A BRIEF INTRODUCTION TO NOISE

The weakest signal that a system can measure (detect, amplify or manipulate) is determined by noise. Noise limits how far you can receive stations on your TV or radio and how small a sample one can use in a scientific investigation. Some knowledge of noise is critical for all but the least demanding circuits.

Noise must be reasonably random since predictable noise could simply be subtracted from our signal of interest. Amplitude and average value are usually useless for characterizing noise. The average value is usually zero and a random fluctuating signal has no well-defined amplitude. The mean square voltage (or current) does not suffer from these problems and is a useful measure of noise.

\[
\text{mean square voltage} = \frac{v_n^2}{T} = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} [v_n(t)]^2 dt
\]

A still more useful characterization of noise is provided by the "spectral density function," \( S_n(f) \). \( S_n(f) \) is the \( v_n^2 \) noise that would result if our noise signal were passed through an ideal noiseless filter of 1 Hz bandwidth with pass frequency \( f \). Since the noise components are random, it can easily be shown that

\[
v_n^2 = \int_{-\infty}^{\infty} S_n(f) df.
\]

Clearly the advantage of a knowledge of \( S_n(f) \) is that one can design his system to use those \( f \) 's for which \( S_n(f) \) is the smallest.

Noise Sources

Noise sources might be roughly divided into two categories, fundamental and "man-made." You can, in principle, do more about avoiding the latter.

Johnson-Noise. Johnson noise is a fundamental noise associated with any resistor. Johnson noise is also known as thermal noise. For Johnson noise
\[ S_n(f) = 4kTR \]

where \( k \) is Boltzmann's constant, \( T \) is the absolute temperature and \( R \) is the value of the resistor. Notice that \( f \) does not appear in \( S_n(f) \). The noise is said to be "white." The formula fails for \( f = kT/\hbar \), but if \( T \approx 300 \) K the associated \( f \approx 3 \times 10^{12} \) Hz. For our frequencies the formula is ok. An actual resistor (many standard composition resistors, for example) may be noisier than this Johnson noise minimum. If their noise is still white, or over a narrow bandwidth, these resistors can be described by a fictitious "noise temperature" which is higher than the true temperature.

**Shot Noise.** Currents are the result of the flow of carriers each of which carries a fixed charge. Statistical fluctuations in the number of carriers flowing result in "shot noise." The current spectral density function for shot noise is

\[ S_n(f) = 2eI. \]

The noise is again white. Since the signal power is proportional to \( I^2 \), the best signal-to-noise ratio occurs at high \( I \), not low \( I \) as might appear to be the case.

**Low Frequency Noise, 1/F Noise, Drifts, Excess Noise.** A whole host of "devices" including transistors, resistors, tubes, the earth's rotation, galactic radiation, etc., show a spectral density noise function which has a frequency dependence of

\[ S_n(f) \alpha \frac{1}{f^\beta} \]

with \( \beta \) varying from 0.8 to 1.3 with 1 its most usual value. The noise is not totally fundamental as far as semiconductor electronics is concerned since the proportionality constant depends on things like surface treatments.

**Vibrations.** Vibrations are "man-made" noise sources which can be avoided in two ways. Either don't shake the circuit or make the circuit insensitive to shaking. Easy to say! Vibrations clearly are the biggest at lower frequencies where vibration amplitudes can be reasonably large. Vibration frequencies above 100 kHz are usually no problem.

**E and M Pick up.** External E and M source may "get into" one's circuit and be a problem. Many of these sources have a characteristic frequency, such as 60 Hz and its harmonics due to ac power line and the rf signals due to radio and television. Some sources are more broad band, for example, the spark noise due to autos.
Living with Noise

The solutions to noise problems are many and varied. The whole subject is so system dependent that a checklist type of solution is impossible. Nevertheless, a few of the more general observations follows. For more details these sources may be useful: "Low-Noise Electronic Design" by Motchenbacker and Fitchen, Wiley; "Grounding and Shielding Techniques in Instrumentation" by Morrison, Wiley; Manufacturers listed under "Low Noise Amplifiers" in the trade publications, e.g., Princeton Applied Research.

**Frequency Choice.** It is clear from the discussion of noise sources that one should avoid low noise attempts at low frequencies or quasi dc because of the 1/f noise disaster. Somehow one must obtain an ac signal of higher frequency to "look at." For example, a low temperature thermocouple puts out a signal in the microvolt range. The noise output of the thermocouple is low since R and T are low. The noise contributed by the amplifier attached to the thermocouple will be entirely dominant unless care is taken. In this case one could "chop" the thermocouple voltage to yield an ac voltage proportional to the old dc voltage.

![Diagram of thermocouple and amplifier system with switch for chopping]

A 60 Hz chopping frequency would be the easiest to obtain, but should be avoided to avoid line pick up problems. In other experiments, ways may be found to "move" the dc signal to frequencies as high as 100 kHz, e.g., magnetic field modulation or light chopping. At 100 kHz the 1/f noise is beaten and vibrations are of little problem.

**Impedance Matching.** In the past you have been warned to avoid loading a source with an amplifier of low input impedance. Now we find that going to the other extreme has its price also. Consider again our chopped thermocouple. Assume the resistance is 1 Ω and the amplifier input resistor is 1000 Ω. Separating each unit into an ideal part and a noise generator we have

![Diagram illustrating impedance matching between thermocouple and amplifier]
For this application the amplifier is terrible. The amplifier contributes 1000 times the noise of the source if both are at the same temperature and more than 1000 times if the thermocouple is at low temperature. We say the amplifier has, in this applications, a bad noise figure, $F$,

$$F = 1 + \frac{\nu_A^2}{\nu_s^2} = 1 + \frac{1000}{1} = 1001$$

or expressed in db

$$N.F. = 10 \log F = 30 \text{ db}.$$  

Impedance matching is needed in our application. Of course, that does not mean one should add 999 $\Omega$ to the thermocouple since that just adds more noise source. Transformer coupling is desirable in cases of low impedance sources. For transformer operation we need ac, but that is what we get by chopping. While the transformer is not without resistance which causes noise, the net effect is a significant gain. An excellent source of good transformers for such applications are the "Geoformer" series by Triad. For example, the G4 will match as low as 1.25 $\Omega$ to as high as 157,000 $\Omega$ over a frequency band of 11 Hz to 5000 Hz. This unit also provides 135 db of shielding against pick up.

**Narrow Banding.**

$$\nu_n^2 = \int \frac{S_n(f)df}{\text{bandwidth}}$$

Noise is minimized by using only the minimum bandwidth needed to transmit the signal. In Lab 10 the output filter of the phase locked loop provided this narrow banding.

In relatively extreme cases bandwidths of 0.1 to 0.01 Hz can be obtained. The technique for achieving such narrow bandwidths will be discussed in the next lecture. Such low bandwidths have a price and that is the information comes in slowly. Recall that modulation, the process of encoding information on a signal, produces sidebands. If a narrow bandwidth is used, only slow variation in the signal can be studied.

**E and M Pick up Shielding.** Shielding out external signals is not as easy as one might think. Just enclosing everything in a conducting can may not work for two reasons: Inductive coupling and connecting leads. At low frequencies (60 Hz is low) the time varying magnetic fields associated with
currents can penetrate a shielded can unless that can is made of magnetic shielding material such as μ metal. Once inside the can the fields generate emf's in loops of the circuit. Transformers are particularly susceptible unless wound for hum bucking and shielded. Leads which enter the enclosure with signals, or power, or grounds can introduce signals into the shielded enclosure.

Ground loops are a particularly important source of interfering signal. Most of Morrison's book is on this subject. We reproduce below John Fluke Co.'s discussion of the guard terminal idea. Besides giving you some idea about grounding problems, this note illustrates another point. There are experts available to help you. Fluke, Hewlett Packard and Princeton Applied Research, to name but three, spend more hours than you can afford solving tricky noise problems. Their (expensive) instruments and their applications information are often the cheapest solution to a noise problem. We also reproduce a brief article by Morrison and a Princeton Applied Research note.
INTRODUCTION

The primary purpose of this Application Bulletin is to show the proper use of the guard (Blue Terminal) and to clarify related specifications. Another purpose of this Application Bulletin is to show how the guard reduces common mode errors. If you are a DVM user, but don't have the time to completely read this Application Bulletin, at least read the answer to the questions, "What happens if I leave the guard disconnected? and Do I need to use a third wire for the guard for every measurement?"

GUARD USAGE

What is the proper hook-up for the guard?
(See Figure 1 below)

Do I need to use a third wire for the guard for every measurement?

No, not all measurements need the third guard wire brought out to the source to be measured. A jumper strap between Lo and Guard at the front or rear panel will do for some measurements as the following general guidelines indicate below:

Third Guard Wire Required:
1. When Common Mode voltages exist
2. When making accurate measurements
3. When making sensitive measurements with resolution below 10uV
4. When using long signal leads
5. When using an input scanner in system applications (Guard must be switched also)

Lo to Guard Jumper Strap OK:
1. When no Common Mode voltage exists
2. When making low accuracy measurements
3. When making insensitive measurements with resolution above 10uV
4. When using short signal leads

Also note that the third wire for the guard can be the shield of a two conductor shielded cable.

What happens if I leave the guard disconnected?

DON'T! If you do, one of two things can happen. You will end up either calling the Fluke Sales Department complaining of incorrect readings or you will be unhappyly calling a Fluke Technical Service Center to get your DVM repaired. Here's why. Leaving the guard disconnected, in the presence of a common mode current, will allow the current to flow in the signal leads through the series combination of the Lo to the Guard (CLG) and Guard to Chassis (CGC) capacitances and through the stray capacitance from the sensitive points in the DVM's amplifiers (the guard now being somewhere between Lo and Chassis potential), both of which will cause reading errors (almost guaranteed). The DVM can also be destroyed by leaving the guard disconnected because the voltage stored on the Lo to Guard capacitance (CLG) may exceed the 100 volt maximum due to static charge accumulation or by the current supplied by an added common mode voltage.

Most Fluke DVM's and many others are rated for only 100 volts breakdown between Lo and Guard. A high common mode voltage could cause a greater than 100 volt condition from Lo to Guard due to the divider action of the Lo to Guard and Guard to Chassis capacitance and leakage resistances. All guarded Fluke DVM's can make a floating-guarded measurement to 1000 volts or 1200 volts (depending on the model used) above chassis (power line ground).

What do I do with the guard during accurate, 4-wire resistance measurements especially when the unknown resistance is at ground or at some potential?
(See Figure 3)

For high value resistance measurements, a Guard Shield can be added around the unknown resistance (connect to Guard) to reduce noise pick-up.

What do I do with the Guard during non-critical resistance measurements?

Leave the Guard strapped to LO at the front panel.
Does guarding apply to a Digital Thermometer?

YES, a digital thermometer is essentially a DVM that measures the voltage produced between two junctions of two dissimilar metals. The DVM also must linearize the non-linear output of a thermocouple but still needs to be properly guarded (See Figure 5 below).

Figure 5

For accurate measurements in application where there is a large common mode voltage present (example-thermocouple attached to a power transistor collector), the guard wire should be attached to the low thermocouple leads as close to the junction as possible without causing a temperature gradient at the couple.

What do I do with the Guard for a bridge hook-up?

For a bridge, refer to the hook-up shown in Figure 6 below.

