



Glencoe/McGraw-Hill's *Electronic GOTCHAS EXPOSED*

CIRCUIT INTEGRITY

Introduction

Bypassing

Decoupling

Groundplane

Shielding

Layout

EMC

E & E Home

TEN

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■ Introduction

Welcome to GOTCHAS Exposed, where essential issues of Circuit Integrity are discussed and potential problems are exposed! Click on the desired topic in the navigation menu at the left to access a module. Each module begins with an outline of its contents with shortcuts to the various module segments.

- As digital becomes increasingly faster, it starts to look more like analog than digital. Therefore, it is necessary to have a good understanding of the analog- and R.F.-like properties of fast digital.
- Attention should be paid to such things as Transmission Line effects, propagation of very high frequencies, crosstalk, power rail bypass and decoupling, shielding techniques, and groundplane

design.

- Because of the speed (nanoseconds), frequencies can be many hundreds of MHz. Also, any conductor, wire, or trace between the gate power pin and the power source can look like unacceptably high impedance.
- In the world of fast edge sensitive logic, it is easy to visualize "inappropriate communications" between logic elements through an unprotected power rail.

■ Module 1: Bypassing

Bypassing and decoupling are subjects that are rarely, if ever, covered in the classroom; but are emphasized in nearly all data sheets & application notes. The legacy this creates is that many new engineers and some technicians ignore it. However, they do so at their peril because it is the single greatest reason for hardware debugging problems!

- When powering any active device, there is one overriding requirement. The point of entry of the power supply (Power Rail) should be as low an impedance (relative to ground) as possible (ideally zero ohms). This will help to insure the stability of the circuit or the Circuit Integrity.
- Bypassing is done to prevent unwanted communications between devices (or different stages of the same device) that share the same power rail.
- Also, implicit in this requirement, is the reduction of noise present on that power rail--at all frequencies.

■ Module 2: Decoupling

As noted in module one, bypassing and decoupling are subjects that are rarely, if ever, covered in the classroom, but are emphasized in nearly all data sheets & application notes. This is the single greatest reason for hardware debugging problems! New engineers and some technicians often make their jobs more difficult because they ignore this.

- Decoupling is a refinement of bypassing. Because bypassing has limitations in creating the ideal voltage source, decoupling, or isolating adjacent noise sources is often required.
- An ideal decoupling element is a lossless path for direct current and infinite impedance for alternating current. This allows devices to be powered with no loss and prevents noise from moving from one load to the next.

■ Module 3: Groundplane

A groundplane serves as the return path for all currents. Like bypassing and decoupling, the groundplane is rarely covered in the classroom, but is often emphasized in application notes, and used in most real designs.

- It is desirable to not have different signals sharing the same ground return paths. The groundplane helps achieve that goal.
- A continuous conductive planar having no discontinuities is the ideal groundplane.

■ Module 4: Shielding

A shield is a blocking or containing barrier against electrostatic fields. It should have no currents flowing through it. Like bypassing, decoupling, and the groundplane, shielding also gets little coverage in the classroom, but is emphasized in many application notes and used in real designs.

- In a circuit or system, there are many discrete signals, which are directed to specific destinations. These signals can interfere with other unintended signal destinations or devices. Shielding can prevent or diminish this effect.
- Like a groundplane, a shield can be constructed of one or more conductive homogenous planars. However, the shield differs from the groundplane by its need to not contain conducted or induced

electrical currents.

■ **Module 5: Layout**

Layout (PCB) is the integration of bypassing, decoupling, groundplane, and shielding, plus a little art. Layout may be mentioned in the classroom, but it is rarely taught. Often described as "...one of those things that is done by draftsmen," a layout improperly done can ruin even the best paper design!

- Layout (PCB) is the creation of a physical realization of a circuit, using all of the subjects in modules 1-5, with primary attention given to signal flow.
- In order for a circuit to work as intended, the interconnection of the circuit elements must be optimized while observing all pertinent rules.
- Proper layout insures economical manufacturing and reliability. Input, output, parts placement, signal flow and power distribution should be considered, along with interference and noise within the circuit layout.
- Observe device rules, such as bypassing, decoupling, shielding, the proper use of groundplanes, and also electromagnetic compatibility (EMC).

■ **Module 6: EMC**

Listening to the news on AM radio while using an electric razor was once a problem due to electromagnetic interference. However, if both the razor and the radio manufacturers adhere to electromagnetic compatibility (EMC) design practices, listening to an AM radio while using an electric razor shouldn't present a problem. For many, designing for and understanding EMC can be mysterious and more art than science. However, it doesn't need to be.

- With the proliferation of electronic systems in every aspect of our daily lives, inevitably comes the issue of electromagnetic compatibility.
- Worldwide governmental regulations prohibit electronic products from emitting or being susceptible to, electromagnetic interference.
- Along with modules 1-5, this module is intended to solve some of EMC's mystery--but not all. The greatest insights are often learned in practice.

■ **Module 7: Prototyping**

Prototyping content here.

■ **Module 8: Troubleshooting**

Fear of trying this or that, or postponing the inevitable when troubleshooting can be a troubleshooter's worst enemy. Fear can cause a person to rationalize trying easy ways first, when another method may be more logical, prolonging the discovery of a problem. Do not confuse the need to avoid these tendencies with a need to ignore precautionary practices or not exercise caution.

- Trust your instincts. Perceptive troubleshooters can sometimes find a problem by simply looking at the circuit. 70% or 80% of the problems I've experienced could have been solved this way.
- Sometimes checking the most easily accessible parts of the circuit first is a good idea.
- A key quality of effective troubleshooters is the ability to evaluate individual cases and determine the most practical approach.

Glencoe/McGraw-Hill's *Electronic GOTCHAS EXPOSED***CIRCUIT INTEGRITY****■ Module I: Bypassing**[Click here for a printable version of this page](#)

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Introduction

Although bypassing and decoupling are rarely covered in the classroom, they are emphasized in nearly all data sheets and application notes!

So while some new engineers and technicians ignore these topics, they do so at their peril because failure to address these needs is often the reason for hardware debugging problems!

[back to top](#)**What Is Bypassing?**

Powering any active device requires that the point of entry of the power supply (power rail) be as low an impedance (relative to ground) as possible, ideally zero ohms! Bypassing insures the stability of the circuit, and therefore provides circuit integrity.

[back to top](#)**Why Do We Bypass?**

Bypassing prevents unwanted communications between different devices (or different stages of the same device) that share the same power rail. Bypassing reduces the noise present on that power rail, at all frequencies.

[back to top](#)**How Do We Implement Bypassing**

Something as simple as placing a bypass capacitor between power and ground (V_{CC} and ground) of each active device will effectively restore this nearly ideal power supply--zero ohms output impedance!

[back to top](#)**Definition: Ideal Voltage Source**

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The Glencoe McGraw-Hill logo, featuring the company name in a stylized font.

Ideal Voltage Source

Furnishes a constant voltage output, regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

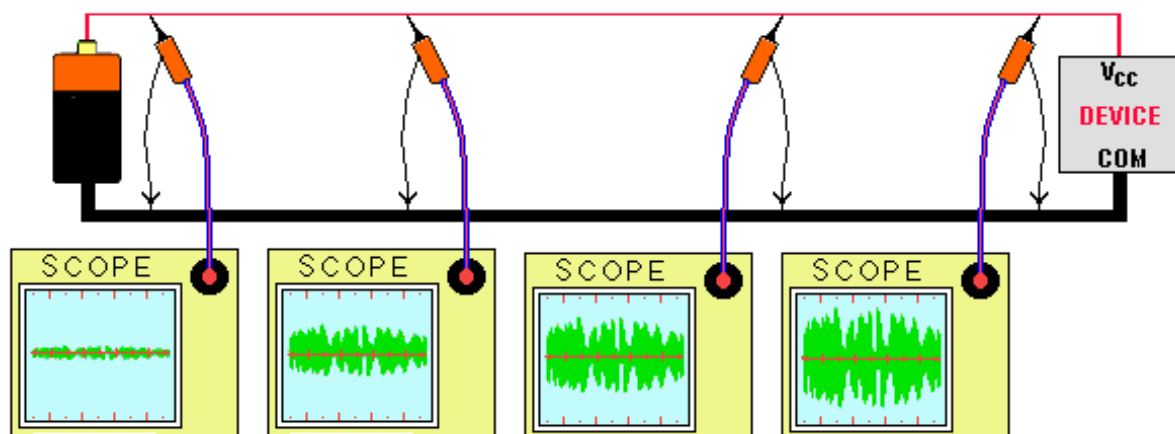
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Power Rails

Because there is distance between any power source and the active device it powers, obviously a conductor, wire, or trace of finite length is required between that power source and device.

Any conductor, wire, or trace has resistance and inductance; both of these properties can cause problems where power is concerned. The resistance problem can be overcome by increasing the cross-sectional area of the conductor; however, the inductive property is another story.

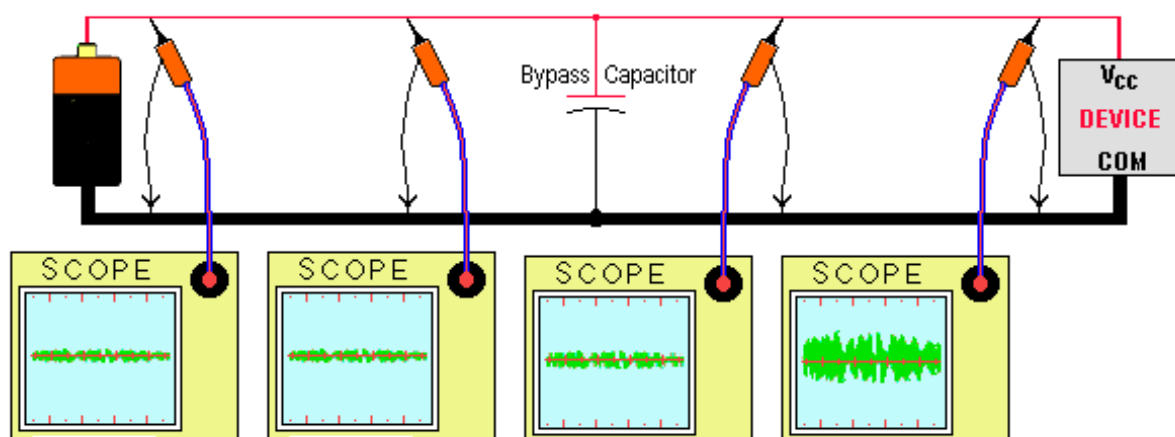
As shown in the figure below, even what might appear to be a small inductance, at high frequencies or very high frequencies can translate to an unacceptable high impedance.



Notice how the inductive reactance (X_L) of the finite length conductor effects the zero ohms impedance. Hence the active device's need for varying rates of current creates more noise as the conductor length (and the reactance) increases.

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Adding Bypass Capacitors



Adding a bypass capacitor to the inductive reactance helps to restore the (virtual) zero ohms impedance.

Note

All active devices have inputs and outputs--but you already knew that, didn't you! Also remember that the power rail (the V_{CC} pin) can be *both* an input and output "port." You only have to examine the schematic of such devices to see that the power rail is common to both input and output stages. The bias resistors of the input stage are connected to the same "rail" as the load resistors of the output stages.

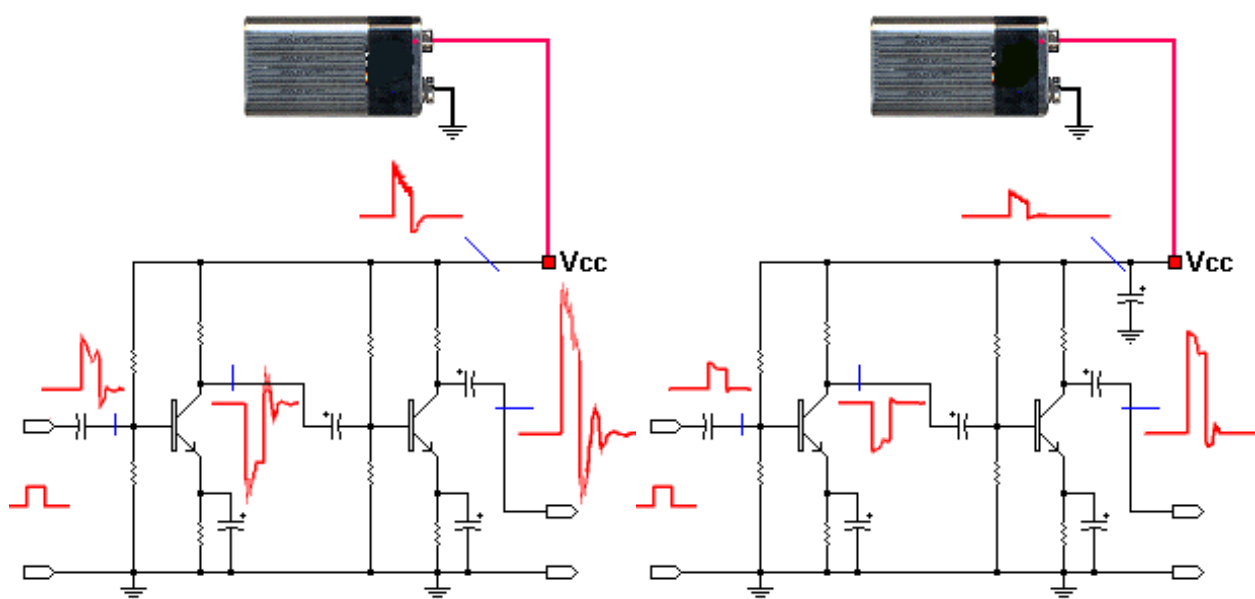
This arrangement is not a bad thing, because it presupposes that this common power rail will always be held at

zero ohms. That is, the rail will be sourced by an ideal voltage source.

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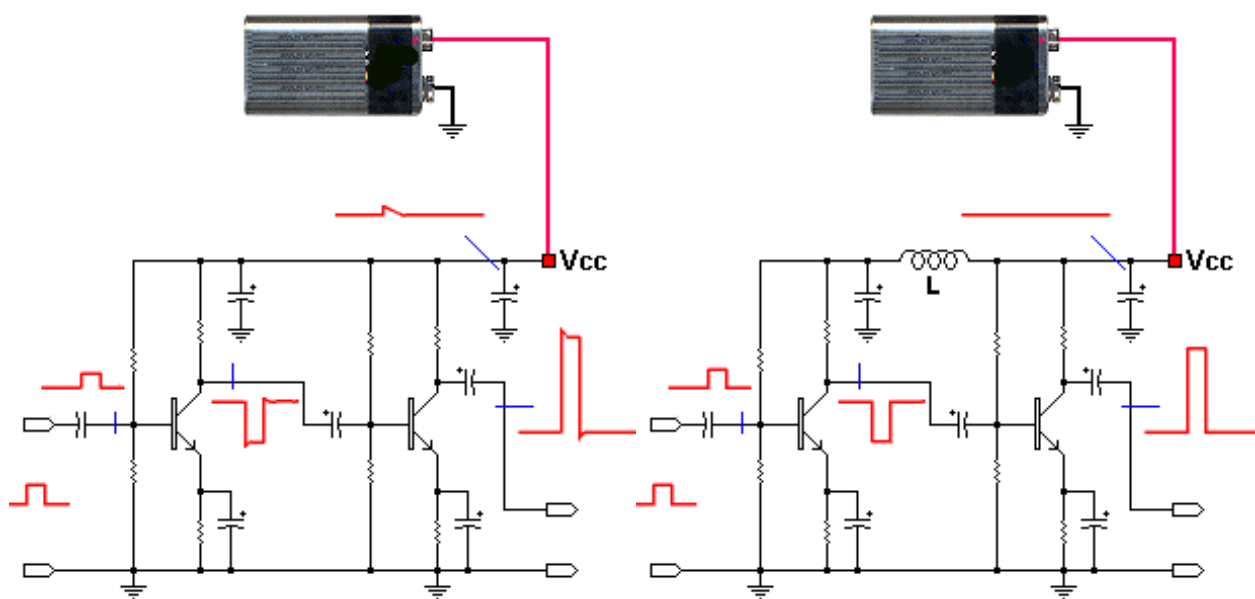
Amplifier

The figure below shows an amplifier with various degrees of power supply stabilization in the form of bypass and decoupling. Notice how the power rail (V_{CC} pin) can be both an input and output "port."



Without Bypass Capacitor

With One Bypass Capacitor



With Two Bypass Capacitors

With Two Bypass Capacitors
& a Decoupling Inductor

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Transistor Transistor Logic (TTL)

Transistor Transistor Logic (TTL) is one great source of noise.

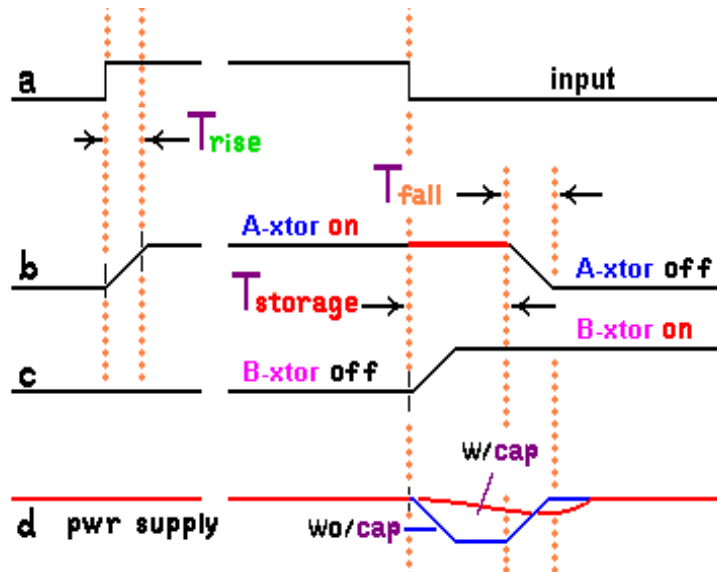
In a typical TTL logic device (gate, flip flop, counter, register, etc.), it is fair to say that at any one time half of the transistors are on, and the other half are off. However, during logic transitions, for a very short time all of the transistors are on.

TTL is a "Saturating Logic." A transistor is either fully off or fully on. When it is fully on, it is said to be in

$$V_{\text{sat.}}$$

A saturated transistor requires more time to become unsaturated than it took to become saturated in the first place. This time difference is called storage time (T_s).

Therefore, during any logic transition (one/zero or zero/one), all of the transistors are on for this short time (T_s), drawing approximately twice its normal current. This latency can last from two or three nanoseconds to as long as fifteen nanoseconds, depending on the logic family. (See figure below)



It takes longer to turn a transistor off than it takes to turn it on. The time to turn on (risetime) = T_r , the time to turn off (falltime) = $T_f + T_s$ (storage time). T_s is the time required for the hole/electron pairs to move back across the base junction, taking the transistor out of saturation (V_{sat}).

Although Schottky devices (74S, 74LS, 74AS, etc.) were meant to eliminate this effect, there is still some storage time.

In systems using thousands to hundreds of thousands of gates, there can be a tremendous demand on the power supply. The power source must supply a constant, non-varying V_{CC} to a load that is random. The load is also very high speed (fast $d_i - d_o$, i.e., a large current change in a short period of time).

If one could supply power to all of the logic devices at a constant V_{CC} , everything would be peachy keen. However, Life—and Murphy—do not allow anything dealing with engineering design to be peachy.

As Mentioned Previously

Because there is distance between any power source and the logic it powers, obviously a conductor, wire, or trace of finite length is required between this power source and the logic.

Any conductor, wire, or trace have the properties of resistance and inductance. Both of these properties can cause problems where power is concerned. The resistance problem can be overcome by increasing the cross-sectional area. However, the inductive property is another story.

Even what might appear to be a small inductance, at high frequencies or very high frequencies can translate to an unacceptable high impedance.

As in the case of the amplifier, above, TTL logic devices have inputs and outputs. The power rail (the V_{CC} pin) can be both an input and output "port." The power rail is common to both input and output stages; the bias resistors of the input stage are connected to the same "rail" as the load resistors of the output stages.

This arrangement, again, presupposes that this common power rail will always be held at zero ohms! That is, it will be sourced by an ideal voltage source.

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Review

In the world of fast-edge, sensitive logic, it is a simple matter to conceive of "inappropriate communications" between logic devices (& elements within a device) through the unprotected, high impedance power rail (V_{CC}).

Because of the speed of this demand on the power supply--Rise and Fall times in the nanoseconds--the frequencies are in the many hundreds of MHz. Any conductor between the device power pin and the power source can look like an unacceptably high resistance--tens of ohms to hundreds of ohms.

Something as simple as placing a capacitor between V_{CC} and the ground of each logic device will effectively create this near Ideal power supply--zero ohms output impedance.

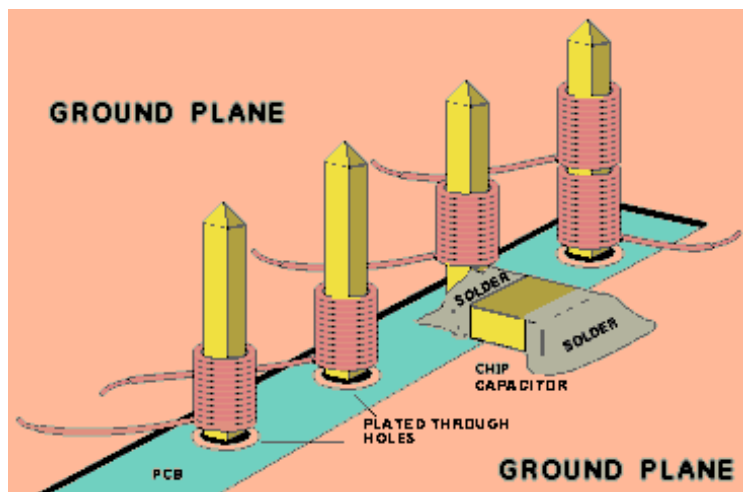
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An Alternative Way to View Bypassing

A bypass capacitor is like a voltage storage reservoir. It supplies instantaneous demand while recharging (from the power supply, via the inductive reactance of the connection) for the next demand.

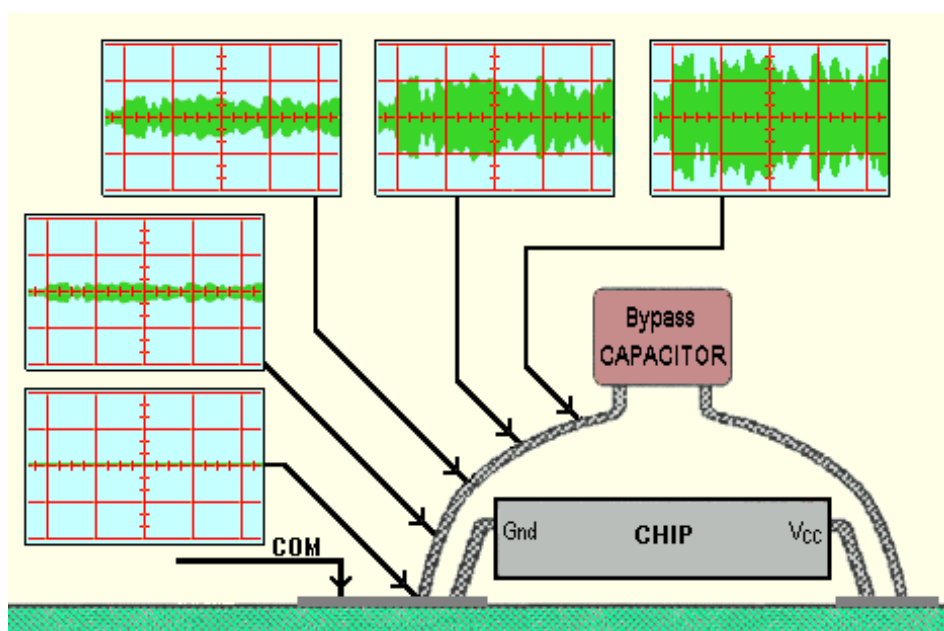
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Adding the Capacitor



Bypassing is the only way to maintain the integrity of the power distribution to the various circuits. It maintains the low impedance of the true voltage source. It counteracts the inductance of the finite length of the conductors that distribute the power to the circuits.

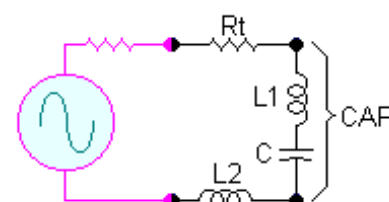
Bypassing is accomplished by applying a sufficiency of capacitance between the supply pin of each device (or stage) and ground (or common) using the shortest path possible.



This illustration shows the effects of inductance in excessive lead length.

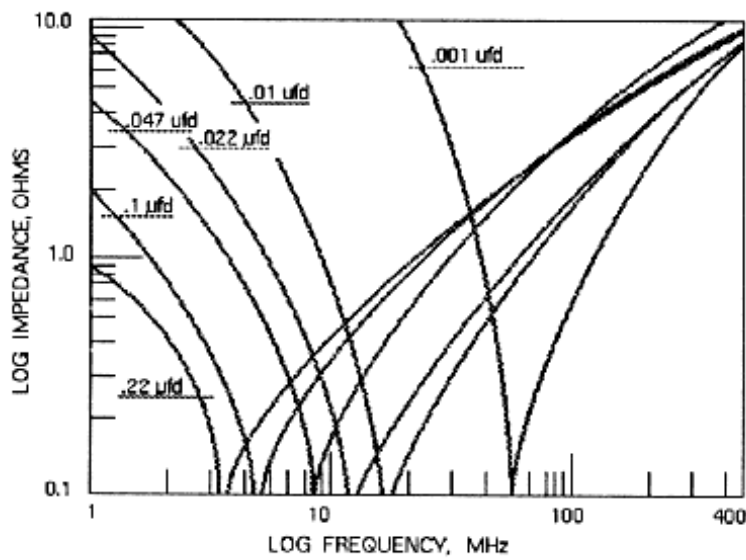
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Capacitor Self Resonance



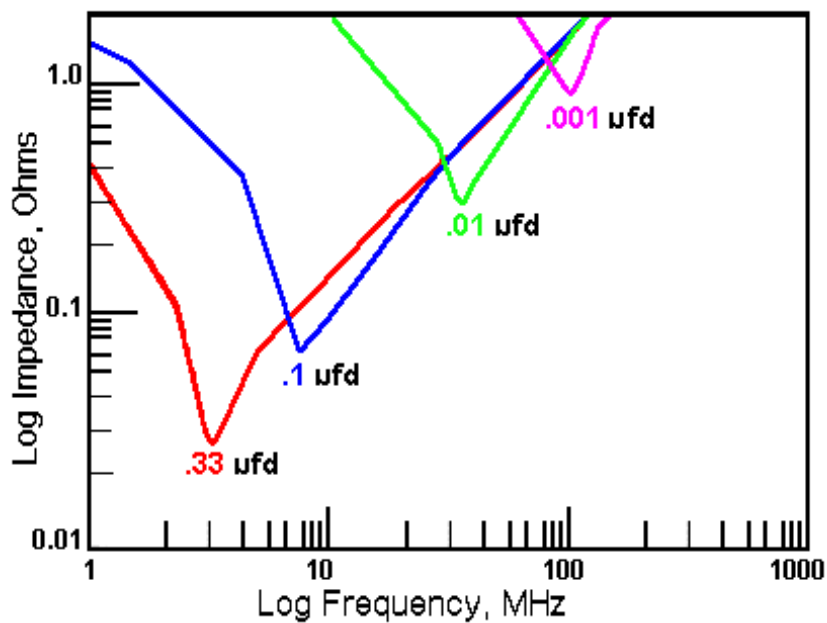
L1 and C represent the capacitor and its leads.

R_t and L2 are Parasitics found in bypass capacitor interconnection.

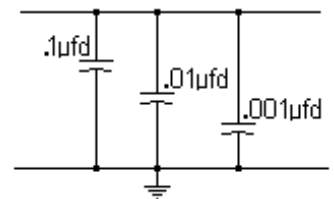


Bypass Capacitors' Self Resonance

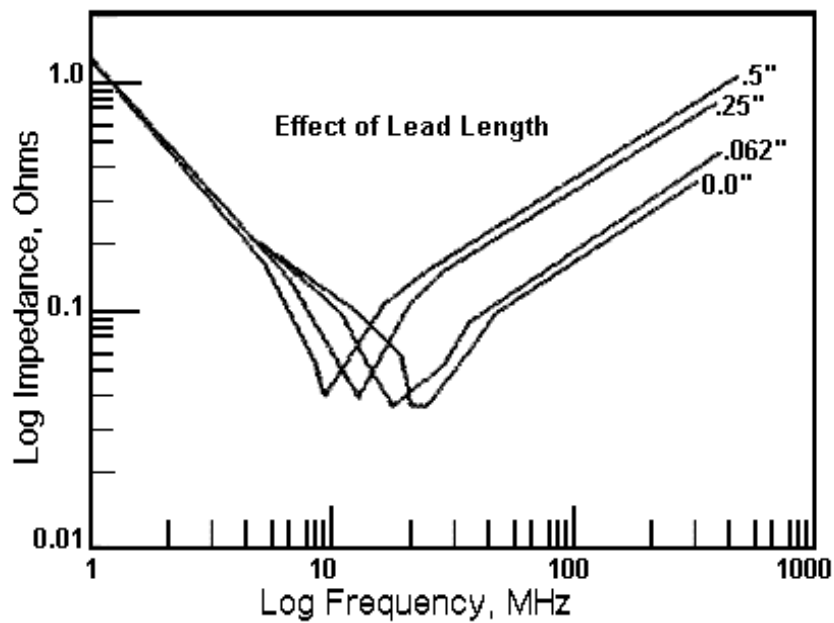
Note
simplified equivalent circuit of
installed bypass capacitor.



Bypass Capacitors' Minimum Impedance at Self-Resonance

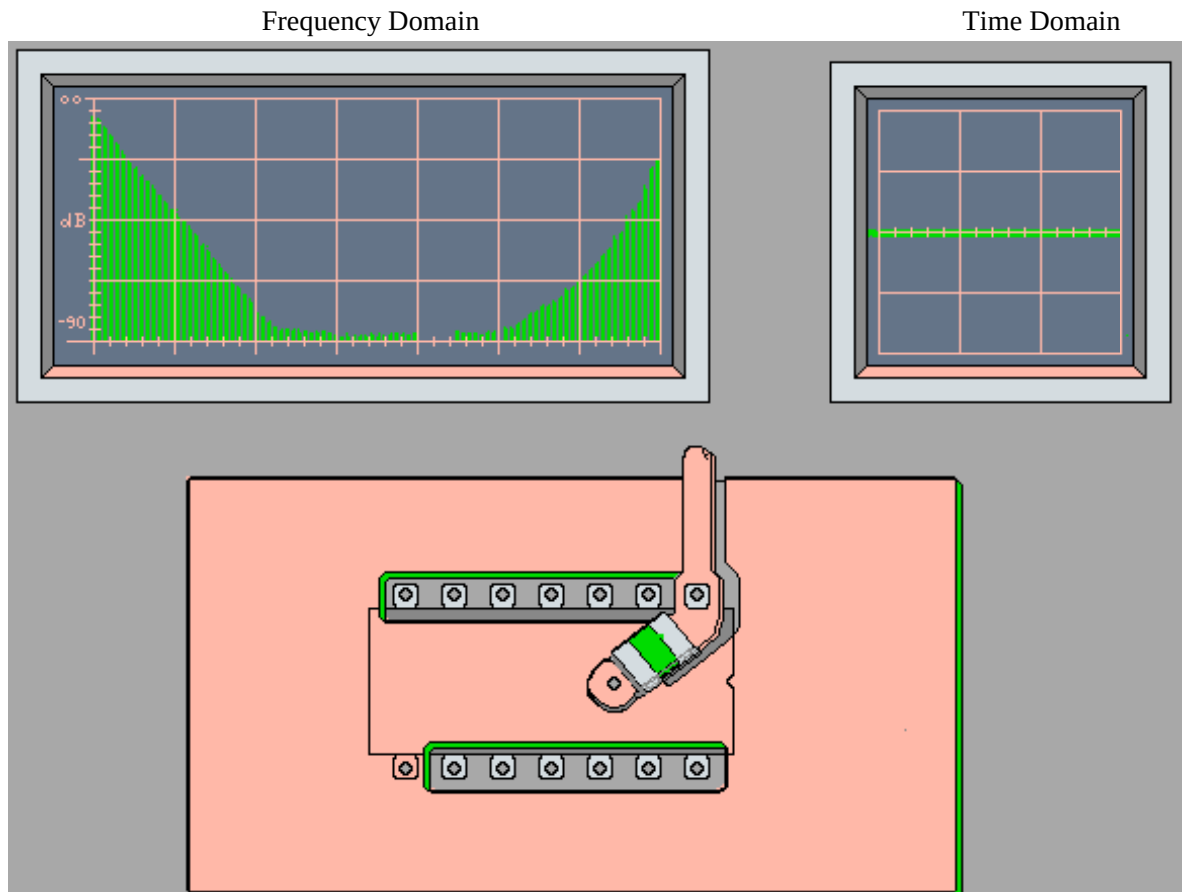


This illustration shows
paralleling bypass capacitors
for maximum effectiveness.

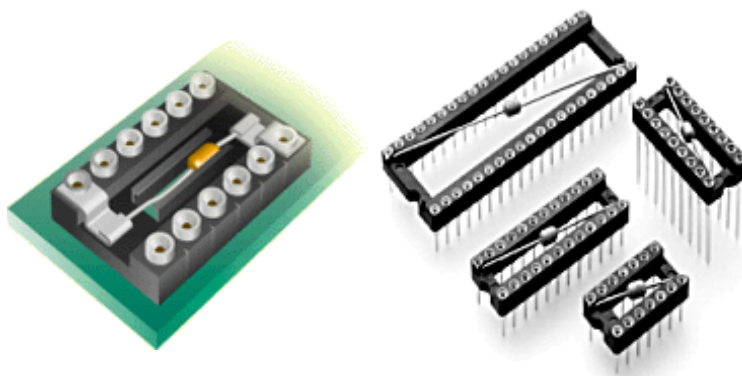


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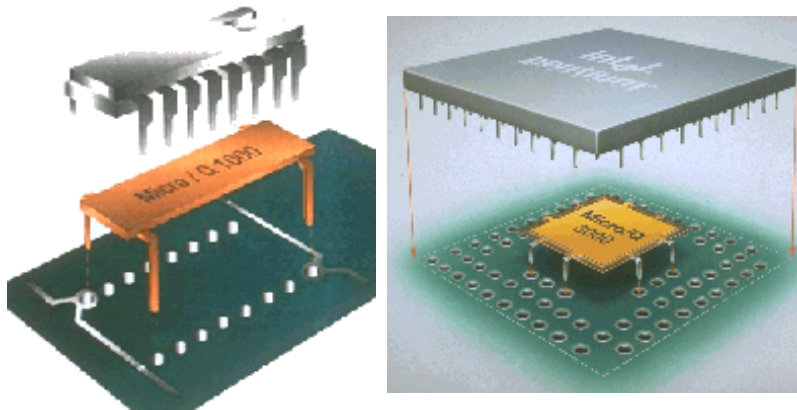
The Effect of Lead Length, Capacitor Type, & Layout on Bypass Capacitor Effectiveness



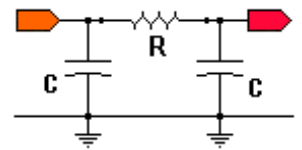
In this example, bypassing becomes more effective as the ground conductor approaches a continuous plane. Ground planes are often used in high-frequency circuit boards for this reason.



In these illustrations bypass capacitors are built in as part of the IC socket.

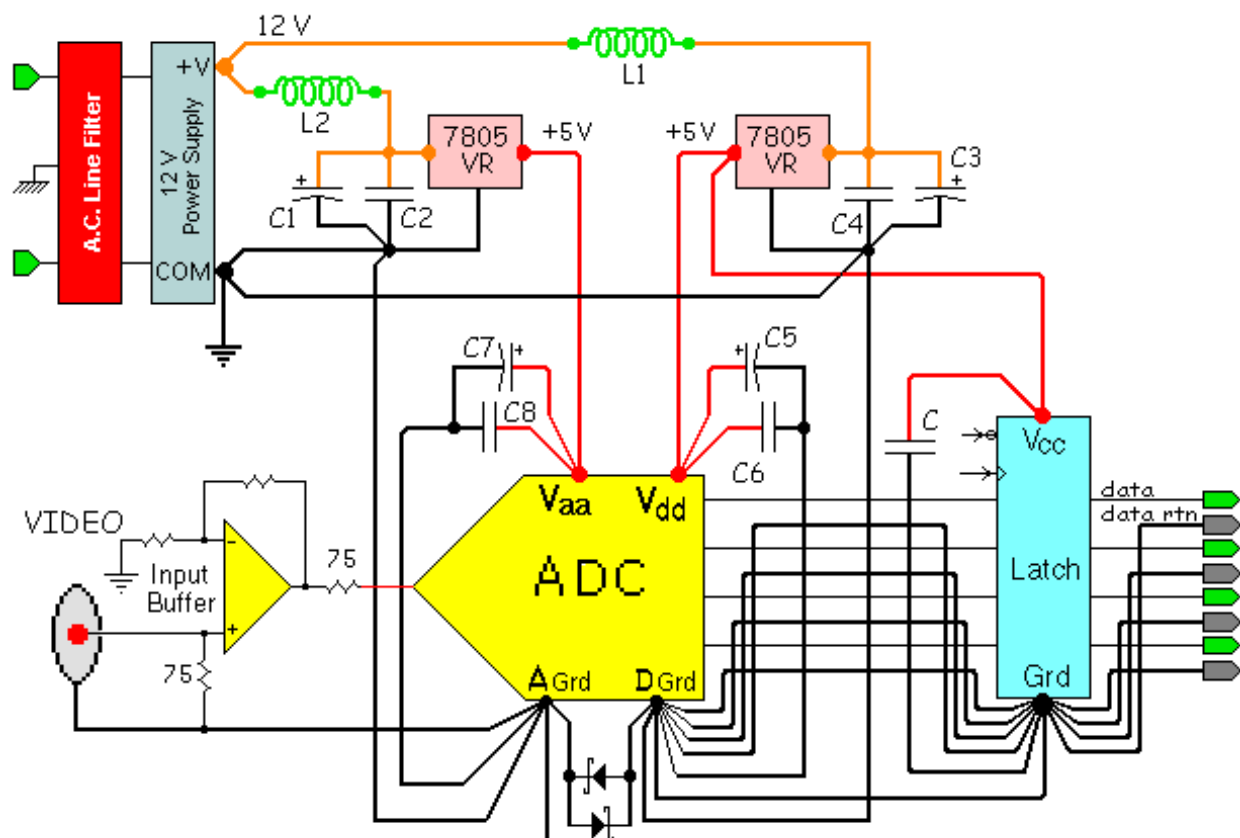


These illustrations show decoupling power distribution and bus bars.



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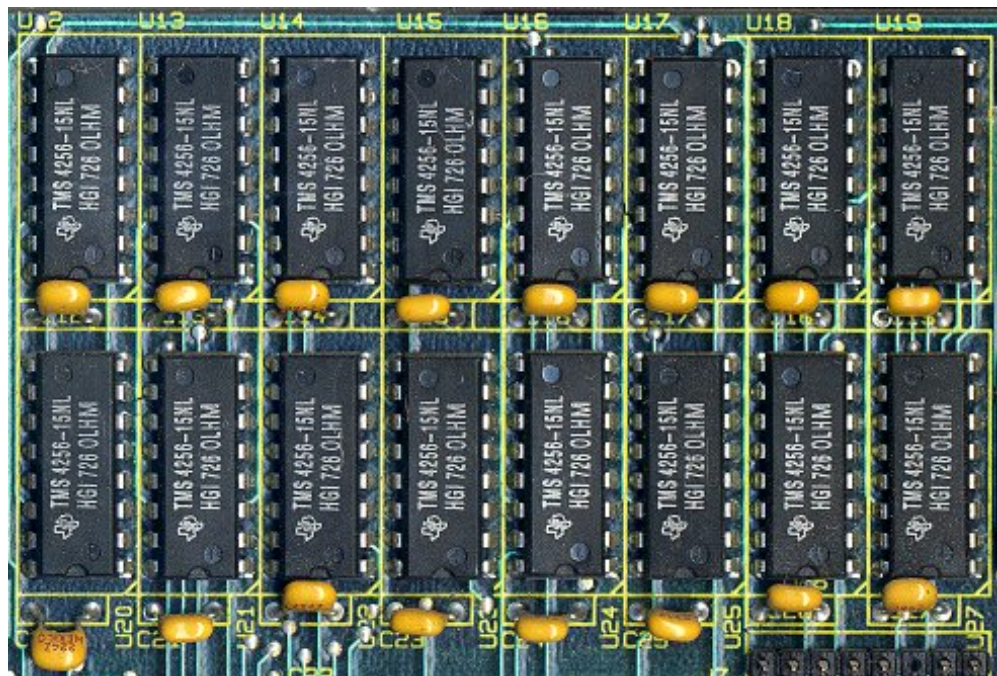
Powering both Analog and Digital



In addition to bypassing, there are instances where decoupling is appropriate (especially when powering both analog and digital from the same power supply).

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Memory Chips with Bypass Capacitors



(Note: one per device.)

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Decoupling Defined**Decoupling**

An element that is a loss-less path for direct current and an infinite impedance for alternating current. This element allows devices to be powered with no loss and prevents any noise from moving from one load to the next.

[back to top](#)**Introduction**

Although bypassing and decoupling are rarely covered in the classroom, they are emphasized in nearly all data sheets and application notes.

So while some new engineers and technicians ignore these topics, they do so at their peril. Failure to address these topics is often the reason for hardware debugging problems!

[back to top](#)**What Is Decoupling?**

Decoupling is a refinement of bypassing. Because of bypassing's finite limitations in creating the ideal voltage source, the decoupling (isolation) of adjacent noise sources is often required.

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Decoupling prevents unwanted communications between different devices (or different stages of the same device) that share the same power rail. Decoupling reduces the noise present on that power rail, at all frequencies.

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How Do We Decouple?

Decoupling completes the implied "RC" (LC) part of the network: the series element (as in a lowpass filter).

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Definition: Ideal Voltage Source

Ideal Voltage Source

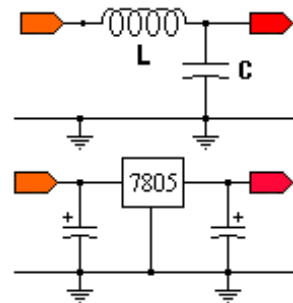
Furnishes a constant voltage output, regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

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Methods of Decoupling

Classic decoupling (see figure at right) uses an "LC" network (lowpass filter).

A not-so classic method of decoupling, uses a voltage regulator in place of the LC network (see figure at right).



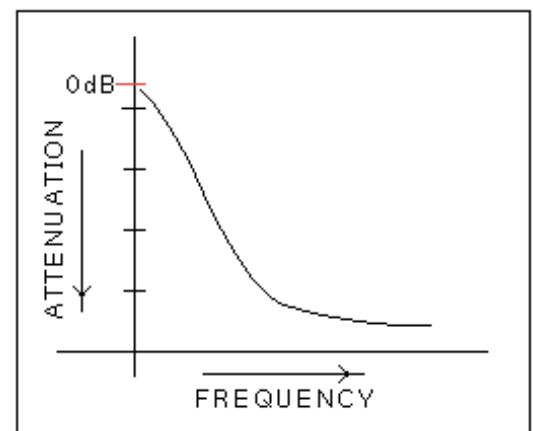
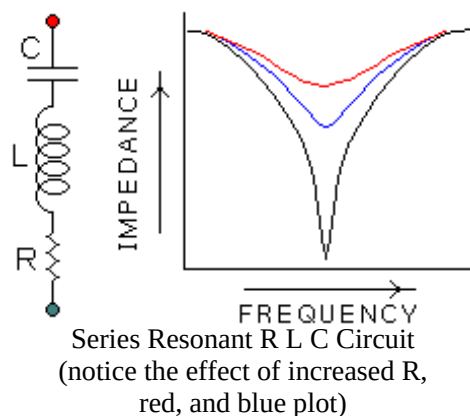
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Something to Remember

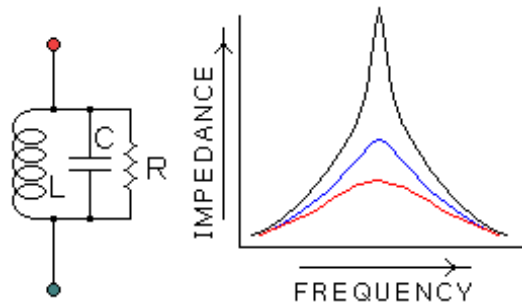
The ideal decoupling device is a loss-less path for DC, and an open circuit for AC.

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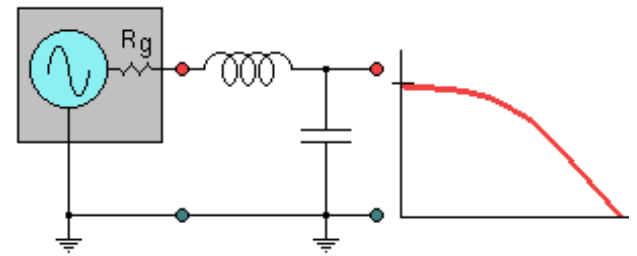
R L C Filter Refresher



Noise Attenuation of
Decoupling and Bypassing



Parallel Resonant R L C Circuit
(notice the effect of increased R,
red, and blue plot)



Low Pass Filter
= Decoupling and Bypassing

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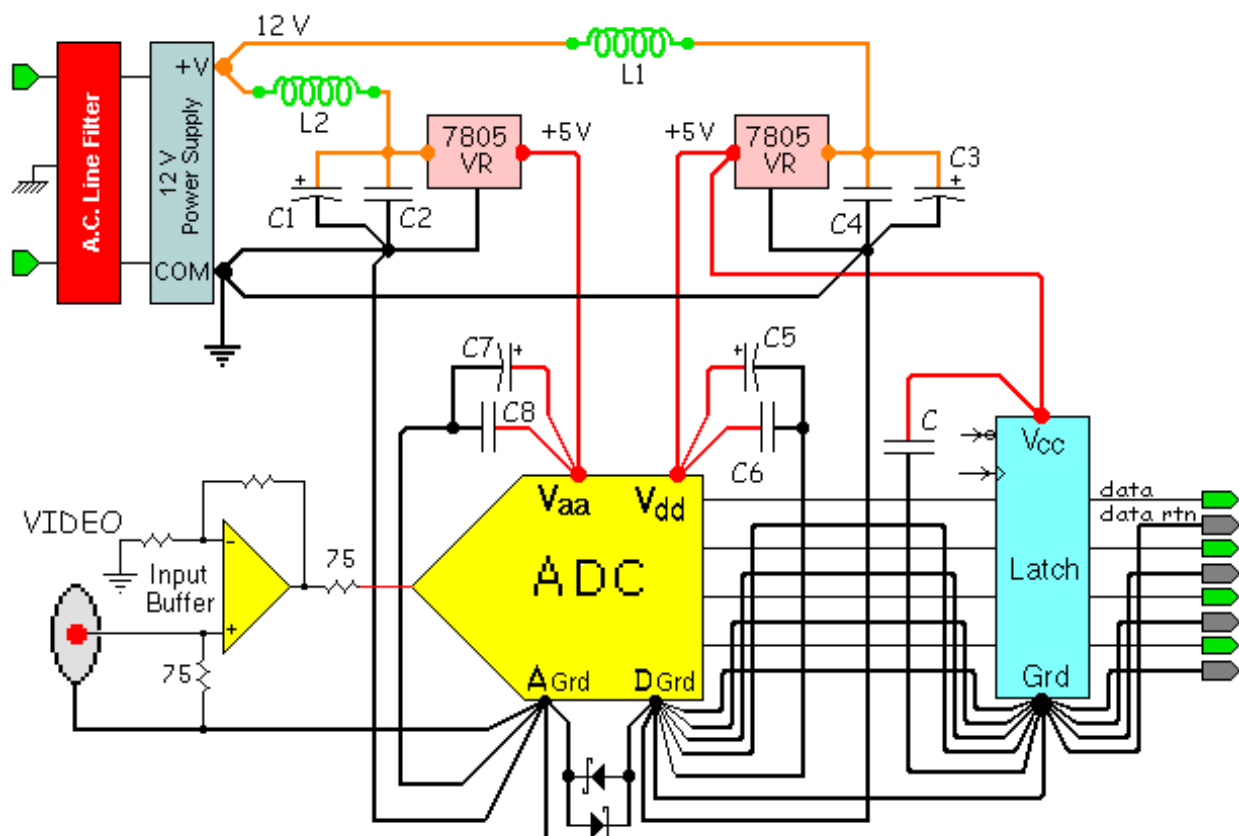
Discussion: What If?

What if the power distribution between stages cannot be sufficiently bypassed? You might be tempted to use several different power supplies. However, by supplying the DC power to each stage through a separate inductor or "RF choke," while also bypassing that stage to ground, the effect can be nearly the same. That is to say, the choke offers a high-impedance path to any errant signals or noise between stages, while offering a very low resistance path to the DC power. This is decoupling.

Active devices such as voltage regulators can also be used for decoupling stages. In fact, considering the size of inductors as compared to surface-mount voltage regulators, regulators might be the better choice. Recall that a choke or inductor is one of the two needed components for a Resonant circuit. Therefore, the combination of decoupling inductor and bypass capacitor could just happen to resonate at the wrong frequency. Having said that, it might appear obvious that the inductor needs to be as small a value as is reasonable, and the bypass capacitor as large as practical. This fact is essentially correct; however, there is still the possibility that the resonant frequency of this combination could cause mischief. If that weren't enough, the inductor can be self-resonant. This problem is caused by the distributed capacitance between windings; i.e., one turn of wire to the adjacent turn of wire, and so on.

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Powering both Analog and Digital

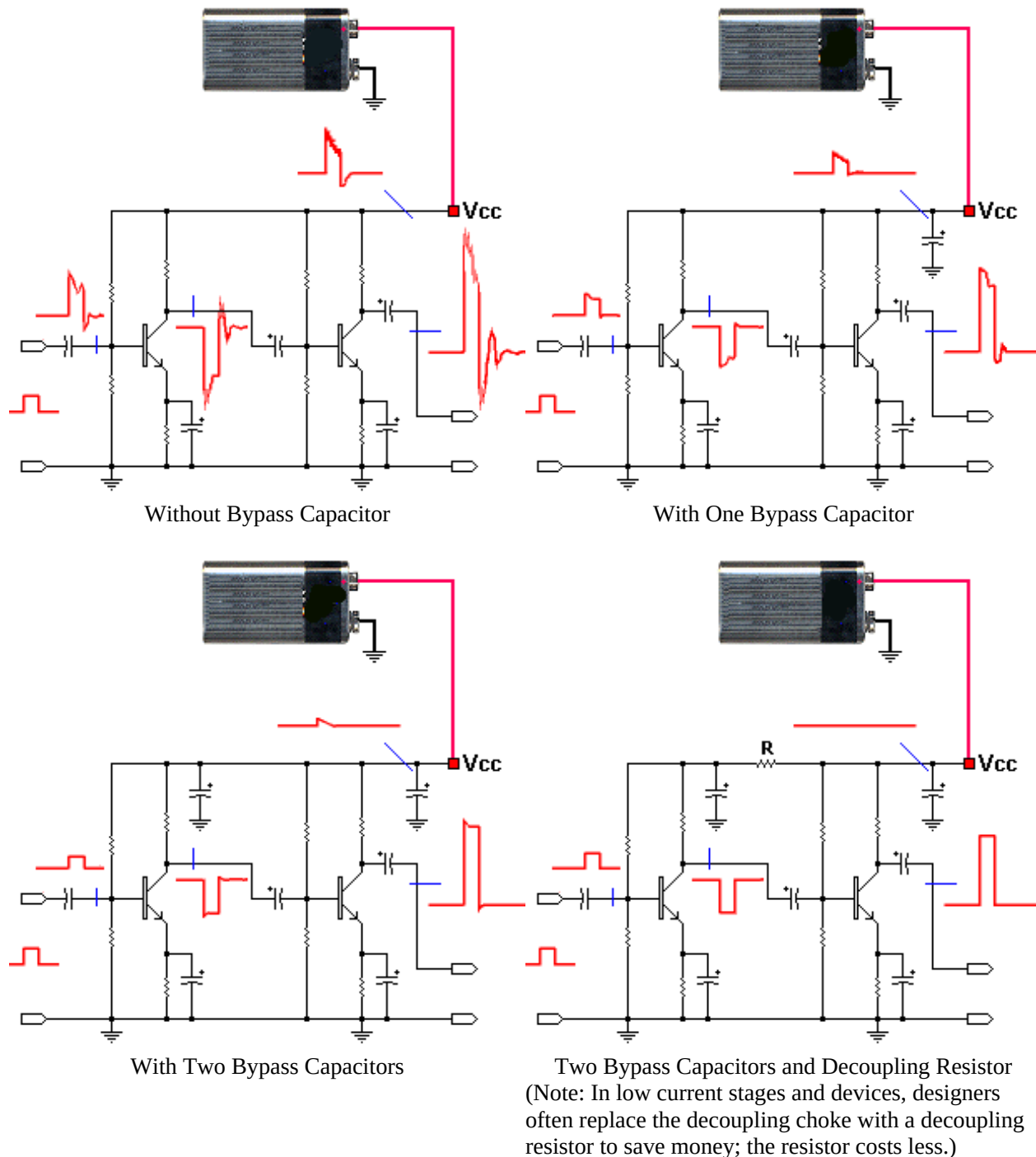


The figure above shows that sometimes both types of decoupling are appropriate. This is especially true when powering both analog and digital from the same power supply.

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RC Amplifier

The illustration below shows an RC amplifier with various degrees of power supply stabilization in the form of bypass and decoupling.



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Discussion: Some Reasons

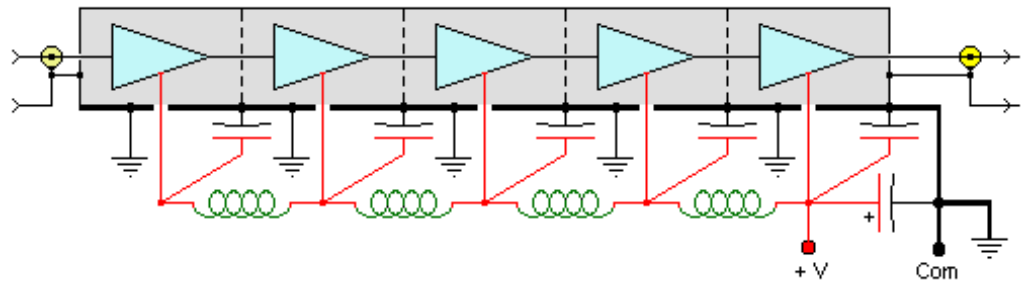
Bypassing, decoupling, shielding, and groundplanes are the elements that allow circuits -- analog and digital-- to function properly. The reason is simple. Let's say you have a cascade of amplifier stages such as the one illustrated in the next section. The stages are boosting or amplifying an otherwise weak signal. The input is very sensitive to small signals, and successive stages are drawing progressively more current in order to produce the larger replica of this weak input signal. In doing so, the output stage draws large amounts of

current at varying rates. This large varying current is seen by the more sensitive input stages through the common power supply rail, which serves all stages. This situation can happen if the power rail, be it wire or PCB traces, is of sufficiently high impedance.

Even if the power supply were ideal (zero ohms), this can still happen. As the frequencies go higher, the inductive reactance, of the leads or PCB traces, increases. For example, if some fast transitions of the input signal caused a resulting perturbation on the power supply rail to propagate down that rail to all of the other circuits, the resulting effect can be oscillations (or some sort of instability) that could cause distortion or even render the circuit inoperative. Think of the effect as inappropriate feedback between stages, facilitated by the power rail not appearing as a virtual AC ground.

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Cascaded Amplifier



The figure above illustrates a bypassed and decoupled cascaded amplifier, with distributed power to cascaded amplifier stages (in essence, a "n" order lowpass filter).

