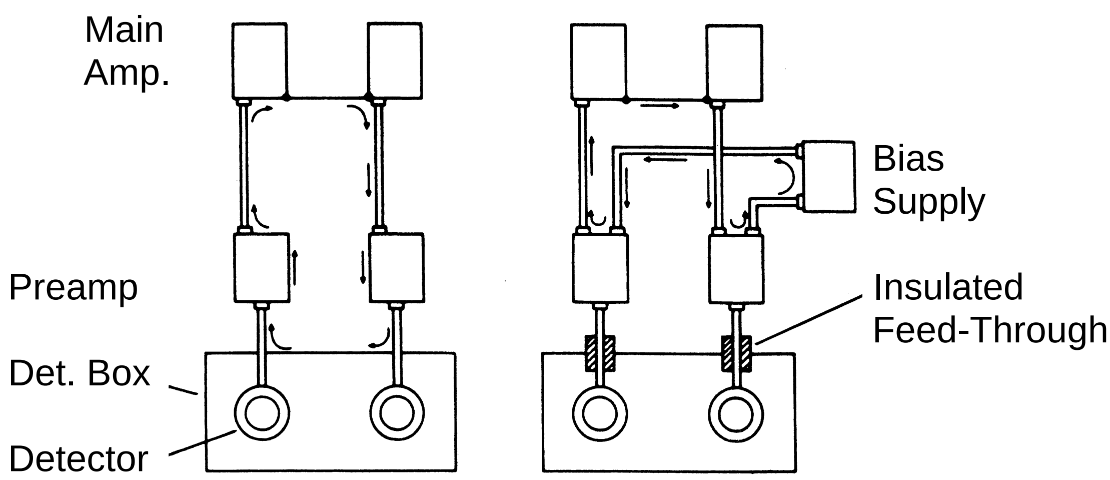
In transferring from stage to stage the signal current flows through local return loops.

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.

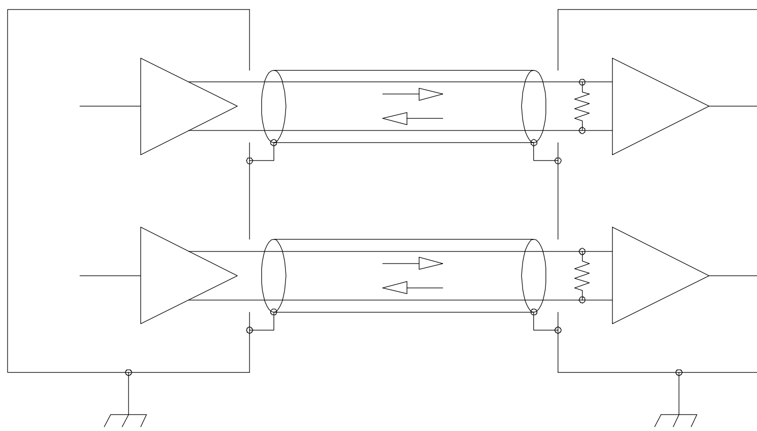
- Although not shown in the schematic illustrations above, both the "detector box" (e.g. a scattering chamber) and the main amplifiers (e.g. in a NIM bin or VME crate) are connected to potential interference sources, so currents can flow through parts of the input signal path.

Breaking shared signal paths, cont'd

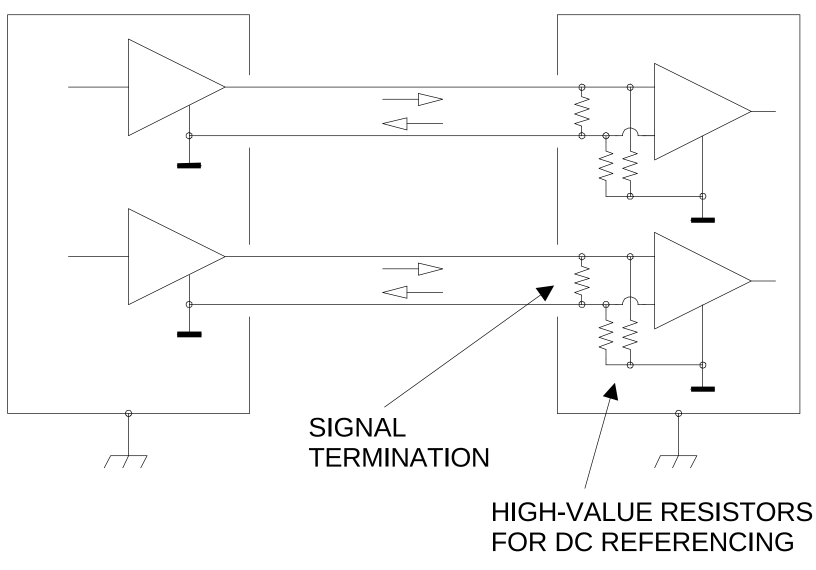
1. Differential Receivers

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

Ideal configuration using differential drivers and receivers

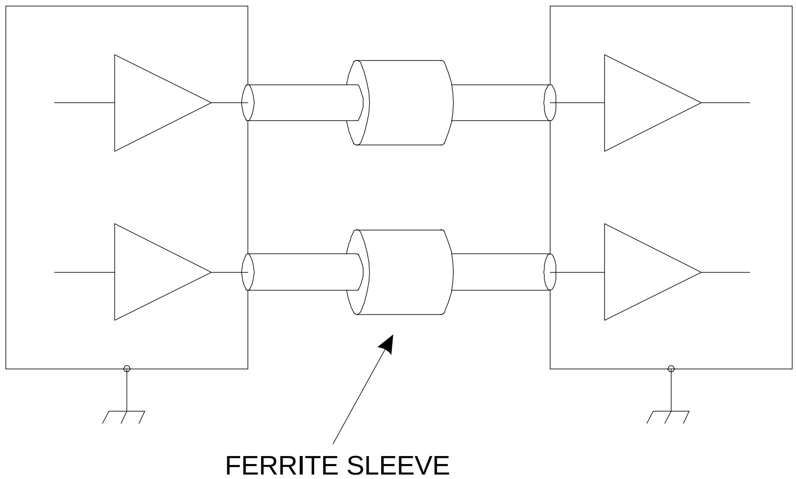


Technique also usable with single-ended drivers



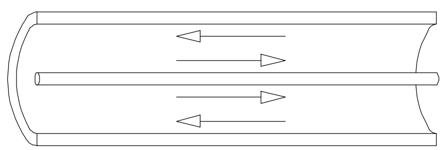
2. Insert high impedances

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.

$\Rightarrow$ Ferrite sleeve does not affect signal transmission.

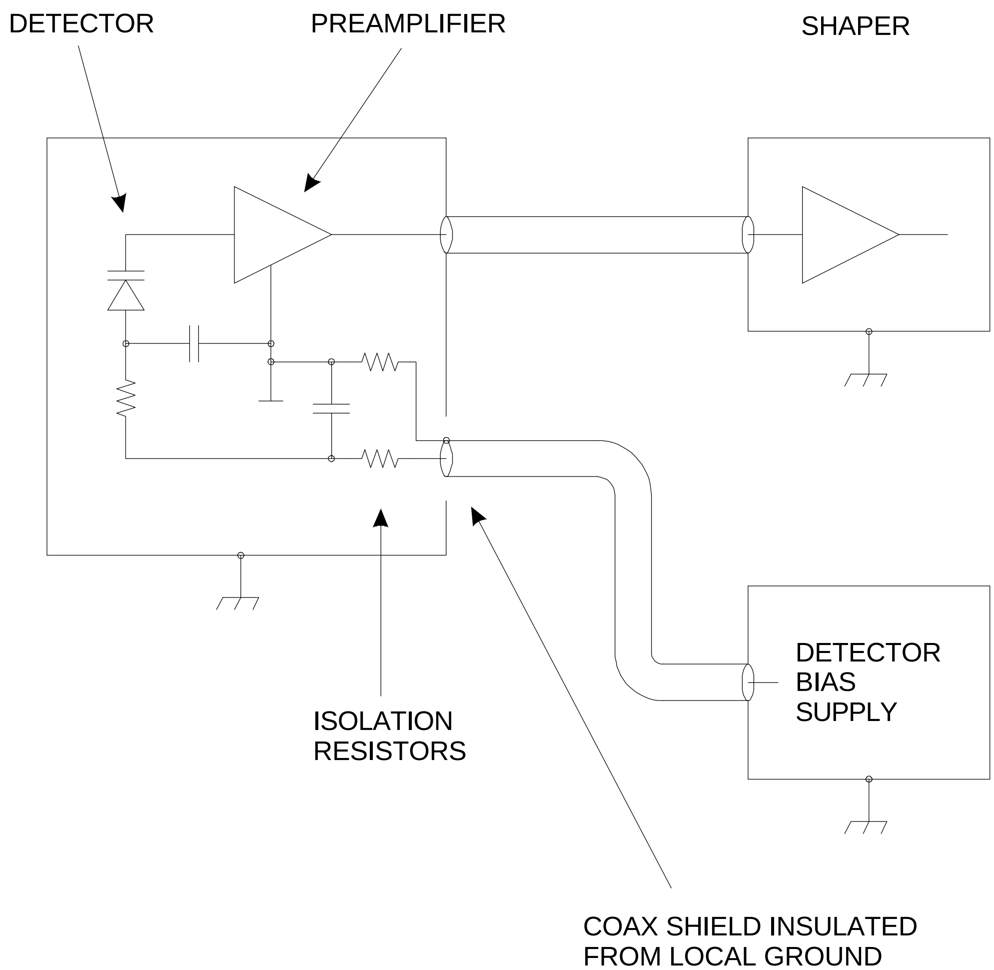
Common mode currents in the coax line
(current flow in same direction on inner and outer conductor) or
current components flowing only on the outside surface of the shield
("ground loops")
will couple to the ferrite and be suppressed.

