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Avoiding Passive-Component Pitfalls

The Wrong Passive Component Can Derail Even the Best Op Amp or Data Converter
Here Are Some Basic Traps to Watch for

by Doug Grant and Scott Wurcer

You've just spent $25 or more for a precision op amp or data converter, only to find that, when plugged into your board, the device doesn't meet spec. Perhaps the circuit suffers from drift, poor frequency response, oscillations—or simply doesn't achieve the accuracy you expect. Well, before you blame the device itself, you should examine your passive components—including capacitors, resistors, potentiometers, and yes, even the printed circuit boards themselves. Subtle effects of tolerance, temperature, parasitics, aging, and user assembly procedures can unwittingly sink your circuit. And these effects all too often go unspecified or underspecified by manufacturers.

In general, if you use data converters having 12 bits or more of resolution, or op amps that cost more than $5, you should pay particularly close attention to passive-component selection. To put the problem in perspective, consider the case of a 12-bit digital-to-analog converter (DAC). One half LSB (least-significant bit) corresponds to 0.012% of full scale, or only 122 parts per million (ppm)! The host of passive-component phenomena can quickly accumulate errors far exceeding this level.

Buying the most-expensive passive components won't necessarily solve your problems either. Often, the correct 25-cent capacitor will yield a better-performing, more cost-effective design than the premium-grade $8 part. Although not necessarily easy, understanding and analyzing passive-component effects may prove quite rewarding, once you understand a few basics.

CAPACITORS

Most designers are generally familiar with the range of capacitors available. But the mechanisms by which both static and dynamic errors can occur in precision circuit designs are easy to forget because of the tremendous variety of capacitor types, e.g.: glass, aluminum foil, solid tantalum and tantalum foil, silver mica, ceramic, Teflon, and the film capacitors, including polyester, polycarbonate, polystyrene, and polypropylene types.

Figure 1 is a workable model of a non-ideal capacitor. The nominal capacitance, C, is shunted by a resistance R_p, representing insulation resistance or leakage. A second resistance, R_s—equivalent series resistance, or ESR—appears in series with the capacitor and represents the resistance of the leads and capacitor plates.* Inductance, L—the equivalent series inductance, or ESL, models the inductance of the leads and plates. Finally, resistance R_{da} and capacitance C_{da} together form a simplified model of a phenomenon non known as dielectric absorption. Dielectric absorption can ruin the dynamic performance of both fast and slow circuits.

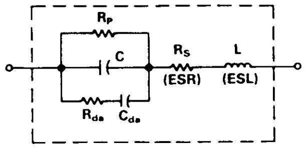

Figure 1. Capacitor equivalent circuit.

Dielectric Absorption

We begin with dielectric absorption, also known as "soakage" and sometimes as "dielectric hysteresis"—perhaps the least understood and potentially most damaging capacitive effect. Upon discharge, most capacitors are reluctant to give up all of their former charge. Figure 2 illustrates the effect. After being charged to V volts at time t_0, the capacitor is shorted by the switch at time t_1. At time t_2, the capacitor is open-circuited; a residual voltage slowly builds up across its terminals and reaches a nearly constant value. This voltage is due to "dielectric absorption."

Figure 2. Residual voltage characterizes capacitor dielectric absorption.

Standards techniques for specifying or measuring dielectric absorption are few and far between. Measured results are usually expressed as the percentage of the original charging voltage that reappears across the capacitor. Typically, the capacitor is charged for more than 1 minute, then shorted for an established time between 1 and 10 seconds. The capacitor is then allowed to recover for approximately 1 minute, and the residual voltage is measured (see reference 10).

In practice, dielectric absorption makes itself known in a variety of ways. Perhaps an integrator refuses to reset to zero, a voltage-to-frequency converter exhibits unexpected nonlinearity, or a sample-and-hold exhibits varying errors. This last manifestation can be particularly damaging in a data-acquisition system, where adjacent channels may be at voltages which differ by nearly full scale. Figure 3 illustrates the case in a simple sample-hold.