In this application, a guard driver amplifier is required for accurate measurements, especially for AC measurements. The function of the guard driver amplifier is to minimize the loading at point A while driving the DVM Guard and
cable shield at the same potential as that at point A. If the Guard is attached directly to point A (which can be done for lesser accurate measurements), the Guard to Chassis impedance will load point A (typical impedance is 100 Megohms/200pF for a plastic cased DVM and 100 Megohms/5000pF for a metal cased DVM).

The guard driver amplifier should be selected with enough output drive capability without oscillating to drive the DVM’s Guard to Chassis capacitance and also to have high input resistance and low input capacitance. It should be hooked-up in the unity gain non-inverting mode. The amplifiers power supply common must be connected to point B, not to the DVM.

An intermediate solution would be to replace the Guard Driver Amplifier with a third pair of resistors to drive the guard. The ratio of these resistors should provide a voltage nearly the same as at point A. The impedance of these resistors should be low compared to the Guard to Chassis impedance.

In general, for all three hook-ups, the Lo lead of the DVM should be connected to the mid-point of the bridge which has the lowest impedance to ground.

What other applications require a guard driver amplifier?

Most off ground accurate ac measurements need a guard driver amplifier (See Figure 7 below).

![Figure 7](image)

Note also that the difference in loading capacitance and loading resistance across each attenuator resistor must be compensated for. The typical input impedance of a DVM in the ac volts mode is 1 megohm/100pF.

Do all DVM’s Have a Guard?

No, a typical 3½ digit DVM is not sensitive enough to require one. Generally, a 4½ digit DVM with a plastic case doesn’t require one because of its small capacitance between Input Lo and Power Line Ground.

What happens when I use a battery operated DVM?

Using a DVM on battery power (or using a floating source) with the power line disconnected, almost completely eliminates the common mode current and any errors it causes. How well it is eliminated will depend upon capacitance and leakage resistance (spacing) to Power Line Ground. Don’t forget most electronic instruments and metal bench tops are at Power Line Ground.

COMMON MODE SPECIFICATIONS

How do I interpret the 120dB or 140dB CMRR spec?

120dB is a ratio of 1,000,000 to 1 and 140dB is a ratio of 10,000,000 to 1. For example, if 100,000 millivolts is to be measured with one microvolt resolution (5½ digit DVM), then a DVM with 120dB of common mode rejection would allow up to one volt peak of common mode voltage before a one digit (1μV) error would be seen

$$\frac{1V}{1\mu V} = 1,000,000:1$$

A DVM with 140dB of common mode rejection would allow 10 volts peak of common mode voltage, etc. (See Figure 8 below).

![Figure 8](image)

Note that the common mode voltage added must also include any difference in potential between the ground lines.

What does 1 kilohm unbalance resistance mean?

It means that either the Hi or Lo lead may have up to 1 kilohm in series with it while still meeting the common mode rejection spec. Some applications require an unbalance resistance. Note that some DVM’s specify the 1 kilohm resistance in the Lo lead. This is because the Lo lead is more critical to common mode currents.

Also note that for ac measurements and some other DVM’s, 100 ohms unbalance is often specified instead of 1 kilohm. A DVM that does not specify an unbalance resistance means
that it can not be used with an unbalance resistance without degrading the Common Mode Rejection Specification.

GUARD THEORY

The purpose of the guard is to reduce common mode currents which in turn will increase the Common Mode Rejection of a DVM (Reduce Common Mode Errors) for DC, AC and Resistance measurements.

What is Common Mode?

It is a current between a DVM and the source being measured that causes errors in the measurement being made (See the Simplified Block Diagram, Figure 9).

![Figure 9](image)

The distributed capacitance (AC) and the leakage resistance (DC) associated with the power transformer and between Input Lo and chassis \( C_L \) in the DVM, cause a current to flow from the AC power lines through the grounding system through the similar capacitance and leakage resistances of the source to be measured. The common mode current flows through the Hi and Lo leads causing a voltage drop across the lead resistances. The DVM sees the voltage across the source plus the voltage across the lead resistances, thereby causing an error especially for sensitive measurements.

Common mode currents also cause errors that are different from instrument to instrument. The current through the capacitance and leakage resistances from critical parts of the DVM's sensitive amplifier to the chassis causes errors.

Figure 9 also shows how non-isolated analog outputs and non-isolated digital outputs can cause common mode currents via external digital and analog equipment. Besides line frequency common mode currents, non-isolated digital outputs create digital pulse type common mode currents thru externally connected equipment such as a computer.

How does the Guard help?

By adding a guard shield (metal-box within a box-type construction), the common mode current is reduced considerably but only when the guard is properly connected. (See Figure 10 below)

The guard shield also surrounds the secondary winding of the DVM power transformer utilizing a foil type shield with the secondary winding wound completely separately from the primary windings and other secondary windings that feed digital circuits outside of the guard. By doing this, the capacitance from the guarded secondary winding to the primary winding and the transformer core can be kept typically below one picofarad. This causes a reduction in the common mode current.

Another reduction in the common mode current effect can be made, however it is up to the user to accomplish. By attaching a third wire to the Guard terminal and to the Lo terminal of the source to be measured, a low impedance path has been formed that will shunt the remaining common mode current out of the Lo and Hi leads. Note that the Hi lead is
Figure 10

not as sensitive to the common mode problem because it has less capacitance and leakage resistance to guard or chassis than does the Lo lead for most DVM's.

Common mode currents caused by digital outputs and remote control inputs are minimized by using guarded pulse transformers or photo isolators. Note that a good guarded DVM actually has three commons; Chassis Ground (Power Line Ground), Input Common (Lo), and Digital Output Common. Analog outputs are more costly to provide because they require a modulator/demodulator approach or a D to A converter approach to isolate the commons. This is why isolated analog outputs are not found on isolated (Guarded) DVM's.
Noise-free systems are difficult to design. Unless the engineer understands where every disturbance is generated he cannot take measures to isolate his signals. If those disturbances are ignored the system will suffer.

A system can be considered to be an interrelation between transducer, instrument, recorder and man. In the case of man - instrument systems, errors may be caused by human deficiencies, such as misreading meters, etc. In transducer - instrument systems, errors may result from ground loops or common-mode problems.

This paper will discuss isolation in terms of the latter class of problem. Isolation from human errors or radiated rf interference, although very important, will not be discussed.

Systems that are small enough to be contained in one chassis can usually be "diddled with" until the system is "clean". Larger systems usually cannot be "diddled" successfully since they may involve many amplifiers, long cables, many types of transducers, and usually grounded recording devices such as tape recorders or computers. This is where most system designers lose their hair because once amplifiers, transducers, and cable runs have been installed, the pieces are not easily modified. Cables cannot then be redesigned with the hope of an improvement. All the transducers cannot be exchanged for different types nor can the transformers in the instruments be replaced with balanced or shielded types. Many a system designer has been in this dilemma. "If only I had ordered differential amplifiers" is a common complaint. (But by this time all the allowed funds have been spent).

The usual reasons that large systems are troublesome are as follows:

1. The resistances of long cables cannot be neglected.
2. Ground connections are inductive as well as resistive.
3. Obscure and unsuspected capacitances permit reactive currents to flow.
4. Transformers are sources of emf's which cause reactive currents.
5. No two ground points are at the same zero potential.
6. No two engineers will agree on how to ground a large system.

Large systems processing high signal levels can readily be built substantially free from difficulties. Freedom, however, is a relative thing. The Edison Company rarely suffers from common-mode problems. Engineers trying to "rescue" millivolt signals at the end of a 1000 foot cable will have troubles because "insidious mechanisms" are at work to destroy their efforts.
The major source of difficulty is current flow in low-level input lines. This can be very troublesome in systems where line resistances must be high as in the case of thermocouples. The unwanted IR drops produce input signals not generated by the transducer. This current flow can be caused by power transformer emf's, ground potential differences, or induced magnetically from power currents. Even in systems where all obvious loops are eliminated, capacitances permit currents to circulate.

For example, a floating transducer can permit current to circulate through its capacitance to ground. Extraneous currents of a few tens of microamperes flowing in a hundred ohms or less can result in noise voltages in the millivolt range, comparable to the full scale output level of many transducers.

Figure 1 illustrates this problem clearly. Consider a floating transducer connected to a single-ended amplifier. The power transformer is shown external to the amplifier for purposes of discussion. Note that one shield is tied to the signal-common of the amplifier. Note the shield-to-primary capacitance shown tied to an average point on the transformer primary.

![Figure 1](image_url)

**Figure 1**
Unwanted Flow of Ground Current with Floating Transducer

A current will circulate as a result of the average potential to power ground in the following manner: Input ground - through the transducer capacitance - through the input ground line to the shield - through the winding capacitance - through a 50 volt emf at 60 cps, to the power ground and returned to input ground through the earth system. 50 volts can easily circulate 100 microamperes here and a 10 ohm input line will produce 1 millivolt of hum at the input to the amplifier (a very large hum voltage for many systems).

The solution to this problem involves guarding the transducer or introducing a second transformer shield. The first method "guards out" the transducer capacitance to ground. The second method eliminates the 50 volt generator. The first approach cannot be taken if the transducer must be ohmically associated with an input ground. Fig. 2 shows the guard method and Fig. 3 shows the added shield in the transformer or the ungrounded input.
Note that in Fig. 3 all the capacitances still exist but the 50 volt emf has been side-stepped. From this discussion, it is almost axiomatic that low-level instrumentation amplifiers should have double-shielded power transformers. If only one shield is used and it is tied to power ground, the power-line emf is eliminated but the secondary windings must be balanced carefully to eliminate a secondary-to-power-ground emf from appearing. This balancing in construction is possible but other problems in constructing low-level amplifiers usually results.

In the above discussion a system problem exists but the trouble really lies in the amplifier. If the amplifier is not suitable for operation with a few ohms in its ground lead then it is not useful in this system. This class of problem is typical. Amplifiers with one shield will perform well on the test bench, but work poorly in a practical system.
A working set of rules for single-ended instrument designs compatible with typical systems problems at low level are as follows:

1. Each amplifier power transformer should have two shields. The primary shield should be tied to power ground and/or rack ground and the secondary shield to the amplifier ground.
2. All amplifiers must have separate, integral, power supplies.
3. The amplifier shield should be floating and insulated from cabinet and from other amplifiers but tied to the signal-common of the amplifier.

Rule 2 eliminates an obvious ground loop between adjacent signal channels. Rule 3 means that only the proper ground potential shields the low-level circuitry of the amplifier.

Differential Amplifiers

There are many amplifiers that qualify as differential amplifiers:

1. They may be differential in or out or both.
2. They may or may not have a common or ohmic tie between input and output.
3. They may be isolated from power supply ground at the input or output or both.
4. They may have any combination of these characteristics.

In the majority of situations, differential amplifiers are used to amplify a difference signal - not a differential signal. A problem usually occurs when the transducer is physically associated (capacitively or by ohmic tie) with one ground potential (the device under test) and the recording end is grounded to a local or instrument ground. The ground difference of potential (common-mode signal) is the unwanted signal that must be rejected by the amplifier. Many people consider that the input signal is differential with respect to the output ground. Any viewpoint is permissible - but getting-down-to-cases, the recorded signal must duplicate the input signal and disregard the ground potential difference.

The question often asked is: "Why not short out remote ground points to eliminate the ground difference of potential?" Skin effects at 60 cps and line inductance both limit the impedance level. Currents circulate in the ground tie and the common-mode voltage is simply reduced not eliminated.