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.

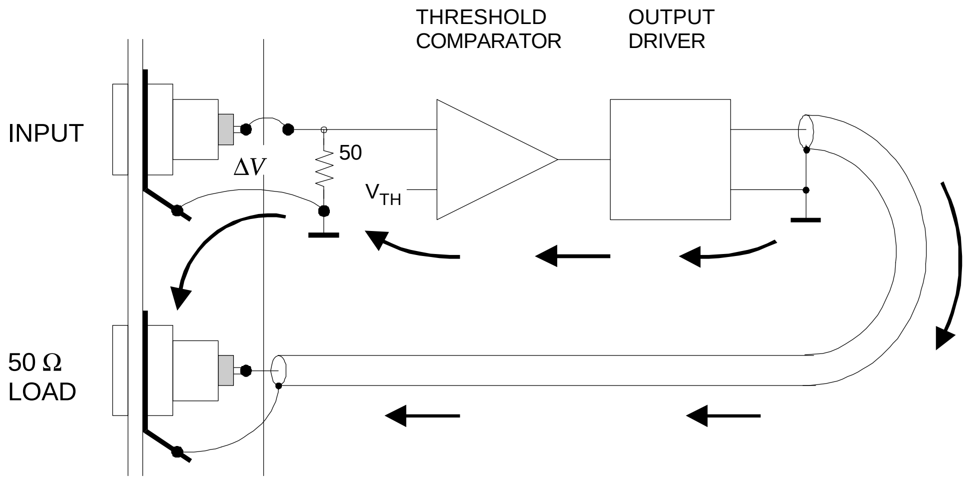
“Ground loops” are often formed by the third wire in the AC power connection. Avoid voltage differences in the “ground” connection by connecting all power cords associated with low-level circuitry into the same outlet strip.

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.

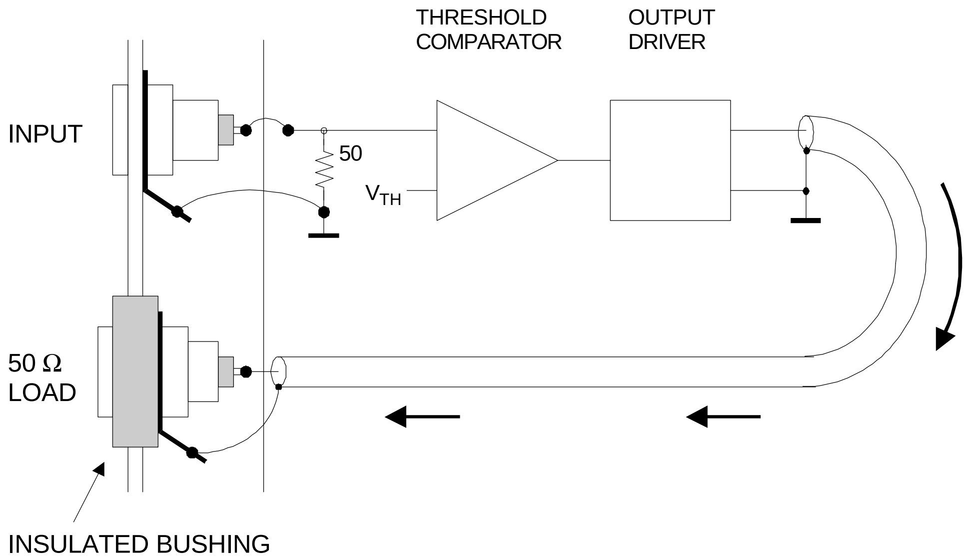
All inputs and outputs were mounted on the front panel. The outputs drove about 20 mA into 50 Ω cables.

Whenever an output fired, the unit broke into oscillation.



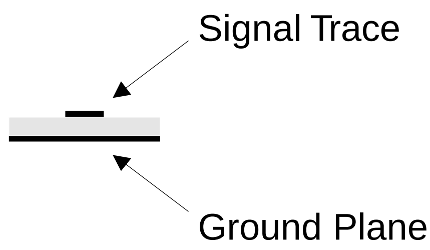
A portion of the output current flowed through the input ground connection. The voltage drop ΔV was sufficient to fire the comparator.

Breaking the loop by insulating the output connector from the front panel fixed the problem.

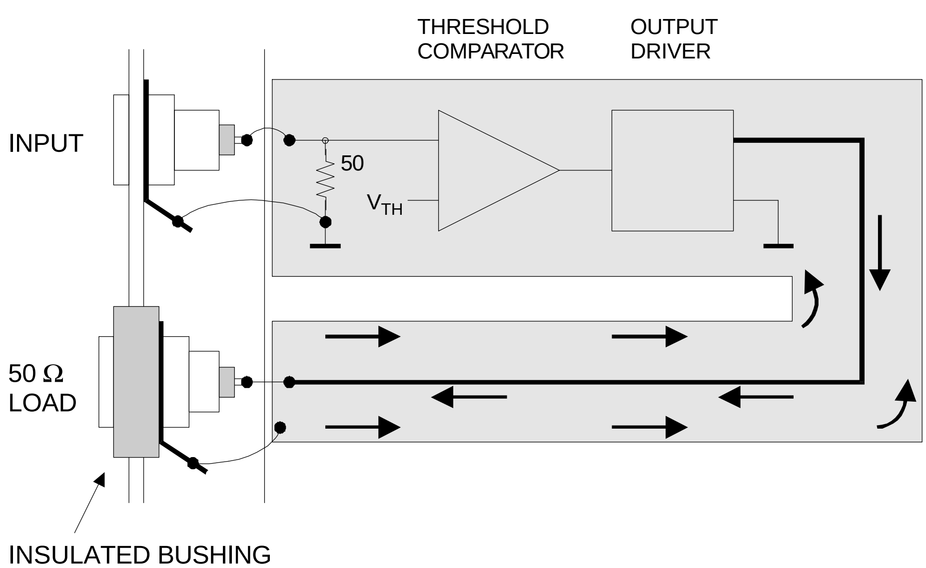


Often it is convenient to replace the coax cable at the output by a strip line integrated on the PC board.

Strip Line:

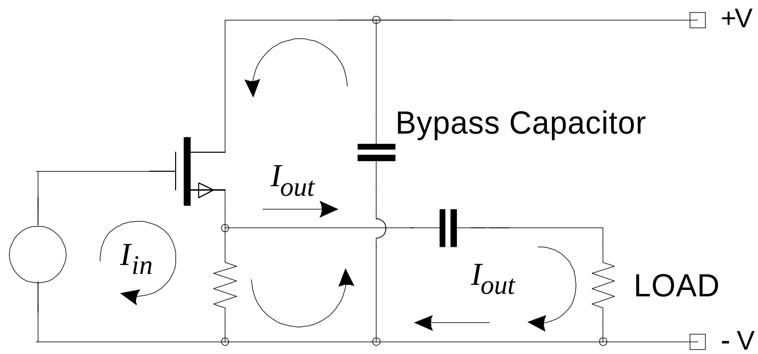


Current paths can be controlled by patterning the ground plane.



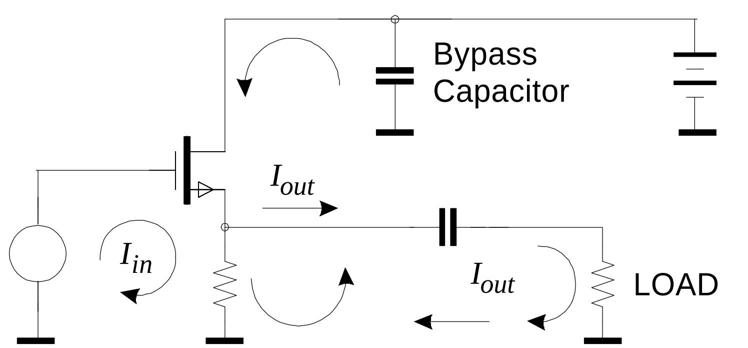
Ground returns are also critical at the circuit level.

Although the desired signal currents circulate as shown on p. 16, there are additional currents flowing in the circuit.



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.

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.

