OHM'S LAW AND OTHER NOVELTIES OF ANALOG DESIGN

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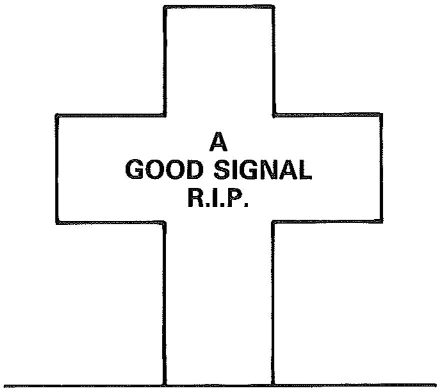
INTRODUCTION

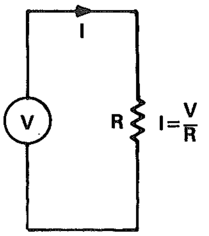
The most difficult part of the design of successful analog circuits is not the system design but making an entirely rational system perform correctly in real world. The commonest reasons for such failure are disregarding Ohm's and Kirchoff's Laws and the non-ideal performance of passive components, and treating ground as a place where good signals go when they die.



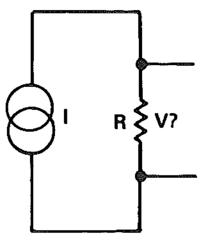
GROUND
WHERE GOOD SIGNALS GO WHEN THEY DIE

OHM'S LAW

It is an uncomfortable fact thay many electronic engineers do not actually believe Ohm's Law. They will claim to do so but in practice they accept that I = V/R but not that V = IR. In other words they have no difficulty in seeing that if a voltage is applied to a resistance a current will flow but they do not consider, in the design and layout of their circuits, that if a resistance is present when a current flows there will be a voltage across it. This can cause all sorts of difficulties.



MOST ENGINEERS BELIEVE THAT AN APPLIED VOLTAGE WILL CAUSE A CURRENT TO FLOW IN A RESISTOR



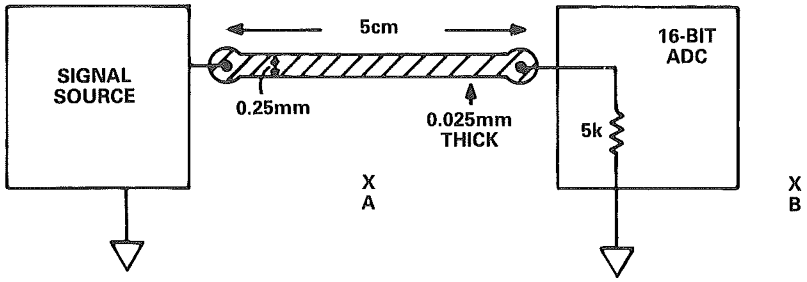
MANY ENGINEERS THINK V = ZERO

BUT IN FACT V = IR

BUT SOME DO NOT BELIEVE THAT A CURRENT WHICH FLOWS IN A RESISTOR PRODUCES A VOLTAGE

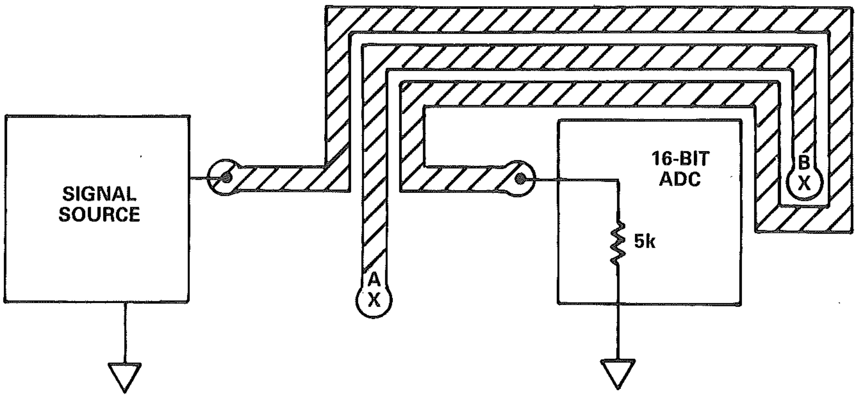
Consider, for instance, a 16-bit analog-digital converter (ADC) with an input resistance of 5K (such a low input resistance, though inconvenient, is not unusual in successive-approximation ADCs). At full scale there would be a voltage drop, and hence an error, of 1 LSB if the resistance of the printed-circuit track between the signal source and the ADC were only 75 milliohms—which is equivalent to only 50 × 0.25 × 0.025mm copper, or 5cm of normal high-density PCB wiring.

OHM'S LAW PREDICTS 1 LSB DROP IN 5cm OF STANDARD PCB TRACK– BUT WHO BELIEVES OHM'S LAW?



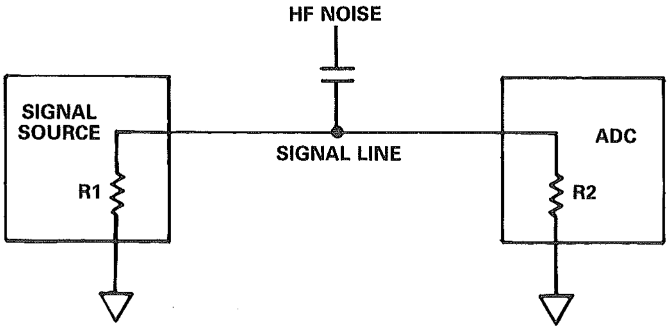
Most computers know even less than engineers about Ohm's law. Computer programs for the design of PCBs normally treat all points in the same metal track as being a "node" and assume that they are at the same potential. This is quite a reasonable assumption for logic circuitry where noise immunities are a volt or more but are unhelpful in precision analog applications. Consider the effect of a small change in the circuit in the previous diagram—points A and B must be joined. A CAD PCB program is quite likely to join the points with a link and then route the previous track around it—it is evident that in a precision analog (or high-frequency) environment such a solution is disastrous.

AT THE DROP OF A NODE A COMPUTER CAN MAKE THINGS TEN TIMES WORSE



There are several solutions. The best is to ensure that signal leads are short and wide. Increasing the input impedance of sensitive circuitry will also help but this may increase its vulnerability to capacitively coupled interference.

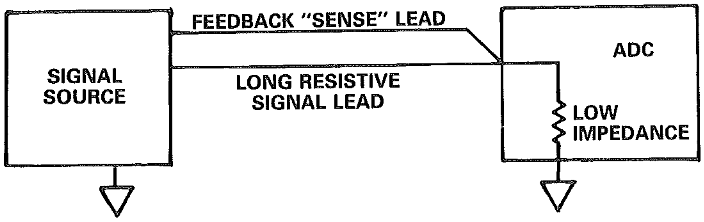
CAPACITIVE COUPLING OF NOISE



THE LARGER THE VALUES OF R1 AND R2 THE LESS ATTENUATION OF CAPACITIVELY-COUPLED NOISE

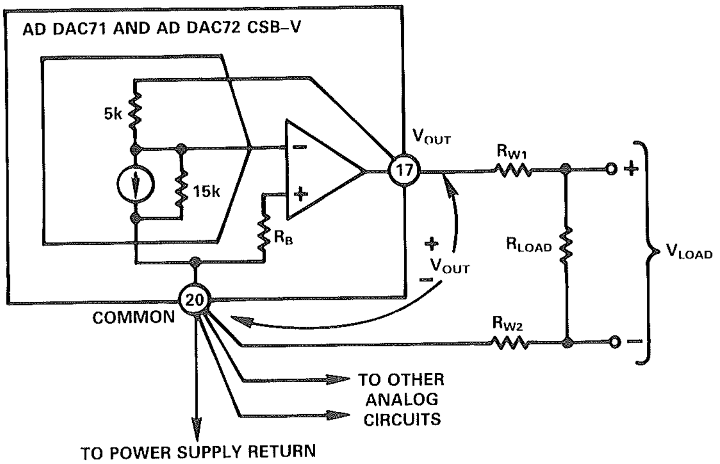
Separate "force" and "sense" leads from a signal source to its load will ensure that the signal source develops its precision at the load itself and not at some "output" pin far from where the precision is needed. In this case it is unlikely that capacitive coupling of interference will cause difficulty.

USE OF A SENSE CONNECTION MOVES ACCURACY TO THE LOAD



The reason for "force" and "sense" connections becomes clear when we consider all the resistances involved in connecting a signal to a load. Using the DAC71 16-bit DAC as an example we have a load R_2 and resistances R_{W1} and R_{W2} in the signal and ground paths respectively.

