Silicon is the Ultimate Simulation

Or why I use the Laboratory and Spice

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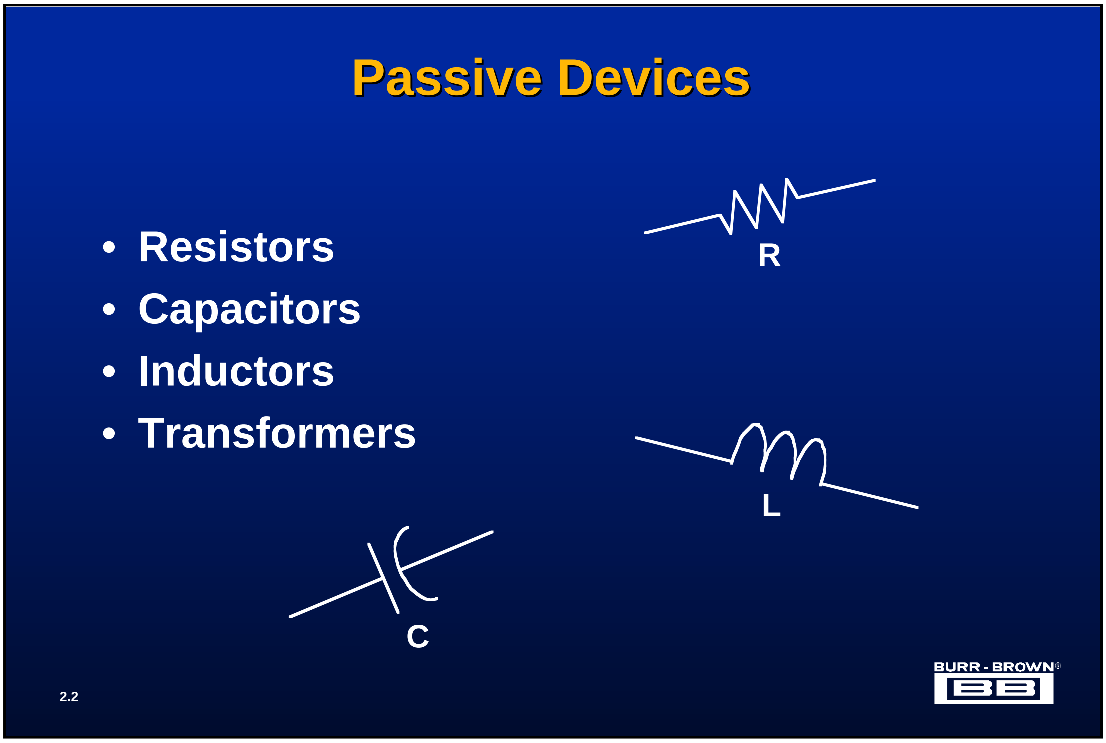

In this section the real world characteristics of passive devices will be examined. Models for these devices based on the typical performance will be developed. Additionally the common applications for the devices will be explored.

Resistors

- Specified by Precision and Power
- Only passive components whose value is easily trimmed
- Available across many orders of magnitude
- Almost always fail open

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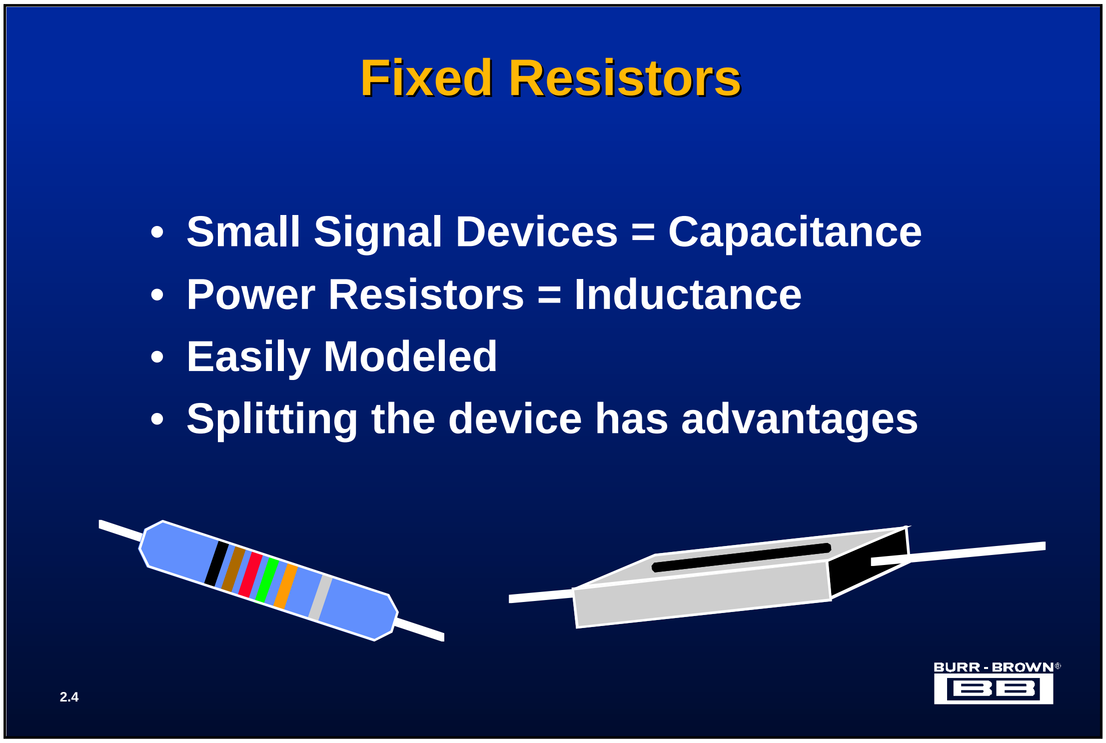
Resistors are perhaps the most easily used component in a designers repertoire. Unless a high power or high value resistor is needed the resistor, more than any other passive device, behaves the most like its theoretical model up to a fairly high frequency.

Resistors are available from 0.01 to 10MΩ with no increase in physical size due to component value. This differs from other passive components where a higher component value always means a larger package size.

Being a dissipative element, the general failure mode for most types of resistors is an open. This is not always the case, for power wire wound resistors where an overheating condition can cause the material inside the resistor to fuse across adjacent turns of the resistor.

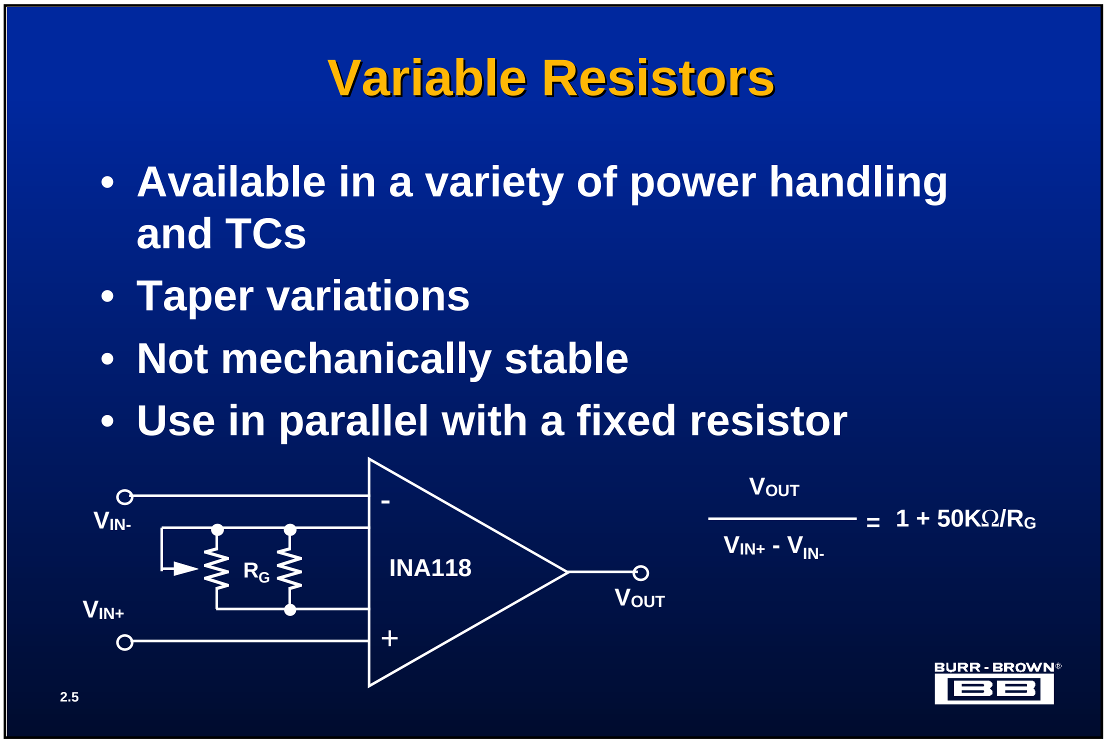


Fixed resistors can be broken into two broad categories based on power handling capacity. The small signal or low power devices are characterized by decreasing impedance at high frequencies. The breakpoint or bandwidth of these resistors decreases as the reactance of the resistor increases. Thus, the low power resistor is modeled by placing a capacitance in parallel with the device. The effect of this capacitance can be diminished by using two or more resistors in a series whose total sum resistance equals the desired value. As an example a 1MΩ, 1/4W, metal film resistor will usually have 8 to 10pF of parasitic capacitance associated with it.

Power resistors, of the wire wound type, are modeled with a stray inductance in series with the resistor as the main parasitic effect. This limits their usefulness when excited by large fast moving current surges. A typical example would be when a wire-wound resistor is used as a current limiting element for a power op amp. A typical value of inductance for a 10Ω, 10W wire-wound resistor would be 40nH.

The table below shows some of the typical characteristics for a variety of resistor types.

Resistor Type	Available Values	Power Range	Operating Temperature	Temp Coeffcient
Metal Film	10Ω to 5MΩ	1/4 to 1W	-55 to 125°C	±25 ppm/°C
Wire Wound	0.1Ω to 1MΩ	1 to 210W	-55 to 275°C	±10 to ±250 ppm/°C
Carbon Composition	5Ω to 5MΩ	1/8 to 2W	-55 to 130°C	±1500 ppm/°C
Chip	1Ω to 22MΩ	1/10 to 1/8W	-55 to 275°C	±25 to ±200 ppm/°C



A variable resistor is useful for trimming a variety of circuit characteristics like the offset and gain of an operational amplifier circuit. The variable resistor is also available in a wide variety of values, power dissipation, and temperature coefficients. The type of taper, the relationship between the location of the wiper and the resistance value, is also another design option available with the variable resistor.

Variable resistors are not as mechanically stable as a fixed resistor. Actual mechanical vibrations and temperature cycling can change the trimmed or selected value of this type of resistor a great deal. So while, for example, it may seem attractive to use a variable resistor as the gain setting element for an op amp to achieve a variable gain function, they should not be used in this manner unless long term mechanical stability is not an issue.

If a variable resistor is used to set an important circuit characteristic, like gain, it should also be used with a fixed resistor. An example would be the resistor used to set the gain of an instrumentation amplifier. In the case of the INA118 the relationship between the gain of the amplifier and the gain setting resistor, R_G, is as follows:

$$\text{Gain} = 1 + 50\text{k}\Omega / R_G$$

This formula has some tolerance which depends on the grade of the device. If an exact value of gain is desired then a fixed resistor should be selected such that the gain achieved with the fixed resistor alone will always be approximately 1 to 3% to high. A variable resistor whose total value is 100 times that of the fixed resistor would then be put in parallel with the fixed device. Now the actual gain of the circuit will be 99% determined by the fixed resistor, which is mechanically stable, and only 1% determined by the variable device, which is not.

Plate Capacitor Equation

$$C = \frac{k \bullet A}{d}$$

C = the capacitance in Farads
k = is the permittivity constant in Farads/meter
A = is the area of the plates in meters^2
d = is the distance between the plates in meters

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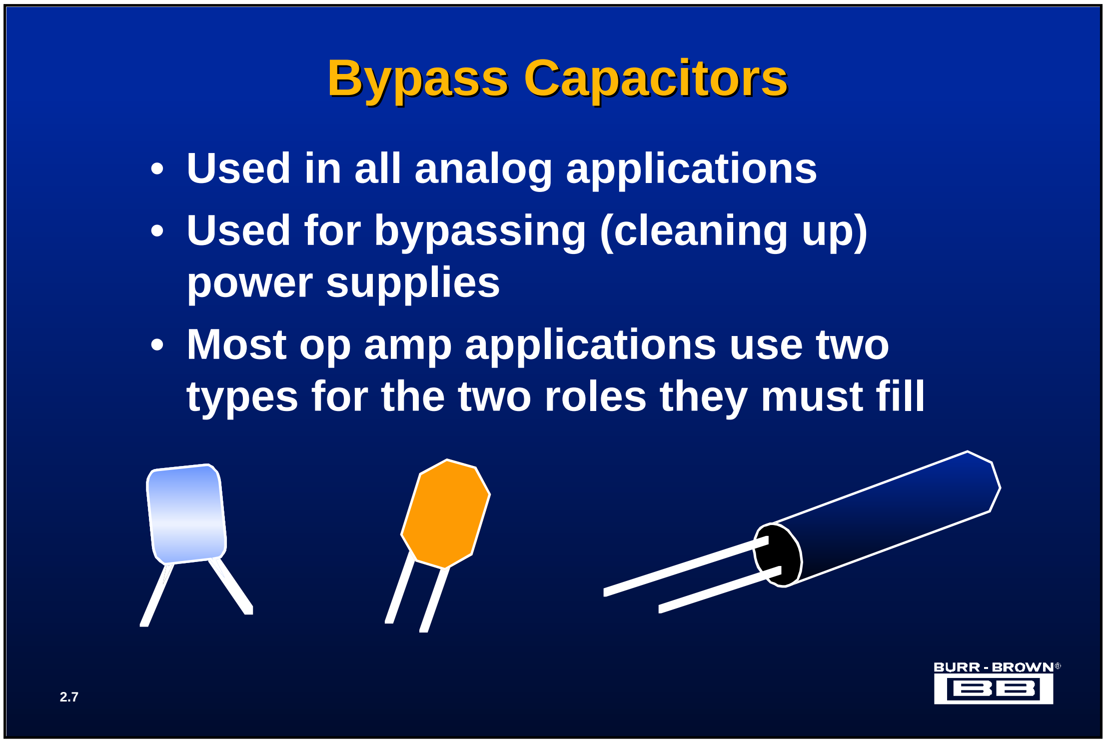
The above equation shows the basic formula for calculating the value of a parallel plate capacitor. All capacitor types discussed here can be modeled with this equation. Depending on the capacitor type one or more of the elements represented by this equation are traded-off for various performance parameters.

For instance, the electrolytic capacitor uses a dielectric that has a very high dielectric constant. This dielectric cannot withstand high levels of electric fields and hence the plates of this capacitor must be relatively far apart. What this means is that the area of the capacitor must be large in order to achieve a capacitor of large value.

The disadvantage of making these tradeoffs lie in the fact that intrinsic parasitics are then built into the capacitor. In the case of the electrolytic device the long distances between the plates of the capacitor leads to higher series resistance and the large plate area leads to higher series inductance.

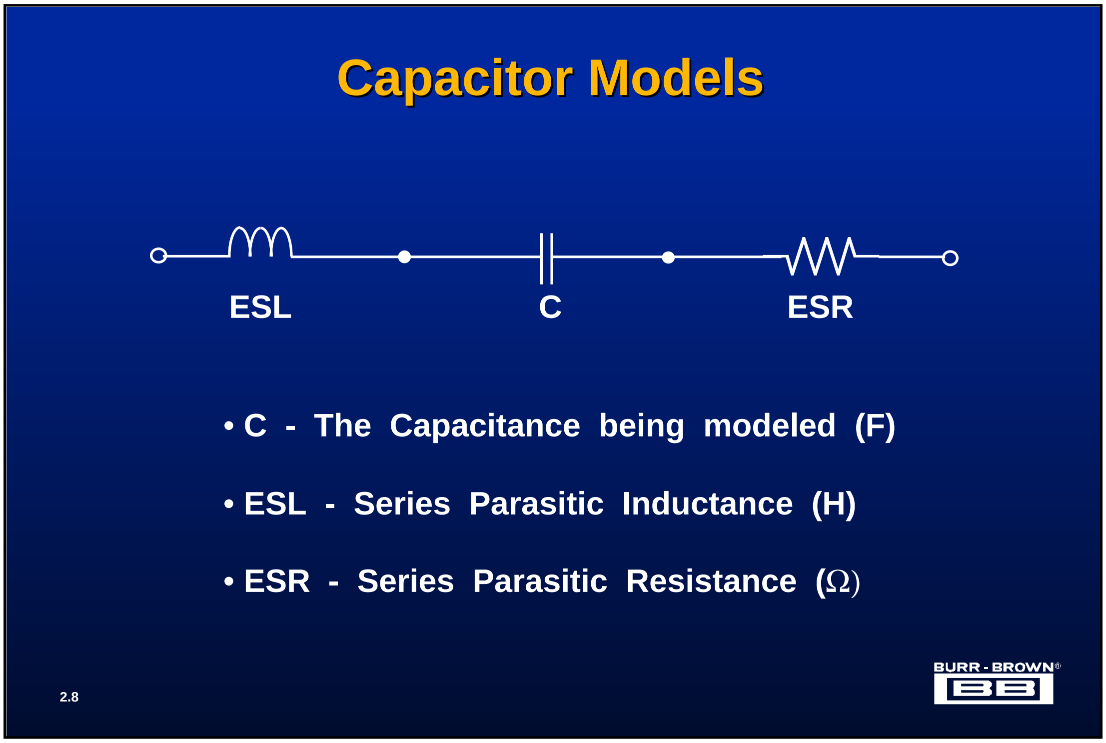


What is a capacitor? The text book answer is that it is a reactive component whose impedance at DC is infinite and a "high" frequencies is zero. Probably the only capacitors that follow this model very closely are those that are very low in value. For instance the capacitors used in CDAC architectures whose dielectric is silicon (glass) and whose electrical attachment is made very closely. These capacitors are never more than 100pF in value.