⇒ 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 ⇒ 2 mV voltage drop,

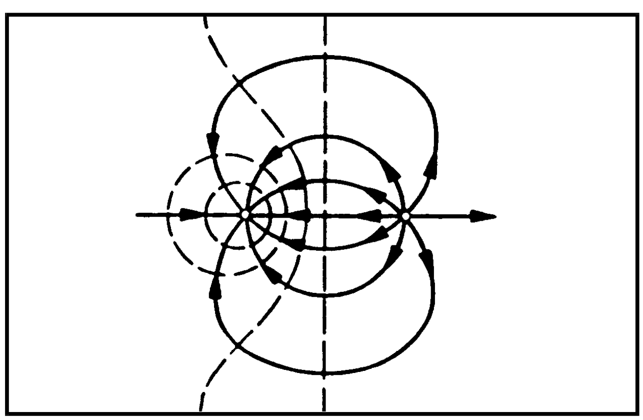
which can be much larger than the signal.

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!

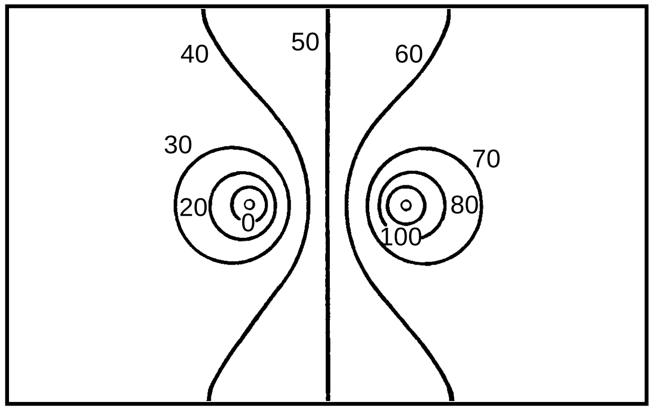
Consider a current loop closed by two connections to a ground plane.

Current distribution around the two connection points:

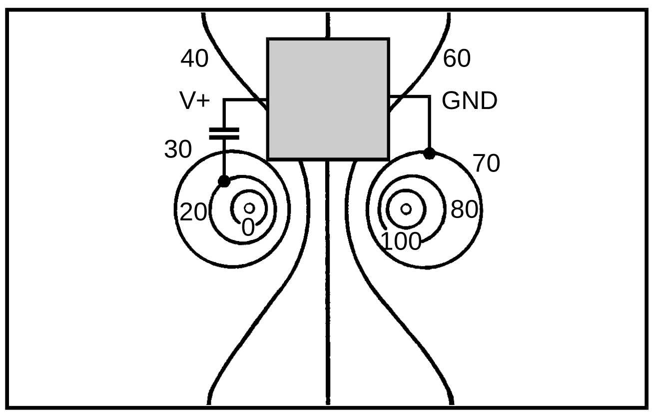


The dashed lines indicate equipotential contours.

Assume a total drop of 100 mV. The resulting potential distribution is

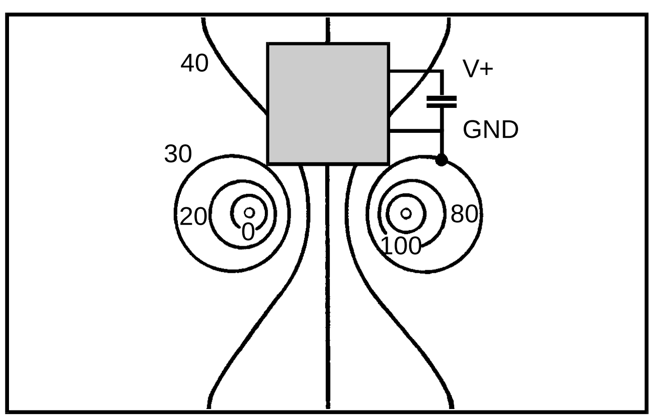


Mounting a circuit block (an IC, for example) with ground and bypass connections as shown below



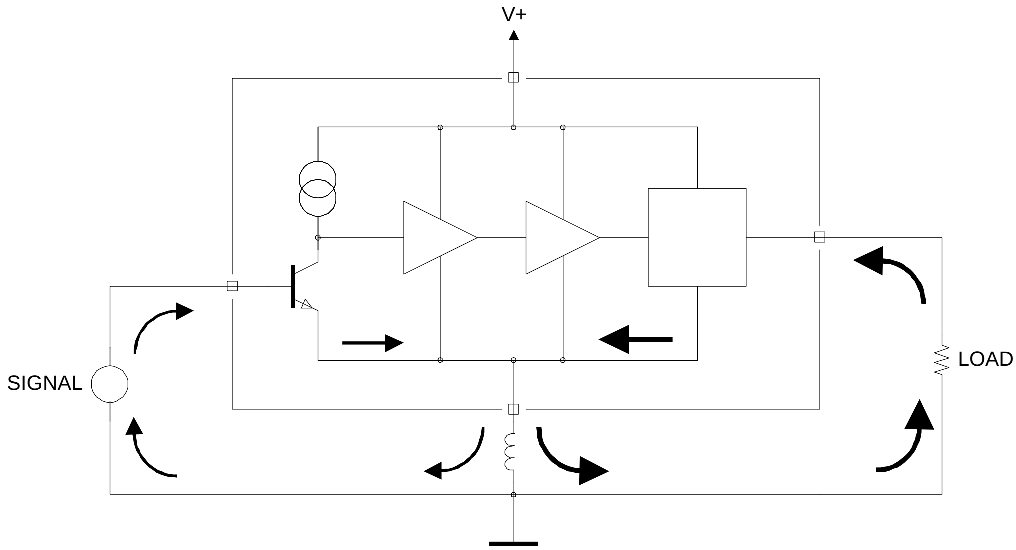
introduces a 50 mV voltage drop in the “ground” path.

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

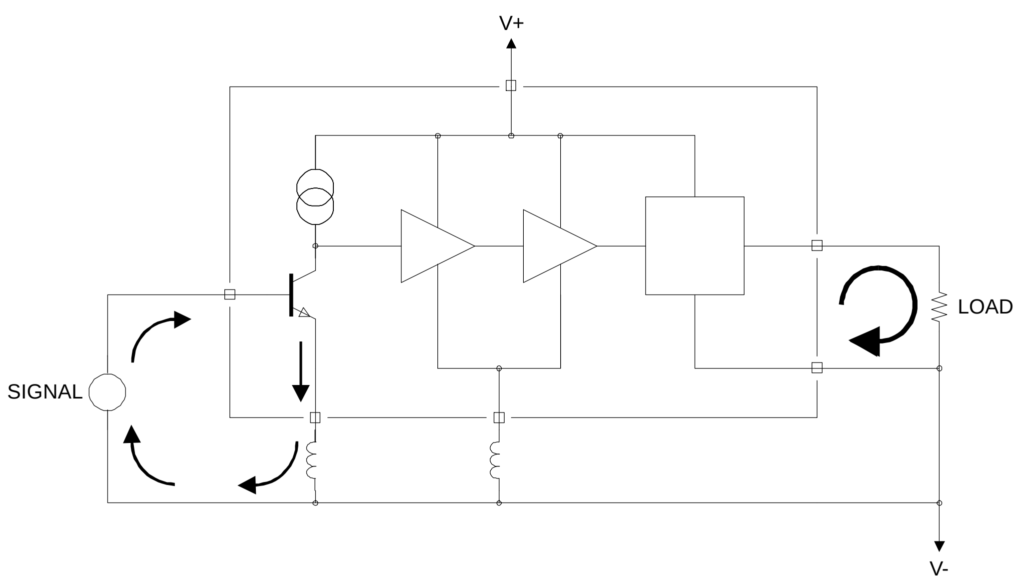
IC comprising a preamplifier, gain stages and an output driver:



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.

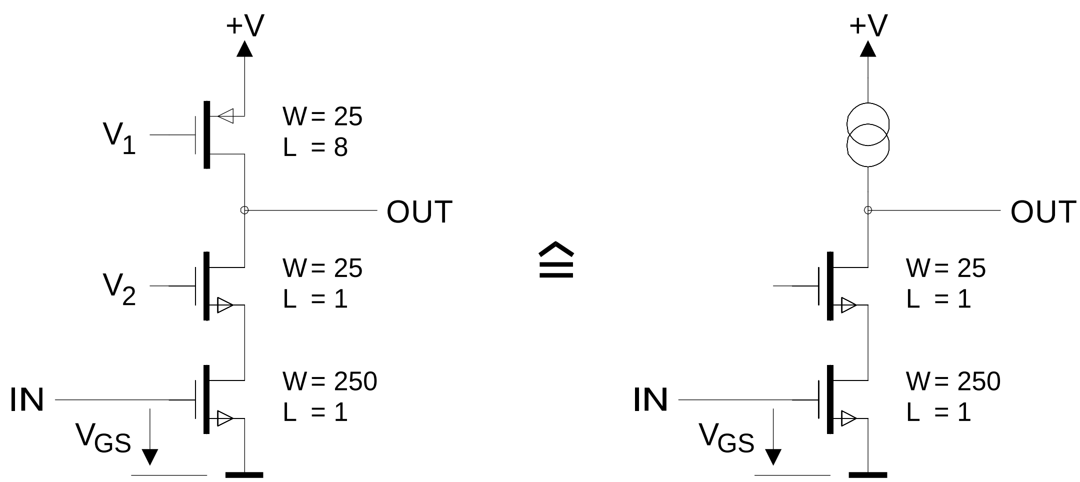
Separating the “ground” connections by current return paths routes currents away from the common impedance and constrains the extent of the output loop, which tends to carry the highest current.