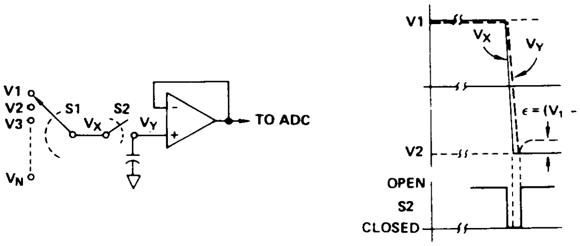

Figure 3. Dielectric absorption induces errors in sample-and-hold application.

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*Capacitor phenomena aren't that easy to separate out. This matching of phenomena and models is for convenience in explanation.

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The dielectric absorption is a characteristic of the dielectric material itself, although it can be affected by inferior manufacturing processes or electrode materials. As a percentage of the charging voltage, dielectric absorption specifications range from a low of 0.02% for Teflon, polystyrene, and polypropylene capacitors to a high of 10% or more for some aluminum electrolytics. For some time-frames, the D.A. of polystyrene can be as low as 0.002%.

Common ceramic and polycarbonate types display typical dielectric absorptions of 0.2%; this corresponds to one-half of an LSB at only 8 bits! Silver mica, glass, and tantalum capacitors typically exhibit even larger dielectric absorptions, ranging from 1.0% to 5.0%, with those of polyester devices falling in the vicinity of 0.5%. As a rule, if your capacitor's spec sheet does not discuss dielectric absorption *in your time frame and voltage range*, exercise caution.

Dielectric absorption can produce long tails in the transient response of fast-settling circuits, such as those found in high-pass active filters or ac amplifiers. In some devices used for such applications, Figure 1's R_{da}-C_{da} model of dielectric absorption can have a time constant of milliseconds.* In fast-charge, fast-discharge applications, the dielectric absorption resembles "analog memory"; the capacitor tries to remember its previous voltage.

In some designs, you can compensate for the effects of dielectric absorption if it is simple and easily characterized, and you are willing to do custom-tweaking. In an integrator, for instance, the output signal can be fed back through a suitable compensation network, tailored to cancel the circuit equivalent of the dielectric absorption by placing a negative impedance effectively in parallel. Such compensation has been shown to improve sample- and-hold circuit performance by factors of 10 or more (Reference 7).

Parasitics and Dissipation Factor

In Figure 1, a capacitor's leakage resistance, R_p, the effective series resistance, R_s, and effective series inductance, L, act as parasitic elements which can degrade an external circuit's performance. The effects of these elements are often lumped together and defined as a dissipation factor, or DF.

A capacitor's leakage is the small current that flows through the dielectric when a voltage is applied. Although modeled as a simple insulation resistance (R_p) in parallel with the capacitor, the leakage actually is nonlinear with voltage. Manufacturers often specify leakage as a megohm-microfarad product, which describes the dielectric's self-discharge time constant, in seconds. It ranges from a low of 1s or less for high-leakage capacitors, such as aluminum and tantalum devices, to the 100's of seconds for ceramic capacitors. Glass devices exhibit self-discharge time-constants of 1,000 or more; but the best leakage performance is shown by Teflon and the film devices (polystyrene, polypropylene), with time constants exceeding 1,000,000 megohm-microfarads. For such a device, leakage paths—created by surface contamination of the device's case or in the associated wiring or physical assembly—can overshadow the dielectric's leakage.

Effective series inductance, ESL (Figure 1) arises from the inductance of the capacitor leads and plates, which, particularly at the higher frequencies, can turn a capacitor's normally capacitive reactance into an inductive reactance. Its magnitude depends on construction details within the capacitor. Tubular wrapped-foil devices display significantly more lead inductance than molded radial-lead configurations. Multilayer ceramic and film-type devices typically exhibit the lowest series impedances, while tantalum and aluminum electrolytics typically exhibit the highest. Consequently, electrolytic types usually prove insufficient for high-speed local bypassing applications.

Manufacturers of capacitors often specify effective series inductance by means of impedance-versus-frequency plots. These show graphically, and not surprisingly, that the devices display predominantly capacitive reactance at low frequencies, with rising impedance at higher frequencies because of their series inductance.