Capacitors that are used to bypass power supplies must satisfy two important criteria. Both of these roles come about because the impedance between the analog circuit they are supporting and the power supply itself is not zero.

First, they must be of sufficient value to keep the power supply lines at a constant value when the current drawn from said lines changes quicker than the power supply can react to the change. Second, they must have a sufficiently low impedance at high frequency to both filter out noise and provide a return path for high frequency noise.

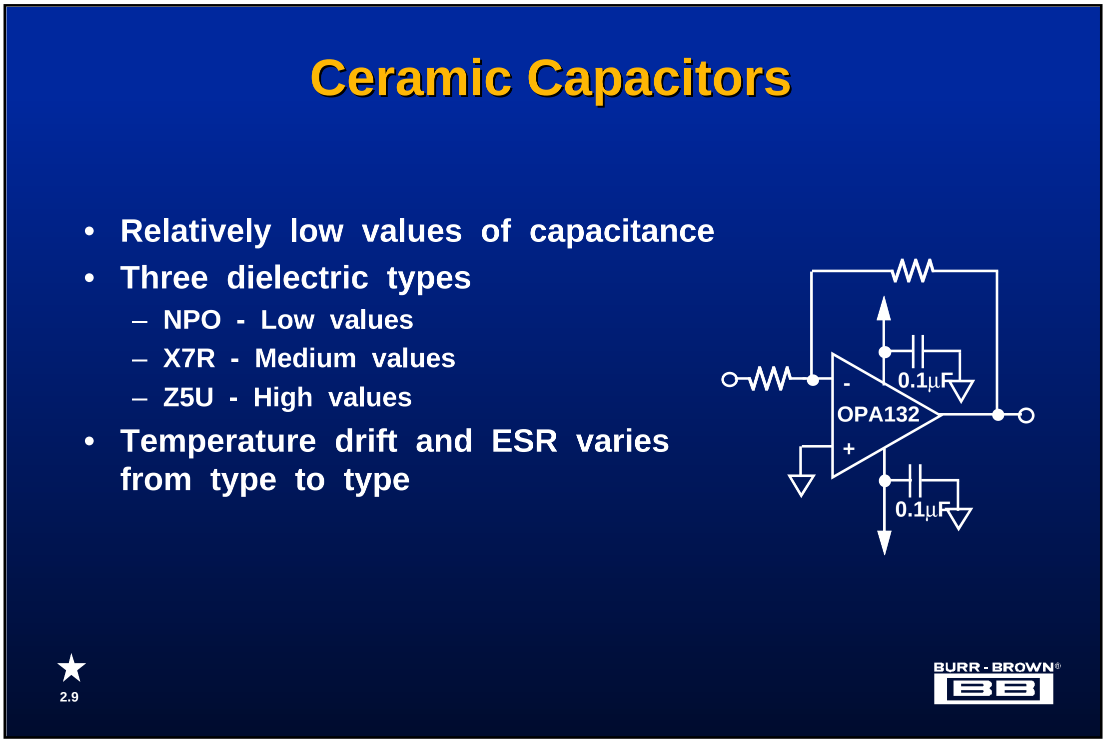
Since no one capacitor type can fill both of these roles, unless price and board space doesn't matter **at all**, two capacitors types are used for this application. A tantalum capacitor has an excellent capacitive value/volume relationship and is used to fill the high value role. Ceramic NPO or X7R capacitors do not offer much capacitance for the volume they occupy but have extremely low impedances at high, > 100kHz, frequencies.



The discussion about capacitors began with bypassing because this application, while being very common, also illustrates two important points about these devices. First, there is no one capacitor type that can satisfy all requirements for a given application. Second, the trade off for volumetric efficiency is usually high frequency performance.

The above diagram shows a model that is suitable for most capacitor types.

In the following slides we will examine the relative sizes of the parasitics associated with this model when different capacitor types are used.



ESR or equivalent series resistance of a capacitor is related to the dissipation factor for the capacitor type according to the following formula.

$$ESR = \frac{Dissipation\ Factor}{2 \bullet \pi \bullet f \bullet C}$$

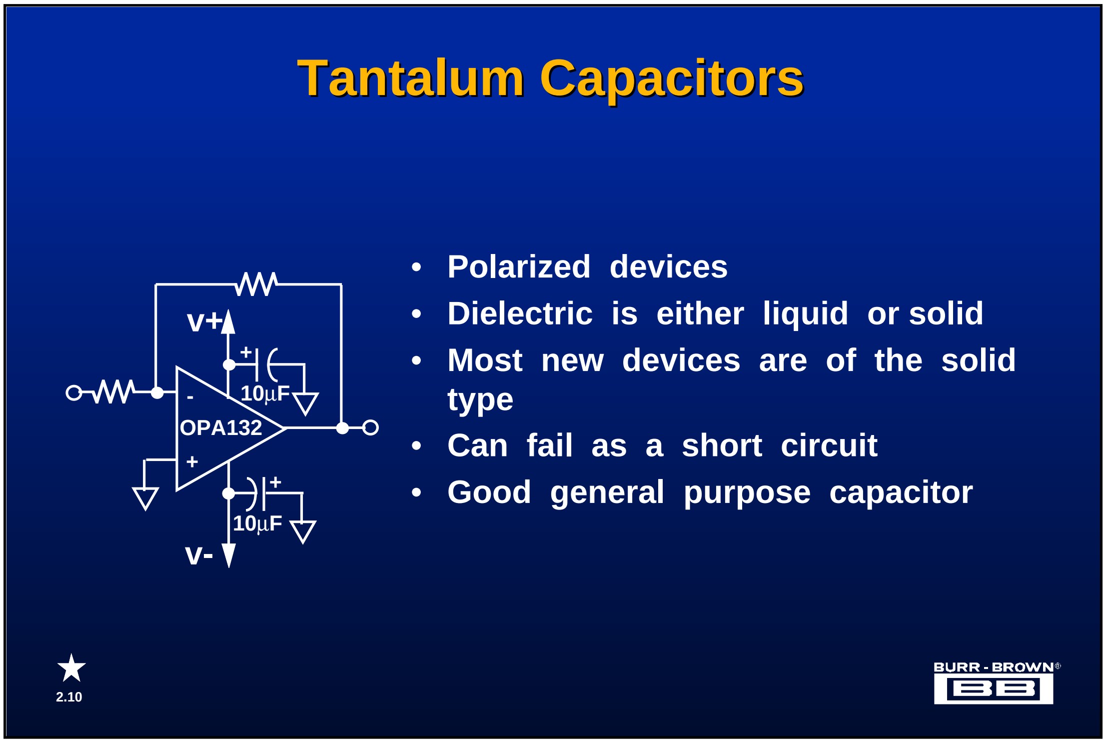
Where: Dissipation Factor is a dimensionless unit

f is the frequency of interest in Hertz

C is the capacitor value in Farads

For the ceramic capacitor types listed above the following table summarizes their electrical differences for a 1nF capacitor.

Dielectric Type	Temperature Range °C	Capacitance change across Temp Range	Dissipation Factor	ESR @ 1MHz	ESR @ 100MHz
NPO	-55 to 125	± 0.3%	0.1%	0.16Ω	1.6mΩ
X7R	-55 to 125	± 15%	2.5%	3.9Ω	39mΩ
Z5U	-55 to 85	+22 and -80	3.0%	4.8Ω	4.8mΩ



Tantalum capacitors are a good choice for those application that require relatively low impedance values at low to medium frequencies (1 to 100kHz). They are often used to bypass power supplies and AC couple signals. Their dissipation factors, and hence their ESR, is 10 to 100 times greater then an equivalent value of ceramic capacitor. Typical values of the dissipation factor range from 8 to 30% for solid tantalums. Tantalum capacitors are however 10 to 100 times smaller than an equivalent value ceramic device.

As to the temperature effects on tantalum capacitors the results are somewhat unpredictable. The value of capacitance goes down for both increasing and decreasing temperatures. The voltage rating of the capacitor goes down for increasing temperature. The dissipation factor goes up for both increasing and decreasing temperatures.

There are two factors to consider when using a tantalum capacitor :

1) Tantalum capacitors quite often fail as a short circuit and present a reliability problem for power supplies if these supplies are not short circuit proofed or fused.

2) A common way to get a tantalum capacitor to fail is to overheat it by drawing excessive ripple current from it. Not only can the capacitor fail short but can also explode from this excessive heating. For a liquid or foil constructed device, the vapor which is exuded during this catastrophic event is quite noxious and in fact is poisonous.

Properties of Tantalum Capacitors

Type	Dissipation Factor	Voltage Derating	Capacitance Derating	Temperature Range
Units	%	%	%	°C
Solid	4 to 10	-66	-33	-55 to 125
Liquid	8 to 40	-20	-40 to +12	-55 to 125

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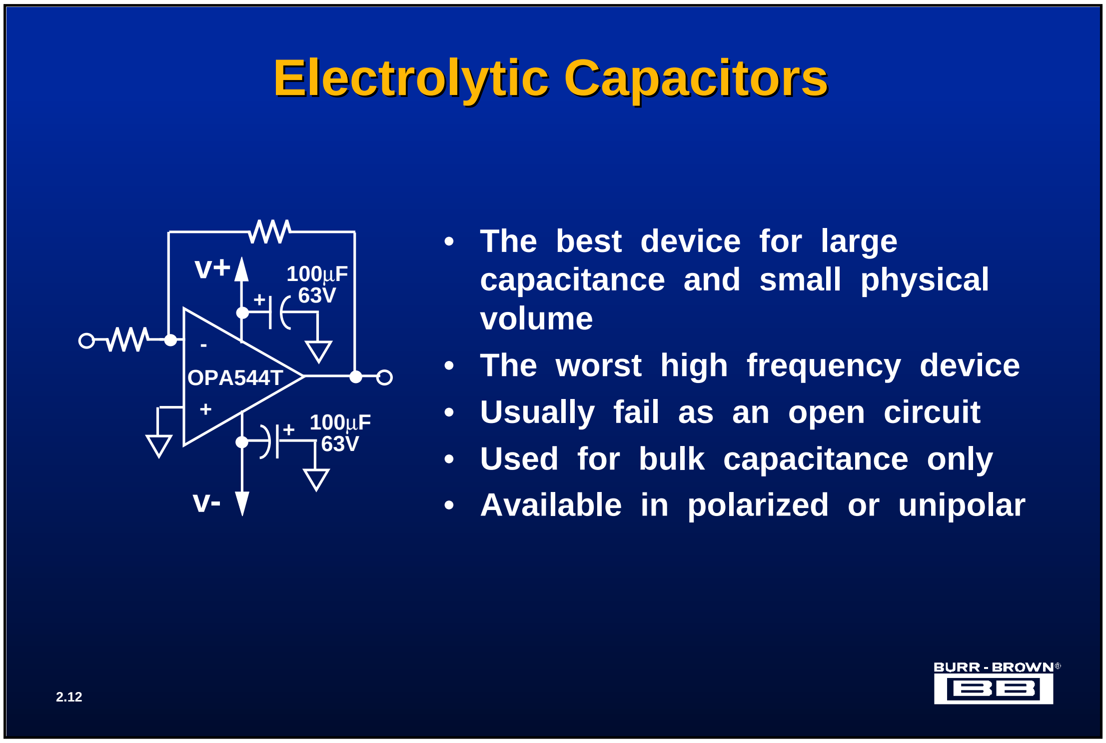
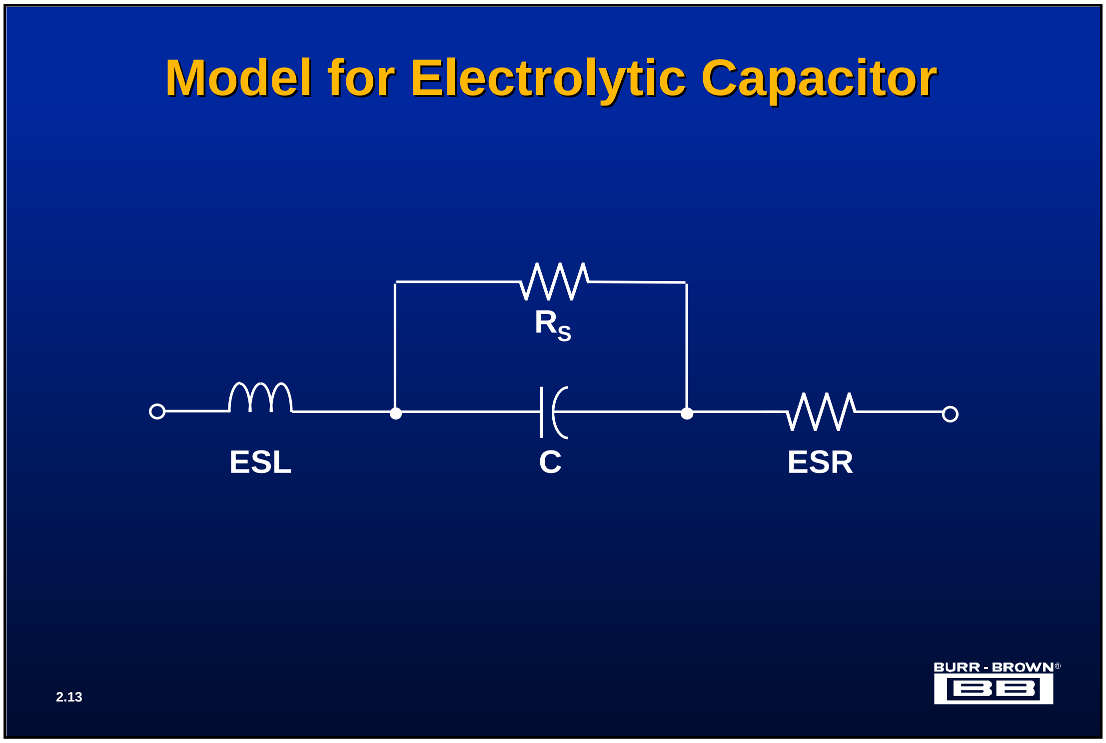
The above chart illustrates the typical characteristics of the tantalum capacitor types. In general the solid dielectric is a better choice for high frequency performance. The solid tantalum capacitors are more readily available in new configurations like surface mount types. Finally the solid SMT versions are also available with built-in fuses, which avoids high current flow if the capacitor should fail due to a short.



Electrolytic capacitors are the oldest capacitor type still in general use today. Many different types and grades are available but all share one thing in common in that they offer a lot of capacitance in a small container.

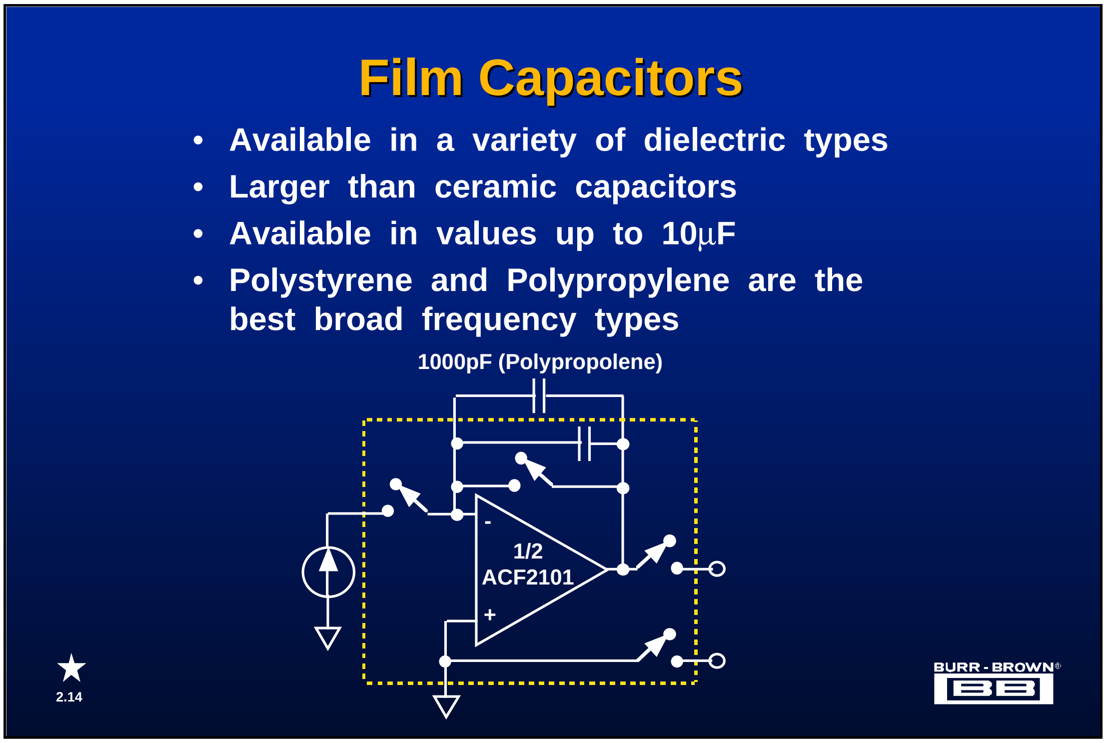
Most electrolytic capacitors are made by rolling a paper insulator between two pieces of foil that serve as the plates of the capacitors. Often this foil is aluminum, and its surface is etched thus increasing its apparent area. The rolled up plates and insulators are then impregnated with a dielectric paste. Finally the entire assembly is placed in a container suitable for the environment and temperature range which the capacitor is to be used.

Because of the way in which the electrolytic capacitor is constructed, i.e. rolled metal, the device has a propensity to have large values of end-to-end inductance or ESL. In addition most of the less expensive electrolytics have a fairly low value of end-to-end resistance or DC impedance.