PRECISION ANALOG SIGNAL HANDLING

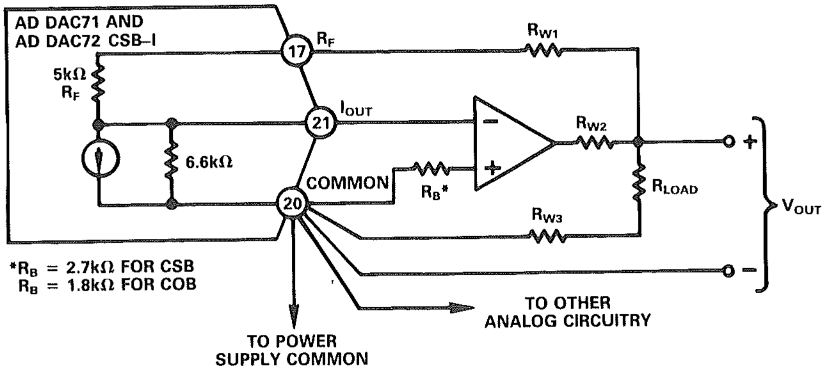


It is evident that the load voltage will be less than the DAC output voltage by the voltage drop in R_{W1} and R_{W2} and that if the error is to be less than 1 LSB.

$$\frac{R_{W1} + R_{W2}}{R_{LOAD}} < \frac{1}{2^{16}}$$

At 16 bits even the voltage drop in the sense lead itself may need to be considered in cases where the impedance of the sense terminal is not very high. This can be seen in the connection of the current output version of the DAC71 where R_{W1} appears in the feedback path and can still have serious consequences.

PRECISION ANALOG SIGNAL HANDLING

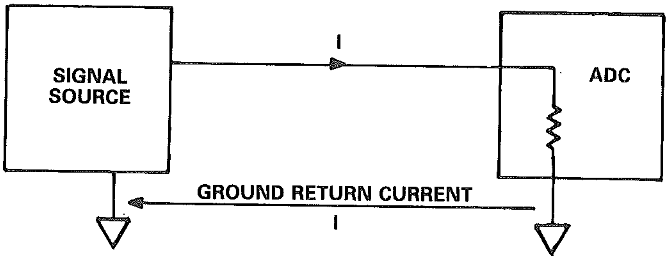


From considering these cases we can derive a general rule: at some stage of the design of any precision analog system all lead resistances should be added to the circuit diagram and their effects on system accuracy computed. In most cases it will be clear that they can be disregarded—in a few cases they will be seen to be critically important to system accuracy.

KIRCHOFF'S LAW

Disregarding Kirchoff's Law is equally dangerous. Kirchoff's law is generally preceived as being relevant only to the analysis of current flowing in networks having several nodes but it is equally relevant in the analysis of a signal source driving a single load.

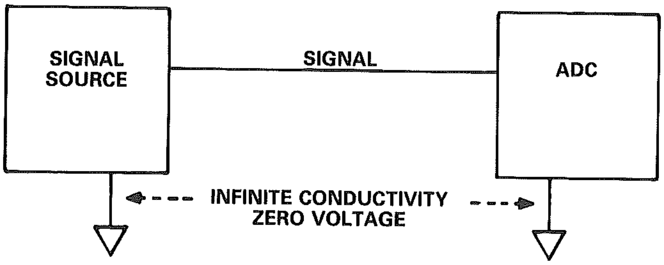
KIRCHOFF'S LAW



AT ANY POINT IN A CIRCUIT
THE ALGEBRAIC SUM OF THE CURRENTS IS ZERO
OR
WHAT GOES OUT MUST COME BACK
WHICH LEADS TO THE CONCLUSION THAT
ALL SIGNALS ARE DIFFERENTIAL
(EVEN IF THEY'RE GROUNDED)

Kirchoff's Law states that the net current at any point in a circuit is zero and therefore implies that the current which goes from a source to a load must return to its source—i.e., that all signals are differential. The signal return is just as important to system accuracy as the so-called "signal path"—and is much more likely to be disregarded during the system design. Far too many designers assume that the return path is "ground" and consider the matter no further. Treating all ground connections as being at exactly the same potential is very dangerous. (A point is a mathematical abstraction—does this tell us anything about "common grounding point"?) The concept of "ground" as a connection to a point of zero potential and infinite conductivity is attractive in theory and may be useful during preliminary system design but it can lead to major errors in real systems.

THE IDEAL GROUND

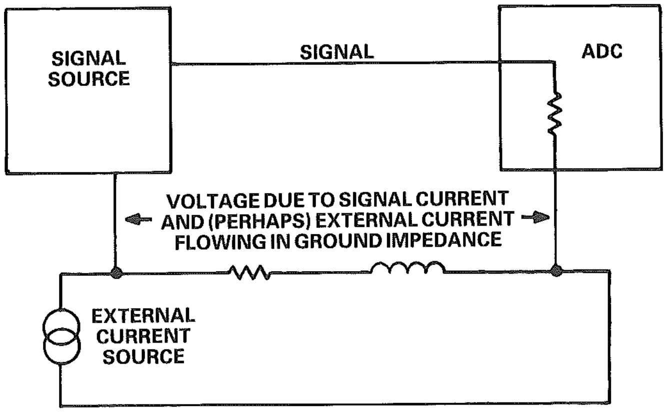


GROUNDS

In real life, ground conductors have both resistance and inductance and may also be carrying unpredictable currents which will give rise to voltage drops when they flow in the ground impedances. CAD PCB programs are particularly bad at ground design because they tend to keep all conductors as thin as possible to conserve copper and board area and this, of course, results in high ground resistance.

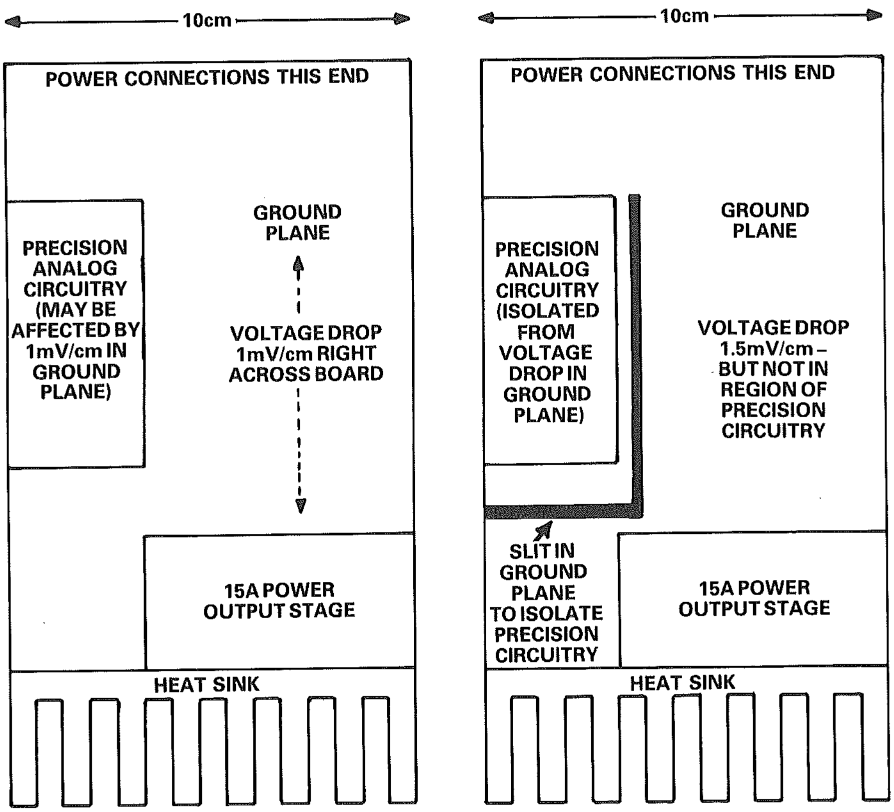
As a general principle the design of PCBs for precision analog applications is far too important to be delegated to an apprentice, the drawing office or, worst of all, a computer but should be the direct responsibility of the project leader.

A MORE REALISTIC GROUND



There is an obvious alternative to thin ground leads—a continuous "ground plane" of copper covering one side of a PCB to which all ground connections are made. The resistance of 0.001″ (0.025mm) copper is approximately 0.67mΩ/square so this solution is frequently adequate—but not always.