Effective series resistance, ESR (resistor R_s of Figure 1), is made up of the resistance of the leads and plates. As noted, many manufacturers lump the effects of ESR, ESL, and leakage into a single parameter called *dissipation factor*, or DF. Dissipation factor measures the basic inefficiency of the capacitor. Manufacturers define it as the ratio of the energy lost to energy stored per cycle by the capacitor. The ratio of equivalent series resistance to total capacitive reactance—at a specified frequency—approximates the dissipation factor, which turns out to be equivalent to the reciprocal of the figure of merit, Q.

Dissipation factor often varies as a function of both temperature and frequency. Capacitors with mica and glass dielectrics generally have DF values from 0.03% to 1.0%. For ceramic devices, DF ranges from a low of 0.1% to as high as 2.5% at room temperature. And electrolytics usually exceed even this level. The film capacitors usually are the best, with DF's of less than 0.1%.

Tolerance, Temperature, and Other Effects

In general, precision capacitors are expensive and—even then—not necessarily easy to buy. In fact, choice of capacitance is limited by the the range of available values and tolerances. Tolerances of ± 1% for some ceramics and most film-type devices are common, but with possibly unacceptable delivery times. Most film capacitors can be made available with tolerances of less than ± 1%, but on special order only.

Most capacitors are sensitive to temperature variations. Dissipation factor, dielectric absorption, and capacitance itself are all functions of temperature. For some capacitors, these parameters vary approximately linearly with temperature; in others they vary quite nonlinearly. Although not usually important for sample-and-hold applications, an excessively large temperature coefficient (ppm/°C) can prove harmful to the performance of precision integrators, voltage-to-frequency converters, and oscillators. NPO ceramic capacitors, with temperature-drift as low as 30 ppm/°C, usually do the best. On the other hand, aluminum electrolytics' temperature coefficients can exceed 10,000 ppm/°C.

A capacitor's maximum working temperature should also be considered. Polystyrene capacitors, for instance, melt near 85°C, compared to Teflon's ability to survive temperatures up to 200°C.

Sensitivity of capacitance and dielectric absorption to applied voltage can also hurt capacitor performance in a circuit application. Although capacitor manufacturers do not always clearly specify voltage coefficients, the user should always consider the possible effects of such factors. For instance, when maximum voltages are applied, some high-density ceramic devices can experience a decrease in capacitance of 50% or more!

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*Much longer time constants are also quite usual. In fact, some devices can be modeled by several paralleled R_{da}–C_{da} circuits, with a wide range of time constants.

Similarly, the capacitance and dissipation factor of many types vary significantly with frequency, mainly as a result of a variation in dielectric constant. In this regard, the better dielectrics are polystyrene, polypropylene, and Teflon.

Assemble Critical Components Last

The designer's worries don't end with the design process. Commonly used printed-circuit-board assembly techniques can prove ruinous to even the best of designs. For instance, some commonly used p-c board cleaning solvents can infiltrate certain electrolytic capacitors—those with rubber end caps are particularly susceptible. Even worse, some of the film capacitors, polystyrene in particular, actually melt when contacted by some solvents. Rough handling of the leads can damage still other capacitors, creating random or even intermittent circuit problems. Etched-foil types are particularly delicate in this regard. To avoid these difficulties, it may be advisable to mount especially critical components as the last step in the board assembly process—if possible.

Designers should also consider the natural failure mechanisms of capacitors. Metallized film devices, for instance, often self-heal. They initially fail due to conductive bridges that develop through small perforations in the dielectric films. But the resulting fault currents can generate sufficient heat to destroy the bridge, thus returning the capacitor to normal operation (at slightly lower capacitance). Of course, applications in high-impedance circuits may not develop sufficient current to clear the bridge.

Tantalum capacitors also exhibit a degree of self-healing, but—unlike film capacitors—the phenomenon depends on the temperature at the fault location rising slowly. Therefore, tantalum capacitors self-heal best in high impedance circuits which limit the surge in current through the capacitor's defect. Use caution, therefore, when specifying tantalums for high-current applications.

Electrolytic capacitor life often depends on the rate at which capacitor fluids seep through end caps. Epoxy end seals perform better than rubber seals, but an epoxy sealed capacitor can explode under severe reverse-voltage or overvoltage conditions.