Because of the relatively low value of end-to-end resistance present in an electrolytic device a new model is needed for this device. The above diagram shows the same model used for the other capacitor type with the addition of R_S or the shunt resistance.

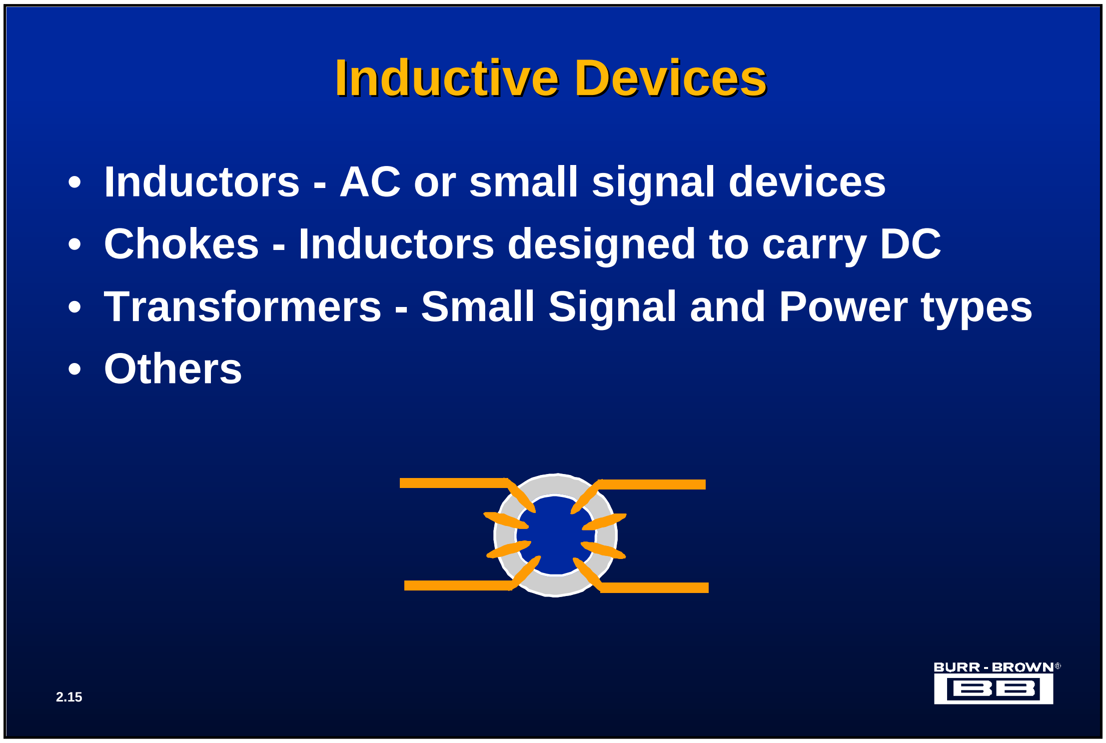
For computer grade, high quality, electrolytic capacitors the resistance values are somewhat larger than commercial devices and the capacitor can hold a charge for a very long time.



Film capacitors are generally used for AC coupling and very high frequency bypassing and filter components. Film capacitors are fabricated in a similar method to electrolytic devices in that a dielectric material, the film, is placed between two rolled up metal plates. The main advantage that film capacitors have over the electrolytic devices lies in the film used as the dielectric.

Most of the film capacitors use a polyester based dielectric and this dielectric is extremely stable with temperature and will withstand very high field voltage potentials. What this means is that the dielectric itself can be very thin, hence the ESR and ESL of the capacitor will be very low. Also the overall characteristics of the capacitors are relatively constant with respect to temperature. Polystyrene capacitors have a capacitance change of only ±1% over temperature which is better than most capacitor types, with the exception of the ceramic NPO.

Film capacitors are also an excellent choice when a moderate capacitor value and good high frequency performance is desired. Polystyrene and Polypropylene capacitors are useful up to frequencies of 10GHz. Other capacitor types are also useful in this frequency range, namely glass dielectric types, but these capacitors are only available in capacitance values up to 0.01µF.

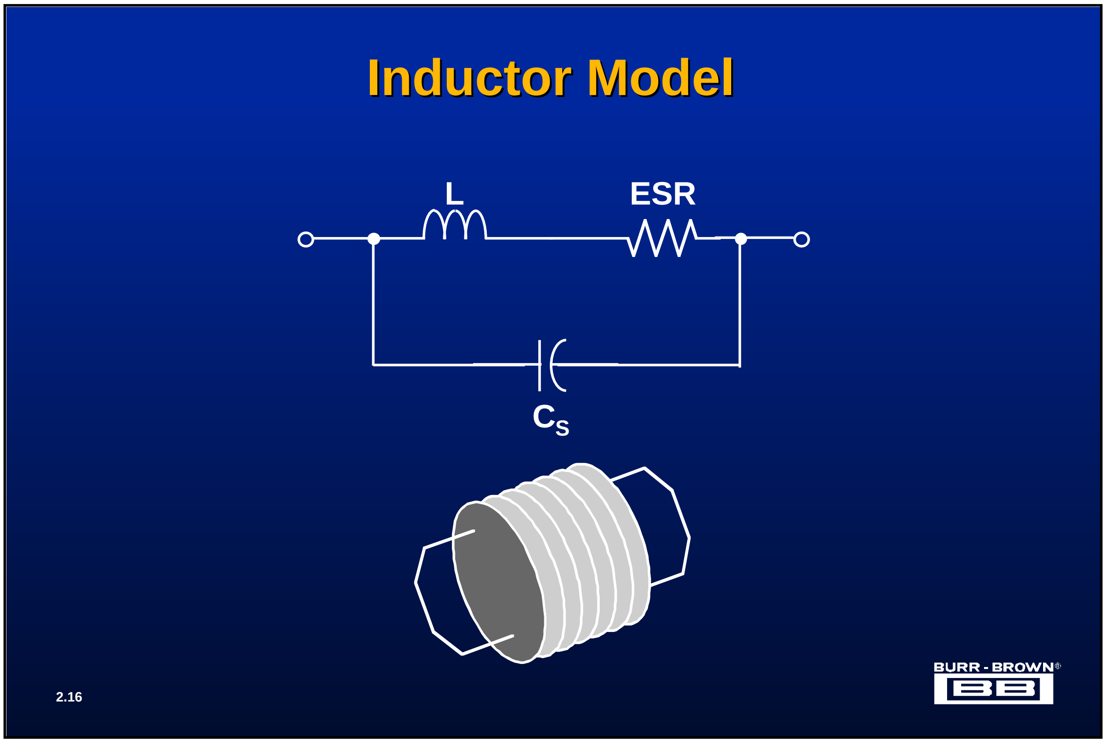


Strictly speaking an inductor is a device which is designed to have increasing impedance with respect to frequency and carries no net DC current. Commonly these devices are used for small signal processing and filtering applications only.

An inductor that has been designed to carry a net DC current is properly referred to as a choke. The only way an inductive component, such as a toroid, can carry a DC current and not “saturate” is for a air gap to be designed into its magnetic path.

A transformer is also a device that is designed to carry zero net DC current but its function is to transmit an AC voltage.

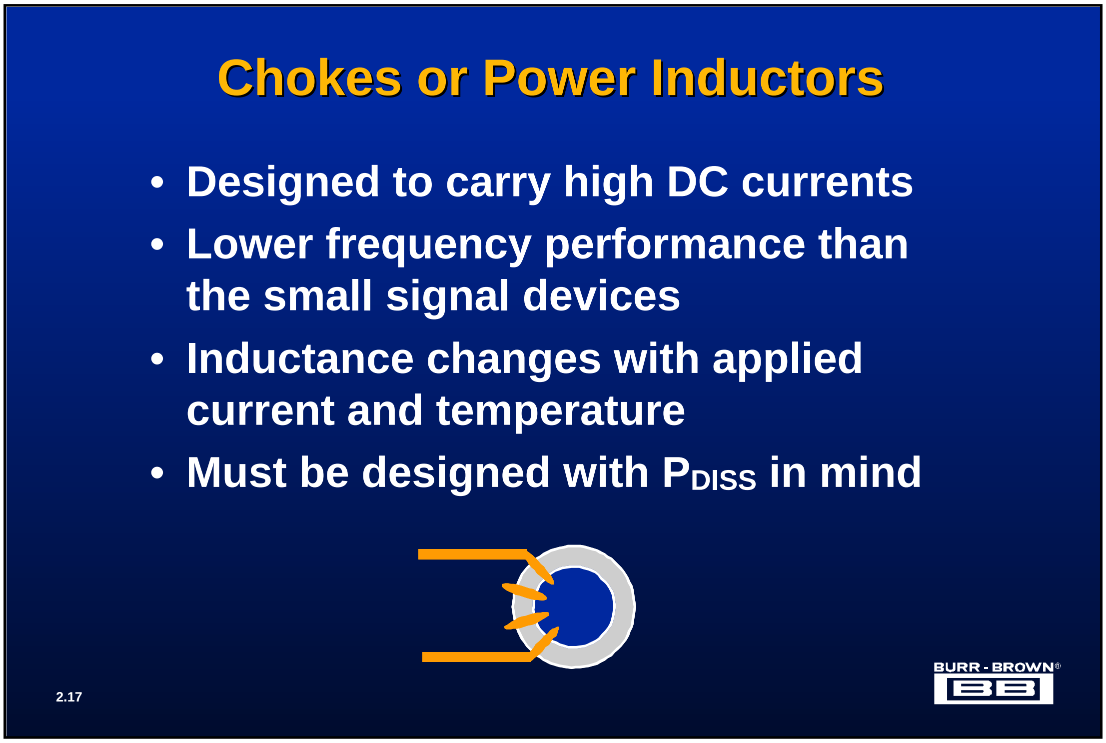
There are other magnetic devices, such as ferrite beads, that are designed for specific purposes. In the case of a ferrite bead the device is designed to provide very small amounts of inductance, 100nH at most, and allow wiring to be run through it.



The small signal or AC inductor is characterized electrically with low to high values of inductance, low to high values of series resistance, and high values of end-to-end capacitance. A typical 10µH inductor would have 2Ω of ESR, 10 to 20pF of capacitance and be approximately .125 square.

It should be noted that most manufactures of these small signal devices call their devices inductors and they are capable of carrying small amounts of DC current. In the example given above an inductor of this size is capable of carrying 100mA.

Also, most of these small signal devices are not packaged in a magnetic structure that is fully enclosed from a magnetics standpoint. An example of a closed magnetic structure being a toroid. Instead these devices are usually wound on a cylindrical piece of ferrite. The result of using such a construction technique is the inductor will radiate electromagnetic energy into the surrounding environment. Thus, if the device were used to say filter a square wave the noise that would be generated would be rather high. This fact makes this type of inductor most suitable for low signal amplitude or sine wave applications.

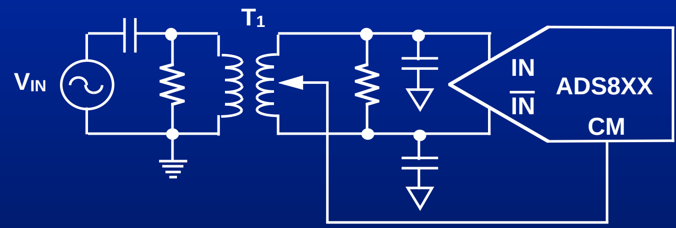


Chokes or power inductors are used to filter the AC component out of a source of current. Probably the most common application for this device is the pass element in a Pi type filter for filtering a power supply.

When using a choke or power inductor, care must be taken not to exceed its maximum rated current. Two factors are responsible for this rating; one is thermal and the other is electrical.

All inductors have some amount of end-to-end or series resistance. This resistance causes the inductor to heat up with applied DC current. The I^2R rating together with the maximum ambient operating temperature defines the environmental conditions for which the device can successfully be operated. Exceeding the current rating can either cause the inductor to fail open or cause the inductance to fall to a very low level. When the inductance of a choke drops off, due to excessive current, the device has become saturated. This is the “electrical” failure mechanism for a choke. The choke and inductors are current limited devices.

Transformers



- Available as signal, pulse, and power devices
- The only component that can transfer large amounts of power across an electrically isolated barrier
- Voltage limited due to construction
- Frequency band set by size and coupling coefficeint

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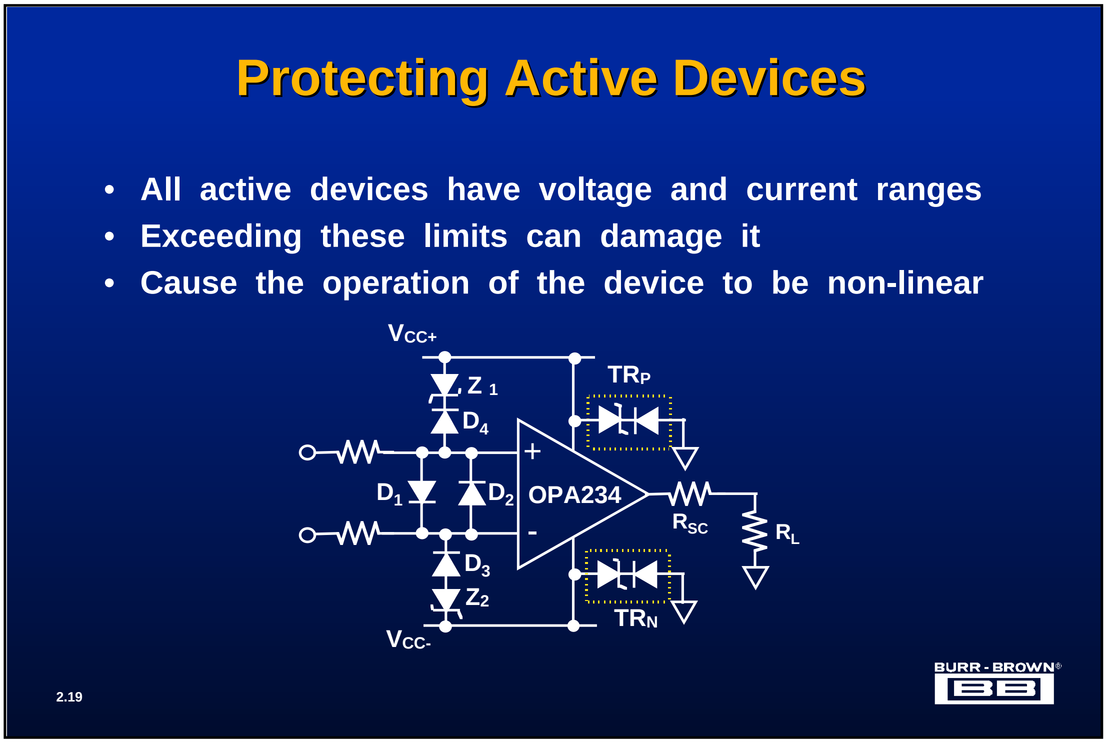
Transformers are unique devices electrically because they have no electrical equivalent. For example the inverse of a capacitor is an inductor. They are also the only devices that allow large amounts of energy or power to be coupled across an electrically isolated barrier.

Transformers are characterized or selected based on the application, small signal or power, turns ratio, the amount by which the secondary voltage exceeds the primary voltage, and the frequency at which the device operates. Like an inductor, a transformer can become electrically saturated if it is misapplied. Unlike an inductor a transformer is not current limited electrically. The current limitation of a transformer is only due to the heating that the current would cause with the resistance of the wire used to construct the transformer.

Whether a signal or power transformer is used, there is a **minimum** frequency and **maximum** volt-second limitation for the device (unless it is built using an air-core). The size of a transformer is inversely proportional to the frequency for which it is used. This is the reason that a 60Hz power supply is so much larger than a 100kHz supply of an equivalent power rating.

In a typical case a transformer would be constructed by winding a certain number of turns of wire around a “core”, like a toroid, to form the primary and secondary windings. The ratio of the number of turns in each winding determines the turns ratio. The number of turns used, together with the size of the core, determines the maximum number of volt-seconds, the voltage applied times the time it is applied, for the transformer. This volt-second relationship also determines the minimum frequency that the device can be used for a given input voltage. Additionally transformers are never allowed to carry a net DC current. They are always driven in a bi-polar fashion or allowed to “reset”.



Protecting an active device is done not only to keep the device from failing but also to insure the device acts in an expected or predictable manner. Depending on what electrical parameter is being safe guarded different protection devices are appropriate. Manufactures list maximum ratings for sensitive connections usually as DC or continuous voltages or currents. If these limits are exceeded for relatively short periods, 100ns for example, the device must be tested extensively for this violation.