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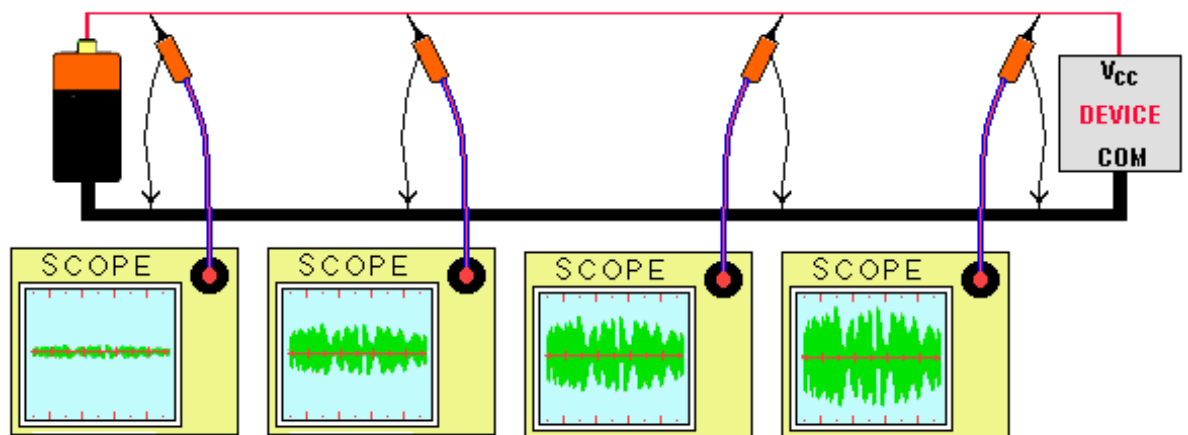
Recap

Intrinsic inductive reactance (X_L) in power distribution.

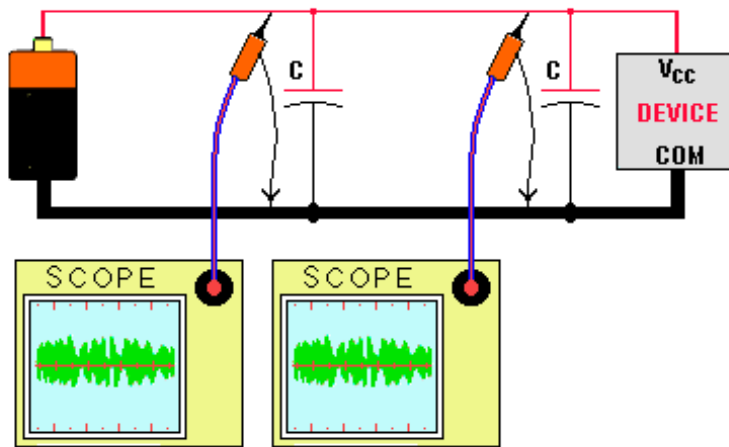
Ideal Voltage Source

The ideal voltage source furnishes a constant voltage regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

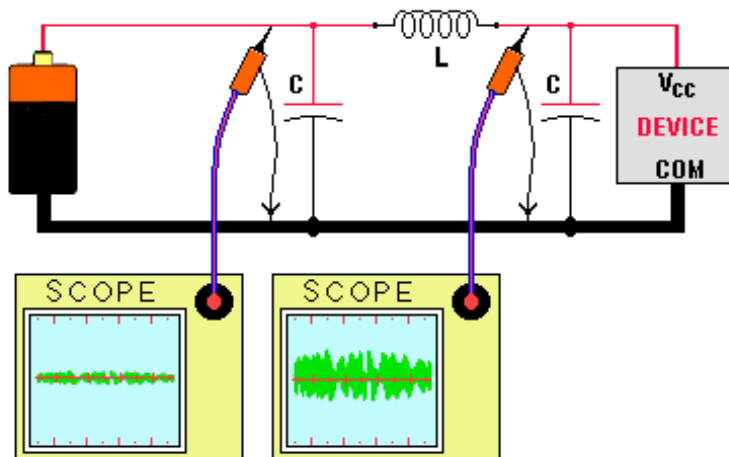
Power Rails



In the illustration above, the "intrinsic" inductive reactance (X_L) of the finite length conductors affects this zero ohms impedance.



Adding bypass capacitors to the intrinsic inductive reactance helps to restore the (virtual voltage source) zero ohms impedance.



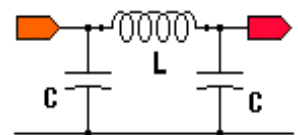
Adding even more inductance in the form of a "decoupling inductor" isolates the bypassed device(s), further helping to restore the (virtual voltage source) zero ohms impedance.

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Discussion: High Q

One more thing to consider about chokes: the "Q" (quality of the inductor) has an effect on its efficiency. As previously stated, the inductor should appear as a perfect path to the DC power it is carrying and a high impedance to any AC (i.e., no series "R."). But in the real world this isn't feasible. If heavy-current-carrying chokes are required, then the choke must have higher Q (i.e., less wire which means lower "R"). This can be achieved by using chokes with ferrite cores, which need considerably less wire for the same value of inductance. The core can be viewed as a multiplier of Q. Small donut - or tubular-shaped ferrites called beads are regularly slipped over leads to act as decouplers. One popular use for ferrite beads is to suppress parasitic high-frequency oscillations in circuits where the gain device (such as a transistor) has significant high-frequency gain.

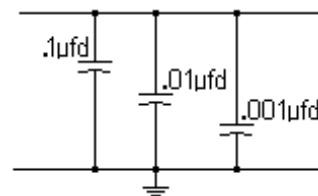
1. One of the most efficient inductors is the ferrite toroid. It has high Q (low R). Because of its toroidal shape, its fields are confined, which minimizes its interaction with other circuit elements.
2. There is always some decoupling built into any circuit. The power conductors act as decoupling inductors. Although short trace lengths are usually desirable, longer ones sometimes actually improve decoupling. However, don't forget that long ground traces or conductors never help. They make effective bypassing impossible!
3. The down-side of ferrite is that it will change inductance as the current or flux changes. In the case of large currents, ferrite can saturate. However, by correct component choice -- frequency, AC and DC current, etc. -- ferrite is a great tool for the designer.
4. LC decoupling is used where the supply voltage cannot be lowered. For example, what if one needed a noise-free +12 volts on a PC bus? You could get a "clean" +12 volts with a voltage regulator; if only there was +15 volts or higher to start with. But this is not the case. So you use a high Q inductor



(RFC choke) along with the proper bypass capacitors to effectively lowpass filter the +12 volt supply rail. For a very noisy supply, you can use more than one network (one or more "pi" networks).

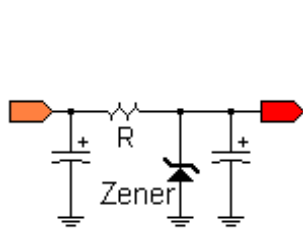


5. One of the most efficient inductors is the ferrite toroid. It has high Q (low R) and because of its toroidal shape, its fields are confined, and therefore it has less stray fields. The super star of high Q inductors or transformers is the pot core. Also, don't forget the ferrite bead. Thread the wire through the bead once or several passes and it may be just what the doctor ordered.
6. Decoupling is only as good as the components that you use. The capacitor part of the network should be of high Q and minimum inductance. The noise is dropped across the inductor, and the capacitor must exclude the remaining noise. In a perfect world the inductor is an open circuit to noise (AC) and the capacitor is a dead short -- Zero, Nada, Caput, Zilch. The slightest inductance in series with that capacitor, and some very high-frequency noise will come through like Gang Busters!
7. SMT or chip capacitors made of ceramic are best. Sometimes in critical circuits, several sizes of capacitors in parallel are appropriate, e.g., $1\mu\text{fd} \parallel .1\mu\text{fd} \parallel .001\mu\text{fd}$, etc. The reason for this is that as the capacitors become smaller in value, they also get physically smaller, hence there is less inductance. However this is less the case with SMT caps. Consult your capacitor data sheets for the impedance verses frequency plots. ([See impedance verses frequency plots.](#))

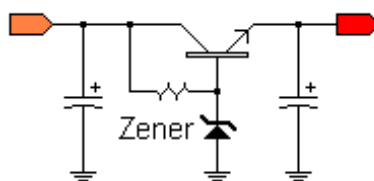


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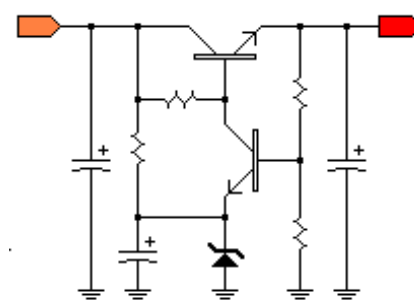
Linear Voltage Regulators as Decoupling Devices



Simple Shunt Regulator



Simple Pass Regulator



Pass Regulator with Gain

The use of three terminal linear voltage regulators, like the 78xx and 79xx devices, is fairly straightforward. However, there are a few things to remember. Always bypass -- there's that word again! -- the input pin to the common pin with a ceramic capacitor no smaller than $0.33\mu\text{fd}$, and use absolutely the shortest leads possible. (There are some transistors with pretty high f_t in that regulator, and if you furnish enough reactance of the wrong kind, Mr. Oscillation will visit.)

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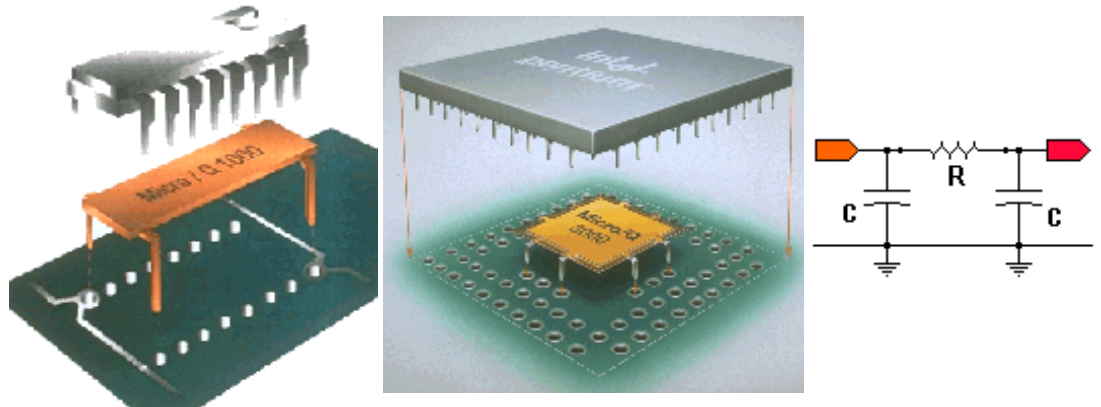
Points to Ponder

1. Unlike bypassing, decoupling is not always used. In fact, decoupling is typically used as a last resort if bypassing fails to give the wanted power-supply stabilization.
2. There is always some decoupling built into any circuit. The very inductive reactance bypassing is meant to overcome are the power conductors. In essence, these conductors act as decoupling inductors. Although short trace lengths are desirable, the power lead being long can sometimes actually improve decoupling.
3. The simple addition of ferrite to these conductors enhance this natural decoupling inductance, sometimes eliminating the need for a special decoupling inductor.

4. The best all around decoupling device is in fact not an inductor, but a voltage regulator (especially the LDO or low drop out regulator).

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Bus Bars



Above are examples of "decoupling" power distribution bus bars.

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Glencoe/McGraw-Hill's *Electronic GOTCHAS EXPOSED***CIRCUIT INTEGRITY****■ Module 3: Groundplane**[Click here for a printable version of this page](#)

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Introduction

A groundplane serves as the return path for all currents. Like bypassing and decoupling, although the groundplane is a topic that is rarely covered in the classroom, it is emphasized in many application notes, and it is used in most real designs.

Again, the problem this creates is that many design engineers and technicians ignore it at their peril!

[back to top](#)**What Is a Groundplane?**

A groundplane is the return path for all currents, signal, and power.

[back to top](#)**Why Do We Use a Groundplane?**

It is desirable to not have different signals sharing the same ground return paths; the groundplane helps in that goal.

[back to top](#)**How Do We Use a Groundplane?**

A continuous conductive planar, having no discontinuities, is the ideal groundplane.

[back to top](#)**Discussion: An Overview**

A groundplane is a crucial component of any circuit. In essence, it is the return path for all signals, including the power distribution. The groundplane can be thought of as homogeneous for the DC power only. In all other situations, it is strictly inhomogeneous, which means strictly that all grounds are not the same.

Various circuits use the ground plane for their signal and power return paths. Thus currents conducted and induced are caused to flow throughout the groundplane. Such currents can potentially affect any or all other circuits or signals, and thus they can cause problems.

One can start to understand the function and design of groundplanes by completing the following:

1. Draw a map of all signals in a circuit, their inputs, outputs, paths, and their various connections to and from the groundplane.
2. Then model the inductances, capacitances, and parallel and series resistances. Note the power distribution

- paths and returns, and their respective noise content.
3. Remember all bypassing and decoupling devices and contributions of each to the model.
 4. Since the groundplane is mostly inductive, take note of any other inductances' proximity to the groundplane (such as shields, transformers, chokes, tuned circuits) and their contributing fields at all relevant frequencies.

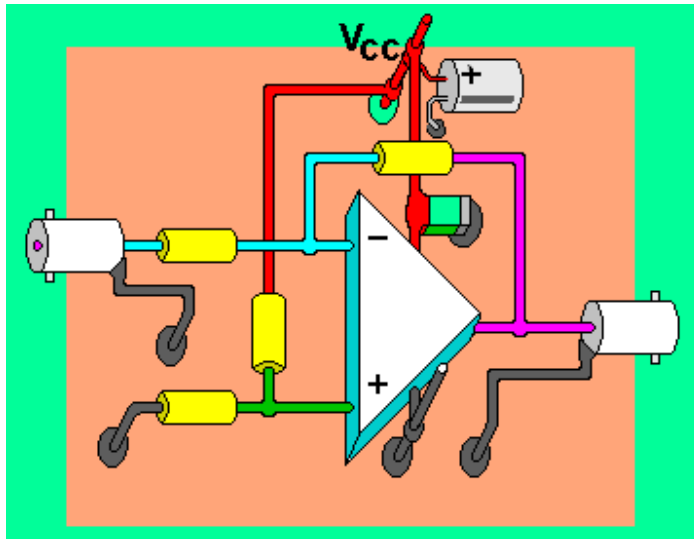
It has been said, "There are only two ways to model the groundplane in a complex signal environment, and nobody knows what they are!"

Good Luck!

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Something to Remember

All grounds are not the same.



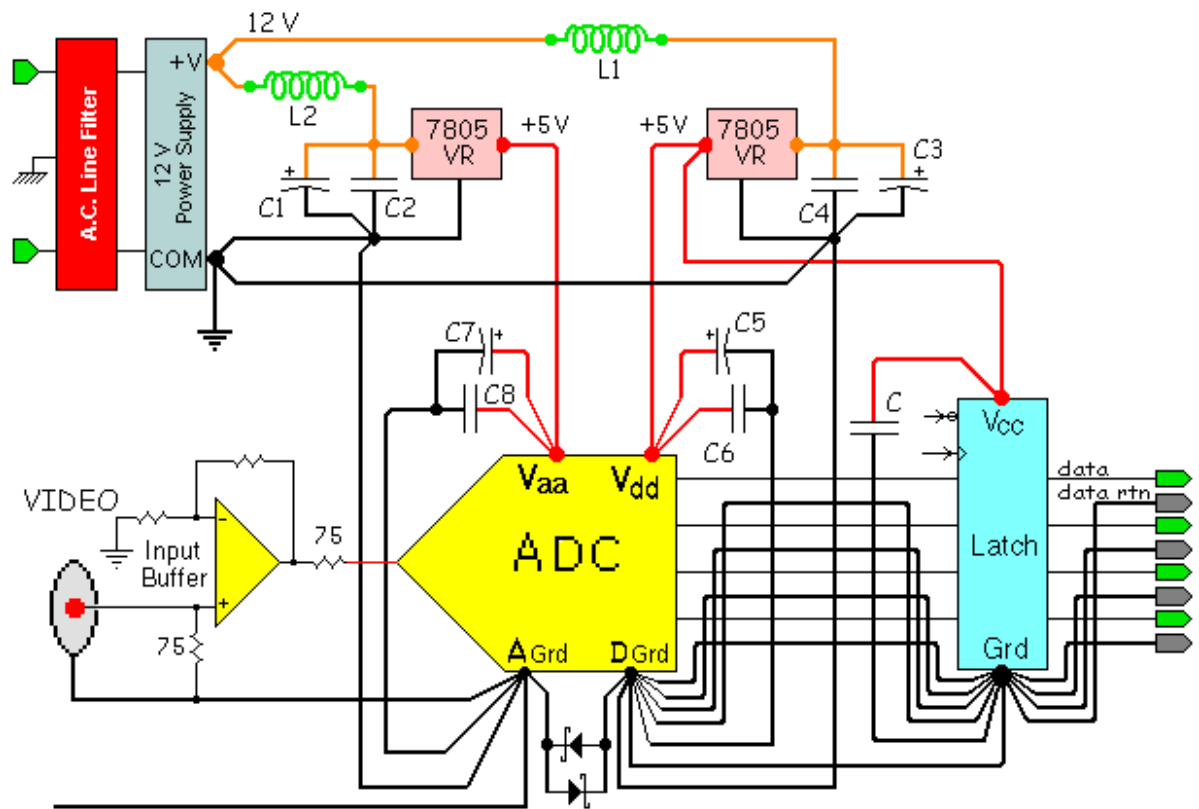
This illustration (left) shows an op amp using groundplane for all return currents.

A groundplane in action!

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Return Paths

The illustration below shows a DC layout, functional diagram power and ground, and signal distribution.



Please notice that schematically, every signal has its own ground return.

In an ideal ground return system, every current has its own separate return path and does not share return path copper.

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Demo: Return Currents in a Groundplane

This groundplane demo uses an audible square wave with fast rise and fall times. the wave is commutated (or keyed) at a slow rate such that it is a Morse code A (dit, dah), and its complement is a Morse code N (dah, dit).

Because A and N are complements of one another, if both signals were summed using equal weights, there would be a continuous tone. If either signal were stronger or weaker than the other, there would be a (faint) A or N with a continuous tone in the background.

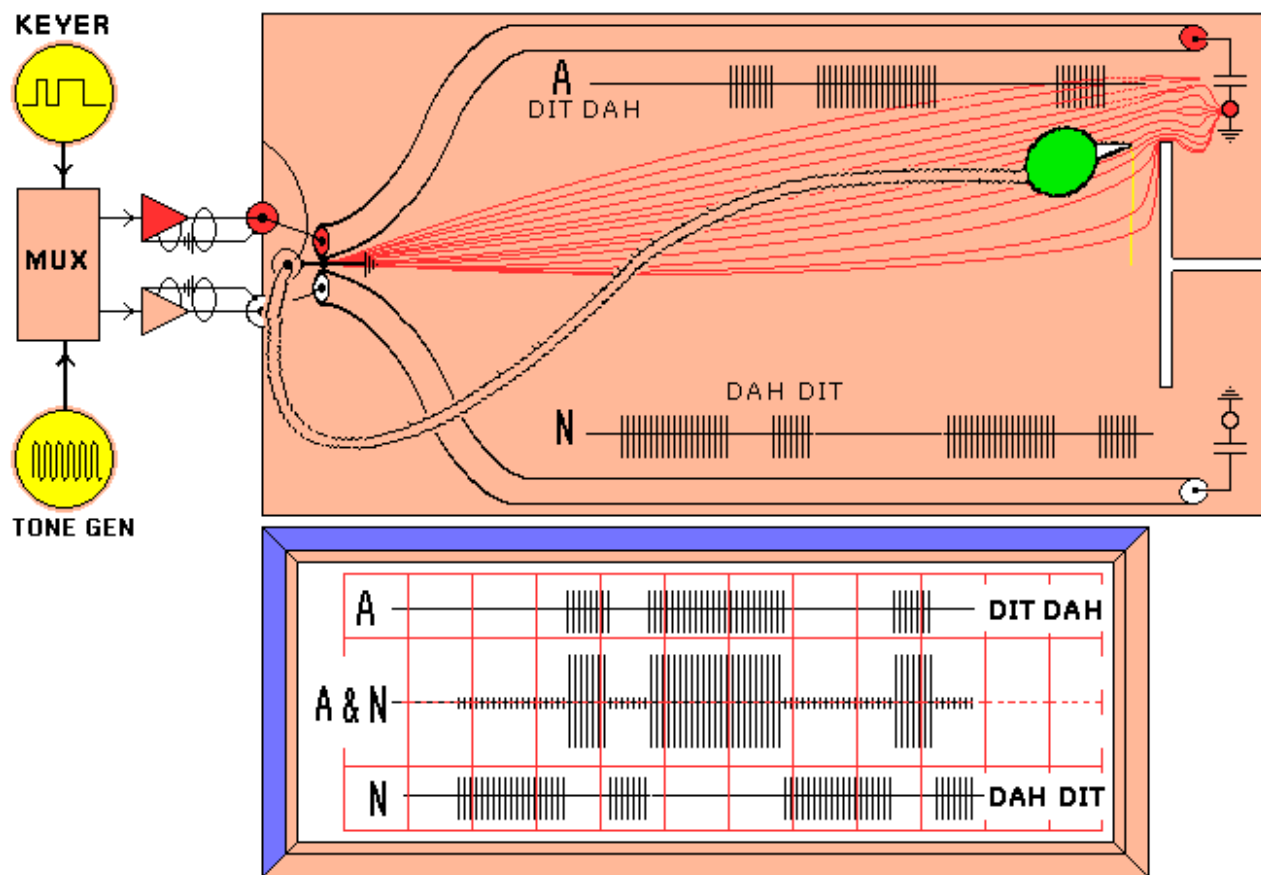
Both signals are amplified and drive onto the groundplane at adjacent corners, forcing the return currents to travel through the groundplane, the shortest distance. (See drawing.)

In the demo, a signal tracer (green probe) is moved across the groundplane. The tracer senses the return currents in the copper-clad groundplane. At either extreme, the Morse code A or N is clearly heard. At mid point, the two signals are of equal levels and appear as a continuous tone.

[Hear](#)  [A and N](#) [Hear](#)  [real A and N](#)

(Demo not synchronized to animation)

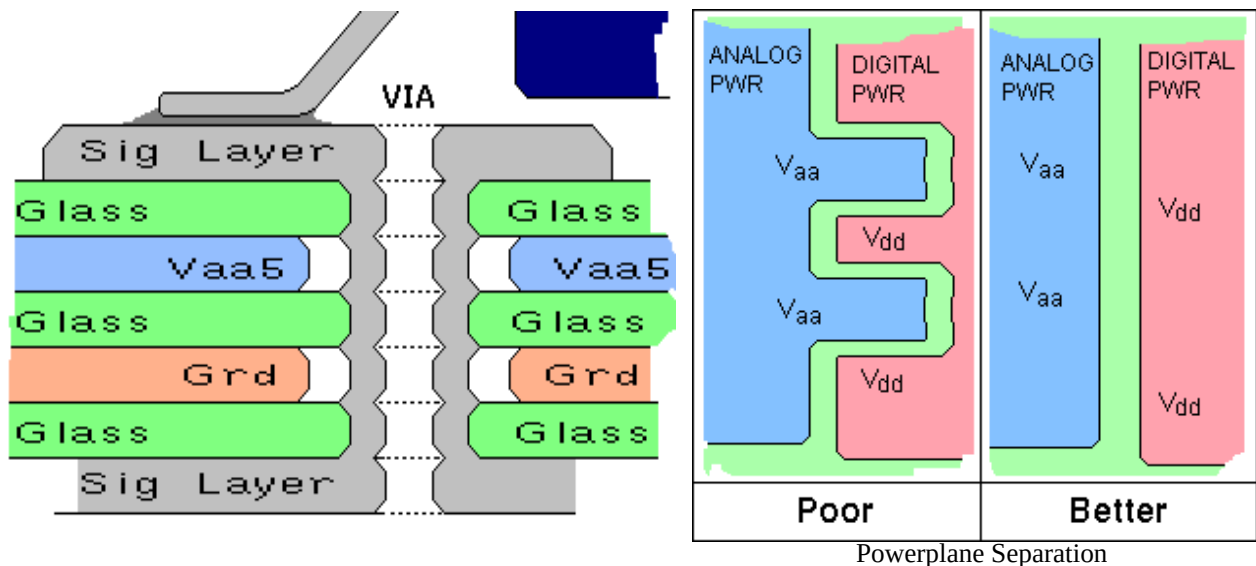
To start the animation, hit your browser's reload button.



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Groundplanes and Powerplanes

Multi-layer printed circuit boards allow for the use of powerplanes and groundplanes.



The use of multi-layer printed circuit boards allows the use of multiple ground planes, as well as buried (under the signal layers) power and ground (V_{cc} and Gnd) layers. These layers are sandwiched together and act as a very efficient distributed bypass capacitor. A variation of this has the power and ground (V_{cc} and Gnd) layers as the outer or intermediate layers, thus shielding the buried signal layers; or some combination thereof. [See EMC](#)

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Resonant Groundplane

The less homogeneous these planes are, the more difficult it is to maintain the circuit's integrity. There can be myriad circuit parasitics (resonant tuned circuits, etc.), especially in the groundplane.

As it turns out, a homogeneous plane (e.g., a shield, etc.) could be placed over the less homogeneous groundplane, these resonant circuits could be made less detrimental. (See the resonant groundplane demo that follows this section.)

In the real-world printed circuit board above, these parasitics can be reduced by the proper placement and layout of the powerplane(s). That is to say, the close proximity of the co-plane reduces the parasitic inductances while raising the resonant frequencies. This lowers the overall groundplane impedances. Also, the shunt "R" diminishes the "Q". --All of which is GOOD.

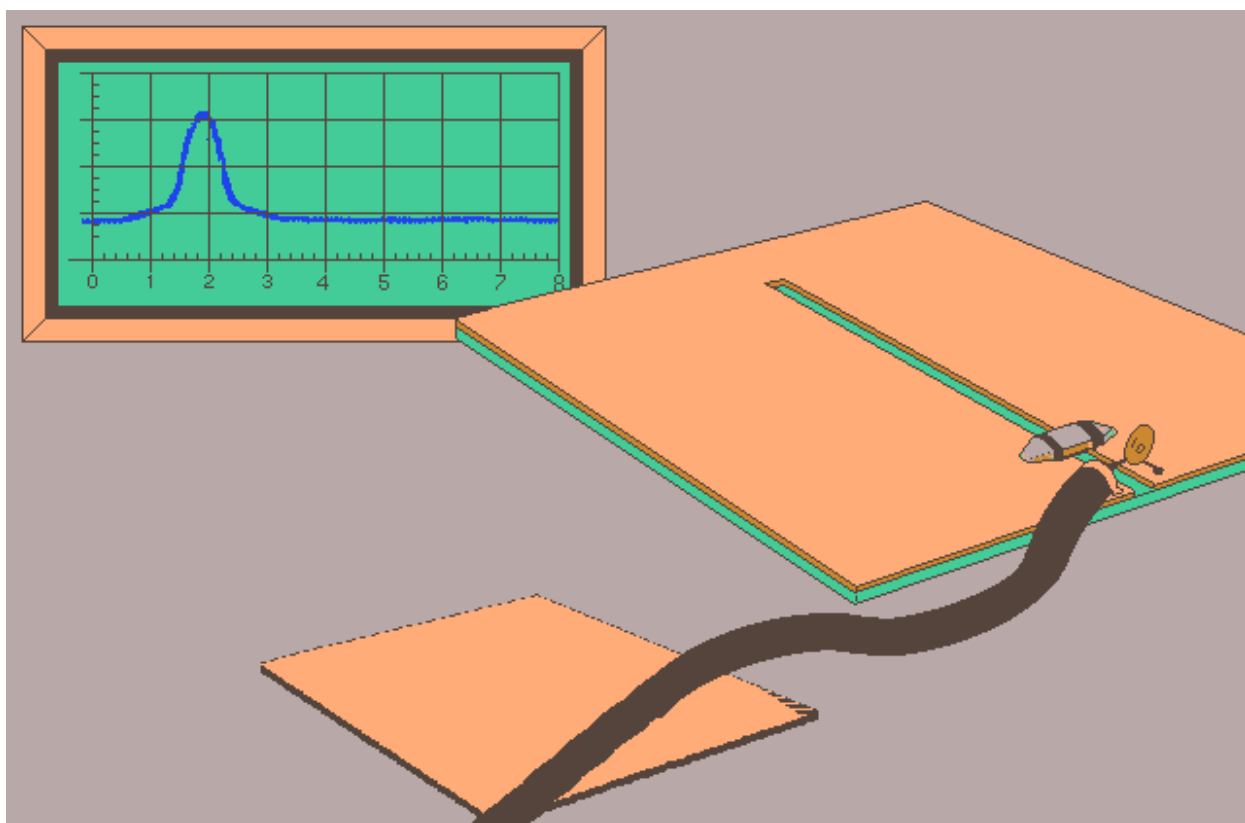
Parallel inductors = less inductance

So far, we have discussed a simple example of what can be a very complex problem. It is also possible to have a non-homogeneous groundplane (many apertures) with many different return currents from many different devices running at various rates; having rise and fall times from a few nanoseconds, to fractions of a nanosecond; with all currents sharing the groundplane as their return paths.

This situation can give rise to device oscillations and instabilities, generating noise and crosstalk. This effect is due to the imperfect AC grounding of active devices, and the many parasitic reactances that inhabit the circuit and board topology. This complex environment could, I suppose, be analyzed and the "tuned circuits" identified. --you get the idea.

The use of good groundplane design is important, especially in a mixed signal environment, analog and digital. The next figure shows an experiment that I call a "resonant groundplane."

In this example, the animation shows a 4" X 6" copper clad board. A narrow (1/8") strip of the copper cladding was peeled almost the length of the board, such that electrically it looked like the letter "U." A 0.33 μ fd capacitor is soldered at the edge of the board where the peeling began, bridging the planes on both sides of the narrow gap. Then both sides are driven (the capacitor is shunting) with a loosely coupled sweep (signal) generator and adjusted until the resonance is found. The display presentation is of a swept network having a definite resonance. A separate homogeneous groundplane is then brought into close proximity. This causes the resonant frequency to increase, as well as causing the "Q" of the resonance to diminish.

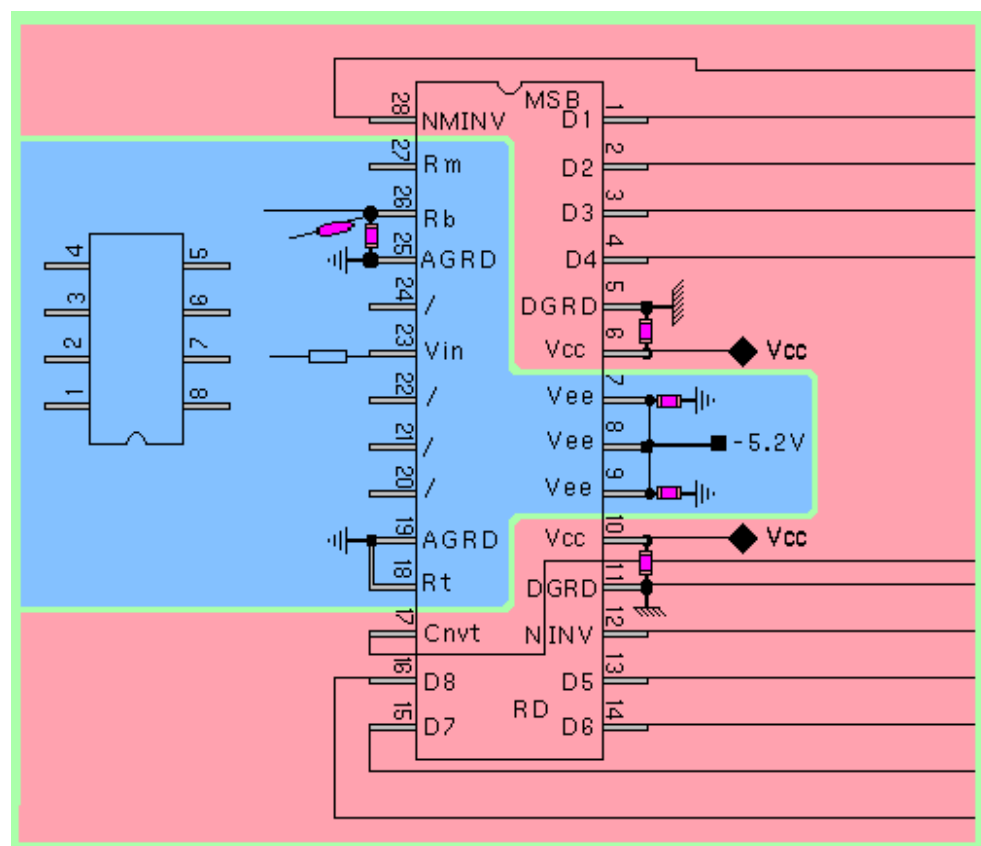


The animation is of a resonant groundplane where a second groundplane (or shield) is brought into proximity. You can see the effect on its resonant frequency.

The point of this is that a good groundplane design should have as few apertures as is practicable. Where apertures are unavoidable, shielding or a secondary parasitic groundplane can ameliorate the effect.

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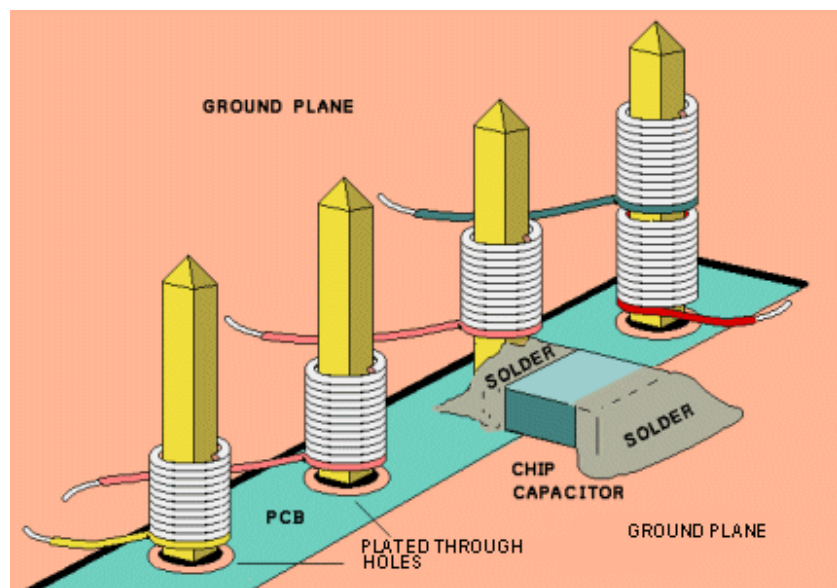
Analog and Digital Groundplanes



Above is an example of a mixed signal layout, AD-9020 ADC.

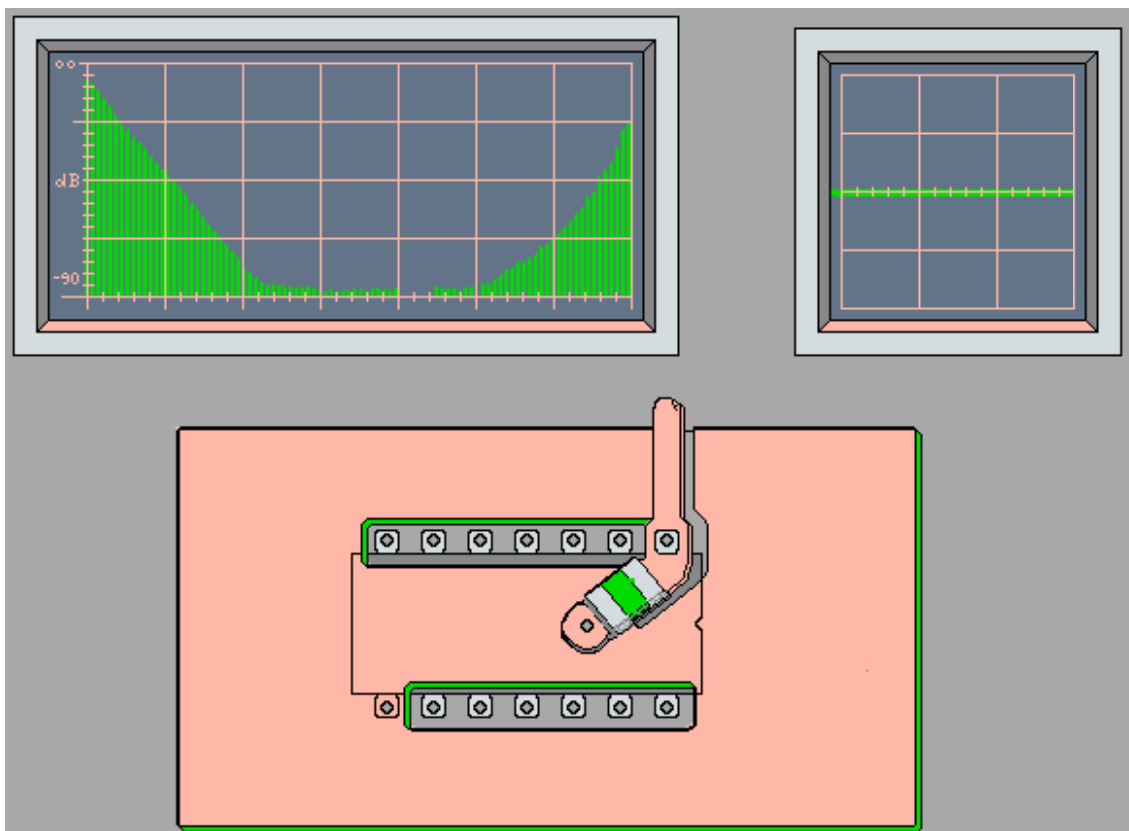
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More Groundplane Examples



Frequency Domain

Time Domain

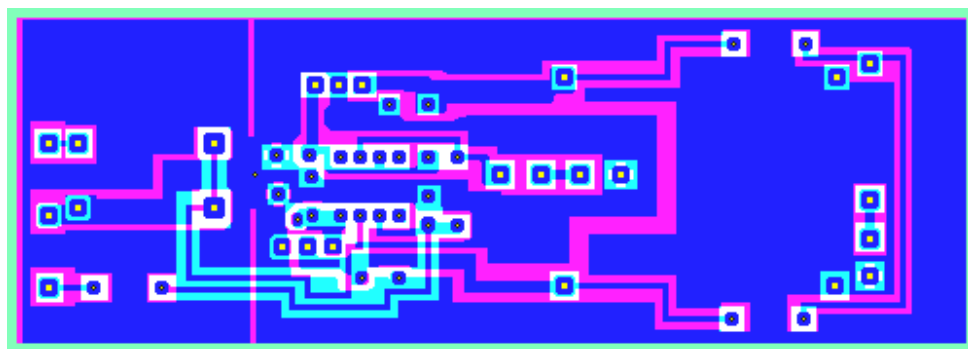


Note how bypassing becomes more effective as the ground conductor approaches a continuous plane. Groundplanes are often used in high-frequency circuit boards for this reason.

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Circuit Board Layout

Below is an amplifier example.



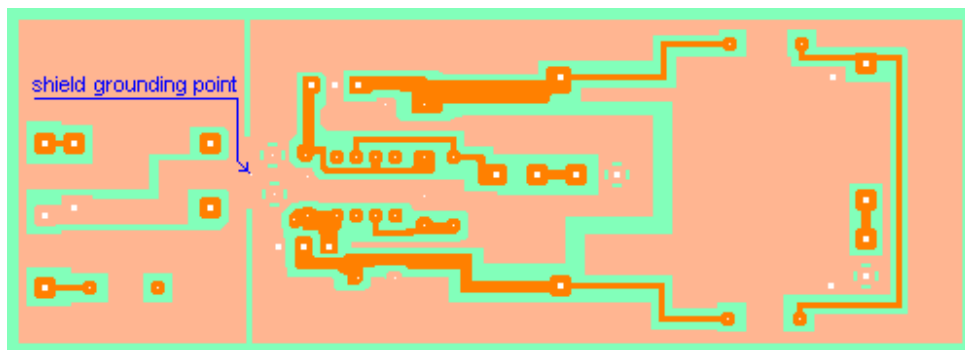
CAD Drawing

Signal Input

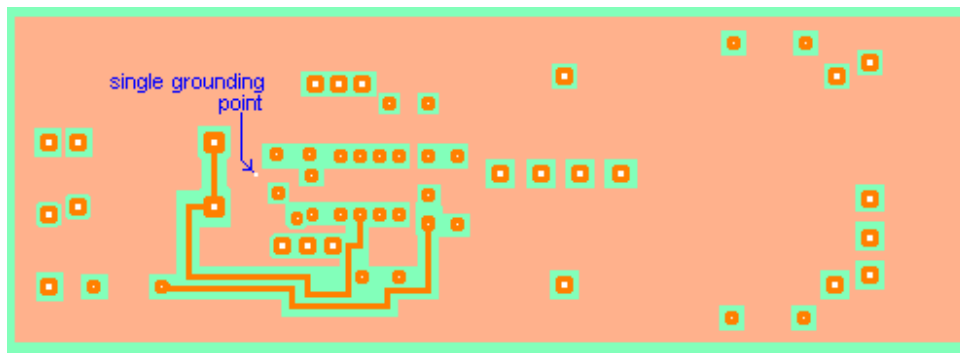
Circuit

Signal Output

Power Input



Groundplane Side



Shield Side
Note the single
grounding
(reference) point.

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Glencoe/McGraw-Hill's *Electronic GOTCHAS EXPOSED***CIRCUIT INTEGRITY****■ Module 4: Shielding**[Click here for a printable version of this page](#)

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- [Real-World Applications of Shielding](#)
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Introduction

A shield should have no currents flowing through it!

As with bypassing, decoupling, and the groundplane, shielding gets little coverage in the classroom, but it is emphasized in many application notes, and used in many real designs!

Again, because of this many design engineers and technicians ignore it at their peril!

[back to top](#)**What is Shielding?**

A shield is a blocking or containing barrier against electrostatic fields.

[back to top](#)**Why Do We Use Shielding?**

In a circuit or system, there are many discrete signals directed to specific destinations only. Often these signals can interfere with other unintended signal destinations or devices. Shielding can prevent or diminish this interference effect.

[back to top](#)**How Do We Use Shielding?**

Like a groundplane, a shield can be constructed of one or more conductive homogenous planars. However, the shield differs from the groundplane by its need to be free of conducted or induced electrical currents.

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Shielding

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The Glencoe McGraw-Hill logo, featuring the company name in a red and black box.

Shielding can be accomplished using anything from a coaxial or shielded cable, to a sealed conductive chamber for circuit isolation. Shielding also has reciprocal purposes. It protects the circuit it is shielding from outside noise or unwanted signals. Conversely, it contains its own signals and thus protects the outside world from interference of its own making.

Shielding is used mostly to block electrostatic or "E" fields (Faraday shield). However, if ferrous metal is used (tempered Mu metal works best for magnetic fields), then both electrostatic shielding and some level of magnetic shielding is accomplished.

Shielding is especially useful where open frame transformers or unshielded coils are used, in cases where these would otherwise exchange signals by mutual inductance.

Fortunately, the magnetic component of the (interfering) signal diminishes as the cube of the distance. That is, for any high-frequency signal the dominant component beyond $\sim 1/6$ wavelength is electrostatic. This fact is referred to as near field and far field radiation. ([See Figure below.](#))

Ideal shields have no current flowing through them. Ideally they are grounded, or referenced at only one point.

For a shield to be effective, there must be no currents flowing through the shield itself. This is best accomplished by connecting the reference or common to only one point on the shield, thus preventing any current flow. The reason for this is that any current flowing in the shield material itself can produce secondary fields on the other side of the shielding material, and therefore reduce the effectiveness of the shield. An example of this might be a shielded cable, where the shield has a different potential at each end. The resulting current flows in the shield, inducing unwanted noise into the center or shielded conductors, as well as to the outside world. In this situation one might try to find a remedy by disconnecting one or the other ends of the cable's shield. However, this fix may not prove satisfactory in certain environments, and may require a "Guard" potential, or better still, optical isolation.

Active Shielding

In active shielding, fields of counter EMF (equal but opposite) are generated to cancel-out the offending fields. A good example of this is an AC power transformer, where a shorted turn is used to generate a nulling field.

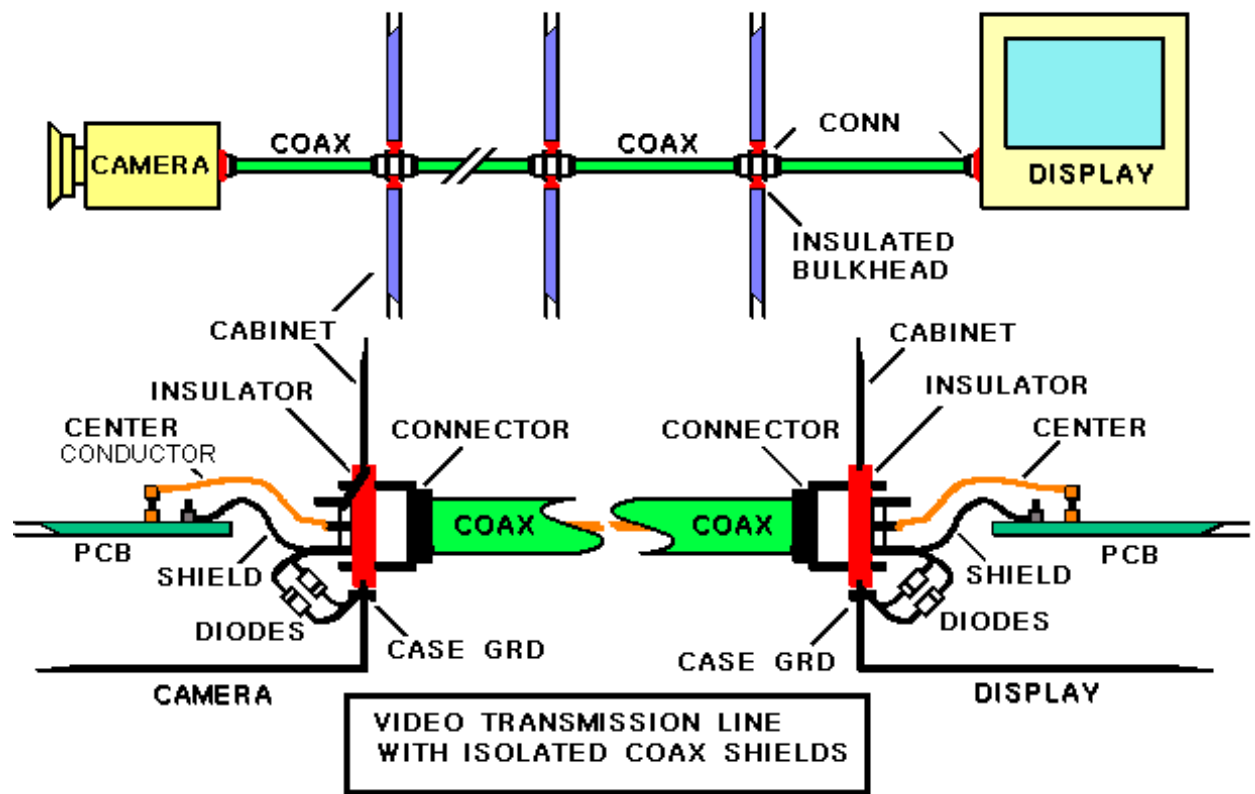
The shorted turn is a seamless band of copper that wraps the transformer core in one direction. When cut by the rising and collapsing magnetic flux -- caused by the transformer action -- the shorted turn acts as a very low-impedance, high-current secondary winding. This generates a counter EMF. Because this winding is shorted, it generates a rising and collapsing magnetic field of opposite polarity, thereby nulling the original stray magnetic flux.

In some cases of severe common mode noise, the shield can be made to carry an equal (but opposite) noise current to counter the interfering noise. However, this fix is not for the faint-of-heart, because with any slight change of the mechanical or electrical parameters, the canceling noise becomes the noise.

Some power transformers use a Faraday shield between the primary and secondary. However, this is not a shorted turn. The current flow in a shorted turn is very high! The shorted turn would have to link only the leakage flux to be workable (in other words, the turn is around the outside of the magnetic core).

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Shielded Cable



Avoid extraneous currents in the coax shield. Maintain shield isolation.

By definition, the ideal shield has no current flowing through it. It is grounded, or referenced at only one point.

In the case of shielded cables, the shield is typically referenced or grounded at both ends.

In the case of coax cables, the shield acts as both the shield and the return current path for the signal carried on the center conductor. However, with a shielded-balanced differential pair (sometimes called twisted pair) the shield is just that – a shield. Often this shield can be grounded at either end. However, in the case of EMI suppression, grounding both ends is prudent.

Though coax and shielded twisted pair are used for both audio and higher frequency signals, there can be differing effects on how the shield is treated. The most difficult case is that of video, where both very low to high frequencies (~ 10 Hz to >4 MHz) are involved.

Audio run on coax is subject to "ground loop" noise. For example, dissimilar ground potentials (especially 60 Hz) can cause a noise current to flow in the shield, inducing that noise into the protected center conductor. As the frequency of interest increases and the coax gets longer, the ground loop problem is diminished. This situation is mainly due to the increased inductive reactance (higher Z) of the coax shield.

When long runs are required and/or the environment is noisy, it is best to use shielded twisted pair. The benefit of this is the differential pair's inherent rejection of common mode noise (CMR).

An extreme case might find a remedy in transformer coupling, or even optical isolation.

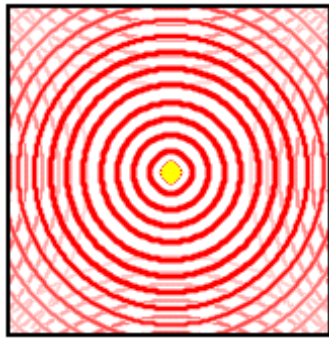
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Something to Remember

It will soon become apparent that shielding is a very popular strategy in EMC applications.

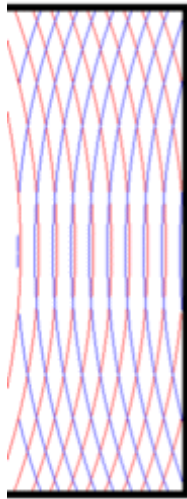
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Shielding Examples

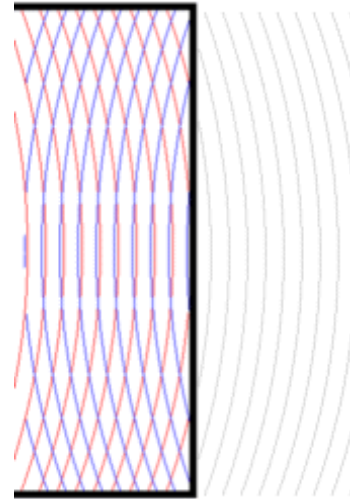


Example of "Ideal" Shielding
(no leakage)

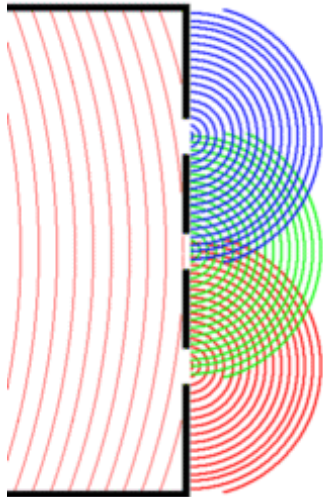
RF emitter inside a shielded enclosure.



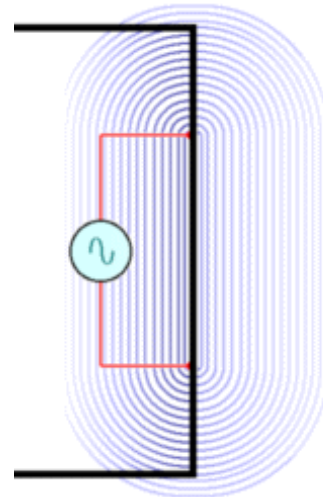
Shield Reflecting



Shield Reflecting
(with some "parasitic" radiation)



Leakage of Apertures in
Shielded Enclosure: Diffraction
(apertures act as point sources)



Driven Shield Radiating
(currents in shield create antenna effect)

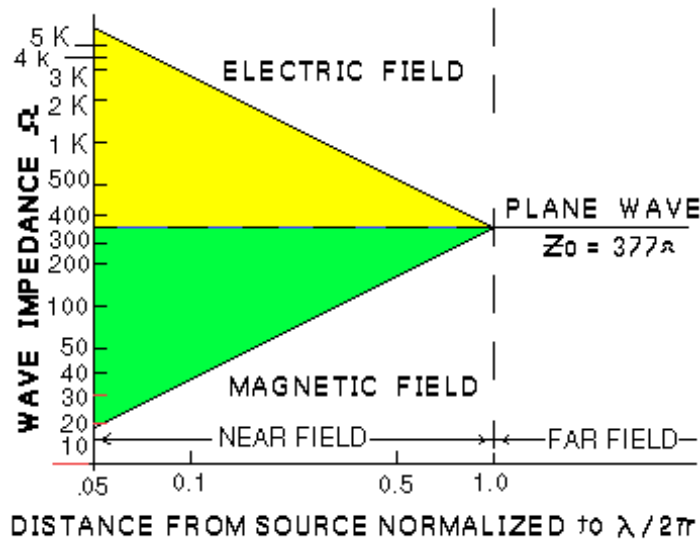
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Something to Remember

The area of an aperture is less important than its length—as in seams or joints. The rule of thumb is the maximum dimension of an aperture should not be greater than $1/20$ the wavelength of the highest frequency of interest. Such apertures can act as slot antennas.

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Near Field and Far Field Radiation



In dealing with a radiation source, whether it is an antenna or a circuit board:

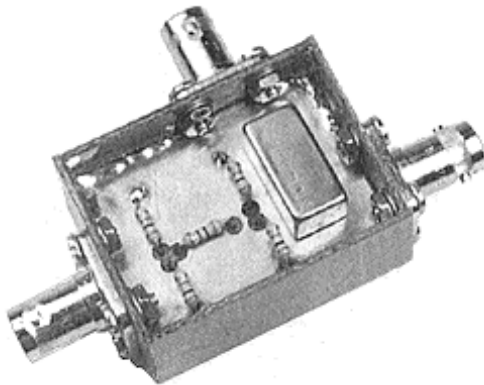
- The dominant energy in the far field is electric.
- The dominant energy in the near field is magnetic.

In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is electromagnetic. This is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic. It is referred to as far field radiation, sometimes called the plane wave.

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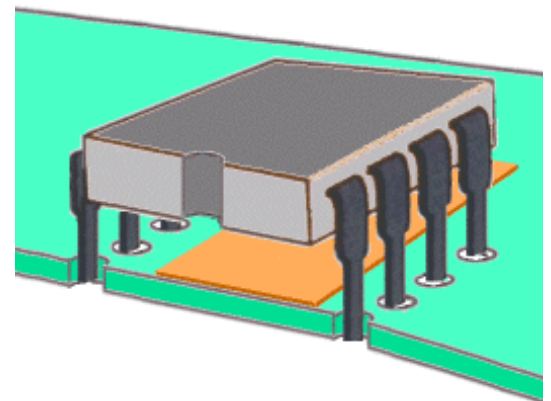
Examples of Shielding



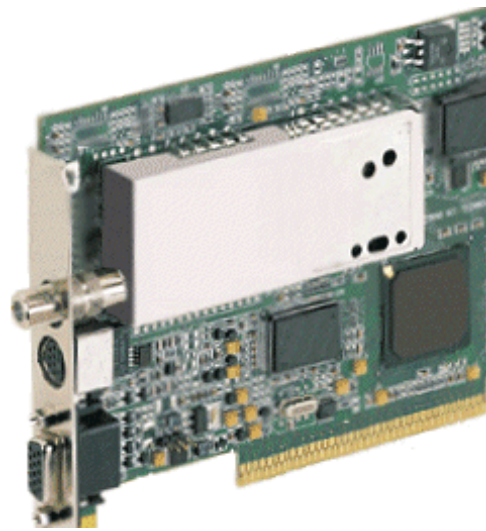
The figure at left is a well-shielded container made from soldered, copper-clad, printed circuit board material.