The Folded Cascode

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

Standard cascode with representative transistor sizes:



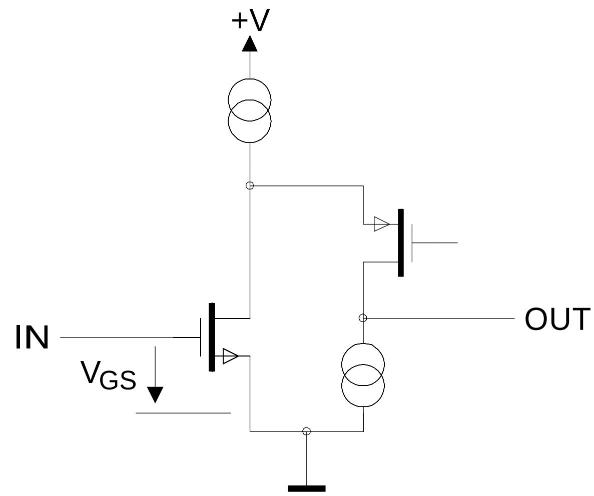
The cascode combines two transistors to obtain

- 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

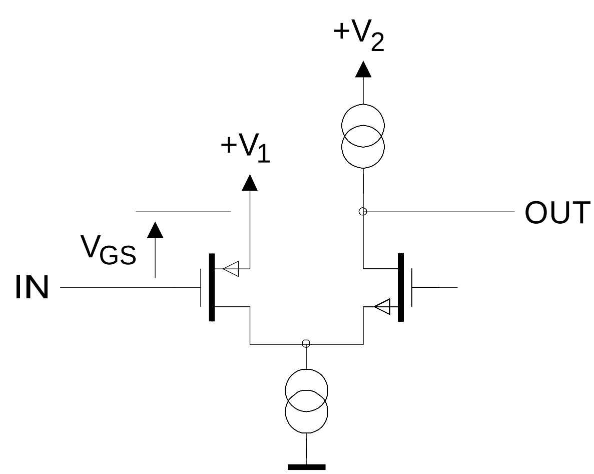
Since the input transistor determines the noise level, its current requirement tends to dominate.

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.

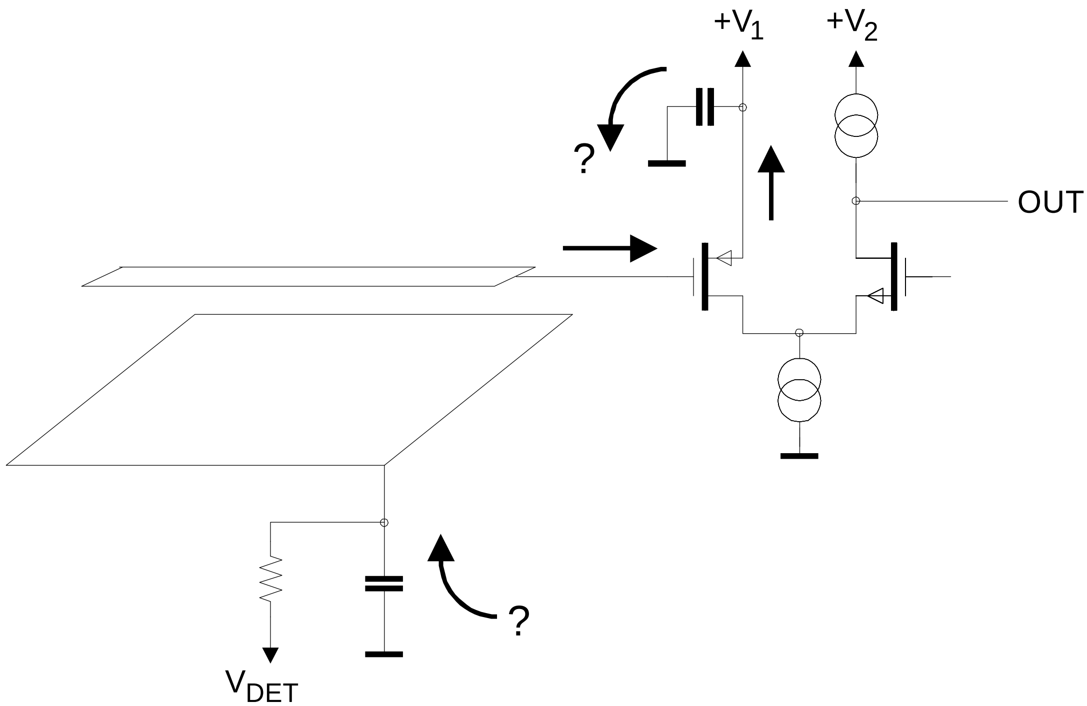


Since PMOS transistors tend to have lower "1/ *f* " noise than NMOS devices, the following adaptation is often used:



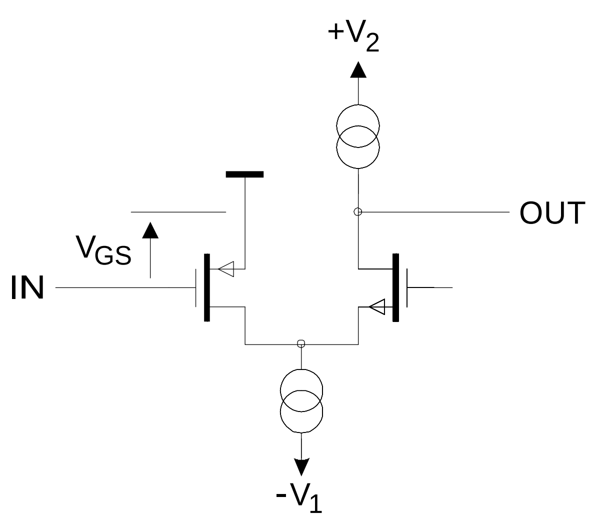
The problem with this configuration is that the supply V_1 becomes part of the input signal path. Unless the V_1 supply bus is very carefully configured and kept free of other signals, interference will be coupled into the input.

Consider the circuit connected to a strip detector:

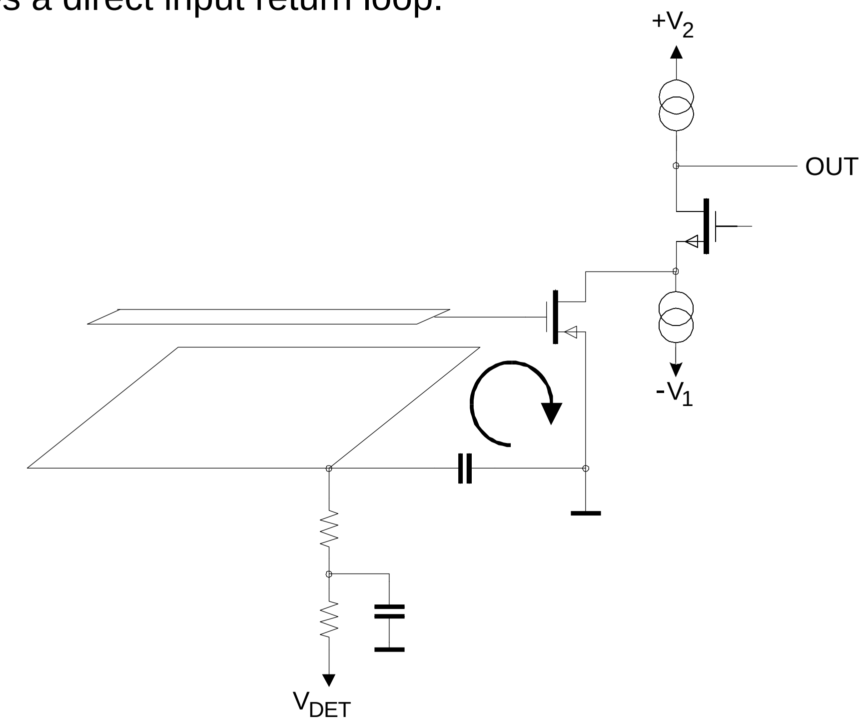


Unless the connection points of the bypass capacitors from the FET source and the detector backplane are chosen carefully, interference will be introduced into the input signal loop.