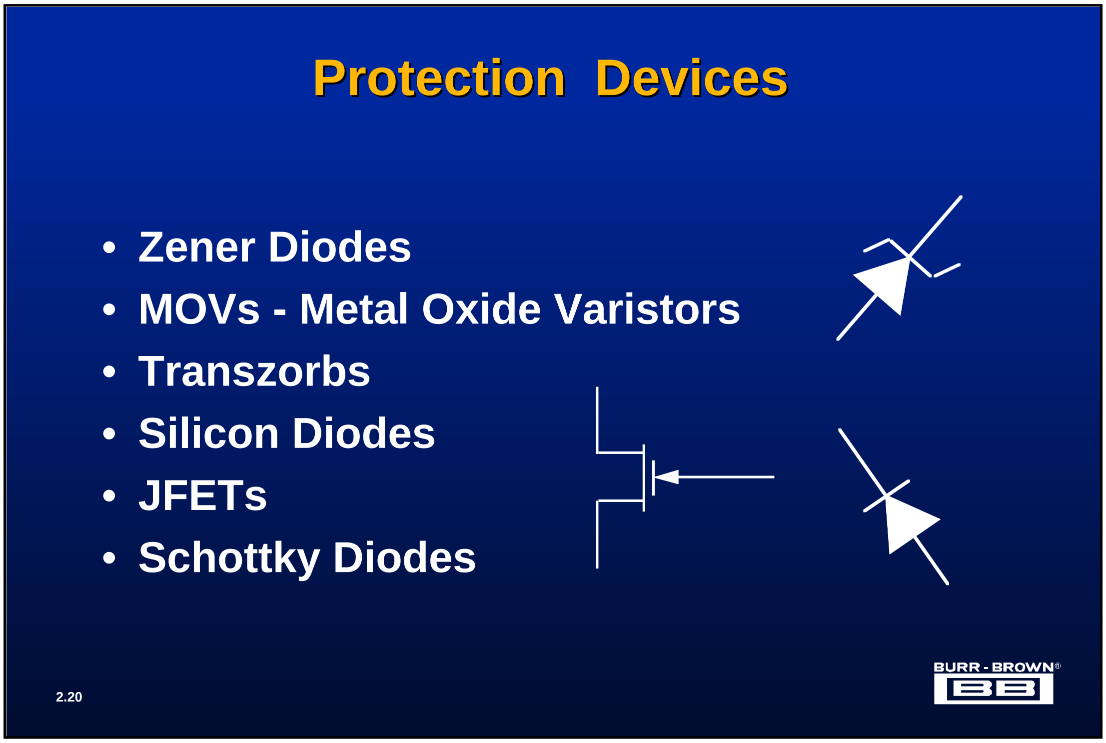
Using an op amp as an example there are at least four restrictions that must typically be observed:

1) Power Supply Rating, usually listed as an absolute maximum and for small signal devices this is usually ±18 to ±25V. Exceeding this maximum usually results in failure of the op-amp.

2) Differential Voltage (V_{DIFF}), the amount by which the inverting and non inverting inputs can differ. Depending on the amplifier this value can be ±0.7 to ± the supply voltage. Exceeding this rating can cause either failure or unexpected operation.

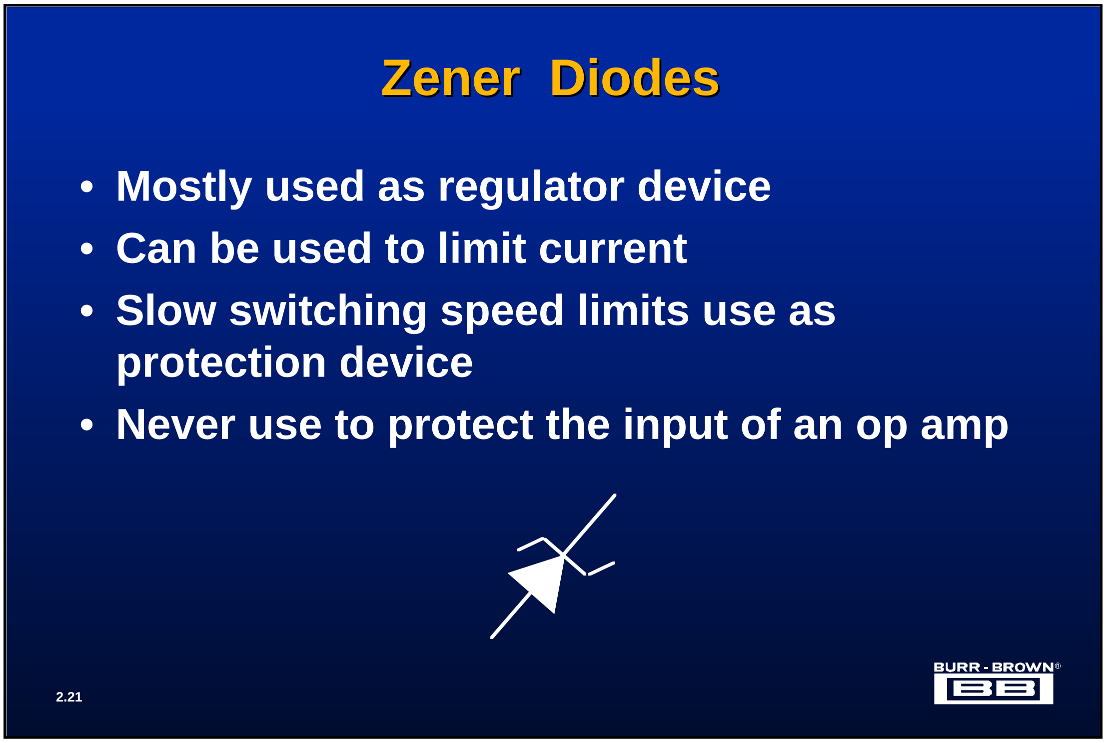
3) Common-Mode Voltage Range (V_{CM}), the voltage which is common to both inputs. This value is expressed as a voltage given a certain power supply voltage. A typical example would be ±11V given a power supply of ±15V. What this rating means is that the inputs must always be at least 4V from either power supply rail. Violating this restriction will usually cause unexpected performance.

4) Short Circuit Current (I_{SC}), the amount of current that will flow when the output is short circuited to ground. If the op amp has current limit protection, this rating will usually be for an indefinite period of time.



Protecting an op amp or other active device is most easily accomplished with a diode. Depending on the application one or more of the above devices will or can be used. These devices can be differentiated based on switching speed and leakage or off current.

Device Type	Switching Speed	Off Current	On Voltage
Zener Diode	Slow	μA	Varies
MOV	Slow	mA	Varies
Transzorb	Very Fast	nA to μA	Varies
Silicon Diode	Medium to Fast	μA	0.7V
JFET	Fast	fA	0.6V
Schottky Diode	Fast	mA	0.3V



Zener diodes are excellent devices for regulating slow moving DC voltages. They can for example be used to protect the the power supply connections on an op amp if the source of DC power is sufficiently slow moving. When an overvoltage condition exits for the power supply in question the zener diode conducts and acts as a low impedance load on the power supply. Hopefully the power supply is sufficiently current limited, such that the voltage level will fall before the zener diode burns open.

Zener diodes are slow, have high levels of end-to-end capacitance (>1000pF), and are very lossy. Using a zener to protect the front end of a precise op amp should never be done. If a spike of voltage of fast rise time were to appear on the front end of an amplifier this spike would not be attenuated by the zener. The capacitance of the zener limits the bandwidth of the amplifier. Finally the leakage current of the zener would appear as extra bias input current for the amplifier.

As a final note zener diodes are fairly noisy when conducting as a regulator. This noise level varies from 1 to 100µV/$\sqrt{Hz}$. The higher the reverse voltage of the zener the higher the noise level.

Metal Oxide Varistors (MOVs)

- Dissipate more power than a zener
- Similar to diodes connected in series
- Degrades each time it clamps an input voltage
- Power is dissipated across the entire surface

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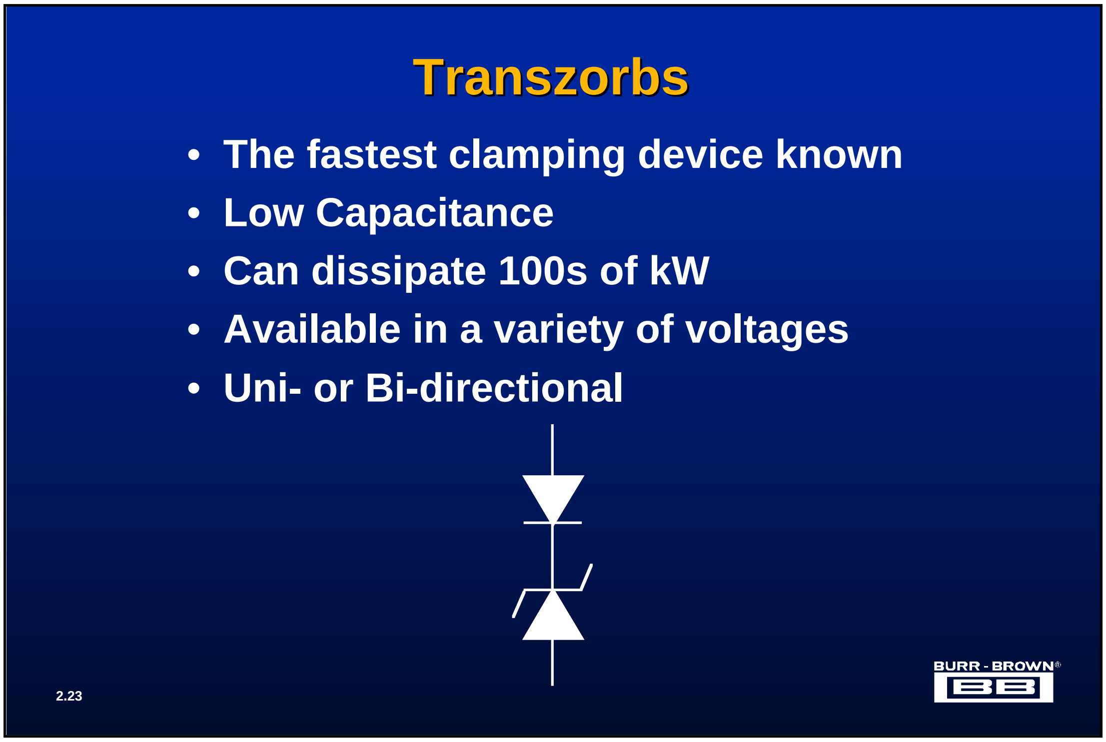
MOVs act like a parallel combination of thousands of zener diodes. The device is not a semiconductor, but rather is fabricated by mixing zinc with other materials in granular form and compressing the mixture. Thus the device is, as its name implies, a form of resistor. Unlike a resistor, the resistance of a MOV is not linear, it is essentially an open circuit until the voltage across it reaches a threshold value and it then becomes very low impedance.

When this threshold value is reached a number of the reverse biased “diodes” become forward biased and the MOV clamps. Although MOVs react relatively quickly they are not as fast as a Zener diode. Also unlike silicon voltage clamps MOVs have a definite lifetime base on how many times the MOV is forced to clamp a transient voltage.

Assuming that the power rating for a silicon based transient device is not exceeded, these devices have an unlimited service life. A MOV, however, is degraded each time a large current surge flows through it. Each time the MOV conducts, local fusing occurs across the “diodes” that clamp the voltage. This phenomenon also causes the MOV to fail as a short, if a large current spike occurs for a long period of time. Thus, if a MOV is used as a transient suppressor in a design it should be fused.



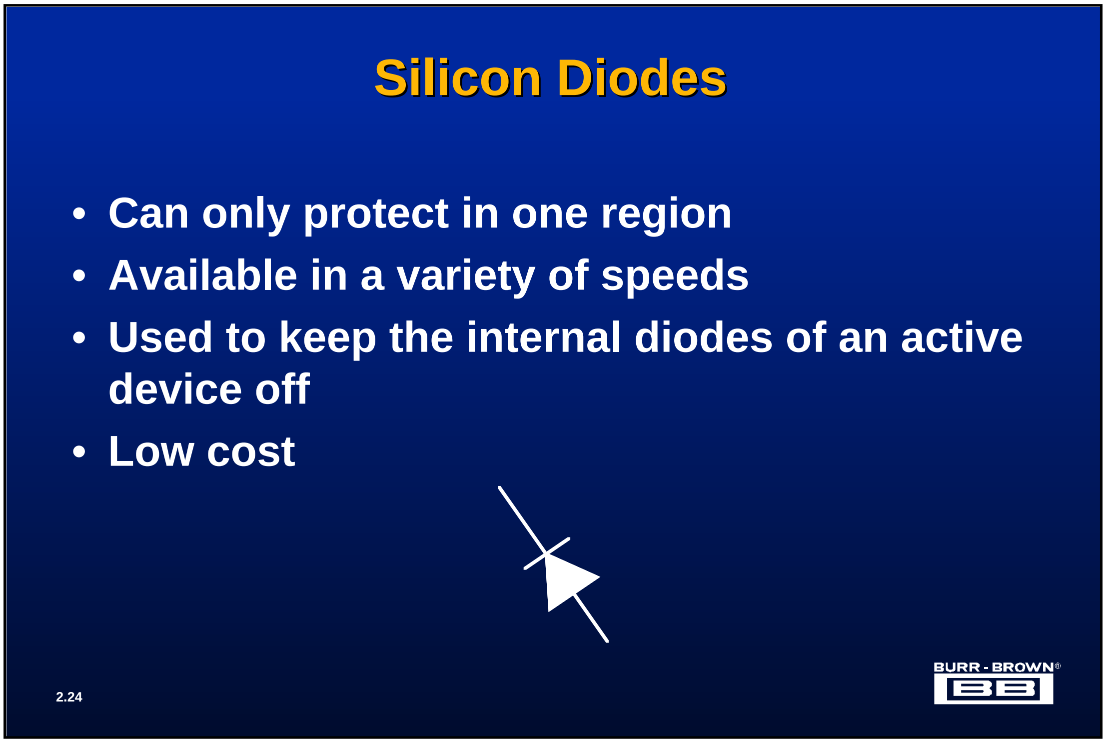
Transzorbs are among the best transient suppressors available today. Their only short coming is that they are relatively expensive. Electrically transzorbs behave like zener diodes, that is they conduct with a diode drop of approximately 0.7V when biased in the forward direction and show a reverse breakdown of the clamping voltage when reverse biased.

Transzorbs differ from zeners, and other silicon based diodes, with respect to the time it takes them to clamp an incoming transient. While most devices can clamp a transient in nanoseconds the Transzorb takes only picoseconds to do the same job. In fact for transzorbs whose clamping voltage is above 6V, the clamping time is 1ps or less.

Transzorbs are available in a number of package styles that allow them to dissipate up to 100kW of instantaneous power. The small resistor size packages can dissipate up to 500W instantaneously.

Transzorbs are available in a bi-directional style. This device behaves like the reverse breakdown characteristic of two opposite polarity zener diodes with no forward region. That is the bi-directional Transzorb will clamp either a positive or negative transient of the clamping voltage desired.

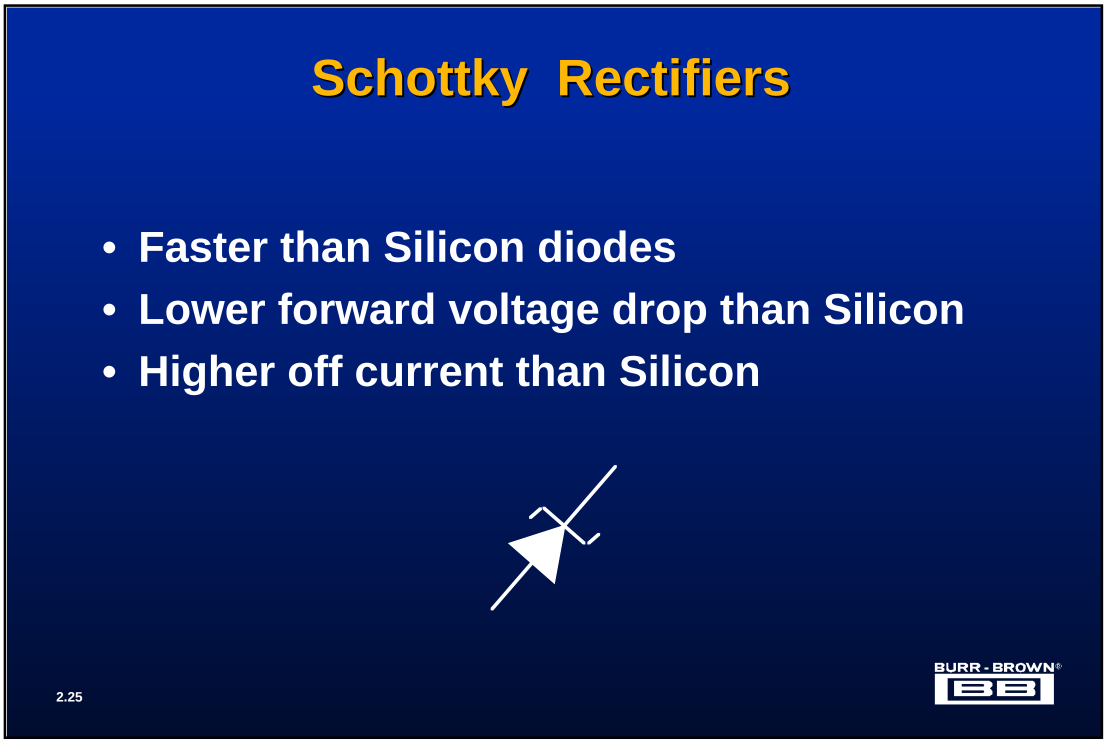
A note about the tolerance of the clamping voltage of a transzorb is that this clamping voltage can vary by more than 1V for a 15V clamping voltage, device-to-device. There are “A” grade devices available that improves this tolerance by approximately 50%. Hence, if an exact transient suppression voltage is desired the transzorb will have to be hand selected for the application.



The silicon diode is certainly the most common protection device used today. Its low cost and the wide variety of electrical characteristics are the reason why. Silicon diodes are available in switching or conduction speeds of nanoseconds to microseconds.

A very common application for a silicon diode is to place one on the power supply connections of a system such that it conducts when the power is applied in the wrong polarity. Thus, the active devices in the system will never see more than 1 diode drop of reverse polarity, provided the diode can handle the power.

Silicon diodes can not be used to protect the signal inputs of an amplifier, like the input section of an op amp, unless bias currents and bandwidth are not a concern. In general the silicon diode draws microamps when off and takes nanoseconds to conduct, thus if a fast rise time transient comes along the input stage of the amplifier will probably be damaged before the device can conduct. Also the 100s of picofarads of capacitance inherent to the diode will degrade the bandwidth of the amplifier.