A SLIT IN A GROUND PLANE CAN RECONFIGURE CURRENT FLOW FOR BETTER ACCURACY

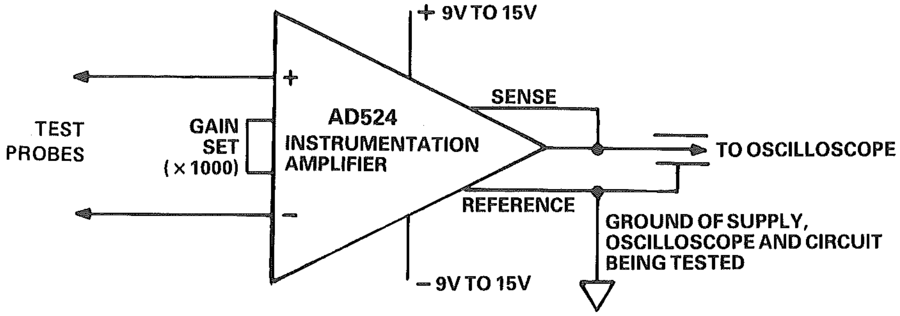


Consider a 15 × 10cm PCB with a ground connection at one end and a power amplifier at the other drawing 15A (it is not possible to mount the amplifier near to the ground bus-bar because it requires a heat-sink). If this current flows in a 0.001″ ground plane on the PCB there will be a voltage drop of about 1mV/cm in the ground plane—which would cause quite serious problems to any high precision circuitry sharing the PCB. If we slit the ground plane so that the high current does not flow in the region of the precision circuitry the situation is greatly improved—even though the voltage drop will increase in the region where the current does flow.

Accuracy (and stability) problems in precision circuitry arising from the causes we have discussed can very often be avoided if the engineer is aware that such problems can occur and takes steps during the system and PCB design to ensure that they do not. When they arise during design changes in existing systems they can be very intractible, not least because it is so hard to measure microvolt potential differences in ground conductors.

There is a simple piece of testgear which can be used to find small (but significant) voltage drops in ground or signal conductors. It consists of a single instrumentation amplifier—such as the AD524—used as a fully differential input stage to an oscilloscope.

AN INSTRUMENTATION AMPLIFIER CAN BE USED TO MEASURE DIFFERENTIAL VOLTAGES DOWN TO A FEW MICROVOLTS



Since the instrumentation amplifier has low noise, good common-mode rejection and gain of up to 1000 it may be used to measure voltage drops of a few microvolts at bandwidths of up to 50kHz. By moving the probes around ground or signal tracks the voltage drops in them may easily be observed and measured (the system is also very useful for finding short-circuits). The high input impedance and low bias current of the amplifier ensure that the measurment may be made with minimal loading of the circuit being measured (this is, of course, unimportant when making ground measurements). The instrumentation amplifier may be powered from the circuit under test or by a pair of 9V batteries—if batteries are used their centre-point must be connected to the circuitry being measured (generally to its ground) to provide a return path for the instrumentation amplifier bias currents.

When a precision analog system is built on a single PCB it is generally possible to overcome the difficulties that we have discussed and make it perform as required. The following steps should be followed:

STEPS IN THE DESIGN OF PRECISION ANALOG CIRCUITS

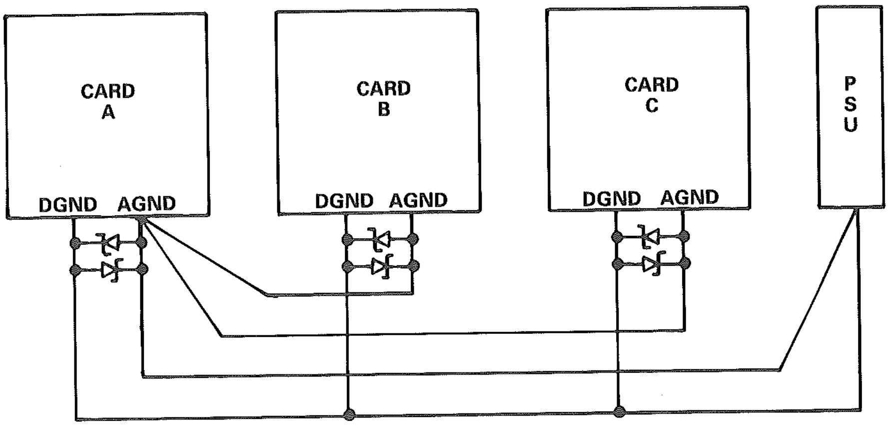
1. **Examine your circuit diagram and determine which voltage differences must be communicated accurately through the circuit and the currents which must flow in transmitting them.**
2. **Redraw the circuit diagram so that "Output" voltages (treated differentially) connect to the desired "Inputs" (also treated differentially). In plain English, hook up the main signal paths without using ground or common connections.**
3. **Identify signal paths which must be shared and eliminate those which are unnecessary.**
4. **Identify high current signal paths so that they can be made low impedance at signal frequencies.**
5. **Now add the power supplies to the diagram, identify and newly-formed signal connections and ensure that they are tolerable (it may be necessary to use isolated power or fully differential amplifiers [such as instrumentation or isolation amplifiers] to overcome problems arising at this point).**
6. **Tie up any loose ends (protection circuitry, location of any digital circuitry, reconfiguration of HF currents with capacitors, etc.) and again check their effect on the diagram in [2] and correct any abominations.**
7. **Build the circuit as you have designed it. Take two aspirins and try it. With luck the problems will be simple enough to find and fix without too much grief.**

NEVER OMIT STEP SEVEN!

These steps are quite clear and easily understood and yet probably as many as 60% of the problems seen by the Applications Department of Analog Devices arise from not following them. In particular step 7 is ESSENTIAL. Any engineer who sends a design to production without first testing it thoroughly is unworthy of the title of engineer—but far too many do just that.

Where systems are built on more than one card or PCB (and where different systems may be made by using different configurations of a few standard cards) it is much harder to follow such a procedure because of the difficulties of separating signal and power return paths. Where it is possible the same principles should be applied (but additional precautions may have to be taken to ensure that unplugging a card does not damage adjacent cards by open-circuiting their ground—a few Schottky diodes will solve this in any application where the difference between the analog and digital ground is unlikely to exceed 250mV).

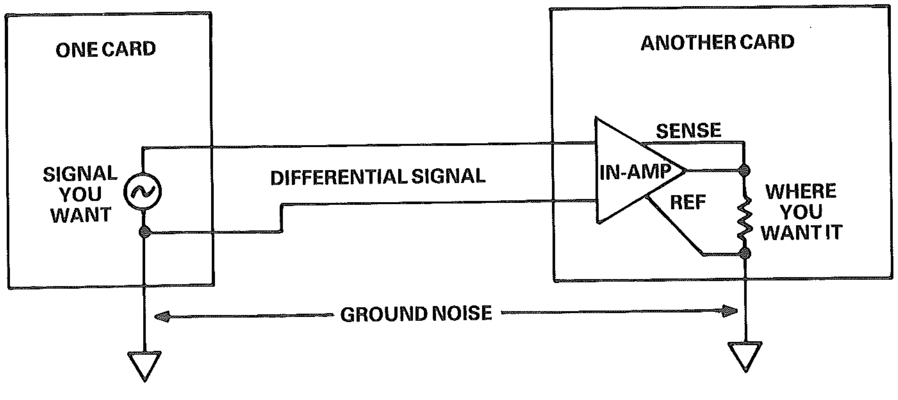
GROUNDING OF A MULTIPLE CARD SYSTEM



SCHOTTKY DIODES PROTECT CARDS IN THE EVENT OF LOSS OF ANALOG GROUND
(THIS GROUNDING SYSTEM MAY BE INADEQUATE AT HIGH RESOLUTION OR WHERE LARGE GROUND CURRENTS FLOW)

Where it is not possible to eliminate ground errors between cards fully differential transmission should be considered for all precision analog signal paths. This will involve the use of instrumentation or isolation amplifiers.

DIFFERENTIAL AMPLIFIERS CAN ELIMINATE GROUND ERRORS



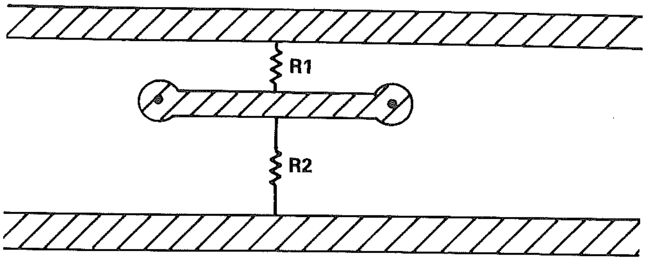
These are both differential amplifiers with high common-mode rejection. They differ in their common-mode ranges and bias requirements: an instrumentation amplifier has a common-mode range of less than its power supply and its bias current must flow to or from one of its supplies or some point between them, while an isolation amplifier has a common-mode range of many hundreds or thousands of volts and its bias current return is referred to its input stages rather than its power supplies. Instrumentation amplifiers, which today are usually monolithic, are less expensive than isolation amplifiers, which are manufactured using hybrid or modular techniques. In most applications instrumentation amplifiers are quite sufficient and cost only a few dollars.