RESISTORS AND POTS

Designers have a broad range of resistor technologies to choose from, including carbon composition, carbon film, bulk metal, metal film, and both inductive and non-inductive wire-wound types. As perhaps the most basic—and presumably most trouble-free—of components, the resistor is often overlooked as a potential source of errors in high-performance circuits. Yet, an improperly selected resistor can subvert the accuracy of a 12-bit design by developing errors well in excess of 122 ppm, (½ LSB). When did you last take the time to actually read a resistor data sheet? You'd be surprised at what can be learned from an informed review of the data.

Consider the circuit of Figure 4, which amplifies a 0-to-100-mV input signal 100 times for conversion by a 12-bit ADC with a 0-to-10-volt input range. The gain-setting resistors can be bought in initial tolerances of as low as ±0.001% (10 ppm) in the form of precision bulk metal-film devices. Alternatively, the initial tolerance of the resistors may be corrected through calibration or selection. Consequently, the initial gain accuracy of the circuit can be set to whatever tolerance is required, limited perhaps by the accuracy of calibration instrumentation.

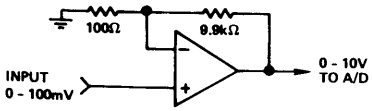

Figure 4. Temperature changes can reduce amplifier accuracy.

Temperature changes, however, can limit the accuracy of the amplifier of Figure 4 in several ways. The absolute temperature coefficients of the resistors are unimportant, as long as they track. Even so, carbon composition resistors, with temperature coefficients of approximately 1,500 ppm/°C, would not suit the application. Even if the tempcos could be matched to an unlikely 1%, the resulting 15 ppm/°C differential would prove inadequate—a shift of as little as 8°C would create a ½-LSB error of 120 ppm.

Manufacturers do offer metal film and bulk metal resistors with absolute temperature coefficients ranging between ±1 and ±100 ppm/°C. Beware, though; temperature coefficients can vary a great deal, particularly among resistors from different batches. To avoid this problem, expensive matched resistor pairs are offered by a few manufacturers, with temperature coefficients that track one another to within 2 to 10 ppm/°C. Low-priced thin-film networks are good and are widely used.

Unfortunately, even matched resistor pairs cannot fully solve the problem of temperature-induced resistor errors. Figure 5a illustrates error-inducing through self-heating. The resistors have identical temperature coefficients but dissipate considerably different amounts of power in this circuit. With an assumed thermal resistance (data sheet) of 125°C/W for ¼-watt resistors, resistor R1's temperature rises by 0.0125°C, while resistor R2's temperature rises by 1.24°C. With a temperature coefficient of 50 ppm/°C, the result is an error of 62 ppm (0.006%).

Even worse, the effects of self-heating create nonlinear errors. In the example of Figure 5a, with half the voltage input, the resulting error is only 15 ppm. Figure 5b graphs the resulting nonlinear transfer function for the circuit of Figure 5a. This is by no means a worst-case example; smaller resistors would give even worse results due to their higher thermal resistance.

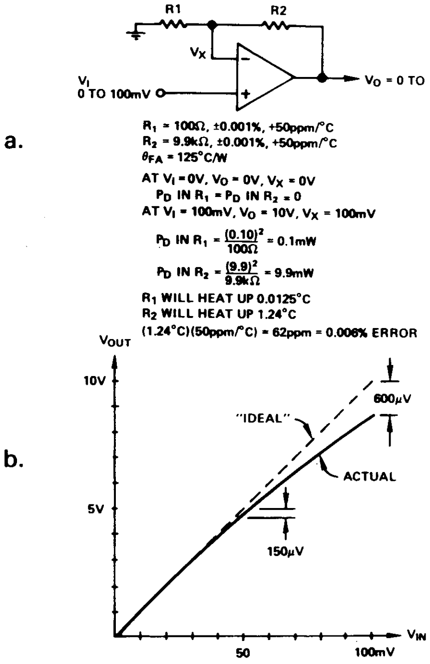

Figure 5. Resistor self-heating leads to nonlinear amplifier response. (a) Anatomy of temperature-induced nonlinearity. (b) Nonlinear transfer function (scale exaggerated).