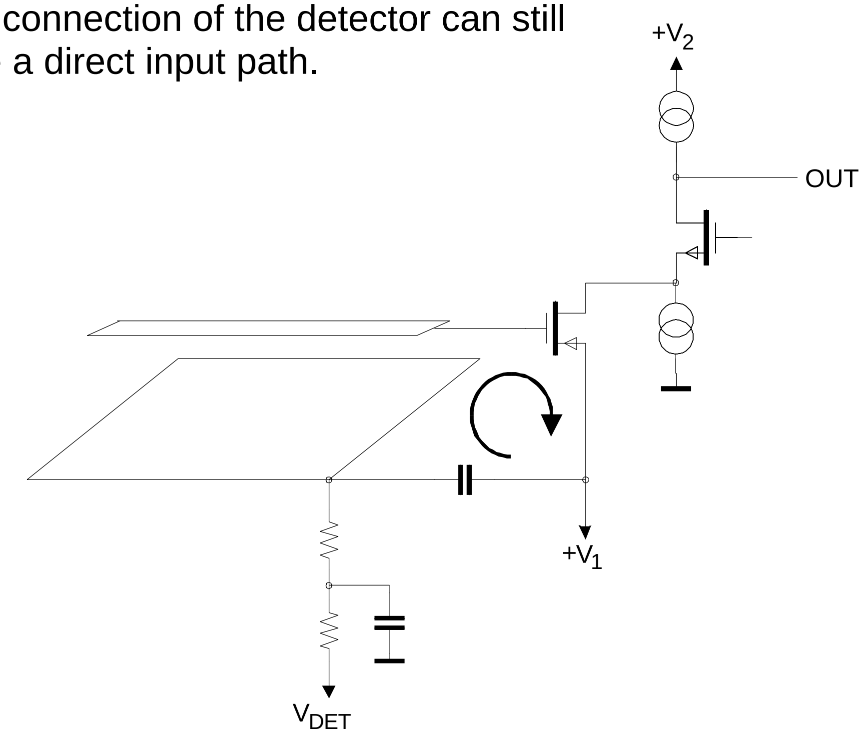
It is much better to “ground” the FET source to a local signal reference and use a negative second supply.



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.



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

System Considerations

1. Choice of Shaper

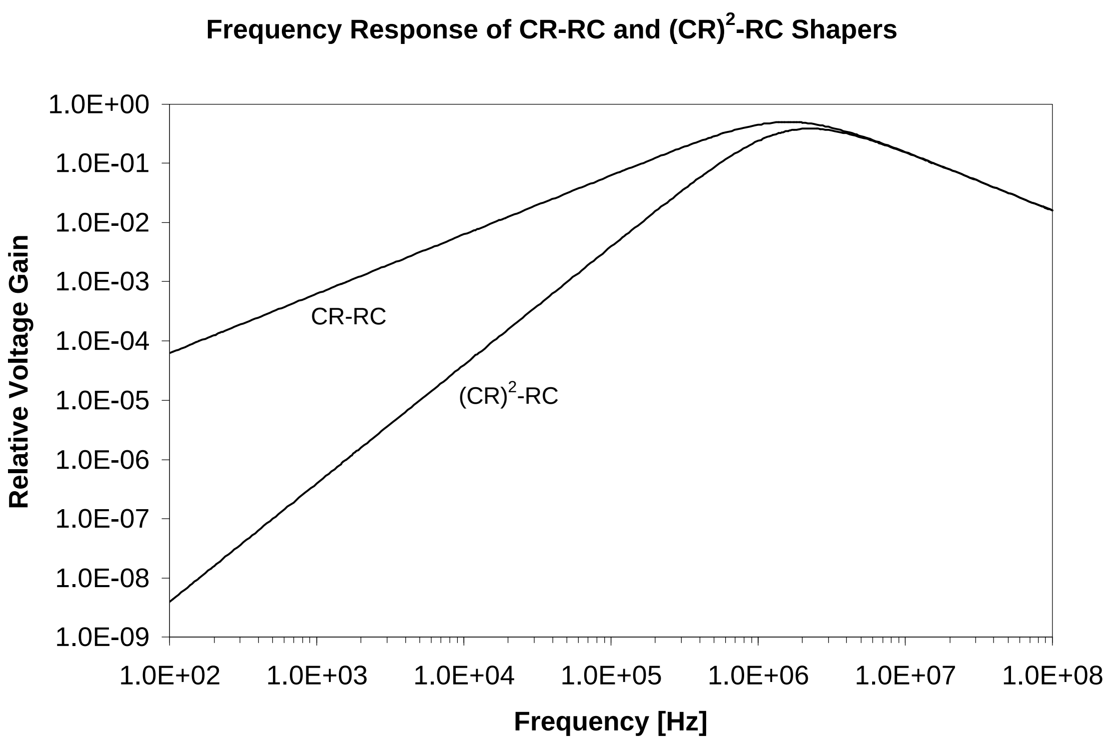
Although a bipolar shaper has slightly inferior noise performance than a unipolar shaper, it may provide better results in the presence of significant low-frequency noise.

Minimum Noise

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

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

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



2. Connections in Multi-Channel Systems

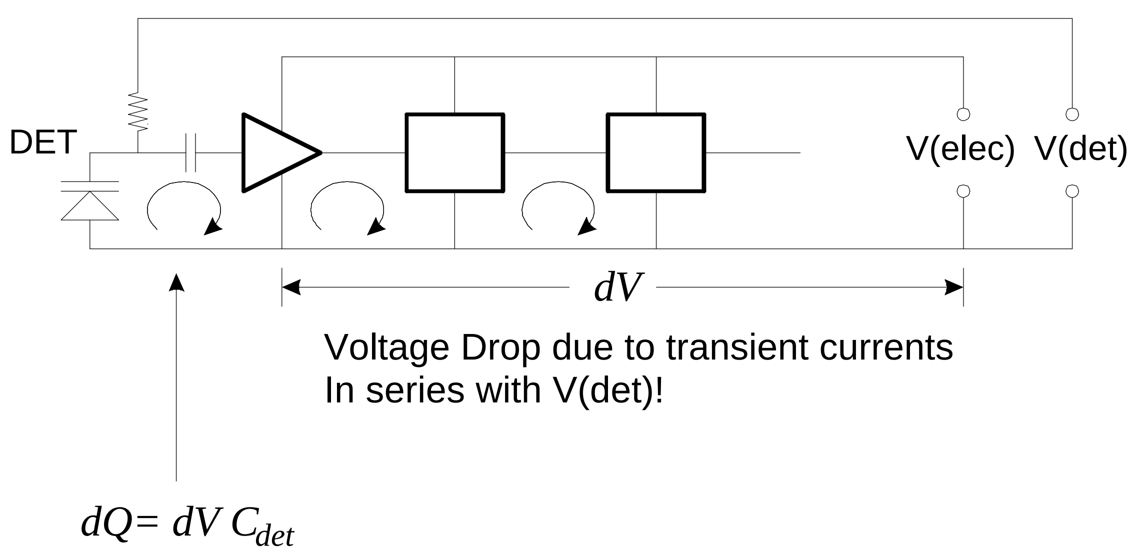
Example: Strip Detector Readout

A single channel of a readout system for strip detectors includes

- low noise preamplification
- additional gain stages
- a comparator for hit recognition
- a clocked pipeline or storage array
- additional multiplexing circuitry to feed the hit flag and possibly analog output signal to the output.

Especially comparators and switching stages inject current spikes into the voltage busses, but even low-level analog stages rely on current changes.

Voltage bussing circuitry on integrated circuitry often has significant resistance, since the lines are narrow and thin, so the current transients cause local voltage changes that can couple into the input.

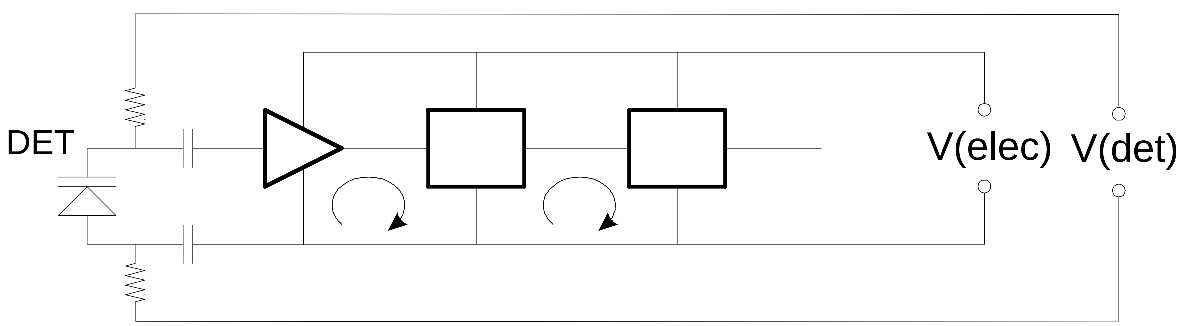


The transient voltage drop dV is superimposed on the detector bias and injects a charge $dQ = dV\,C_{det}$ into the input.

Propagation of current and voltage transients can be controlled by filter networks comprising resistors or inductors and capacitors.