LEAKAGE CURRENTS

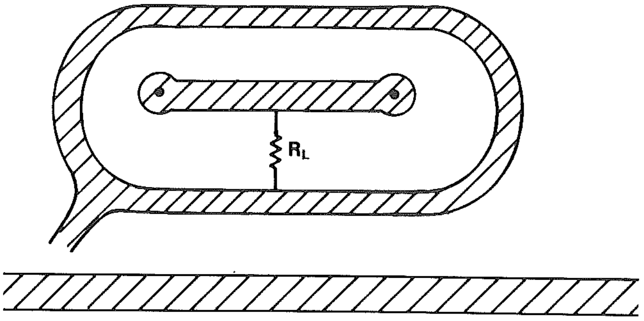
Disregard of Ohm's Law is not confined to overlooking the resistance of conductors—problems also arise from ignoring the conductivity of insulators. We have considered the difficulties we may encounter when comparatively large signal currents flow in small resistors—when using transducers with very small output currents stray leakage currents can be equally damaging.

When amplifying signals from photocells and electrochemical cells source impedances may be many millions or billions of ohms. If PCBs are inadequately cleaned after etching the residual electrolytes on the board surface may result in comparable resistances between nearby conductors and even with properly cleaned boards leakage resistances of no more than 10^{12} ohms can be expected. These resistances, moreover, are unlikely to be isotropic so that the resistance between two adjacent tracks may be higher than that between two tracks separated by a much larger gap. For this reason the inputs to low-level I/V converters should be protected by guard rings ON BOTH SIDES OF THE PCB connected to a point at the same potential as the summing junction. If this is done the exact value of the leakage resistance is unimportant since the potential difference across it will be small.

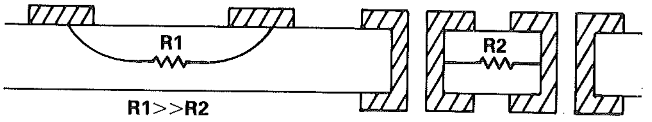
LEAKAGE RESISTANCE ON PRINTED CIRCUIT BOARDS



SURFACE LEAKAGE ON A PCB IS UNPREDICTABLE. R1 IS NOT NECESSARILY LESS THAN R2



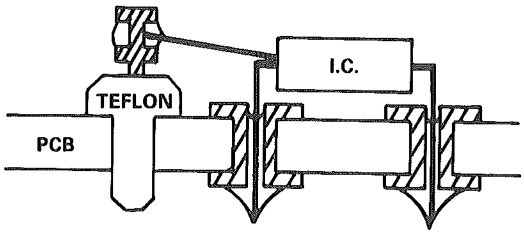
IF A VULNERABLE CONDUCTOR IS SURROUNDED BY A GUARD RING (ON BOTH SIDES OF THE BOARD) WHICH IS AT THE SAME POTENTIAL AS THE CONDUCTOR IT IS GUARDING THE EFFECTS OF LEAKAGE RESISTANCE WILL BE MINIMIZED



LEAKAGE RESISTANCE BETWEEN SURFACE TRACKS ON A PCB IS GENERALLY MUCH LARGER THAN BETWEEN PLATED HOLES

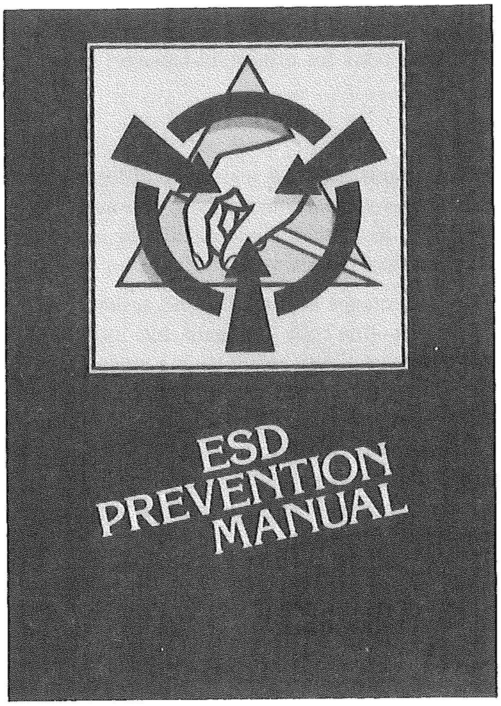
In applications of this type the use of plated-through holes (PTH) is inadvisable. The bulk resistivity of PCB material is much lower than the sheet resistivity of its surface and it is very difficult to fabricate a guard ring in the bulk of a board. The best approach of all is to connect such high impedance amplifier terminals to a virgin teflon stand-off insulator rather than a PCB track. (A virgin teflon insulator is made from a solid piece of new teflon which has not been welded together from powder or grains.)

A VIRGIN TEFLON STANDOFF INSULATOR HAS MUCH LOWER LEAKAGE THAN A PCB TRACK



ELECTROSTATIC DAMAGE (ESD)

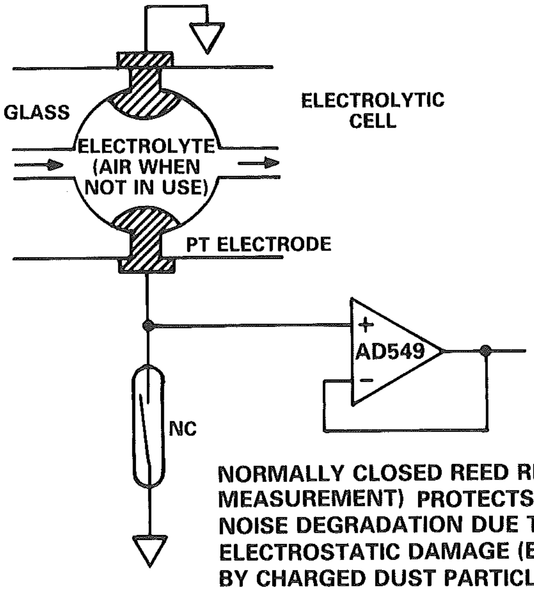
Where resistance is very high there is often the possibility of electrostatic charge—and electrostatic damage. A full discussion of electrostatic damage (ESD) is given in the Analog Devices' Application Note on the subject which is available free of charge from any Analog Devices office or agent.



ESD
PREVENTION
MANUAL

At this juncture it is sufficient to point out that all integrated circuit structures are vulnerable to damage from the high voltages and high peak currents involved in even small electrostatic discharges but that precision analog circuits suffer from a special disadvantage—the circuitry used to protect integrated circuit structures from ESD can often degrade the analog accuracy of the circuit where it is employed. Thus we have the choice of high performance or a high degree of protection. Which we choose will depend on individual circumstances but it is essential to realize that the choice may have to be made—and if it is made in favour of accuracy then the circuit involved must not be exposed to electrostatic discharge.

An interesting example of an unobvious effect of ESD occurred in Finland, where the very cold Winters produce very low humidity and particularly severe electrostatic problems. A customer complained that a particular BIFET amplifier type had poor long-term reliability and this its noise performance degraded during a few years of use.



NORMALLY CLOSED REED RELAY (OPENED DURING MEASUREMENT) PROTECTS ELECTROMETER FROM NOISE DEGRADATION DUE TO LOW-LEVEL ELECTROSTATIC DAMAGE (ESD) CAUSED BY CHARGED DUST PARTICLES

The amplifier was being used as a unity gain buffer with an electrochemical cell and the noninverting input was connected to a platinum electrode and to nothing else. In use this electrode was immersed in electrolyte but after use it was washed (automatically) in deionised water and air dried. It was then left unconnected until the machine was next used.

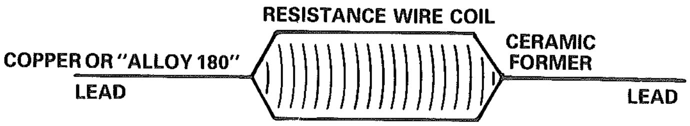
Although there is no possibility of the electrode being touched at this time (it was in the very centre of the machine) it could encounter random particles of electrostatically charged dust—and the pulse currents as these discharged were sufficient to cause slow degradation of the noise figure. As soon as arrangements were made to ground the electrode (with an NC reed relay for minimum leakage) the problem disappeared.