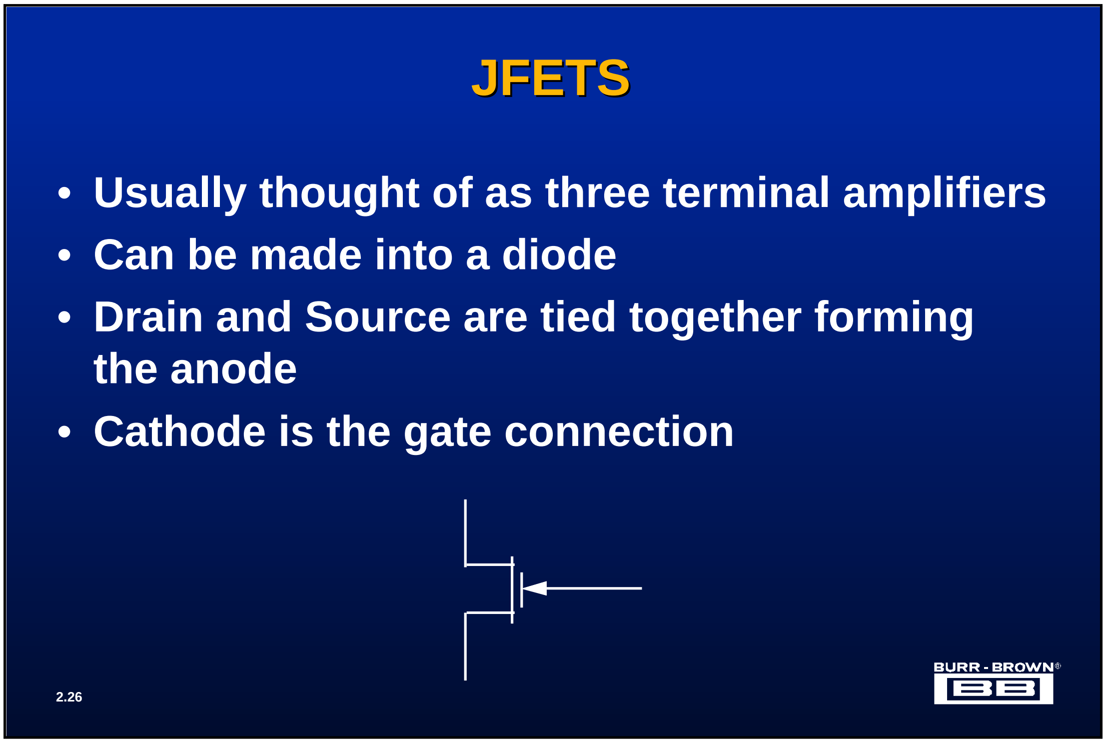


The schottky diode is different from the silicon device because of the manner in which it is fabricated. Instead of having the anode and cathode being made from two opposite polarity silicon regions, the schottky device is fabricated by depositing metal on to glass that was itself grown on a n-type silicon substrate. Depending on which type of metal is used the “built-in voltage” can vary from 0.3 to 0.5V typically. Usually the metal is aluminum and the built-in voltage for low values of forward current is about 0.3V.

The schottky diode has very fast switching speeds, usually less than 1ns. The reason for these fast switching speeds is that the diode does not rely on minority carrier transport to obtain its rectifying characteristics.

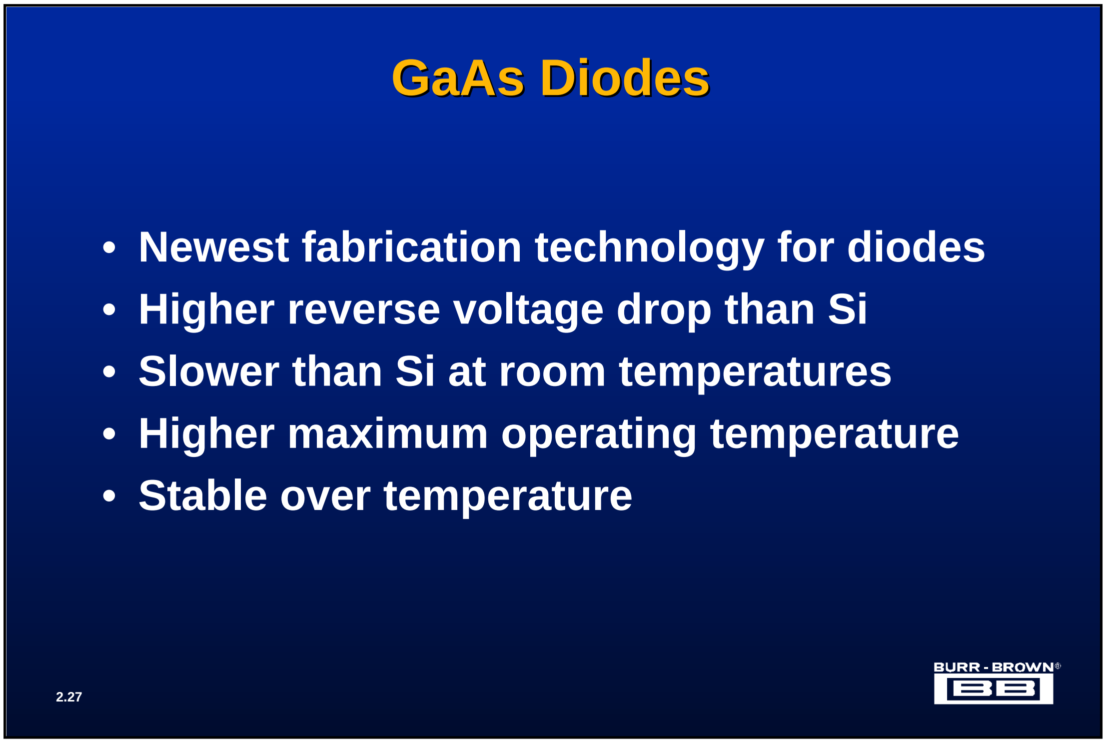
The biggest disadvantage of this diode is that, when reversed biased, the leakage current is much higher than an equivalent silicon device. Also this current can range over several orders of magnitude from room to high temperatures. If we compare the 1N4148 silicon diode to the 1N5819 schottky diode we find the following:

Characteristic	1N4148	1N5819	units
Reverse Recovery Time	2.7	<1.0	ns
Forward Voltage Drop at 100mA	1.0	0.3	V
Reverse Current at 15V and 25°C	0.03	0.1	mA
Reverse Current at 15V and 125°C	0.1	10.0	mA
Reverse Capacitance at 15V	1.2	40.0	pF



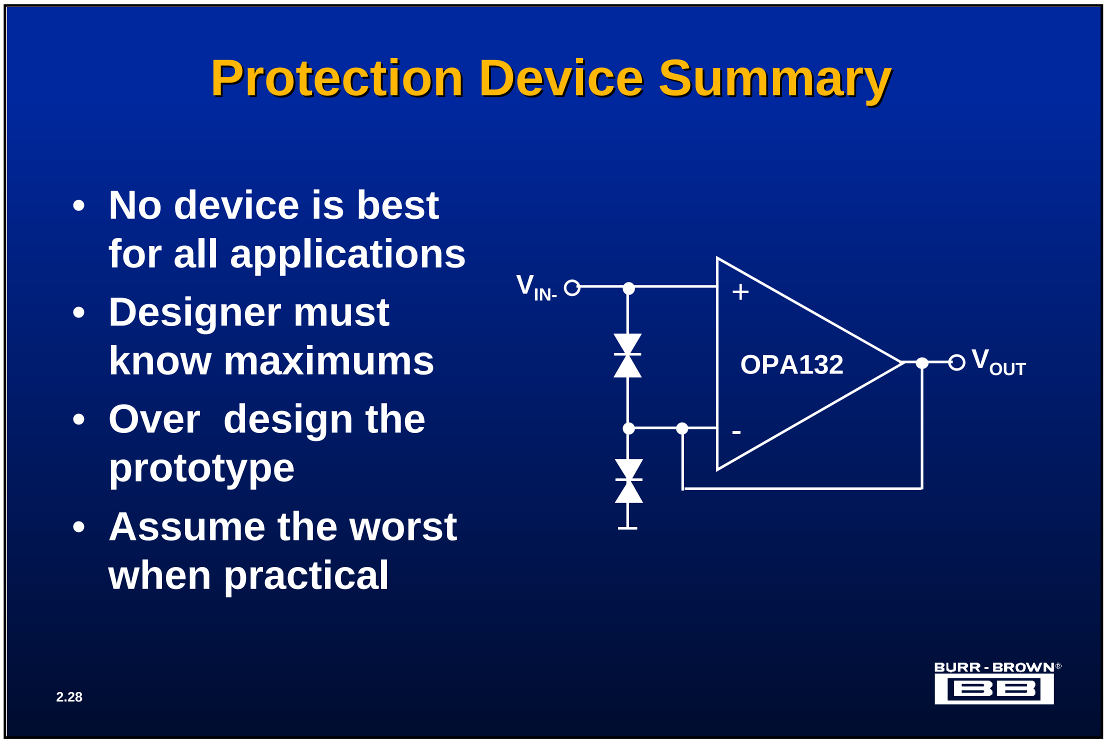
The J-FET, as well as being a good high frequency transimpedance amplifier, can be used to create a very low leakage diode. In fact it is very common to find amplifier designs that use a diode that is in fact a J-FET with the drain and source connected as an input protection device.

A diode made this way will exhibit leakage current of less than 200fA. The diode is not especially fast but it does have a forward voltage drop of less than 0.6V under low forward currents. The J-FET will not conduct large amounts of current for a long time. An acceptable way to use this device is to place a series of resistance between the diode and the potential source of the overvoltage to protect both the J-FET and the active circuit from large current surges.



GaAs or Gallium Arsenide technology has been used for some time for ultra fast low power devices. The technology differs from that of Si or Silicon, such as the bandgap voltage. The bandgap voltage is 1.42eV for GaAs and 1.1eV for Silicon. This difference in bandgap energy results in a higher forward voltage drop for the GaAs device but a much lower, by as much as three orders of magnitude, reverse current than an equivalent Silicon device.

The biggest advantage of this new technology, besides the leakage current, is the temperature stability of a GaAs device. For a silicon device the reverse recovery time will typically more than double from 25 to 125°C. Over this same temperature range an equivalent GaAs device will change by less than 20%. GaAs devices also have a much higher maximum junction temperature than Si, 260 vs 150°C. This allows the GaAs diodes to be operated with higher current densities. This results in a smaller diode structure and package size, for a given power dissipation and application.



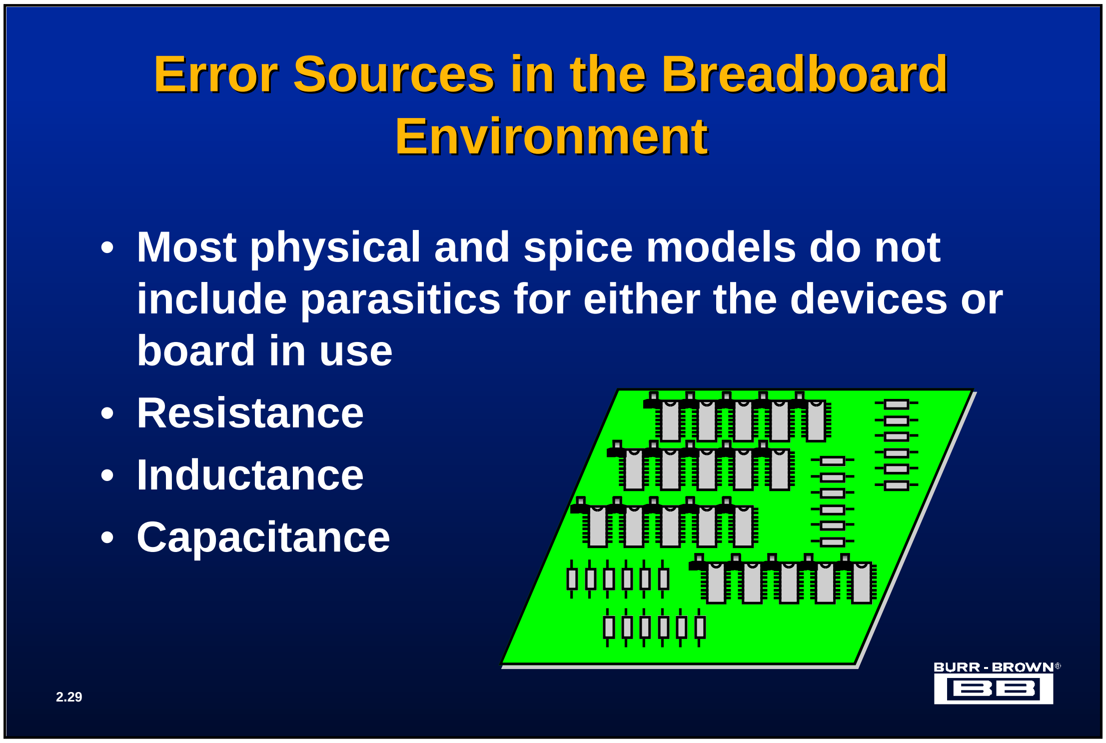
Returning to the example of the op amp and assuming that maximum performance in terms of bandwidth and input stage accuracy is desired the following summary illustrates which protection devices are best for the given parameters.

1) Power Supply Rating. A zener diode is the best choice to keep the voltage from overshooting provided the power supply itself is current limited and does not have a fast rise time. If this is not the case than a transzorb should be used. A transzorb should also be used to protect the power supply itself and thus prevent a high voltage transient from causing the power supply to fail short.

2) Differential Input Rating. A J-FET connected as a diode will give the least amount of added capacitance and leakage current. Actually two such diodes will be necessary to provide bi-directional protection.

3) Common-Mode Range. For this application it depends on whether the inputs to the op amp include a common-mode range that is closer than a diode drop from the power supply rails. If this is the case than the J-FET diode will work best. If the inputs must be kept away from the power supply rails by more than a volt than a transzorb in series with a J-FET is the best choice.

4) Short Circuit Current. If the op amp in use does not have short circuit protection then the best way to protect the op amp is to use external resistance from the output of the op amp to the load. This resistor should have a value that will limit the current flowing from the op amp to less than the maximum allowable current that would cause the op amp to overheat.



Unless the design being contemplated is simulated with a very specialized piece of simulation software, the effects of the layout and parasitics of the components will not show up in simulation. Also the adjacency of other components and signals will not be known.

Unless a breadboarding and or prototyping step is included in the design phase of a new circuit the previously mentioned effects will not be known until production begins. If these effects are enough to affect overall performance, then the production units will fail some parametric test. At this point the designer has an abundant source of very expensive breadboards and usually delivery problems on top of it.

The best way to simulate a circuit's performance is to use the actual silicon that is to be used in the finished product.

Silicon is the ultimate simulator. A prototype contains all of the parasitics not found in the spice model. It also allows the designer to evaluate adjacency problems like trace-to-trace coupling and ground loops. The prototype is infinitely easier to modify and cost much less than the final product from a changability and evaluation point of view.

Models are Just That

- Be careful that spice models include all parasitics
- Academic models do not represent reality
- SOA and dissipation violations are not easily modeled
- Bandwidth of passive components are never advertised

2.30

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All successful design engineers carry a toolbox that includes a model for every component that they have ever seen, simulated, issued a Purchase Order for, designed in, or turned into smoke.

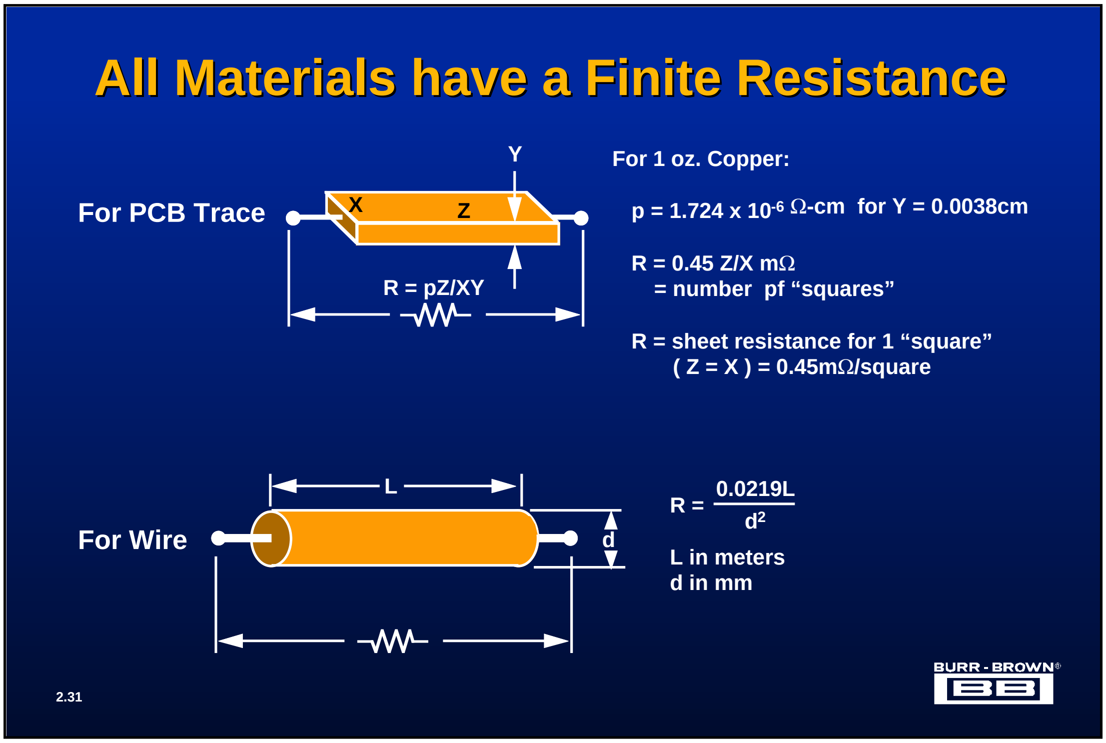
These models have a basis for their existence in the real world based on the individuals experience with them.