If the ground ties cannot be shorted out, one must then ask how well must they be severed to eliminate the common-mode problem. If the hum level at the input is to be kept below 10 microvolts for 10 volts common-mode signal and if there is 100 ohms of unbalance, the common-mode current must be limited to 0.1 microampere. The impedance level is then 100 megohms and this is a minimum requirement.
Many practical systems require up to 1000 ohms unbalance and the capability of handling 50 volts of common-mode potential. Fig. 4 shows a typical system with line resistances. These resistances can also include transducer unbalance.

![Diagram of a system showing transducer, resistors, and amplifier with line resistances and output voltages.](image)

**Figure 4**

Use of Differential Amplifier to Prevent Flow of Unwanted Ground Current

If currents flow from $E_1$ to $E_2$ through $R_1$ and $R_2$ and $R_1$ differs from $R_2$ then the difference emf is amplified and presented to the load. Isolation at 60 cps involving impedance levels higher than 100 megohms obviously means that the only permitted paths are small capacitances of the order of a few picofarads.

Another solution to the problem involves balancing the input lines so that $R_1 = R_2$. In this way the current flowing from $E_1$ to $E_2$ does not cause a difference signal to appear at the amplifier input terminals. It is easy to see that the more current that is permitted to flow the closer $R_1$ must be balanced to $R_2$.

The following very severe problems arise if any balancing is required:

1. Balancing must be the same at all frequencies as difference potentials are rarely sinusoidal.
2. Balancing after installation is often impossible since actually driving grounds with a signal generator can be impossible in an actual system.

Some systems can have ground potential differences that only arise during the test. Ground potential difference can stem from a large variety of situations such as:

1. Starting of ac machinery.
2. Explosions.
3. Atmospheric phenomena.
5. Rain
Amplifiers with low leakage paths between input and output can be built using a guarding philosophy. The source or input ground potential drives a floating shield that surrounds all input circuitry. This insures a minimum leakage path for current to the output ground. If power grounds must be guarded, the power transformer would have to be at least triply-shielded. Signal information must then be transformer - coupled out of the amplifier guard-shield by some form of a carrier system as shown in Fig. 5.

\[\text{Figure 5}\]

Note that the only leakage path for current flowing between \(E_1\) and \(E_2\) in the input lines is through the guard-shield. Leakage paths below 1 picofarad can be attained with careful design. This places a burden on the user of such a device. The input shield system must be electrically tight. A leakage path of 1 pf to a foreign ground system will permit common-mode current to flow and this will result in a considerable reduction in performance.
Isolation Problems In Strain-Gage Power Supplies

The complications of designing a good strain-gage power supply comes as a shock to the young engineer.

The need for tight isolation and shielding specifications becomes acutely obvious to the system designer particularly after he purchases a so-called good supply and it causes a "noisy" system. The big problem is what to specify and why. The designing engineer must know why and how to solve isolation problems if his instrument is to operate satisfactorily in a system.

The basic difficulty can be simply stated: A strain-gage power supply that is power-line operated has capacities through its power transformer to the primary 117 volts ac. Also, neither side of the power supply output is grounded when it is used to power a strain-gage. (Here, we are assuming that a single-ended amplifier is used to amplify the gage output.)

Figure 6 shows a typical interconnection. If any unwanted current flows in the gage arms between amplifier common and power supply common, unwanted pickup results. The current causes a voltage drop across the gage arms and introduces an unwanted signal into the amplifier.

![Diagram of power supply and amplifier](image)

Figure 6
Flow of Unwanted Current in a Strain Gage Bridge Through the Direct Transformer Capacity

To help eliminate the flow of current caused by the transformer, an electrostatic shield tied to the primary ground can be placed into the power transformer of the power-supply. This reduces one problem but places the balancing of the transformer into focus.

Figure 7 shows the flow of current through the gage arms after one shield $(S_1)$ has been added.
Figure 7
Addition of Single Shield ($S_1$) to Transformer

Note that if $C_1$ and $C_2$ were balanced, the resulting current could be quite low.

It is quite proper to ask the obvious question: Can the transformer be adequately balanced? A simple calculation will disclose the answer to this question.

If a 1000 ohm gage resistance is used, and we want the hum pickup to be below the noise level of the amplifier, the pickup level should be below $2\mu$ volts rms. (Good instrumentation amplifiers typically have a noise figure of $10\mu$ volts rms.) A $2\mu$ volt noise figure implies a current flow of less than $2\times10^{-9}$ amperes assuming a transformer voltage of 10 volts. The capacities would have to balance to within 0.05 pf to keep the current below $2\times10^{-9}$ amperes.

This is obviously difficult, even with external balancing schemes, and dictates a second shield in the transformer tied to the power supply common.

The flow of ground current has not been fully eliminated but the current that does flow is not influenced by any of the transformer voltages.

Figure 8 shows the second shield ($S_2$) addition and the remaining current flow caused by the difference in ground emf's between power ground and instrumentation ground. This current is only damaging because it flows in one of the bridge arms.

If a shunting path were provided for this current, our problem would be essentially solved.
Figure 8
Addition of the Second Shield (S₂) to Eliminate the Requirement for Transformer Balancing

This shunting path can be provided by adding a third shield to the transformer. This shield serves a second important function. It completes the electrostatic enclosure of all circuits attached to the input line of the amplifier. Figure 9 shows the third shield (S₃) and the closure of the shield surrounding the amplifier. Note that current does not flow in the bridge arms as in the previous example.

Figure 9
Addition of Third Shield (S₃) and Electrostatic Enclosure of the Input System.

It might be argued that with the addition of shield S₃, shield S₁ is no longer required. Shield S₁ still eliminates a large reactive current component since the average ac potential from the primary to the closest shield is one half the primary voltage. The resulting current flows in the signal input shields or in the signal-common leads depending on shield connections. Thus the omission of the primary shield (S₁) can be troublesome in many system application.
Fewer shields can only be used in limited applications and quite often force the engineer into "fiddling" with grounds and shields.

The conclusion to be reached is that strain-gage power supplies should be triply-shielded to provide good system performance.

CONCLUSION

Ground-loops must be carefully weeded out in system design. Many loops are hidden from view and they involve transformer voltages and unsuspected capacitances. Careful instrumentation selection can help to eliminate some of these problems.

Systems can be made clean. If basic trouble is inherent in one instrument of the system it may be impossible to find a solution through any combination of ground practices. The entire system must be thought out in detail with each and every source of unwanted current given its proper treatment.
GROUNDING AND SHIELDING IN ELECTROCHEMICAL INSTRUMENTATION—SOME BASIC CONSIDERATIONS

I. INTRODUCTION
As long as man has tried to process electronic data, he has been plagued by contamination of that data by electromagnetic fields and their induced voltages on instrument chassis. The smaller the signal of interest, and therefore the more sensitive the instrument, the greater has been his difficulty in dealing with electromagnetic interference. Probably worst and most common among the possible sources of interference are fields produced at the power line frequency and its harmonics by wiring and machines using power.

This paper is designed to acquaint the user of P.A.R.C. electrochemical instruments with basic considerations in grounding and shielding which might be required in any experiment. There has developed a considerable art in the application of recognized engineering principles to ground and ground loops. Commensurate with that, there is an aura of black magic surrounding the identification of noise sources, and determination of the appropriate combination of techniques to best combat their resultant interference. Having read this paper, one should be equipped to solve the basic grounding difficulties which cause the majority of experimental problems. More importantly, effective communication with more experienced practitioners should be possible, aiding in the solution of the remaining small percentage of interference problems. It should be stipulated that at the outset that that small percentage constitutes by far the most esoteric and difficult set of interference conditions, and that it is this group that has led to the general aura of "art" or "black magic" that surrounds grounding and interference.

II. GROUNDING AND SAFETY
Good engineering practice, as well as the electrical codes in most countries, requires that the chassis of all instruments in a system be at the same potential in order to prevent shock hazard to the operator. Typically, this is accomplished by connecting every chassis to the power line ground via a third wire in the power cord.

The existence of that power line ground is assumed throughout our discussion, even though, in some cases, it contributes to ground loop problems. IN NO CASE "SHOULD THE CHASSIS OF ANY INSTRUMENT BE ALLOWED TO FLOAT. POWER LINE GROUNDS MUST NOT BE REMOVED OR BROKEN. DOING SO CONSTITUTES A LIFE THREATENING PROCEDURE.

III. GROUND LOOPS AND POWER LINE INTERFERENCE
Although safety requirements dictate that instrument chassis be at the same potential, ohmic losses in the grounding circuits actually result in those chassis being only satisfactorily close to the same potential to remove the shock hazard. More often than not several hundred millivolts difference will exist between two chassis in the same experiment. When those instruments are connected together with a signal carrying cable, a closed circuit is set up, and currents flow, as in Figure 1.

![Figure 1. GROUND-LOOP INTERFERENCE](image)

The amount of current which flows in the loop is a function of the potential difference which exists between the chassis, and the resistance of the cable shield. Since the instrument in our figure senses the potential difference between the shield and center conductor of the input circuit, the ac voltage developed across the shield adds with the signal.

A question of semantics arises when one discusses "grounding". The problem in Figure 1 is not one of bringing all chassis to Earth potential, but rather, bringing all chassis to the same potential. The term "ground" is used indiscriminately in both contexts. Throughout this discussion, wherever a direct Earth connection is involved, the circuit involved will be described as "Earthy". Grounded, on the other hand, implies a common connection among instruments aimed at bringing them closer to the same potential. Being "Earthy" does not necessarily imply that instruments are satisfactorily "grounded", and vice-versa.
Power line grounds, water pipes and direct Earth grounds all can be demonstrated to be above ground by some finite dc resistance. In addition, as the frequency increases, the length of the ground path becomes more significant. The power line grounds are all eventually Earthed; and all are eventually bonded together within a given building. But two outlets on the same wall can easily travel hundreds of feet before their grounds come together. There is little wonder that measuring between power line "grounds" on different sides of a room can sometimes show several volts difference!

**MINIMIZING POTENTIALS BETWEEN CHASSIS**

All power cords from all instruments in an experiment should be connected to the same wall outlet. If necessary, use an industrial type multi-outlet cable, plug all instruments into it, and it in turn into the wall outlet. This way, all instruments chassis will be one power cord length from the same point. (Be sure to include pumps, stirrers, and all associated equipment, as they can be significant noise interference sources.)

**THE POWER CORDS SHOULD BE ROUTED TOGETHER, AWAY FROM ALL SIGNAL BEARING CABLES AND INSTRUMENTS NOT IN THE SYSTEM.**

Once these basic precautions have been taken, we can seriously begin examining the symptoms of differing chassis potentials—namely, ground loops. The first approach is designed to reduce the amount of current flow through signal circuit braids by providing additional paths. This is often called the "strap-them-together approach" (Figure 2), and it has a number of different configurations. The easiest is to use a large sized (=10 or larger) copper wire, making direct connections between all chassis in the experiment, following the shortest possible path (2-3 feet at most). Connecting that to the laboratory cold water pipe at the nearest point or to power line ground at the nearest outlet sometimes also helps reduce chassis potentials.

![Figure 2. THE STRAP-THEM-TOGETHER APPROACH](image)

Another arrangement that produces satisfactory results uses solid copper strap, between 2" and 4" wide and 1/32" thick, run directly between instruments, following the shortest possible path. Connection to the instruments is usually made by soldering a short (1"-2") piece of =10 or larger wire to the strap. This is in turn connected to the instrument chassis.