RESISTORS

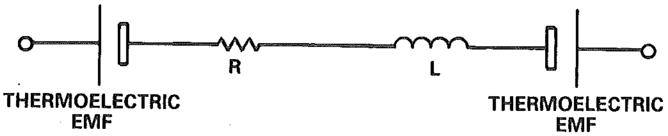
Between the low resistance of conductors and the high resistance of insulators there is yet another resistive source of inaccuracy in precision circuitry—resistors themselves. We normally assume that a resistor is a simple component which actually performs much as it might theoretically be expected to do. In fact it is necessary to consider a number of additional factors when designing high precision analog circuits incorporating resistors.

The most obvious imperfection is the inductance of a wirewound resistor. A wirewound resistor consists of a coil of resistance wire on a ceramic former—the coil, of course, has inductance as well as resistance which will affect the high frequency performance of any circuit using such a resistor (even a low frequency circuit built with an inductive resistor may suffer loss of accuracy if the inductance causes an oscillation—and such oscillation may be at too high a frequency to be observed on an LF oscilloscope). Some wirewound resistors have half their turns wound clockwise and the other half wound anticlockwise—this technique minimizes their reactance but rarely causes it to disappear altogether. Residual inductances of up to 20μH are quite normal for resistance values below 10K but the dominant reactance may actually take the form of shunt capacitance of the order of 5pF for noninductively wound resistors above 10K.

WIREWOUND RESISTORS



WIREWOUND RESISTOR



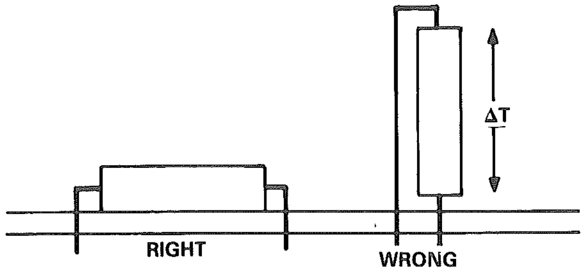
EQUIVALENT CIRCUIT

THE INDUCTANCE OF WIREWOUND RESISTORS CAUSES ERRORS WHEN THEY ARE USED IN HF PRECISION CIRCUITRY AND MAY CAUSE UNSUSPECTED VHF INSTABILITY EVEN IN LF AND DC CIRCUITRY.

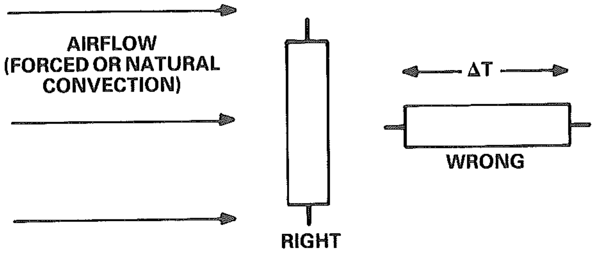
THE NET THERMOELECTRIC OUTPUT OF A WIREWOUND RESISTOR IS ZERO IF BOTH ENDS OF THE RESISTOR ARE AT THE SAME TEMPERATURE. IF THEY ARE NOT THE EMF MAY BE 42μV/°C TEMPERATURE DIFFERENCE.

Wirewound resistors have another problem. The junction of the resistance wire and the lead forms a thermocouple which has a thermoelectric EMF of 42μV/°C for the standard "Alloy 180"/Nichrome junction of an ordinary wirewound resistor (if a resistor is chosen with the [more expensive] Copper/Nichrome junction the value is 2.5μV/°C ["Alloy 180" is an alloy of 77% copper & 23% nickel]). Such thermocouple effects are unimportant in ac circuitry or where a resistor is at a uniform temperature but if the dissipation in a resistor, or its location with respect to heat sources, can cause one of its ends to be warmer than the other then there will be a net thermoelectric EMF which will introduce a dc error into the circuit. With a normal wirewound resistor a temperature differential of only 4°C will introduce a dc error 168μV—which is greater than 1 LSB in a 10V/16-bit system.

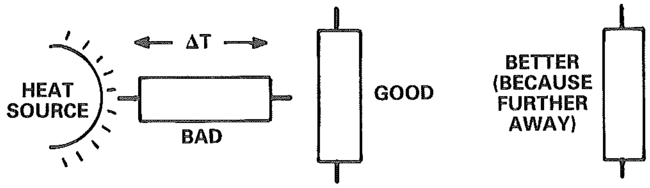
MINIMIZING THERMOCOUPLE EFFECTS IN WOREWOUND RESISTORS



LEADS SHOULD BE OF EQUAL LENGTH TO EQUALIZE THERMAL CONDUCTION



ANY AIRFLOW SHOULD BE NORMAL TO THE RESISTOR BODY - NOT ALONG IT



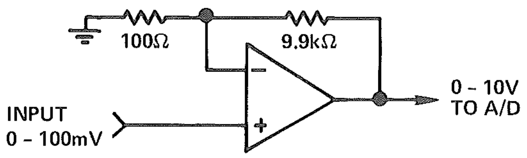
RESISTORS SHOULD BE PLACED SO THAT HEAT SOURCES WARM BOTH ENDS EQUALLY - AND SHOULD BE AS FAR FROM HEAT SOURES AS POSSIBLE

The problem may be minimized by mounting wirewond resistors to ensure that temperature differentials are minimized. This may be done by ensuring that both leads are of equal length to equalize thermal conduction through them, by making any airflow (whether forced or natural convection) normal to the resistor body, and by taking care that both ends of the resistor are the same distance from any heat source on the PCB, and that, notwithstanding the above precautions, all precision resistors are located as far as possible from any sources of heat. Even after these precautions have been taken it is still wise to use resistors with copper, rather than "Alloy 180", leads.

The best discrete resistors for most precision applications are metal film or carbon film types. These are stable, accurate and low noise and are available with low temperature coefficients. Carbon composition resistors should be avoided in precision circuitry because they are noisy and have poor temperature coefficients and worse long-term stability.

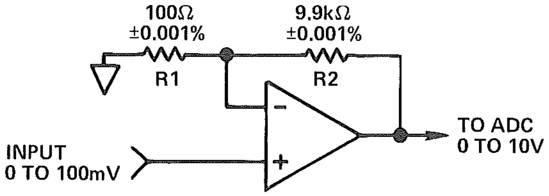
But all discrete resistors have problems. Consider a simple circuit comprising an operational amplifier and two resistors configured to make a precision amplifier with a gain of 100.

GAIN OF 100 STAGE



Let us assume that the amplifier is made with a perfect op-amp and that the two resistors are perfectly accurate at 25°C. If the temperature coefficients of the two resistors are 1500 and 1515ppm/°C (i.e., they differ by only 1%) then a temperature change of only 8°C would cause a change in resistor matching of 120ppm which would represent a full-scale gain error of 0.5LSB in a 12-bit system. This is obviously unacceptable.

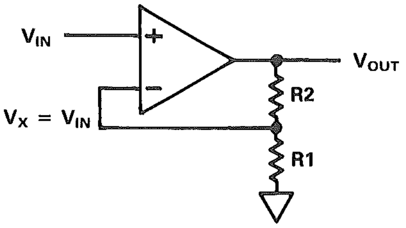
TEMPERATURE EFFECTS × 100 AMPLIFIER



TC_1 (of R_1) = 1500ppm/°C
TC_2 (of R_2) = 1515ppm/°C
$TC_2 - TC_1 = \Delta TC$ = 15ppm/°C
(15ppm/°C)(8°C) = 120ppm
= 1/2LSB

It would seem, therefore, that we require our precision resistors to have both their resistance values and temperature coefficients well-matched—but even this is not enough.