What is a Model? It is the mathematic equivalent of the electrical or physical properties that the component represents in the real world.

Is the model Real? As real as the engineer cares to modify or learn about it.

Most models of electrical components represent a compromise between physical reality and economic compromise. When a component is selected from a Spice database it most often represents the actual electrical equivalent of the exact *physical* equivalent expressed in electrical engineering terms. If all engineers could design with such components then engineering would have been finished long ago.

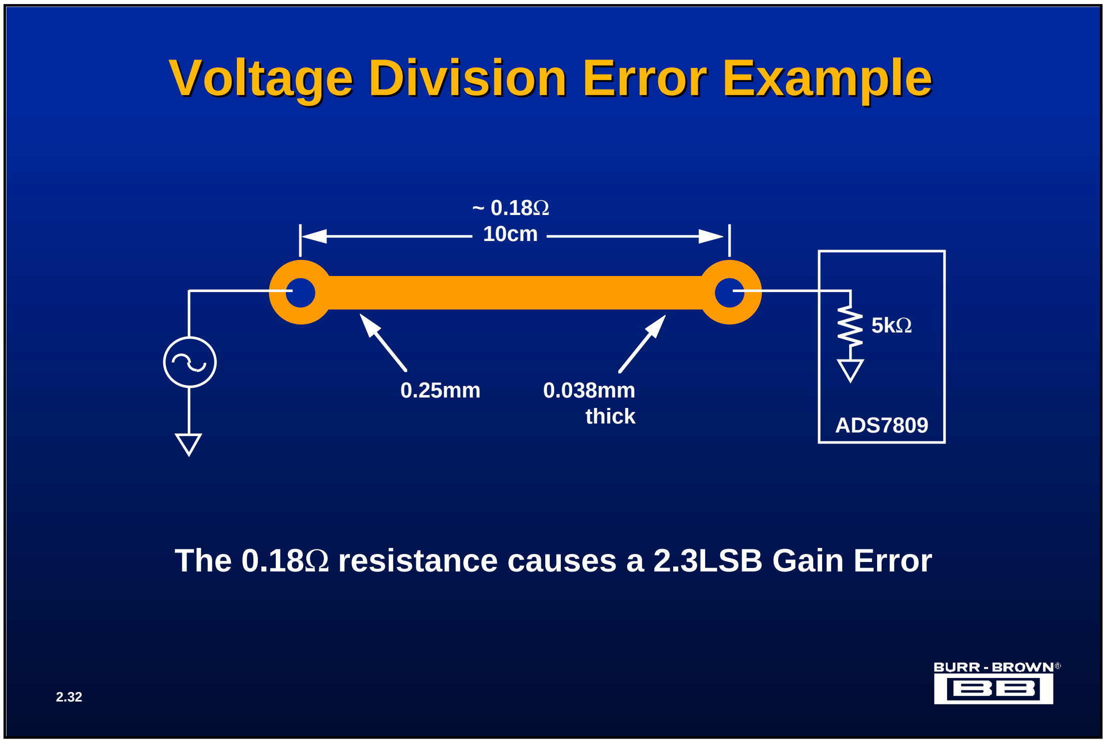
A resistor is not a dissipative element which releases heat in exchange for excitation by an electrical field except at DC. This element like all other components used by engineers is not ideal. It will, for example, turn into vapor if the field is to strong. It also will cease to resist an electrical field if this field is modulated at a sufficiently high frequency.



All conductors, unless they are superconductors, have some finite resistance. Depending on the type and orientation of the conductor this resistance is calculable using the appropriate equation. Even though these resistances are small compared to actual resistors, this parasitic resistance can cause very undesirable effects. Basically these effects can be broken down into two categories.

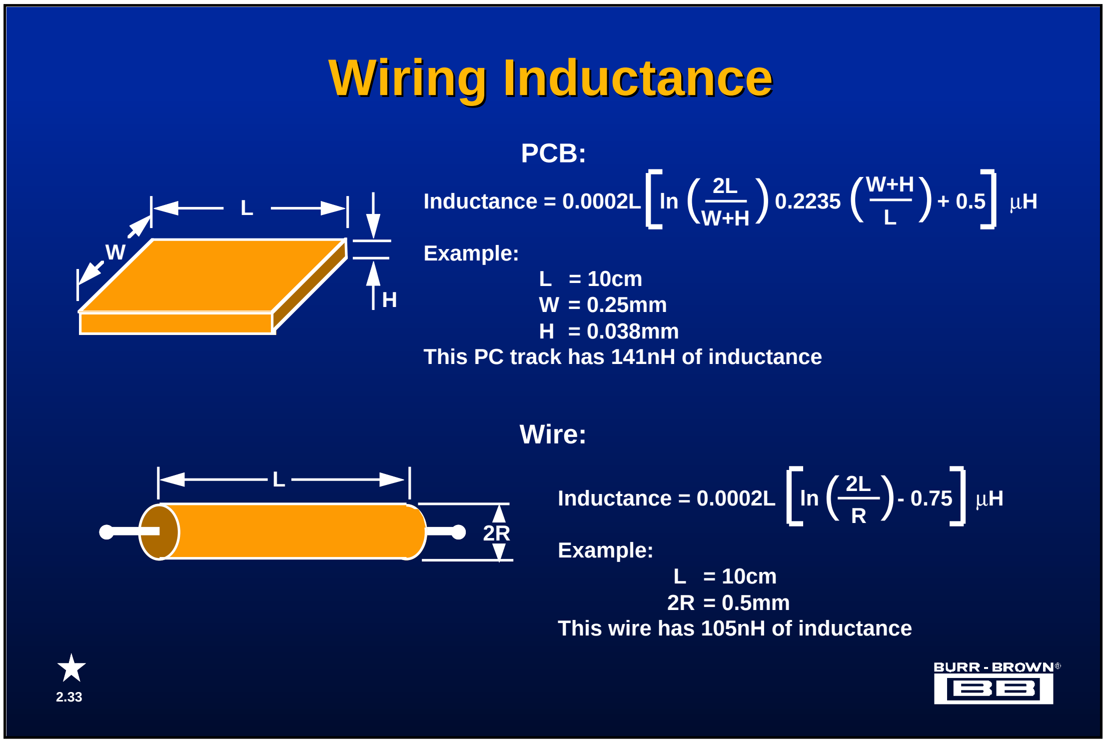
IR losses. This effect causes the voltage that should be present at all nodes of a circuit to be different due to current flow through a resistive conductor. This type of loss also causes the efficiency or power dissipation to be less than ideal.

Voltage division losses. If the output of a voltage source is connected to a resistive trace and this trace is then connected to some fairly low input impedance (1Ω to 10kΩ) then the signal seen will not be exactly what is expected. This is because the output of the voltage source is divided down by the ratio of the input impedance over the total impedance of the trace plus the input impedance.



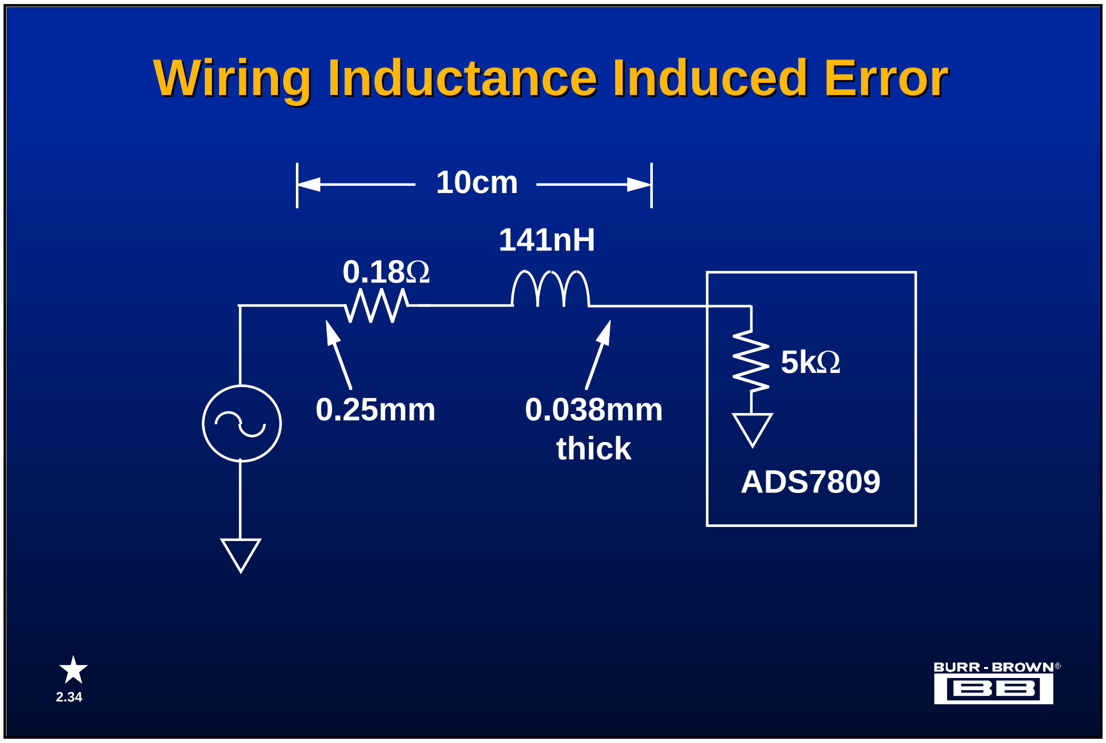
In this example a 5V source is hooked up to the input of the ADS7809 through a 10cm trace of copper on a PCB. The impedance of this trace is only 0.18Ω but by division through the input impedance an error of 180µV is introduced. Since the resolution of the converter is 16 bits and with an input voltage range of 5V, each LSB count is worth $5V/2^{16}$ or 76.3µV/LSB. Thus an error of (180µV/76.3µV) or 2.3 LSBs will be introduced.

This error can be trimmed out by the user of the ADS7809 but not all converters have this trim option. Additionally the impedance of the trace will change with respect to temperature and hence the trimmed value will only be valid at the trimmed temperature.



In addition to DC parasitics PCB traces and wires also have AC parasitics in the form of Inductance and Capacitance. This AC impedance interacts with the DC impedance to form a transmission line. The simple model for this impedance is an L-R circuit that will attenuate signals at high frequency.

Using our 10cm example from the previous page we can calculate the inductance of the trace to be 141nH. This inductance in series with the 0.18Ω resistors forms a low pass filter with a pole frequency of 203kHz.



Imagine the 5V (pk-pk) source being driven in to the ADS7809 connected by 10 cm of copper trace. The ADS7809 can sample at rates up to 100kHz. At that frequency the trace impedance would have a magnitude of 0.18Ω+ 2•π•100kHz•141nH or 0.268Ω of impedance. If the signal source was a sine wave of 5V peak to peak then the actual signal as seen by the converter would only have a magnitude of

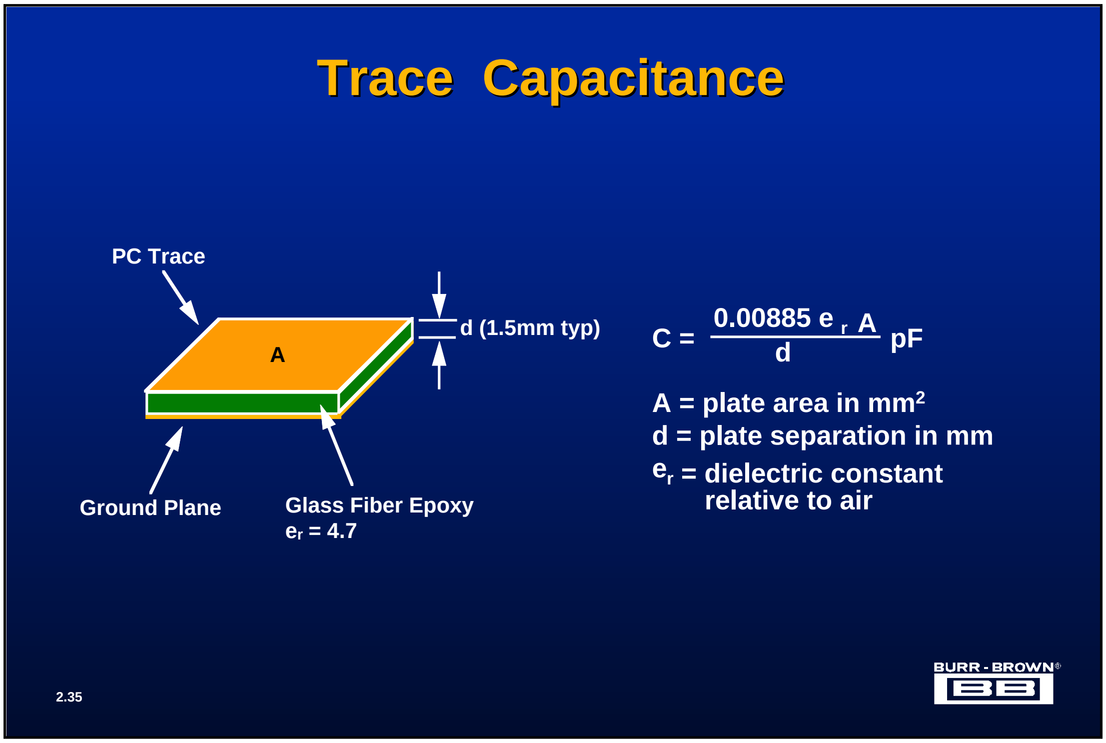
$$5V \left(\frac{5000}{5000+0.268}\right) = 4.999732$$

This results in an error of 268µV or 3.5 LSBs.

Since the maximum error for the ADS7809B is only in the 1.5 LSB range it does not make sense to build in more error than the converter has by just attaching the part electrically.

The obvious solution to both the DC and AC sources of error is to move the source closer to the converter or make the trace widths greater. Moving the source closer is probably not feasible since a distance of four inches is not so great. Making the trace width greater will ultimately increase the capacitance.

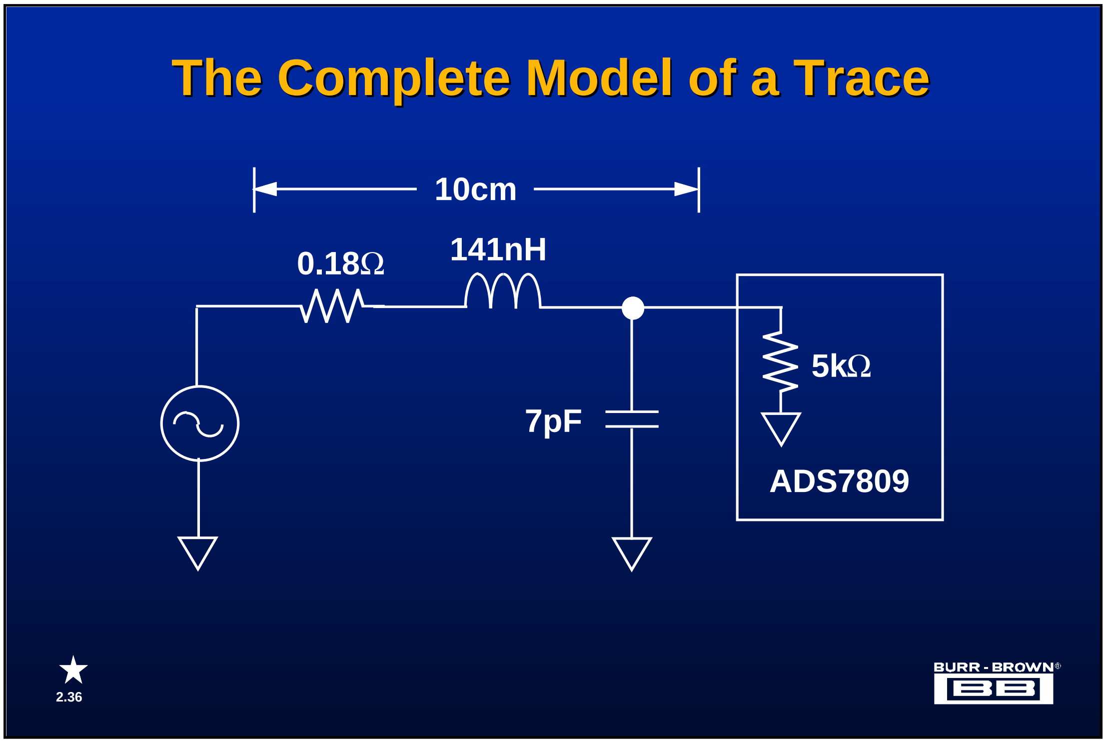
The best solution for these problems is to use a high impedance op amp or buffer at the input of the ADS7809. This solution illustrates a general rule about some analog components and that is to drive with low impedances and receive with high impedances. This rule should also be followed when using a multiplexer.