Perhaps the ultimate arrangement involves use of a stainless steel laboratory table similar to that used in optical work. All instruments are placed on this table, as close together as the experiment allows. Each instrument is grounded via a short (1"-2") piece of =10 or larger copper wire to a grounding lug, which is bolted to the table top. The table top is in turn connected to the power line ground (with cold water pipe ground and a direct earth ground also being tried) via the shortest possible path. This represents a substantial investment in time and effort, and generally is used only where interference is in the radio frequency range. More will be said about this when discussing noise sources at other than power frequencies.

The techniques described above are all useful in reducing ground loop interference at power line frequencies. In general, however, once the chassis have been connected together with wire, additional "BRUTE FORCE" efforts will not produce results equal to the effort involved. There are more sophisticated ways to reduce the amount of power frequency current flow along signal carrying circuits which produce significant results.

An examination of Figure 1 might prompt the observation that breaking the current loop would eliminate the problem. However, this would require removing the power line grounds from the instruments, which would result in a hazard to life. An alternate, and safe, approach is called the semi-floating ground. It is used in most of the preamplifiers manufactured by Princeton Applied Research Corporation.

![Figure 3. SEMI-FLOATING INPUT GROUND](image)

In most of these preamplifiers, the coaxial cable shield is raised above ground at the input by between 10 and 100 ohms. The semi-floating ground approach achieves results approaching the actual breaking of the ground circuit. By inserting the series resistor, the ground loop currents are attenuated and most of the loop voltage is developed across the resistor instead of across the braid. In effect the ground loop signal is reduced by the ratio of the braid resistance to the resistor. Or, in our Figure 3 example:

Assuming RG-58 cable, 3' long @ $1 \times 10^{-4}$ ohms/ft

$$R_{braid} = 3 \times 10^{-3}$$

$$\frac{3 \times 10^{-3}}{10} = 3 \times 10^{-4}$$

Differential input circuits are generally useful in reducing signal contamination. These operate in such a way that unwanted interference is presented to both inputs (Figure...
4) and is canceled. Care must be taken to ensure that both input cables are of the same length and follow exactly the same path, in order that the interference is presented to both inputs in the same way.

Since most of P.A.R.C.’s electrochemical instruments are involved in experiments where signals are of the single ended, ground referenced variety, differential inputs will generally not be employed. Most, in fact, use current input circuitry, because they are concerned with the current which flows through a cell being swept over a pre-determined voltage range. These currents may be as small as $1 \times 10^{-5}$ amperes. Typically, electrode cables to these cells are connected to ground on one end only, and not subject to power line ground loop problems.

The cells in P.A.R.C. electrochemical instruments do sometimes fall prey to induced fields at the power line frequency. It is important that cabling to the cell be routed away from all power cables, such as that going to a stirrer, in order that the reference electrode not have a power frequency component induced on it. If this happens, it generally will be reflected on an X-Y recorder as a varying baseline at some sub-harmonic of the power frequency.

In general, it is possible to eliminate power frequency problems by carefully routing the cell cables away from anything producing a field at the power frequency. Sources of these fields may be identified by turning off one by one all lights, motors and power consuming instruments near the experiments. Once these sources are identified, separating them from the experiment should resolve the difficulties. Remember, however, that if the field is generated by one instrument used in the experiment, its power cable must be plugged into the same outlet as the rest of the instruments in the experiment.

![Figure 4. DIFFERENTIAL MEASUREMENT OF "SINGLE-ENDED" SIGNAL](image)

**FARADAY SHIELDS**

Essentially, a Faraday Shield constitutes a one turn, short circuited transformer secondary. The primary of that transformer is whatever sources are producing electromagnetic fields in the vicinity of the experiment. Currents which are flowing in the shield cannot flow in and among instruments inside the shield.

A Faraday Shield may be constructed from a fine wire mesh, sufficiently large to accommodate the experiment cell. Seams in the shield should be soldered. Cables from the experiment should enter and exit the shield at one point, through a circular hole no larger than necessary. (Shields on these cables should not be connected to the Faraday Shield.) The Shield should be grounded to the common system ground at one point only, using the most direct routing possible.

Often, a grounded metal fume hood will provide a perfectly satisfactory way of escaping the influence of power line fields and other interference. As a practical matter, that probably should be tried before constructing any special shielding.

In extreme cases, and particularly where the interference source is other than the power line, encasing the entire experiment in a shield may be the only solution. If this is determined to be necessary, all instruments must be grounded to the Faraday shield, but AT ONE POINT ONLY. That point must be the same one used to connect the shield to the power line ground and cold water pipes. This prevents ground loop currents from flowing in the shield and being re-induced inside the cage.

**IV. NOISE SOURCES AT RADIO FREQUENCIES**

Since Princeton Applied Research Corporation’s electrochemical instruments are not involved with signals at radio frequencies, the behavior of grounding circuits at these frequencies takes on importance only when considering noise sources outside the experiment. Experience shows that interference from such sources will occur only in a small percentage of the cases. Nevertheless, it is important to understand the behavior of grounding circuits into the VHF range (30-300 MHz), because noise sources can contain significant components in that area.

As one moves higher in frequency, the length of a ground path takes on significance beyond its resistance per unit length. The nature and quality of “ground” is considerably obscured as the length of the ground path becomes significant with respect to a wavelength ($\lambda$). For example, at 100 MHz, $\lambda/2$ or 0.5 wavelength is equal to 4.68 feet. In Figure 5, one can see that the voltage developed over this length goes from 0 V to a maximum at $90^\circ$, and back to 0 V again. Thus $\lambda/4$, or $90^\circ$, is a significant distance. A 2.34 foot long ground wire ceases to be ground at 100 MHz.

Transients events such as the discharge pulses coupled to the power lines by high powered lasers may often contain components in the 100 MHz range. Arcing at the brushes of electric motors frequently will produce broad band radio frequency noise into the 30 MHz region ($90^\circ \approx 8^\circ$). Fluorescent lights, power hand tools, elevator motors, hood exhaust fans, the ubiquitous laboratory refrigerator, laser power supplies, RF generators used to modulate lasers or excite plasmas are but a few of the possible sources of noise which must be considered. Even though signals of interest to the electrochemical experimenter are relatively low in frequency, indeed, mostly dc, the possibility of interference at significantly higher frequencies must be considered.
Power line filters are available which may be plugged into the power circuit of the instruments in an experiment. Isolation transformers are effective as well in rejecting interference that may be carried along the power lines. But in general, the propagation path for radio frequency interference (RFI) is not as simple as that, and not at all easy to identify. For that reason, it is best to treat interference at its source. The aforementioned power line filters and isolation transformers will work equally well in limiting the amount of interference which will reach the power line. Where power levels allow, they might be considered on the noise source. Bypassing of the power line circuit with capacitors may prove helpful, as close to the source of the noise as possible. (NOTE: THIS SHOULD NOT BE ATTEMPTED BY ANYONE OTHER THAN A QUALIFIED ELECTRICIAN OR ELECTRONICS TECHNICIAN.) Construction of a Faraday Shield around the offending noise source will be effective in reducing escaping interferences as well, although it is frequently not possible to do this.

Treatment of RFI sources is usually straightforward, once one has identified the source and the path by which the interference is reaching the experiment. In general, the procedure is to identify the interference in as many ways as possible. The impact on sampled data, interference waveform, duration, repetition rate, frequency of components, and the time it’s observed all take on significance. Once the interference has been characterized, potential sources may be logically eliminated one by one, until the source is identified.

V. SUMMARY
Care has been taken in the design of Princeton Applied Research Corporation's instruments to make them immune to most interference. Nevertheless, experiments involving extremely low level signals conducted in the presence of high level interference fields can produce problems. The reader should, at this point, be equipped to set up his instruments to allow operation in all but the most hostile environments.

In that small percentage of cases where the interference difficulties are extremely complex, it is recommended that the experimenter recruit the help of personnel experienced in RFI. In addition, Princeton Applied Research Corporation stands ready to consult with owners of P.A.R.C.'s instruments on their applications difficulties.

For the reader who would like further background on grounding and shielding, the following provides a theoretical discussion:

UNDERSTANDING INTERFERENCE-TYPE NOISE
How to Deal with Noise without Black Magic
There Are Rational Explanations for—and Solutions to—Noise Problems
Alan Rich

If the circuit doesn't work, add a decoupling capacitor anywhere—
a 0.01 μF ceramic disc, of course; they'll fix anything! Or when
your circuit is broadcasting its noise, a shield will cure it; just wrap
a piece of metal around the circuit, connect that shield to
"ground," and watch the noise disappear!

Unfortunately, Nature is not that kind to us in real life. That
0.01 μF disc you added only increased the noise; and the shield you
added was totally ineffective—or, worse yet, the noise reappeared
in a remote part of the circuit.

This article is the first of a two-part series to help you understand
and deal effectively with interference noise in electronic systems.
We will consider here the mechanism that causes noise to be picked
up, since the first step in solving any noise problem is to identify
the source of the noise and the coupling mechanism; only then can
an effective solution be implemented.

The second article will suggest specific techniques and guidelines
for effective shielding against electrostatic and magnetically
coupled noise.*

WHAT KIND OF NOISE ARE WE TALKING ABOUT?
electronic system contains many sources of noise. Three basic
kinds in which it appears are: transmitted noise, received with the
original signal and indistinguishable from it, intrinsic noise, (such
as thermally generated Johnson noise, shot noise, and popcorn
noise) originating within the devices that constitute a circuit, and
interference noise, picked up from outside the circuit. This last
case may either be due to natural disturbances (e.g., lightning) or be
coupled in from other electrical apparatus in the system or its vicin-
ity, for example computers, switching power supplies, SCR
controlled heaters, radio transmitters, switch contacts, etc.

This article will consider only the last category, man-made noise,
the most pervasive form of system noise in data-acquisition or test
systems. Although it is most annoying in low-level circuits, no part
of the system is immune to it. But it is the only form of noise that
can be influenced by choices of wiring and shielding.

ASSUMPTIONS AND ANALYTICAL TOOLS
Although Maxwell's equations—with all the mathematical agony
that they imply—are necessary for a complete and accurate de-
scription of how electrical systems behave, conventional circuit
analysis is a useful tool in most cases. The assumptions that permit
circuit analysis to be valid in solving these problems are:
1. All electric fields are confined to the interior of capacitors.
2. All magnetic fields are confined to the immediate vicin-
y of inductors.
3. Dimensions of the circuits are small compared to the
wavelengths under consideration.

*Another helpful and relevant article that appeared in these pages was "Analog Signal Handling for High Speed and Accuracy," by A. Paul Brokaw, Analog Dialogue 11-2, 1977, pp. 10-16.

Reprinted from Analog Dialogue 16-3, 1982

Using these assumptions, we can model noise-coupling channels
as lumped circuit elements. A magnetic field coupling two conduc-
tors is modeled as a mutual inductance. Stray capacitance can be
modeled as two conductors with an electric field between them.
Figure 1 shows an equivalent circuit of a situation where two short
wires are adjacent to one another over a system ground.

Figure 1. Noise-equivalent circuit of two adjacent wires and
a ground plane.

Once the complete noise equivalent-circuit is obtained for a sys-
tem, the problem becomes one of solving network equations for
a desired parameter. All standard linear circuit analysis techniques
can be applied, including node equations, loop equations, matrix
algebra, state variables, superposition, Laplace transforms, etc.
When circuits exceed 5 or 6 nodes, manual calculation becomes
difficult; at this point, computer-aided programs, such as SPICE,
and other CAD techniques become necessary. Experienced de-
designers can make appropriate simplifying assumptions; but their
validity should always remain in question until proven.