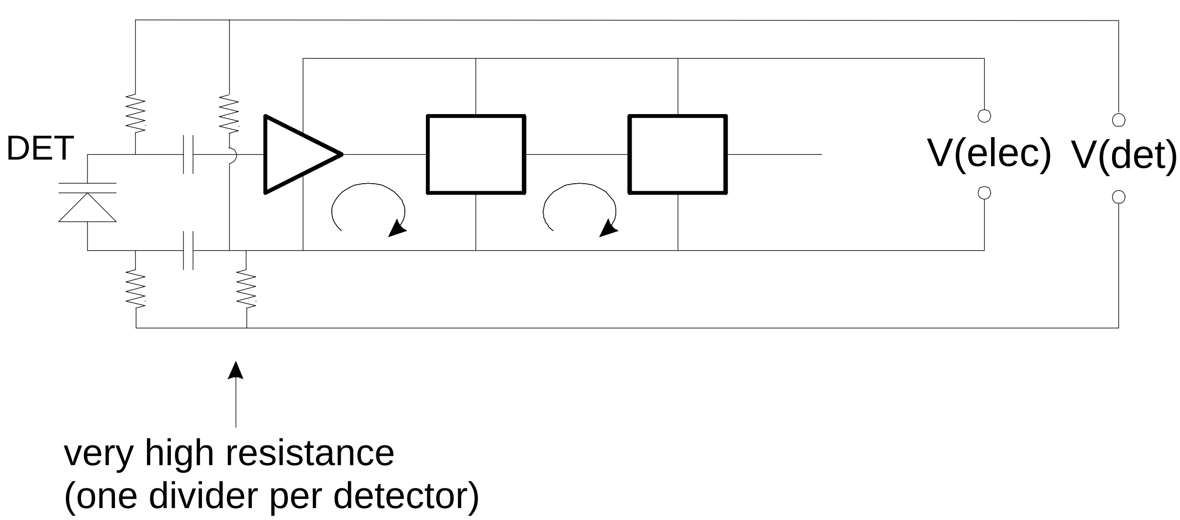
In tracking systems the use of such networks is somewhat restricted, as capacitors can add substantial material and small inductors use ferrite cores that saturate in magnetic fields.

The cross-coupling of detector and electronics voltages can be removed by separating the shared paths:

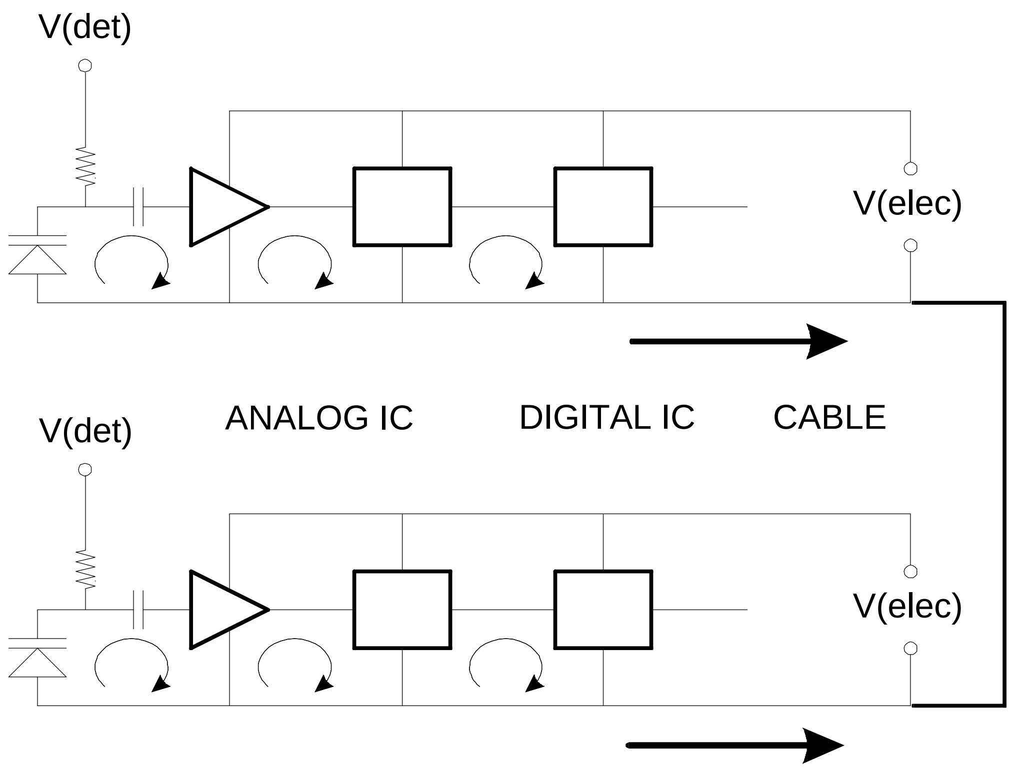


The resistors in both legs of the bias connection isolate the sensitive input node by presenting a high impedance to external signals. Only one of the two capacitors at the input may be necessary, depending on system requirements.

If the detector uses integrated coupling capacitors (often with little voltage margin), the bias and electronics supply voltages must be referenced to one another, for example by a local resistive divider.



Ideally, multiple channels are configured so that only local signal loops exist.



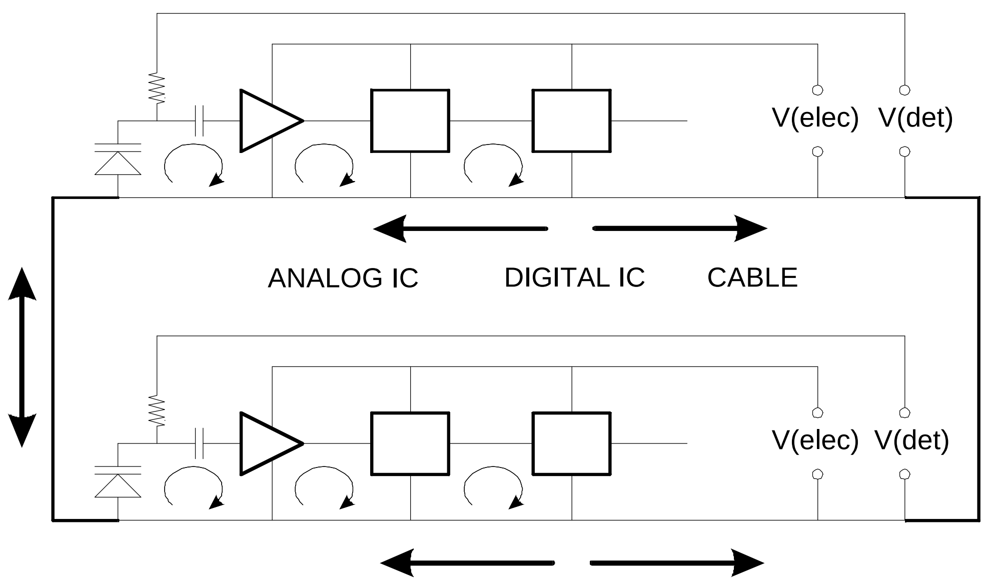
Since the path of least resistance is provided by the cabling and connections to the power supplies and data acquisition system, current transients originating in the front-end circuitry do not flow towards the input.

In reality, the inputs of adjacent channels and chips are coupled by the strip-to-strip capacitance and the common detector substrate.

The loop formed by common connections at both the input and the output allows current transients to propagate to the input.

This is also applies to channels on the same side of the detector.

Consider current spikes originating in the digital circuitry:



Since the cross-connection at the input is formed by the connection of multiple chips to the detector, it is unavoidable.

Breaking the cross-connection at the output is impractical (common data line for multiple chips on a hybrid).

What can be done to break the secondary current path?

Since the most serious current spikes originate in the digital circuitry, it should be isolated from the analog section.

Commonly, the analog and digital supply voltages are fed separately, but this doesn't address the main problem, which is the common return connection (typically the "ground").

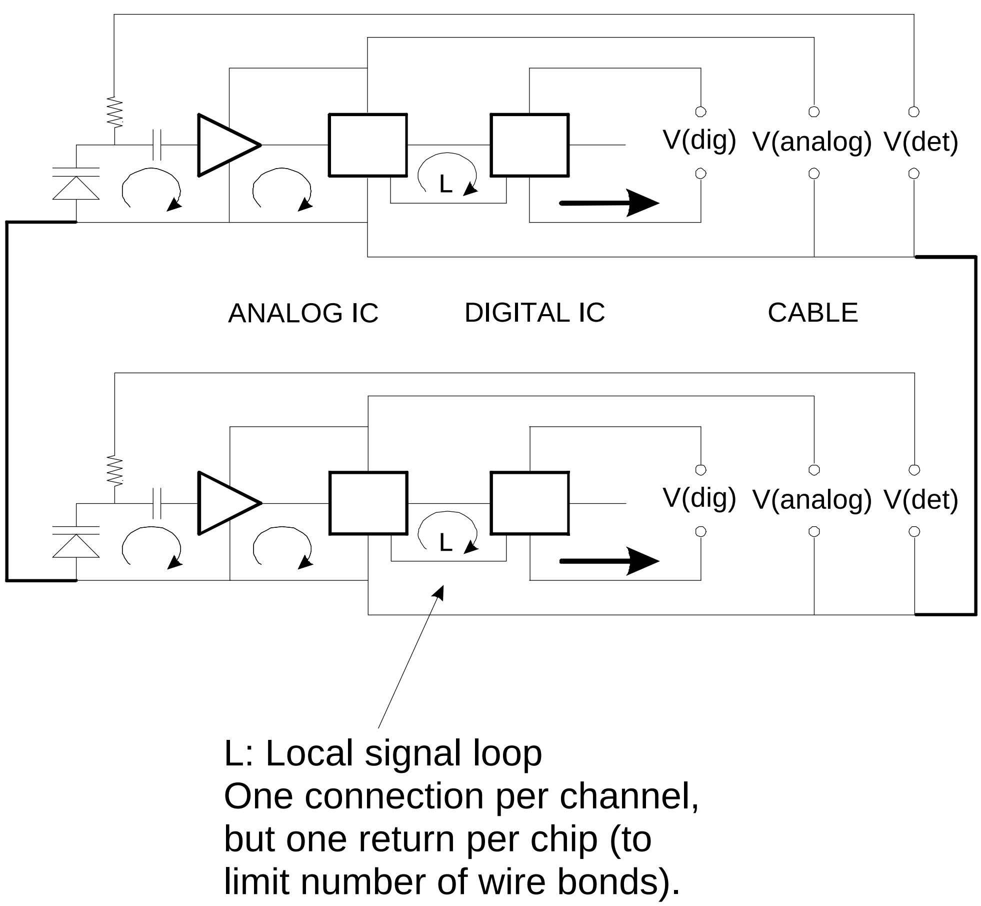
The only necessary connection between the analog and digital circuitry is the data path.