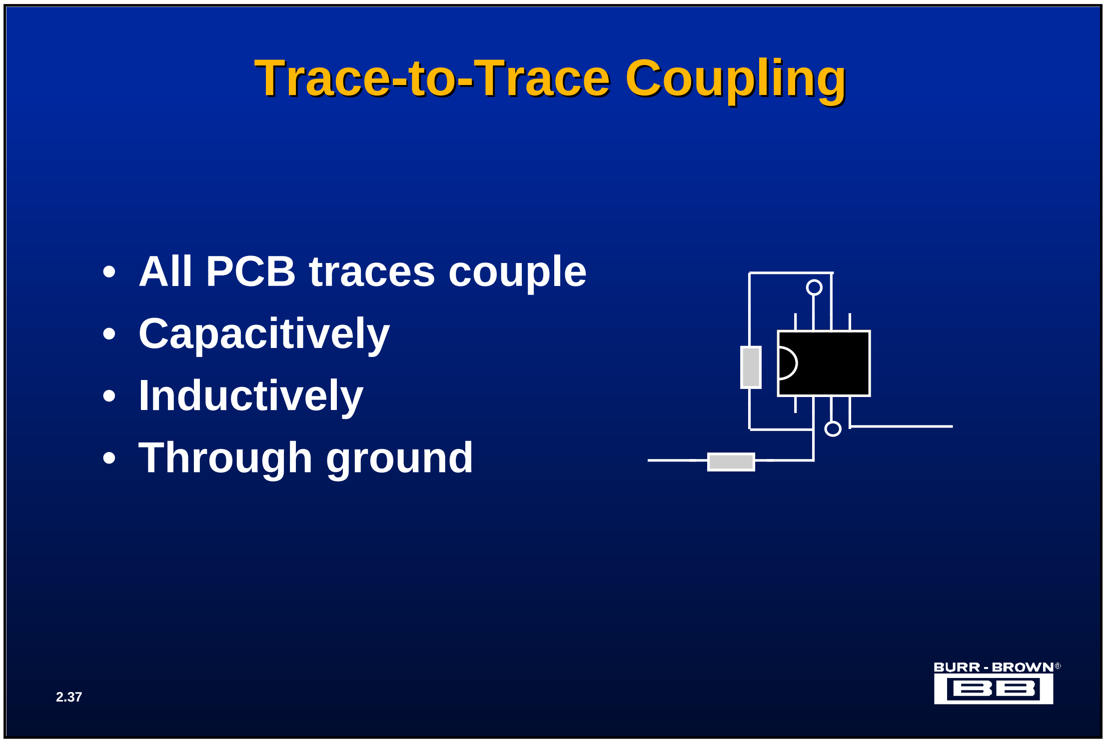
A PCB trace that runs above a ground plane is just another example of the parallel plate capacitor. The amount of capacitance is determined by the total area of the trace, the separation between the trace and the ground plane, and the dielectric constant of the PCB material. The equation given above is useful for calculating the amount of this capacitance.

It is useful to notice that techniques for reducing the amount of this capacitance usually increases the trace resistance and/or degrades the effect of the ground plane. For example, if a trace width were reduced by one half, its capacitance would decrease by one half, the trace resistance however would then double. The only technique for minimizing the trace capacitance that does not increase the trace resistance is to minimize the overall trace length.

Returning to the example of the 10cm trace we can calculate the amount of this trace capacitance to be approximately 7pF.



What would seem to be just a wire or line in a schematic is shown above as a lumped model of the example 10cm trace. Whether or not the trace parasitics are important depends on the frequency and accuracy of the design. This model also illustrates some typical values of these parasitic elements that would be useful to include in every connection used in a Spice simulation. To summarize, it is likely that mΩs, nHs, and pFs will be associated with every wire or trace that is used in a design.

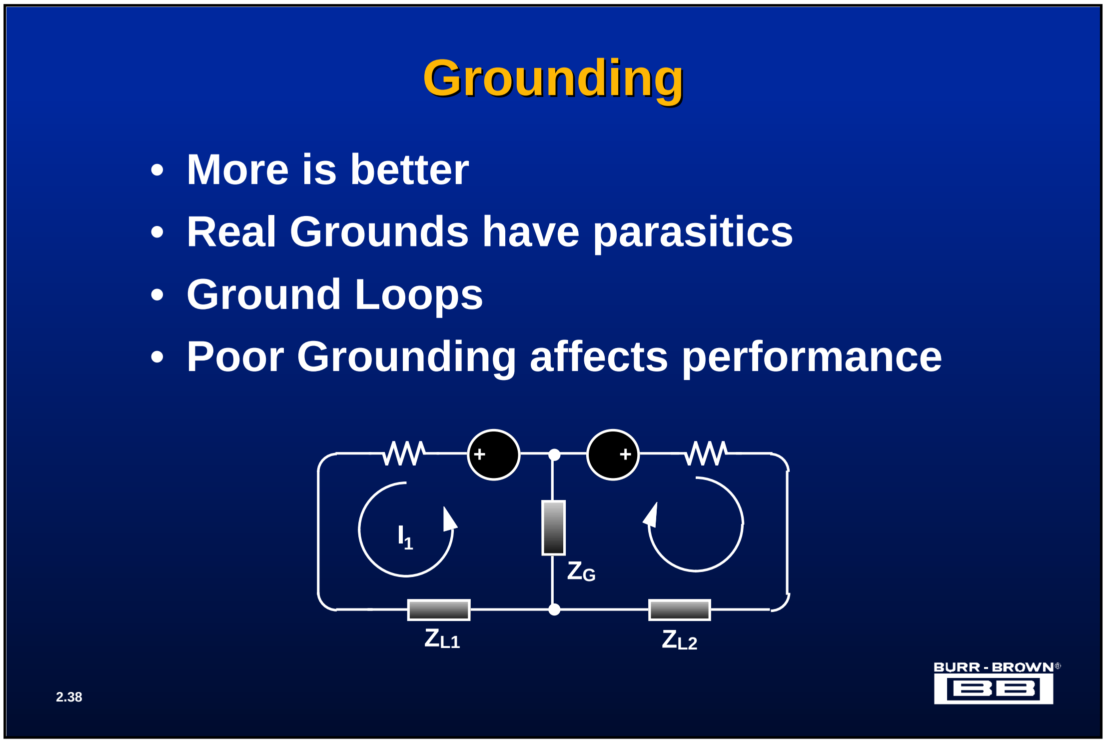


All individual traces in a PCB design will also couple to other traces due to the fact that the PCB environment is not ideal. Depending on the aspect ratio and distances between traces the amount and type of coupling will vary.

In general the trace-to-trace capacitance is most important for voltage coupling between traces. The dielectric constant used to calculate this capacitance is that of the PCB in use. As might be expected the closer the traces are to each other the greater the value of this capacitance. A common way to keep adjacent traces from “talking” to each other is to use a ground connected guard trace between the traces. This trace has the effect of shielding the two traces and forcing any extraneous signals to ground.

Inductive coupling is important for traces whose instantaneous differences in current amplitudes are high. Except in the case of ferrite devices the permeability used to calculate the amount of trace-to-trace inductance is that of air. In fact most materials have a permeability of air because most materials are mostly air.

Signals can also couple from traces into a ground plane. If this ground plane is not of sufficiently low impedance at high frequencies then the ground plane will not only become noisy but it will also conduct high frequencies to other high impedance traces in the system.

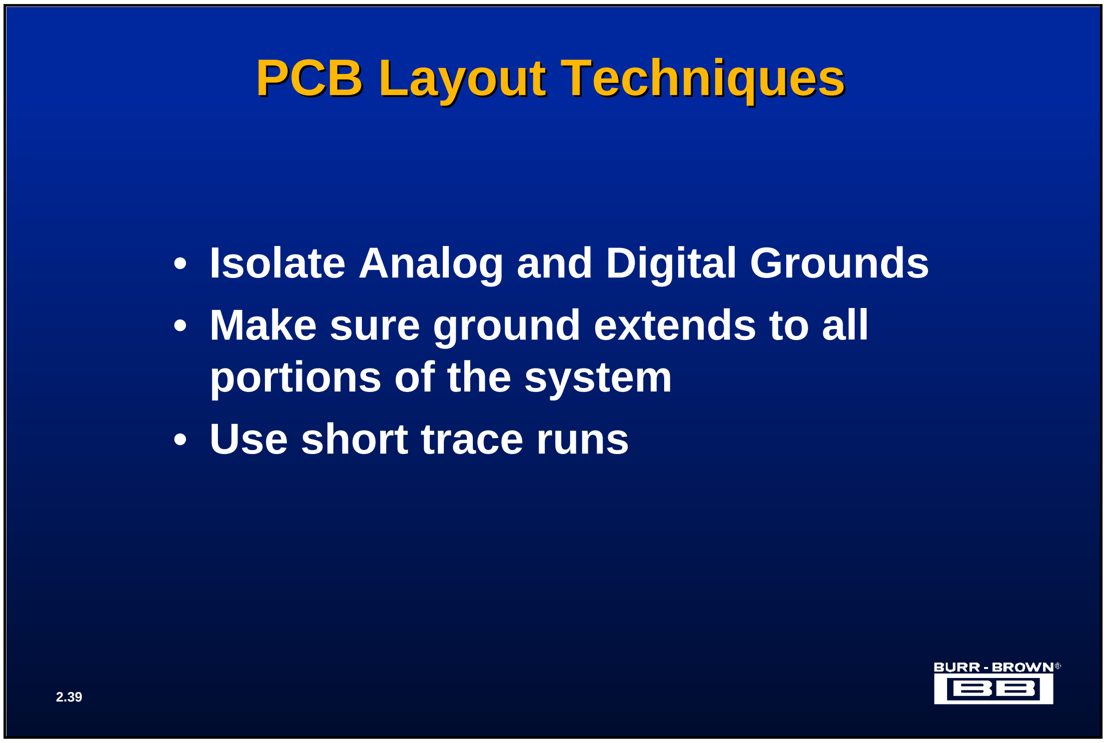


A ground plane is required for all low noise high accuracy systems. This plane **must** be used. The ground plane, like any other trace, has a parasitic capacitance and inductance. These parasitics are most important between the connection of the power supply and the ground planes.

Since the ground plane is also typically used to return supply currents current density is also important. If the current through the ground plane is of sufficient magnitude the impedance of the ground plane will interact with this current and the ground plane will actually develop a potential. From an AC point of view, current density is usually not a problem, but the higher the impedance, the plane becomes at high frequencies, the worse the shielding becomes.

In general to solve both of these problems the best rule is to use as much ground plane as possible. This plane should be as the name implies a true plane. If the currents must travel in a circuitous loop to reach a low potential a ground loop has been created. This loop will not only make the impedance and noise higher but will also act as an antenna and transmit noise.

Data converters of both the industrial and audio types are very sensitive to grounding. To achieve SNRs that reach into the 100dB or keep the linearity of a 16-bit converter in the 2- to 3-bit range requires very careful attention to the ground situation in a layout. A manufacturer’s demo-board is the best source of design hints for the design of this critical layer.



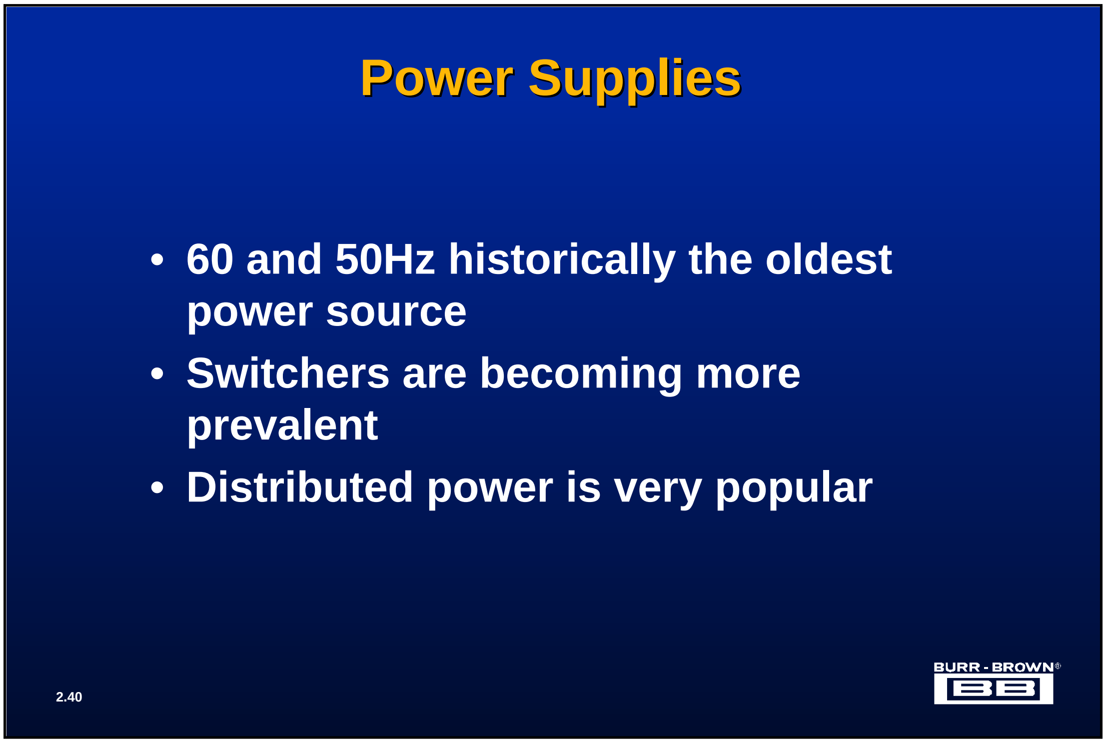
A complete coverage of good PCB layout techniques is beyond the scope of this portion of the seminar but there are some general guidelines that should be followed when either designing a finished PCB or an adequate prototype.

First and foremost for all analog designs, and most high speed digital circuits, power supplies **must** be bypassed close to active devices with high quality capacitors, ceramic or film. When a less than an ideal breadboard is being evaluated the performance of the active devices will be greatly affected if the power supplies have a lot of noise on them.

Use a ground plane even if this means using conductive tape on top of devices, when it is not possible to include a ground plane in the breadboard, like a white board.

Keep noisy digital grounds away from sensitive analog grounds and signals. This usually means using separate analog and digital grounds.

Make sensitive traces as short as possible. Sending low level analog signals differentially will increase the noise immunity and signal integrity of these signals.

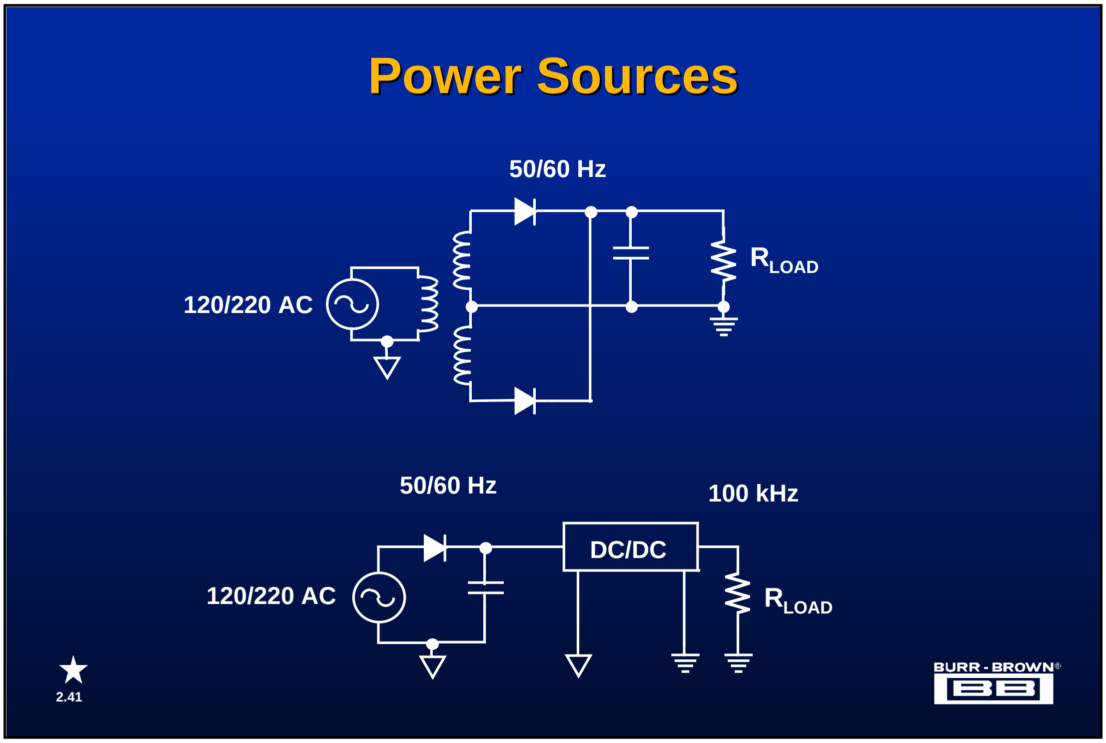


The most common source for the power used to supply analog circuits is the 120/220V, 50 or 60Hz line power. This power source is converted in to the low voltage DC power using a variety of methods. Isolation from the mains is done using a transformer.

Historically this power is isolated, stepped down and rectified at 60Hz. This method has the benefit of having been around a very long time and hence there are a lot of components and design methodologies around to support this method of power conversion.

Distributed power is a method whereby the mains is rectified directly and filtered via a large capacitor. This un-isolated DC voltage is then distributed to the various subsections of an electronic system. This high voltage, > 170V, is then stepped down using a DC/DC converter at each card or board.