Shielded Audio Cable



Isolated copper island under IC (acting as a shield)



Graphics Card with Shielded TV Tuner



Shielded PC power supply

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Real-World Applications of Shielding



Conductive paint



Custom gasket



Solderable and snap-in metal shields



"O" Ring



Conductive ATV



Connector gaskets



Compressible gasket

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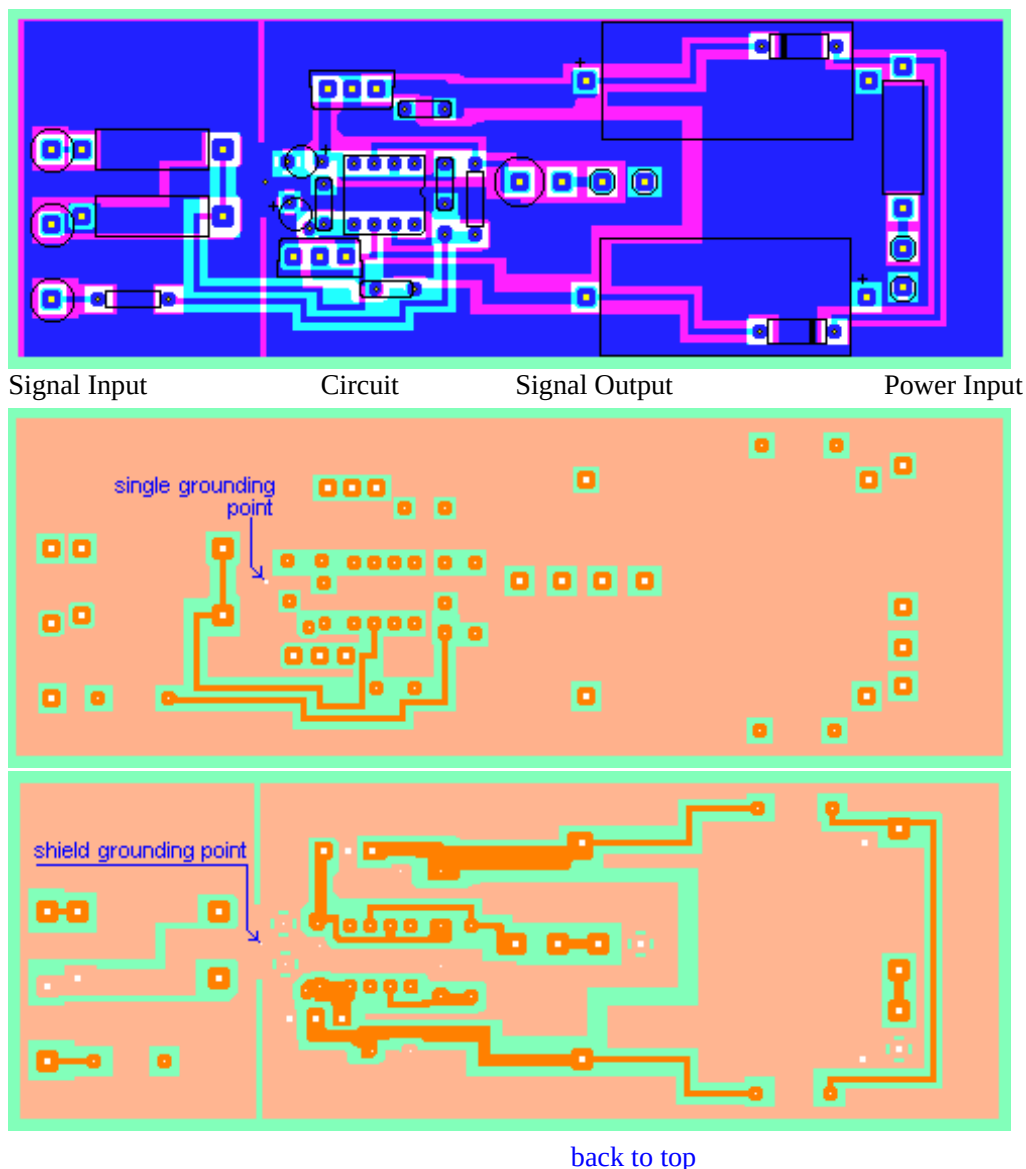
Additional Shielding Aids

Some other shielding aids include conductive paint, conductive gasket making silicone (ATV), and assorted conductive gaskets.

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Circuit Board Layout

Amplifier example.



Summary

1. Shielding can be accomplished by using anything from a coaxial or shielded cable, to a sealed conductive chamber for circuit isolation.
2. Shielding serves a reciprocal purpose: it protects the circuit it is shielding, and also protects the outside world.
3. There must be no currents flowing through the shield itself.
4. To prevent current flow, connection to common should be at only one point on the shield.
5. The maximum dimension of an aperture should not be greater than $1/20$ wavelength.

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Glencoe/McGraw-Hill's *Electronic GOTCHAS EXPOSED***CIRCUIT INTEGRITY****■ Module 5: Layout**[Click here for a printable version of this page](#)

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Introduction

Layout is the integration of bypassing, decoupling, groundplane, and shielding, plus a little art.

Layout (PCB) is another subject that is mentioned in the classroom, but rarely taught. It is often dismissed as "...one of those things done by drafters."

The truth is, an improper layout can ruin the best paper design!

[back to top](#)**What Is a Layout?**

Layout is the creation of a physical realization of the circuit using all of the subjects covered in the previous modules, with primary attention given to signal flow.

[back to top](#)**Why Do We Use a Layout?**

An effective layout promotes optimized interconnection of the circuit elements, while observing all pertinent rules. In addition, the proper layout insures economical manufacturing and high circuit reliability.

[back to top](#)**How Do We Use a Layout?**

When planning a layout, input output, parts placement, signal flow and power distribution all must be considered. Also, attention should be given to interference and noise within the circuit layout. In addition, device rules, such as bypassing, decoupling, shielding, the proper use of groundplanes, and last but not least, EMC, must all be observed.

[back to top](#)**Discussion: Steps to a Successful Layout**

Remember, from the layout of a printed circuit board (PCB) comes the creation of a physical realization of the circuit.



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Bypassing

Decoupling

Groundplane

Shielding

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The Glencoe McGraw-Hill logo, featuring the company name in a stylized font.

1. Determine the board size, type or standard, connections, and so on. This decision is often dictated by the application (PC adapter card, etc.).

Consider the end use (industrial, medical, military, commercial). Also consider environmental impact, product life, and the costs.

Once these parameters are identified, there is a finite amount of flexibility remaining for the designer.

2. Choose the number of layers, device selection, function integration, and then the actual layout.

This is where the input/output connections, parts placement, interconnections, routing, signal flow, and power distribution all must be considered. Special attention should be paid to interference and noise within the circuit layout.

3. Finally make sure the layout follows device rules such as bypassing, decoupling, shielding, the proper use of groundplanes, and EMC considerations.

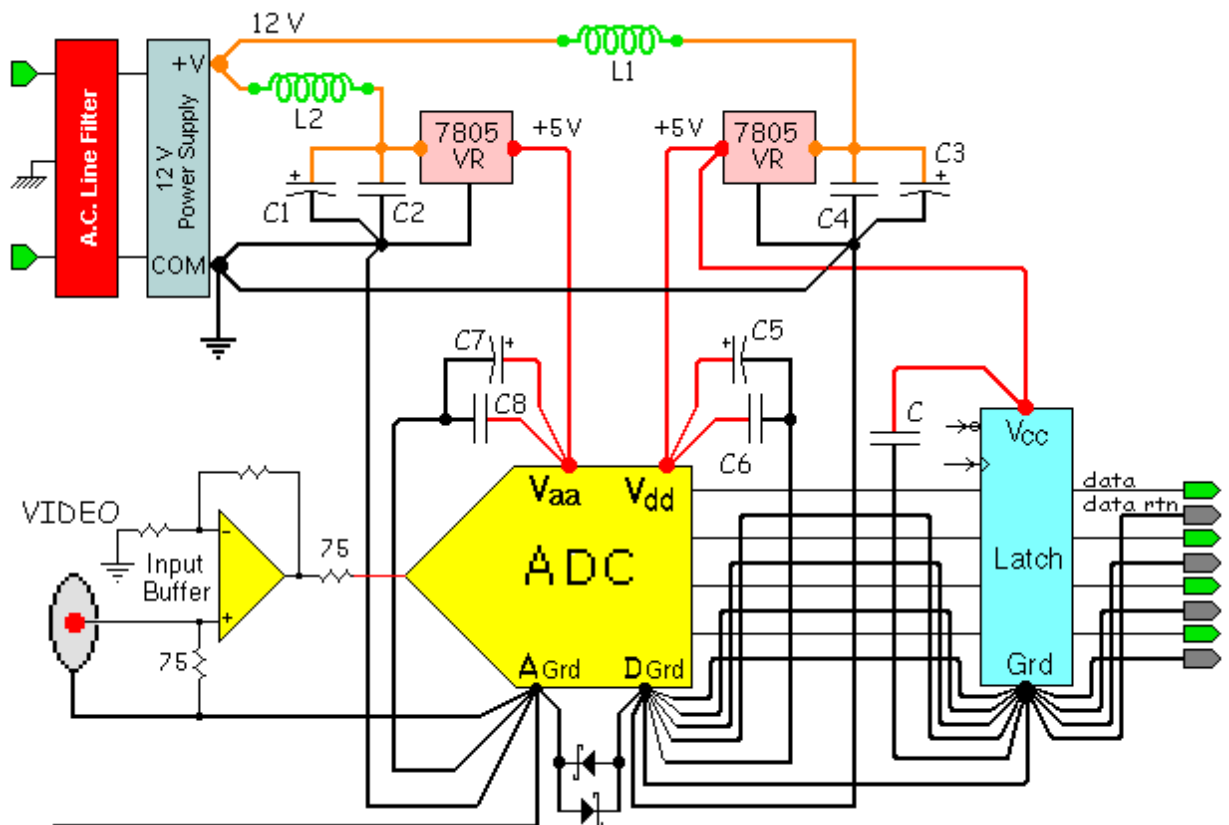
Remember that in an "ideal" ground return system, every current has its own separate return path, and that currents do not share return path copper!

Of course, in the real world ideals are not always possible. However, any design stands a much greater chance of success when the designer keeps these items in mind.

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ADC Layout, Functional Diagram

Below is an illustration of power and ground, and signal distribution.

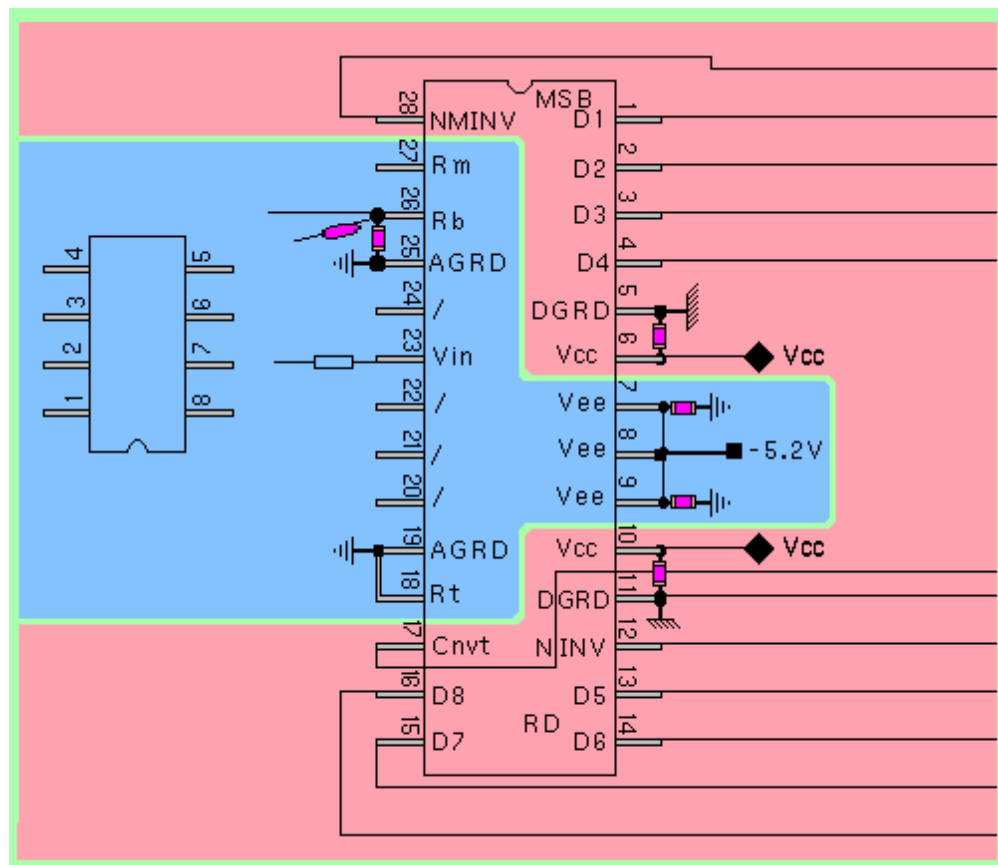


This layout incorporates bypassing and decoupling with proper ground returns. Please notice that schematically, every signal has its own ground return.

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Physical Layout

Analog & digital

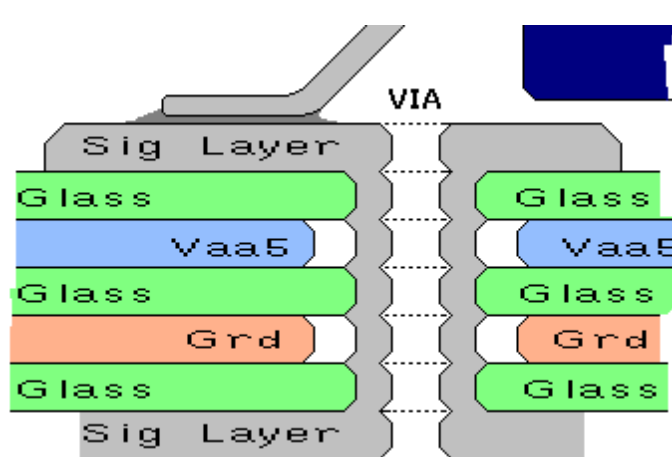


Physical layout of the Analog Devices, Inc., AD-9020 Video ADC

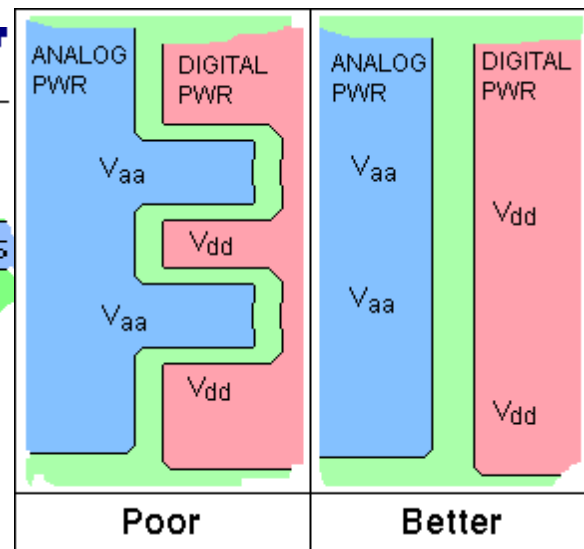
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Groundplanes and Powerplanes

For multilayer printed circuit boards:



Multi-layer printed circuit board



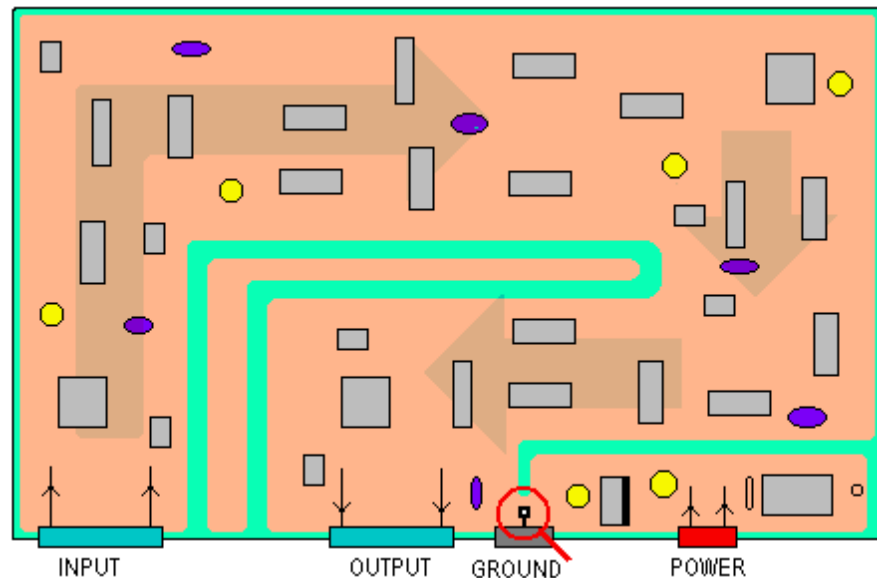
Powerplane Separation

Currents in either powerplane can couple noise to the other; the coupling mechanism is mostly magnetic.

The use of multi-layer printed circuit boards allows the use of multiple groundplanes, as well as buried (under the signal layers) power and ground (V_{cc} and ground) layers. These layers are sandwiched together and act as a very efficient distributed bypass capacitor. A variation of this is to have the power and ground (V_{cc} and ground) layers as the outer or intermediate layers, thus shielding the buried signal layers (or some combination of them). (See EMC.)

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Folded Layout



Notice the single grounding point in this illustration.

In laying out a board, signal flow should be the dominant consideration. Place the input connector as far away from the output as possible. Likewise, place the power entry to the board away from the input, but nearer the output.

In the case of mixed signals, segregate analog from digital.

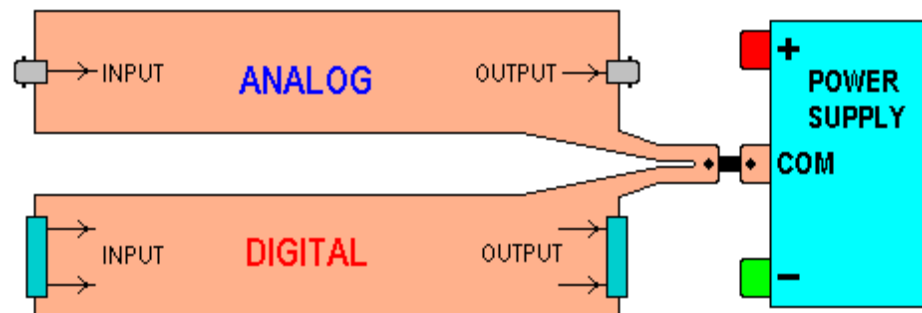
Neatness counts in writing, not in layouts. Keep runs as short as possible.

If you must have long runs, don't parallel the same lines close together. If possible, swap relative line positions to reduce crosstalk.

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Separation of Groundplanes

Separate analog and digital groundplanes with single point unified grounding (COM).

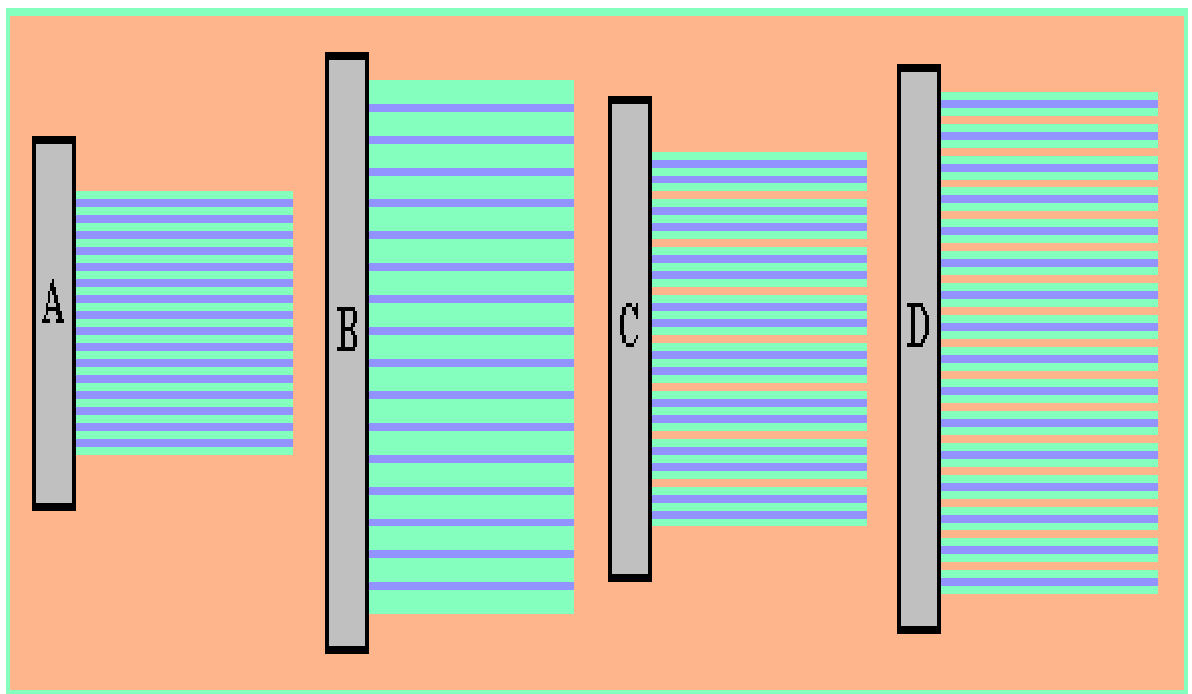


Analog and digital groundplanes do not share return currents.

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Bus Layout

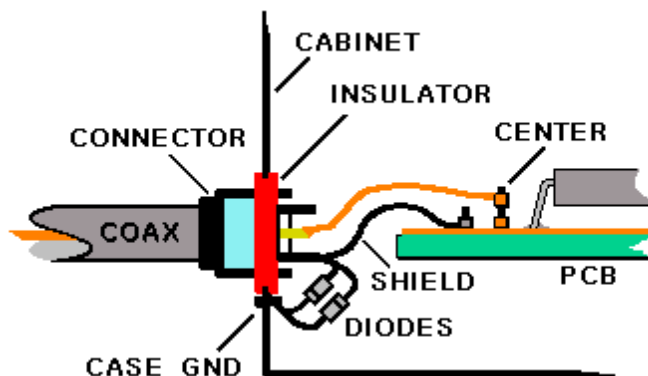
Buses are sometimes required to span long distances across a board, which can lead to crosstalk. This crosstalk can be ameliorated by allowing adequate spacing between traces (see part B of the figure below). However, there can be instances where this approach either doesn't work or there is not enough board area available. Therefore, interleaving ground returns may be required. (See parts C and D of the figure below.)



- . Simple 16 bit bus, close spacing.
- B. Wide spacing.
- C. Interleaved ground traces, 1 ground per 2 signal.
- D. 1 ground per signal.

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I/O Termination



Notice in this illustration that the shield, which is isolated above the cabinet, is returned directly to the device input common pin, not just to ground.

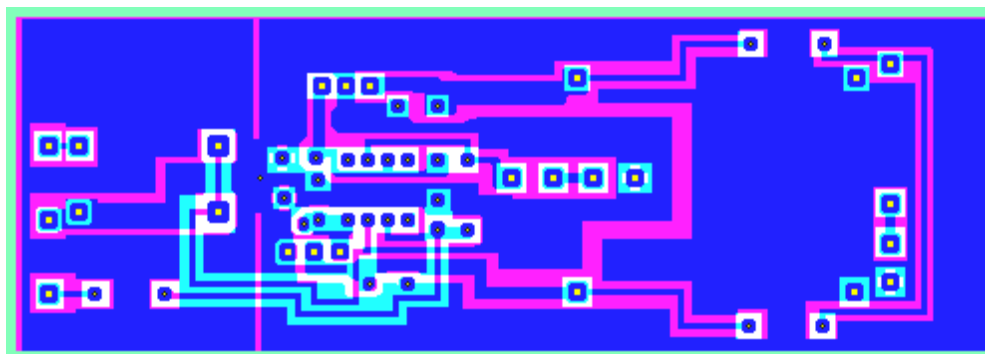
Shottkey diodes protect against severe ground loops.

An example of coaxial cable termination.

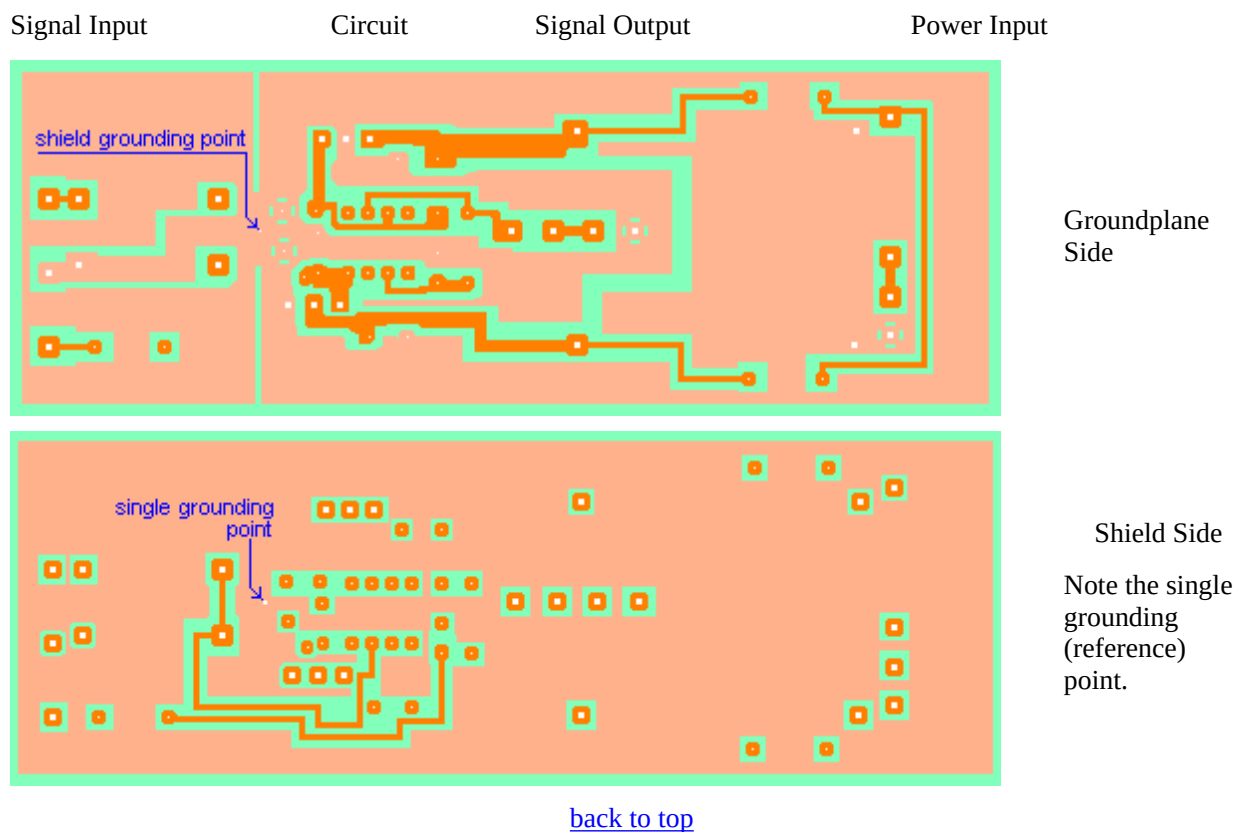
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Circuit Board Layout

Amplifier



CAD Drawing



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Computer Aided Design (CAD) Package:

1. Schematic capture.
2. Part selection.
3. Part placement.
4. Auto routing.
5. Simulation.

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CIRCUIT INTEGRITY

■ Module 6: EMC

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- [EMI Reduction Check List](#)
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 - [C. Receiver Noise Reduction](#)
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Definition of Electromagnetic Compatability

Electromagnetic compatability, it is said, is when "you can watch Oprah with your television set sitting on top of a working PC."

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Introduction

For many, designing for, and understanding EMC has been, and remains an art more than a science. However, it needn't be that way. Using what you have learned in the proceeding modules, this module intends to remove some of the mystery from this subject--but not all!

The greatest insights remain to be discovered in practice.

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What is EMC?

Electromagnetic compatibility (EMC) is an inevitable challenge in a world with a proliferation of electronic systems. Today, thanks to EMC design practices, listening to the news on an AM radio while using an electric razor is not a problem, as it was in the past.

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Why Do We Need EMC?

If EMC design practices are adhered to by both the razor and the radio manufacturers, then listening to an AM radio while using an electric razor presents no problem.

In fact, worldwide governmental regulations prohibit electronic products from emitting or being susceptible to electro-magnetic interference.

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How Do We Implement EMC?

Emission, susceptibility, and path are the three constituents of EMC, though unwanted emission causes the most incompatibilities. Emission, however, also yields the greatest number of solutions. Susceptibility, on the other hand, is more subtle in its effect and its solutions. Finally, the path can be an arbiter of both.

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The Dichotomy of EMC

What is good practice for the circuit isn't necessarily best for EMC. What is good practice for EMC isn't

necessarily best for the circuit.

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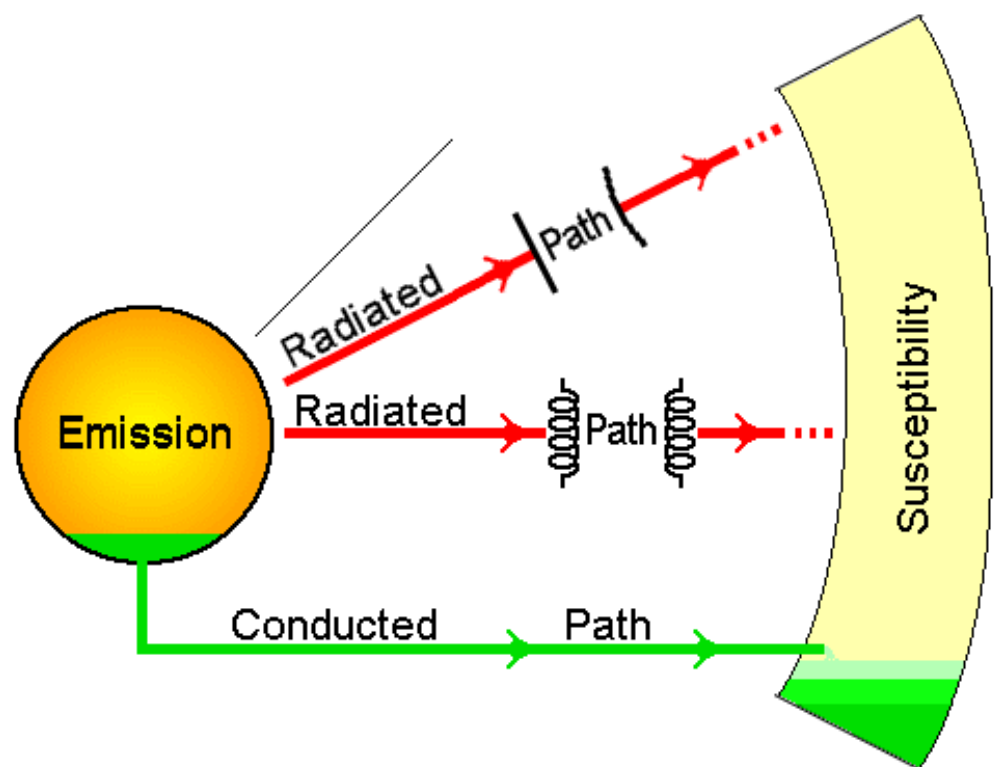
Discussion: Two Approaches

EMC can be approached in two ways: before the fact, and after the fact. Before the fact means designing well for EMC. After the fact is patch work/cleanup; essentially band-aids. Of course, designing in EMC safeguards ahead of time is always best. However, even in the "best" designs these safeguards sometimes aren't enough. Band-aids may still be necessary. Thus the "art" aspect of EMC.

The three constituents of EMC are (unwarranted) emissions, (inappropriate) susceptibility, and the (unintended) path between them. An electric razor's motor brushes arcing is a case of unwarranted emission. A radio picking up the noise created by the arcing of a razor's motor brushes through the path(s) (power line, and/or through the air), is unnecessary susceptibility.

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EMC Paradigm



Block Diagram Depicting the EMC Paradigm

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EMC Path

EMC path consists of radiated and conducted energy.

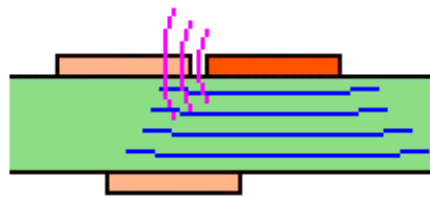
1. Radiated (electromagnetic field)
2. Inductively coupled (magnetic field)
3. Capacitively coupled (electric field)
4. Conducted (electric current)



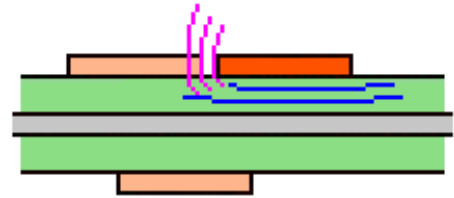
Inductively coupled (magnetic field)



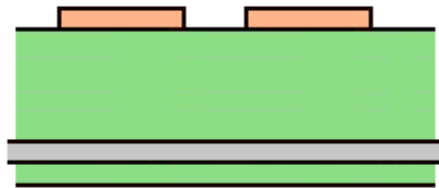
Inductively coupled (magnetic field)



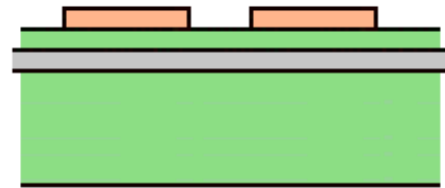
Capacitively coupled (electric field)



Capacitively coupled w/shield (electric field)



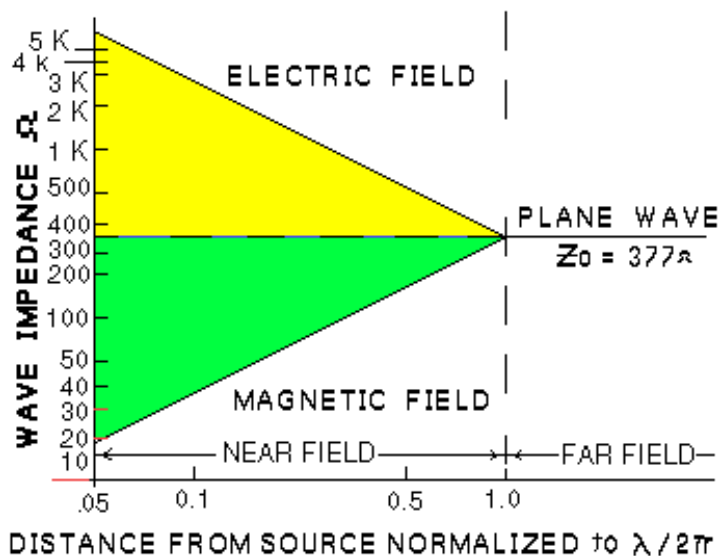
Microstrip transmission line characteristic impedance affected by groundplane proximity:
 $Z = \text{high}$



Microstrip transmission line characteristic impedance affected by groundplane proximity:
 $Z = \text{low}$

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Radiation: Near Field, Far Field



In dealing with a radiation source--be it an antenna or a circuit board:

- The dominant energy in the far field is electric.
- Plane wave radiation is how radio works.
- 377 ohms is the impedance of free space.
- The dominant energy in the near field is magnetic.

In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is electromagnetic. This is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic. This is referred to as far field radiation, and sometimes called the plane wave. Plane wave radiation is how radio works, and 377 ohms is the impedance of free space.

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Interference Culprits

Who are the culprits we are trying to control?

EMI Electro-Magnetic Interference

An electrical disturbance in a system due to natural phenomena, low-frequency waves from electromechanical devices or high-frequency waves (RFI) from chips and other electronic devices. Allowable limits are governed by the FCC.

RFI Radio Frequency Interference

High-frequency electromagnetic waves that emanate from electronic devices such as chips and other electronic devices. Allowable limits are governed by the FCC.

TVI Television Interference

High-frequency electromagnetic waves that emanate from electronic devices causing interference to television reception.

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Radiated and Conducted EMI

Radiated

Radiated EMI is most often measured in the frequency range from 30 MHz to 10 GHz (according to the FCC).

Emission Sources:

Clocks, clock lines, data lines; switching power supplies.

Susceptibility:

Clock lines and data lines poorly laid out, improperly terminated;

Solutions:

Balanced transmission lines, proper terminations, groundplanes, shielding, limited rise and fall time drivers.

Solutions:

Shielding, layout, filtering, groundplanes, differential line receivers.

Conducted

Conducted EMI is most often measured in the frequency range of several kHz to 30 MHz (according to the FCC).

Emission Sources:

Power supplies (switching), power rails, motors, relays.

Susceptibility:

A.C. power cord poorly filtered, power rails poorly decoupled.

Solutions:

Good bypassing and decoupling practices, layout, groundplanes, shielding.

Solutions:

Good bypassing and decoupling practices, layout, groundplanes, shielding, power line filtering.

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Solutions to EMI

[Spread spectrum](#), clocks reduce measured interference. Spread spectrum is where frequency hopping and bandwidth spreading reduce measured interference.

[Line drivers with controllable rise and fall times](#).

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Regulations

Residential, Commercial, Industrial, and Military

Entity	Standards
USA / FCC	Part 15, subpart J
Canada	CSA
Japan	VCCI
European	EU (European Union) 89/336/EEC EN specifications: Electronic Equipment Spec. Industrial, scientific and medical equipment EN55011 Broadcast receivers and associated equipment EN55013 Electrical motor-operated and thermal appliances for household and similar purposes, electrical tools and similar apparatus EN55014 Electrical lighting and similar apparatus EN55015 Information technology equipment EN55022
Military	MIL-STD-461/462
Aviation	DO-160
Belcore	GR1089
Automotive	SAE, GM, Ford

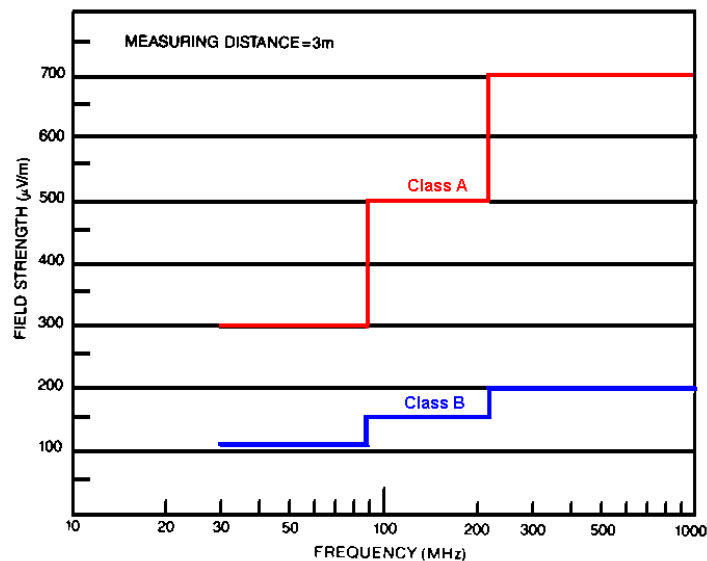
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Measuring EMI and RFI



Spectrum Analyzer
(EMI Receiver)

(Click to Enlarge Image)



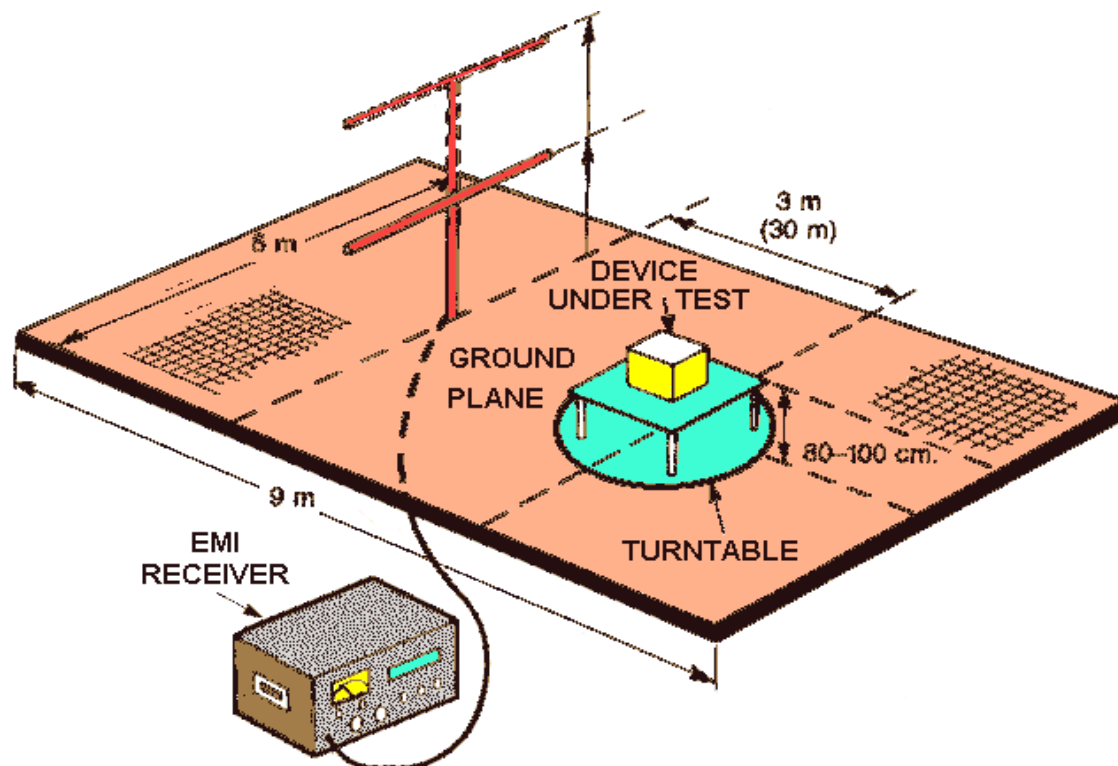
Field Strength FCC: Class A and Class B

Class A limits industrial, commercial, or business use.

Class B limits are more stringent and intended for residential use.

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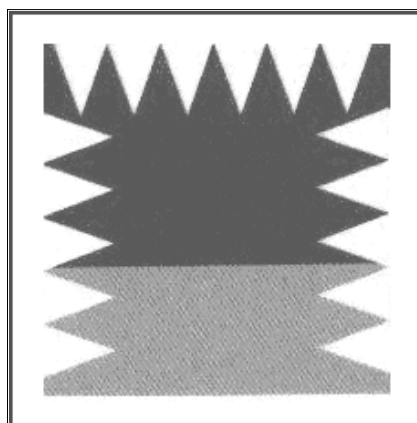
Test Setup



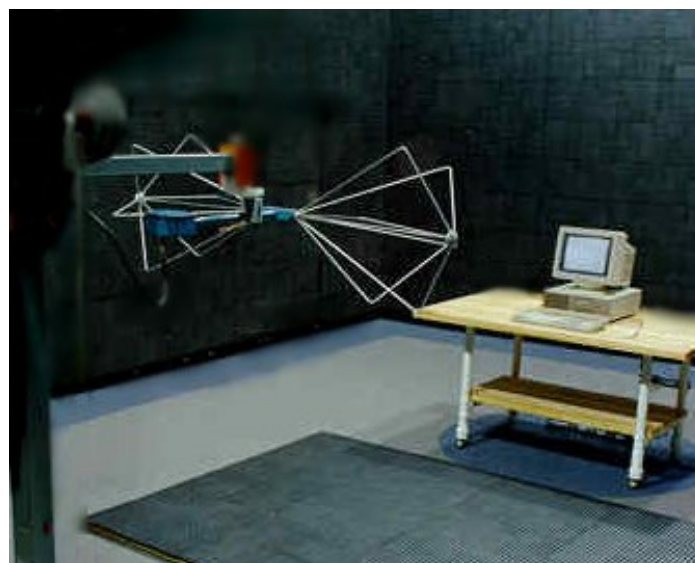
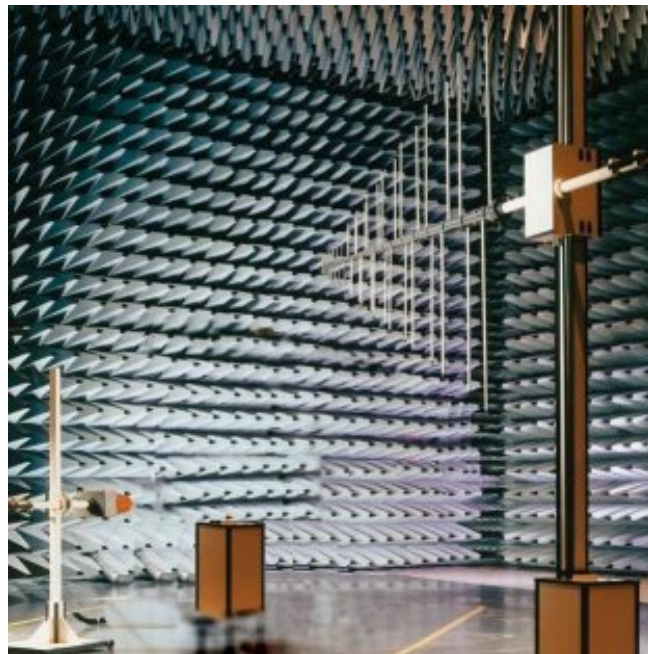
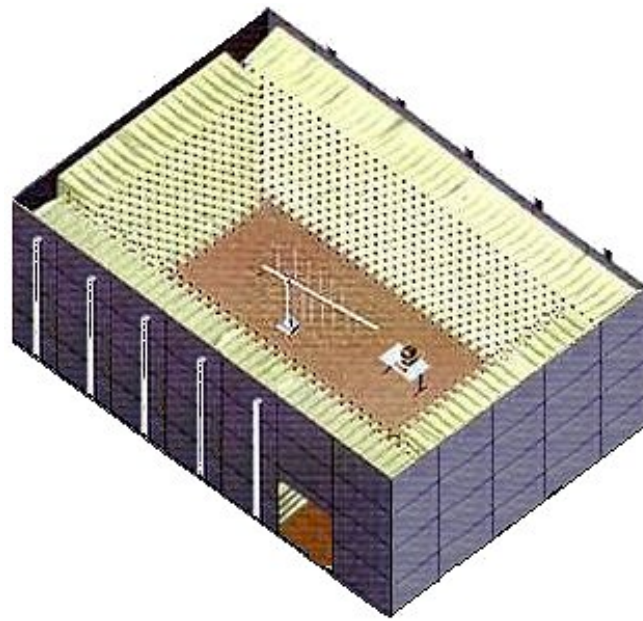
Equipment Setup

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Anechoic Chamber



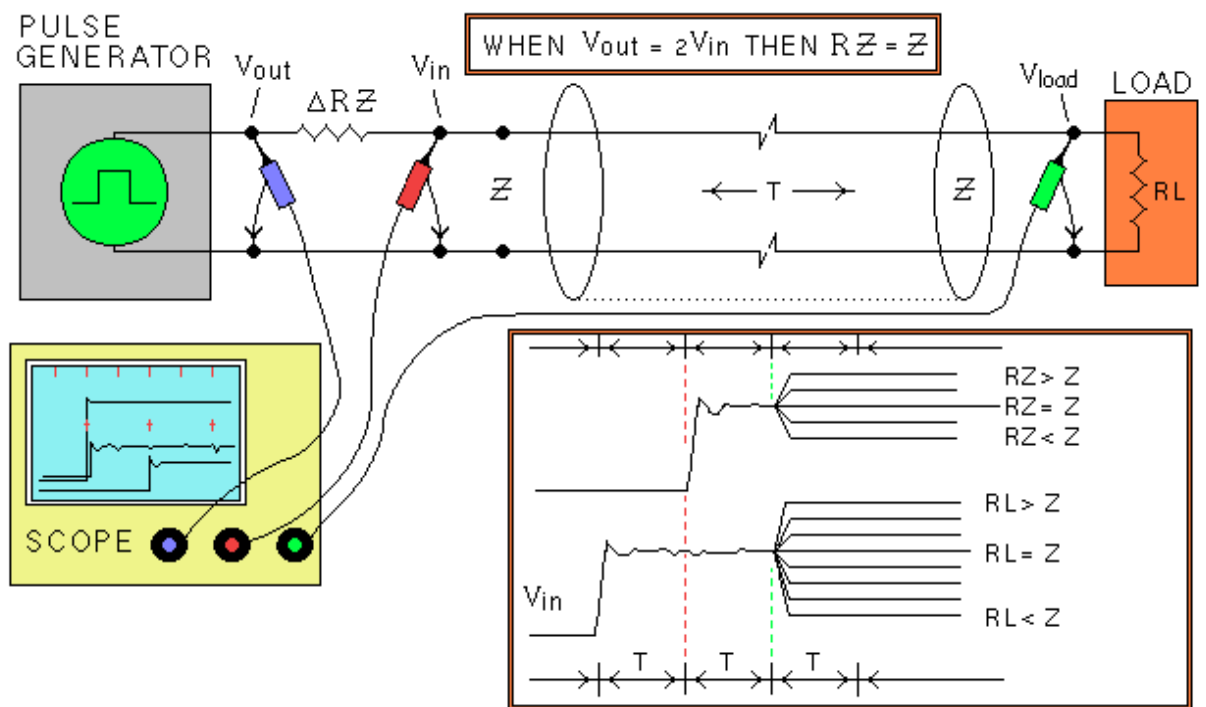
The materials used in the walls and ceiling of an anechoic chamber allow little or no reflection of electromagnetic waves. This is accomplished due to the geometry and the absorptive nature of these materials.



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Transmission Lines

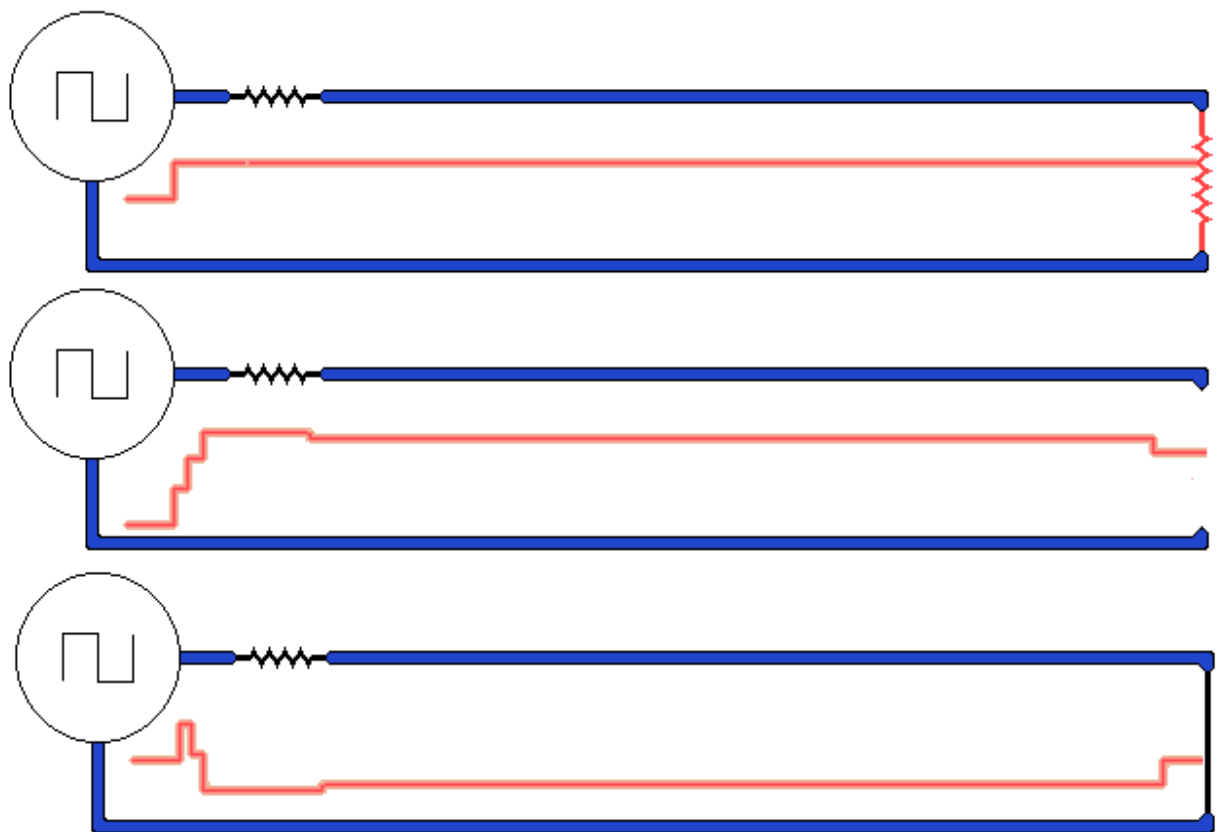
One source of interference can be from improperly terminated or defective transmission lines. Standing waves on a coax can cause the shield to radiate like an antenna.



This illustration shows transmission line reflections due to improper termination impedance.

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Transmission Line Termination Effects



This illustration shows proper termination, open circuit, and short circuit.

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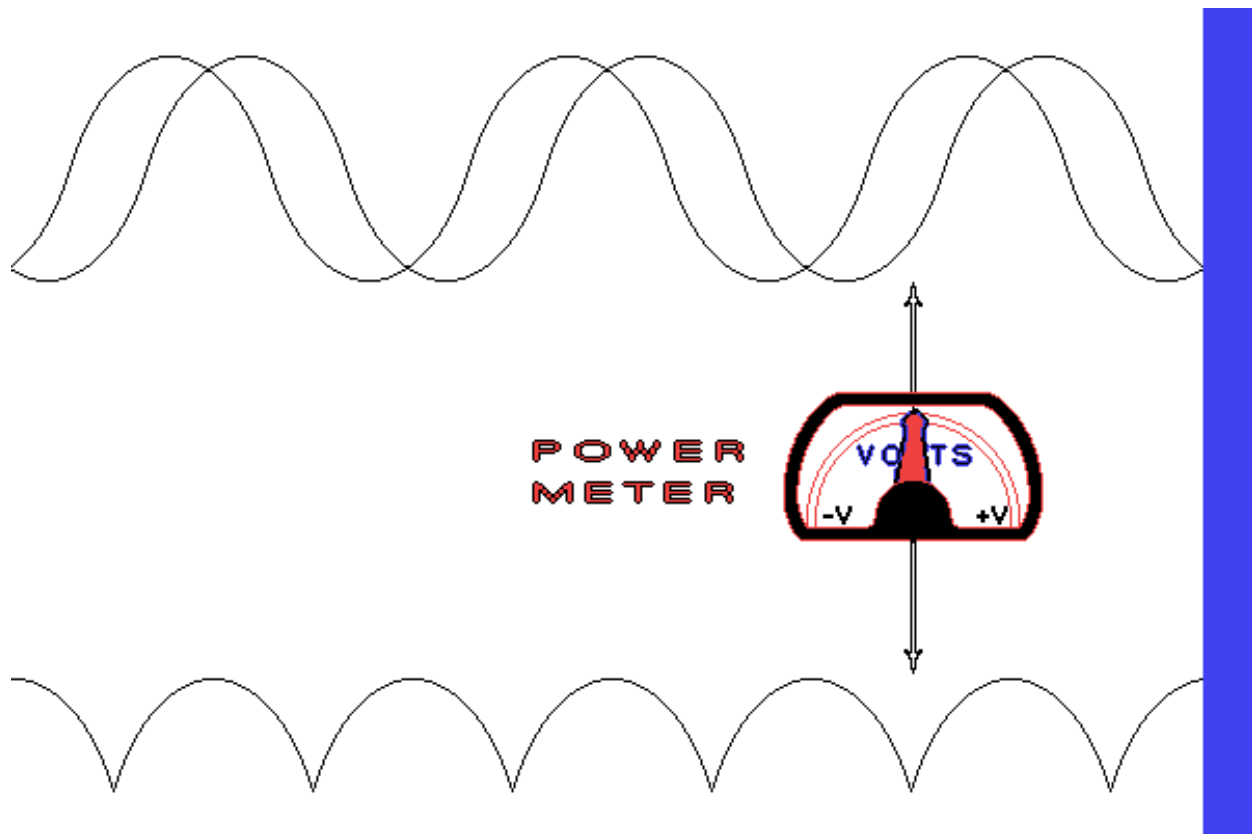
Time Domain Reflectometry Measurements

Time Domain Reflectometry (TDR) measurements have been long used to find transmission line faults.

Applying a fast pulse to a transmission line, while observing the resulting reflections within the transmission line, one can deduce the nature of any faults or discontinuities, as well as, the distance to those faults--assuming one knows the velocity factor of the transmission line dielectric material (insulating material).