The lumped-element approach will not always give an accurate
numerical answer, but it will show clearly how noise depends on
system parameters. Just the act of drawing a reasonably faithful
equivalent circuit may offer clues to methods to reduce noise levels.
Once network equations or CAD programs are written, the quan-
titative effects of noise-suppression techniques can be studied.

In spite of all the modern technical advances, such as microproces-
sors and switching power supplies, wires still have resistance and
inductance, capacitance still exists in the real world, and such
phenomena must be reckoned with.

THE BASIC PRINCIPLE
There are always three elements involved in a noise problem: a
noise source (line transients, relays, magnetic fields, etc.), a
coupling medium (capacitance, mutual inductance, wire), and a
receiver, a circuit that is susceptible to the noise (Figure 2).

Figure 2. Noise pickup always involves a source, a coupling
medium, and a receiver.

To solve the problem, one or more of these three elements must
be removed, reduced, or diverted. Their role in the problem must
be thoroughly understood before the problem can be solved. If the

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solution is inappropriate, it may only make the noise problem worse! Different noise problems require different solutions; adding a capacitor or a shield will not solve every such problem.

TYPES OF SYSTEM NOISE
Noise in any electronic system can originate at a large number of sources, including computers, fans, power supplies, adjacent equipment, test devices; noise sources can even include improperly connected shields and ground wires that were intended to combat noise. Our discussion of noise sources and coupling mechanisms will include the following topics:

- Common-impedance noise
- Capacitively coupled noise
- Magnetic coupled noise
- Power-line transients
- Miscellaneous noise sources

Common-impedance noise. As the name implies, common-impedance noise is developed by an impedance that is common to several circuits. Figure 3 shows the basic configuration, which might occur when a pulse output source and an op amp’s reference terminal are both connected to a “ground” point having tangible impedance to the power-supply return terminal. The noise current (the noisy return current of Circuit 1) will develop across impedance, Z, a voltage, Vnoise, which will appear as a noise signal to Circuit 2.

Typically, this type of noise has a repetition rate that is set by the rate of the noise source. The actual waveshape is determined by the characteristics of the impedance, Z. For example, if Z is purely resistive, the noise voltage will be proportional to the noise current and of similar shape (Figure 4a). If Z is an R-L-C, the noise voltage will ring at a frequency, 1/(2π√LC) and decay exponentially at a rate set by L/R (b).

If noise of this kind is found in a circuit, its origin may be readily deduced from the repetition rate and waveshape. The repetition rate will point to the source of noise, since the noise and its source are synchronized. For example, a noise waveform like that shown in (c), at a 25kHz repetition rate and a 25% duty cycle, might be typical of a switching power supply containing a regulating loop using pulse-width modulation.

The waveshape will help identify the impedance that is actually generating the undesired noise. If, for example, the waveform of the noise is the simple damped sinusoid shown in Figure 5, the following features allow us to deduce the nature of Z:

- A constant resistance, R, is in series with the line. The voltage change, V1, is the product of R and a current step, I1.
- The natural frequency of the oscillation, f1, is determined by the series L and shunt C, f1 = 1/(2π√LC).
- The damping time constant, TD, is determined by L/R.

![Figure 5 Waveshape for an undamped R-L-C circuit.](image)

Capacitively coupled noise. Noise is also produced by capacitive coupling from a noise source to another circuit. This type of noise is often seen when signals with fast rise-and-fall times or high frequency content are in close proximity to high-impedance circuits. Stray capacitance couples the fast edges of the signal into adjacent circuits, as the circuit model of Figure 6 shows. The nature of the impedance, Z, determines the shape of the response. Typical capacitances are listed in Table 1.

![Figure 6 Stray capacitance couples noise into high-impedance circuits.](image)

**Table 1. Typical capacitances.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human standing on an insulator to earth</td>
<td>700 pF</td>
</tr>
<tr>
<td>Power input (ac) to output (dc) of ± 15-V dc supply</td>
<td>100 pF</td>
</tr>
<tr>
<td>Two-conductor shield cable:</td>
<td></td>
</tr>
<tr>
<td>Conductor to conductor</td>
<td>40 pF/ft</td>
</tr>
<tr>
<td>Conductor to shield</td>
<td>65 pF/ft</td>
</tr>
<tr>
<td>RG58 coaxial cable, center conductor to shield</td>
<td>33 pF/ft</td>
</tr>
<tr>
<td>Connector, pin to pin</td>
<td>2 pF</td>
</tr>
<tr>
<td>Optical isolator, LED to photodetector</td>
<td>2 pF</td>
</tr>
<tr>
<td>1/2-watt resistor (end to end)</td>
<td>1.5 pF</td>
</tr>
</tbody>
</table>

Capacitive pickup can occur in many ways, shapes, and sizes. Here are a few examples:

- A TTL digital signal produces fast edges, with a typical rise time of 10 nanoseconds and voltage swings of 5 volts. If Z is a 1 megohm resistor, even 0.1pF will produce 5-volt spikes with decay time constants of 100 nanoseconds.

- Crosstalk may result between two adjacent wires. For example, if two wires in a 10-foot (3-meter) length of cable have a capacitance of 40 pF/ft, the total capacitance is 400 pF. If a test voltage of 10 V at 1 kHz is on one conductor, 250 mV at 1 kHz will be coupled into the adjacent wire if Z is a 10 kΩ resistance.

- Noise on the ac power line, developed through common impedances, will couple into other circuits. A common case is when transients couple through the interwiring capacitance of power-supply transformers.

It is amazing how little capacitance can cause serious problems. For example, consider the situation where high noise-immunity CMOS logic is used in an industrial circuit where 2500-volt, 1.5 MHz noise transients (IEEE Standard 472-1974) are present. Suppose that stray capacitance of only 0.1 pF exists between a CMOS input and the noise source, as shown in Figure 7. The calculated noise voltage, \( V_c \), will be 2.4 volts, steady state, with an initial 50-V transient, which will cause improper logic operation or worse!

\[ V_n = 2\pi f B A \cos \theta \times 10^{-8} \]  

volts, where \( f \) is the frequency of the sinusoidally varying flux density, \( B \) is the rms value of the flux density (gauss), \( A \) is the area of the closed loop (cm²), and \( \theta \) is the angle of \( B \) to area \( A \).

For example, consider the circuit of Figure 9. It shows the calculation for two one-foot conductors, separated by 1 inch, in a 10-gauss 60-Hz magnetic field (typical of fans, power wiring, transformers). The maximum voltage induced in the wires is 3 mV.

![Figure 9. Example demonstrating magnitude of magnetic pickup.](image)

The equation tells us that the noise voltage can be reduced by reducing \( B \), \( A \), or \( \cos \theta \). The \( B \) term can be reduced by increasing the distance from the source of the field or—if the field is caused by currents flowing through nearby pairs of wires—twisting those wires to reduce the net field to zero by alternating its direction.

The loop area, \( A \), can be reduced by placing the conductors closer together. For example, if the conductors in the example were placed 0.1" apart (separated only by insulation), the noise voltage would be reduced to 0.3 mV. If they can be twisted together, the area is, in effect, reduced to small positive and negative increments that cancel, practically nullifying the magnetic pickup.

The \( \cos \theta \) term can be reduced by proper orientation of the receiving wires to the field. For example, if the conductors were perpendicular to the field, the pickup would be minimized, while if they were run together in the same cable (\( \theta = 0 \)), pickup would be maximized.

The rms induced voltage, \( V_n \), in a conductor in parallel with a second conductor, carrying a current \( I_2 \) at an angular frequency \( \omega = 2\pi f \), with a given mutual inductance, \( M \), is

\[ V_n = \omega M I_2 \]  

The application of this relationship shown in Figure 10 illustrates why only one end of a shield should be grounded. A 100-ft length of shielded cable is used to carry a high-level low-impedance signal (10V) to a 12-bit data-acquisition system (1 LSB = 2.4 mV). The shield, which has series resistance of 0.01 ohms per foot and mutual inductance to the conductor of 0.6 \( \mu \)H/ft, has been grounded at both the source and the destination. A potential of 1 volt at 60 Hz exists between the two ground points, causing a current of 1 ampere to flow in the 1-ohm total resistance of the shield. By (2), the noise voltage induced in the conductor is
or 10 LSBs, thereby reducing the effective resolution of the system to less than 9 bits. This noise voltage is a direct consequence of the large current flowing in the shield because it is grounded at both ends. And the 1-volt potential assumed between the grounds was conservative! In heavy-industry environments, 10 to 50 volts between earth grounds is not uncommon.

Power-Line Transients. Another type of system noise is that generated by high-voltage transients in inductive circuits, such as relays, solenoids, and motors, when they are turned on and off. When devices having high self-inductance are turned off, the collapsing fields can generate transients of the order of kilovolts, with frequencies from 0.1 to 3 megahertz, that appear on the power line.

Besides creating noise in sensitive circuitry, via capacitive and conductive coupling and radiated energy, these transients are hazardous to equipment and people. Standards exist to characterize certain transient waveforms for the purpose of protection; however, besides being designed to withstand them, systems should also be designed to deal with their potential interference with signals. Figure 11 shows 4 typical waveforms existing in industry standards.

Miscellaneous Noise Sources. Finally, there is a group of noise sources that can be considered as miscellaneous—or just “flakey.”

For low-level signals at high impedance, the cable itself can become a noise source. A charge can be produced on the dielectric material within the cable; if the dielectric does not maintain contact with the conductors, this charge will act as a noise source within the cable, unless the cable can be kept rigid. This noise is highly dependent on any motion of the cable; noise levels of 5 to 100 mV were reported by Belden Corporation. Noise of similar character (5 to 25 mV) was observed in the laboratory for RG188 coaxial cable, as it was moved and flexed.

Another type of motion-related noise occurs when a cable is moved through a magnetic field. Voltage will be induced in the cable as the cable cuts flux lines or the flux density, B, changes. This kind of noise is troublesome in a high-vibration environment, where the cables can be in the field. If the cable can be kept from vibrating relative to the field, this noise will not occur.

Finally, if instrumentation is operating in close proximity to a radio or television station, signals may be picked up from the transmissions. In addition to AM, FM, and television transmitters, the RFI may come from CB radios, amateur radios, walkie-talkies, paging systems, etc. High-frequency noise should be considered as a possible source of mysterious drifts in dc circuitry, due to rectification of picked-up rf; investigations of drift should always be conducted with a wideband oscilloscope.

**SUMMARY**

We have described here the different types of interference noise that will exist in any electronic system. Table 3 lists the noise sources discussed above and some effective approaches to solving the pickup problem. It is important to understand the complete noise system (source, coupling medium, receiver, and relationships) before noise-reduction techniques are employed.

Noise reduction is not a mystical job for wizards; it is a practical and analytical job for engineers. Needless to say, the most effective approach is prevention—applying noise-reduction analysis and minimization techniques before the system is built.

In part 2 of this article, we will describe the proper application of shielding and guarding techniques for noise reduction.

**Further Reading:**

Ralph Morrison, op. cit.


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**Figure 11. Examples of transients existing in standards for industrial power-line equipment.** (a) IEEE Standard 472.1974 “Guide for Surge Withstand Capability.” (b) Impulse wave, 8 × 20, 1000V peak, 5µs/div. (c) Impulse wave, 10 × 1000, 1500V peak, 0.2ms/div. (d) 100kHz ac surge, 6kV peak (500kHz leading edge); successive peaks down by 40% (1kV/div, 2µs/div).