The use of higher-wattage resistors for those devices that dissipate the greatest power can minimize the effects of resistor self-heating. Alternatively, thin- or thick-film resistor networks minimize the effects of self heating by spreading the heat more evenly over all the resistors in a given package.

Often overlooked as a source of error, the temperature coefficient of resistance of typical wire or pc-board interconnects can add to a circuit's errors. Metals used in p-c boards and for interconnecting wires (e.g., copper) have a temperature coefficient as high as 3,900 ppm/°C. A precision 10-ohm, 10 ppm/°C wirewound resistor, with 0.1-ohms of interconnect resistance, for instance, effectively turns into a 45 ppm/°C resistor. The temperature coefficients of interconnects play a particularly significant role in precision hybrids, where thin-film interconnects have non-negligible resistance.

One final consideration applies mainly to designs that see widely varying ambient temperatures: a phenomenon known as temperature retrace describes the change in resistance which occurs after a specified number of cycles of exposure to low and high ambients with constant internal dissipation. Temperature retrace can exceed 10 ppm, even for some of the better metal-film components.

In summary, to design resistance circuits for minimum temperature-related errors, consider the following (along with their cost):

- Closely match resistance-temperature coefficients.
- Use resistors with low absolute temperature coefficients.
- Use resistors with low thermal resistance (higher power ratings, larger cases).
- Tightly couple matched resistors thermally; (use standard resistance networks or multiple resistors in a single package).
- For large ratios, consider using stepped attenuators.

Resistor Parasitics

Resistors can exhibit significant levels of parasitic inductance or capacitance, especially at high frequencies. Manufacturers often specify these parasitic effects as a reactance error, in % or ppm, based on the ratio of the difference between the impedance magnitude and the dc resistance, to the resistance, at one or more frequencies.

Wirewound resistors are especially susceptible to difficulties. Although resistor manufacturers offer wirewound components in either normal or noninductively wound form, even noninductively wound resistors create headaches for designers. These resistors still appear slightly inductive (of the order of 20 μH) for R values below 10,000 ohms. Noninductively wound resistors that exceed 10,000 ohms actually exhibit about 5 pF of shunt capacitance.

These parasitic effects can raise havoc in dynamic circuit applications. Of particular concern are applications using wirewound resistors with values both greater and less than 10,000 ohms. Here it is not uncommon to see peaking, or even oscillation. These effects become evident at frequencies in the low-kHz range.

Even in low-frequency circuit applications, parasitic effects in wire wound resistors can create difficulties. Exponential settling to 1 ppm takes 20 time constants or more. Parasitics associated with wire wound resistors can increase settling time beyond the length of those time constants significantly.

Unacceptable amounts of parasitic reactance are often found even in resistors that aren't wirewound. For instance, some metal-film types have significant interlead capacitance, which shows up at high frequencies. Carbon resistors do the best at high frequencies.

Thermoelectric Effects

The junction between any two dissimilar metals creates a thermal EMF. In many cases, it can easily produce the dominant error in a precision circuit design. In wire wound resistors, for instance, the resistance wire generates a thermal EMF of 42 microvolts/°C when joined to the leads (A typical lead material is Alloy 180, consisting of 77% copper and 23% nickel). If the resistor's two terminations see the same temperature, the EMFs cancel and no net error results. However, if the resistor is mounted vertically a temperature gradient may exist between the bottom and top of the resistor because of air flow past the long lead and its lower heat capacity.

For a temperature difference of as little as 1°C, an error voltage of 42 microvolts results, a level which easily overwhelms the 25-microvolt offsets of typical precision op amps! A horizontally mounted resistor (Figure 6) can resolve the difficulty. Alternatively, some resistor manufacturers offer, on special order, tinned copper leads, which reduce the thermal EMF to 2.5 microvolts/°C.

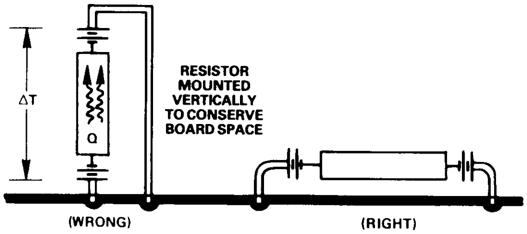

Figure 6. Thermal gradients create significant thermoelectric circuit errors.