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Power Distribution in a Standing Wave

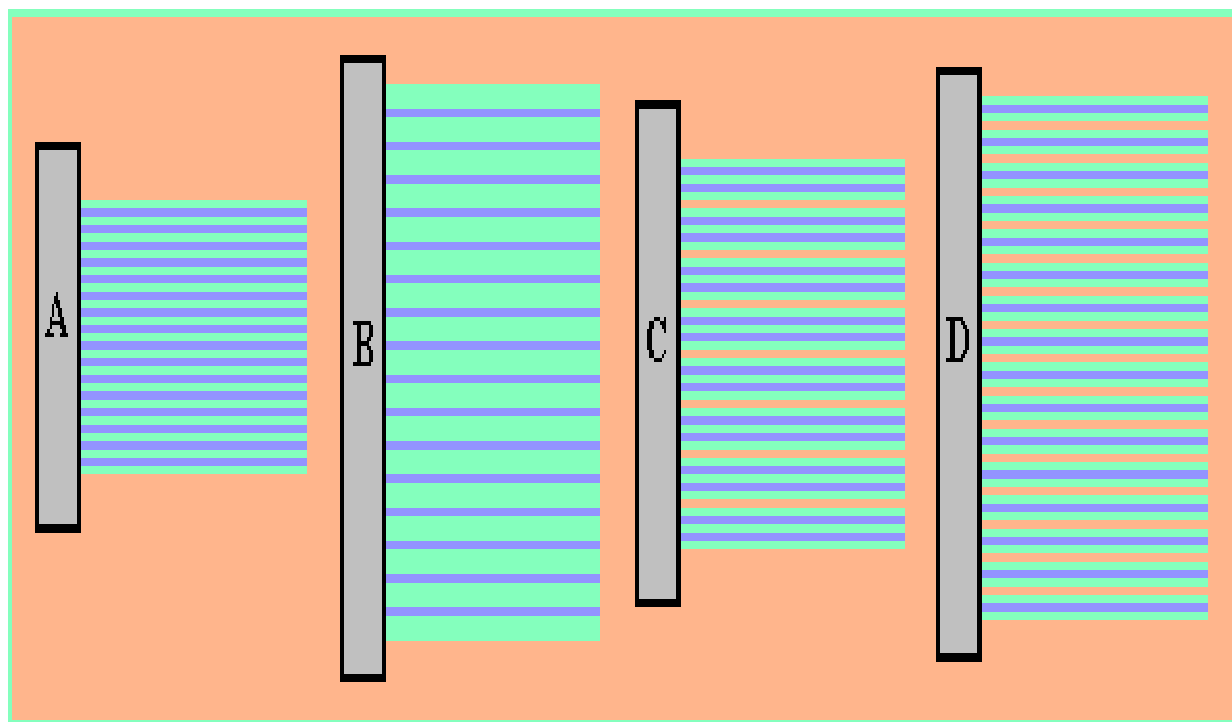


The figure above illustrates standing wave ratio (SWR).

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Data Buses and Clock Lines

Buses are sometimes required to span long distances across a board, which can lead to crosstalk. This can be ameliorated by allowing adequate spacing between traces (see part B of the illustration below). However, there can be instances where this either doesn't work or there is not enough board area available; in which case interleaving ground returns may be required. (See parts C and D of the illustration below.)



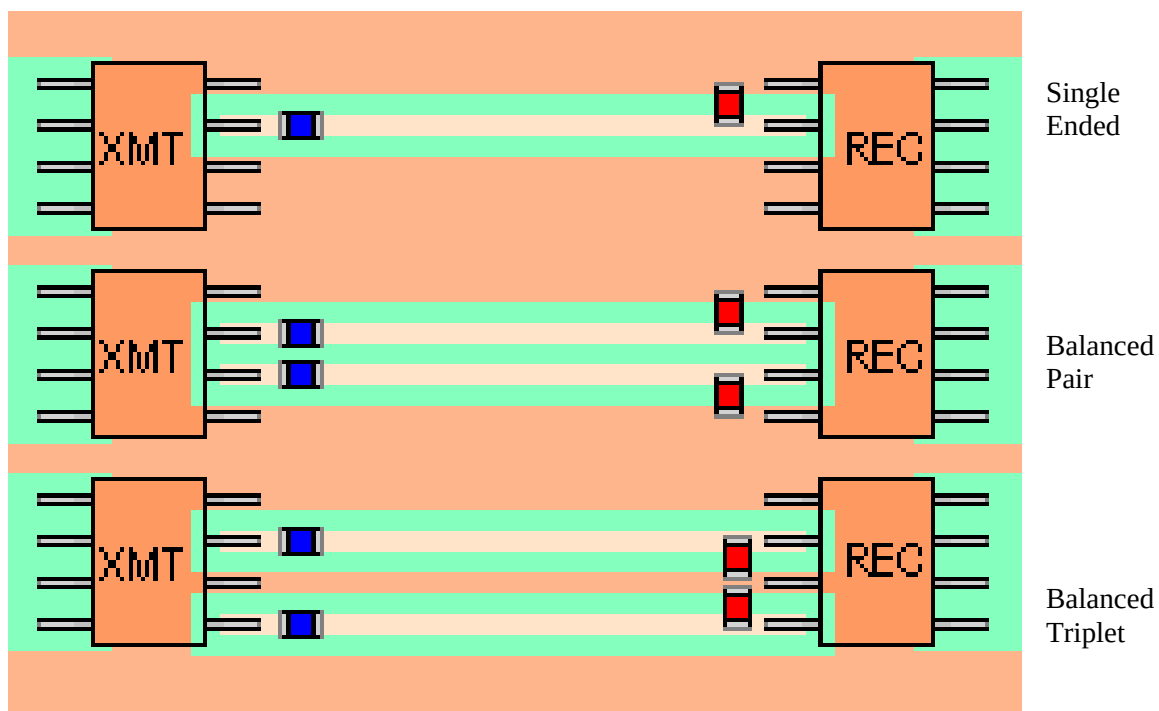
Bus Layout

- . simple 16 bit bus, close spacing
- B. wide spacing
- C. interleaved ground traces, 1 ground per 2 signal
- D. 1 ground per signal

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System Clocks

System clocks are often the single greatest source of EMI.



Series Termination
(SMD chip resistors)

Parallel Termination
(SMD chip resistors)

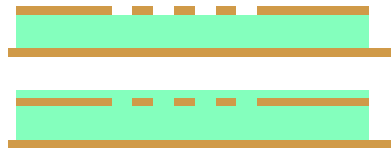
* SMD: Surface Mount Device

Clock Line Drivers and Receivers on PCB Layout

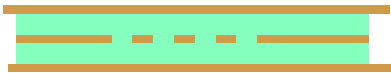
Using single ended, balanced pair, and balanced triplet lines, with series and parallel termination

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Microstrip and Stripline Transmission Lines



Microstrip



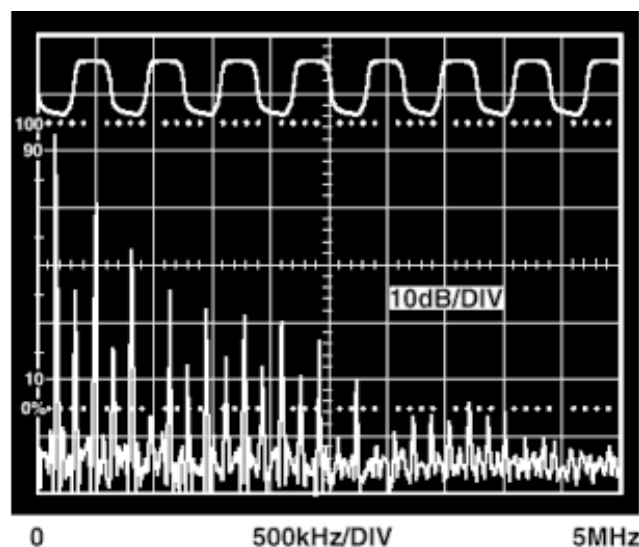
Stripline

Microstrip and stripline transmission lines allow optimum operation of very fast logic, especially ECL (emitter coupled logic) logic. An important resulting benefit of this is reduced EMI.

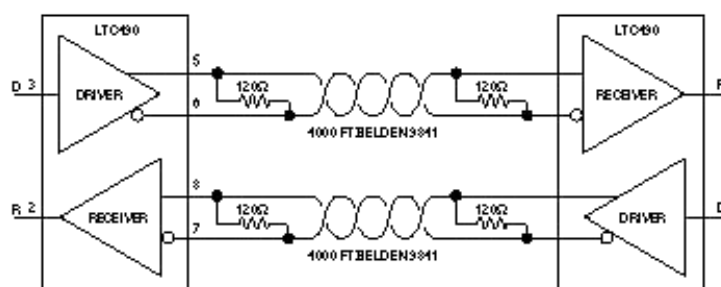
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Less traveled Ways of EMI Reduction

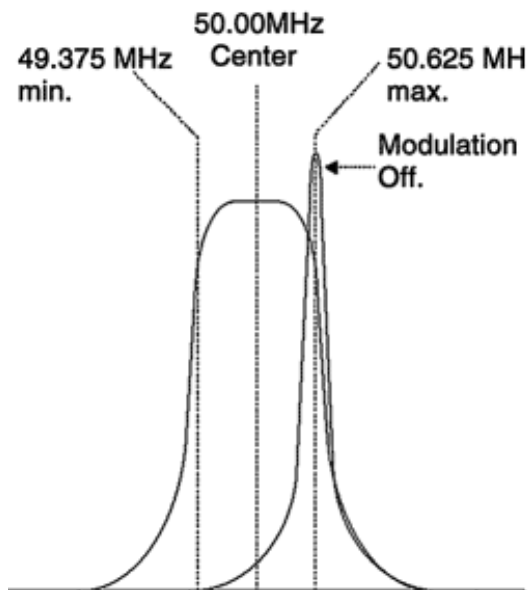
Drivers that Have Programmable/Controlled Rise and Fall Times



To reduce EMI, some line drivers use internal slew rate limiting. The figure shows an FFT plot when transmitting a 150 kHz data stream. As may be seen, the slew limiting attenuates the high frequency components. EMI is therefore reduced, as are reflections due to improperly terminated cables. The objective is to control the level of emissions, both conducted and radiated. Conducted emissions are assumed to predominate below 30 MHz, while radiated emissions predominate above this frequency.



Spread Spectrum System Clock

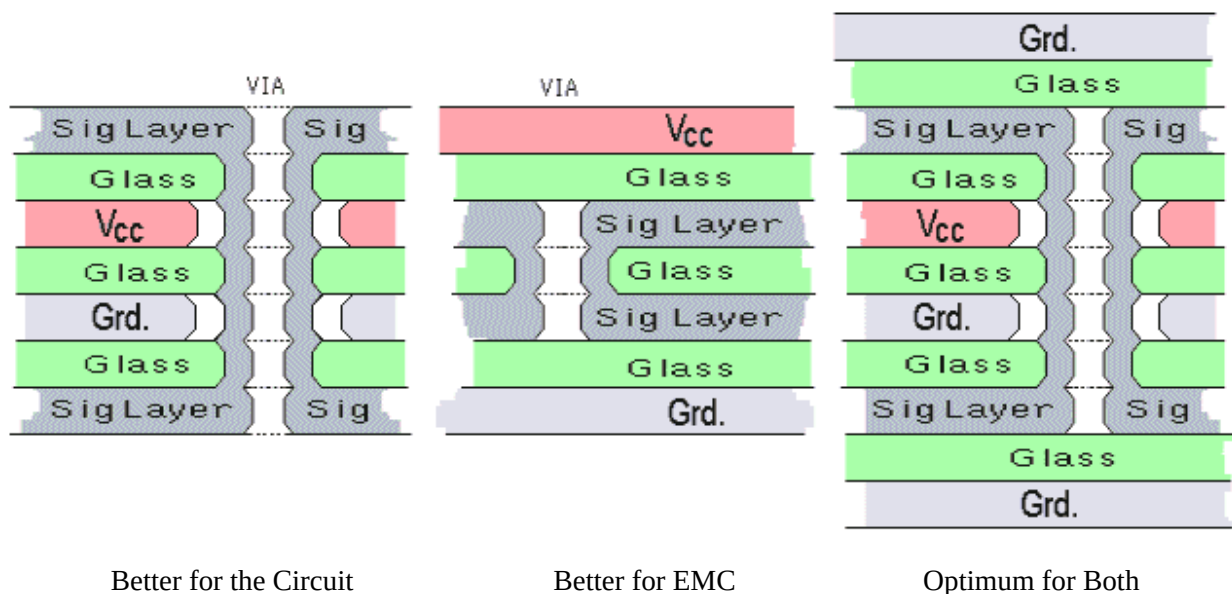


All digital clocks generate unwanted energy in their harmonics. Conventional digital clocks are square waves with a duty cycle that is very close to 50%. Because of the 50/50 duty cycle, digital clocks generate most of their harmonic energy in the odd harmonics, i.e.; 3rd, 5th, 7th, etc. It is possible to reduce the amount of energy contained in the fundamental and harmonics by increasing the bandwidth of the fundamental clock frequency. Conventional digital clocks have a very high Q factor, which means that all of the energy at that frequency is concentrated in a very narrow bandwidth, consequently, higher energy peaks. Regulatory agencies test electronic equipment by the amount of peak energy radiated from the equipment. By reducing the peak energy at the fundamental and harmonic frequencies, the equipment under test is able to satisfy agency requirements for Electro-Magnetic Interference (EMI). Conventional methods of reducing EMI have been to use shielding, filtering, multi-layer PCBs, etc. The SM532 uses the approach of reducing the peak energy in the clock by increasing the clock bandwidth, and lowering the Q; this method can also be thought of as "frequency dithering."

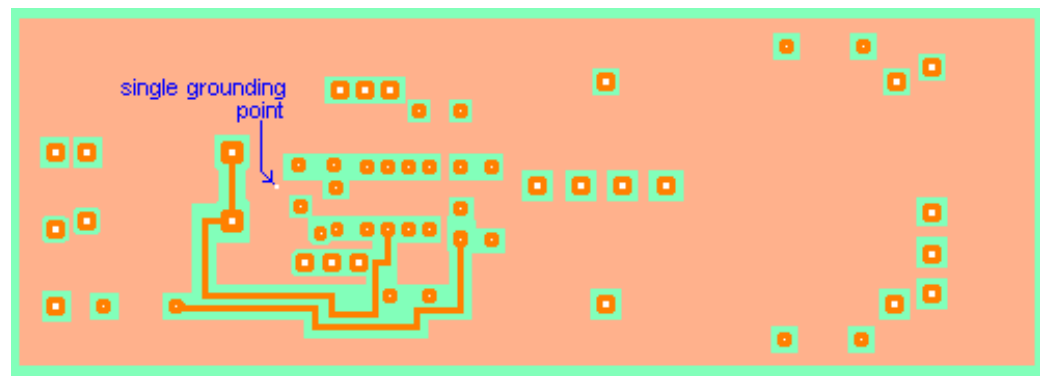
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PCB Layering

Signal, Power, Groundplane, and Shielding



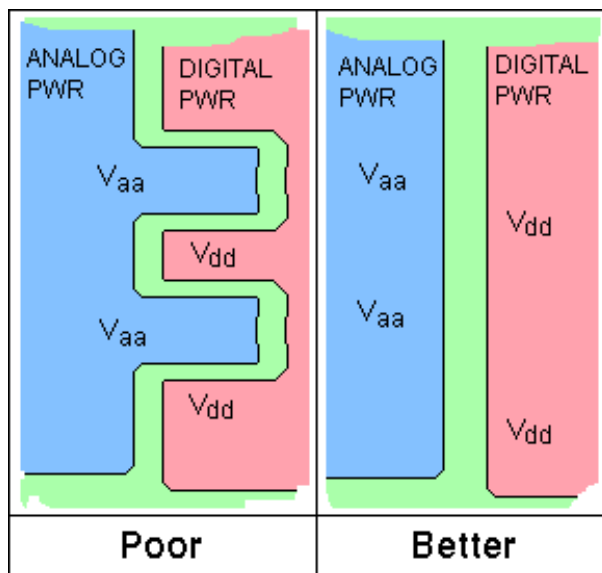
Shield Layer



Note the single grounding (reference) point.

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Analog and Digital Powerplanes



Currents in either powerplane can couple noise to the other; the coupling mechanism is mostly magnetic.

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Power Supplies

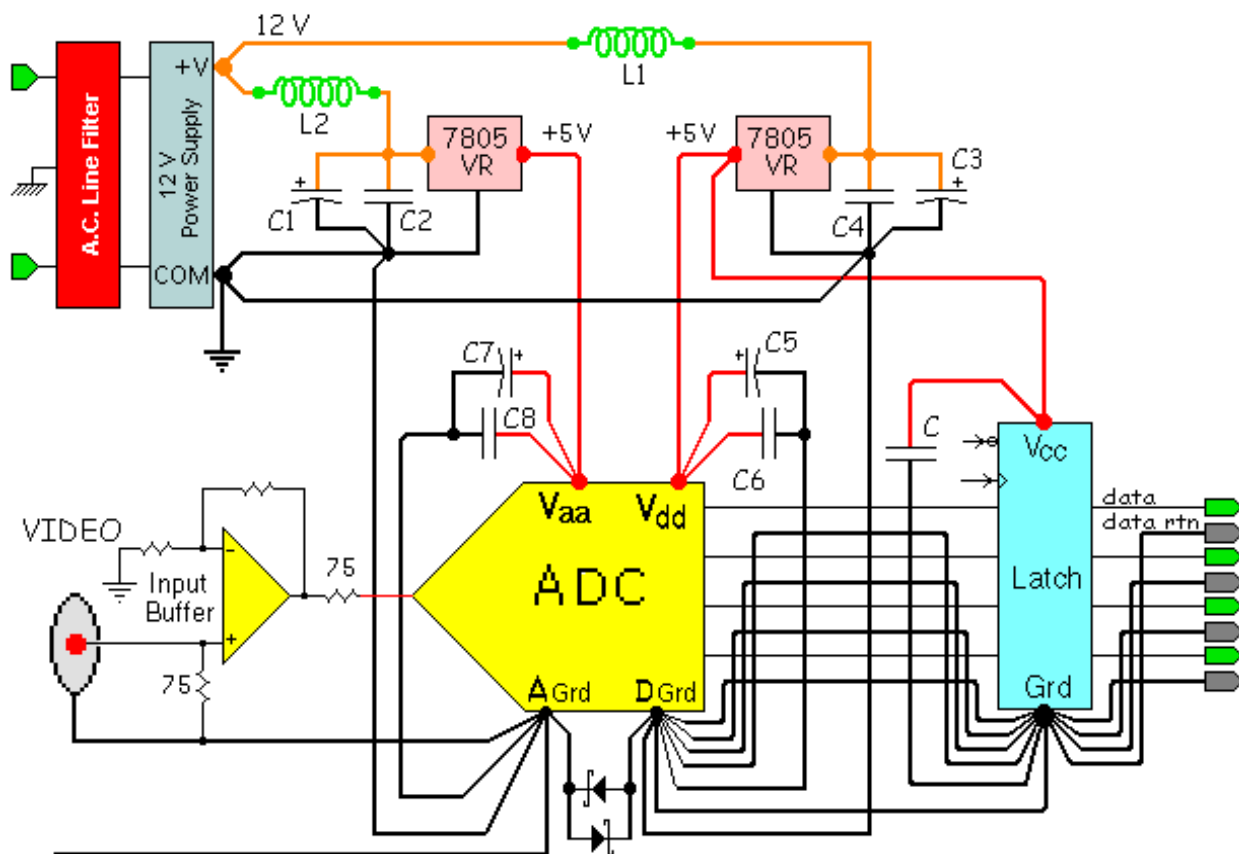
Power supply and distribution are common sources of emissions, as well as paths for conducted and radiated EMI.

Linear Supplies

Linear power supplies, if designed and laid out properly, offer little or no EMI problems. Layout, bypassing, and decoupling are critical to this.

Switching Supplies

Switching power supplies can be a large source of EMI. Proper layout, bypassing, decoupling, and shielding are critical to the ultimate success of switching power supplies.

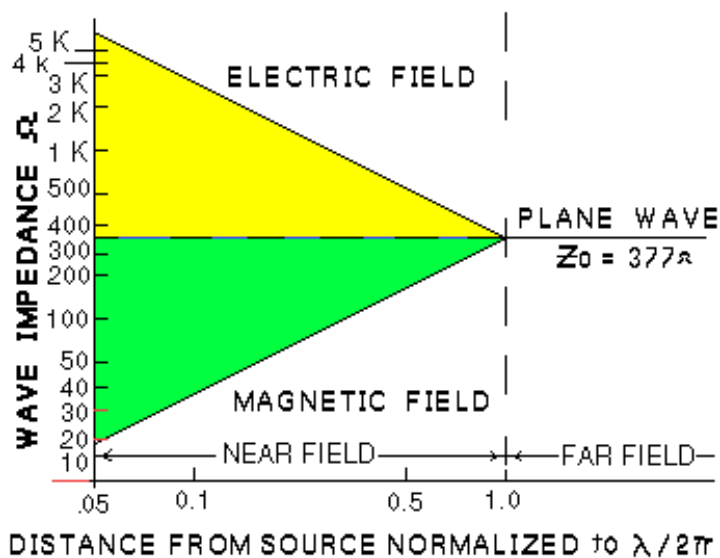


Notice the ground returns in this illustration.

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Reminder

This illustration shows near field and far field radiation.



In dealing with a radiation source--be it an antenna or a circuit board:

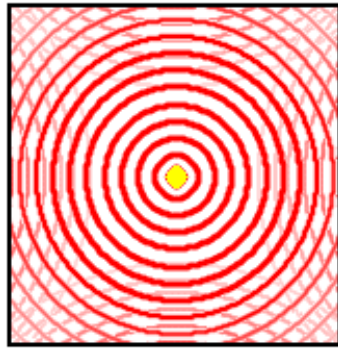
- The dominant energy in the far field is electric.
- Plane wave radiation is how radio works.
- 377 ohms is the impedance of free space.
- The dominant energy in the near field is magnetic.

In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is electromagnetic; this is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic, and is referred to as far field radiation; sometimes called the plane wave. Plane wave radiation is how radio works and the 377 ohms is the impedance of free space.

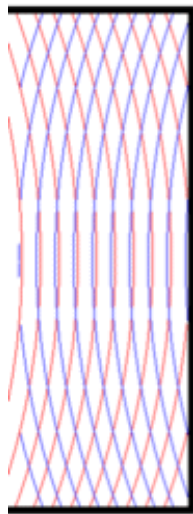
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Shielding as a Method of EMI Control

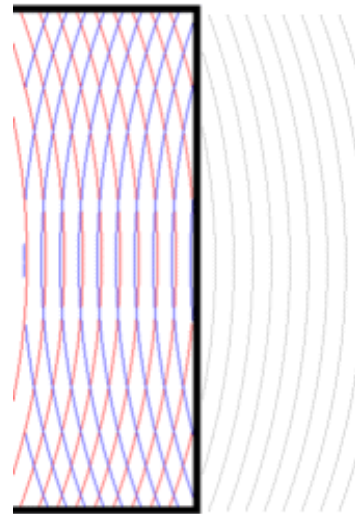


An RF emitter inside a shielded enclosure.

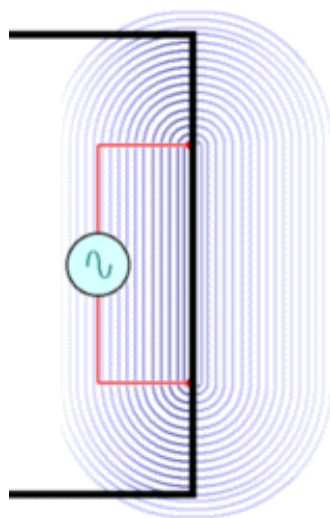
Above is an example of ideal shielding: no leakage.



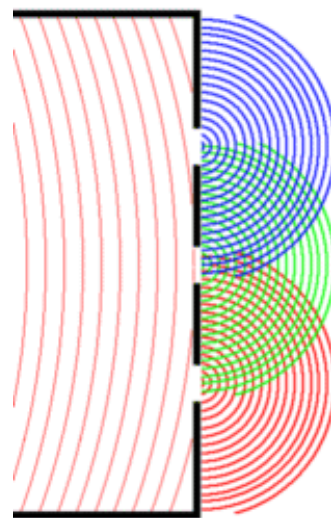
Shield Reflecting



Shield Reflecting,
(with some "parasitic" radiation)



Driven Shield Radiating
(currents in shield create antenna effect)



Leakage of Apertures in Shielded Enclosure
(diffraction apertures act as point sources—
e.g., slot antennas)

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Something to Remember

The area of an aperture is less important than its length (as in seams or joints). The rule of thumb is the maximum dimension of an aperture should not be greater than $1/20$ the wavelength of the highest frequency of interest. Such apertures can act as slot antennas.

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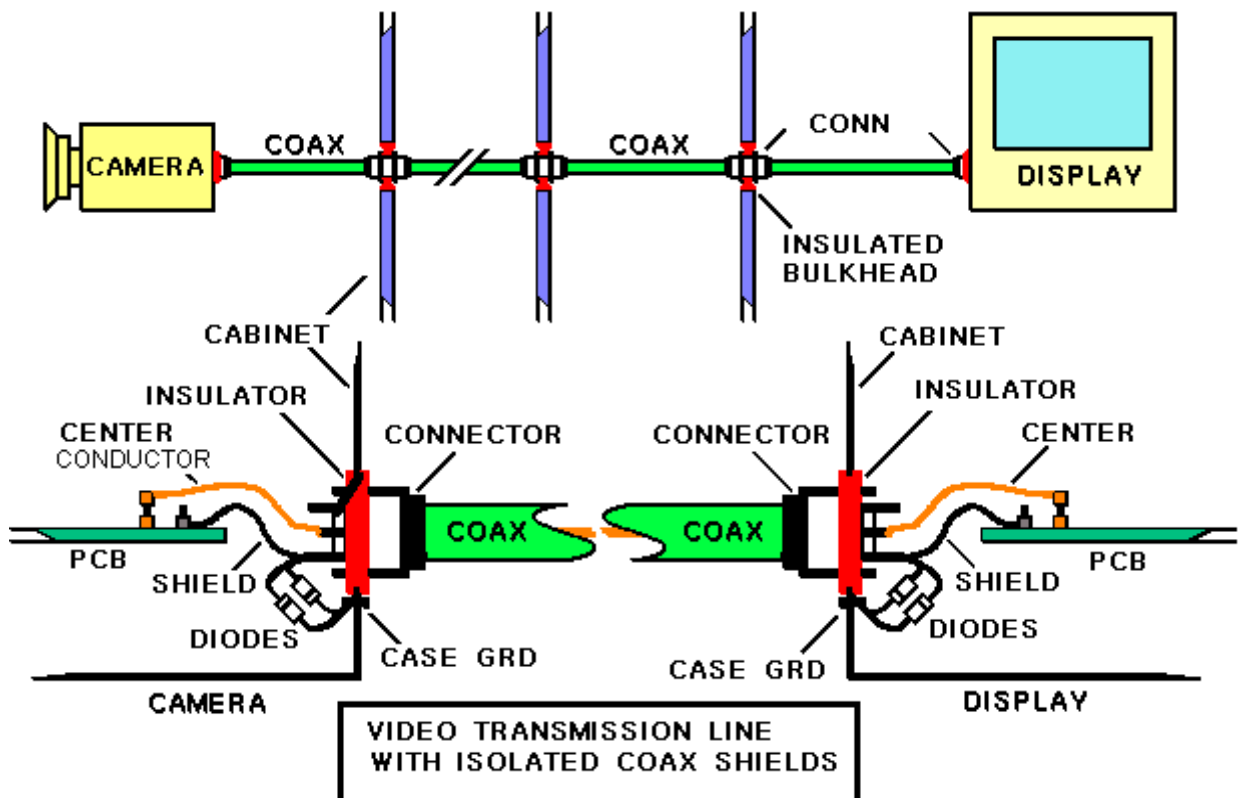
Some Notorious Apertures I Have Known

- CRTs
- Meter bezels
- Lamps/LEDs
- Switches
- Connectors
- Control knobs (such as volume)
- Sheet metal enclosures
- Cable entrances

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Shielded Cable

Avoid extraneous currents in the coax shield; maintain shield isolation.



By definition: the ideal shield has no current flowing through it, and is "grounded" or referenced at only one point.

In the case of shielded cables, the shield is typically referenced or grounded at both ends.

In the case of coax cables the shield acts as both the shield and the return current path for the signal carried on the center conductor. However, with shielded balanced differential pair (sometimes called twisted pair) the shield is just that, a shield. Often this shield can be grounded at either end. However, in the case of EMI suppression, grounding both ends is prudent.

Though coax and shielded twisted pair are used for both audio and higher frequency signals, there can be differing effects on how the shield is treated. The most difficult case is that of video, where both very low to high frequencies (~ 10 Hz to >4 MHz) are involved.

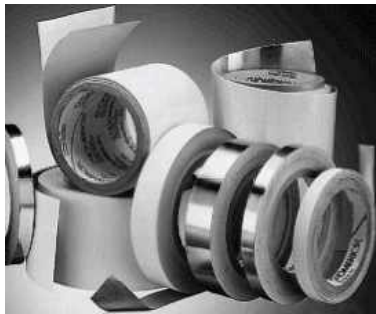
Audio run on coax is subject to "ground loop" noise, i.e., dissimilar ground potentials (especially 60 Hz) which can cause a noise current to flow in the shield, inducing that noise into the protected center conductor. As the frequency of interest increases and the coax gets longer the ground loop problem is diminished; mainly due to the increased inductive reactance (higher Z) of the coax shield.

When long runs are required and/or the environment is noisy, it is best to use shielded twisted pair. The reason is the differential pair's inherent rejection of common mode noise (CMR).

In an extreme case, a remedy might be found in transformer coupling or even optical isolation.

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EMI Protective Arsenal



Metal Foil Tape
(conductive adhesive, and solderable)



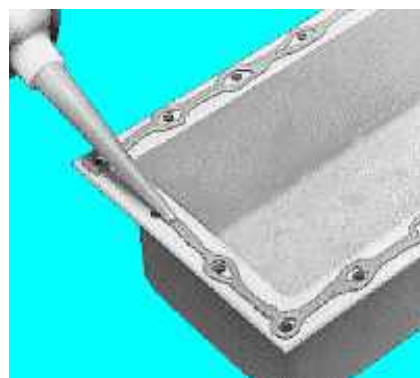
Conductive Paint
(copper, nickel, silver, etc.)



Conductive Plastic Cases



Bronze Finger Stock
(for access panels, doors, drawers, etc.)



Conductive Conformal Gasket Material
(for access panels, etc.)



Custom Conductive Gasket

Conductive Caulking



Solderable & snap-in metal shields



"O" Ring



Conductive ATV



Connector Gaskets



Compressible Gasket

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Additional Shielding Aids

Conductive paint, conductive gasket making silicone (ATV), and assorted conductive gaskets.

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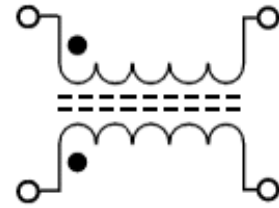
EMI Suppression

Power Line and Data Line EMI Suppression Using Ferrite

Common Mode Noise Suppression



Common Mode Transformers



Common Mode Transformer



Common Mode Transformer



Two Section A.C. Line Filter



A.C. Line Filter
(two section)

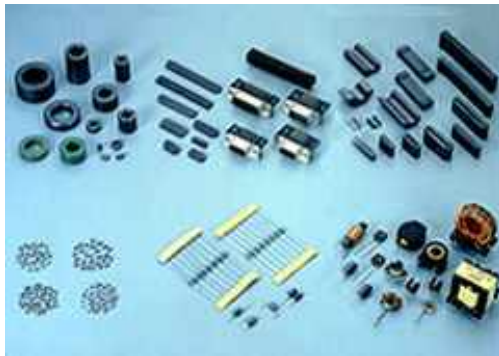


A.C. Line Filter



A.C. Line Filter
(built in receptacle)

Assorted EMI Suppression Devices Using Ferrites



Assorted Ferrites



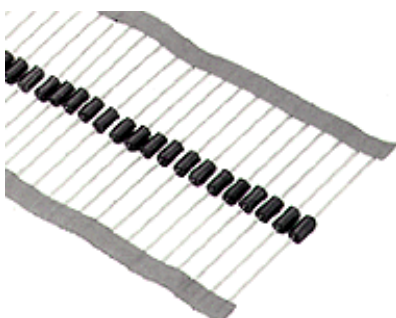
Ferrite Snap-in



Balun (ferrite core)



Tubular & Toroidal Ferrite



Ferrite Beads
Axial Leads



SMT Ferrite Beads



Flat Cable Ferrite Cores

Multilayer Ferrite Chip Beads



"DB" Data-Connector

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Summary

Transmission Lines

Be careful of high SWR (Standing Wave Ratio) on all transmission lines such as twisted pair, coax, PCB traces, etc.. If not terminated correctly, or if there are discontinuities (e.g., unterminated stubs, damaged cable, etc.) they can radiate.

Properly terminated, differentially driven and received shielded twisted pair offer the best performance.

Bypass & Decouple

- Bypass all active devices!
- Remember that bypass capacitors are self resonant.
- Connect capacitors using the shortest leads!

Voltage regulators offer the best decoupling.

Caution: voltage regulators will generate parasitic oscillations if not properly bypassed.

Groundplane

Every signal should have its own ground return.

Shielding

By definition, real shields have no current flowing through them. They are grounded (referenced) at only one point.

Enclosures

Leakage Apertures

Diffraction: openings or apertures in enclosures appear as point sources, and radiate their venomous exhaling.

Area of the apertures is less important than the longest dimension, e.g., seams and joints; greater than $\sim 1/20$ wavelength of the highest frequency of interest. They start looking like slot antennas.

Some Apertures

- CRTs
- lamps/LEDs
- switches
- connectors

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EMI Reduction Check List

Suppression of Emitter EMI

1. Enclose noise sources in a shielded enclosure.
 2. Filter all leads leaving a noisy environment.
 3. Limit pulse rise and fall times.
 4. Relay coils should have surge damping.
 5. Shield and/or twist noisy leads.
 6. Ground both ends of shields used to suppress radiated interference (shield should be insulated).
- B.

Reducing Noise Coupling

1. Twist low-level signal leads.
2. Place low-level leads near chassis (especially if the circuit impedance is high).
3. Twist and shield signal leads (coaxial cable may be used at high frequencies).
4. Shielded cables used to protect low frequency, low-level signal leads should be grounded at only one end (coaxial cable may be used at high frequencies with shield grounded at both ends).
5. Insulate shield on signal leads.
6. When low-level signal leads and noisy leads are in the same connector, separate them and place the ground leads between them.
7. Carry shield on signal leads through connectors on a separate pin.
8. Avoid common ground leads between high-level and low-level equipment.
9. Keep hardware grounds separate from circuit grounds.
10. Keep ground leads as short as possible.
11. Use conductive coatings in place of nonconductive coatings for protection of metallic surfaces.
12. Separate noisy and quiet leads.
13. Ground low frequency, low-level circuits at one point only (high frequencies and digital logic are exceptions).
14. Avoid questionable or accidental grounds.
15. For very sensitive applications, operate source and load balanced to ground.
16. Place sensitive equipment in shielded enclosures.
17. Filter or decouple any leads entering enclosures containing sensitive equipment.
18. Keep the length of sensitive leads as short as possible.
19. Keep the length of leads extending beyond cable shields as short as possible.
20. Use low impedance power distribution lines.
21. Avoid ground loops in low frequency, low-level circuits.
22. Consider using the following devices for breaking ground loops:
 - a. isolation transformers
 - b. common-mode chokes
 - c. optical couplers

- d. differential amplifiers
 - e. guarded amplifiers
 - f. balanced circuits
 - g. hybrid ground
- C.

Receiver Noise Reduction

1. Use only necessary bandwidth.
 2. Use frequency selective filters when applicable.
 3. Provide proper power supply decoupling.
 4. Bypass electrolytic capacitors with small, high-frequency capacitors.
 5. Separate signal, noisy, and hardware grounds.
 6. Use shielded enclosures.
- D.
7. When using tubular capacitors, connect the outside foil end to ground.

Controlling Digital System Emissions

1. Minimize ground inductance by using a ground plane or ground grid.
2. Locate bypass capacitors next to each IC in the system (use shortest leads possible).
3. Use the smallest value decoupling capacitor that will do the job.
4. Use a bulk decoupling capacitor to recharge the individual IC decoupling capacitors.
5. Clock signal loop areas should be kept as close to zero as possible.
6. All cables should be treated to minimize their common-mode current.
7. All unused inputs on logic gates should be connected to either power or ground.
8. I/O drivers should be located near where the cables leave the system.
9. Use the lowest frequency clock and slowest rise time that will do the job.
10. Keep clock circuits and leads away from the I/O cables.

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CIRCUIT INTEGRITY

■ Module I: Bypassing

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- [Why Do We Bypass?](#)
- [How Do We Implement Bypassing?](#)
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- [Memory Chips with Bypass Capacitors](#)

Introduction

Although bypassing and decoupling are rarely covered in the classroom, they are emphasized in nearly all data sheets and application notes!

So while some new engineers and technicians ignore these topics, they do so at their peril because failure to address these needs is often the reason for hardware debugging problems!

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What Is Bypassing?

Powering any active device requires that the point of entry of the power supply (power rail) be as low an impedance (relative to ground) as possible, ideally zero ohms! Bypassing insures the stability of the circuit, and therefore provides circuit integrity.

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Why Do We Bypass?

Bypassing prevents unwanted communications between different devices (or different stages of the same device) that share the same power rail. Bypassing reduces the noise present on that power rail, at all

frequencies.

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How Do We Implement Bypassing

Something as simple as placing a bypass capacitor between power and ground (V_{CC} and ground) of each active device will effectively restore this nearly ideal power supply--zero ohms output impedance!

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Definition: Ideal Voltage Source

Ideal Voltage Source

Furnishes a constant voltage output, regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

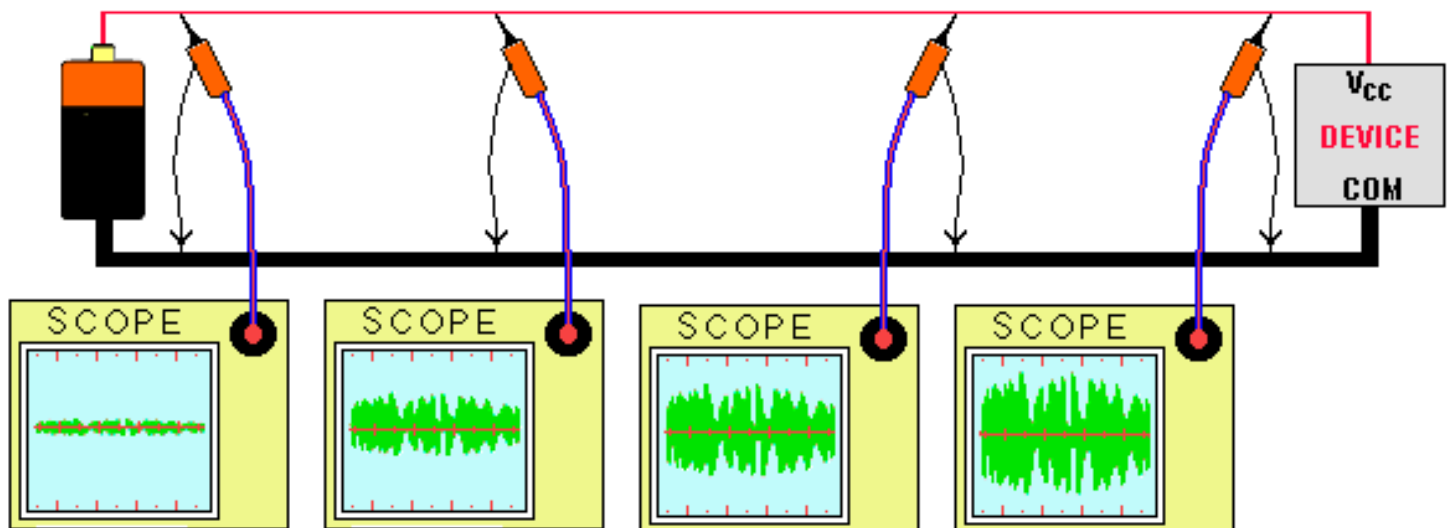
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Power Rails

Because there is distance between any power source and the active device it powers, obviously a conductor, wire, or trace of finite length is required between that power source and device.

Any conductor, wire, or trace has resistance and inductance; both of these properties can cause problems where power is concerned. The resistance problem can be overcome by increasing the cross-sectional area of the conductor; however, the inductive property is another story.

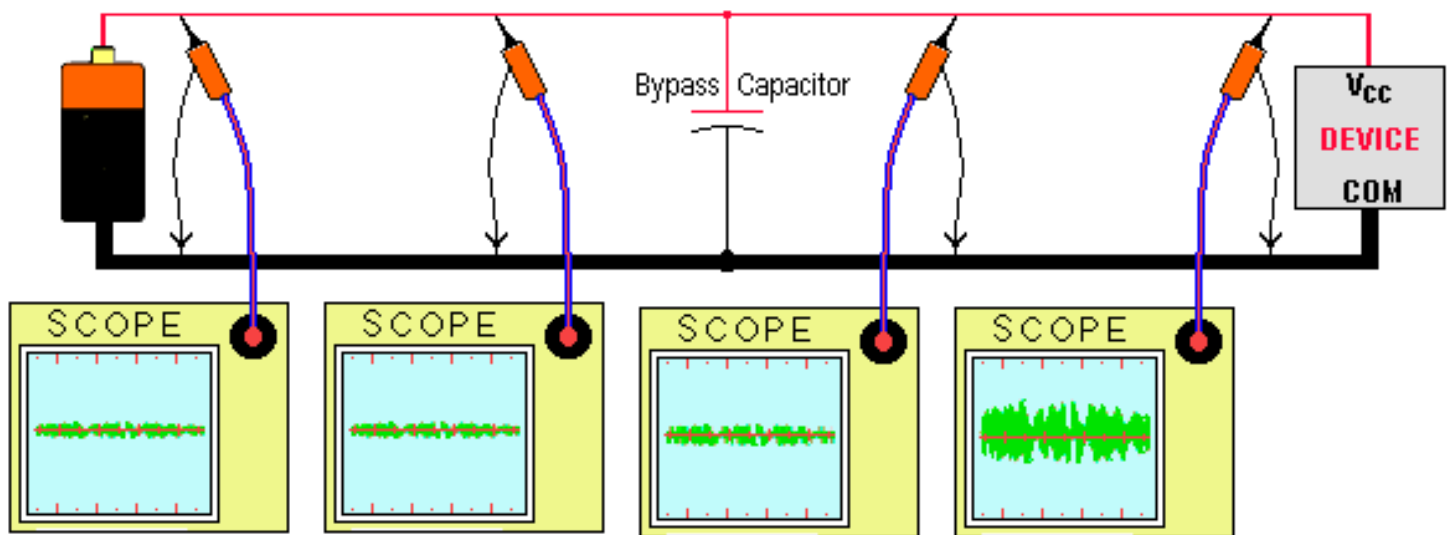
As shown in the figure below, even what might appear to be a small inductance, at high frequencies or very high frequencies can translate to an unacceptable high impedance.



Notice how the inductive reactance (X_L) of the finite length conductor effects the zero ohms impedance. Hence the active device's need for varying rates of current creates more noise as the conductor length (and the reactance) increases.

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Adding Bypass Capacitors



Adding a bypass capacitor to the inductive reactance helps to restore the (virtual) zero ohms impedance.

Note

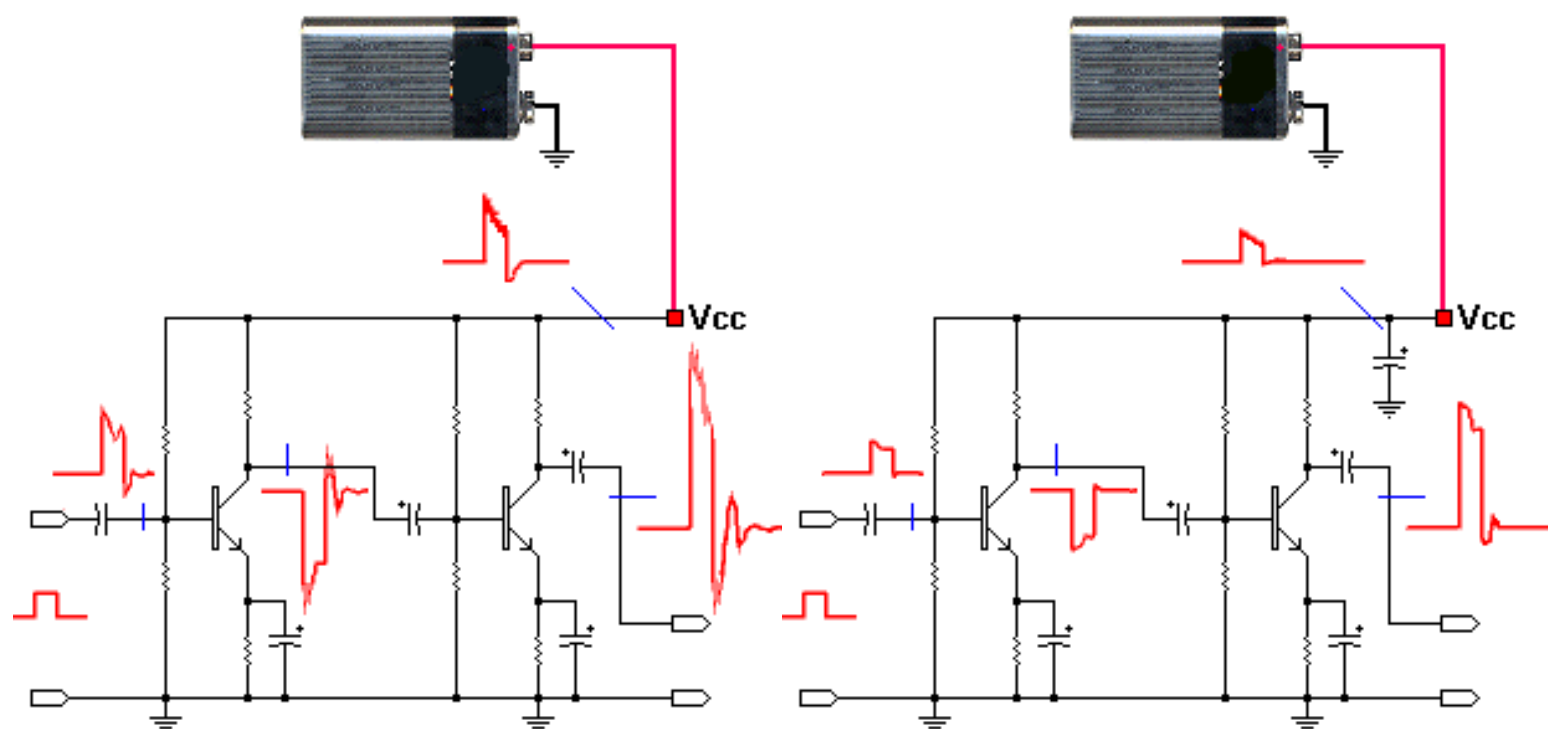
All active devices have inputs and outputs--but you already knew that, didn't you! Also remember that the power rail (the V_{cc} pin) can be *both* an input and output "port." You only have to examine the schematic of such devices to see that the power rail is common to both input and output stages. The bias resistors of the input stage are connected to the same "rail" as the load resistors of the output stages.

This arrangement is not a bad thing, because it presupposes that this common power rail will always be held at zero ohms. That is, the rail will be sourced by an ideal voltage source.

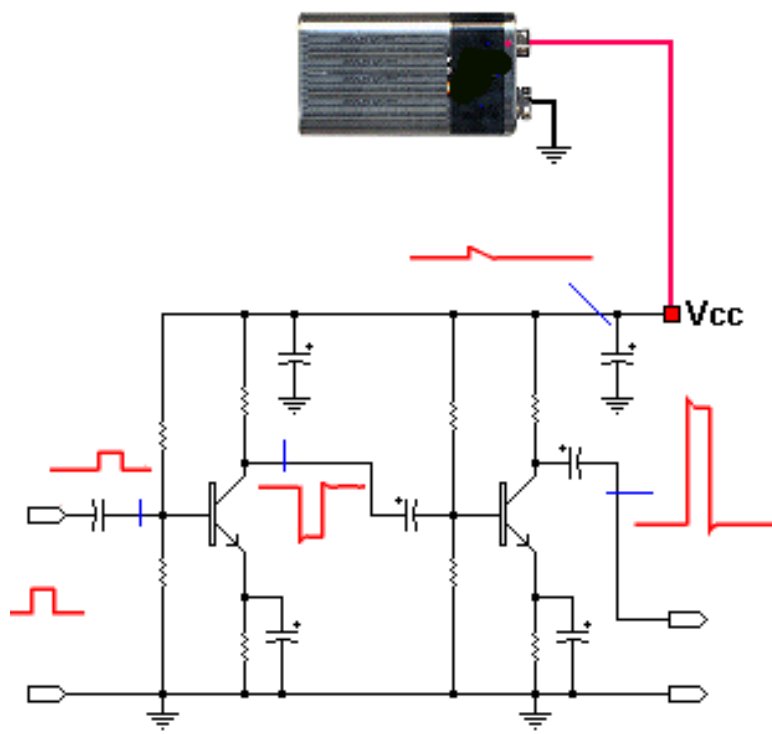
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Amplifier

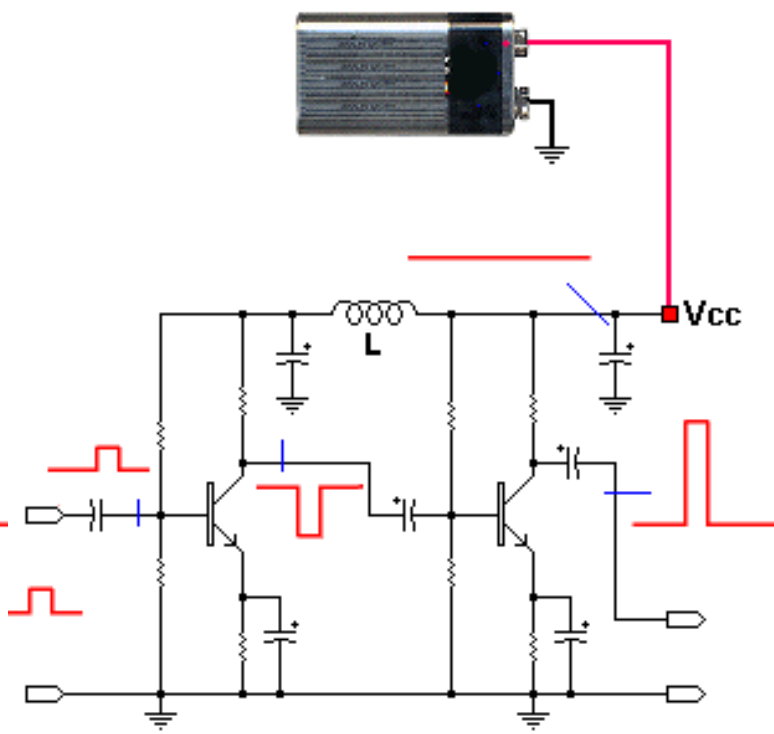
The figure below shows an amplifier with various degrees of power supply stabilization in the form of bypass and decoupling. Notice how the power rail (V_{cc} pin) can be both an input and output "port."



Without Bypass Capacitor



With One Bypass Capacitor



With Two Bypass Capacitors

With Two Bypass Capacitors
& a Decoupling Inductor

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Transistor Transistor Logic (TTL)

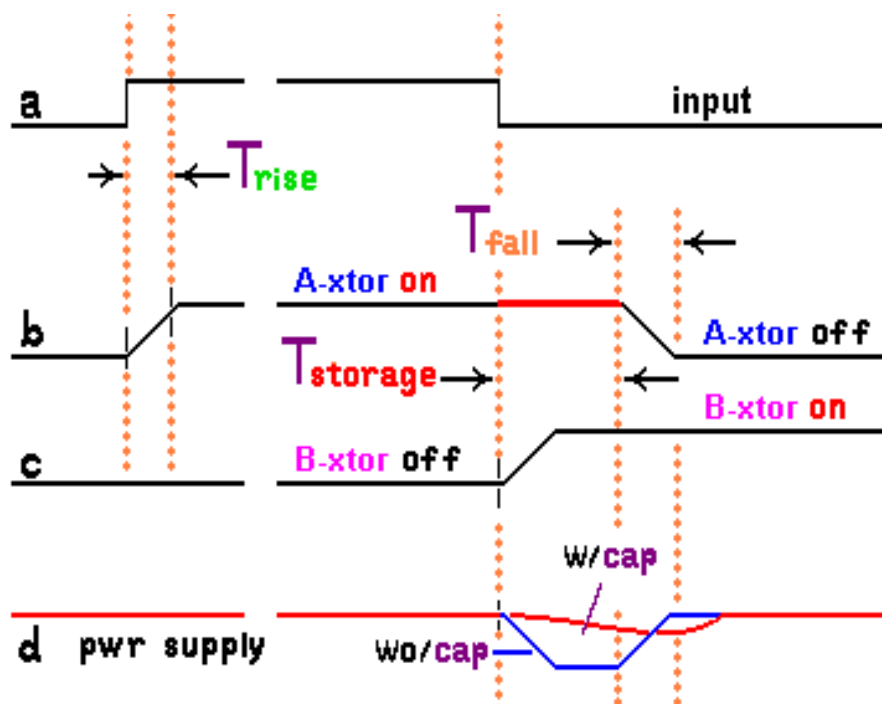
Transistor Transistor Logic (TTL) is one great source of noise.

In a typical TTL logic device (gate, flip flop, counter, register, etc.), it is fair to say that at any one time half of the transistors are on, and the other half are off. However, during logic transitions, for a very short time all of the transistors are on.

TTL is a "Saturating Logic." A transistor is either fully off or fully on. When it is fully on, it is said to be in V_{sat} .

A saturated transistor requires more time to become unsaturated than it took to become saturated in the first place. This time difference is called storage time (T_s).

Therefore, during any logic transition (one/zero or zero/one), all of the transistors are on for this short time (T_s), drawing approximately twice its normal current. This latency can last from two or three nanoseconds to as long as fifteen nanoseconds, depending on the logic family. (See figure below)



It takes longer to turn a transistor off than it takes to turn it on. The time to turn on (risetime) = T_r , the time to turn off (falltime) = $T_f + T_s$ (storage time). T_s is the time required for the hole/electron pairs to move back across the base junction, taking the transistor out of saturation (V_{sat}).

Although Shottkey devices (74S, 74LS, 74AS, etc.) were meant to eliminate this effect, there is still some storage time.

In systems using thousands to hundreds of thousands of gates, there can be a tremendous demand on the power supply. The power source must supply a constant, non-varying V_{cc} to a load that is random. The load is also very high speed (fast $d_i - d_o$, i.e., a large current change in a short period of time).

If one could supply power to all of the logic devices at a constant V_{cc} , everything would be peachy keen. However, Life—and Murphy—do not allow anything dealing with engineering design to be peachy.

As Mentioned Previously

Because there is distance between any power source and the logic it powers, obviously a conductor, wire, or trace of finite length is required between this power source and the logic.

Any conductor, wire, or trace have the properties of resistance and inductance. Both of these properties can cause problems where power is concerned. The resistance problem can be overcome by increasing the cross-sectional area. However, the inductive property is another story.

Even what might appear to be a small inductance, at high frequencies or very high frequencies can translate to an unacceptable high impedance.

As in the case of the amplifier, above, TTL logic devices have inputs and outputs. The power rail (the V_{cc} pin) can be both an input and output "port." The power rail is common to both input and output stages; the bias resistors of the input stage are connected to the same "rail" as the load resistors of the output stages.

This arrangement, again, presupposes that this common power rail will always be held at zero ohms! That is, it will be sourced by an ideal voltage source.

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Review

In the world of fast-edge, sensitive logic, it is a simple matter to conceive of "inappropriate communications" between logic devices (& elements within a device) through the unprotected, high impedance power rail (V_{cc}).

Because of the speed of this demand on the power supply--Rise and Fall times in the nanoseconds--the frequencies are in the many hundreds of MHz. Any conductor between the device power pin and the power source can look like an unacceptably high resistance--tens of ohms to hundreds of ohms.

Something as simple as placing a capacitor between V_{CC} and the ground of each logic device will effectively create this near Ideal power supply--zero ohms output impedance.

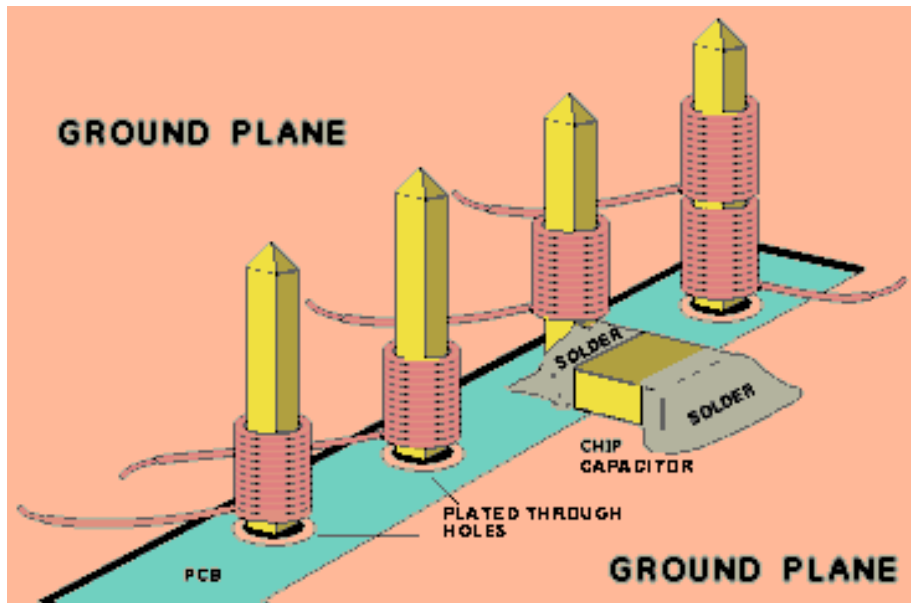
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An Alternative Way to View Bypassing

A bypass capacitor is like a voltage storage reservoir. It supplies instantaneous demand while recharging (from the power supply, via the inductive reactance of the connection) for the next demand.