By implementing this in a manner that

- provides a signal path from the analog to the digital circuitry,

  but

- presents a high impedance from the digital to the analog section, i.e. in the opposite direction, the input loop can be broken.



Double-sided detectors pose similar problems.

The figure below represents a double-sided strip detector readout, where the upper electronics chain connects to one side (A) of the detector and the lower chain to the opposite side (B).

Since the signal return path includes

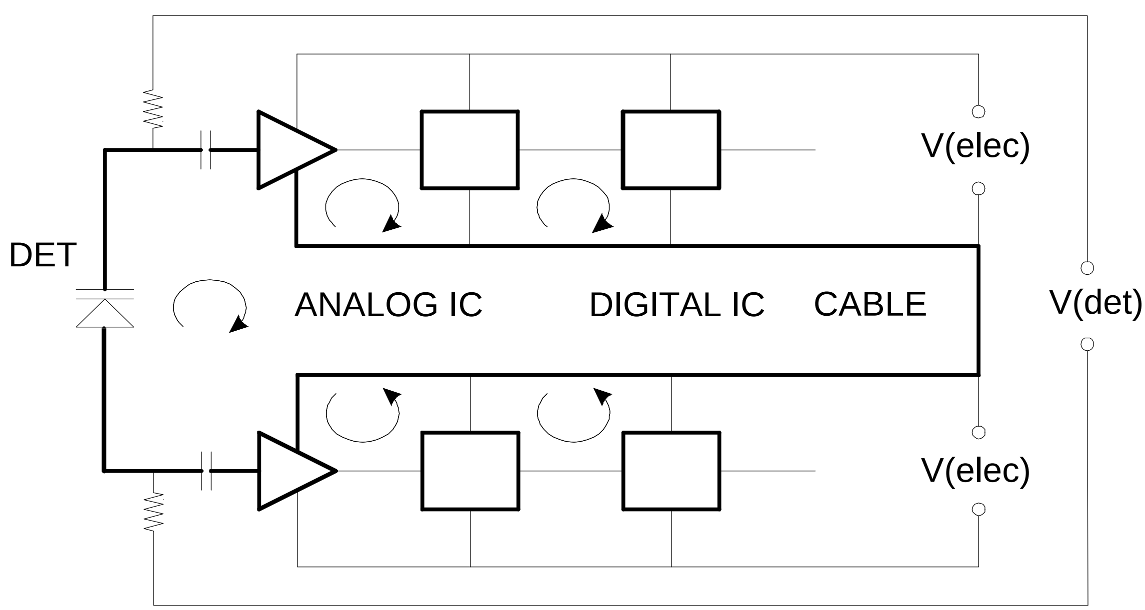
a) the adjacent channels

b) strips on the opposite side

the system must be designed carefully to avoid loops that introduce interference currents into the input circuit.

Typical configuration:

side A



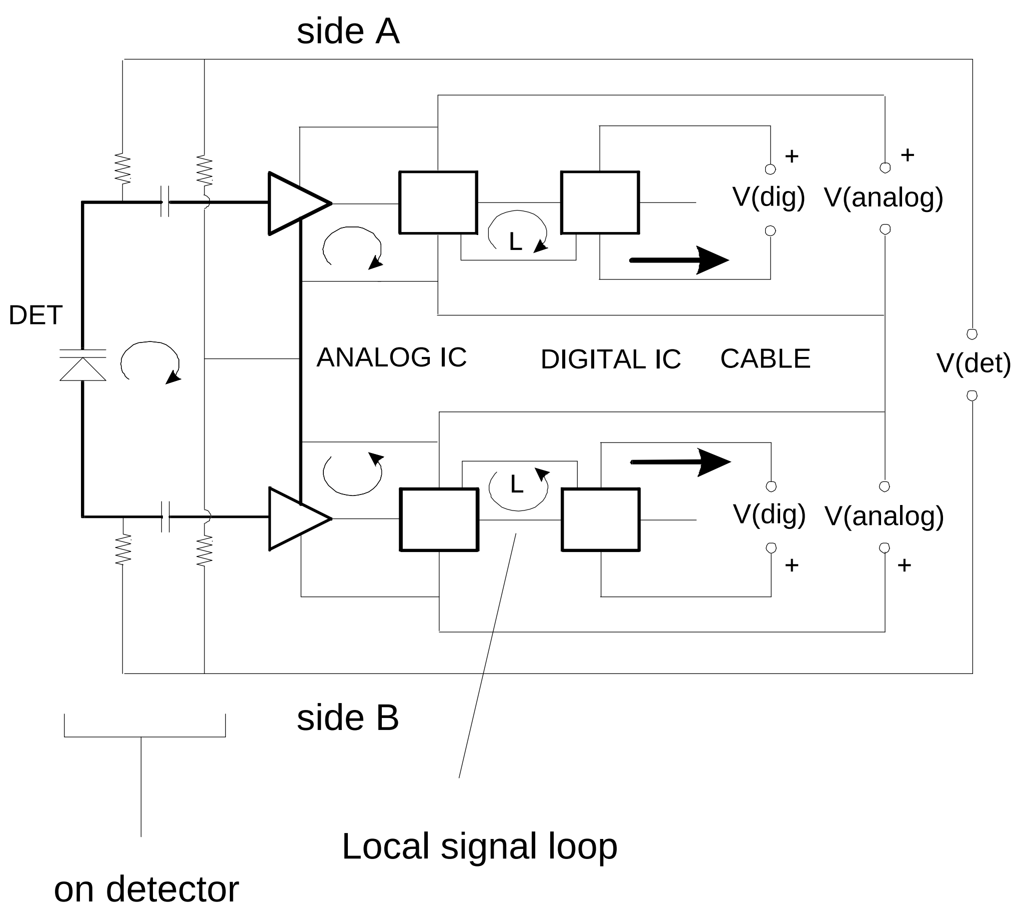
side B

In this arrangement voltage transients formed on the busses of both readout sides couple into the input circuit.

Not recommended!

The technique of using a unidirectional driver with local return loop to isolate the digital from the analog circuitry can also be applied to double-sided detectors.

The double-sided detector is AC-coupled, i.e. it has integrated coupling capacitors and bias resistors per strip. A resistive divider is included for voltage referencing.



Note that the input signal return path is well-defined by incorporating a direct connection between the reference (“ground”) connections of the input stages on both sides.

In the schemes described above it is critical that

- all of the above circuits rely on local signal referencing, rather than “system grounds”.
- the power supply lines are balanced, i.e. both the positive and negative legs present the same (preferably high) impedance to the remote system ground.

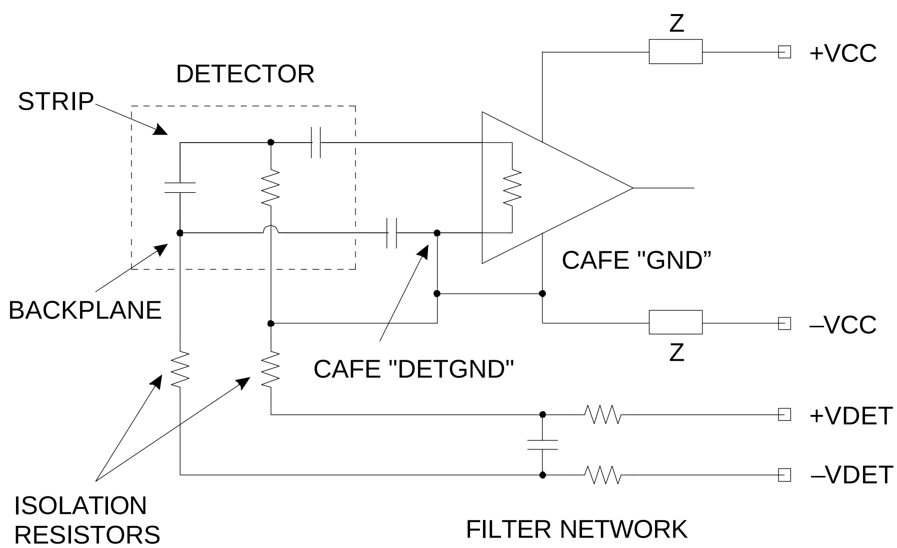
Reducing Sensitivity to External Pickup

The most critical node is the input, and the most vulnerable connection is the one to the backplane, i.e. the detector bias line.