In general, designers should strive to avoid thermal gradients on or near critical circuit boards. Often this means thermally isolating components that dissipate significant amounts of power. Thermal turbulence created by large temperature gradients can also result in dynamic noise-like low-frequency errors.

Voltage, Failure, and Aging

Resistors are also plagued by changes as a function of applied voltage. The deposited-oxide high-megohm type components are especially sensitive, with voltage coefficients ranging from 1 ppm/volt to more than 200 ppm/volt. This is another reason to exercise caution in precision applications, such as high-voltage dividers.

Resistors' failure mechanisms can also create circuit difficulties if not carefully considered. Carbon-composition resistors fail safely by turning into open circuits. Consequently, in some applications, these components play a useful secondary role as a fuse. Replacing such a resistor with a carbon-film type can lead to trouble, since carbon-film devices can fail as short circuits. (Metal-film components usually fail as open circuits.)

All resistors tend to change slightly in value with age. Manufacturers specify long-term stability in terms of change—ppm/year. Values of 50 or 75 ppm/year are not uncommon among metal film resistors. For critical applications, metal-film devices should be burned-in for at least one week at rated power. During burn-in, R values can shift by up to 100 or 200 ppm. Metal film resistors may need 4,000 or 5,000 operational hours for full stabilization, especially if they are deprived of a burn-in period.

Resistor Excess Noise

Most designers have some familiarity with thermal, or Johnson, noise in resistors. But a less widely recognized second noise phenomenon, called excess noise, can prove particularly troublesome in precision op amp and converter circuits. Excess noise becomes evident only when current passes through a resistor.

To review briefly, thermal noise results from the thermally induced random vibration of charge carriers in a resistor. Although the average current from these vibrations remains zero, instantaneous charge motions result in an instantaneous voltage across the resistor's terminals.

Excess noise, on the other hand, occurs primarily when dc flows in a discontinuous medium, such as a carbon composition resistor. The current flows unevenly through the compressed carbon granules, creating microscopic particle-to-particle "arcing". The phenomenon gives rise to a 1/f noise-power spectrum, in addition to the thermal noise spectrum. In other words, the excess spot noise voltage increases as the inverse square-root of frequency.

Excess noise often surprises the unwary designer. Resistor thermal noise and op amp noise set the noise floor in typical op-amp circuits. Only when voltages appear across input resistors and cause current to flow does the excess noise become a significant—and often dominant—factor. In general, carbon composition resistors generate the most excess noise. As the conductive medium becomes more uniform, excess noise becomes less significant. Carbon film resistors do better, and metal film resistors do better yet.

Manufacturers specify excess noise in terms of a noise index—the number of microvolts of rms noise in the resistor in each decade of frequency per volt of dc drop across the resistor. The index can rise to 10dB (3 microvolts per dc volt per decade of bandwidth) or more. Excess noise is most significant at low frequencies. Above 100 kHz, thermal noise predominates.

Potentiometers

Trim potentiometers can suffer from most of the phenomena that plague fixed resistors. Users must also remain vigilant against additional hazards unique to these components.

For instance, many trim potentiometers are not sealed and can be severely damaged by board-washing solvents, and even by excessive humidity. Vibration—or simply extensive use—can damage resistive-element and wiper terminations. Contact noise, tempcos, parasitic effects, and limitations on adjustable range can all hamper circuit operation. Furthermore, the limited resolution of wirewound types and the hidden limits to resolution in cermet and plastic types (hysteresis, incompatible material tempcos, slack) make the obtaining and maintaining of precise settings anything but an "infinite resolution" process. Rule: Use infinite care and infinitesimal adjustment range to avoid infinite frustration.

PRINTED-CIRCUIT BOARDS

Printed-circuit boards act as "unseen components" in all precision circuit designs. Since designers rarely consider the electrical characteristics of PC boards as additional circuit components, the circuit's performance usually ends up worse than predicted.