**Table 3. Noise sources and possible solutions.**

<table>
<thead>
<tr>
<th>Common-Impedance Noise</th>
<th>Proper circuits for distributing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation transformers, optical isolators, analog isolators</td>
<td>Shielding of sensitive circuits</td>
</tr>
<tr>
<td>Capacitively Coupled Noise</td>
<td>Reducing noise sources</td>
</tr>
<tr>
<td>Properly implemented shields (very effective)</td>
<td>Reducing stray capacitance</td>
</tr>
<tr>
<td>Magnetically Coupled Noise</td>
<td>Careful routing of wiring</td>
</tr>
<tr>
<td>High-permeability (munetal) shields (the most effective)</td>
<td>Reducing area of receiver circuit (twisted pairs, physical wire placement)</td>
</tr>
<tr>
<td>Reducing the noise source (twisted pairs, driven shields to cancel field)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power-Line Transients</th>
<th>Coil suppression on relays, solenoids, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-crossing turnoff for relays, solenoids, etc.</td>
<td>Shielding</td>
</tr>
<tr>
<td>Reducing stray capacitance</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
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SHIELDING AND GUARDING
How to Exclude Interference-Type Noise
What to Do and Why to Do It—A Rational Approach

by Alan Rich

This is the second of two articles dealing with interference noise. In the last issue of Analog Dialogue (Vol. 16, No. 3, pp. 16-19), we discussed the nature of interference, described the relationship between sources, coupling channels, and receivers, and considered means of combating interference in systems by reducing or eliminating one of those three elements.

One of the means of reducing noise coupling is shielding. Our purpose in this article is to describe the correct uses of shielding to reduce noise. The major topics we will discuss include noise due to capacitive coupling, noise due to magnetic coupling, and driven shields and guards. A set of guidelines will be included, with do's and don'ts.

From the outset, it should be noted that shielding problems are always rational and do not involve the occult; but they are not always straightforward. Each problem must be analyzed carefully. It is important first to identify the noise source, the receiver, and the coupling medium. Improper shielding and grounding, based on faulty identification of any of these elements, may only make matters worse or create a new problem.

You can think of shielding as serving two purposes. First, shielding can be used to confine noise to a small region; this will prevent noise from extending its reach and getting into a nearby critical circuit. However, the problem with such shields is that noise captured by the shield will still cause problems if the return path the noise takes in not carefully planned and implemented by understanding of the ground system and making the connections correctly.

Second, if noise is present in a system, shields can be placed around critical circuits to prevent the noise from getting into sensitive portions of the circuits. These shields can consist of metal boxes around circuit regions or cables with shields around the center conductors. Again, where and how the shields are connected is important.

CAPACITIVELY COUPLED NOISE
If the noise results from an electric field, a shield works because a charge, \( Q_e \), resulting from an external potential, \( V_s \), cannot exist on the interior of a closed conducting surface (Figure 1).

![Figure 1. Charge \( Q_e \) cannot create charge inside a closed metal shell.](image)

Coupling by mutual, or stray, capacitance can be modeled by the circuit of Figure 2. Here, \( V_n \) is a noise source (switching transistor, TTL gate, etc.), \( C_s \) is the stray capacitance, \( Z \) is the impedance of a receiver (for example, a bypass resistor connected between the input of a high-gain amplifier and ground), and \( V_{no} \) is the output noise developed across \( Z \).

![Figure 2. Equivalent circuit of capacitive coupling between a source and a nearby impedance.](image)

A noise current, \( i_n = V_n/(Z + Z_C) \), will result, producing a noise voltage, \( V_{no} = V_n/(1 + Z_C/Z) \). For example, if \( C_s = 2.5 \text{ pF} \), \( Z = 10 \text{ k\Omega} \) (resistive), and \( V_n = 100 \text{ mV at 1.3 MHz} \), the output noise will be 20 mV (0.2% of 10V, i.e., 8 LSBs of 12 bits).

It is important to recognize the effect that very small amounts of stray capacitance will have on sensitive circuits. This becomes increasingly critical as systems are being designed to combine circuits operating at lower power (implying higher impedance levels), higher speed (implying lower nodal stray capacitance, faster edges, and higher frequencies), and higher resolution (much less output noise permitted).

When a shield is added, the change to the situation of Figure 2 is exemplified by the circuit model of Figure 3. With the assumption that the shield has zero impedance, the noise current in loop A-B-D-A will be \( V_n/Z_{C_1} \), but the noise current in loop D-B-C-D will be zero, since there is no driving source in that loop. And, since no current flows, there will be no voltage developed across \( Z \). The sensitive circuit has thus been shielded from the noise source, \( V_n \).

![Figure 3. Equivalent circuit of the situation of Figure 2, with a shield interposed between the source and the impedance.](image)

Guidelines for Applying Electrostatic Shields
- An electrostatic shield, to be effective, should be connected to the reference potential of any circuitry contained within the shield. If the signal is earthed or grounded (i.e., connected to a metal chassis or frame, and/or to earth), the shield must be earthed or grounded. But grounding the shield is useless if the signal is not grounded.
- The shield conductor of a shielded cable should be connected to the reference potential at the signal-reference node (Figure 4).
- If the shield is split into sections, as might occur if connectors are used, the shield for each segment must be tied to those for the
adjoining segments, and ultimately connected (only) to the signalreference node (Figure 5).

![Figure 5. Shields must be interconnected if interrupted.]

- The number of separate shields required in a system is equal to the number of independent signals that are being measured. Each signal should have its own shield, with no connections to other shields in the system, unless they share a common reference potential (signal "ground"). If there is more than one signal ground (Figure 6), each shield should be connected to its own reference potential.

![Figure 6. Each signal should have its own shield connected to its own reference potential.]

- Don't connect both ends of the shield to "ground". The potential difference between the two "grounds" will cause a shield current to flow (Figure 7). The shield current will induce a noise voltage into the center conductor via magnetic coupling. An example of this can be found in Part 1 of this series, Analog Dialogue 16-3, page 18, Figure 10.

![Figure 7. Don't connect the shield to ground at more than one point.]

- Don't allow shield current to exist (except as noted later in this article). The shield current will induce a voltage in the center conductor.

- Don't allow the shield to be at a voltage with respect to the reference potential (except in the case of a guard shield, to be described). The shield voltage will couple capacitively to the center conductor (or conductors in a multiple-conductor shield). With a noise voltage, \( V_n \), on the shield, the situation is as shown in Figure 8.

![Figure 8. Don't permit the shield to be at a potential with respect to the signal.]

The fraction of \( V_s \) appearing at the output will be

\[
V_o = \frac{V_s}{\sqrt{1 + \frac{1}{(2\pi R_e q C_{sc})^2}}}
\]

where \( V_s \) is the open-circuit signal voltage, \( R_e \) is the signal's source impedance, \( C_{sc} \) is the cable's shield-to-conductor capacitance, and \( R_{eq} \) is the equivalent parallel resistance of \( R_e \) and \( R_L \). For example, if \( V_s = 1 \)V at 1.5MHz, \( C_{sc} = 200 \)pF (10 feet of cable), \( R_e = 1000 \) ohms, and \( R_L = 10k \)ohms, the output noise voltage will be 0.86 volts.

This is an often-ignored guideline; serious noise problems can be created by inadvertently applying undesired potentials to the shield.

- Know by careful study how the noise current that has been captured by the shield returns to "ground." An improperly returned shield can cause shield voltages, can couple into other circuits, or couple into other shields. The shield return should be as short as possible to minimize inductance.

Here is an example that illustrates the problems that can arise in relation to these last two guidelines: Consider the improperly configured shield system shown in Figure 9, in which a precision voltage source, \( V_1 \), and a digital logic gate share a common shield connection. This situation can occur in a large system where analog and digital signals are cabled together.

![Figure 9. A situation that generates transient shield voltages.]

A step voltage change in the output of the logic circuit couples capacitively to its shield, creating a current in the common 2-foot
shield return. This, in turn, develops a shield voltage common to both the analog and digital shields. An equivalent circuit is shown in Figure 10, in which $V(t)$ is a 5-volt step from a TTL logic gate, $R_{og}$ is the 13-ohm output impedance of the logic gate, $C_{wi}$ is the 470-pF capacitance from the shield to the center conductor of the shielded cable, and $R_s$ and $L_s$ are the 0.1-ohm resistance and 1-microhenry inductance of the 2-foot wire connecting the shield to the system ground.

![Figure 10. Equivalent circuit for generating shield voltage.](image)

The shield voltage, $V_s(t)$, can be solved for by conventional circuit-analysis techniques, or simulated by actually building and carefully making measurements on a circuit with the given parameters. For the purpose of demonstration, the calculated response waveform, illustrated in Figure 11, with a 5-volt initial spike, resonant frequency of 7.3 MHz, and damping time constant of 0.15 ms, is sufficient to illustrate the nature of the voltage that appears on the shield and is capacitively coupled to the analog input. If the voltage is looked at with a wideband oscilloscope, it will look like a noise “spike.” We can see that this transient will couple a fast damped waveform of significant peak amplitude to the analog system input.

![Figure 11. Computed response of circuit of Figure 10.](image)

Even in a purely digital system, noise glitches can be caused to appear in apparently remote portions of a system having the kind of situation shown. This can often explain some otherwise inexplicable system bugs.

In quite a few cases, the proper choice of shield connection among the many possibilities may not be immediately obvious, and the guidelines may not provide us with a clear choice. There is no alternative but to analyze the various possibilities and choose the approach for which the lowest noise may be calculated.

For example, consider the case illustrated in Figure 12, in which the measurement system and the source have differing ground potentials. Should we connect the shield to A: the low side at the measurement-system input, B: ground at the system input, C: ground at the signal source, or D: the low side at the source?

A is a poor choice, since noise current is allowed to flow in a signal conductor. The path of the noise current due to $V_{G1}$, as it returns through $C_4$, is shown in Figure 13a.

B is also a poor choice, since the two noise sources in series, $V_{G1}$ and $V_{G2}$, produce a component across the two signal wires, developed by the source impedance in parallel with $C_2$, in series with $C_1$, as shown in Figure 13b.

C is poor, too, since $V_{G1}$ produces a voltage across the two signal wires, by the same mechanism as (B), as Figure 13c shows.

D is the best choice, under the given assumptions, as can be seen in Figure 13d. It also tends to confirm the grounding guideline to connect the shield at the signal’s reference potential.

![Figure 12. Possible grounds where system and source have differing ground potentials.](image)

![Figure 13. Equivalent circuits.](image)

**NOISE RESULTING FROM A MAGNETIC FIELD**

Noise in the form of a magnetic field induces voltage in a conductor or circuit; it is much more difficult to shield against than elec-
electric fields because it can penetrate conducting materials. A typical shield placed around a conductor and grounded at one end has little if any effect on the magnetically induced voltage in that conductor.

As a magnetic field, B, penetrates a shield, its amplitude decreases exponentially (Figure 14). The skin depth, δ, of the shield material, is defined as the depth of penetration required for the field to be attenuated to 37% (exp(-1)) of its value in free air. Table 1 lists typical values of δ for several materials at various frequencies. You can see that any of the materials will be more effective as a shield at high frequency, because δ decreases with frequency, and that steel provides at least an order of magnitude more effective shielding at any frequency than copper or aluminum.