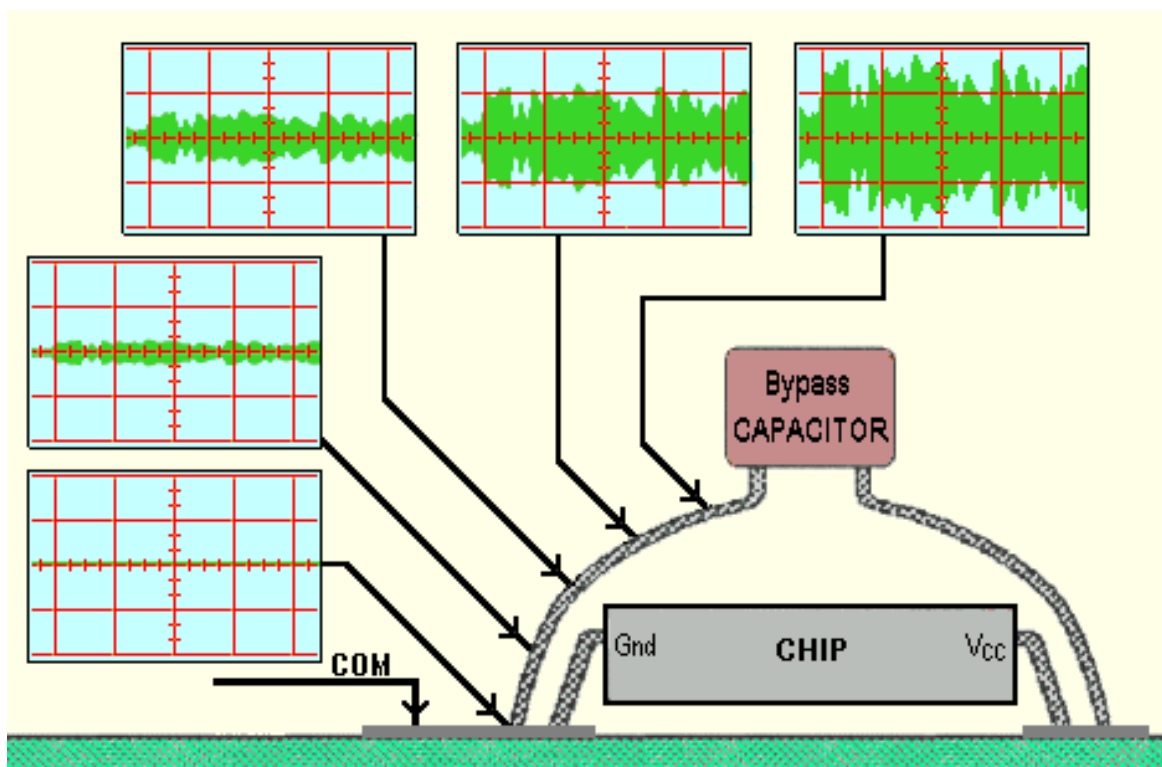
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Adding the Capacitor



Bypassing is the only way to maintain the integrity of the power distribution to the various circuits. It maintains the low impedance of the true voltage source. It counteracts the inductance of the finite length of the conductors that distribute the power to the circuits.

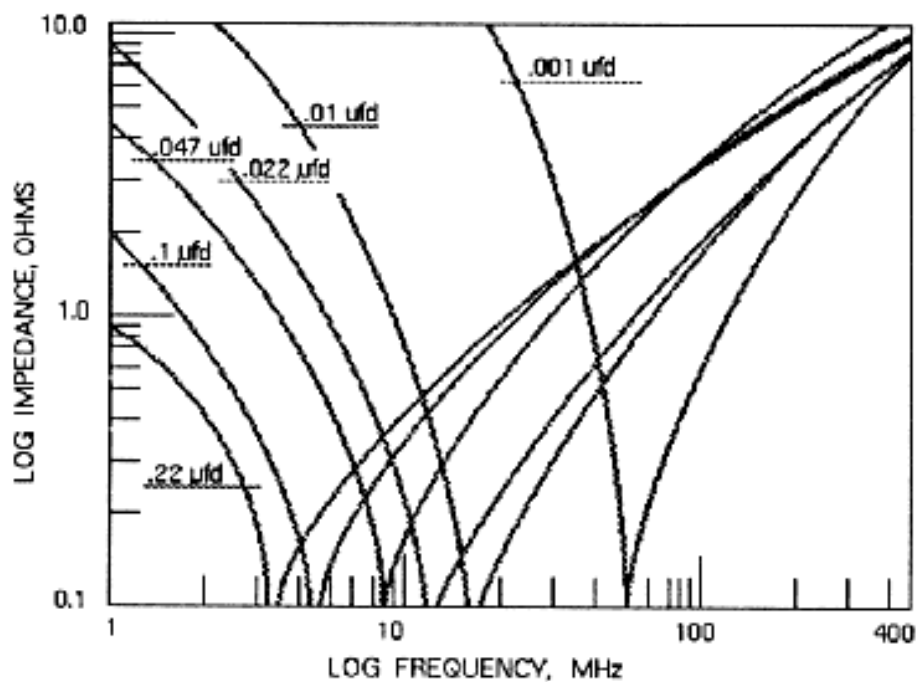
Bypassing is accomplished by applying a sufficiency of capacitance between the supply pin of each device (or stage) and ground (or common) using the shortest path possible.



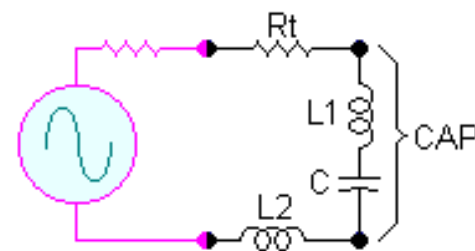
This illustration shows the effects of inductance in excessive lead length.

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Capacitor Self Resonance



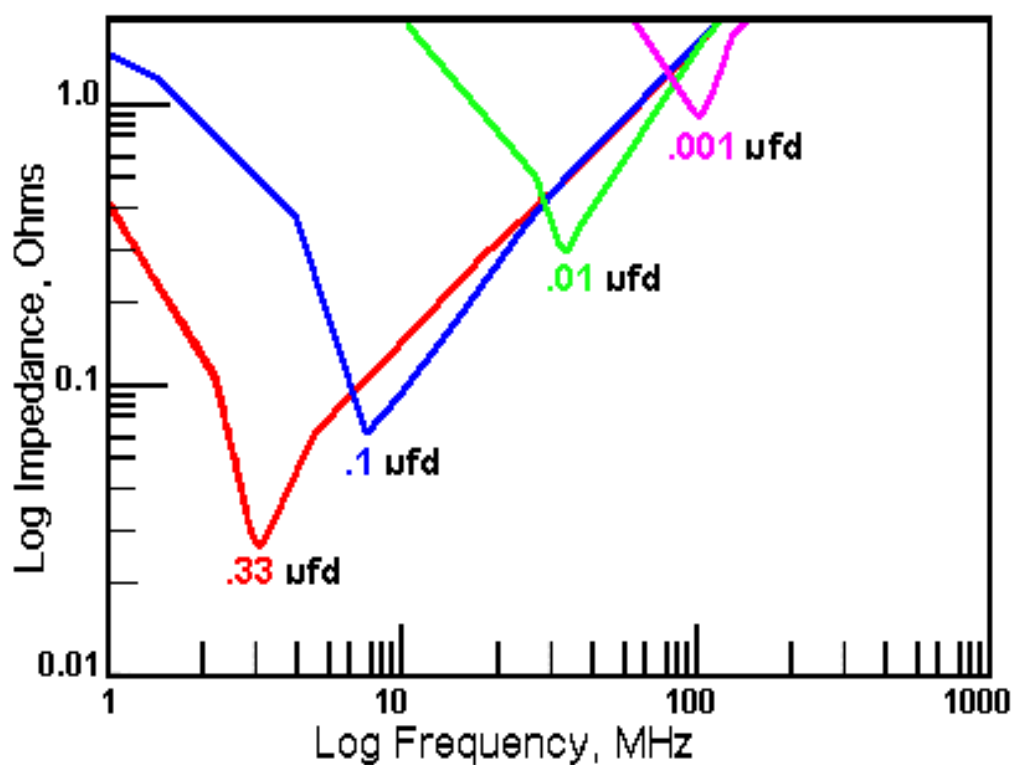
Bypass Capacitors' Self Resonance



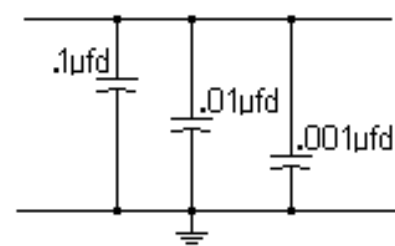
L_1 and C represent the capacitor and its leads.

R_t and L_2 are Parasitics found in bypass capacitor interconnection.

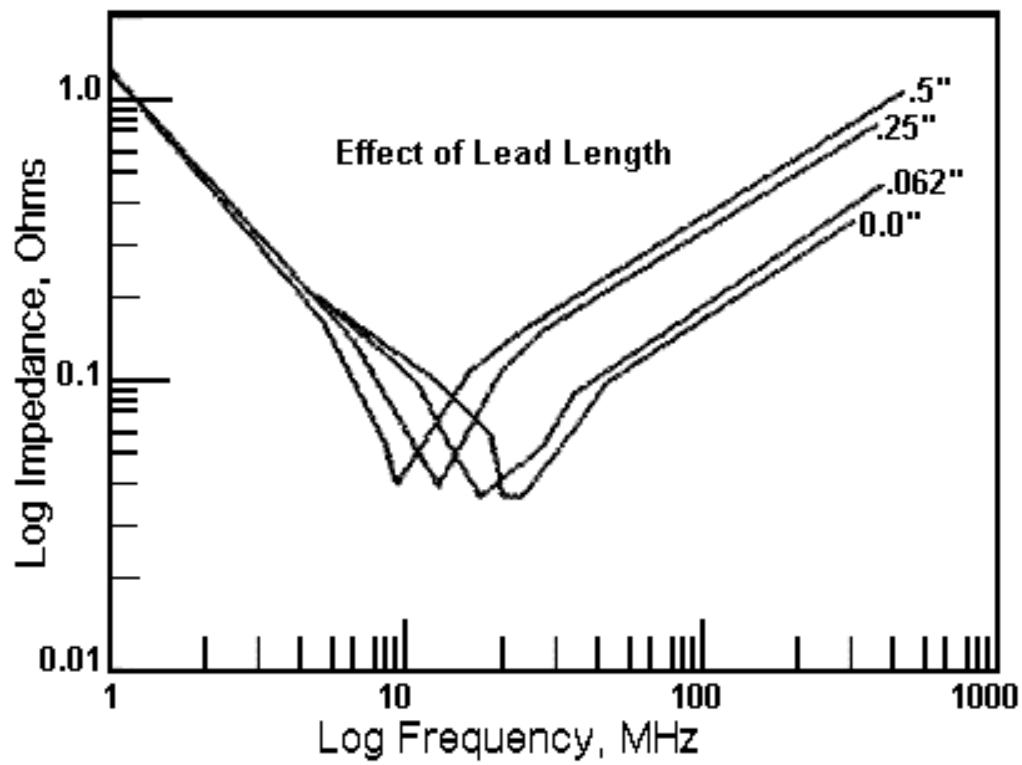
Note
simplified equivalent circuit of installed bypass capacitor.



Bypass Capacitors' Minimum Impedance at Self-Resonance



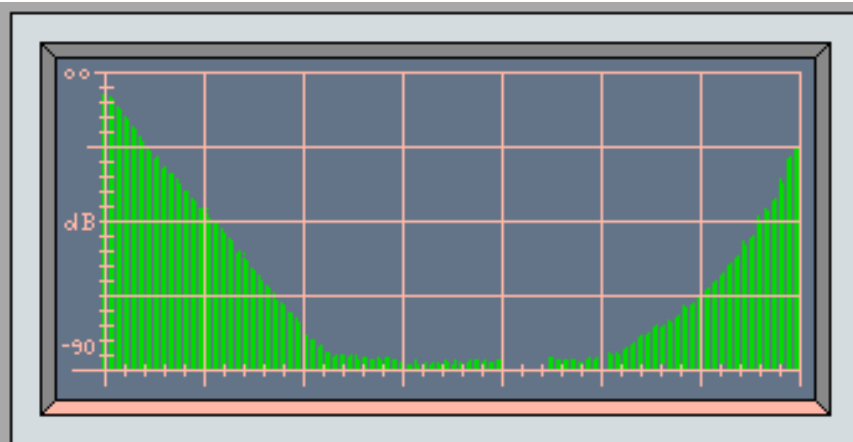
This illustration shows paralleling bypass capacitors for maximum effectiveness.



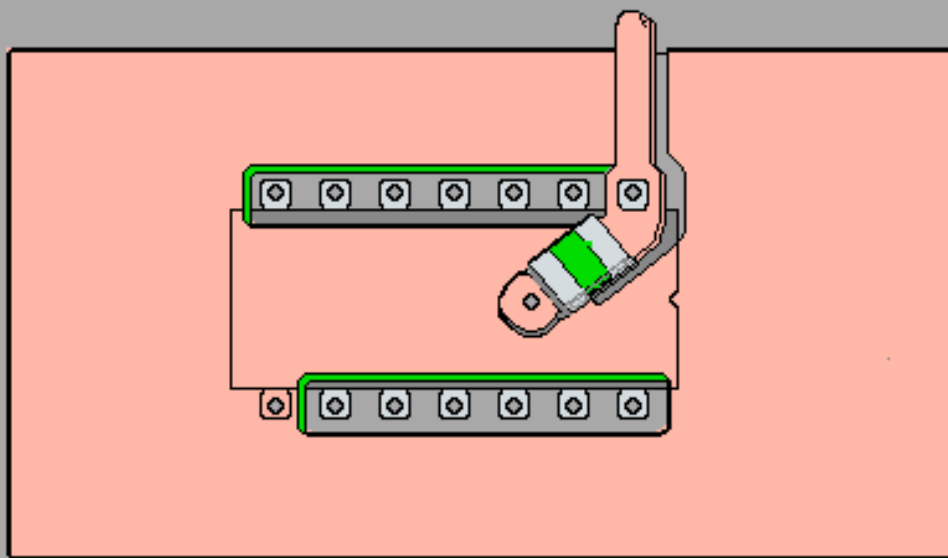
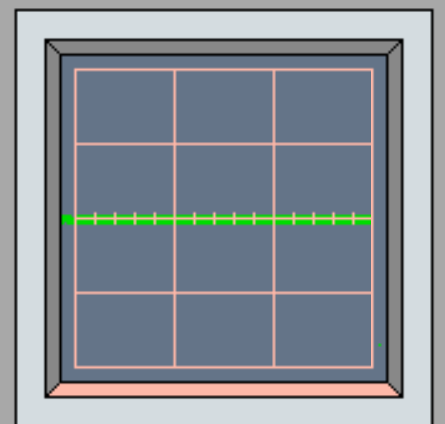
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The Effect of Lead Length, Capacitor Type, & Layout on Bypass Capacitor Effectiveness

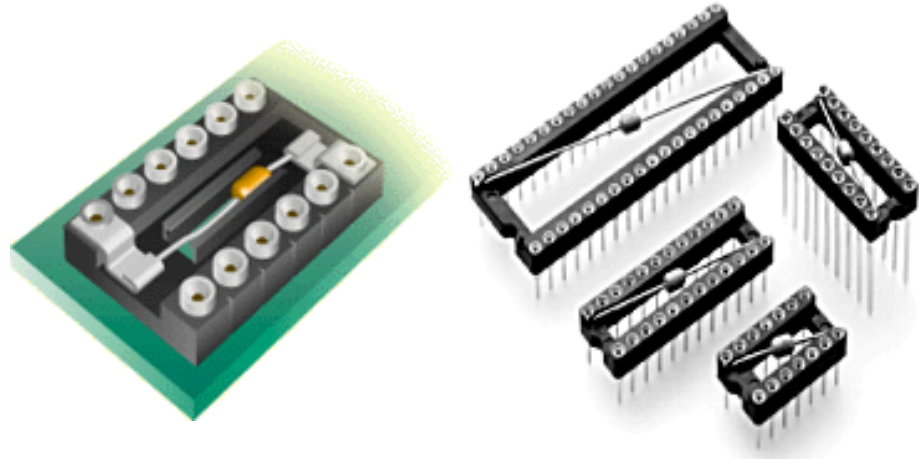
Frequency Domain



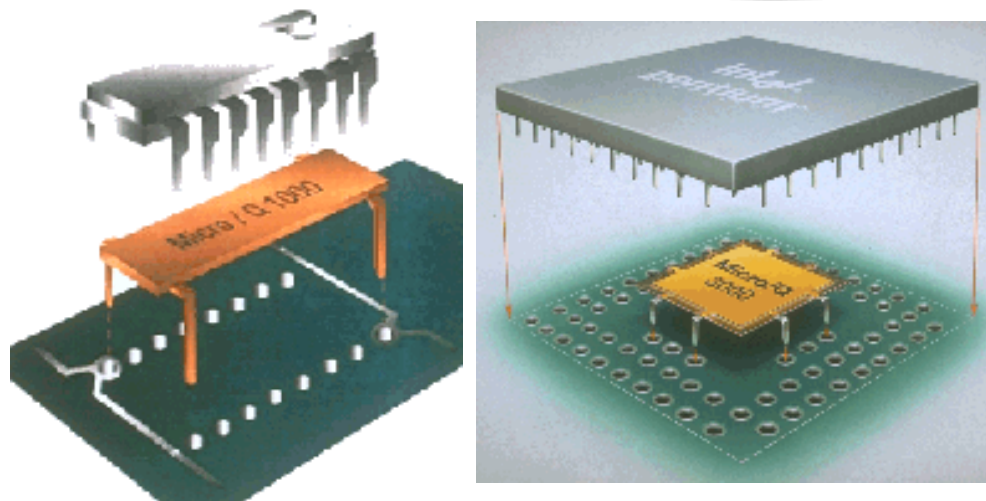
Time Domain



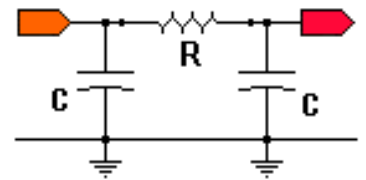
In this example, bypassing becomes more effective as the ground conductor approaches a continuous plane. Ground planes are often used in high-frequency circuit boards for this reason.



In these illustrations bypass capacitors are built in as part of the IC socket.

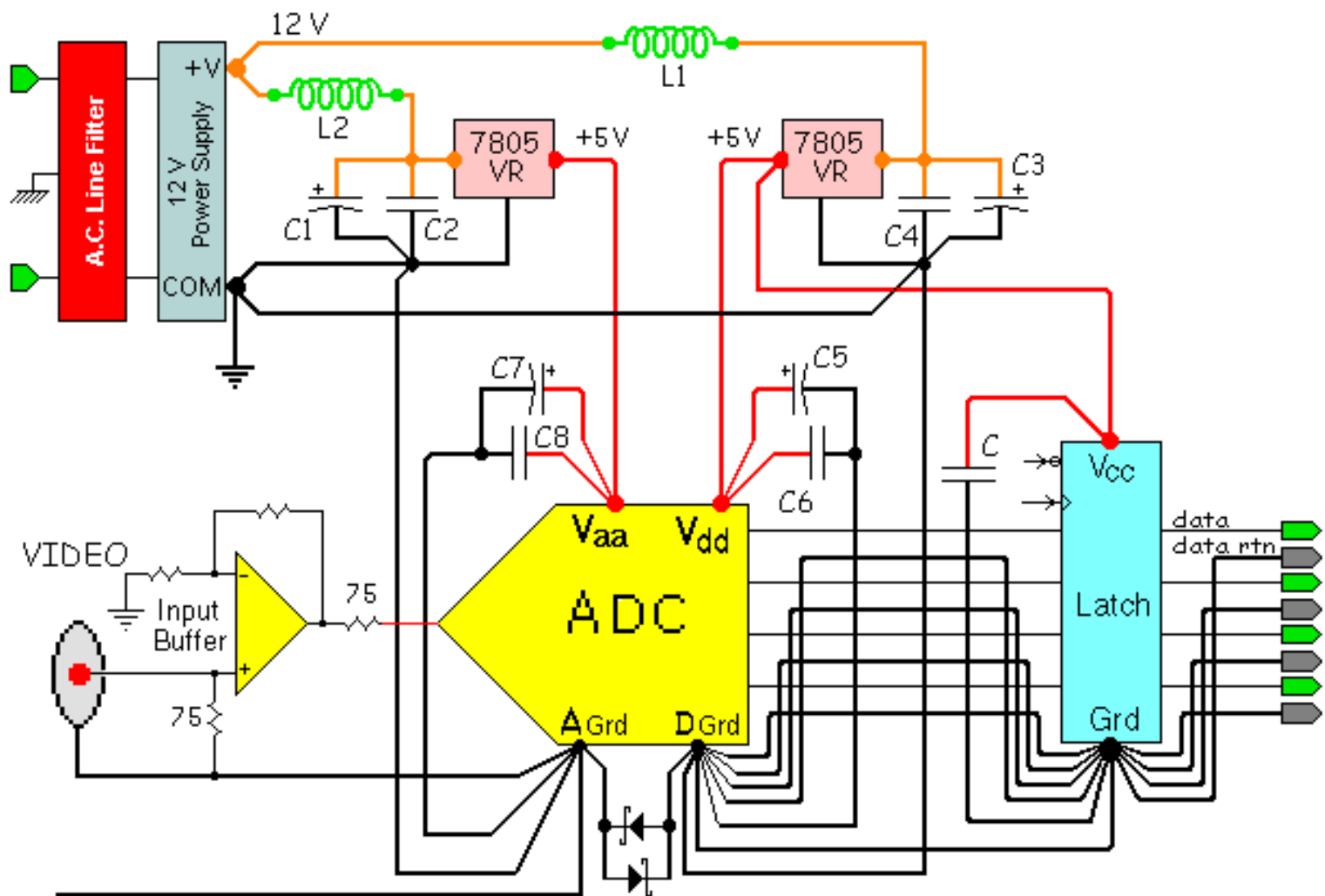


These illustrations show decoupling power distribution and bus bars.



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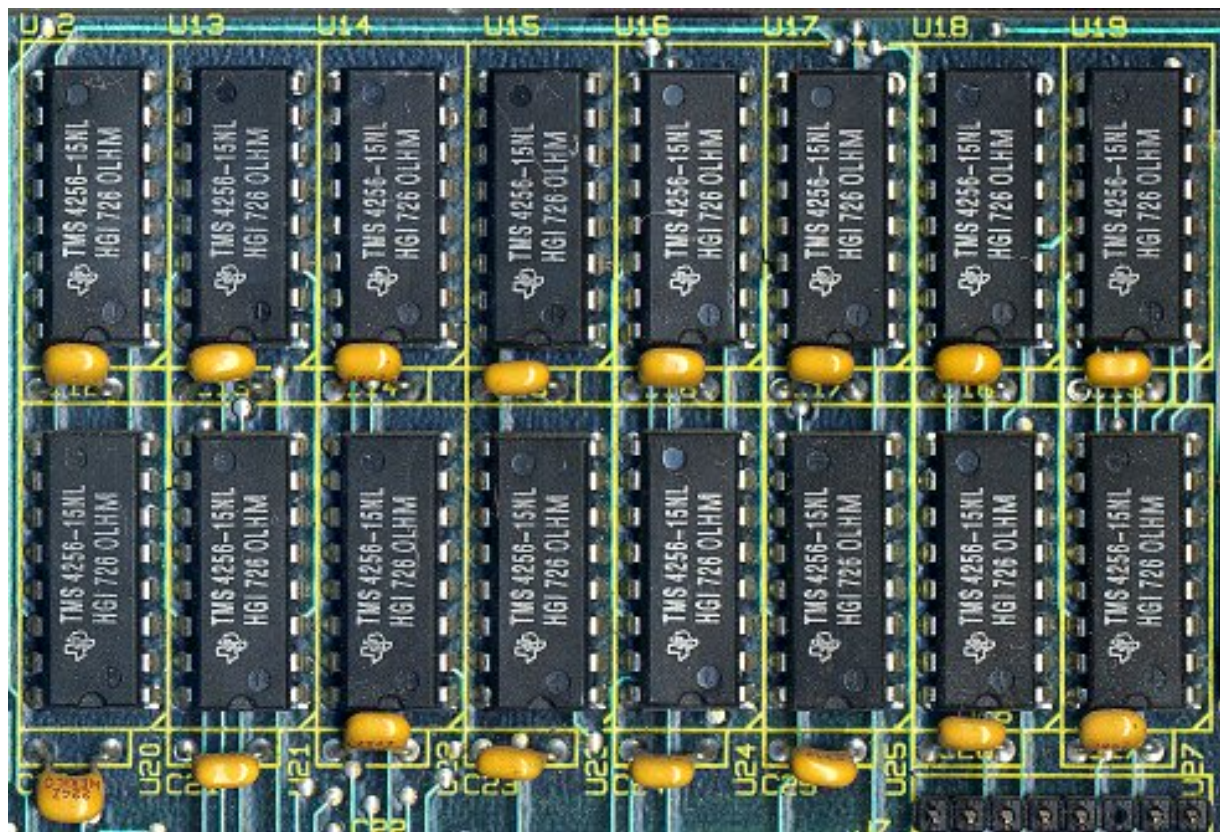
Powering both Analog and Digital



In addition to bypassing, there are instances where decoupling is appropriate (especially when powering both analog and digital from the same power supply).

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Memory Chips with Bypass Capacitors



(Note: one per device.)

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CIRCUIT INTEGRITY

■ Module 2: Decoupling

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- [How Do We Decouple?](#)
- [Definition: Ideal Voltage Source](#)
- [Methods of Decoupling](#)
- [Something to Remember](#)
- [R L C Filter Refresher](#)
- [Discussion: What If?](#)
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- [Discussion: Some Reasons](#)
- [Cascaded Amplifier](#)
- [Recap](#)
 - [Ideal Voltage Source](#)
 - [Power Rails](#)
- [Discussion: High Q](#)
- [Linear Voltage Regulators as Decoupling Devices](#)
- [Points to Ponder](#)
- [Bus Bars](#)

Decoupling Defined

Decoupling

An element that is a loss-less path for direct current and an infinite impedance for alternating current. This element allows devices to be powered with no loss and prevents any noise from moving from one load to the next.

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Introduction

Although bypassing and decoupling are rarely covered in the classroom, they are emphasized in nearly all data sheets and application notes.

So while some new engineers and technicians ignore these topics, they do so at their peril. Failure to address these topics is often the reason for hardware debugging problems!

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What Is Decoupling?

Decoupling is a refinement of bypassing. Because of bypassing's finite limitations in creating the ideal voltage source, the decoupling (isolation) of adjacent noise sources is often required.

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Why Do We Decouple?

Decoupling prevents unwanted communications between different devices (or different stages of the same device) that share the same power rail. Decoupling reduces the noise present on that power rail, at all frequencies.

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How Do We Decouple?

Decoupling completes the implied "RC" (LC) part of the network: the series element (as in a lowpass filter).

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Definition: Ideal Voltage Source

Ideal Voltage Source

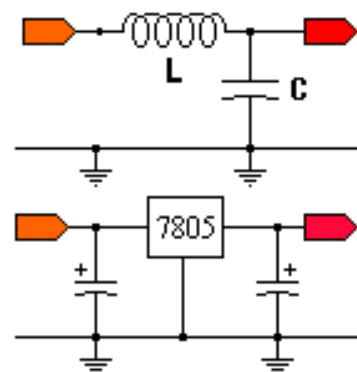
Furnishes a constant voltage output, regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

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Methods of Decoupling

Classic decoupling (see figure at right) uses an "LC" network (lowpass filter).

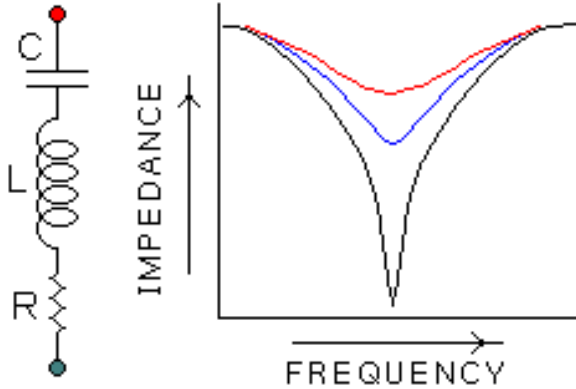
A not-so classic method of decoupling, uses a voltage regulator in place of the LC network (see figure at right).



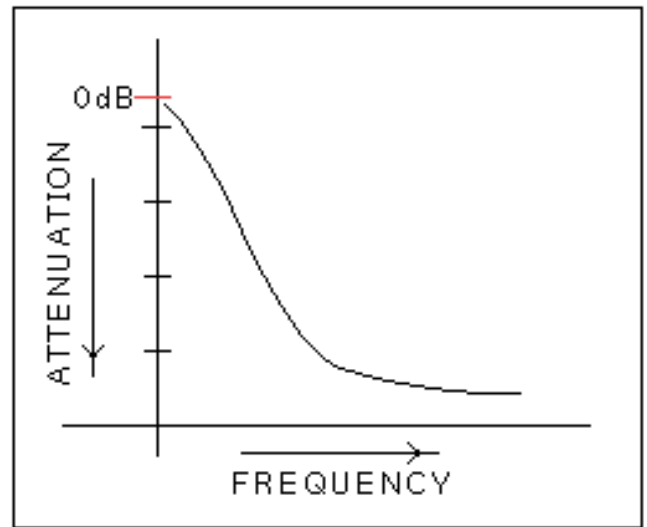
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Something to Remember

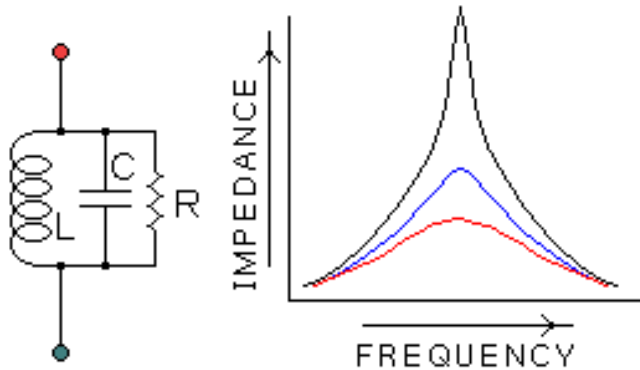
The ideal decoupling device is a loss-less path for DC, and an open circuit for AC.

[back to top](#)**R L C Filter Refresher**

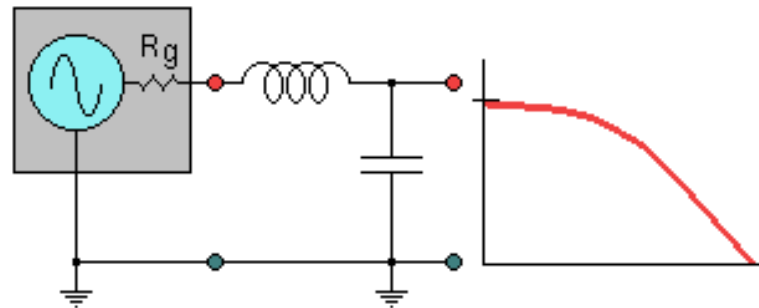
Series Resonant R L C Circuit (notice the effect of increased R, red, and blue plot)



Noise Attenuation of Decoupling and Bypassing



Parallel Resonant R L C Circuit (notice the effect of increased R, red, and blue plot)

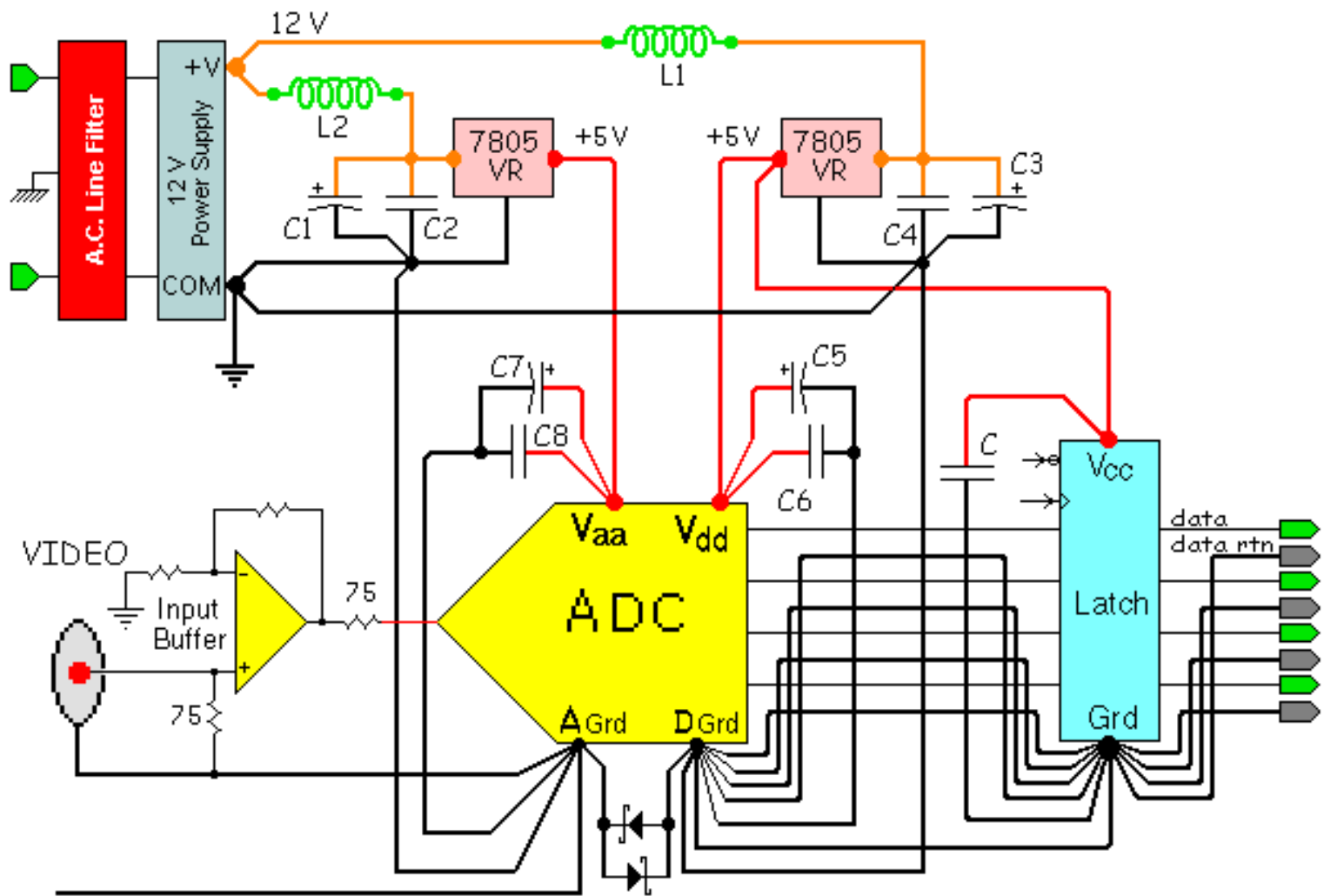


Low Pass Filter = Decoupling and Bypassing

[back to top](#)**Discussion: What If?**

What if the power distribution between stages cannot be sufficiently bypassed? You might be tempted to use several different power supplies. However, by supplying the DC power to each stage through a separate inductor or "RF choke," while also bypassing that stage to ground, the effect can be nearly the same. That is to say, the choke offers a high-impedance path to any errant signals or noise between stages, while offering a very low resistance path to the DC power. This is decoupling.

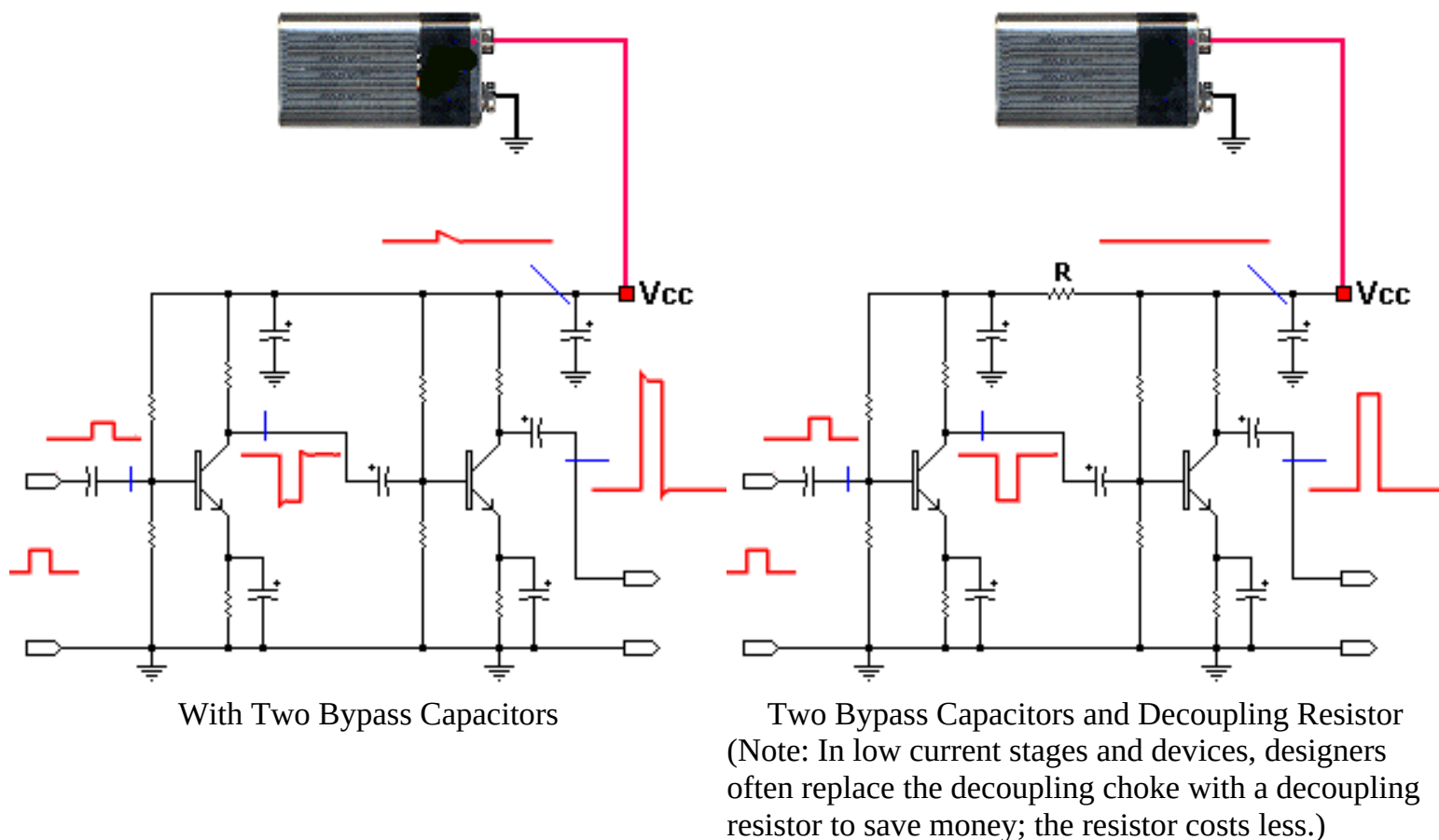
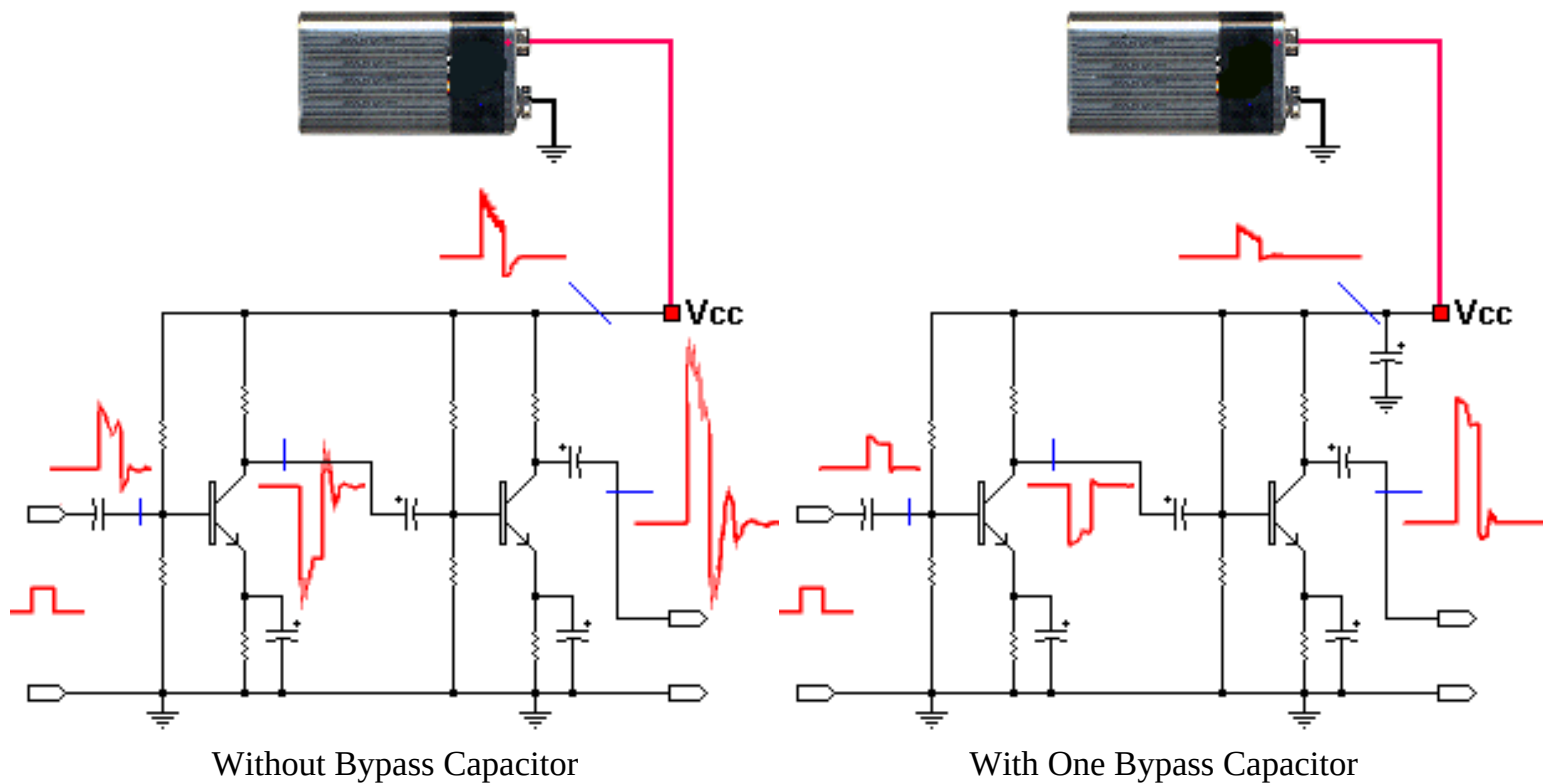
Active devices such as voltage regulators can also be used for decoupling stages. In fact, considering the size of inductors as compared to surface-mount voltage regulators, regulators might be the better choice. Recall that a choke or inductor is one of the two needed components for a Resonant circuit. Therefore, the combination of decoupling inductor and bypass capacitor could just happen to resonate at the wrong frequency. Having said that, it might appear obvious that the inductor needs to be as small a value as is reasonable, and the bypass capacitor as large as practical. This fact is essentially correct: however, there is still the possibility that the resonant frequency of this combination could cause mischief. If that weren't enough, the inductor can be self-resonant. This problem is caused by the distributed capacitance between windings; i.e., one turn of wire to the adjacent turn of wire, and so on.

[back to top](#)**Powering both Analog and Digital**

The figure above shows that sometimes both types of decoupling are appropriate. This is especially true when powering both analog and digital from the same power supply.

[back to top](#)**RC Amplifier**

The illustration below shows an RC amplifier with various degrees of power supply stabilization in the form of bypass and decoupling.



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Discussion: Some Reasons

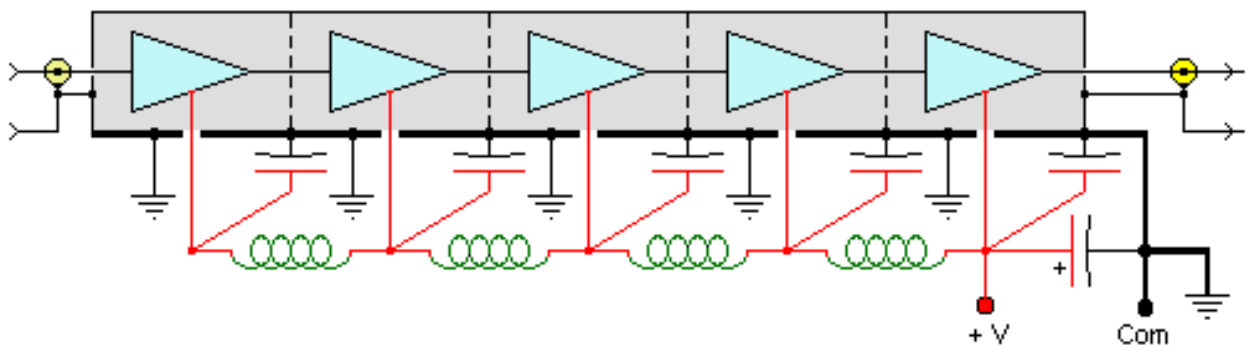
Bypassing, decoupling, shielding, and groundplanes are the elements that allow circuits -- analog and digital-- to function properly. The reason is simple. Let's say you have a cascade of amplifier stages such as the one illustrated in the next section. The stages are boosting or amplifying an otherwise weak signal. The input is

very sensitive to small signals, and successive stages are drawing progressively more current in order to produce the larger replica of this weak input signal. In doing so, the output stage draws large amounts of current at varying rates. This large varying current is seen by the more sensitive input stages through the common power supply rail, which serves all stages. This situation can happen if the power rail, be it wire or PCB traces, is of sufficiently high impedance.

Even if the power supply were ideal (zero ohms), this can still happen. As the frequencies go higher, the inductive reactance, of the leads or PCB traces, increases. For example, if some fast transitions of the input signal caused a resulting perturbation on the power supply rail to propagate down that rail to all of the other circuits, the resulting effect can be oscillations (or some sort of instability) that could cause distortion or even render the circuit inoperative. Think of the effect as inappropriate feedback between stages, facilitated by the power rail not appearing as a virtual AC ground.

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Cascaded Amplifier



The figure above illustrates a bypassed and decoupled cascaded amplifier, with distributed power to cascaded amplifier stages (in essence, a "n" order lowpass filter).

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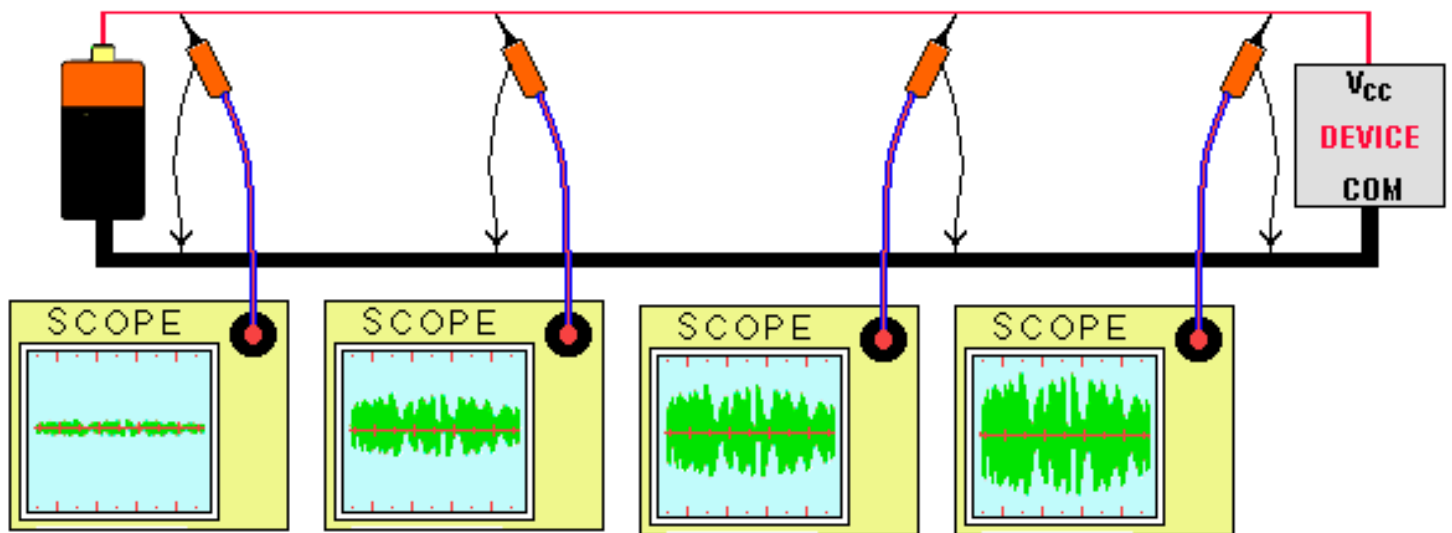
Recap

Intrinsic inductive reactance (X_L) in power distribution.

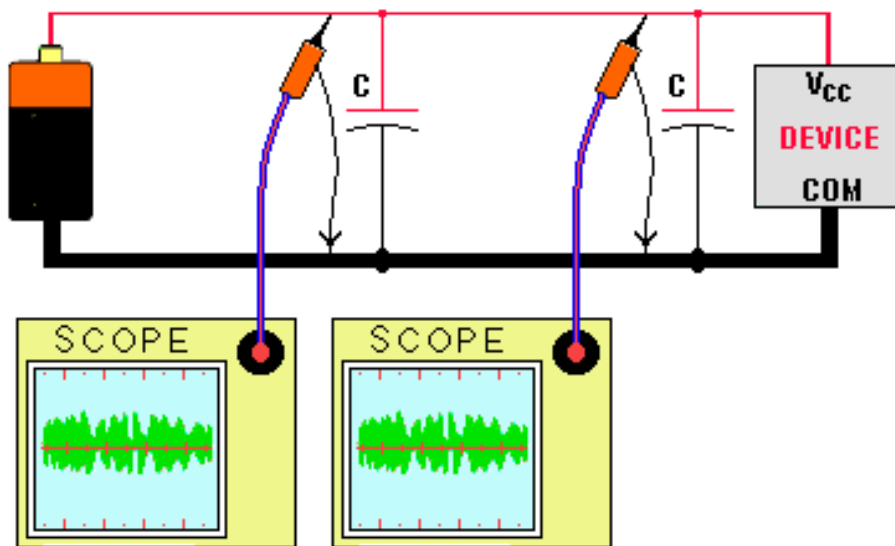
Ideal Voltage Source

The ideal voltage source furnishes a constant voltage regardless of the load or load variations. The output impedance = zero ohms at all frequencies and in all conditions.

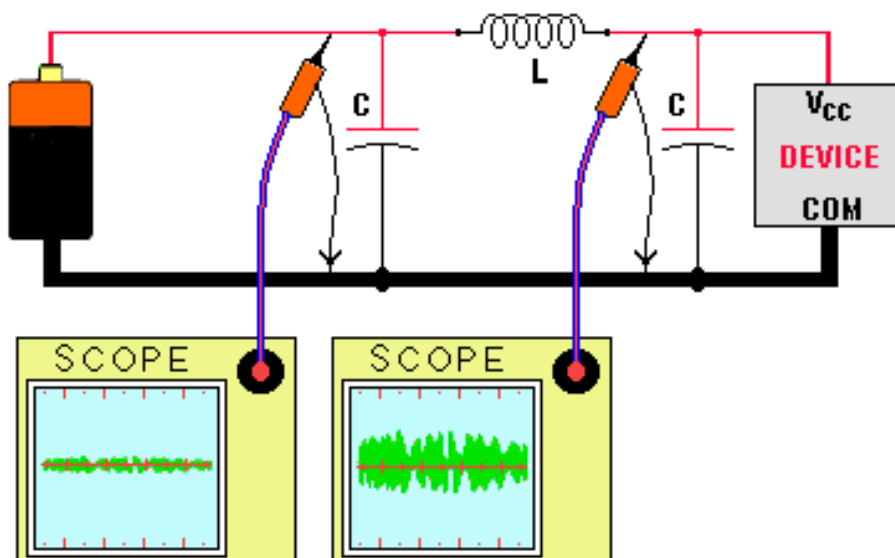
Power Rails



In the illustration above, the "intrinsic" inductive reactance (X_L) of the finite length conductors affects this zero ohms impedance.



Adding bypass capacitors to the intrinsic inductive reactance helps to restore the (virtual voltage source) zero ohms impedance.



Adding even more inductance in the form of a "decoupling inductor" isolates the bypassed device(s), further

helping to restore the (virtual voltage source) zero ohms impedance.

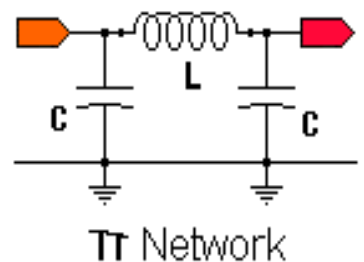
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Discussion: High Q

One more thing to consider about chokes: the "Q" (quality of the inductor) has an effect on its efficiency. As previously stated, the inductor should appear as a perfect path to the DC power it is carrying and a high impedance to any AC (i.e., no series "R."). But in the real world this isn't feasible. If heavy-current-carrying chokes are required, then the choke must have higher Q (i.e., less wire which means lower "R"). This can be achieved by using chokes with ferrite cores, which need considerably less wire for the same value of inductance. The core can be viewed as a multiplier of Q. Small donut - or tubular-shaped ferrites called beads are regularly slipped over leads to act as decouplers. One popular use for ferrite beads is to suppress parasitic high-frequency oscillations in circuits where the gain device (such as a transistor) has significant high-frequency gain.

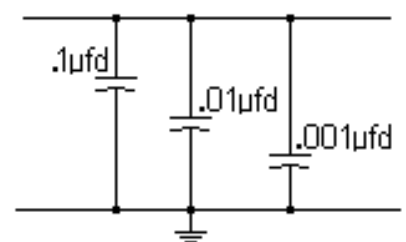
1. One of the most efficient inductors is the ferrite toroid. It has high Q (low R). Because of its toroidal shape, its fields are confined, which minimizes its interaction with other circuit elements.
2. There is always some decoupling built into any circuit. The power conductors act as decoupling inductors. Although short trace lengths are usually desirable, longer ones sometimes actually improve decoupling. However, don't forget that long ground traces or conductors never help. They make effective bypassing impossible!
3. The down-side of ferrite is that it will change inductance as the current or flux changes. In the case of large currents, ferrite can saturate. However, by correct component choice -- frequency, AC and DC current, etc. -- ferrite is a great tool for the designer.

4. LC decoupling is used where the supply voltage cannot be lowered. For example, what if one needed a noise-free +12 volts on a PC bus? You could get a "clean" +12 volts with a voltage regulator; if only there was +15 volts or higher to start with. But this is not the case. So you use a high Q inductor (RFC choke) along with the proper bypass capacitors to effectively lowpass filter the +12 volt supply rail. For a very noisy supply, you can use more than one network (one or more "pi" networks).



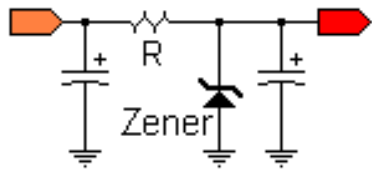
5. One of the most efficient inductors is the ferrite toroid. It has high Q (low R) and because of its toroidal shape, its fields are confined, and therefore it has less stray fields. The super star of high Q inductors or transformers is the pot core. Also, don't forget the ferrite bead. Thread the wire through the bead once or several passes and it may be just what the doctor ordered.
6. Decoupling is only as good as the components that you use. The capacitor part of the network should be of high Q and minimum inductance. The noise is dropped across the inductor, and the capacitor must exclude the remaining noise. In a perfect world the inductor is an open circuit to noise (AC) and the capacitor is a dead short -- Zero, Nada, Caput, Zilch. The slightest inductance in series with that capacitor, and some very high-frequency noise will come through like Gang Busters!