Printed-circuit-board effects that are harmful to precision circuit performance include leakage resistances, voltage drops in ground foils, stray capacitances, dielectric absorption and related "hook" (a salient feature of the circuit's step-response waveform). In addition, the tendency of p-c boards to absorb atmospheric moisture ("hygroscopicity") means that changes in humidity often cause the contributions of some parasitic effects to vary from day to day.

In general, printed-circuit-board effects can be divided into two categories—those that most noticeably affect the static or dc operation of the circuit, and those that most noticeably affect dynamic or a-c circuit operation.

Static PC-Board Effects

Leakage resistance is the dominant static circuit board effect. Contamination of the board's surface, in the form of flux residues, deposited salts, and other debris can create leakage paths between circuit nodes. Even on well cleaned boards, it is not unusual to find 10 nA or more of leakage to nearby nodes from 15-volt supply rails.* Nanoamperes of leakage current into the wrong nodes often cause volts of error at a circuit's output; for example, 10 nA into a 10-megohm resistance causes 0.1 V of error.

To identify nodes sensitive to the effects of leakage currents, ask the simple question: If a spurious current of a few nanoamperes or more were injected into this node, would it matter?

If the circuit is already built, you can localize moisture sensitivity to a suspected node with a classic test. While observing the circuit's operation, blow on potential trouble spots through a simple soda straw. The soda straw focuses the breath's moisture, which, with the board's salt content in susceptible portions of the design, disrupts circuit operation upon contact.

There are several means of eliminating simple surface leakage problems. Thorough washing of circuit boards to remove residues helps considerably. A simple procedure includes vigorously brushing the boards with isopropyl alcohol, followed by a thorough washing with deionized water and an 85°C bakeout for a few hours. Be careful when selecting board-washing solvents, though. If cleaned with Freon-based solvents, some water-soluble fluxes create salt deposits, exacerbating the leakage problem.

Unfortunately, if a circuit displays a sensitivity to leakage, even the most rigorous cleaning can offer only a temporary solution. Problems soon return upon exposure to handling, foul atmospheres, and high humidity. *Guarding*, on the other hand, offers a fairly reliable and permanent solution to the problem of surface leakage. Well-placed guards can eliminate leakage problems, even for circuits exposed to harsh industrial environments.

Guarding principles are simple: Surround sensitive nodes with conductors that can readily sink stray currents, and maintain those conductors at the exact potential of the sensitive node. The guard potential must be maintained close to the potential of the sensitive node, otherwise the guard will serve as a source rather than a sink. For example, to keep the leakage current into a node below a picoampere, assuming 1000-megohm leakage resistance, the guard and the node must be within 1.0 millivolts of one another.

Figures 7a and 7b illustrate the guarding principle as applied to typical inverting and non-inverting op-amp applications. Figure 7c illustrates an actual circuit-board layout for a guard. Note that, to be most effective, the guard pattern should appear on both sides of the circuit board. Try to include the guards when first laying out a new board pattern, from the beginning of the layout process. At later stages, there is usually insufficient space left to locate them optimally—if at all.

Dynamic PC-Board Effects

Although static pc board effects can come and go with changes in humidity or board contamination, problems that most noticeably

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*Unfortunately, the standard op-amp pinout places the − 15V supply pin right next to the + input, which is often hoped to be at high impedance.