![Figure 14. Magnetic field in a shield as a function of penetration depth.](image)

Figure 14 compares absorption loss as a function of frequency for two thicknesses of copper and steel. 1/8-in. steel becomes quite effective for frequencies above 200 Hz, and even a 20-mil (0.5 mm) thickness of copper is effective at frequencies above 1 MHz. However, all show a glaring weakness at lower frequencies, including 50-60-Hz line frequencies—the principal source of magnetically coupled noise at low frequency.

![Figure 15. Absorption loss vs. frequency for two thicknesses of copper and steel.](image)

For improved low-frequency magnetic shielding, a shield consisting of a high-permeability magnetic material (e.g., Mumetal) should be considered. Figure 16 compares a 30-mil thickness of Mumetal with various materials at several frequencies. It shows that, below 1 kHz, Mumetal is more effective than any of the other materials; while at 100 kHz it is the least effective. However, Mumetal is not especially easy to apply, and if it is saturated by an excessively strong field, it will no longer provide an advantage.

As you can see, it is very difficult to shield against magnetic fields, i.e., to modify the coupling medium by shielding. Therefore, the most effective approaches at low frequency are to minimize the strength of the interfering magnetic field, minimize the receiver loop area, and minimize coupling by optimizing wiring geometries. Here are some guidelines:

- Locate the receiving circuits as far as possible from the source of the magnetic field.
- Avoid running wires parallel to the magnetic field; instead, cross the magnetic field at right angles.
- Shield the magnetic field with an appropriate material for the frequency and field strength.
- Use a twisted pair of wires for conductors carrying the high-level current that is the source of the magnetic field. If the currents in the two wires are equal and opposite, the net field in any direction

![Figure 16. Shielding attenuation of Mumetal and other materials at several frequencies.](image)

Table 1. Skin depth, δ, vs. frequency

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>δ for Copper (mm)</th>
<th>δ for Aluminum (mm)</th>
<th>δ for Steel (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60Hz</td>
<td>0.335</td>
<td>0.429</td>
<td>0.034</td>
</tr>
<tr>
<td>100Hz</td>
<td>0.260</td>
<td>0.333</td>
<td>0.026</td>
</tr>
<tr>
<td>1kHz</td>
<td>0.082</td>
<td>0.105</td>
<td>0.008</td>
</tr>
<tr>
<td>10kHz</td>
<td>0.026</td>
<td>0.038</td>
<td>0.003</td>
</tr>
<tr>
<td>100kHz</td>
<td>0.008</td>
<td>0.011</td>
<td>0.0008</td>
</tr>
<tr>
<td>1MHz</td>
<td>0.003</td>
<td>0.008</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

*Table 1 and Figures 15 and 16 are from Ott, H.W., Noise Reduction Techniques in Electronic Systems (New York: John Wiley & Sons, © 1976).*

![Figure 17. Connections to a twisted pair.](image)
over each cycle of twist will be zero (Figure 17a). For this arrangement to work, none of the current can be shared with another conductor, for example, a ground plane. Figure 17b shows what can happen if a ground loop is formed; if part of the current flows through the ground plane (depending on the ratio of conductor resistance to ground resistance), it will form a loop with the twisted pair, generating a field determined by \( i_3 = i_1 - i_2 \).

The ground connection between A and B need not be as simple as a short circuit to cause trouble. Any stray unbalanced capacitance or resistance from \( R_{load} \) circuits to the ground plane will also unbalance the currents and produce a net current through the wires and the ground plane, producing a ground loop and a related magnetic field. For this reason, it is also good practice to run the twisted pair close to the ground plane to tend to balance the capacitances from each side to ground, as well as to minimize loop area.

- Use a shielded cable with the high-level source circuit's return current carried in the shield (Figure 18). If the shield current, \( i_2 \), is equal and opposite to that in the center conductor, the center-conductor field and the shield field will cancel, producing a zero net field. In this case, which seems to violate the "no shield current" rule for receiver circuits, the concentric cable is not used to shield the center lead; instead, the geometry produces cancellation.

Figure 18. Use of shield for return current to noisy source.

This scheme can be usefully employed in an ATE system where accurate measurements must be performed on devices with high power-supply currents that may be noisy. For example, Figure 19 shows the application of this technique to the connections for the high-current logic supply for an A/D converter under test—at the end of a test cable.

Figure 19. Application of circuit of Figure 18 in a test system.

- Since magnetically induced noise depends on the area of the receiver loop, the induced voltage due to magnetic coupling can be reduced by reducing the loop's area. What is the receiver loop? In the example shown in Figure 20, the signal source and its load are connected by a pair of conductors of length \( L \) and separation \( D \). The circuit (assuming it has a rectangular configuration) forms a loop with area \( D \cdot L \).

Figure 20. Area of a loop that receives magnetically coupled noise.

The voltage induced in series with the loop is proportional to the area and the cosine of its angle to the field. Thus, to minimize noise, the loop should be oriented at right angles to the field, and its area should be minimized.

The area can be reduced by decreasing the length of and/or decreasing the distance between the conductors. This is easily accomplished with a twisted pair, or at least a tightly cabled pair, of conductors. It is good practice to pair conductors so that the circuit wire and its return path will always be together. To do this, the designer must be certain of the actual path that the return current takes in getting back to the signal source. Quite often, the current returns by a path not intended in the original design layout.

If wires are moved (for example, by a technician troubleshooting some other problem), the loop area and orientation to the field may change, so that yesterday's acceptable noise level may be transformed to tomorrow's disastrous noise level. Which may lead to a service call . . . and another repetition of the cycle. The bottom line: Know the loop area and orientation, do what must be done to minimize noise—and permanently secure the wiring!

**DRIVEN SHIELDS AND GUARDING**

We have discussed the role of a current-driven shield carrying an equal and opposite current to reduce generated noise by reducing the magnetic field around a conductor.

Guarding is similar, in that it involves driving a shield, at low impedance, with a potential essentially equal to the common-mode voltage on the signal wire contained within the shield. Guarding has many useful purposes: It reduces common-mode capacitance, improves common-mode rejection, and eliminates leakage currents in high-impedance measurement circuits.

Figure 21 shows an example of an op amp with negligible bias current connected as a high-impedance non-inverting amplifier with gain. The purpose of the cable is to shield the high input-impedance signal conductor from capacitively coupled noise and to minimize leakage currents. The signal comes from a 10-megohm source, and the cable is assumed to have 1000 megohms of leakage resistance (which may change as a function of temperature, humidity, etc.) from conductor to shield. If connected as shown, the equivalent input circuit is an attenuator which loses 1% of the

Figure 21. Op amp connected as high-impedance non-inverting amplifier with gain, with shielded input lead.
signal at the time it is measured, and an unknown fraction at other times. Also, the cable capacitance produces a substantial lag time constant, $R_C C_c$.

Figure 22 has the same players, but the shield is connected to the tap of the gain divider (usually at low impedance). Being connected to the inverting input of the op amp, it should be at the same potential as the amplifier’s non-inverting input. Since there is no voltage across the cable’s leakage resistance, there is no current through it and its resistance value doesn’t matter; $V_s$ must therefore be equal to $V_n$, since bias current was assumed negligible.

![Figure 22](image)

Figure 22. Same as Figure 21, but cable shield connected as a guard.

Also, there is no voltage across the cable capacitance, hence no charging or discharging of the cable; thus the lag time constant depends mainly on circuit strays and the amplifier’s input capacitance. For stability, capacitance should be connected between the output and the negative input, such that $C_R C_F = C_s R_n$, where $C_s$ is sum of the stray capacitance between shield and ground and the input capacitance.

There must be no noise voltage applied to the guard. In noisy systems, as Figure 22 shows, capacitively coupled noise will be differentiated, emphasizing the higher-frequency components. This can be avoided (Figure 23) by either using a buffer follower with fast response and low output impedance to drive the guard (a) or a second shield, around the guard, grounded to the signal common (b).

![Figure 23](image)

(a) Driven guard.

(b) Shielded guard.

Figure 23. Avoiding noise pickup on the guard.

In high-impedance current-input inverting configurations, where a length of shielded wire is used to guard the lead from the current source to the amplifier’s inverting input, the guard should either be driven by a buffer at the same potential as the non-inverting input (and connected nowhere else), or be tied directly to the non-inverting input, with a second outer shield connected to the signal’s reference point.

**SUMMARY**

Table 2 summarizes the important points made in this article. All are important to maintaining a high-integrity shield system. However, we cannot emphasize too strongly the two subjects that are most-often ignored: appearance of noise voltage on signal shields and proper disposition of shield noise currents. Noise voltage must not exist on the shield; shield-to-conductor capacitance will couple the noise directly to the center conductor. If shield currents are not returned properly, they can show up in a remote part of the system and perhaps cause trouble in a location totally unrelated to the shielding problem that was “solved.”

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Universal</th>
<th>Electric</th>
<th>Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Know the noise source, coupling medium, and receiver.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Different shielding techniques are required for different noise sources, coupling channels, and receivers.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>In most situations, conventional circuit analysis using lumped elements can be used.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Connect the shield at the signal-source end only.</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Carry shields through connectors.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual shields should not be tied together.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do not ground both ends of a shield.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do not allow shield current to flow, except for driven shields - to cancel magnetic fields</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do not allow voltage on a shield, except for guarding.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Know exactly where noise current from the shield will flow.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use short connections to return noise current from the shield.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrostatic shields have little effect in reducing noise resulting from magnetic fields.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce magnetic fields by physical separation proper orientation, twisted pairs, and/or driven shields.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Know the receiver loop area and orientation to the field. Keep field at right angles and reduce the loop area by using paired conductors, preferably twisted pairs, and minimize wire lengths.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use guarding in high-impedance circuits in high-impedance circuits, be extremely careful of shield noise.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**BRIEF BIBLIOGRAPHY**

For further reading, see:


Noise and Noise Reduction Techniques

The limit of the sensitivity of an electronic data acquisition system depends upon how low one can make the noise background in the system. In general, the noise in the data acquisition system can be divided into two categories.

1) Inherent Electronic Noise. This is noise which is due to the fundamental Quantum Limitations of the electronic components. Usually this noise is wideband, meaning it extends over a very wide range of frequencies.

2) Interference Noise or "Pickup" Noise. This noise is electronic noise which is picked up from some other equipment or even another part of the same circuit. In general, this noise tends to be very narrow-band; i.e. at a single frequency (like 60 Hz).
Inherent Electronic Noise and Resolution

There are many sources to inherent electronic noise. In its most general meaning, inherent electronic noise includes statistical fluctuations in both the signal and the background measured level as well as electronic component noise.

Consider a system which measures intensity of flashes of light in a lit room.

![Graph showing signal and background levels over time](image)

The signal is the number of photons above the background level.

The total noise in the measurement is the sum in quadrature of the fluctuations in the background $N_{back}$.
Fluctuations in the signal $N_{sig}$ and fluctuations in the electronics (intrinsic electronic noise level) $N_{inh}$:

$$\text{Noise} = N_{inh}^2 + N^2_{sig} + N^2_{back}$$

A couple of terms here:

If $N_{back} \gg N_{sig}$

and

$N_{back} \gg N_{inh}$

Measurement is said to be Background Limited.

If $N_{sig} \gg N_{inh}$

and

$N_{sig} \gg N_{back}$

Measurement is said to be Signal Limited.

If $N_{inh} \gg N_{sig}$ and

$N_{inh} \gg N_{back}$

Measurement is Electronics Limited.
in the ideal situation one wants to be signal limited. In this case one maximizes the measurement sensitivity to the ultimate limit.