7. SMT or chip capacitors made of ceramic are best. Sometimes in critical circuits, several sizes of capacitors in parallel are appropriate, e.g., 1 μ fd || .1 μ fd || .001 μ fd, etc. The reason for this is that as the capacitors become smaller in value, they also get physically smaller, hence there is less inductance. However this is less the case with SMT caps. Consult your capacitor data sheets for the impedance verses frequency plots. ([See impedance verses frequency plots.](#))

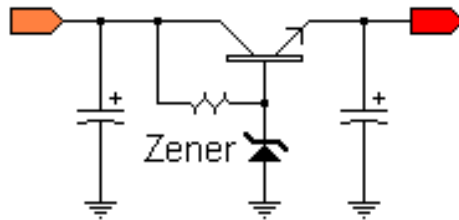


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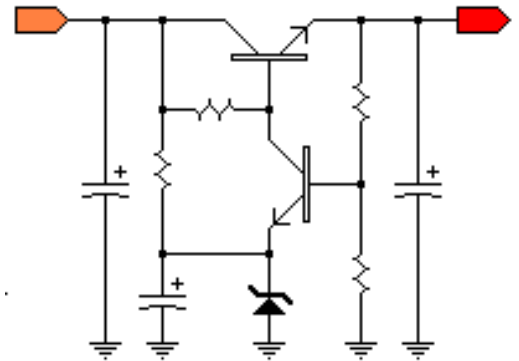
Linear Voltage Regulators as Decoupling Devices



Simple Shunt Regulator



Simple Pass Regulator



Pass Regulator with Gain

The use of three terminal linear voltage regulators, like the 78xx and 79xx devices, is fairly straightforward. However, there are a few things to remember. Always bypass -- there's that word again! -- the input pin to the common pin with a ceramic capacitor no smaller than 0.33 ufd, and use absolutely the shortest leads possible. (There are some transistors with pretty high f_t in that regulator, and if you furnish enough reactance of the wrong kind, Mr. Oscillation will visit.)

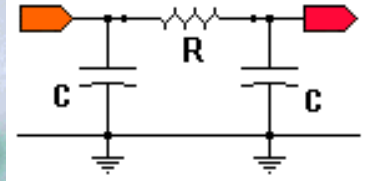
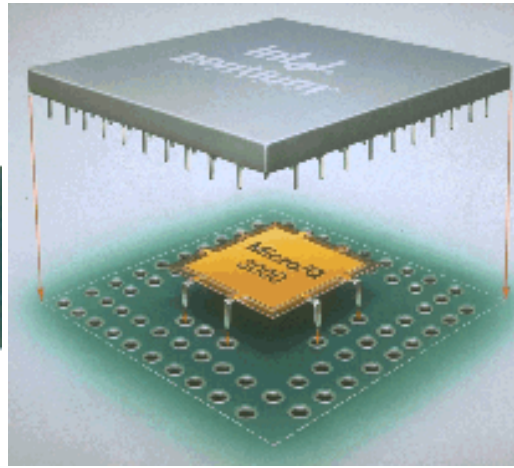
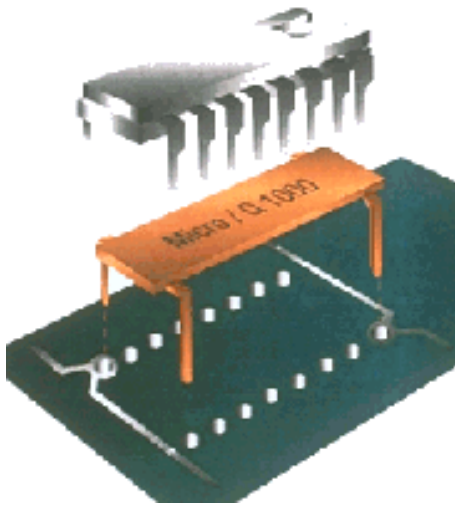
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Points to Ponder

1. Unlike bypassing, decoupling is not always used. In fact, decoupling is typically used as a last resort if bypassing fails to give the wanted power-supply stabilization.
2. There is always some decoupling built into any circuit. The very inductive reactance bypassing is meant to overcome are the power conductors. In essence, these conductors act as decoupling inductors. Although short trace lengths are desirable, the power lead being long can sometimes actually improve decoupling.
3. The simple addition of ferrite to these conductors enhance this natural decoupling inductance, sometimes eliminating the need for a special decoupling inductor.
4. The best all around decoupling device is in fact not an inductor, but a voltage regulator (especially the LDO or low drop out regulator).

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Bus Bars



Above are examples of "decoupling" power distribution bus bars.

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CIRCUIT INTEGRITY

■ Module 3: Groundplane

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- [Why Do We Use a Groundplane?](#)
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Introduction

A groundplane serves as the return path for all currents. Like bypassing and decoupling, although the groundplane is a topic that is rarely covered in the classroom, it is emphasized in many application notes, and it is used in most real designs.

Again, the problem this creates is that many design engineers and technicians ignore it at their peril!

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What Is a Groundplane?

A groundplane is the return path for all currents, signal, and power.

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Why Do We Use a Groundplane?

It is desirable to not have different signals sharing the same ground return paths; the groundplane helps in that goal.

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How Do We Use a Groundplane?

A continuous conductive planar, having no discontinuities, is the ideal groundplane.

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Discussion: An Overview

A groundplane is a crucial component of any circuit. In essence, it is the return path for all signals, including the power distribution. The groundplane can be thought of as homogeneous for the DC power only. In all other situations, it is strictly inhomogeneous, which means strictly that all grounds are not the same.

Various circuits use the ground plane for their signal and power return paths. Thus currents conducted and induced are caused to flow throughout the groundplane. Such currents can potentially affect any or all other circuits or signals, and thus they can cause problems.

One can start to understand the function and design of groundplanes by completing the following:

1. Draw a map of all signals in a circuit, their inputs, outputs, paths, and their various connections to and from the groundplane.
2. Then model the inductances, capacitances, and parallel and series resistances. Note the power distribution paths and returns, and their respective noise content.
3. Remember all bypassing and decoupling devices and contributions of each to the model.
4. Since the groundplane is mostly inductive, take note of any other inductances' proximity to the groundplane (such as shields, transformers, chokes, tuned circuits) and their contributing fields at all relevant frequencies.

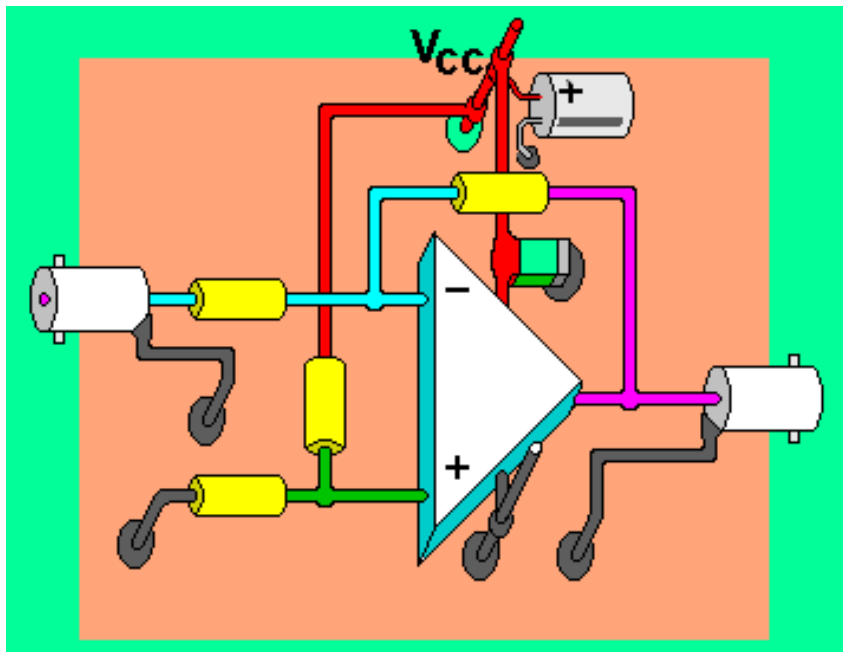
It has been said, "There are only two ways to model the groundplane in a complex signal environment, and nobody knows what they are!"

Good Luck!

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Something to Remember

All grounds are not the same.



This illustration (left) shows an op amp using groundplane for all return currents.

A groundplane in action!

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Return Paths

The illustration below shows a DC layout, functional diagram power and ground, and signal distribution.

In an ideal ground return system, every current has its own separate return path and does not share return path copper.

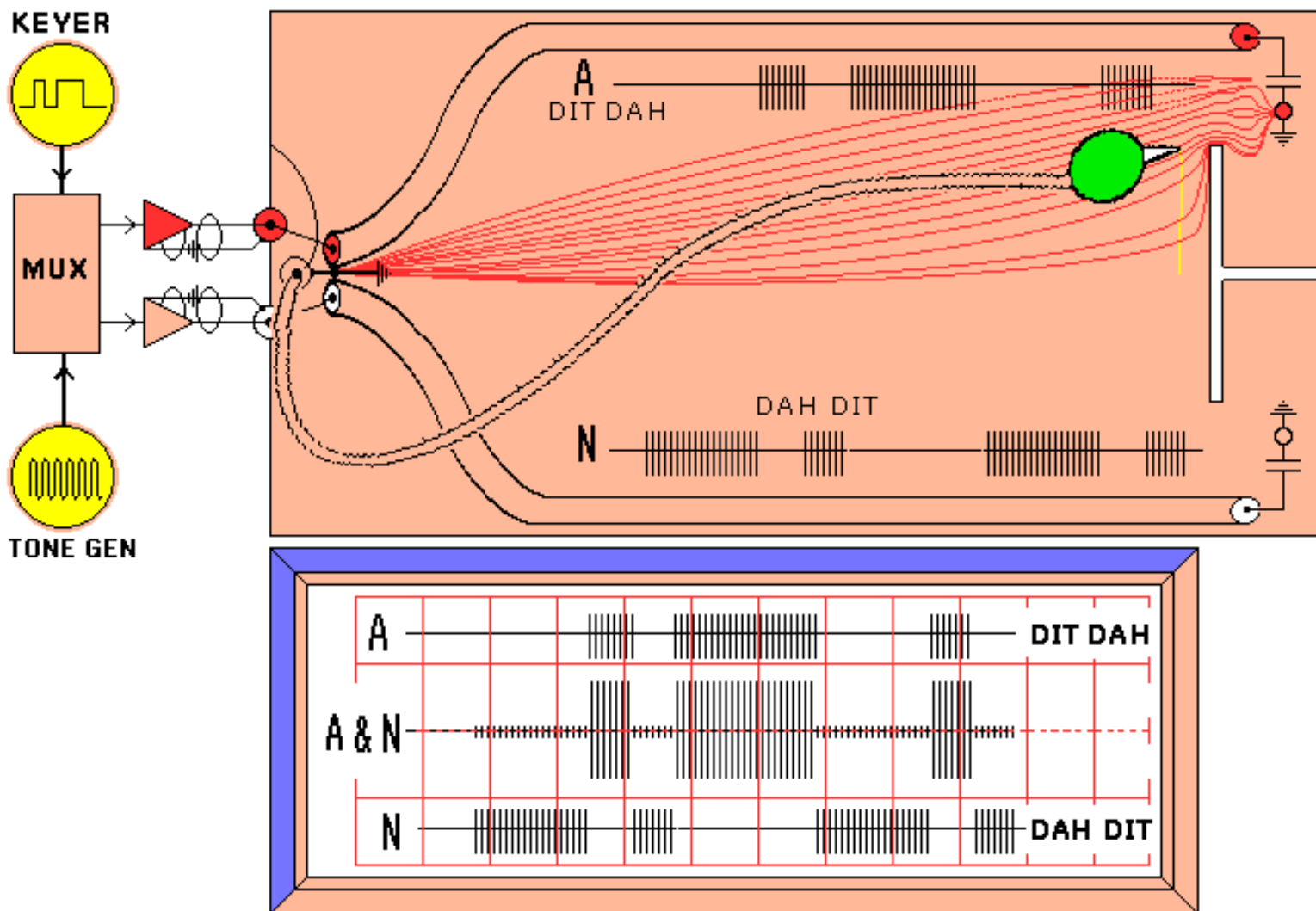
Demo: Return Currents in a Groundplane

Because A and N are complements of one another, if both signals were summed using equal weights, there would be a continuous tone. If either signal were stronger or weaker than the other, there would be a (faint) A or N with a continuous tone in the background.

In the demo, a signal tracer (green probe) is moved across the groundplane. The tracer senses the return currents in the copper-clad groundplane. At either extreme, the Morse code A or N is clearly heard. At mid point, the two signals are of equal levels and appear as a continuous tone.

(Demo not synchronized to animation)

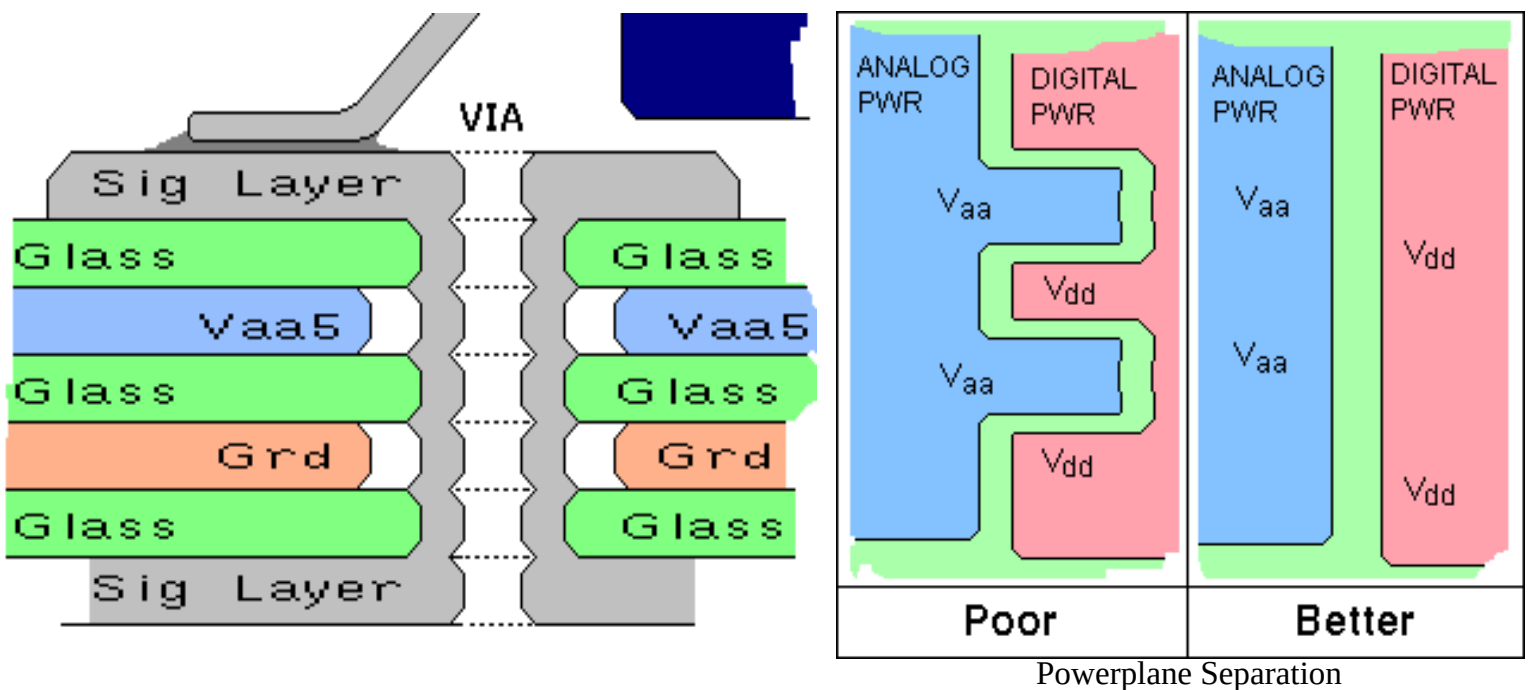
http://www.glencoe.com/ps/ee/williamson/groundplane_print.html (3 of 9) [3/12/2004 17:48:54]



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Groundplanes and Powerplanes

Multi-layer printed circuit boards allow for the use of powerplanes and groundplanes.



Powerplane Separation

The use of multi-layer printed circuit boards allows the use of multiple ground planes, as well as buried (under the signal layers) power and ground (V_{cc} and Gnd) layers. These layers are sandwiched together and act as a very efficient distributed bypass capacitor. A variation of this has the power and ground (V_{cc} and Gnd) layers as the outer or intermediate layers, thus shielding the buried signal layers; or some combination thereof. [See EMC](#)

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Resonant Groundplane

The less homogeneous these planes are, the more difficult it is to maintain the circuit's integrity. There can be myriad circuit parasitics (resonant tuned circuits, etc.), especially in the groundplane.

As it turns out, a homogeneous plane (e.g., a shield, etc.) could be placed over the less homogeneous groundplane, these resonant circuits could be made less detrimental. (See the resonant groundplane demo that follows this section.)

In the real-world printed circuit board above, these parasitics can be reduced by the proper placement and layout of the powerplane(s). That is to say, the close proximity of the co-plane reduces the parasitic inductances while raising the resonant frequencies. This lowers the overall groundplane impedances. Also, the shunt "R" diminishes the "Q". --All of which is GOOD.

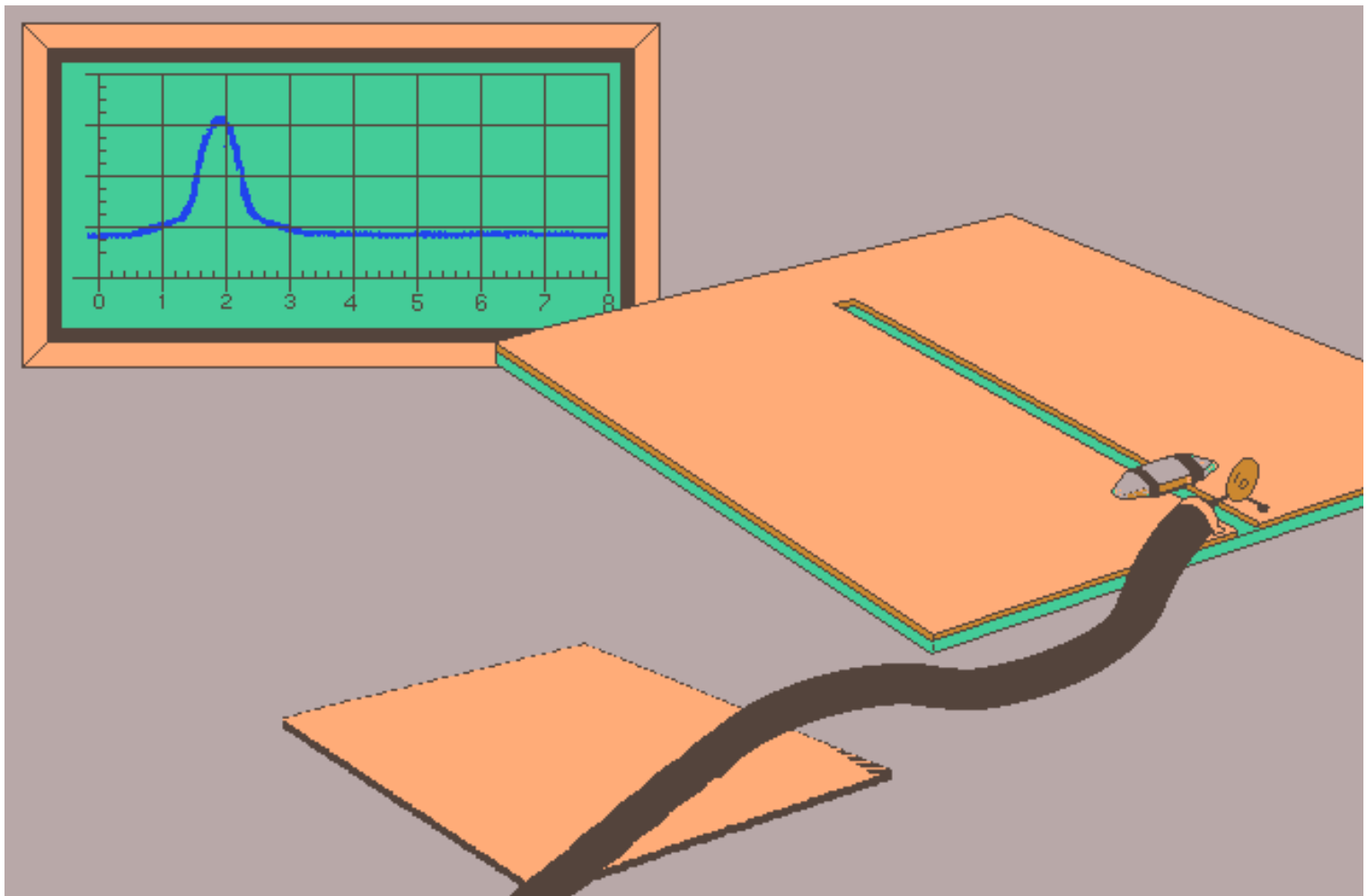
Parallel inductors = less inductance

So far, we have discussed a simple example of what can be a very complex problem. It is also possible to have a non-homogeneous groundplane (many apertures) with many different return currents from many different devices running at various rates; having rise and fall times from a few nanoseconds, to fractions of a nanosecond; with all currents sharing the groundplane as their return paths.

This situation can give rise to device oscillations and instabilities, generating noise and crosstalk. This effect is due to the imperfect AC grounding of active devices, and the many parasitic reactances that inhabit the circuit and board topology. This complex environment could, I suppose, be analyzed and the "tuned circuits" identified. --you get the idea.

The use of good groundplane design is important, especially in a mixed signal environment, analog and digital. The next figure shows an experiment that I call a "resonant groundplane."

In this example, the animation shows a 4" X 6" copper clad board. A narrow (1/8") strip of the copper cladding was peeled almost the length of the board, such that electrically it looked like the letter "U." A 0.33 μ fd capacitor is soldered at the edge of the board where the peeling began, bridging the planes on both sides of the narrow gap. Then both sides are driven (the capacitor is shunting) with a loosely coupled sweep (signal) generator and adjusted until the resonance is found. The display presentation is of a swept network having a definite resonance. A separate homogeneous groundplane is then brought into close proximity. This causes the resonant frequency to increase, as well as causing the "Q" of the resonance to diminish.

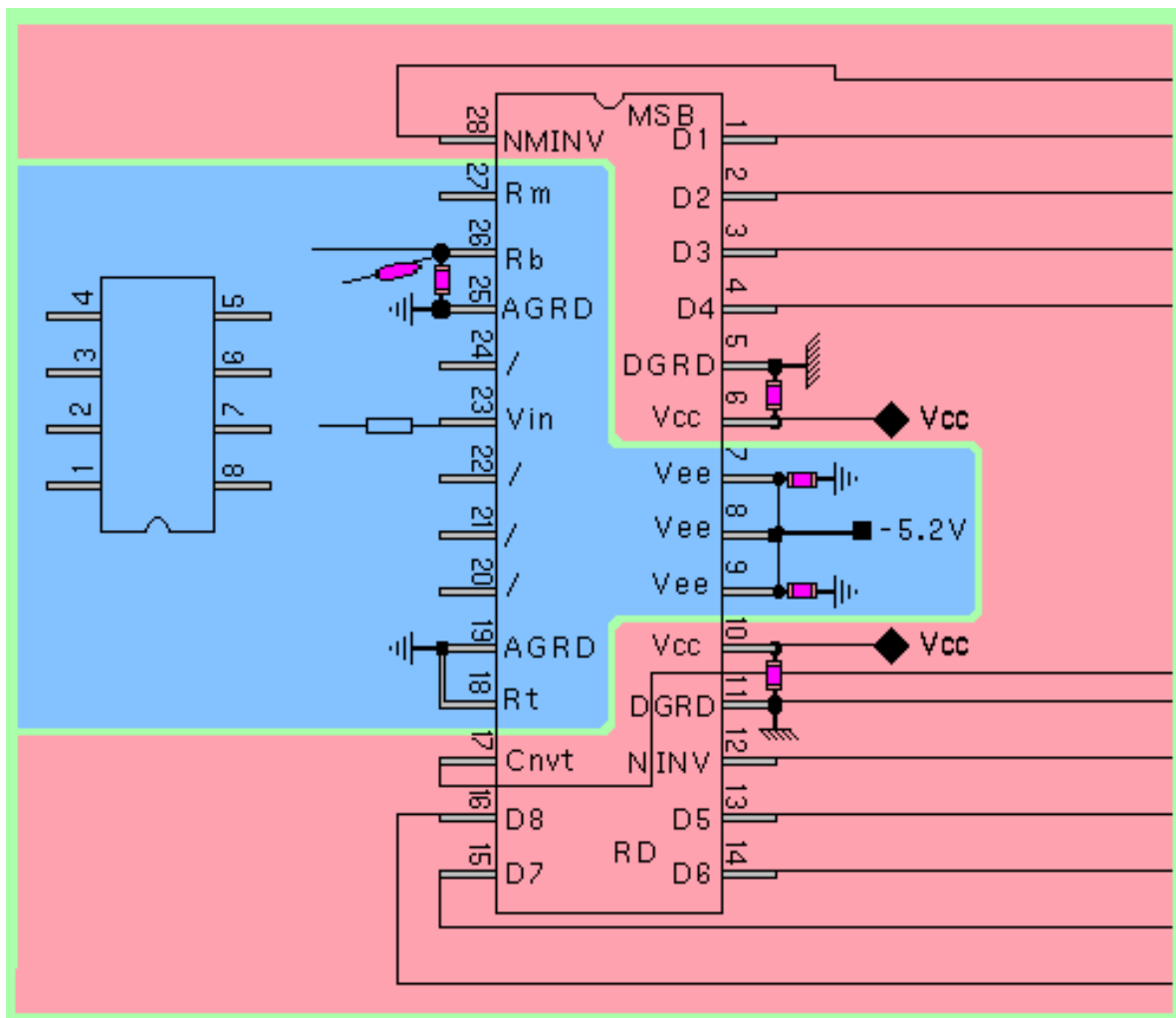


The animation is of a resonant groundplane where a second groundplane (or shield) is brought into proximity. You can see the effect on its resonate frequency.

The point of this is that a good groundplane design should have as few apertures as is practicable. Where apertures are unavoidable, shielding or a secondary parasitic groundplane can ameliorate the effect.

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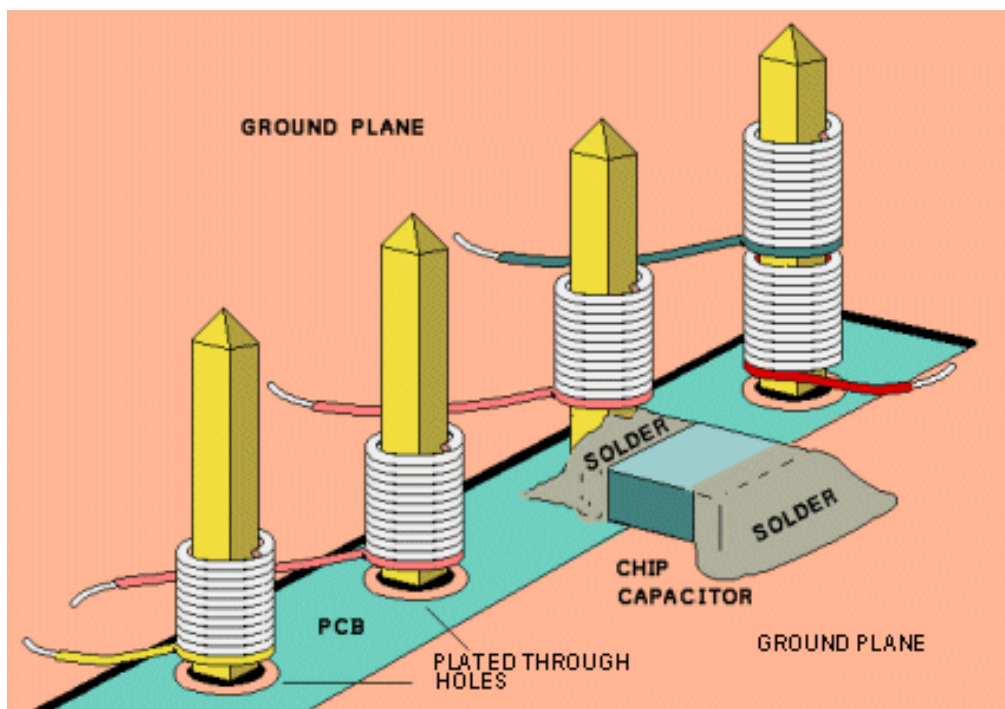
Analog and Digital Groundplanes



Above is an example of a mixed signal layout, AD-9020 ADC.

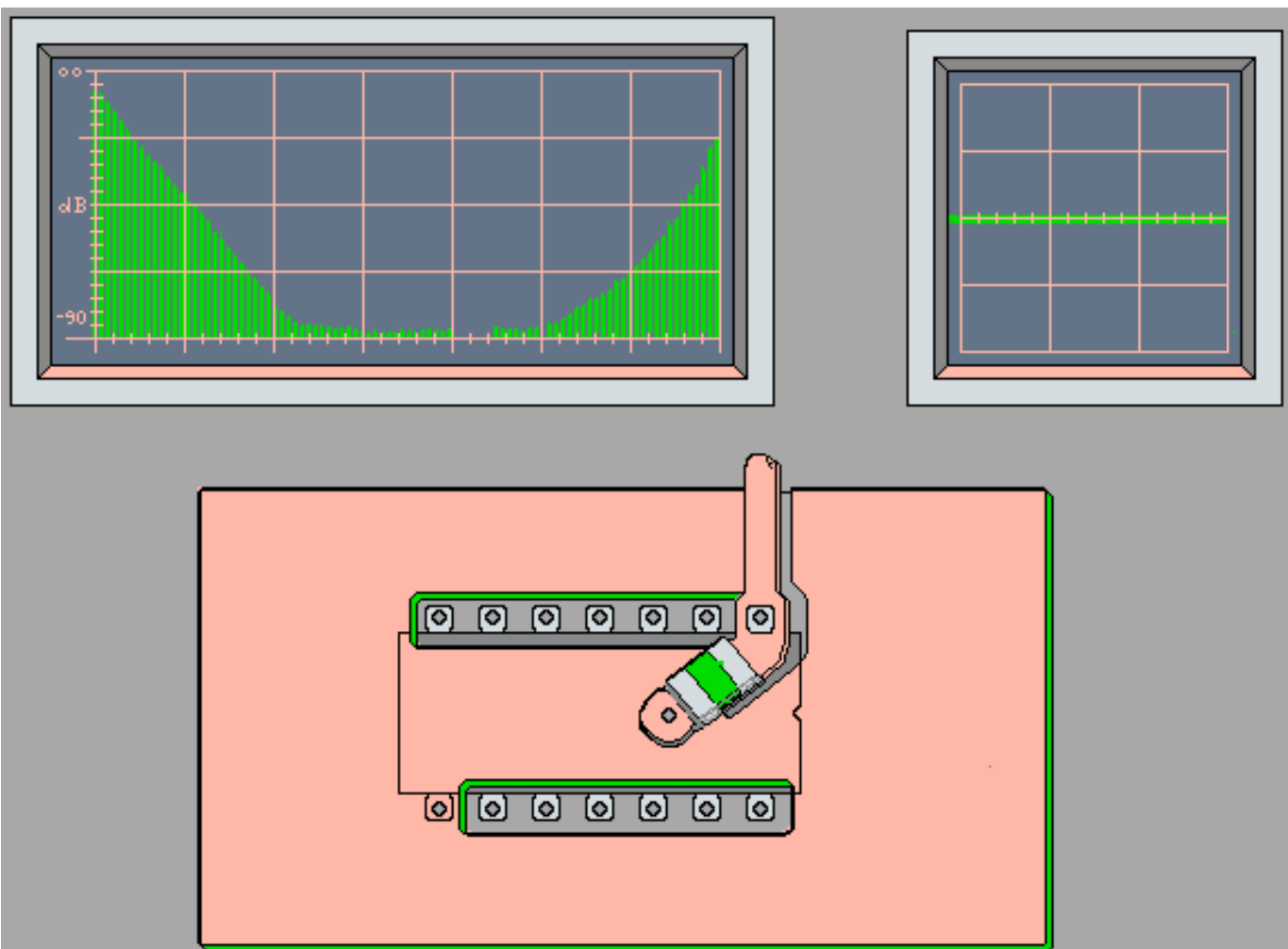
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More Groundplane Examples



Frequency Domain

Time Domain

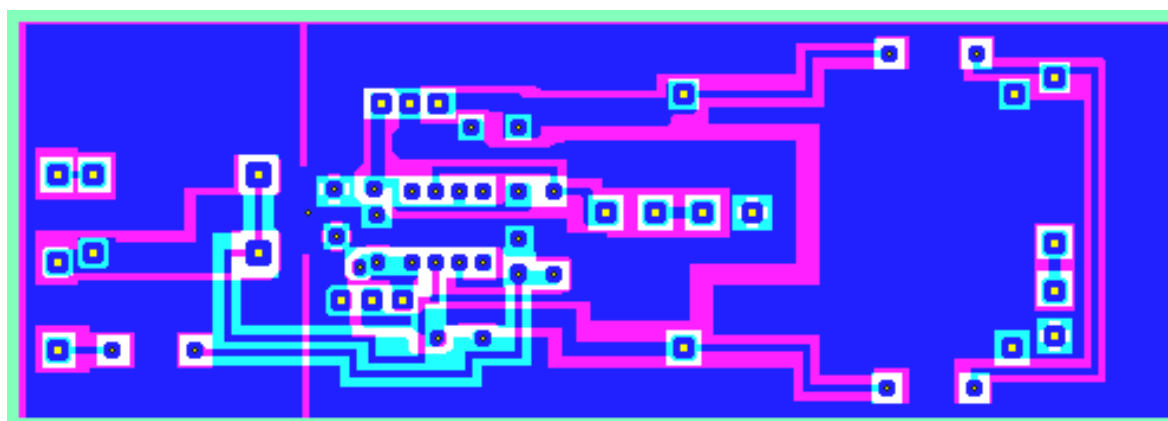


Note how bypassing becomes more effective as the ground conductor approaches a continuous plane. Groundplanes are often used in high-frequency circuit boards for this reason.

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Circuit Board Layout

Below is an amplifier example.



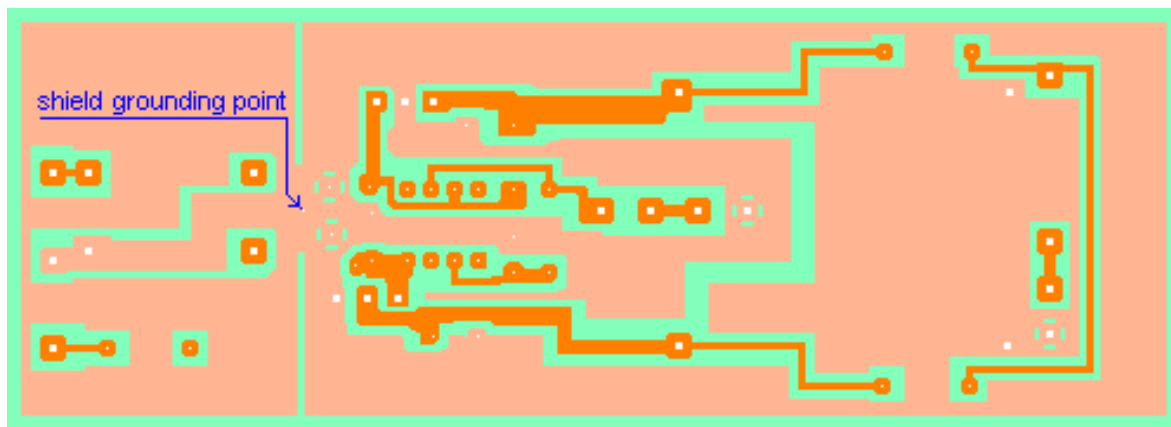
CAD Drawing

Signal Input

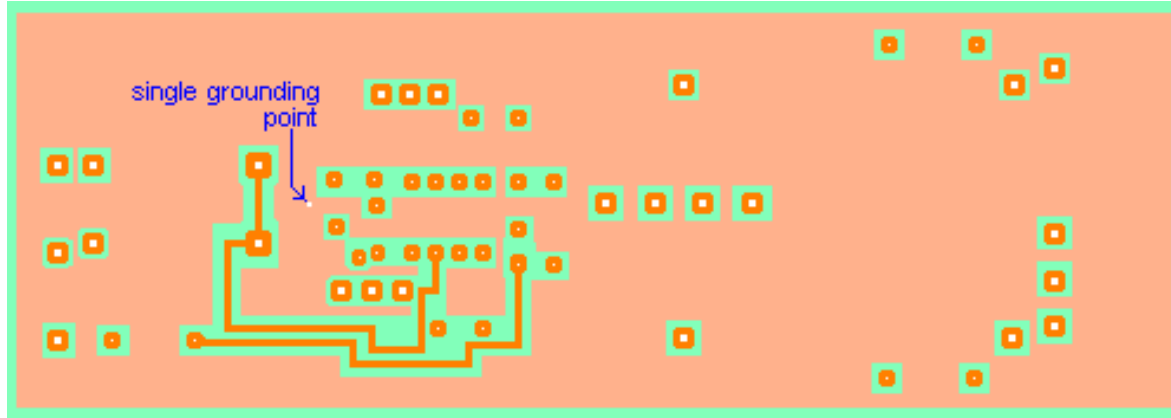
Circuit

Signal Output

Power Input



Groundplane Side



Shield Side

Note the single
grounding
(reference) point.

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CIRCUIT INTEGRITY

■ Module 4: Shielding

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-

Introduction

A shield should have no currents flowing through it!

As with bypassing, decoupling, and the groundplane, shielding gets little coverage in the classroom, but it is emphasized in many application notes, and used in many real designs!

Again, because of this many design engineers and technicians ignore it at their peril!

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What is Shielding?

A shield is a blocking or containing barrier against electrostatic fields.

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Why Do We Use Shielding?

In a circuit or system, there are many discrete signals directed to specific destinations only. Often these signals can interfere with other unintended signal destinations or devices. Shielding can prevent or diminish this

interference effect.

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How Do We Use Shielding?

Like a groundplane, a shield can be constructed of one or more conductive homogenous planars. However, the shield differs from the groundplane by its need to be free of conducted or induced electrical currents.

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Discussion:

Shielding can be accomplished using anything from a coaxial or shielded cable, to a sealed conductive chamber for circuit isolation. Shielding also has reciprocal purposes. It protects the circuit it is shielding from outside noise or unwanted signals. Conversely, it contains its own signals and thus protects the outside world from interference of its own making.

Shielding is used mostly to block electrostatic or "E" fields (Faraday shield). However, if ferrous metal is used (tempered Mu metal works best for magnetic fields), then both electrostatic shielding and some level of magnetic shielding is accomplished.

Shielding is especially useful where open frame transformers or unshielded coils are used, in cases where these would otherwise exchange signals by mutual inductance.

Fortunately, the magnetic component of the (interfering) signal diminishes as the cube of the distance. That is, for any high-frequency signal the dominant component beyond $\sim 1/6$ wavelength is electrostatic. This fact is referred to as near field and far field radiation. ([See Figure below.](#))

Ideal shields have no current flowing through them. Ideally they are grounded, or referenced at only one point.

For a shield to be effective, there must be no currents flowing through the shield itself. This is best accomplished by connecting the reference or common to only one point on the shield, thus preventing any current flow. The reason for this is that any current flowing in the shield material itself can produce secondary fields on the other side of the shielding material, and therefore reduce the effectiveness of the shield. An example of this might be a shielded cable, where the shield has a different potential at each end. The resulting current flows in the shield, inducing unwanted noise into the center or shielded conductors, as well as to the outside world. In this situation one might try to find a remedy by disconnecting one or the other ends of the cable's shield. However, this fix may not prove satisfactory in certain environments, and may require a "Guard" potential, or better still, optical isolation.

Active Shielding

In active shielding, fields of counter EMF (equal but opposite) are generated to cancel-out the offending fields. A good example of this is an AC power transformer, where a shorted turn is used to generate a nulling field.

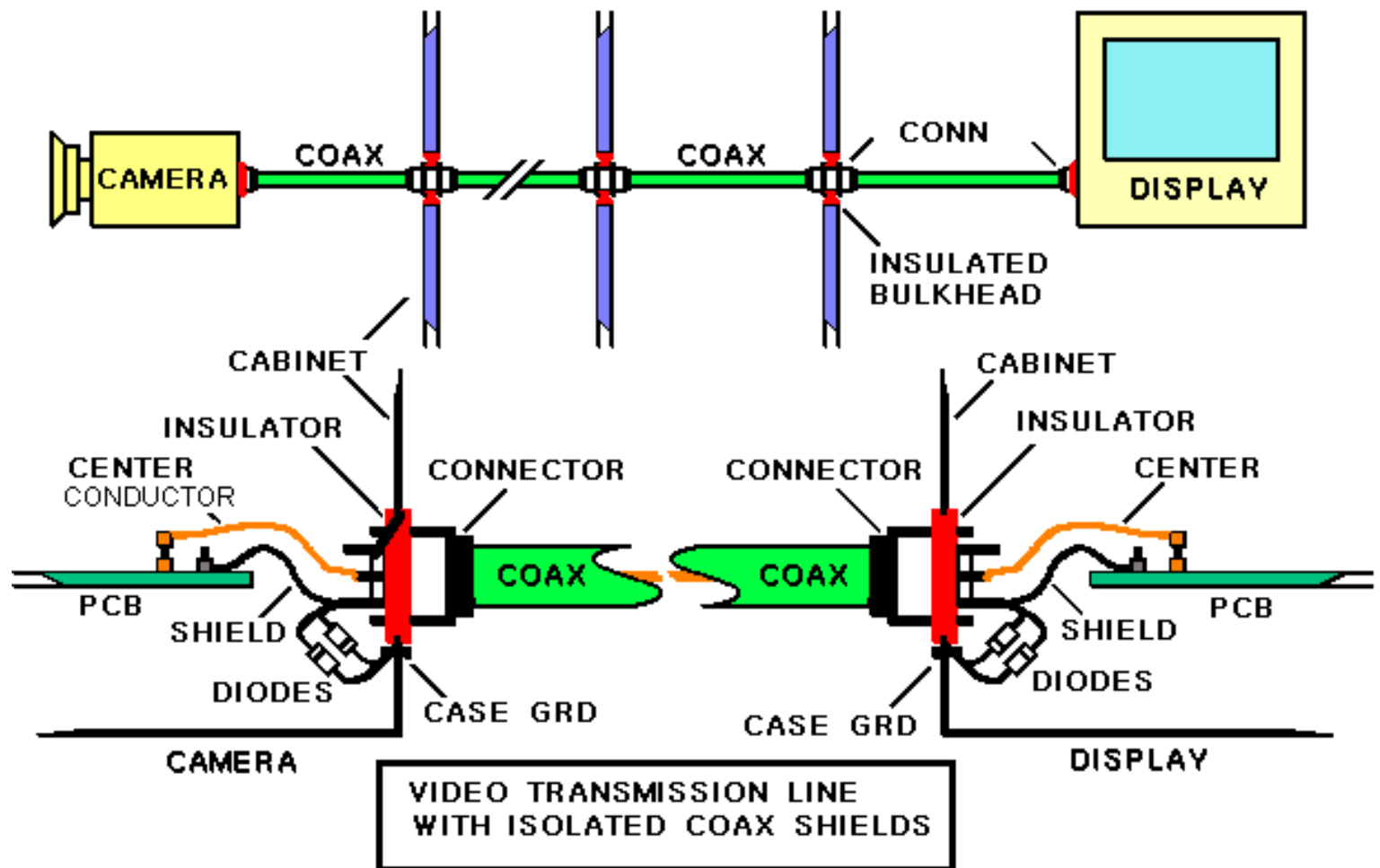
The shorted turn is a seamless band of copper that wraps the transformer core in one direction. When cut by the rising and collapsing magnetic flux -- caused by the transformer action -- the shorted turn acts as a very low-impedance, high-current secondary winding. This generates a counter EMF. Because this winding is shorted, it generates a rising and collapsing magnetic field of opposite polarity, thereby nulling the original stray magnetic flux.

In some cases of severe common mode noise, the shield can be made to carry an equal (but opposite) noise current to counter the interfering noise. However, this fix is not for the faint-of-heart, because with any slight change of the mechanical or electrical parameters, the canceling noise becomes the noise.

Some power transformers use a Faraday shield between the primary and secondary. However, this is not a shorted turn. The current flow in a shorted turn is very high! The shorted turn would have to link only the leakage flux to be workable (in other words, the turn is around the outside of the magnetic core).

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Shielded Cable



Avoid extraneous currents in the coax shield. Maintain shield isolation.

By definition, the ideal shield has no current flowing through it. It is grounded, or referenced at only one point.

In the case of shielded cables, the shield is typically referenced or grounded at both ends.

In the case of coax cables, the shield acts as both the shield and the return current path for the signal carried on the center conductor. However, with a shielded-balanced differential pair (sometimes called twisted pair) the shield is just that – a shield. Often this shield can be grounded at either end. However, in the case of EMI suppression, grounding both ends is prudent.

Though coax and shielded twisted pair are used for both audio and higher frequency signals, there can be differing effects on how the shield is treated. The most difficult case is that of video, where both very low to high frequencies (~ 10 Hz to >4 MHz) are involved.

Audio run on coax is subject to "ground loop" noise. For example, dissimilar ground potentials (especially 60 Hz) can cause a noise current to flow in the shield, inducing that noise into the protected center conductor. As the frequency of interest increases and the coax gets longer, the ground loop problem is diminished. This situation is mainly due to the increased inductive reactance (higher Z) of the coax shield.

When long runs are required and/or the environment is noisy, it is best to use shielded twisted pair. The benefit of this is the differential pair's inherent rejection of common mode noise (CMR).

An extreme case might find a remedy in transformer coupling, or even optical isolation.

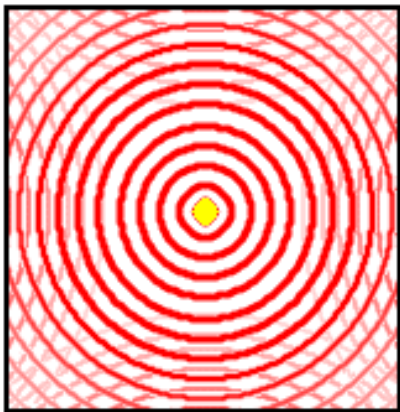
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Something to Remember

It will soon become apparent that shielding is a very popular strategy in EMC applications.

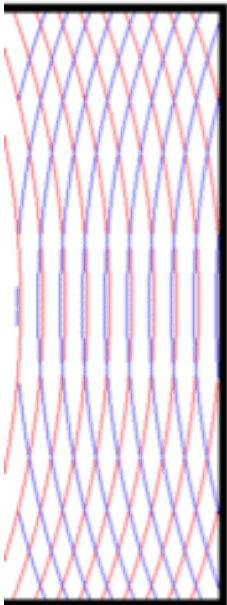
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Shielding Examples

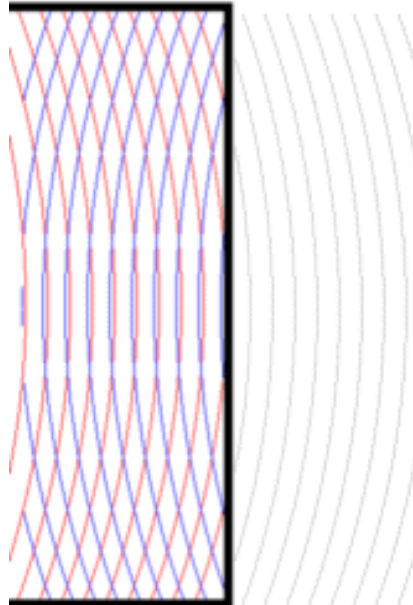


RF emitter inside a shielded enclosure.

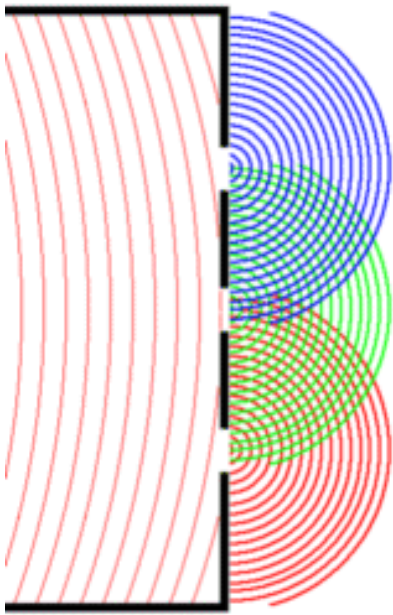
Example of "Ideal" Shielding
(no leakage)



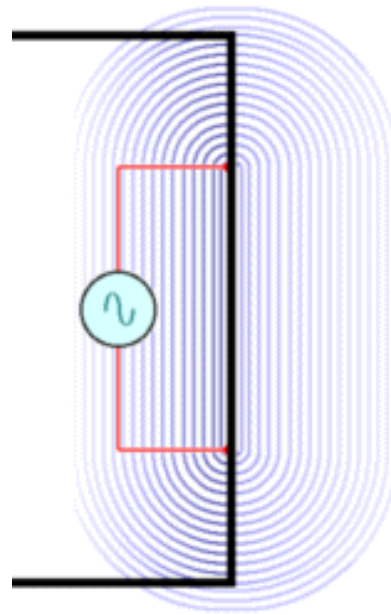
Shield Reflecting



Shield Reflecting
(with some "parasitic" radiation)



Leakage of Apertures in
Shielded Enclosure: Diffraction
(apertures act as point sources)



Driven Shield Radiating
(currents in shield create antenna effect)

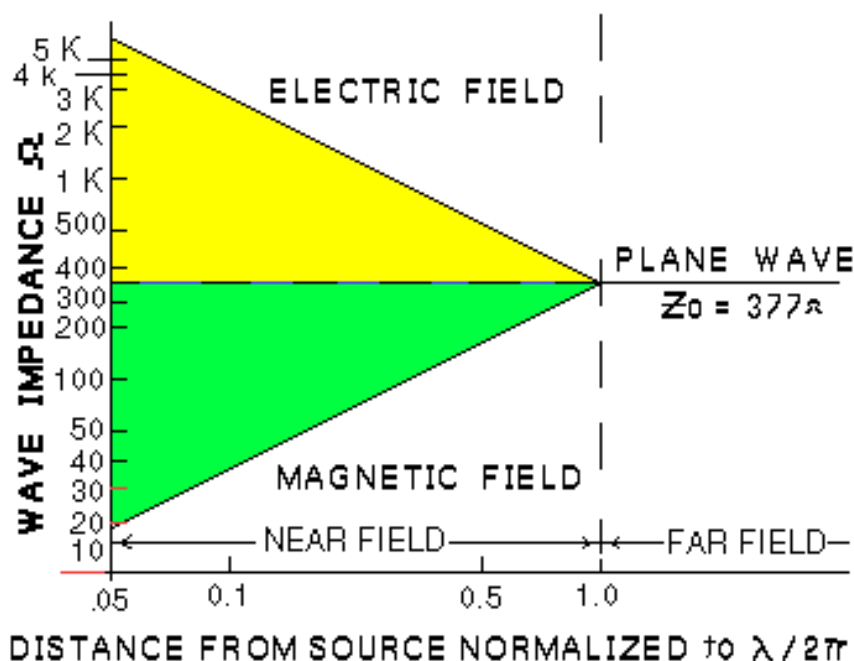
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Something to Remember

The area of an aperture is less important than its length—as in seams or joints. The rule of thumb is the maximum dimension of an aperture should not be greater than $1/20$ the wavelength of the highest frequency of interest. Such apertures can act as slot antennas.

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Near Field and Far Field Radiation



In dealing with a radiation source, whether it is an antenna or a circuit board:

- The dominant energy in the far field is electric.
- The dominant energy in the near field is magnetic.

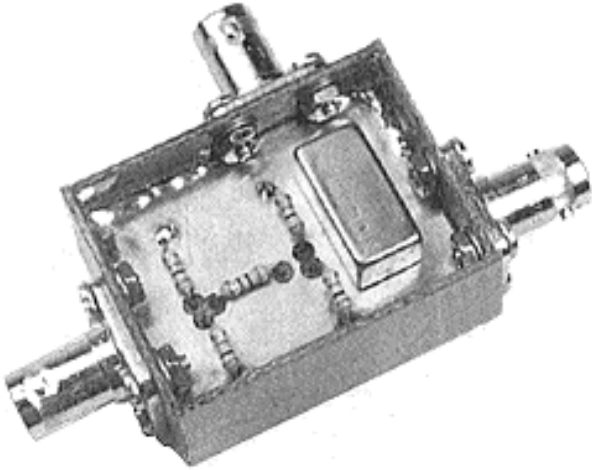
In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is

electromagnetic. This is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic. It is referred to as far field radiation, sometimes called the plane wave.

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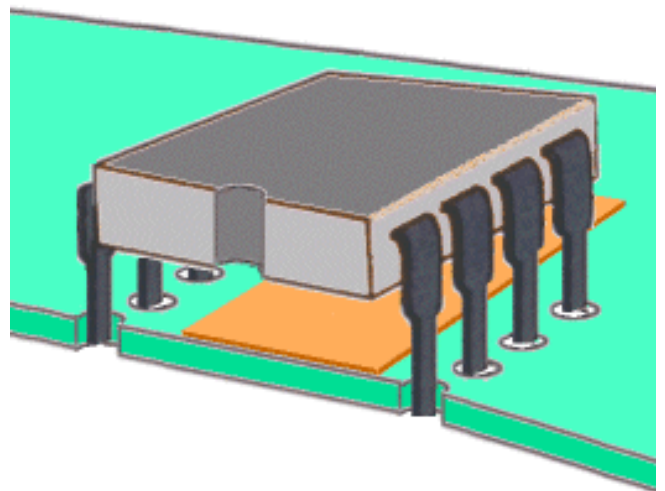
Examples of Shielding



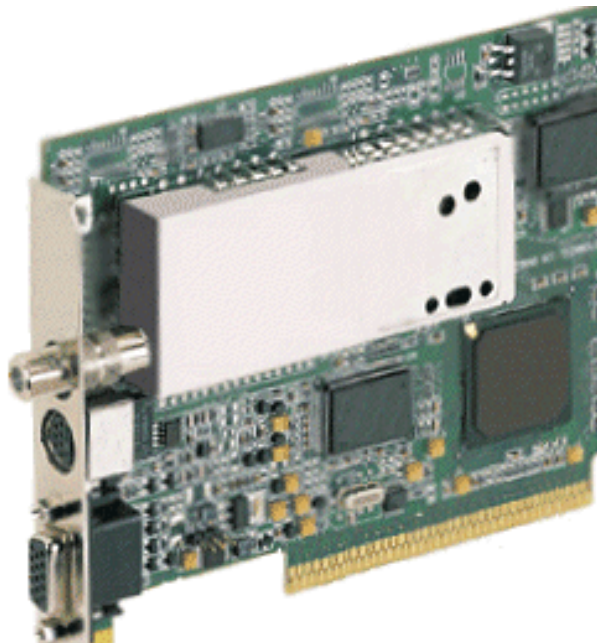
The figure at left is a well-shielded container made from soldered, copper-clad, printed circuit board material.



Shielded Audio Cable



Isolated copper island under IC (acting as a shield)



Graphics Card with Shielded TV Tuner



Shielded PC power supply

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Real-World Applications of Shielding



Conductive paint



Custom gasket



Solderable and snap-in metal shields



"O" Ring



Conductive ATV



Connector gaskets



Compressible gasket

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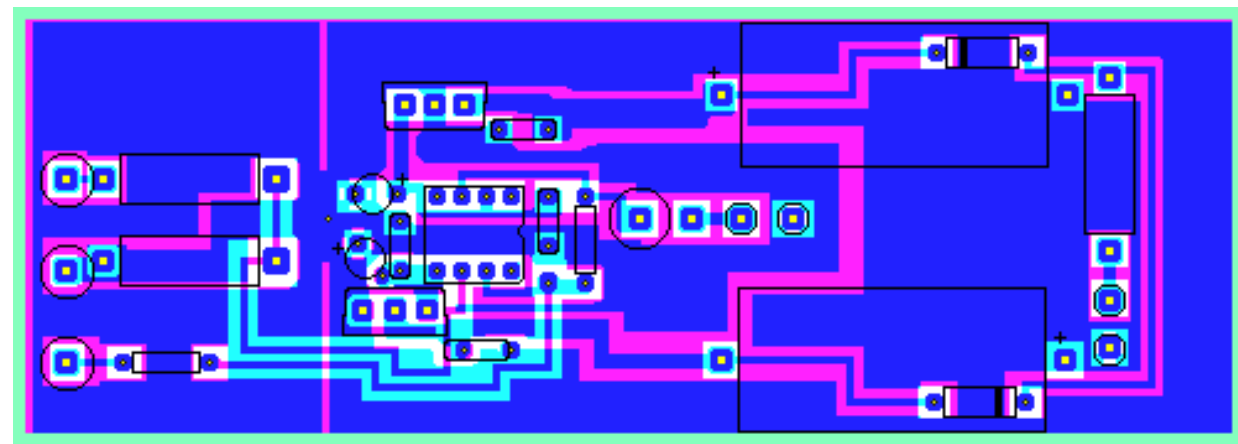
Additional Shielding Aids

Some other shielding aids include conductive paint, conductive gasket making silicone (ATV), and assorted conductive gaskets.