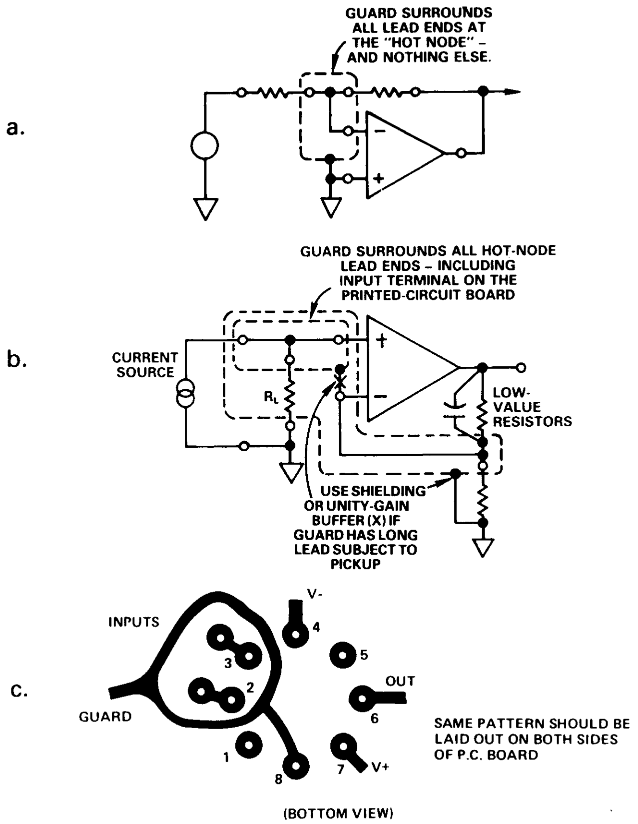

Figure 7. Proper circuit guarding resolves both static and dynamic pc-board induced errors. (a) Use of guard in inverting application. (b) Use of local guard in non-inverting application. Voltage buffer would help in guarding cable. (c) Printed-circuit board guard pattern for op amp.

affect the dynamic performance of a circuit usually remain relatively constant. Short of a new design, they can't be fixed by washing or any other simple fixes. As such, they can permanently and adversely affect a design's specifications and performance.

The problems of stray capacitance, linked to lead and component placement, are reasonably well known to most circuit designers. Since lead placement can be permanently dealt with by correct layout, any remaining difficulty is solved by training assembly personnel to orient components or bend leads in an optimal way.

Dielectric absorption, on the other hand, represents a more troublesome and still poorly understood circuit-board phenomenon. Like dielectric absorption in capacitors, dielectric absorption in a printed-circuit board can be modeled by a series resistor and capacitor connecting two closely spaced nodes (Figure 8). Its effect is inverse with spacing and linear with length. The model's effective capacitance ranges from 0.1 to 2.0 pF, with the resistance ranging from 50 to 500 MΩ. Values of 0.5 pF and 100 MΩ are most common. Consequently, circuit-board dielectric absorption interacts the most with high-impedance circuits.

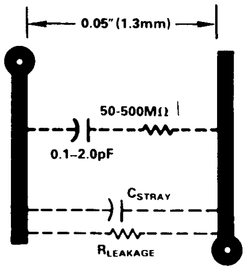

Figure 8. Dielectric absorption plagues dynamic response of pc-based circuits.

Such dielectric absorption most noticeably influences dynamic circuit response, for example, settling time. Unlike circuit leakage, the effects are not usually linked to humidity or other environmental conditions, but rather, are a function of the board's dielectric properties. The chemistry involved in producing plated-through holes seem to exacerbate the problem. If your circuits do not meet expected transient response specs, you should consider circuit-board dielectric absorption as a possible cause.

Fortunately, there are solutions. As in the case of capacitor dielectric absorption, external components can be used to compensate for the effect. More importantly, surface guards that totally isolate sensitive nodes often completely eliminate the problem (The guards must be duplicated on both sides of the board).

Circuit-board "hook", similar if not identical to dielectric absorption, is characterized by a variation in effective circuit-board capacitance with frequency. In general, it affects the transient response of high-impedance circuits where the board's capacitance is an appreciable portion of the total circuit capacitance. Circuits operating at frequencies below 10 kHz are the most susceptible. As in circuit-board dielectric absorption,the board's chemical makeup very much influences its effects.

DON'T OVERLOOK ANYTHING

Remember, if your precision op-amp or data-converter-based design does not meet specs, try not to overlook anything in your efforts to find the error sources. Analyze both active and passive components, and try to identify and challenge any assumptions or preconceived notions that may blind you to the facts. Take nothing for granted.

For example, when not tied down to prevent motion, cable conductors, moving within their surrounding dielectrics, can create significant static charge buildups that cause errors, especially when connectd to high-impedance circuits. Rigid cables, or even costly low-noise Teflon-insulated cables, are an expensive alternative.

As more high-precision op amps and higher resolution data converters become available, and system designs call for higher speed and accuracy, a thorough understanding of the error sources described in this article becomes more important.

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