EFFECTS OF RESISTOR SELF-HEATING



R1 = 100Ω **BOTH ABSOLUTELY ACCURATE @ 25°C**
R2 = 9.9kΩ **0.125W (125°C/W) & 100ppm/°C**

$V_{IN} = 0$ **THEREFORE $V_{OUT} = 0$ THEREFORE DISSIPATION IS ZERO.**
$V_{IN} = 0.1V$ **THEREFORE $V_{OUT} = 10V$**

	THEREFORE DISSIPATION	TEMPERATURE RISE	DELTA R
R1:	$\frac{(0.1)^2}{100} = 0.025mW$	0.0125°C	1.25ppm
R2:	$\frac{(9.9)^2}{9900} = 9.9mW$	1.24°C	124ppm

GAIN ERROR = 123ppm = ½LSB (12-BIT)

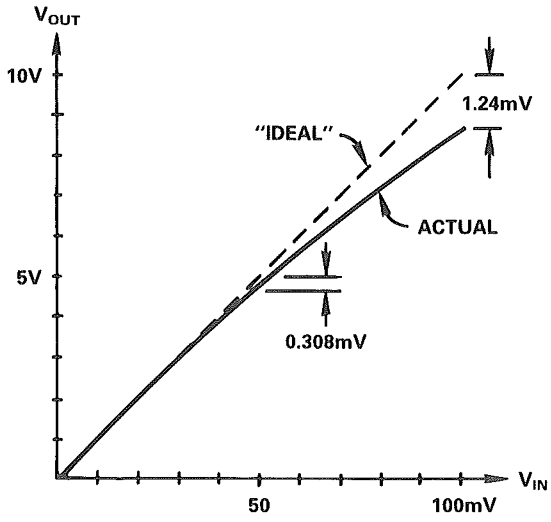
BUT THE EFFECT IS NONLINEAR

$V_{IN} = 0.05V$ THEREFORE $V_{OUT} = 5V$

R1:	$\frac{(0.05)^2}{100} = 0.025mW$	0.003°C	0.4ppm
R2:	$\frac{(4.95)^2}{9900} = 2.48mW$	0.3°C	30.8ppm

GAIN ERROR = 30ppm = ⅛LSB (12-BIT)

AMPLIFIER CIRCUIT TRANSFER FUNCTION



Consider the same amplifier built with a perfect op-amp and perfectly matched 0.125W metal film resistors which are matched not only for resistance but for their temperature coefficient of 100ppm/°C. When the input voltage is zero the output is also zero and neither resistor dissipates any power—the amplifier gain is accurate. If, on the other hand, an input of 100mV is applied to the amplifier the output is 10V and a current flows in both R1 and R2.

The voltage across R2 is 9.9V and the dissipation is 9.9mW, which causes the temperature of R2 to increase by 1.24°C. The dissipation in R1, on the other hand, is only 0.1mW and the temperature rise only 0.0125°C. The change of temperature difference due to resistor self-heating is therefore approximately 1.24°C and as a result the resistor match will be degraded by $1.24 \times 100 = 124$ppm—which is 0.5 LSB at 12-bits.

Worse—the effect is nonlinear. At half scale the heating (which is, of course, proportional to the square of the voltage) is only one quarter as great and the error is only 0.125 LSB. Thus self-heating makes the circuit nonlinear as well as inaccurate.

RESISTOR SELF-HEATING
PRODUCES
GAIN AND LINEARITY ERRORS

Thermal Time Constants Make the Error Dependant Not On the Current Resistor Dissipation But On the rms Voltage On the Resistor During the Previous Few Seconds –

Which Makes Compensation Virtually Impossible

The Problem May Be Prevented By Ensuring that Resistors Used Have:

- **Closely Matched TCs**
- **Low Absolute TCs**
- **Low Thermal Resistance**
- **Tight Thermal Coupling Between Resistors Whose Matching is Critical**

BEST SOLUTION IS TO USE A MONOLITHIC CHIP CONTAINING BOTH THE AMPLIFIER AND THE RESISTOR NETWORK OVERALL PERFORMANCE IS THEN GUARANTEED BY THE INTEGRATED CIRCUIT MANUFACTURER.

WHERE THIS IS NOT POSSIBLE A SINGLE THIN-FILM RESISTOR NETWORK SHOULD CONTAIN ALL THOSE RESISTORS WHOSE MATCHING IS CRITICAL

There is yet another effect. Since the heating is not instantaneous the error in the gain of the amplifier will depend, not on the present input, but on the rms input during the previous few seconds. This is obviously most unsatisfactory and is best solved by not using discrete resistors.

If several thin-film resistors are manufactured on a single substrate from a single resistive film then we can reasonably expect that their temperature coefficients will be very well matched. Also if they are on the same substrate dissipation in one resistor will heat them all so that there will be no differential temperature to cause errors. Thus it is evident that if the matching of several resistors is critical for the performance of a precision analog circuit than all the resistors should be fabricated on a single substrate.

Such resistor networks are readily available on ceramic substrates and may be used wherever precision resistor matching is required. There is an even better solution, however,—the use of monolithic integrated circuits which contain laser-trimmed resistor networks in addition to such active circuit elements as amplifiers or digital-analog converters (DACs). Such devices are not yet available for all applications but where they are available they are undoubtedly the best solution to the problem because the integrated circuit manufacturer has guaranteed the overall performance of both the amplifier and resistors supplied with it (he may even have arranged for nonlinearities in one to be compensated in the other).

Precision applications involving very high value resistors cannot use resistors on a monolithic chip or a thin-film network, which are limited to values between a few tens of ohms and a few megohms. In this case there is no alternative to carbon film or cermet resistors. Some high value resistors suffer quite badly from voltage variable resistance and devices whose data sheets indicate that they are liable to this problem should not be used in precision applications. The best high megohm resistors are packaged in glass and treated with silicone varnish to minimize the effects of humidity. The resistor bodies should never be touched with ungolved hands as surface contamination of the glass can cause leakage currents larger than the currents in the resistor—ruining the accuracy.

RESISTOR COMPARISON CHART

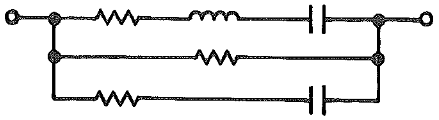
TYPE		ADVANTAGES	DISADVANTAGES
DISCRETE	Carbon Composition	Lowest Cost High Power/Small Case Size	Poor Tolerance (5%) Poor Temperature Coefficient (1500ppm/°C)
	Wire-Wound	Excellent Tolerance (0.01%) Excellent TC (1ppm/°C) High Power	Reactance May be a Problem Large Case Size Most Expensive
	Metal Film	Good Tolerance (0.1%) Good TC (<1 to 100ppm/°C) Moderate Cost	Must be Stabilized with Burn-In Low Power
	Bulk Metal or Metal Foil	Excellent Tolerance (to 0.005%) Excellent TC (to <1ppm/°C) Low Reactance	Low Power Very Expensive
	High Megohm	Very High Values ($10^8 - 10^{14}\Omega$) Only Choice for Some Circuits	High Voltage Coefficient (200ppm/V) Fragile Glass Case Expensive
NETWORKS	Thick Film	Low Cost High Power Laser-Trimmable Readily Available	Fair Matching (0.1%) Poor TC (>100ppm/°C) Poor Tracking TC (10ppm/°C)
	Thin Film on Glass	Good Matching (<0.01%) Good TC (<100ppm/°C) Good Tracking TC (2ppm/°C) Moderate Cost Laser-Trimmable Low Capacitance	Delicate Often Large Geometry Low Power
	Thin Film on Ceramic	Good Matching (<0.01%) Good TC (<100ppm/°C) Good Tracking TC (2ppm/°C) Moderate Cost Laser-Trimmable Low Capacitance Suitable for Hybrid IC Substrate	Often Large Geometry
NETWORKS	Thin Film on Silicon	Good Matching (<0.01%) Good TC (<100ppm/°C) Good Tracking TC (2ppm/°C) Moderate Cost Laser-Trimmable Suitable for Monolithic IC Construction	Some Capacitance to Substrate Low Power
	Thin Film on Sapphire	Good Matching (<0.01%) Good TC (<100ppm/°C) Good Tracking TC (2ppm/°C) Laser-Trimmable Low Capacitance	Higher Cost Low Power

CAPACITORS

Capacitors can also behave in ways which are inconsistant with their simple model and thus introduce errors into precision circuitry. An ideal capacitor is a simple device—real capacitors suffer from a number of different problems which cause difficulties in different applications. While it would be possible to make a general model of nonideal capacitor and use it in all circuit analyses it would be unprofitable to do so since different features are important in different applications.

EQUIVALENT CIRCUITS OF A REAL CAPACITOR

IDEAL CAPACITOR

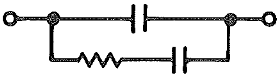


MOST GENERAL MODEL OF A REAL CAPACITOR

LEAKAGE CURRENT MODEL

HIGH CURRENT MODEL

HIGH FREQUENCY MODEL



DIELECTRIC ABSORBTION (D.A.) MODEL

Capacitors are used for coupling (passing ac signals while blocking dc), for decoupling (removing ac superimposed on dc in both power and signal circuitry), for building filters or frequency-selective networks, and for storing charge in "sample and hold" circuits (also known as "track and hold" circuits or SHAs, SAHs or THAs).