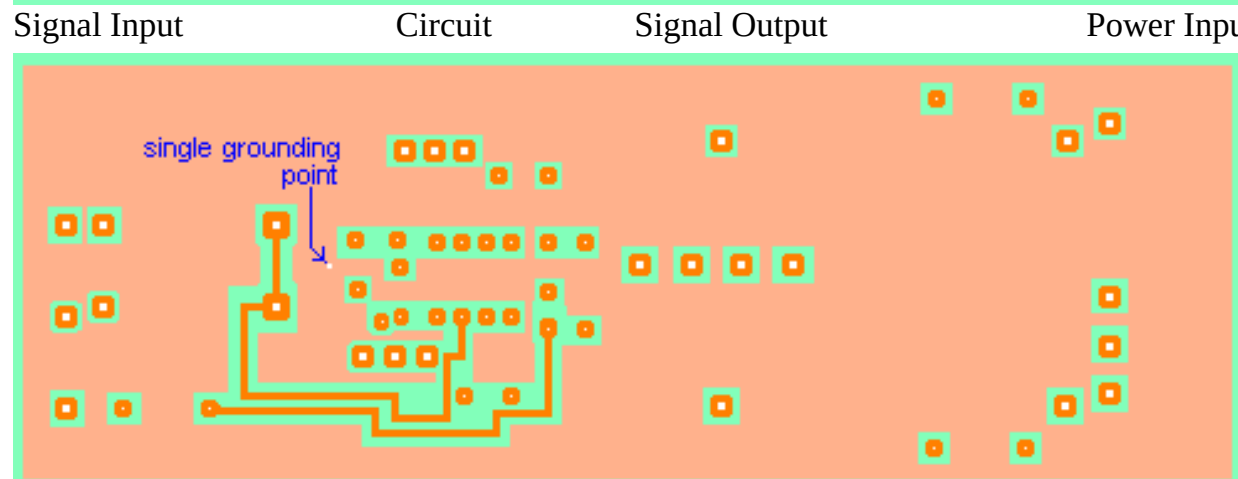
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Circuit Board Layout

Amplifier example.

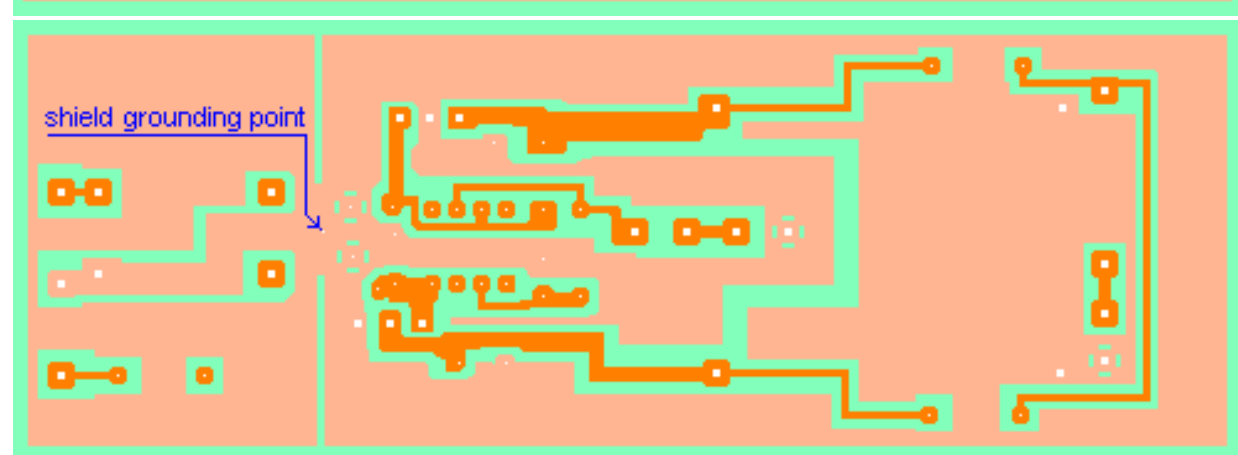


CAD Drawing



Shield Side

Note the single grounding (reference) point.



Groundplane Side

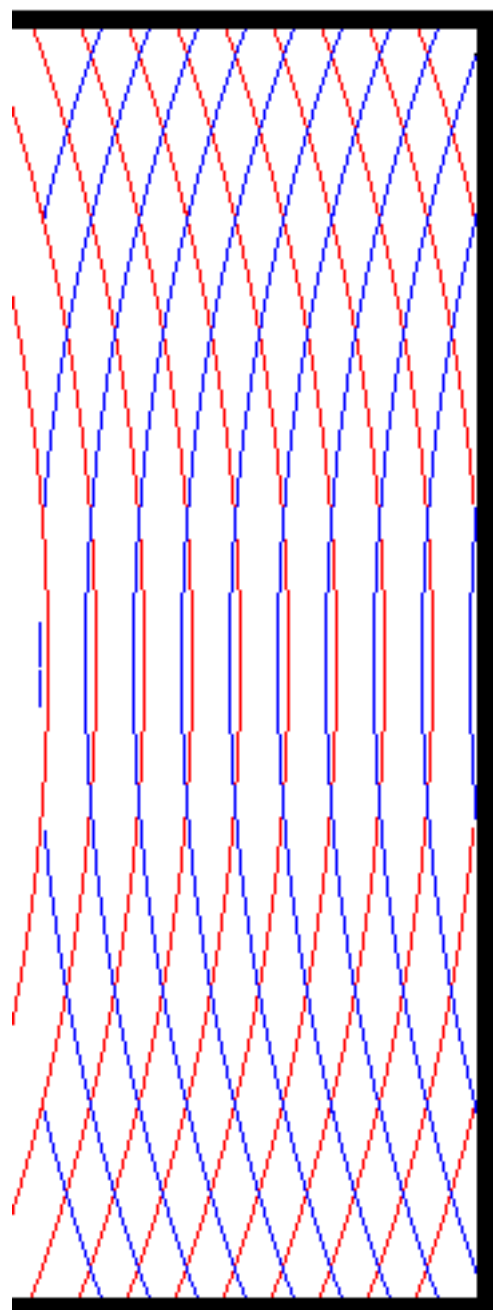
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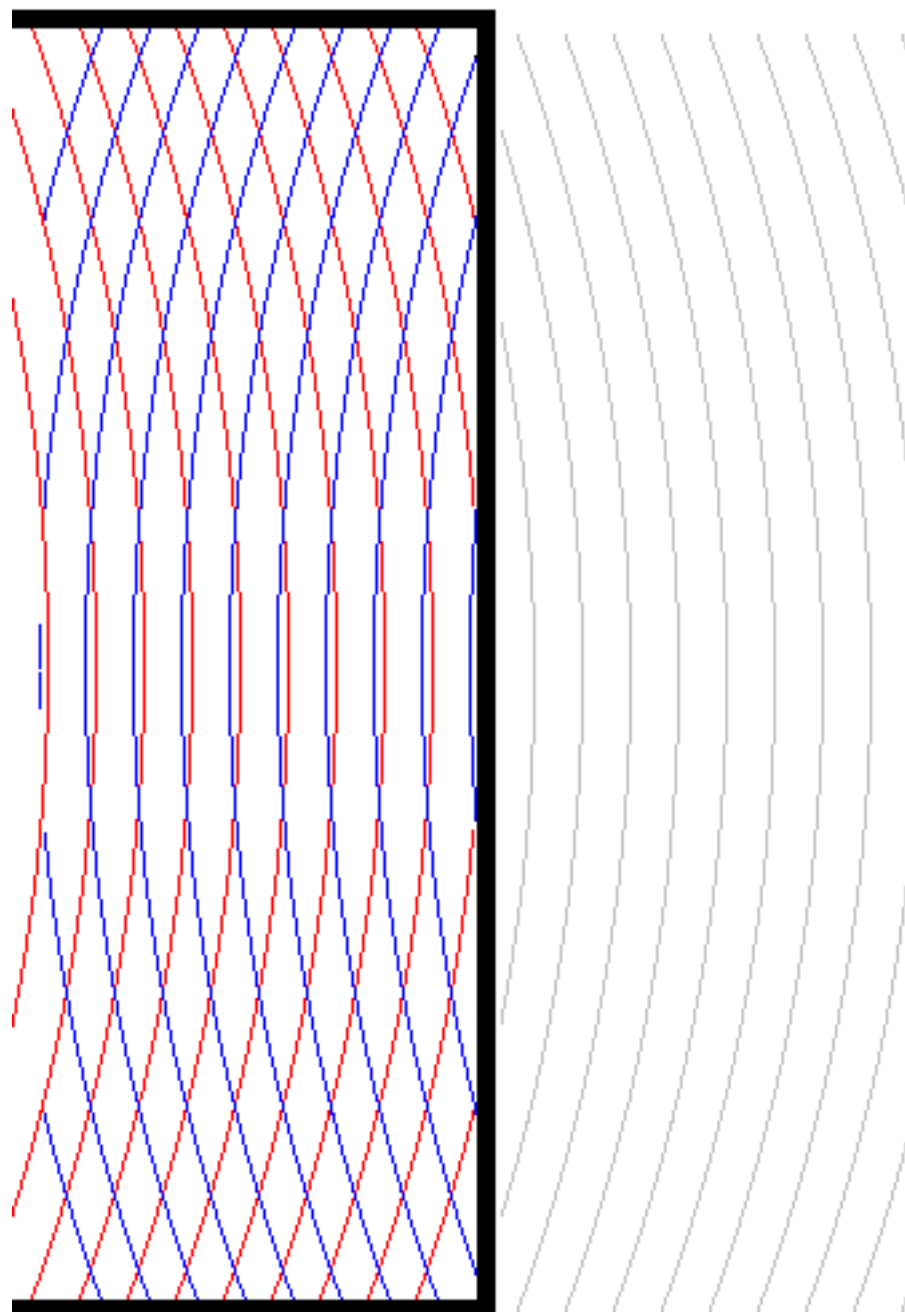
Summary

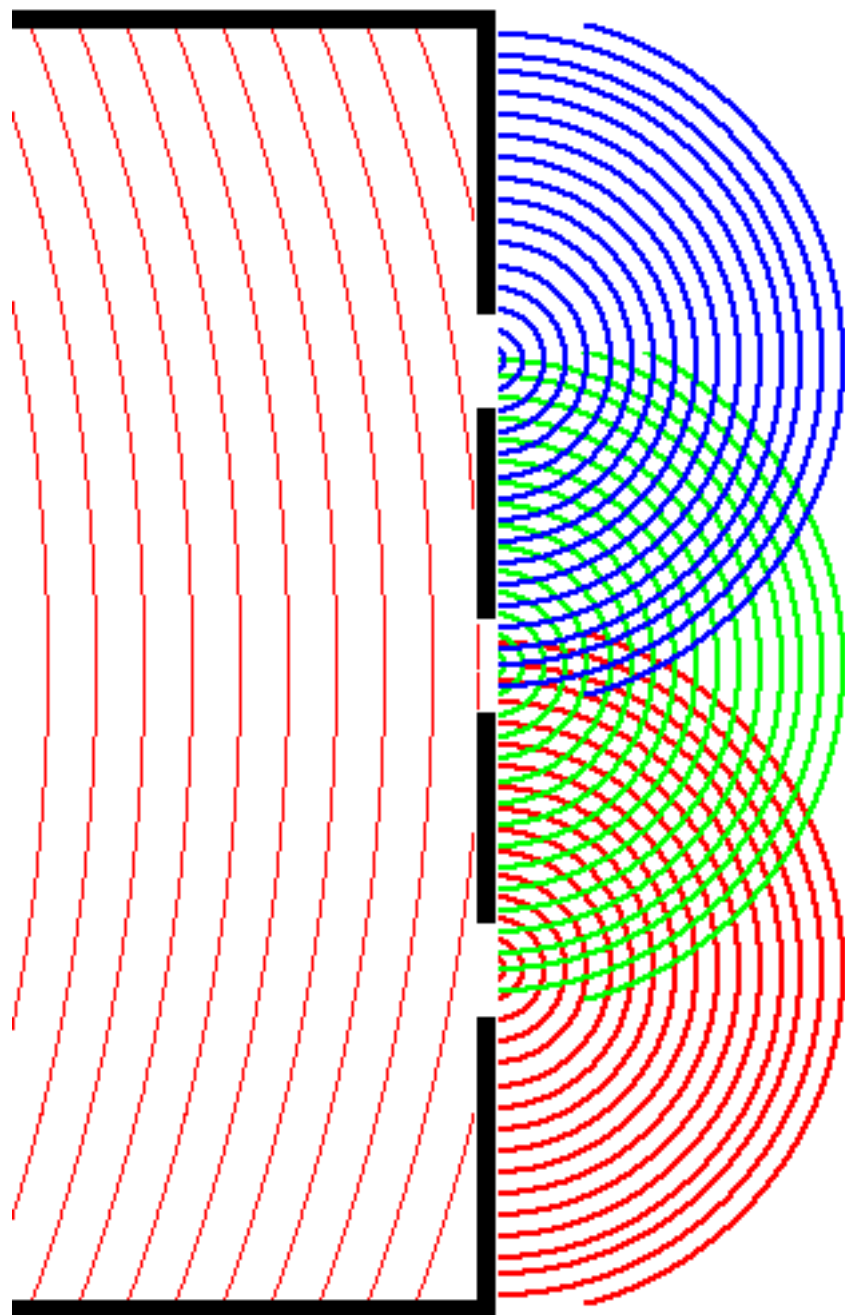
1. Shielding can be accomplished by using anything from a coaxial or shielded cable, to a sealed conductive chamber for circuit isolation.
2. Shielding serves a reciprocal purpose: it protects the circuit it is shielding, and also protects the outside world.
3. There must be no currents flowing through the shield itself.
4. To prevent current flow, connection to common should be at only one point on the shield.
5. The maximum dimension of an aperture should not be greater than $1/20$ wavelength.

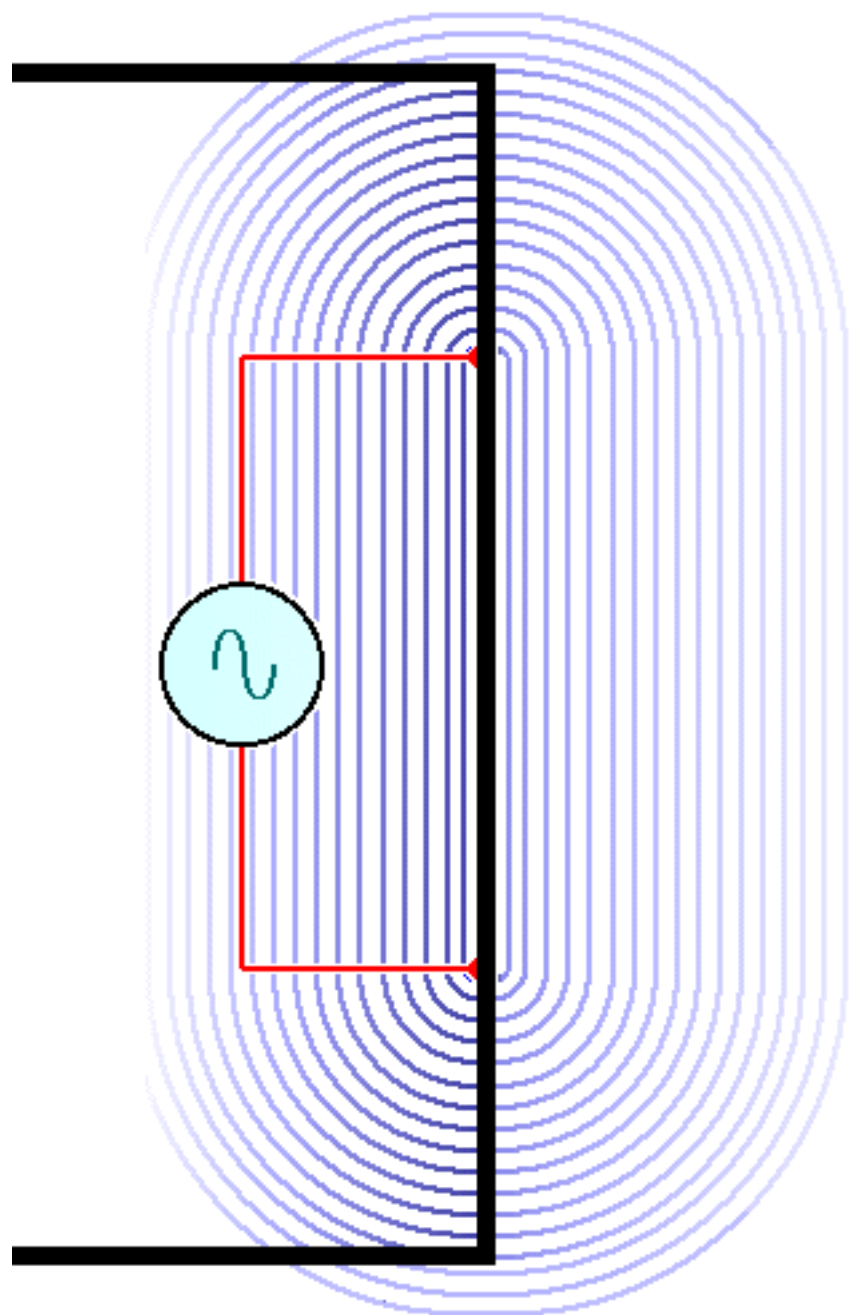
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CIRCUIT INTEGRITY

■ Module 5: Layout

- [Introduction](#)
- [What Is a Layout?](#)
- [Why Do We Use a Layout?](#)
- [How Do We Use a Layout?](#)
- [Discussion: Steps to a Successful Layout](#)
- [ADC Layout, Functional Diagram](#)
- [Physical Layout](#)
- [Groundplanes and Powerplanes](#)
- [Folded Layout](#)
- [Separation of Groundplanes](#)
- [Bus Layout](#)
- [I/O Termination](#)
- [Circuit Board Layout](#)
- [Computer Aided Design \(CAD\) Package](#)

Introduction

Layout is the integration of bypassing, decoupling, groundplane, and shielding, plus a little art.

Layout (PCB) is another subject that is mentioned in the classroom, but rarely taught. It is often dismissed as "...one of those things done by drafters."

The truth is, an improper layout can ruin the best paper design!

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What Is a Layout?

Layout is the creation of a physical realization of the circuit using all of the subjects covered in the previous modules, with primary attention given to signal flow.

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Why Do We Use a Layout?

An effective layout promotes optimized interconnection of the circuit elements, while observing all pertinent rules. In addition, the proper layout insures economical manufacturing and high circuit reliability.

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How Do We Use a Layout?

When planning a layout, input output, parts placement, signal flow and power distribution all must be considered. Also, attention should be given to interference and noise within the circuit layout. In addition, device rules, such as bypassing, decoupling, shielding, the proper use of groundplanes, and last but not least, EMC, must all be observed.

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Discussion: Steps to a Successful Layout

Remember, from the layout of a printed circuit board (PCB) comes the creation of a physical realization of the circuit.

1. Determine the board size, type or standard, connections, and so on. This decision is often dictated by the application (PC adapter card, etc.).

Consider the end use (industrial, medical, military, commercial). Also consider environmental impact, product life, and the costs.

Once these parameters are identified, there is a finite amount of flexibility remaining for the designer.

2. Choose the number of layers, device selection, function integration, and then the actual layout.

This is where the input/output connections, parts placement, interconnections, routing, signal flow, and power distribution all must be considered. Special attention should be paid to interference and noise within the circuit layout.

3. Finally make sure the layout follows device rules such as bypassing, decoupling, shielding, the proper use of groundplanes, and EMC considerations.

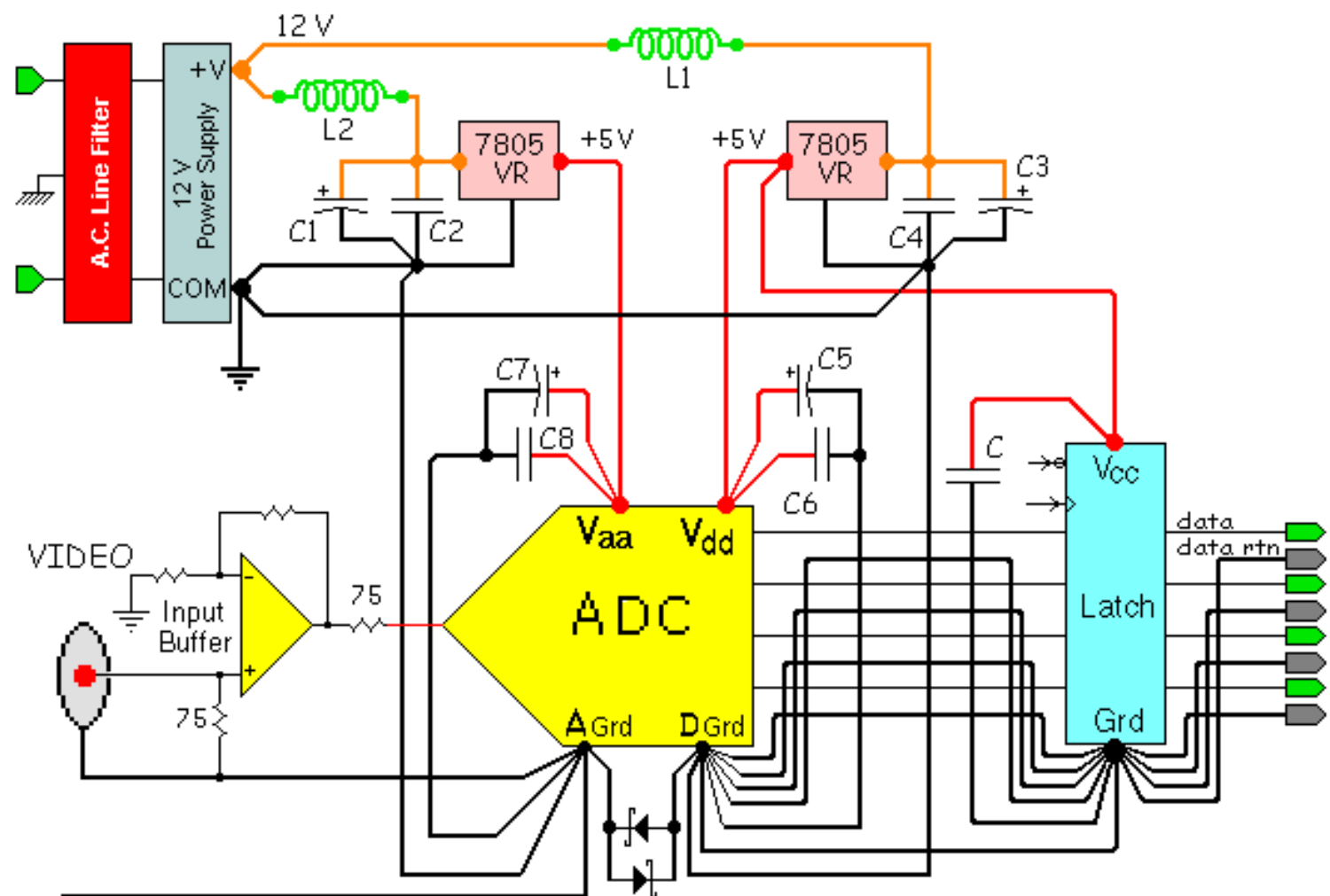
Remember that in an "ideal" ground return system, every current has its own separate return path, and that currents do not share return path copper!

Of course, in the real world ideals are not always possible. However, any design stands a much greater chance of success when the designer keeps these items in mind.

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ADC Layout, Functional Diagram

Below is an illustration of power and ground, and signal distribution.

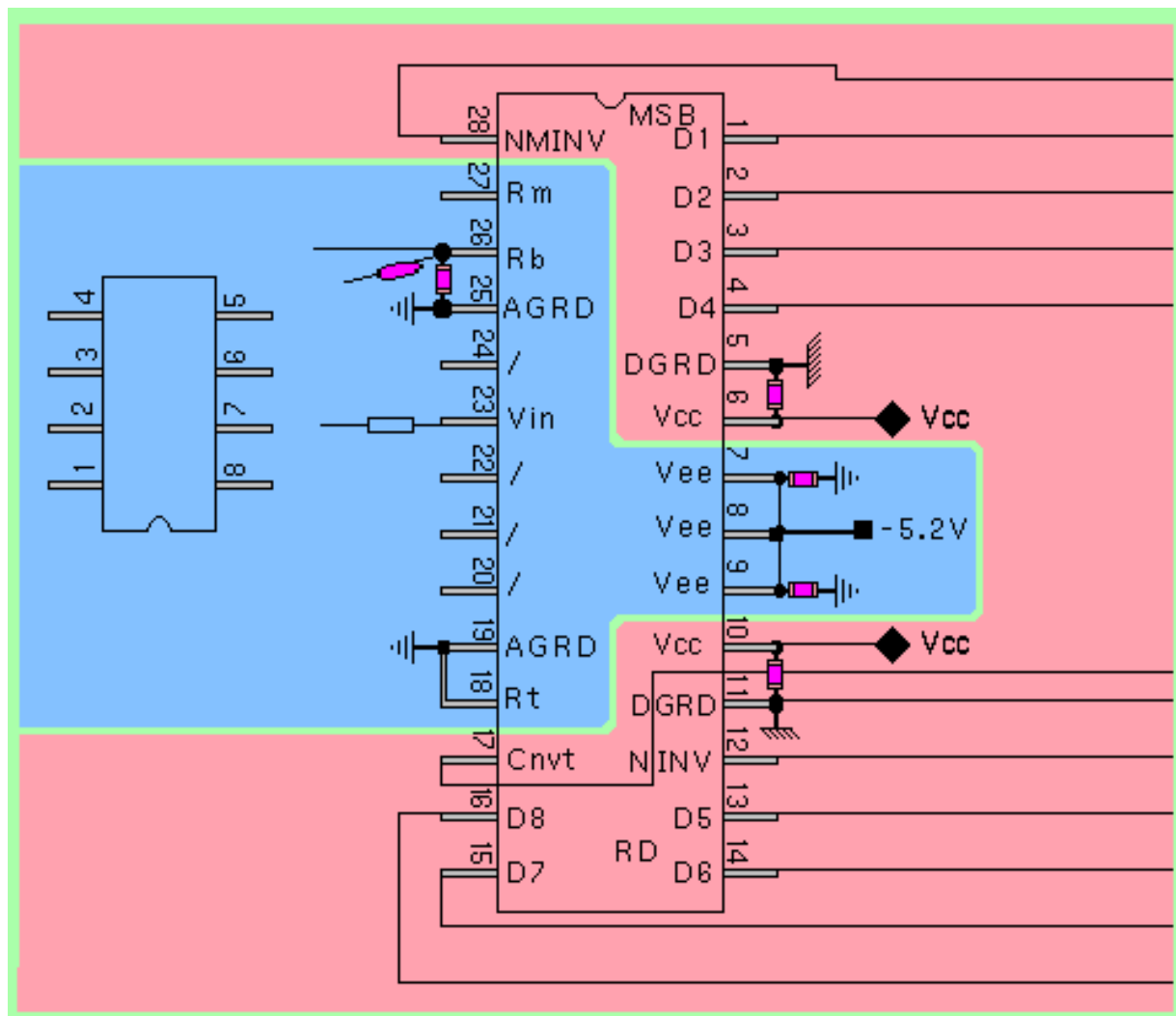


This layout incorporates bypassing and decoupling with proper ground returns. Please notice that schematically, every signal has its own ground return.

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Physical Layout

Analog & digital

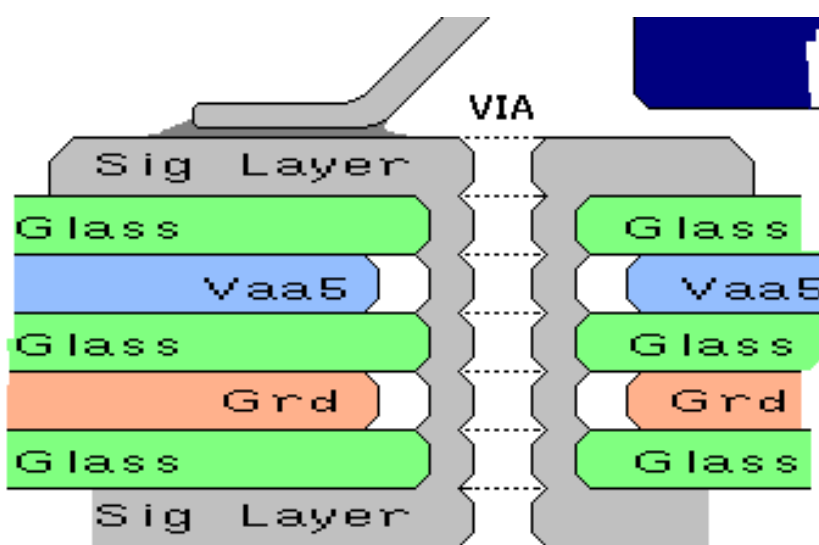


Physical layout of the Analog Devices, Inc., AD-9020 Video ADC

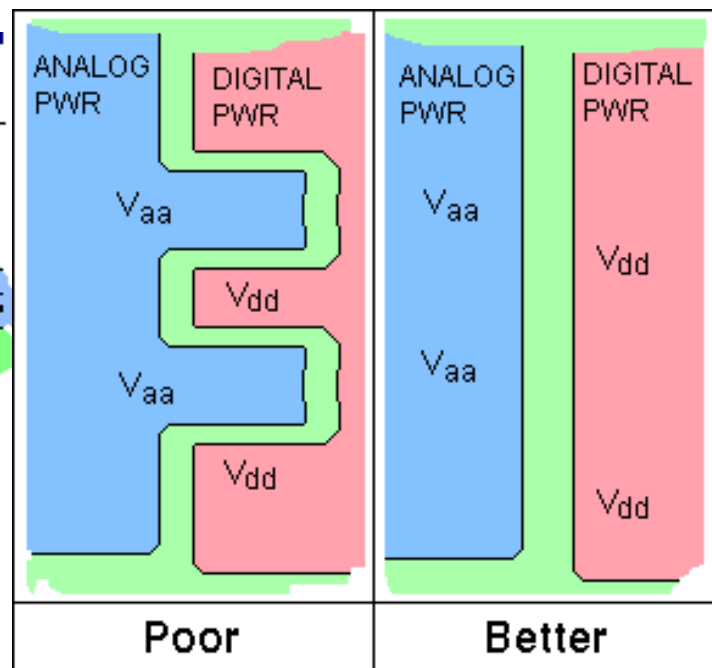
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Groundplanes and Powerplanes

For multilayer printed circuit boards:



Multi-layer printed circuit board



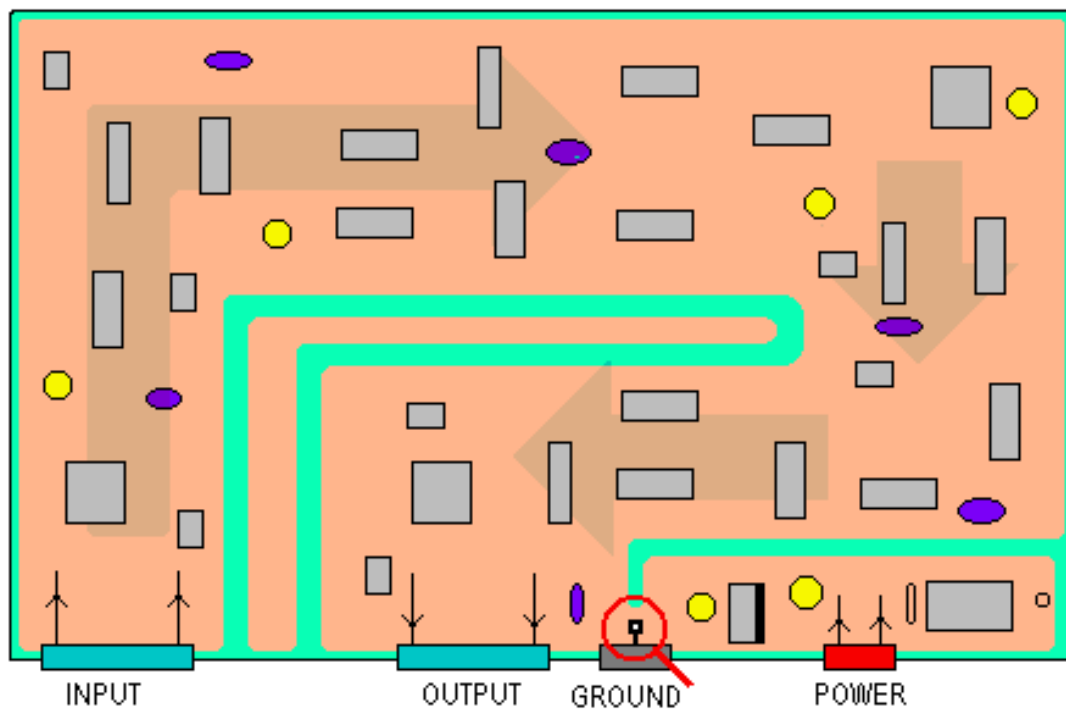
Powerplane Separation

Currents in either powerplane can couple noise to the other; the coupling mechanism is mostly magnetic.

The use of multi-layer printed circuit boards allows the use of multiple groundplanes, as well as buried (under the signal layers) power and ground (V_{cc} and ground) layers. These layers are sandwiched together and act as a very efficient distributed bypass capacitor. A variation of this is to have the power and ground (V_{cc} and ground) layers as the outer or intermediate layers, thus shielding the buried signal layers (or some combination of them). ([See EMC.](#))

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Folded Layout



Notice the single grounding point in this illustration.

In laying out a board, signal flow should be the dominant consideration. Place the input connector as far away from the output as possible. Likewise, place the power entry to the board away from the input, but nearer the output.

In the case of mixed signals, segregate analog from digital.

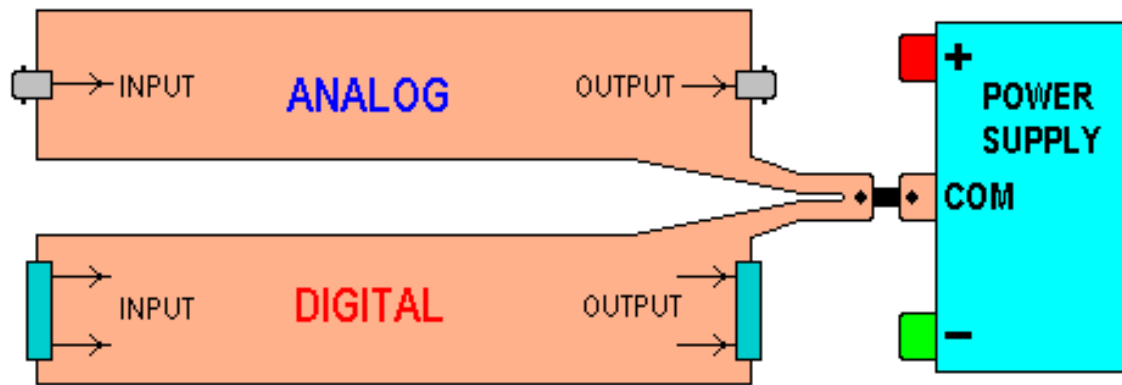
Neatness counts in writing, not in layouts. Keep runs as short as possible.

If you must have long runs, don't parallel the same lines close together. If possible, swap relative line positions to reduce crosstalk.

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Separation of Groundplanes

Separate analog and digital groundplanes with single point unified grounding (COM).

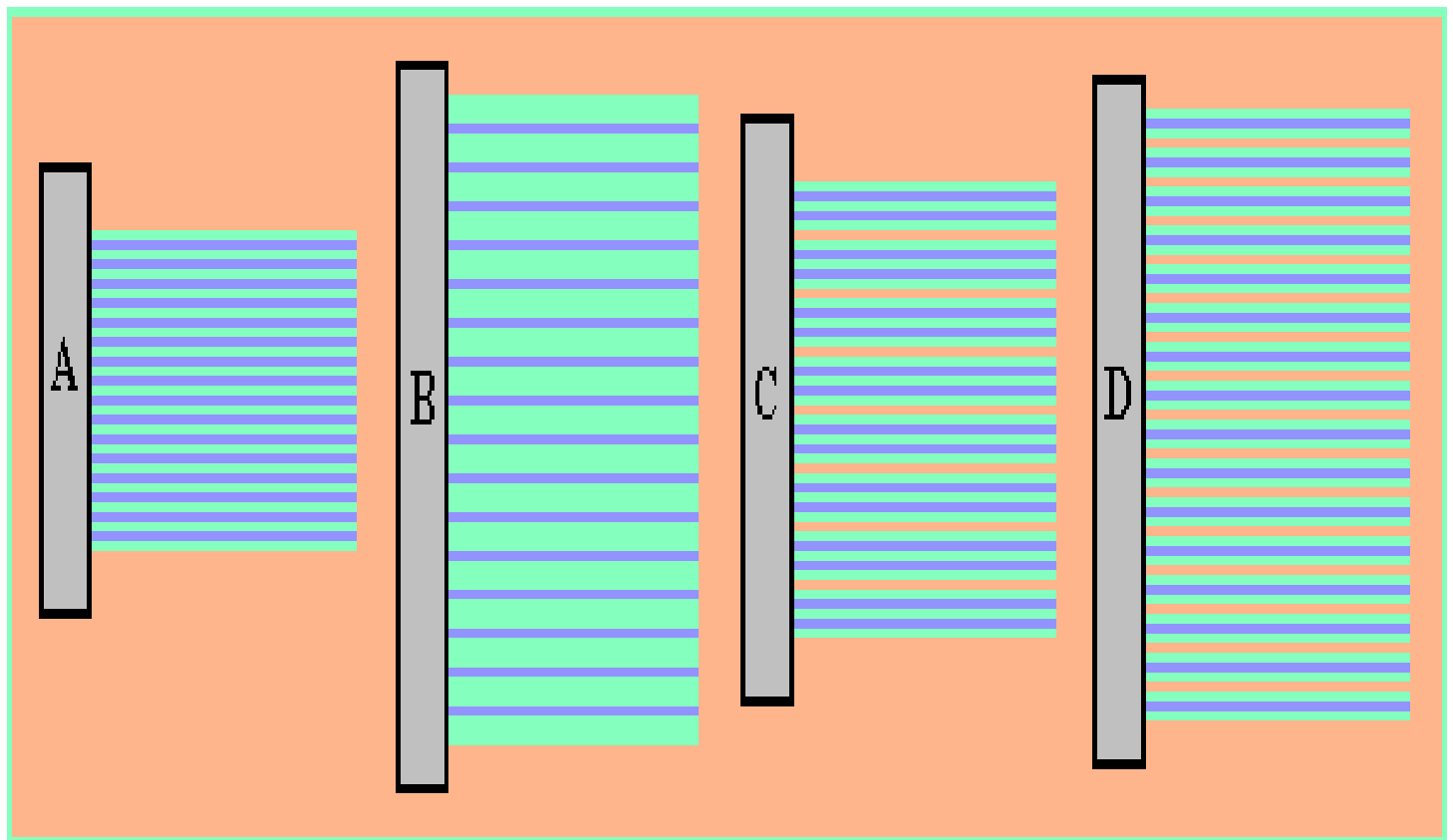


Analog and digital groundplanes do not share return currents.

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Bus Layout

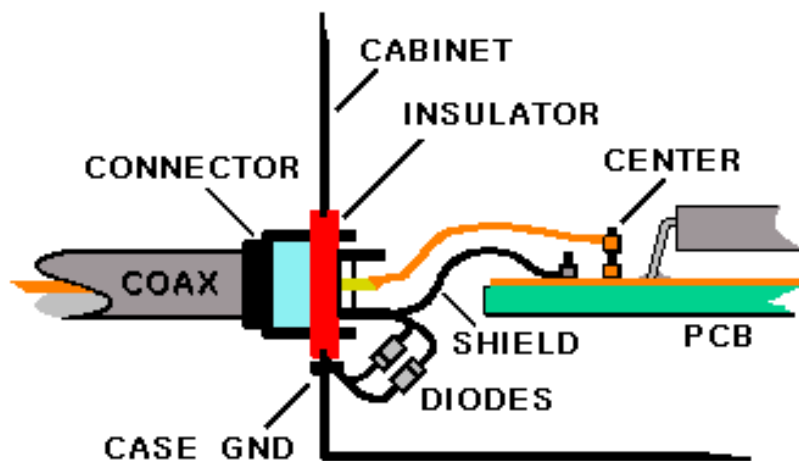
Buses are sometimes required to span long distances across a board, which can lead to crosstalk. This crosstalk can be ameliorated by allowing adequate spacing between traces (see part B of the figure below). However, there can be instances where this approach either doesn't work or there is not enough board area available. Therefore, interleaving ground returns may be required. (See parts C and D of the figure below.)



- . Simple 16 bit bus, close spacing.
- B. Wide spacing.
- C. Interleaved ground traces, 1 ground per 2 signal.
- D. 1 ground per signal.

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I/O Termination



Notice in this illustration that the shield, which is isolated above the cabinet, is returned directly to the device input common pin, not just to ground.

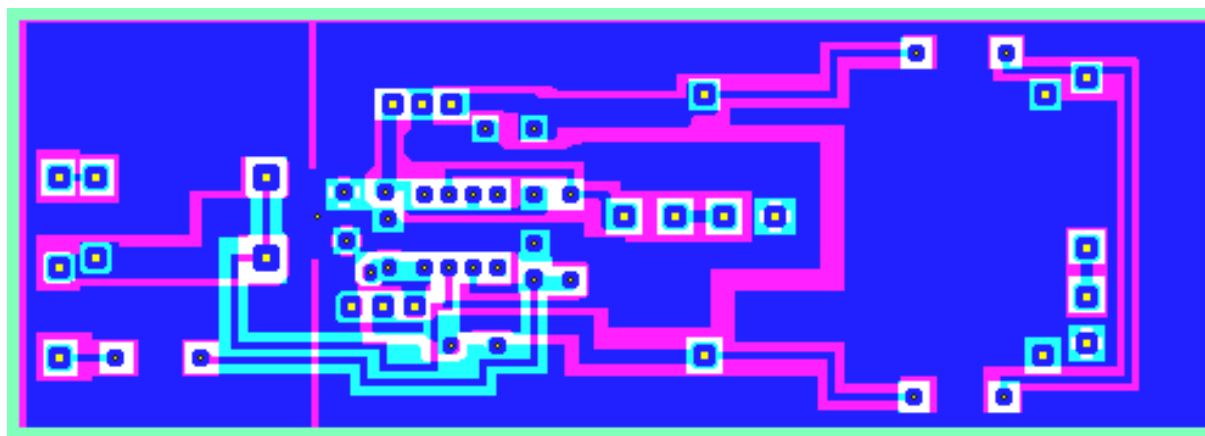
Shottkey diodes protect against severe ground loops.

An example of coaxial cable termination.

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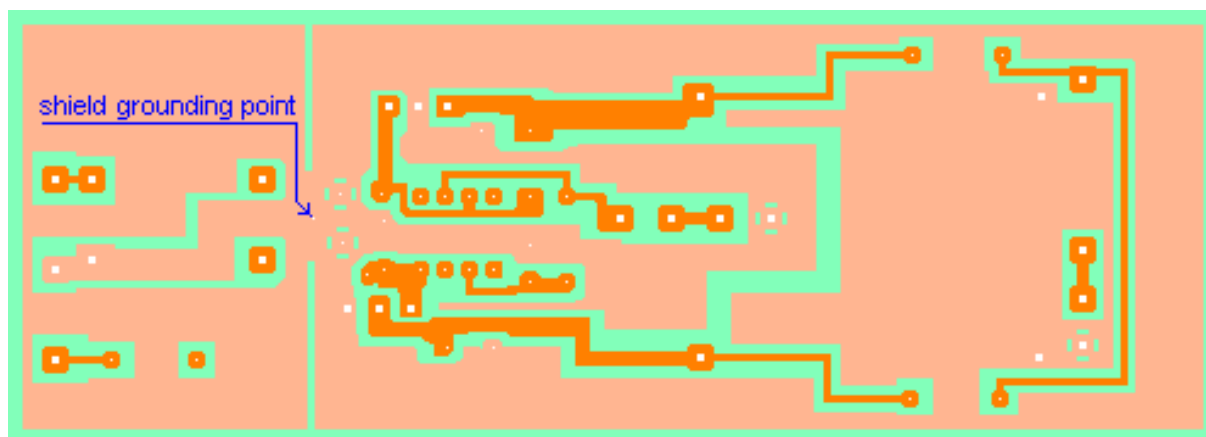
Circuit Board Layout

Amplifier

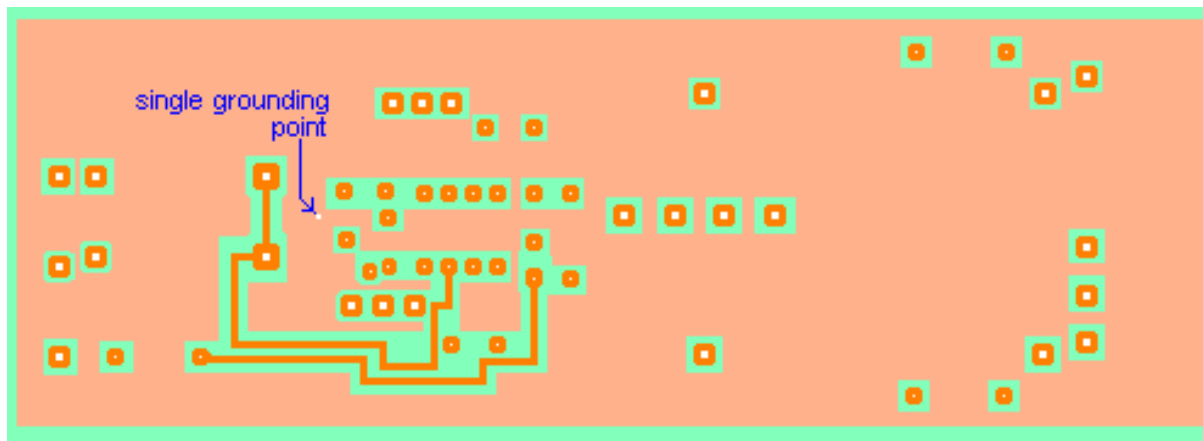


CAD Drawing

Signal Input Circuit Signal Output Power Input



Groundplane
Side



Shield Side

Note the single
grounding
(reference)
point.

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Computer Aided Design (CAD) Package:

1. Schematic capture.
2. Part selection.
3. Part placement.
4. Auto routing.
5. Simulation.

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CIRCUIT INTEGRITY

■ Module 6: EMC

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- [Introduction](#)
- [What is EMC?](#)
- [Why Do We Need EMC?](#)
- [How Do We Implement EMC?](#)
- [The Dichotomy of EMC](#)
- [Discussion](#)
- [EMC Paradigm](#)
- [EMC Path](#)
- [Radiation: Near Field, Far Field](#)
- [Interference Culprits](#)
- [Radiated and Conducted EMI](#)
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 - [EMI Reduction Check List](#)
 - [A. Suppression of Emitter EMI](#)
 - [B. Reducing Noise Coupling](#)
 - [C. Receiver Noise Reduction](#)
 - [D. Controlling Digital System Emissions](#)
-

Definition of Electromagnetic Compatability

Electromagnetic compatability, it is said, is when "you can watch Oprah with your television set sitting on top of a working PC."

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Introduction

For many, designing for, and understanding EMC has been, and remains an art more than a science. However, it needn't be that way. Using what you have learned in the proceeding modules, this module intends to remove some of the mystery from this subject--but not all!

The greatest insights remain to be discovered in practice.

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What is EMC?

Electromagnetic compatibility (EMC) is an inevitable challenge in a world with a proliferation of electronic systems. Today, thanks to EMC design practices, listening to the news on an AM radio while using an electric razor is not a problem, as it was in the past.

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Why Do We Need EMC?

If EMC design practices are adhered to by both the razor and the radio manufacturers, then listening to an AM radio while using an electric razor presents no problem.

In fact, worldwide governmental regulations prohibit electronic products from emitting or being susceptible to electro-magnetic interference.

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How Do We Implement EMC?

Emission, susceptibility, and path are the three constituents of EMC, though unwanted emission causes the most incompatibilities. Emission, however, also yields the greatest number of solutions. Susceptibility, on the other hand, is more subtle in its effect and its solutions. Finally, the path can be an arbiter of both.

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The Dichotomy of EMC

What is good practice for the circuit isn't necessarily best for EMC. What is good practice for EMC isn't necessarily best for the circuit.

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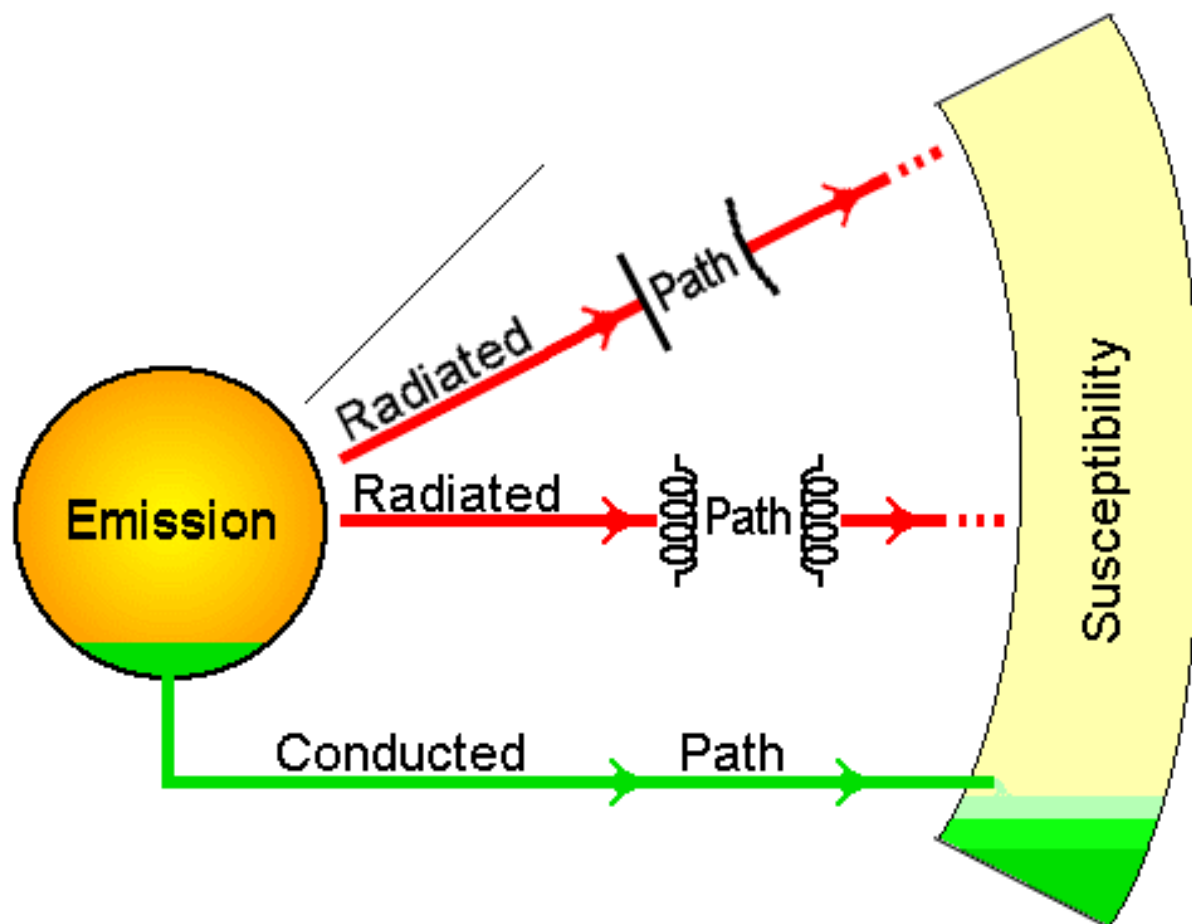
Discussion: Two Approaches

EMC can be approached in two ways: before the fact, and after the fact. Before the fact means designing well for EMC. After the fact is patch work/cleanup; essentially band-aids. Of course, designing in EMC safeguards ahead of time is always best. However, even in the "best" designs these safeguards sometimes aren't enough. Band-aids may still be necessary. Thus the "art" aspect of EMC.

The three constituents of EMC are (unwarranted) emissions, (inappropriate) susceptibility, and the (unintended) path between them. An electric razor's motor brushes arcing is a case of unwarranted emission. A radio picking up the noise created by the arcing of a razor's motor brushes through the path(s) (power line, and/or through the air), is unnecessary susceptibility.

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EMC Paradigm



Block Diagram Depicting the EMC Paradigm

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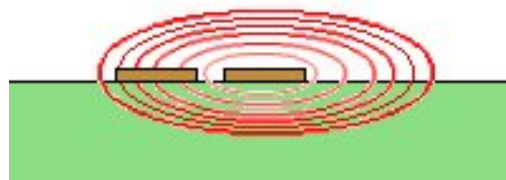
EMC Path

EMC path consists of radiated and conducted energy.

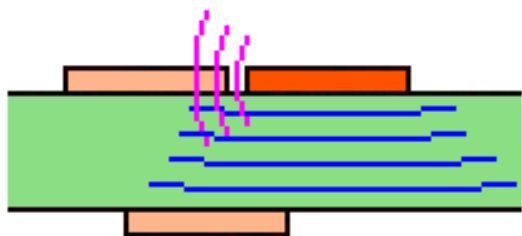
1. Radiated (electromagnetic field)
2. Inductively coupled (magnetic field)
3. Capacitively coupled (electric field)
4. Conducted (electric current)



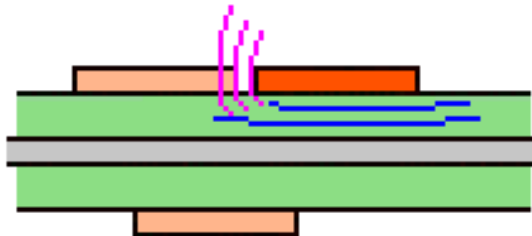
Inductively coupled (magnetic field)



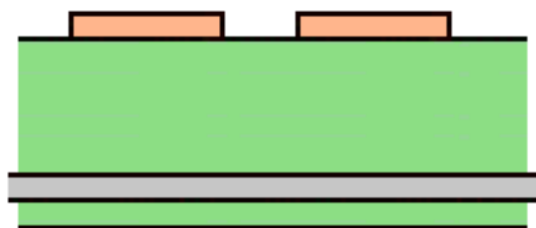
Inductively coupled (magnetic field)



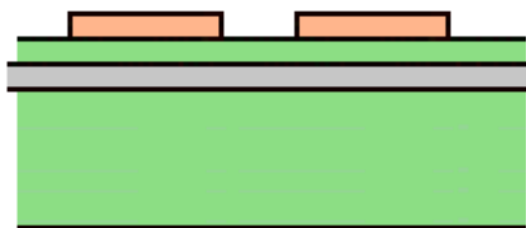
Capacitively coupled (electric field)



Capacitively coupled w/shield (electric field)



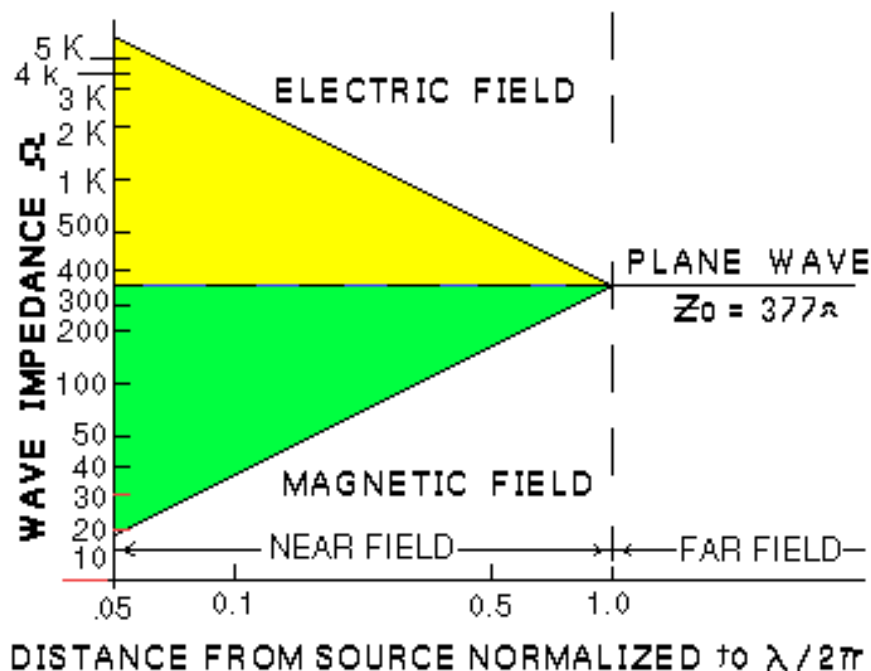
Microstrip transmission line characteristic impedance affected by groundplane proximity:
 $Z = \text{high}$



Microstrip transmission line characteristic impedance affected by groundplane proximity:
 $Z = \text{low}$

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Radiation: Near Field, Far Field



In dealing with a radiation source--be it an antenna or a circuit board:

- The dominant energy in the far field is electric.
- Plane wave radiation is how radio works.
- 377 ohms is the impedance of free space.
- The dominant energy in the near field is magnetic.