For example, assume the signal in the light measure has $10^3$ photons, and the background photon level is 100 photons per millisecond. Assume the signal occurs over 5 milliseconds.

The total signal measured is (for a single measurement) $10^3$ photons $\pm \sqrt{10^3}$ and the background photon level is $(100)5 = 500$ photon $\pm \sqrt{500}$

The total noise in a single measurement is

$$ (\sqrt{10^3})^2 + (\sqrt{500})^2 = N^2_{\text{inh}} = N^2_{\text{noise}} $$

$$ N^2_{\text{noise}} = 1500 + N^2_{\text{inh}} $$
\[ N_i = 10 \text{ photons equivalent} \]
\[ \text{Total Noise} = 1500 + 10^2 \]
\[ = 1600 \]

So expect noise level for photon measurement to be \( \sim \sqrt{1600} = 40 \) photons.

Notice that the noise level is larger than just the fluctuations in the signal itself.

In this example, we assumed the conversion from photon to electric current was perfect (Quantum efficiency = 1).

In reality, this conversion is not = 1, but more like 0.1 photo electrons/photon. This gives larger fluctuations. Since now we would have only \( (1000)(0.1) = 100 \) photo electrons.

The fluctuation in this number is
\[ 100 \pm \sqrt{100} = 100 \pm 10 = 70\% \]
whereas before...
The fluctuations were
\[ \sqrt{1000} = 30 \text{ out of } 1000 \]
\[ = 3\% \]

Similarly, the background noise level has larger fluctuations
\[ (500)0.1 = 50 \text{ photoelectrons } \pm \sqrt{50} \]
\[ = 50 \pm 7 = 14\% \text{ fluctuations} \]

(compared to 500 ± 22 = 4.4\% fluctuations)

What are the sources of \( N_i \)?


Noise power available per unit bandwidth
\[ \text{Noise power} \rightarrow \frac{N_t}{\Delta f} = \text{energy} = \frac{kT}{\Delta f} \left( \frac{h\nu}{kT} \right) \]

(at room temp \( \frac{h\nu}{kT} \ll 1 \))

So \[ \frac{h\nu/kT}{e^{h\nu/kT} - 1} \sim 1 \]
Noise in Circuits

Consider a circuit of which we want to measure the voltage. (Such as an op amp input.)

\[ V_{in} \rightarrow R_1 \rightarrow \text{Op Amp} \rightarrow R_2 \rightarrow V_{out} \]

Here we ground the input, and expect the output voltage to be equal to zero. At the output, this is not close to what is observed except when one looks at Vout on the millivolt scale.

Consider the op amp output on a scope. V 1 volt/div. V 1 mV/div. A sample trace is shown.
\((-\)) \((e)^2 = +\) cannot cancel the \(+\).

\[
\overline{V_n^2} = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{T} V_n(t)^2 dt
\]

If one has a pulse height spectrum, one can also define an equivalent frequency spectrum of the noise.

\[
S_m(f)
\]

\(S_m(f)\) is the \(\overline{V_n^2}\) noise that is produced at a \(1\) Hz wide slice of the frequency spectrum at frequency \(f\).
Max power is when \( R_{\text{load}} = \frac{V}{R} \)

\[ V = \frac{V_{\text{noise}}}{2} \]

Total power delivered = \( \frac{(V_{\text{noise}}/2)^2}{R} = \frac{V^2}{4R} = N_t \)

\[ = kT \Delta f \]

So \( V_{\text{rms}} = \sqrt{4R kT \Delta f} \)

\[ 4kT = 1.6 \times 10^{-20} \ \Omega^{-1} \ Hz^{-1} \ \text{Volts}^2 \]

at room temp.

\[ \text{Example:} \quad \text{1000 \ O\ Resistor at Room Temp} \]

\( \Delta f = 1 \ Hz \)

\[ V_{\text{rms}} = 4/10^3 V = 4 \times 10^{-3} V \]

\[ \text{Example:} \quad \Delta f = 10 \ \text{MHz} \]

\( R = 1 \ \text{MS} \)

\[ V_{\text{rms}} = 4 \times 10^{-4} V = 0.4 \text{mV} \]
If you had a gain 100 amplifiers could have some real problem

\[ V_{\text{out\ noise}} \sim 0.4 \text{mV} \times 100 = 40 \text{mV} \]

Noise adds in quadrature

\[ V_1 = \sqrt{4R_1 kT f} \quad V_2 = \sqrt{4R_2 kT f} \]

\[ V_{\text{total}}^2 = V_1^2 + V_2^2 = 4(R_1 + R_2)kT f \]

\[ V_{\text{total}} = \sqrt{4(R_1 + R_2)kT f} \quad \text{as expected.} \]

Johnson noise has flat spectrum.

\[ S_n(f) = \frac{4kT R}{f} \]

\[ f \text{ falls off above } \frac{kT}{h} \text{ at room temp} \]

\[ f \sim \frac{kT}{h} - 3 \times 10^{12} \text{ Hz} \]
Noise for parallel resistors must be careful.

Noise current adds in parallel.

\[ (I_{\text{total}})^2 = \left(\frac{I_{\text{rms}}}{R_1}\right)^2 + \left(\frac{I_{\text{rms}}}{R_2}\right)^2 \]

\[ (I_{\text{total}})^2 = \frac{4kT\Delta f}{R_1} + \frac{4kT\Delta f}{R_2} \]

\[ = 4kT\Delta f \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \]

\[ (I_{\text{rms}})^2 = \frac{\Delta f 4kT}{R_1} \]

\[ \frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} \]
Shot noise: флуктуации в состоянии устойчивого тока

\[ S_n(f) = 2eI \quad \text{independent of frequency.} \]

Since signal power \( \propto V = I^2R \)
and noise \( \propto 2eI \) power

\[ \frac{\text{signal}}{\text{noise}} \propto \frac{I}{I^2} = \frac{1}{I} \]

At higher currents, signal to noise improves. Usually include this term as \( \frac{1}{\text{Noise}} \)

\[ \frac{1}{f} \text{ noise: } S_n(f) \propto \frac{1}{f^x} \quad \text{for } x = 1-2 \quad \text{typical} \]

Colored noise \( (\text{p.p.k.}) \)

Characteristics of op-amp noise increase, fractal noise, semiconductor, transistors, diodes

\[ S(f) \]

\[ \frac{1}{f^x} \]

\[ f \]
Reducing Johnson noise.

Usually want $R_n > > R_T$ so that $V_A$ is maximized.

However, if $R_n$ too large, then Johnson noise dominates from $R_n$.

i.e. $R_T = \frac{1}{1000} R_n$

$\text{Noise in } R_T \sim \sqrt{\frac{1}{1000}} \text{ Noise in } R_n \sim \frac{1}{30}$

So measurement dominated by $R_n$ noise.

Try impedance match transformer.

But transformer reduces voltage by factor of 10!

Noise from $R_n \sim \text{Noise from } R_T$
also \[ \text{cool R}_f \]

\[ 300 \text{ k} \rightarrow 10 \text{k} \text{ gives} \]

\[ \sqrt{30} \approx 5.5 \text{ noise reduction.} \]

\text{Narrow band DF peck.}

\[ \Delta f \approx 10 \text{ MHz, reduced to } 10 \text{ Hz.} \]

Reduces noise by factor of \( 10^3 \)

\text{pickup noise: Reduction}

1. \text{proper grounding} \rightarrow \text{no ground loops}

2. \text{Narrow filters to kill specific frequency}

3. \text{Shielding from magnetic induced currents.}
Other noise levels are here:

"Capacitive noise"

\[ \text{if } C_{\text{FET}} \ll C_{\text{sensor}}, \text{ not much} \]

\[ \text{signal charge in } C_{\text{sensor}} \text{ passes to } C_{\text{FET}} \]

\[ Q = CV \]

\[ Q_{\text{sensor}} = C_{\text{sensor}} V \]

\[ Q_{\text{FET}} = C_{\text{FET}} V \]

\[ V_{\text{same for both}} \Rightarrow \frac{Q_{\text{FET}}}{Q_{\text{sensor}}} = \frac{C_{\text{FET}}}{C_{\text{sensor}}} \]

For silicon PIN diode, \( C_{\text{sensor}} \approx 100 \text{ pF} \)

Large area \( C_{\text{FET}} \approx 1 \text{ pF} \)

So only \( \frac{1}{100} \) of the pin photodiode charge actually makes it out of the PIN junction.
However if too high a ratio, resistance of coil, losses in transformers generate noise.

Optimal coupling gives

\[ L_{\text{opt}} = 3 \times 10^5 \sqrt{C_d(m \omega)} \]

\[ L_{\text{opt}} \approx 8 \left( k_T \frac{C_{\text{sensor}}}{C_d} \right)^{1/2} \]

Typical \( L_{\text{opt}} \approx 3 \times 10^5 \sqrt{C_d(m \omega)} \)

for \( \omega f = 10 \text{ mHz} \).
Noise Reduction Techniques:

1. for \( N_{\text{inh}} \ll N_{\text{signal}}, N_{\text{Background}} \):
   \[ N_{\text{signal}} \sim N_{\text{background}} \]
   Use signal averaging:
   
   Make multiple measurements of exact same event, waveform, etc.
   
   after \( N \) events total background = \((N_{\text{events}})^2 \) \( N_{\text{background}} \)
   
   So \( \frac{\text{signal}}{\text{noise}} \sim (N_{\text{events}})^{-\frac{1}{2}} \)

2. for \( f_{\text{signal}} \ll \) noise, use phase locked loop. Lock in amplifier.
Before

$V$

$1/f$ noise

Signal in

$1/f$ Bandwidth

$\text{Signal/Noise} \approx 0.5$ at Best

After

$10\text{kHz}$

$\times$

$-10\text{kHz}$

$+ \text{noise}$

$10\text{kHz}$
Noise Reduction Techniques:

Superheterodyne Receiver

Total spectrum is broken up into multiple independent signal bandwidths

\[ f_0, f_1, f_2, \ldots \]

E.g., signal \( f_1 \) occupies band \( f_0 \) to \( f_1 \); signal \( f_2 \) goes from \( f_1 \) to \( f_2 \), etc.

How do we recover a single selectable Band of Signal?

One could try adjustable Bandpass →

It doesn't work well

Good Bandpass cannot be maintained, we adjust 1 or 2 components
Super heterodyne receiver

Signal: \( w_0, w_1, w_2, w_3 \)

1. **Local Oscillator** \( W_{\text{local}} \)
2. **Fixed Bandpass Filter**
3. **Oscillation** \( w_{\text{local}} \)
4. **Low Pass Filter**

Adjustable

\( w_0 \) \( w_1 \) \( w_2 \)

\( w_2 - W_{\text{local}} \) \( W_{\text{local}} - W_0 \)

\( w_2 + W_{\text{local}} \) \( W_{\text{local}} - W_0 \)

\( w_{\text{out}} \)
Choose (adjust) \( W_{\text{local}} \) so that
\[ W_{\text{local}} + W_i = W_{\text{band}}. \]
\[ W_{\text{local}} = W_{\text{band}} - W_i. \]

Then signal looks like:

\[ W_i + W_{\text{local}} \]
\[ \downarrow \quad \text{multiply} \]
\[ \uparrow \]

This signal.
To recover band near \( W = 0 \), do another move.
Multiply by \( W_{\text{band}} \).
Then put through a low pass filter.

Result

Original signal is now around $w = 0$. 

Then put through a low pass filter.