In coupling and SHA applications the leakage of the capacitor can be important. Electrolytic capacitors, where the dielectric is formed by an electrochemical reaction, have relatively high leakage currents of microamperes or even more and so are not used in applications where leakage matters. The leakage of electrolytic capacitors is greater during the first few minutes of operation after a period of storage (the leakage current while the capacitor is is use keeps the dielectric in good condition and it may deteriorate slightly in storage)—this feature can be important in equipment which must perform correctly after a long quiescent period.

The leakage of tantalum electrolytic capacitors is lower than that of aluminum ones and so in applications where capacitances of tens of microfarads or more (which can be achieved only with electrolytic capacitors) are required tantalum ones are used, despite their extra cost, if particularly low values of leakage current are necessary. At room temperature the leakage of aluminum electrolytic capacitors is of the order of 20nA/μF and that of tantalum ones is 5nA/μF.

Another feature of electrolytic capacitors, both aluminum and tantalum, is that most of them are polarized and require a dc bias for correct operation—a reverse bias may do damage and will certainly increase leakage.

Most other types of capacitor have leakage resistances in excess of hundreds of gigohms so that for most applications their leakage currents can be disregarded.

The series resistance of capacitors causes them to dissipate power when high ac currents are flowing in them. This can have serious consequences at RF and in high current supply decoupling capacitors but is unlikely to have much effect in precision analog circuitry. The series inductance, however, can have very inconvenient consequences.

The transistors used in precision analog circuits have transition frequencies (ft) of hundreds of MHz or even several GHz, even though the precision circuitry itself may be operating at dc or low frequencies. This makes it essential that the power supply terminals of such circuits should be decoupled properly at high frequency.

A common structure for capacitors is two sheets of metal foil separated by sheets of dielectric and formed into a roll. Such a structure has considerable inductance and behaves as an inductance at frequencies of more than a few MHz. It is therefore inadvisable to use electrolytic capacitors, paper capacitors or plastic film ones for decoupling at high frequencies.

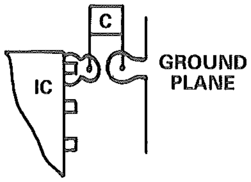
Monolithic ceramic capacitors have very low series inductance (they are formed of a multilayer sandwich of metal films and ceramic dielectric and all the films are joined to a bus-bar rather than being connected in series). They are therefore ideal for high frequency decoupling. Disc ceramic capacitors, on the other hand, are sometime quite inductive, although less expensive.

The best way of ensuring that an analog circuit is adequately decoupled at both high and low frequencies is to use a tantalum bead capacitor in parallel with a monolithic ceramic one. The combination will have high capacitance but will remain capacitive at VHF frequencies.

There is little point in taking great care in the choice of a noninductive capacitor if it is then unsuitably mounted. As quite short lengths of wire have appreciable inductance HF decoupling capacitors must be mounted on short leads as close as possible to the points that they are decoupling—and their PCB tracks must also be as short and wide as possible. It is also important to understand where HF decoupling currents should flow and why HF decoupling is more important at some points than at others—there are additional comments on this in the operational amplifier section of the seminar.

HIGH FREQUENCY DECOUPLING

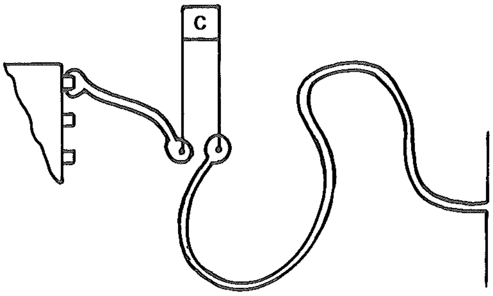
(REQUIRED EVEN BY LF ANALOG CIRCUITS)



IDEAL HF DECOUPLING HAS

1. LOW INDUCTANCE CAPACITOR (MONOLITHIC CERAMIC)
2. MOUNTED VERY CLOSE TO THE IC
3. WITH SHORT LEADS
4. AND SHORT, WIDE PC TRACKS

IT MAY BE SHUNTED WITH A TANTALUM BEAD ELECTROLYTIC TO PROVIDE GOOD LF DECOUPLING AS WELL.

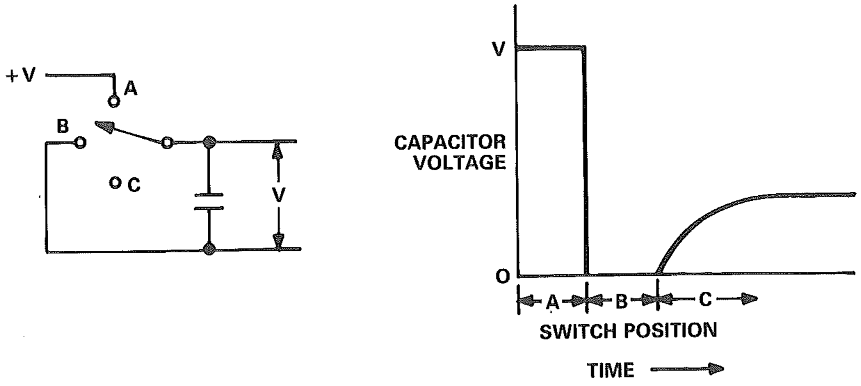


THIS SORT OF THING IS USELESS!

HF instability in analog circuits is commoner than is realized. Oscillation at hundreds of MHz will cause serious malfunction of precision circuitry but may not affect an oscilloscope (indeed the presence of an oscilloscope probe may damp the oscillation). It is quite good practice to use a broadband spectrum analyzer (say 1–1500MHz) and a low capacity FET probe to check for parasitic oscillation any analog circuit which is malfunctioning for no obvious reason. This test will also show if the malfunction is due to the presence of a strong RF field from an external source.

Monolithic ceramic capacitors are excellent for HF decoupling but they have considerable dielectric absorption, which makes them unsuitable for use as the hold capacitor of an SHA. Dielectric absorption causes a capacitor which is quickly discharged and then open-circuited to recover some of its charge. Since the amount of charge recovered is a function of its previous charge this is, in effect, a charge memory and will cause errors in any SHA where dielectric absorption is present in the hold capacitor.

CAPACITORS HAVING SIGNIFICANT D.A. ARE USELESS FOR SAMPLE AND HOLD APPLICATIONS



DIELECTRIC ABSORBTION CAUSES A BRIEFLY DISCHARGED CAPACITOR TO RECOVER A PERCENTAGE OF ITS PREVIOUS CHARGE ON BEING OPEN CIRCUITED.

Capacitors for this application should therefore be selected to have minimal dielectric absorption. The best startegy is to use a SHA which is supplied with an internal capacitor or where the SHA manufacturer supplies the capacitor with the SHA. If this is not possible (sometimes one may require a longer hold time—and hence extra capacity) a capacitor should be chosen which has its low dielectric absorption (DA) specified on its data sheet.

Such capacitors are normally plastic dielectric types (polystyrene, polypropylene or teflon) but it is not safe to use just any plastic dielectric capacitor with a SHA as special processing and testing is necessary to ensure that it has low DA. For use with a SHA a capacitor should be chosen which is specified for use in SHAs.

FEATURES OF COMMON CAPACITORS

TYPE	TYPICAL DIELECTRIC ABSORPTION	ADVANTAGES	DISADVANTAGES
NPO Ceramic	**0.1%**	**Small Case Size Inexpensive Good Stability Wide Range of Values Many Vendors Low Inductance**	**DA too High for More than 8-Bit Applications**
Polystyrene	**0.001% to 0.02%**	**Inexpensive Low DA Available Wide Range of Values Good Stability**	**Destroyed by Temperature > +85°C Large Case Size High Inductance**
Polypropylene	**0.001% to 0.02%**	**Inexpensive Low DA Available Wide Range of Values**	**Destroyed by Temperature > +105°C Large Case Size High Inductance**
Teflon	**0.003% to 0.02%**	**Low DA Available Good Stability Operational Above +125°C Wide Range of Values**	**Relatively Expensive Large High Inductance**

FEATURES OF COMMON CAPACITORS

TYPE	TYPICAL DIELECTRIC ABSORPTION	ADVANTAGES	DISADVANTAGES
MOS	0.01%	Good DA Small Operational Above +125°C Low Inductance	Limited Availability Available only in Small Capacitance Values
Polycarbonate	0.1%	Good Stability Low Cost Wide Temperature Range	Large DA Limits to 8-Bit Applications High Inductance
Polysulfone	0.1%	Good Stability Low Cost Wide Temperature Range	Large DA Limits to 8-Bit Applications High Inductance
Monolithic Ceramic	>0.2%	Low Inductance Wide Range of Values	Poor Stability Poor DA
Mica	>0.003%	Low Loss at HF Low Inductance Very Stable Available in 1% Values or Better	Quite Large Low Values (<10nF) Expensive
Aluminium Electrolytic	High	Large Values High Currents High Voltages Small Size	High Leakage Usually Polarized Poor Stability Poor Accuracy Inductive
Tantalum Electrolytic	High	Small Size Large Values Medium Inductance Reliable	Quite High Leakage Usually Polarized Expensive Poor Stability Poor Accuracy