The separate detector bias connection should be implemented as a balanced, differential supply (shown below for the CAFE chip).

⇒ Pickup on the detector bias line couples equally to both legs, so the difference is unaffected.

This requires a “groundless” system, i.e. the impedance Z presented by both the +VCC and –VCC lines to the remote system ground must be much greater than the input impedance of the amplifier.
The isolation impedance Z can be provided by the inductance of long connecting cables, depending on the critical frequency range.



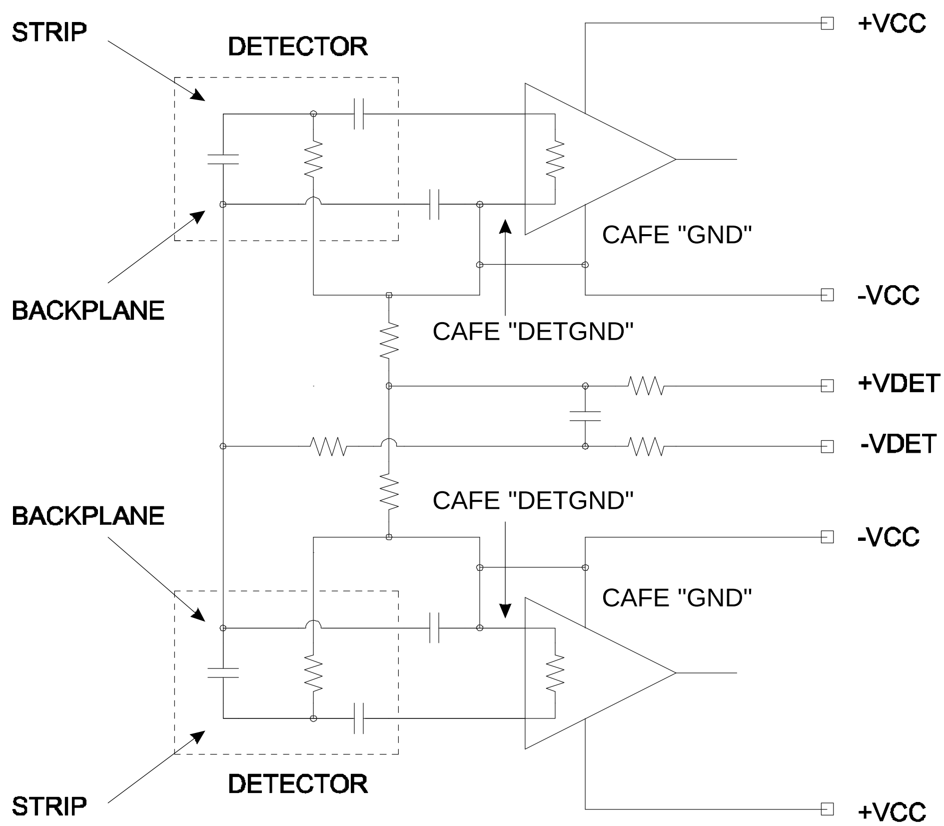
Any differential pickup on the bias line is attenuated by the filter network. Connecting the capacitor between the lines rather than to ground keeps interference currents from flowing to the front-end.

The isolation resistors introduce a high impedance into the bias supply line to avoid formation of a parasitic signal path.

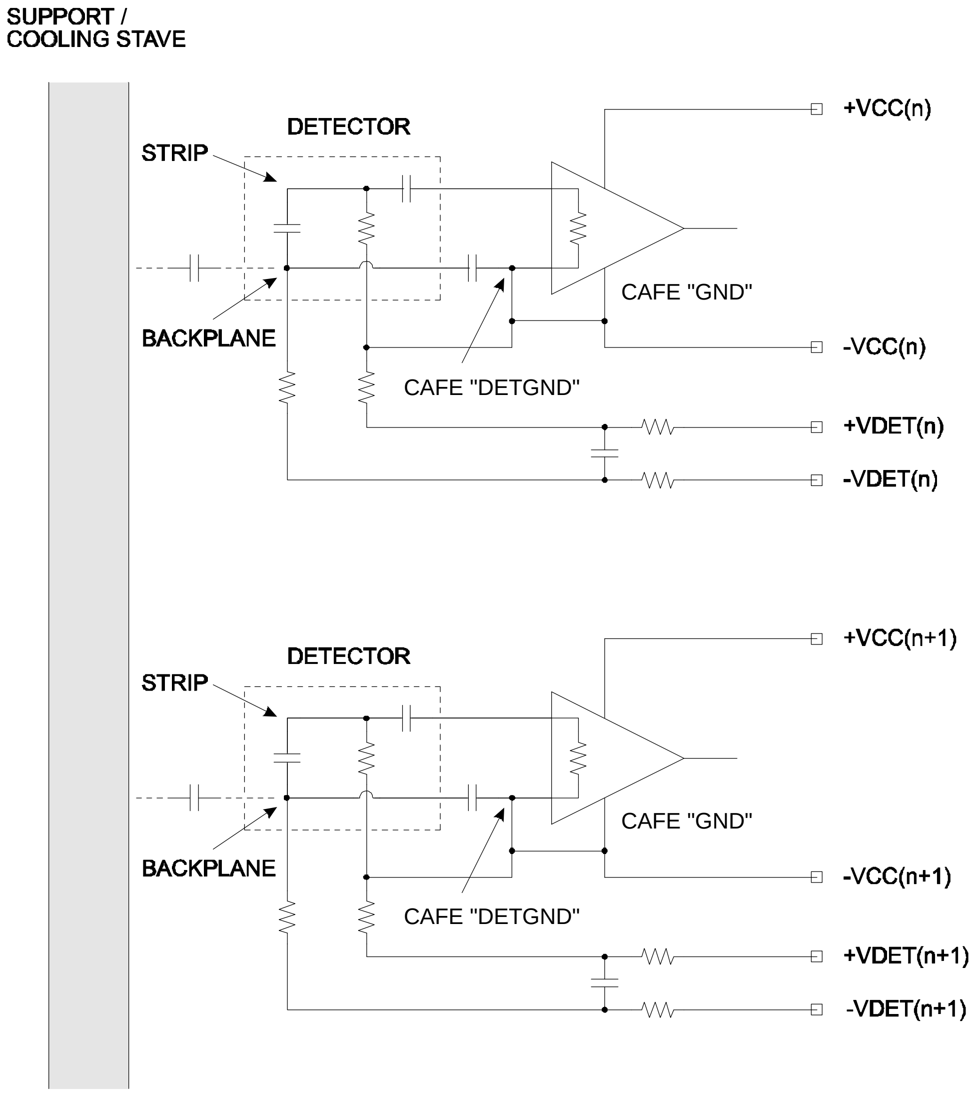
The capacitor connecting the detector backplane to CAFE “DETGND” is usually called a bypass capacitor, but it really is a coupling capacitor that closes the input signal return path.

“Bypass” implies that interference is being shunted to ground, which is the opposite of what is intended here. Since the input common connection is not a zero impedance point, we don’t want to inject any interference into this node.

Differential bias feed applied to a double-sided detector formed by gluing two single-sided detectors back-to-back:



Interference can also be coupled into the front-end through mechanical mounting systems.



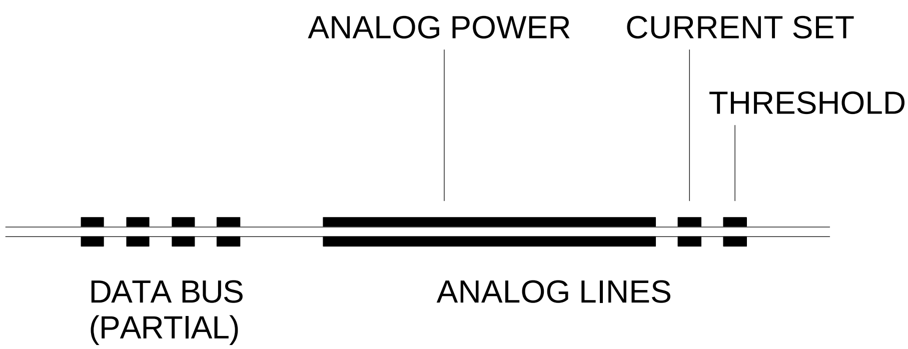
Maximum noise immunity obtains when coupling from the cooling stave to the backplane is a common mode effect, i.e. both the input and the reference node change by the same amount. This requires

- a balanced power bus, such that both +VCC and –VCC lines present the same impedance to the remote system ground,
- that the impedance presented by the +VCC and –VCC lines to the remote system ground is much greater than the input impedance of the amplifier,
- that the two coupling capacitors are much greater than the detector capacitance (strip to backplane).

"Self-Shielding" Cables

In mixed analog-digital systems, radiation from cables, especially digital signal cables, is a concern.

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:	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

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.