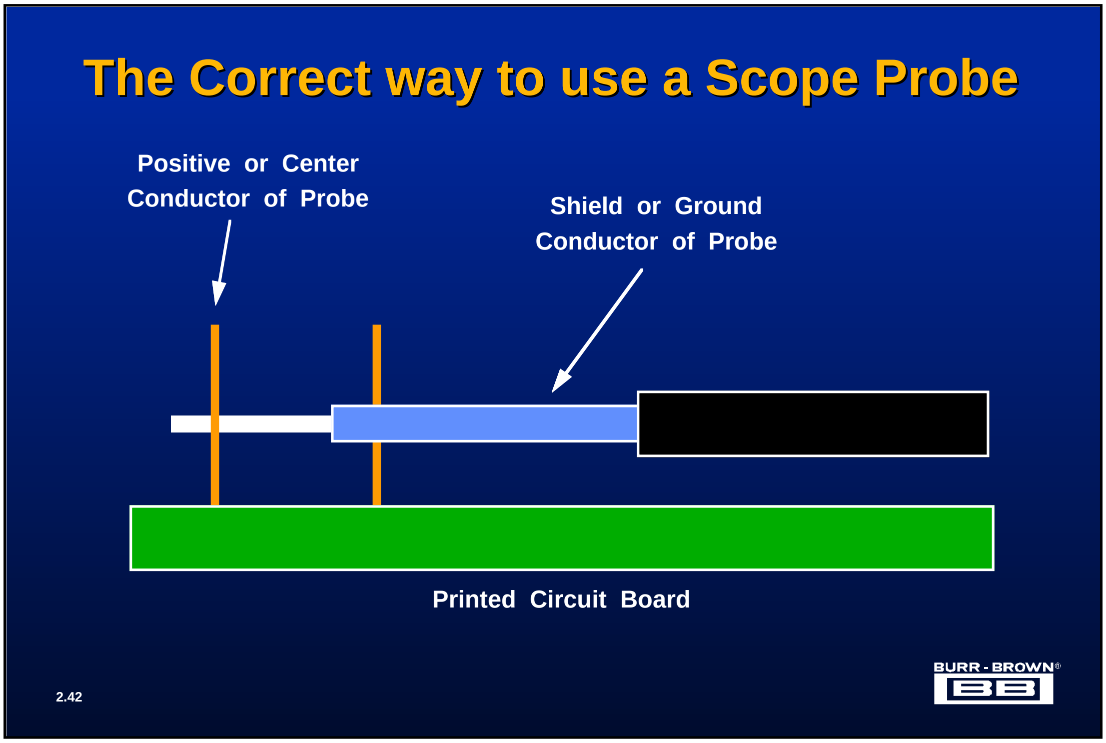
Both of these techniques have advantages and disadvantages but the reason that distributed power is gaining so much acceptance is that this method has the edge economically. The economic advantage of distributed power comes about because of the high frequencies at which the power from the mains is rectified and filtered.



The above diagram shows the key elements of both the conventional and the distributed power supply schemes. In the case of the conventional scheme the largest elements are the transformer and filter capacitor. The distributed scheme also uses a large filter capacitor but not a large transformer.

This diagram also illustrates another difference between these two conversion methods; switching frequency. In a distributed scheme which uses a DC/DC converter it is not unusual to encounter ripple voltages that start at 100kHz and extend into the MHz region. While these ripple voltages are small in magnitude, >50mV(pk-pk), since they are of such a high frequency filtering is no easy matter. A low value, >10µF, ceramic capacitor is usually required for the switching supply.

Additionally, the DC/DC converter can emit high values of high frequency EMI. This noise can become of sufficient magnitude that sensitive circuitry might have to be shielded to avoid being effected.



While the discussion of power supplies and ripple voltages is at hand, it is useful at this point to describe how to correctly use an oscilloscope probe to measure it. The ground lead of the probe shown above will act as an antenna and couple noise into the relatively high impedance front end of an oscilloscope. Even for frequencies as low as 100kHz this antenna will introduce 100s of mV of erroneous signal.

When making low amplitude high frequency measurements the correct way to do so is to remove the antenna. All scope probes made by Hewlett Packard and Tektronix have removable ground clips. If the cover which surrounds the scope probe is removed, what is seen is a small diameter probe which is electrically isolated from the outer shield. This probe is the actual input to the scope probe and the shield is ground. With the cover removed the scope probe can be connected to the circuit or node in question by either method shown above.

Analog and Digital Differences

- Both types or circuits have simulation and breadboard limitations
- Digital circuits have built in noise immunity
- Analog circuits have no inherent noise immunity
- Proper layout, grounding, and shielding can aid in circuit performance

2.43

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In the simplest sense, all digital signals are either 0 or 1, or high or low. All digital logic has some built in noise immunity due to the fact that there is a range for which a signal is defined to be 0 or 1. Any voltage between these two values is not recognized as either value. This voltage value is defined as the noise immunity of the circuit. As supply voltages for all systems fall, i.e. 3.3V, this noise immunity value goes lower as well.

Linear circuits have no built in noise immunity as these circuits will process any signal presented to them. The only limiting factors are the gain, bandwidth, and noise of the said analog or linear block.

In order to optimize the performance of any analog, or for that matter digital, circuit careful attention must be paid to the layout, grounding, and simulation of the circuit.

It is imperative that for every new design attempted, the circuit designer should pursue the following steps to verify circuit performance.

1) Paper design or conceptualize what the circuit should do.

2) Simulate, if possible, with the most complete circuit models available.

3) Breadboard the actual circuit or parts therein to get a gross feel for what the real world devices will actually do.

4) Prototype the circuit in an actual PCB environment to refine the operation of the circuit as gleaned from the Breadboard stage.

Prototyping Techniques

- Plug in Vector Boards - Useful for DC and Low Frequencies
- Dead Bug or 3-D “Kluges” - Easy to modify
- Vector or Vero Boards - Good Platform for Wire-Wrapping
- Actual PC Boards - Closest to the real thing

2.44

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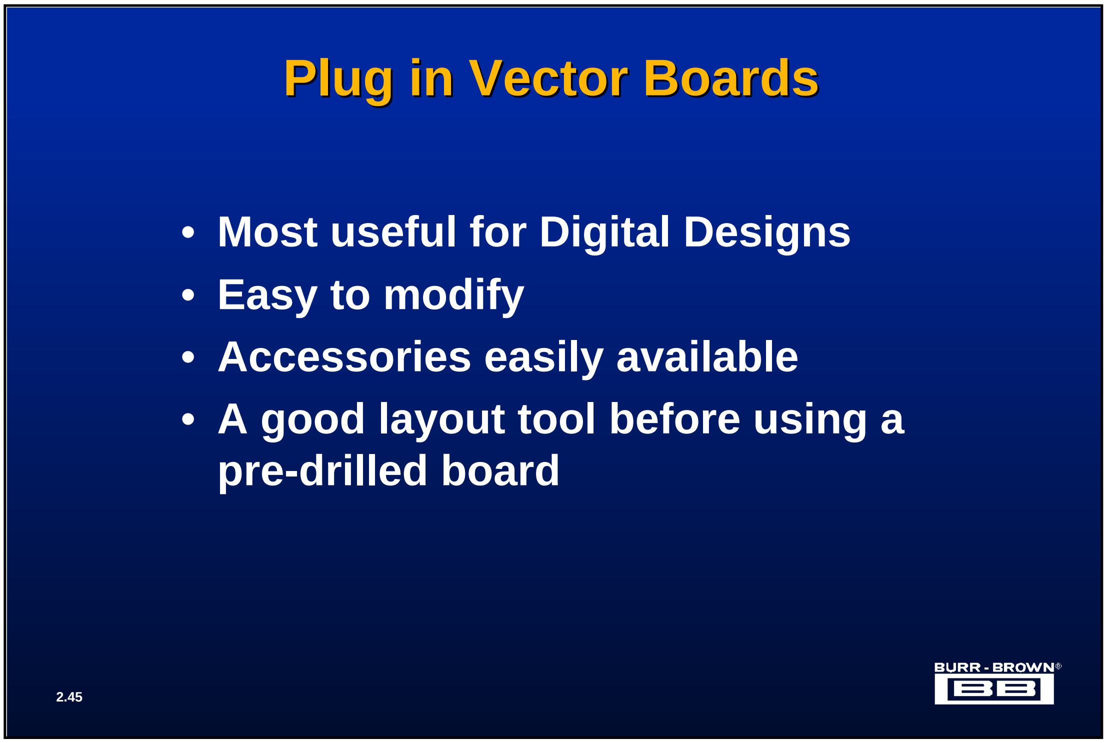
Every successful design cycle for any complex analog circuit begins with a breadboarding or prototyping stage. Just what type of breadboard is used depends on what information the designer is trying to extract about the circuit design.

The above breadboarding techniques and platforms are just a few of the many that are available to the circuit designer. If time and design cost were no object the designer would be able to test every variation of the design on a PC board. This would result in there being no question in whether the extra parasitics inherent in the other breadboarding techniques, caused the prototype not to work or perform as desired.

This scenario almost never occurs so the benefits and pitfalls of the other techniques will be explored.

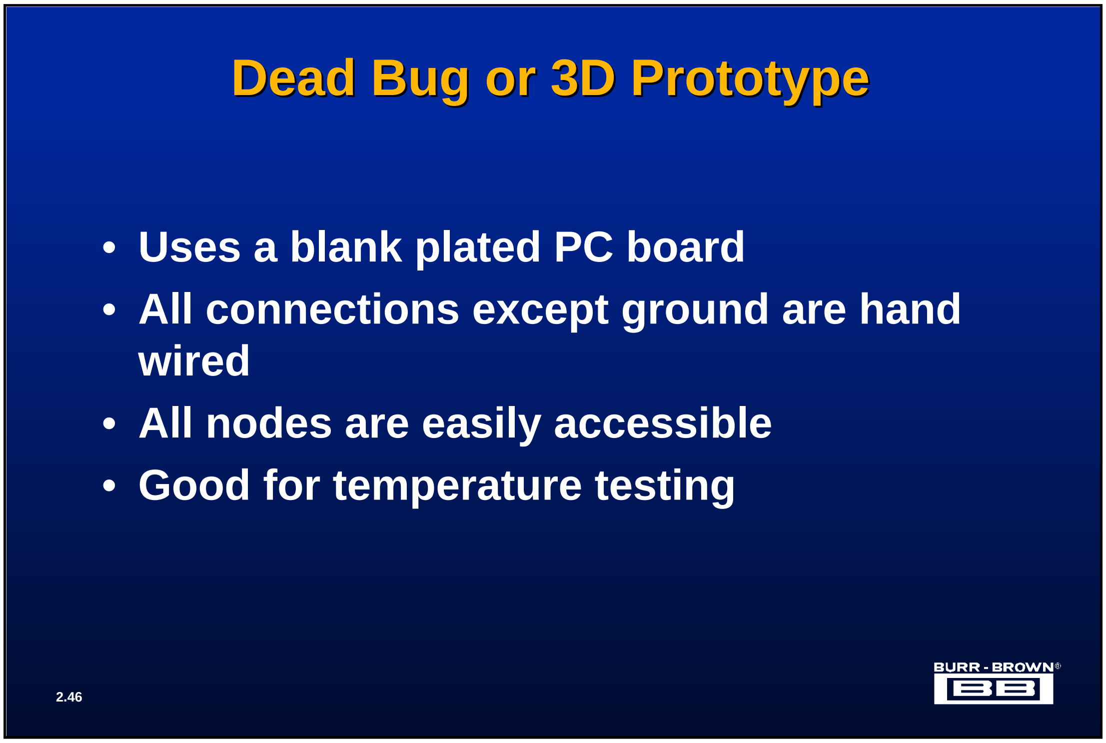


The white-board approach to prototyping is probably the most popular and most misused technique of all the breadboarding techniques. When a strictly digital design is being evaluated, this technique has been shown to work up to signal/ clock frequencies of several MHz. The reason for this is that digital circuits have noise immunities ranging from 100s of millivolts up to several volts. Thus, the inherent trace-to-trace capacitance built in to these boards does not cause enough signal coupling to cause false triggering, etc.

When a high gain analog circuit is evaluated in this manner it is a different story entirely. Consider an op amp with an open-loop gain of 120dB with its summing junction coupled to at least two other traces with a capacitance of 10s of pF. Depending on the rise and fall times of the signals on the other traces the output of the op amp can never be predicted based strictly on the apparent inputs to the op amp.

This is not to say that white boards are not at all useful for analog designs, there uses are just severely limited. Evaluating the DC performance or general functionality of such a design can be very successfully done in this environment. Questions like, does the circuit work at all or does the the output go the right direction in response to the inputs can be answered. If the bandwidth of an analog design is less than 100kHz, including the harmonics, then this technique is appropriate.

Another benefit of this technique has to do with laying out a single layer prototype. If the user is careful and lays out the board carefully with no overlapping wires the layout can be transferred to a predrilled board where the built-in parasitics are much lower.



The "dead bug" approach uses a blank copper clad PC-board as the foundation for the design. This technique, whose results resemble bad modern art, has the big benefit of being easily modified and tested as all of the nodes of the circuit are visible.

Construction of such a breadboard begins by bending all of the leads of the components to be assembled down if they are to be connected to ground. The remaining leads then form the tie points for all of the interconnections which are made by soldering wire in between the nodes.

Connecting power supplies, inputs and outputs to this prototype is a little more difficult than the white board approach. Attaching the non- conducting portions of banana jacks to the copper ground plane with "super glue" provides a strong mechanical connection for power connections. The conducting portion of a banana jack, and the ground connection of BNC connectors can be easily soldered to the PC board and provide both the physical and electrical connections to the prototype.

Finally this protoyping technique can be expanded using a rotary cutting tool, like the Dremel tool. The ground plane can be cut into 2 or more portions to either provide separate analog and digital grounds or provide a convenient "island" where a number of connections must be made. If this variation of this prototyping technique is used then the copper clad PC board should be at least 40 mils thick to insure the board itself is not cut in two.

Vector or Predrilled Boards

- Holes are laid out on 100 mil centers
- Available in a variety of types
- Grounding can be an issue
- Lead parasitics are low

2.47

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The Vector or predrilled board is a hard version of the white board. This type of board is also a good second version of a white board prototype due to its similarity in construction.

Many versions of this board type are available including some types that include ground and power traces or layers. Use only the best versions of the dielectric offered or available with this board to minimize trace-to-trace impedance.

This breadboarding technique also lends itself to other methods of lead hookup. Wire wrapping and socket use are easy to implement with this technique.

In general this breadboard technique has the ease of white boarding with the benefits of ground planes and lower trace-to-trace capacitance. It is a good compromise for complex circuits which do not require high performance at frequencies in the 100MHz region.

Prototype PC Board

- The best prototyping technique
- The most expensive option
- Manufacturer’s Evaluation Board
- Can be difficult to modify

2.48

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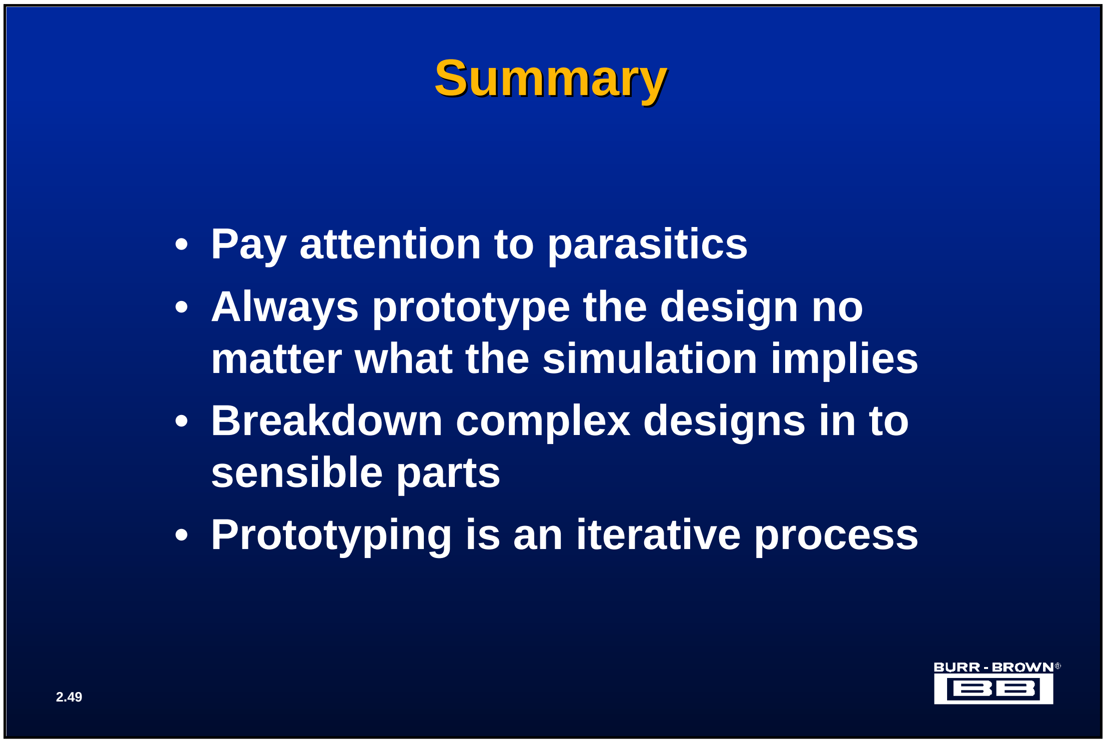
The best way to prototype a design is to use the construction technique that will be used in the final product. Since this is most often a PCB layout this is the best way to proceed.

A manufacturers demo board, if available, is a suitable way to proceed. Usually these boards are laid out such that the optimum performance can be achieved from the device the demo-board is made for. If artwork for these boards is available it should be duplicated in the finished product or prototype. Some times these boards are very liberal in the use of ground planes and bypass capacitors. If there is sufficient real estate available in the final product then these characteristics of the demo-board should be duplicated as well. Quite often the demo-board uses different layouts and components than is shown in the typical application section of the data sheet for a given product.

Even if a demo-board layout is not being used in the prototype or final product the data sheet for the demo-board should be checked for additional layout techniques and tips.



To summarize, getting the most information from the prototyping or breadboarding phase of a design cycle requires some knowledge of just what should be expected from a particular technique or component. 100MHz performance can not be evaluated from either a breadboard that will not perform at this frequency, like a white board, or from a component that is not suitable for this frequency range, like an electrolytic capacitor.

What is the best breadboarding technique? Answer, all of them. Each technique has its place and validity depending on the application. The Burr-Brown applications staff uses all of the techniques mentioned in this seminar to address application issues. Generally high speed or high frequency questions are answered using a demo-board or custom built PCB board. For DC applications and questions all manner of components, including the high frequency parts, can be successfully evaluated on a white board.

When a complex design must be evaluated it makes sense to break the design down into a series of blocks. Each block should have a noise insensitive input and a low impedance output to avoid interaction between the sections.

Finally, all successful design procedures for new designs require a breadboarding or prototyping phase. If this step is not included in the original schedule for a product then almost with out fail Murphy's law will build it into the actual schedule.