HORRIBLE EXAMPLES

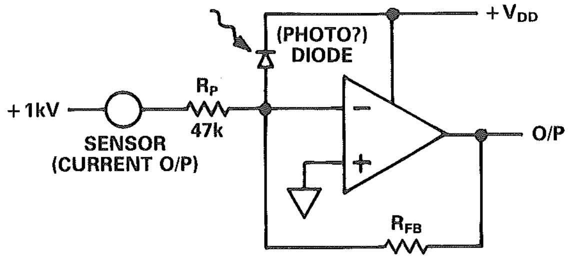
This section of our seminar has demonstrated how unconsidered aspects of well-known physical laws, especially Ohm's and Kirchoff's Laws, and the nonideal behaviour of passive components, can damage the performance of precision analog circuitry. We have also shown how circuit techniques which are appropriate for digital circuitry with noise immunities of hundreds or thousands of millivolts may be totally unsuited to precision analog systems where even millivolts of error may be too much.

This section could be extended almost indefinitely, particularly if we included case studies from Analog Devices' Application Department. They have some real horror stories to tell and it might be instructive to complete the section with two examples of how the laws of physics go on working even when one would rather that they didn't—and in the process can foul up quite well-considered designs. We shall call our studies "The Case of the Hum from Nowhere" and "The Case of the Two-Coloured Wire".

THE CASE OF THE HUM FROM NOWHERE

When the signal source of an op amp contains an energizing voltage which is much higher than the op-amp supply it is common to use a diode and a current limiting resistor to protect the op amp in the event of a sensor short-circuit. In normal operation the diode is reverse biassed and contributes only its (low) leakage current to the circuit but should the sensor be short-circuited the resulting current will flow through the diode to the op-amp supply rather than destroy the op amp. It is, of course, important to choose the resistor so that it neither degrades the noise performance of the system nor allows too much current to pass under fault conditions.

THE CASE OF THE HUM FROM NOWHERE



THE DIODE PROTECTS THE OP AMP UNDER FAULT CONDITIONS BY DIVERTING FAULT CURRENT (LIMITED BY R$_P$) TO THE SUPPLY RAIL. THE DIODE SHOULD NOT BY PHOTO-RESPONSIVE, OTHERWISE FLUORESCENT LIGHTING MAY MODULATE ITS LEAKAGE CURRENT AT 100/120Hz AND CAUSE HUM. USE A PLASTIC DIODE - NOT A GLASS ONE.

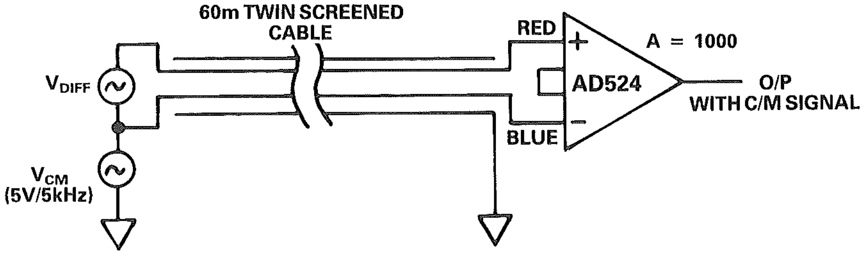
We encountered such a system where about 10% of all the amplifiers built suffered from severe hum at twice the power line frequency. The customer, of course, blamed the op amp for poor supply rejection but analysis showed that even when the circuit was powered from batteries the problem persisted. The cause eventually turned out to be the protective diode—a 1N914 in a glass case.

About 10% of diodes from the particular manufacturer were quite active as photodiodes and when illuminated by fluorescent lights their leakage current was modulated at 120Hz—and the 120Hz was, or course, amplified with the sensor signal. Use of a black epoxy packaged diode provided a complete cure.

The Case of the Two-Coloured Wire

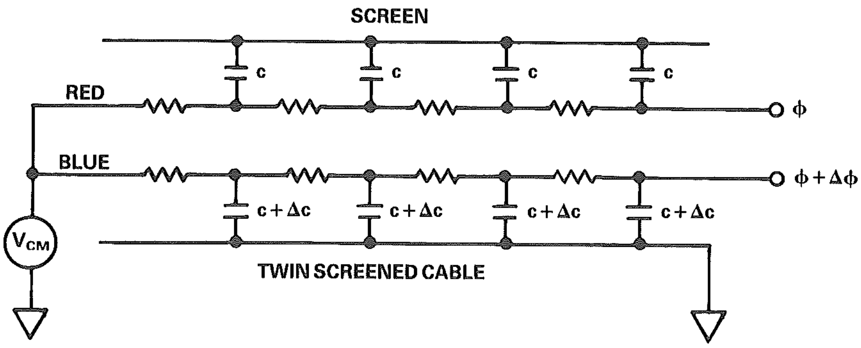
Another customer complained that one of our instrumentation amplifiers did not have the common-mode rejection that we advertised. He was using the AD524 to amplify a small differential signal in the presence of several volts of 5kHz common mode and the signal was applied to it via about sixty metres of twin screened cable.

THE CASE OF THE TWO-COLOURED WIRE (1)



The problem was the result of differential phase shift in the cable. The red conductor has slightly thicker insulation than the blue, which accordingly has slightly more capacitance and therefore produced slightly greater phase shift to ac signals. A common mode 5kHz signal applied to one end of the 60 metre cable underwent a differential phase shift of a fraction of a degree in transit—this phase shift caused a small DIFFERENTIAL 5kHz signal at the instrumentation amplifier input in addition to the large common-mode signal. Unfortunately the differential 5kHz was about the same amplitude as the original wanted signal.

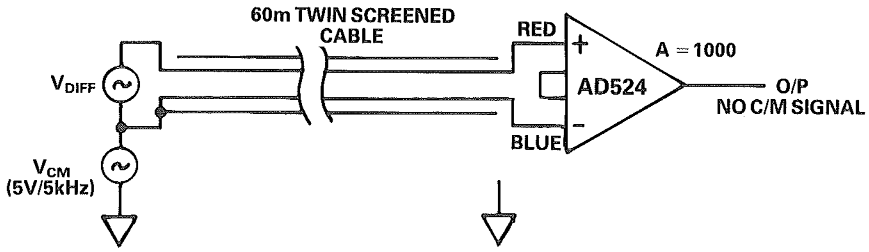
THE CASE OF THE TWO-COLOURED WIRE (2)



DIFFERENTIAL PHASE SHIFT DUE TO DIFFERENCES IN CORE CAPACITANCE

The cure is to drive the screen of the cable with the common-mode signal (bootstrap it). Common-mode phase shift does not then take place and the instrumentation amplifier input contains only common-mode signals at 5kHz—which it rejects.

THE CASE OF THE TWO-COLOURED WIRE (3)



The bootstrapping is most simply done (as in this case) by connecting the cable screen to the common-mode signal at the signal end of the cable. In some cases this is not possible and the shield must be driven by an additional buffer amplifier (known as a "shield driver") which is fed with common-mode signal, which can be obtained from the AD524.

CONCLUSION

Such examples might be continued *ad infinitum* but the important message of this part of our seminar is that the design of precision analog circuits and systems follows the same physical laws as the design of any other electronic apparatus but that the priorities during such design depend on the high performance that we wish to achieve. The fundamental rules are:

GROUND IS A DIRTY WORD

ALL VOLTAGES ARE DIFFERENTIAL

ALL COMPONENTS HAVE EXTRAS
(EXTRA INDUCTANCE, EXTRA CAPACITANCE, ETC.)
BE GRATEFUL YOU ARE NOT CHARGES FOR THEM
(IT'S ALL YOU HAVE TO BE GRATEFUL FOR)

NEVER BELIEVE DATA SHEETS

ALL THE LAWS OF PHYSICS ALWAYS WORK
(THAT'S WHY THEY'RE CALLED LAWS)

ANY EFFECT YOU THINK CAN BE DISREGARDED – CAN'T

AN UNTESTED PAPER DESIGN IS WORTH LESS THAN ITS MATERIALS

AND FINALLY – MURPHY DIDN'T KNOW HALF OF IT