In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is

electromagnetic. This is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic. This is referred to as far field radiation, and sometimes called the plane wave. Plane wave radiation is how radio works, and 377 ohms is the impedance of free space.

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Interference Culprits

Who are the culprits we are trying to control?

EMI Electro-Magnetic Interference

An electrical disturbance in a system due to natural phenomena, low-frequency waves from electromechanical devices or high-frequency waves (RFI) from chips and other electronic devices. Allowable limits are governed by the FCC.

RFI Radio Frequency Interference

High-frequency electromagnetic waves that emanate from electronic devices such as chips and other electronic devices. Allowable limits are governed by the FCC.

TVI Television Interference

High-frequency electromagnetic waves that emanate from electronic devices causing interference to television reception.

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Radiated and Conducted EMI

Radiated

Radiated EMI is most often measured in the frequency range from 30 MHz to 10 GHz (according to the FCC).

Emission Sources:

Clocks, clock lines, data lines; switching power supplies.

Susceptibility:

Clock lines and data lines poorly laid out, improperly terminated;

Solutions:

Balanced transmission lines, proper terminations, groundplanes, shielding, limited rise and fall time drivers.

Solutions:

Shielding, layout, filtering, groundplanes, differential line receivers.

Conducted

Conducted EMI is most often measured in the frequency range of several kHz to 30 MHz (according to the FCC).

Emission Sources:

Power supplies (switching), power rails, motors, relays.

Susceptibility:

A.C. power cord poorly filtered, power rails poorly decoupled.

Solutions:
Good bypassing and decoupling practices,
layout, groundplanes, shielding.

Solutions:
Good bypassing and decoupling practices,
layout, groundplanes, shielding, power line
filtering.

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Solutions to EMI

[Spread spectrum](#), clocks reduce measured interference. Spread spectrum is where frequency hopping and bandwidth spreading reduce measured interference.

[Line drivers with controllable rise and fall times.](#)

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Regulations

Residential, Commercial, Industrial, and Military

Entity	Standards
USA / FCC	Part 15, subpart J
Canada	CSA
Japan	VCCI
European	EU (European Union) 89/336/EEC EN specifications: Electronic Equipment Spec. Industrial, scientific and medical equipment EN55011 Broadcast receivers and associated equipment EN55013 Electrical motor-operated and thermal appliances for household and similar purposes, electrical tools and similar apparatus EN55014 Electrical lighting and similar apparatus EN55015 Information technology equipment EN55022
Military	MIL-STD-461/462
Aviation	DO-160
Belcore	GR1089
Automotive	SAE, GM, Ford

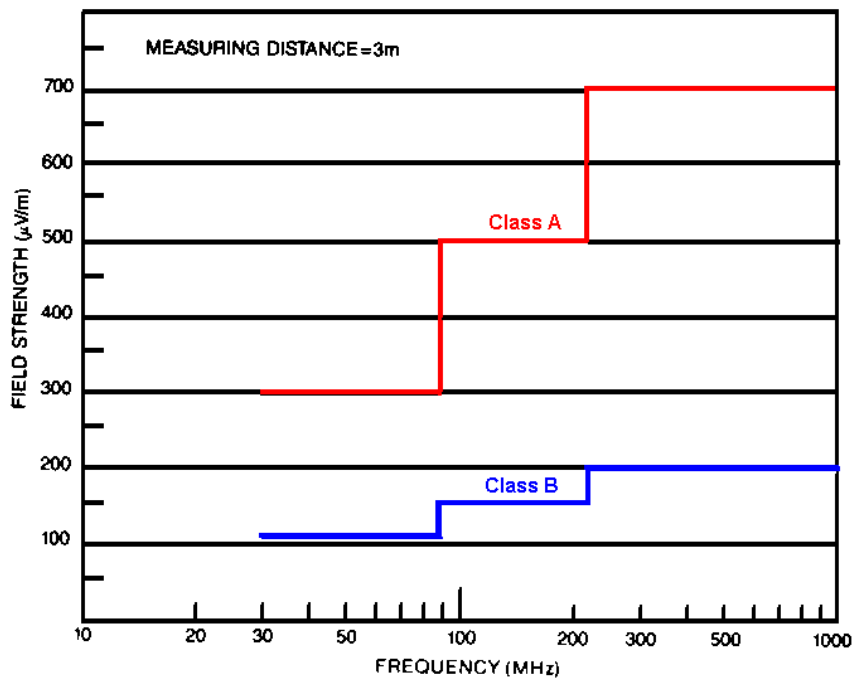
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Measuring EMI and RFI



Spectrum Analyzer
(EMI Receiver)

(Click to Enlarge Image)



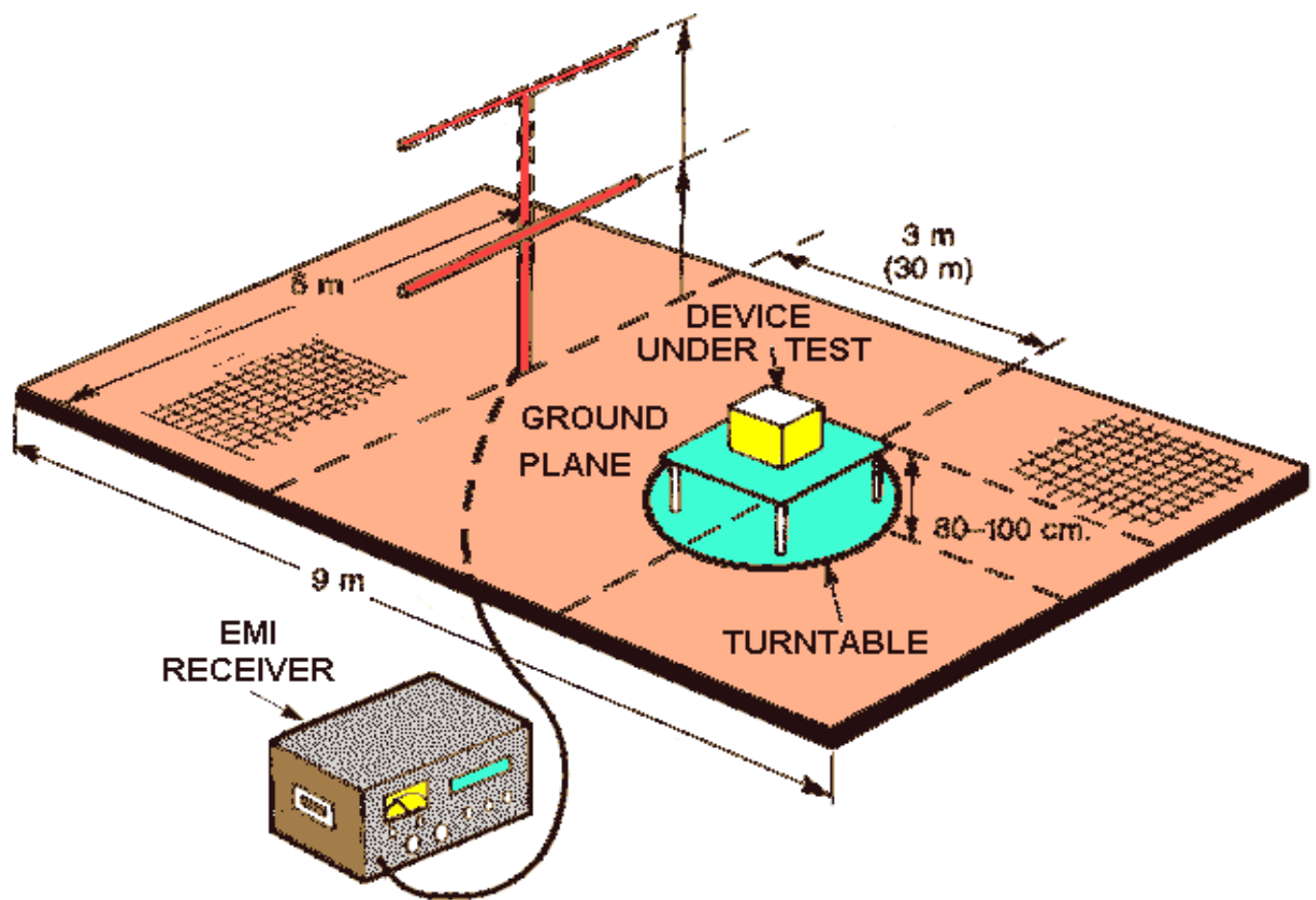
Field Strength FCC: Class A and Class B

Class A limits industrial, commercial, or business use.

Class B limits are more stringent and intended for residential use.

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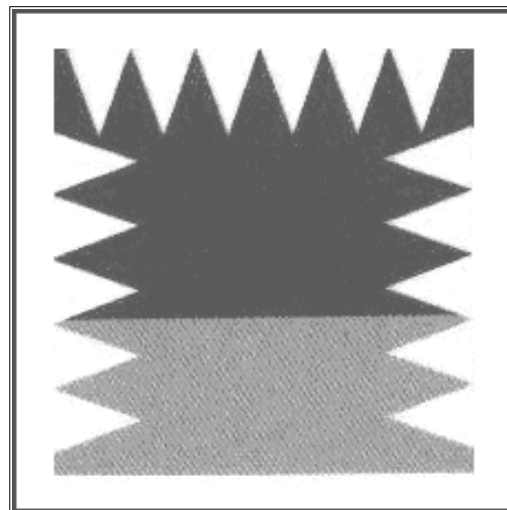
Test Setup



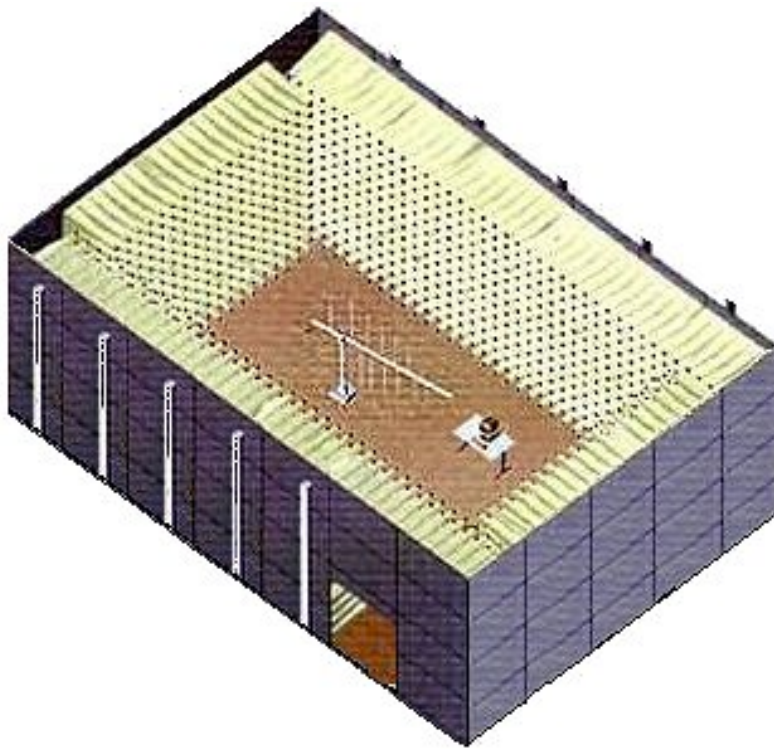
Equipment Setup

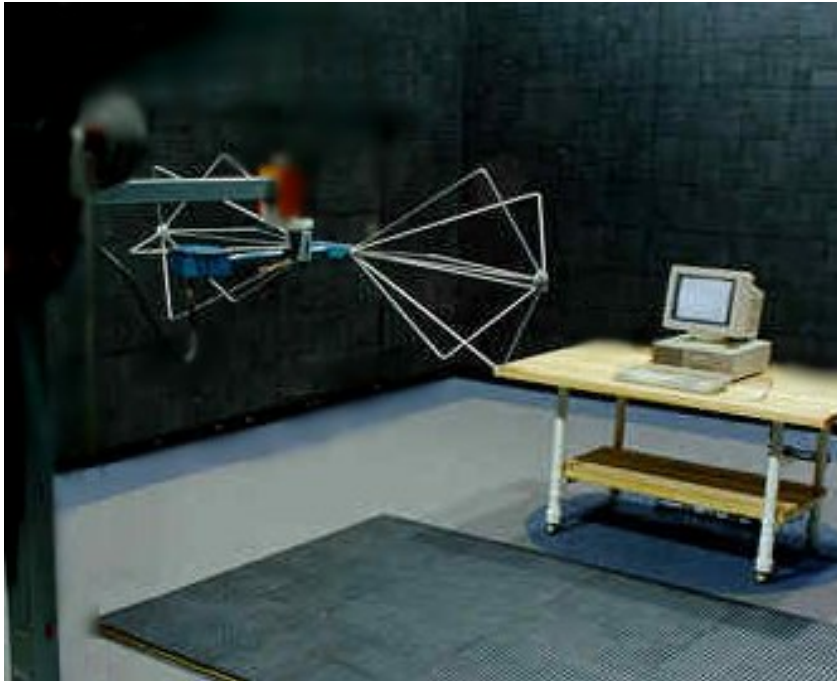
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Anechoic Chamber



The materials used in the walls and ceiling of an anechoic chamber allow little or no reflection of electromagnetic waves. This is accomplished due to the geometry and the absorptive nature of these materials.

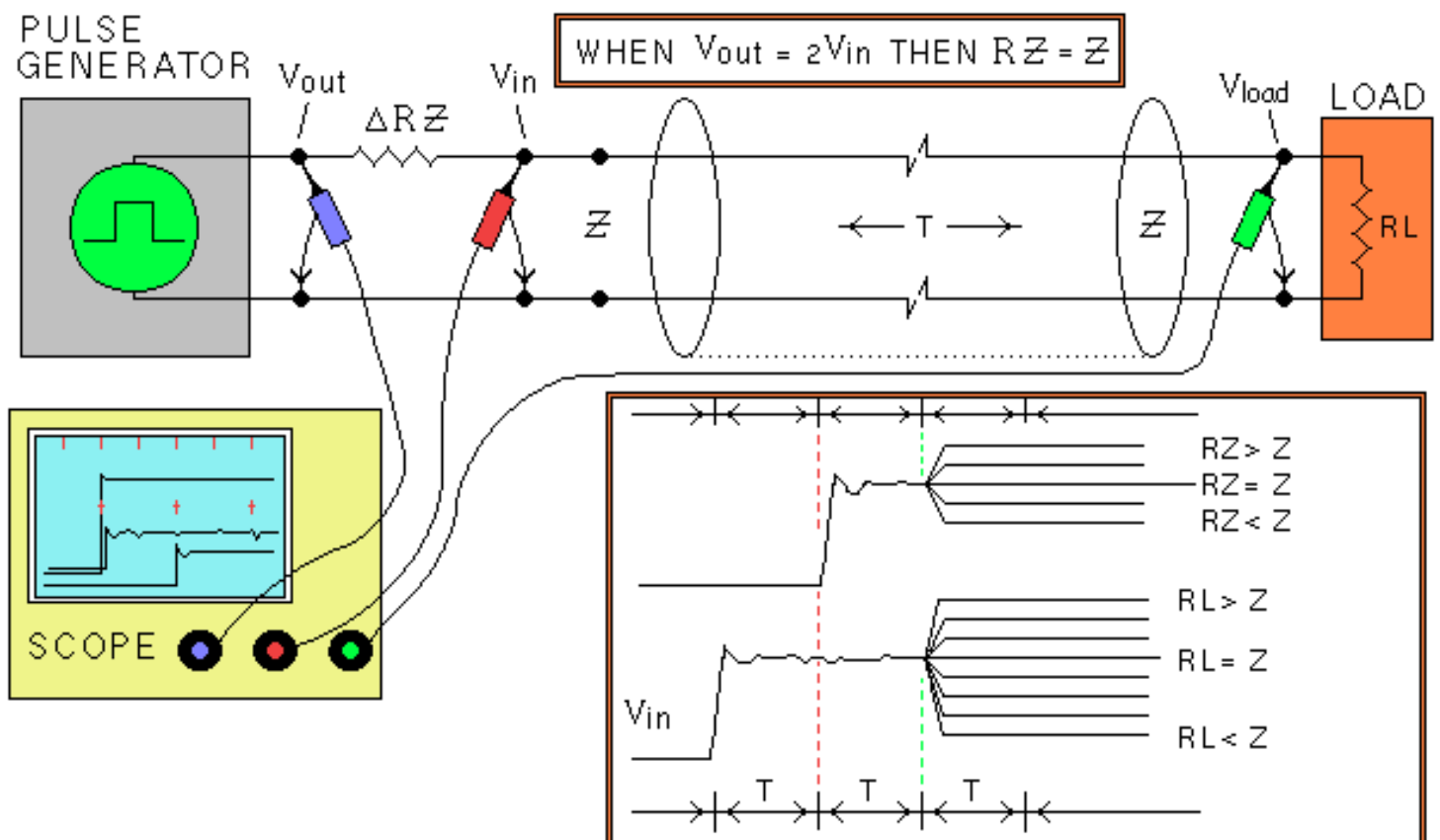




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Transmission Lines

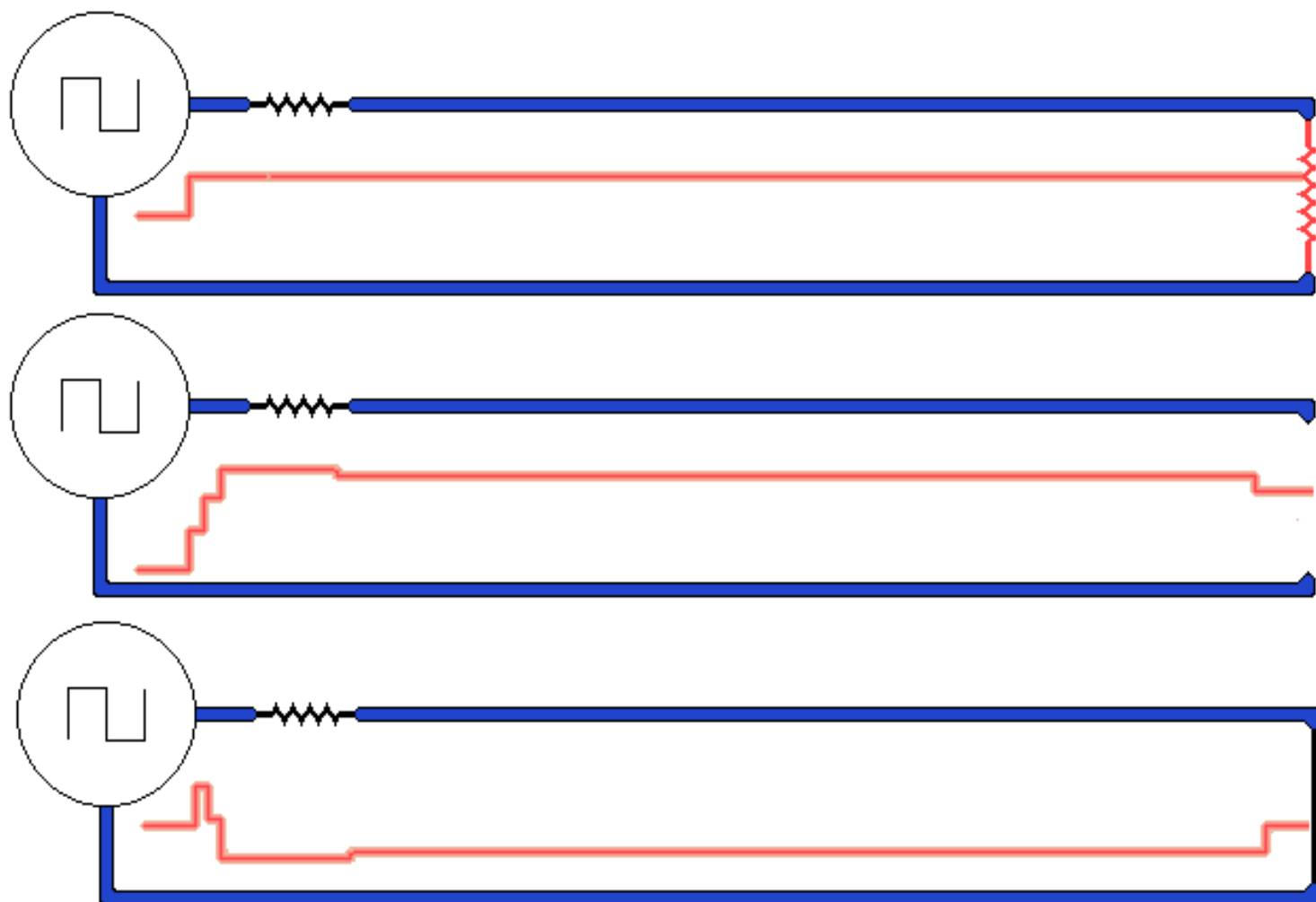
One source of interference can be from improperly terminated or defective transmission lines. Standing waves on a coax can cause the shield to radiate like an antenna.



This illustration shows transmission line reflections due to improper termination impedance.

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Transmission Line Termination Effects



This illustration shows proper termination, open circuit, and short circuit.

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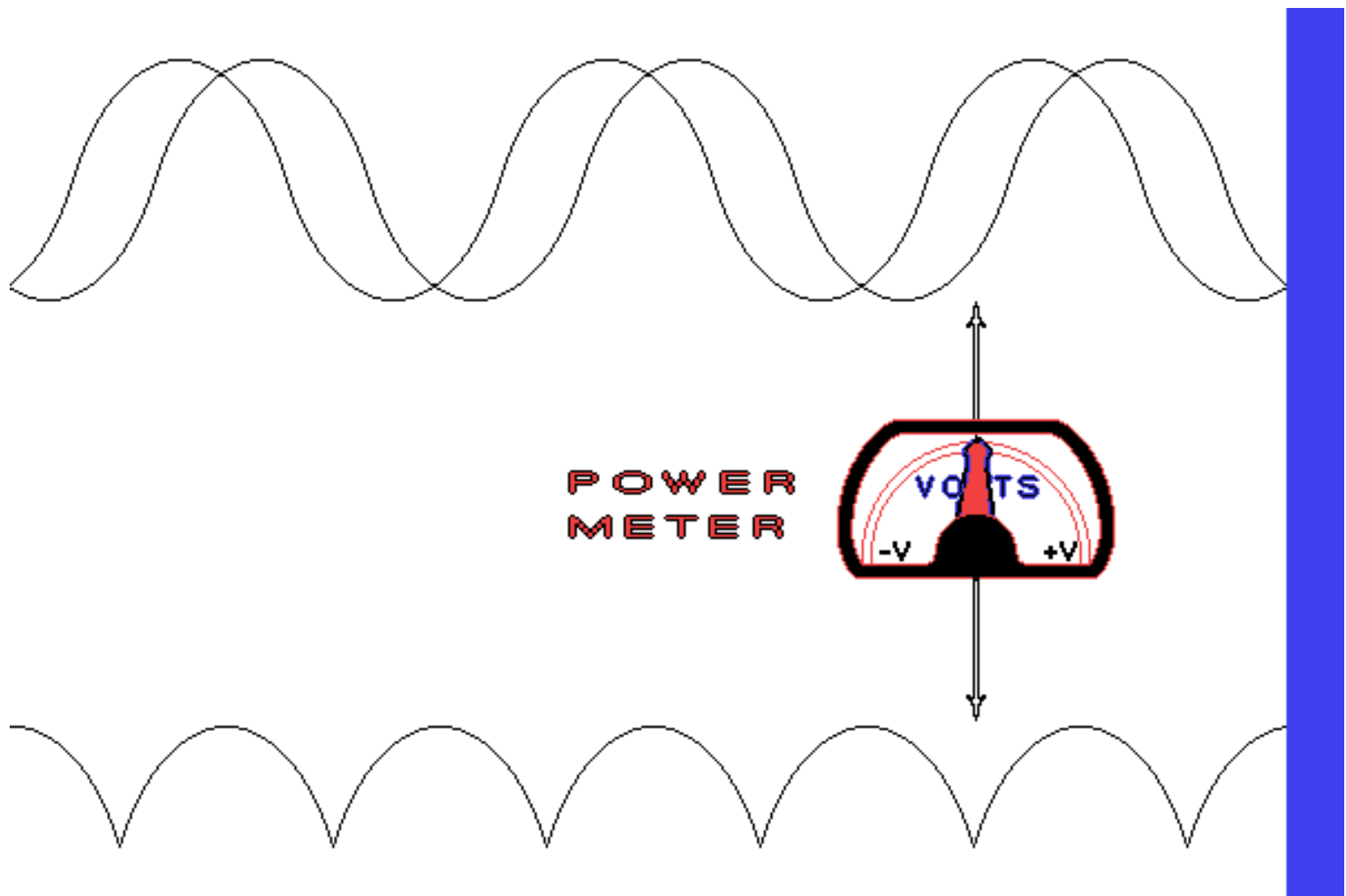
Time Domain Reflectometry Measurements

Time Domain Reflectometry (TDR) measurements have been long used to find transmission line faults.

Applying a fast pulse to a transmission line, while observing the resulting reflections within the transmission line, one can deduce the nature of any faults or discontinuities, as well as, the distance to those faults--assuming one knows the velocity factor of the transmission line dielectric material (insulating material).

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Power Distribution in a Standing Wave

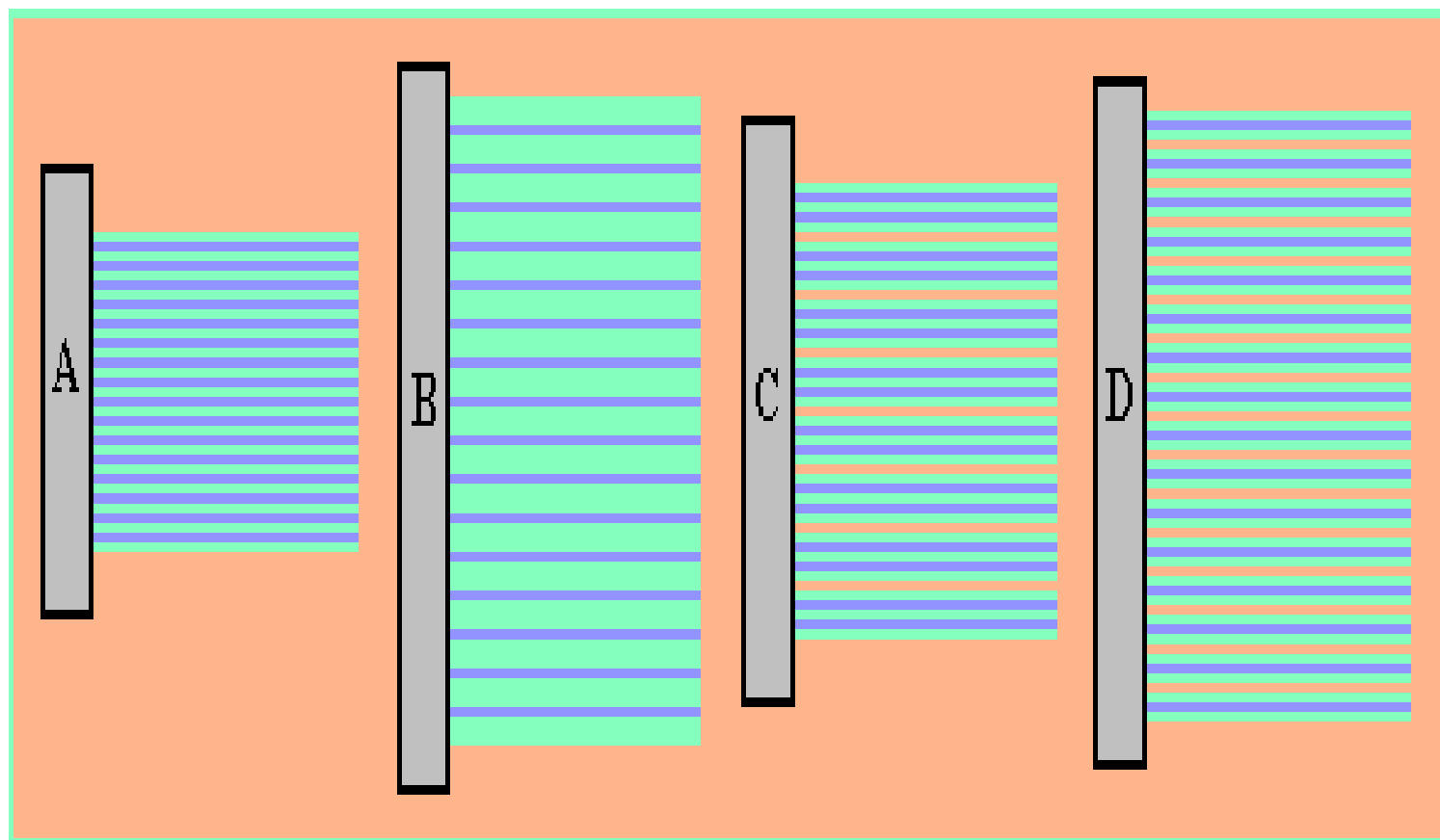


The figure above illustrates standing wave ratio (SWR).

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Data Buses and Clock Lines

Buses are sometimes required to span long distances across a board, which can lead to crosstalk. This can be ameliorated by allowing adequate spacing between traces (see part B of the illustration below). However, there can be instances where this either doesn't work or there is not enough board area available; in which case interleaving ground returns may be required. (See parts C and D of the illustration below.)



Bus Layout

- . simple 16 bit bus, close spacing
- B. wide spacing
- C. interleaved ground traces, 1 ground per 2 signal
- D. 1 ground per signal

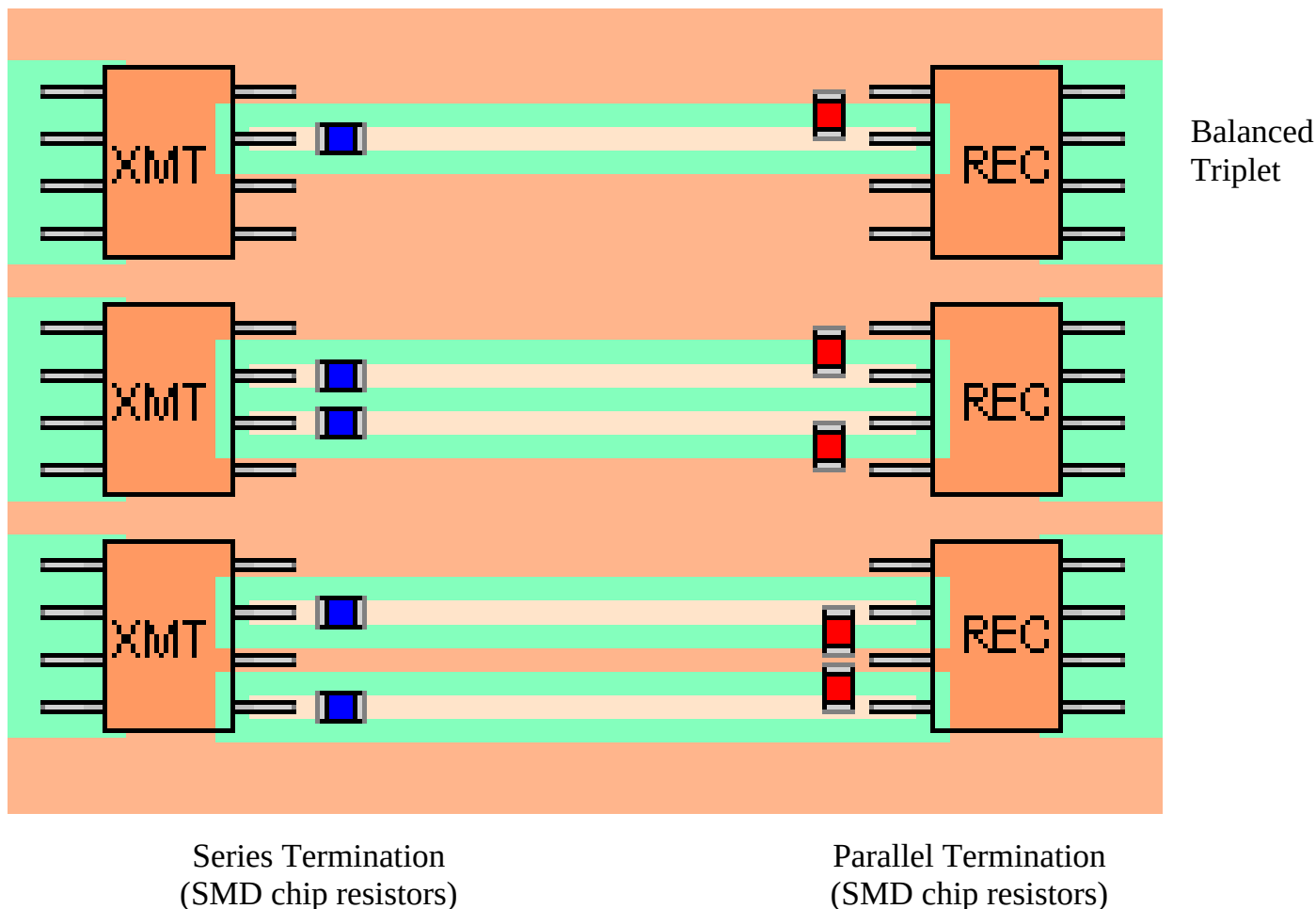
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System Clocks

System clocks are often the single greatest source of EMI.

Single
Ended

Balanced
Pair



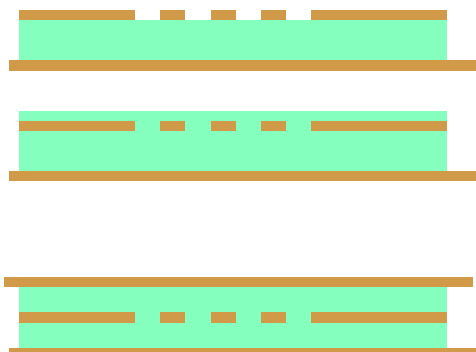
* SMD: Surface Mount Device

Clock Line Drivers and Receivers on PCB Layout

Using single ended, balanced pair, and balanced triplet lines, with series and parallel termination

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Microstrip and Stripline Transmission Lines



Microstrip

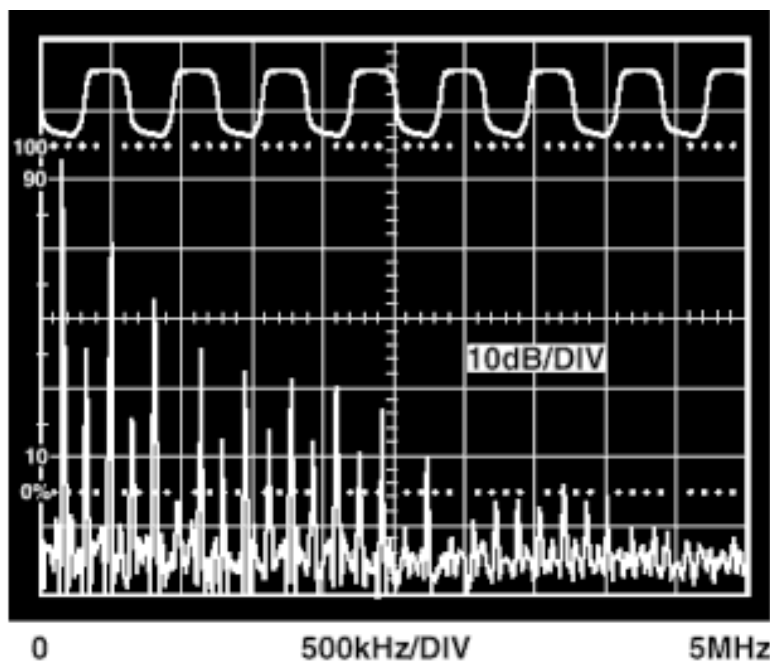
Stripline

Microstrip and stripline transmission lines allow optimum operation of very fast logic, especially ECL (emitter coupled logic) logic. An important resulting benefit of this is reduced EMI.

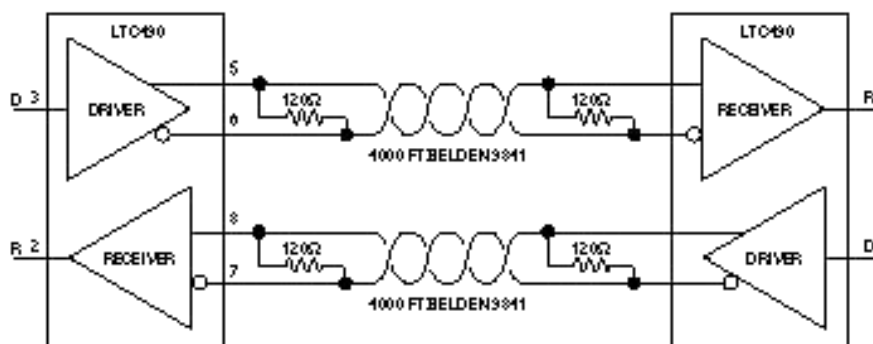
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Less traveled Ways of EMI Reduction

Drivers that Have Programmable/Controlled Rise and Fall Times

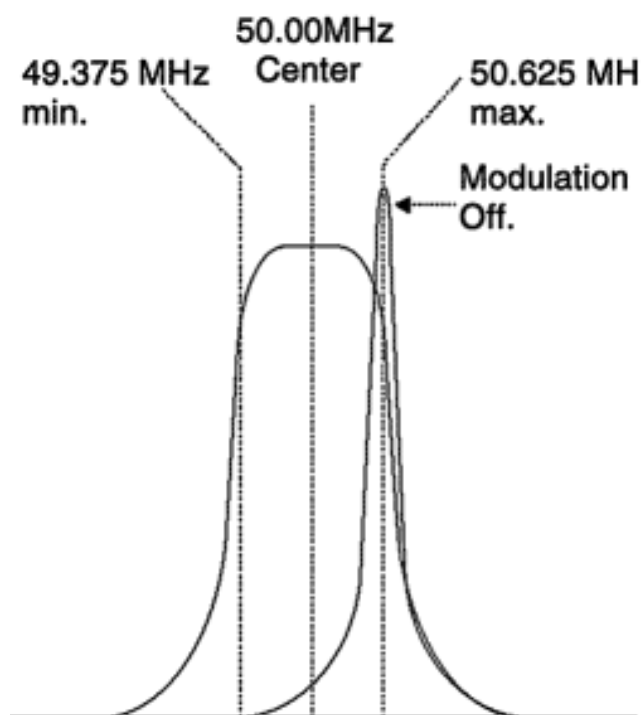


To reduce EMI, some line drivers use internal slew rate limiting. The figure shows an FFT plot when transmitting a 150 kHz data stream. As may be seen, the slew limiting attenuates the high frequency components. EMI is therefore reduced, as are reflections due to improperly terminated cables. The objective is to control the level of emissions, both conducted and radiated. Conducted emissions are assumed to predominate below 30 MHz, while radiated emissions predominate above this frequency.



Spread Spectrum System Clock

All digital clocks generate unwanted energy in their harmonics. Conventional digital clocks are square waves with a duty cycle that is very close to 50%. Because of the 50/50 duty cycle, digital clocks generate most of their harmonic energy in the odd harmonics, i.e.; 3rd, 5th, 7th, etc. It is possible to reduce the amount of energy contained in the fundamental and harmonics by increasing the bandwidth of the fundamental clock frequency. Conventional digital clocks have a very high Q factor, which means that all of the energy at that frequency is concentrated in a very narrow bandwidth, consequently, higher energy peaks. Regulatory

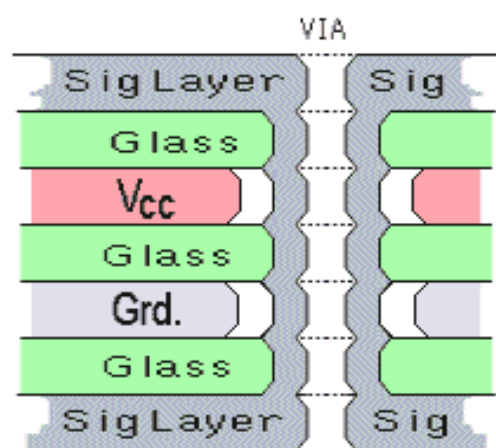


agencies test electronic equipment by the amount of peak energy radiated from the equipment. By reducing the peak energy at the fundamental and harmonic frequencies, the equipment under test is able to satisfy agency requirements for Electro-Magnetic Interference (EMI). Conventional methods of reducing EMI have been to use shielding, filtering, multi-layer PCBs, etc. The SM532 uses the approach of reducing the peak energy in the clock by increasing the clock bandwidth, and lowering the Q; this method can also be thought of as "frequency dithering."

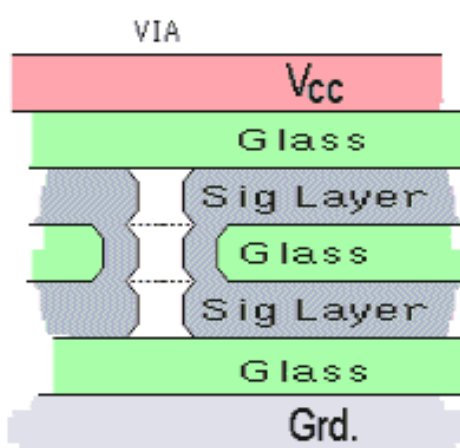
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PCB Layering

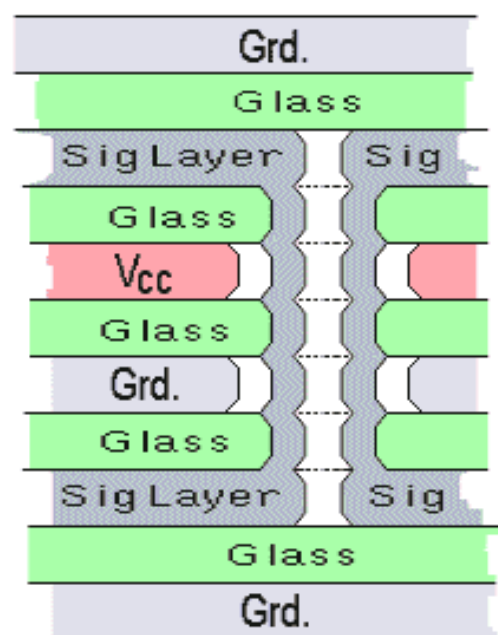
Signal, Power, Groundplane, and Shielding



Better for the Circuit

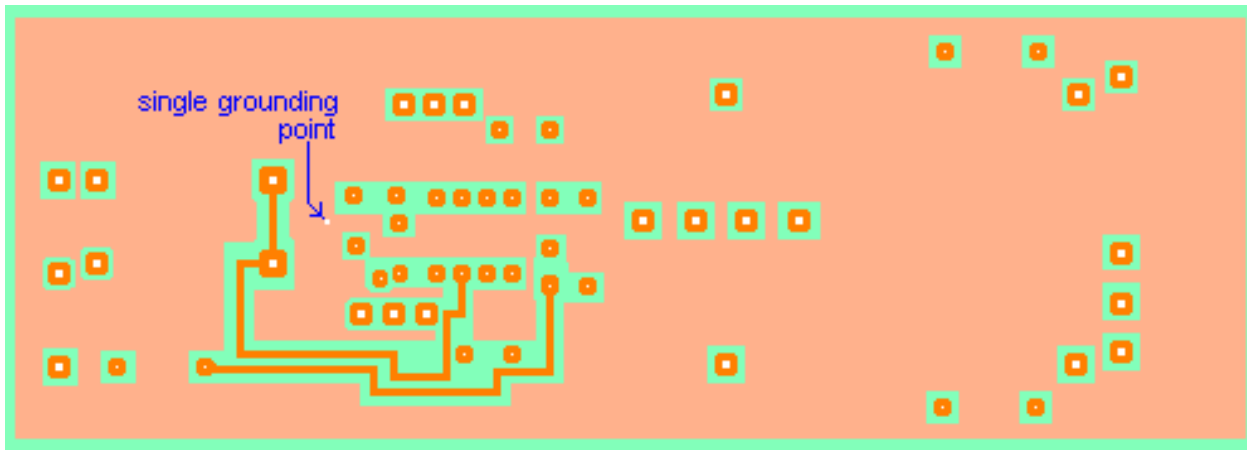


Better for EMC



Optimum for Both

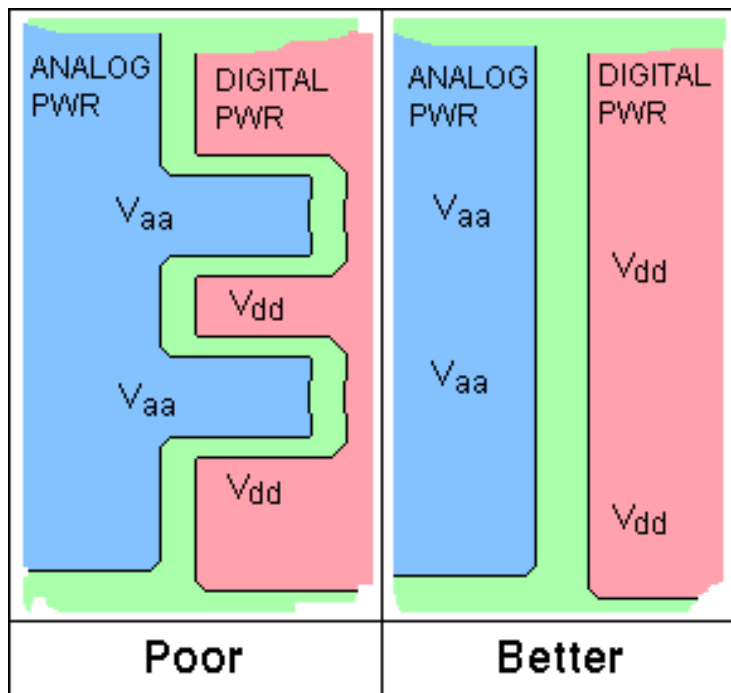
Shield Layer



Note the single grounding (reference) point.

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Analog and Digital Powerplanes



Currents in either powerplane can couple noise to the other; the coupling mechanism is mostly magnetic.

Separation

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Power Supplies

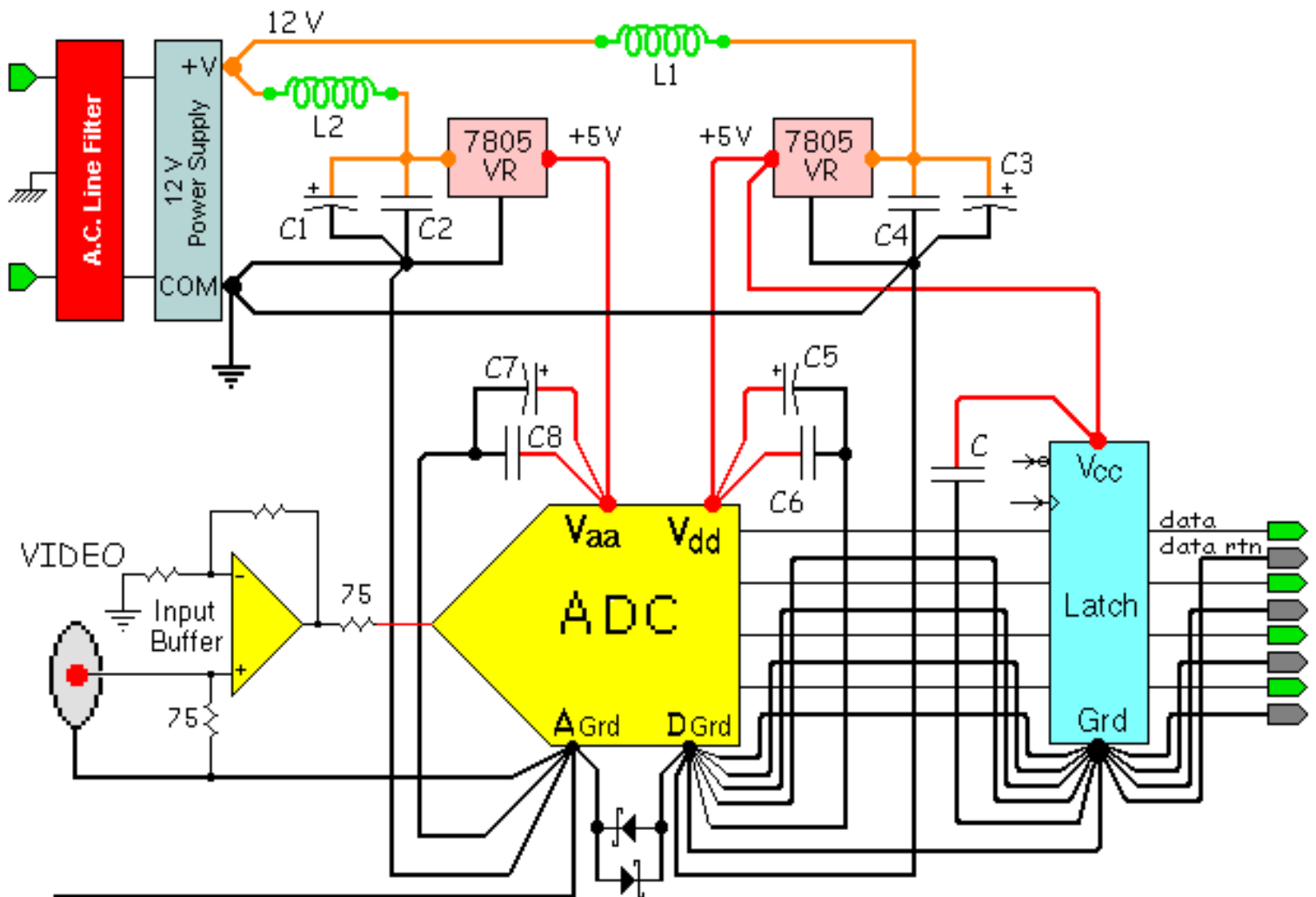
Power supply and distribution are common sources of emissions, as well as paths for conducted and radiated EMI.

Linear Supplies

Linear power supplies, if designed and laid out properly, offer little or no EMI problems. Layout, bypassing, and decoupling are critical to this.

Switching Supplies

Switching power supplies can be a large source of EMI. Proper layout, bypassing, decoupling, and shielding are critical to the ultimate success of switching power supplies.

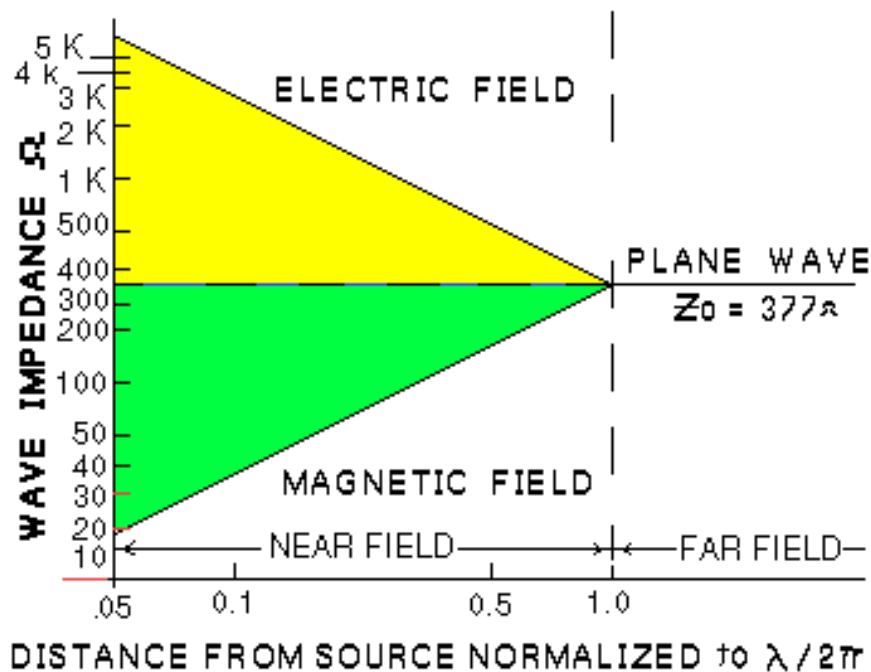


Notice the ground returns in this illustration.

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Reminder

This illustration shows near field and far field radiation.



In dealing with a radiation source--be it an antenna or a circuit board:

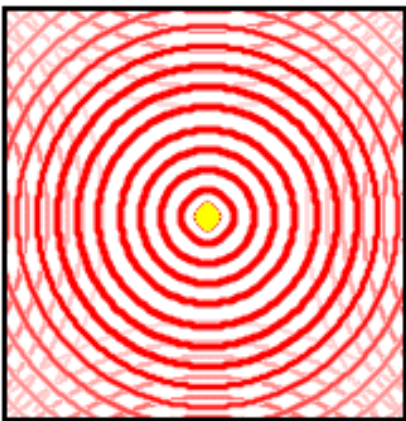
- The dominant energy in the far field is electric.
- Plane wave radiation is how radio works.
- 377 ohms is the impedance of free space.
- The dominant energy in the near field is magnetic.

In any high-frequency signal, the dominant radiation component under $\sim 1/6$ wavelength from the source is electromagnetic; this is referred to as near field radiation.

Any signal beyond $\sim 1/6$ wavelength is electrostatic, and is referred to as far field radiation; sometimes called the plane wave. Plane wave radiation is how radio works and the 377 ohms is the impedance of free space.

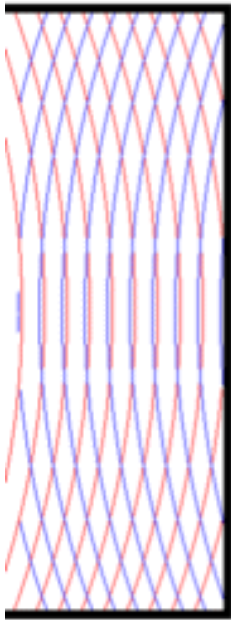
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Shielding as a Method of EMI Control

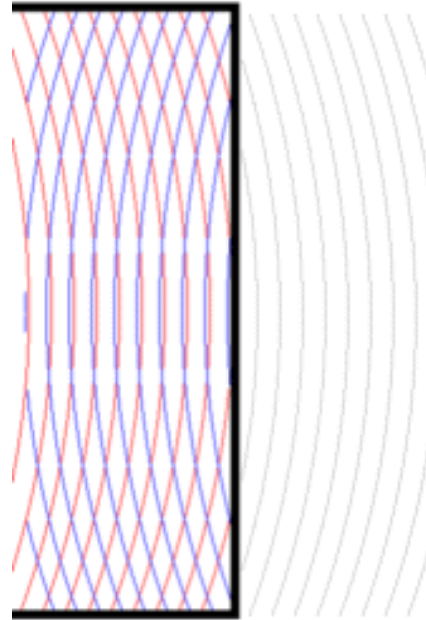


An RF emitter inside a shielded enclosure.

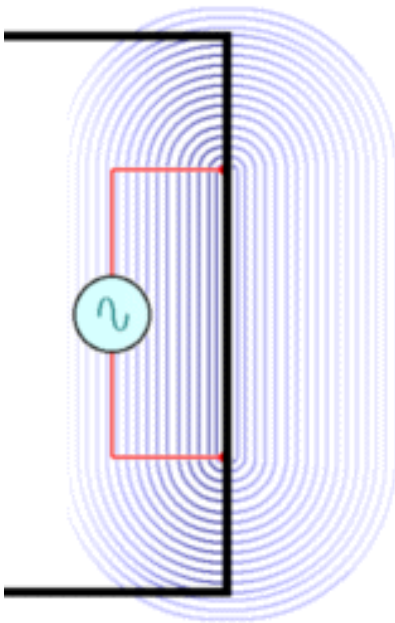
Above is an example of ideal shielding; no leakage.



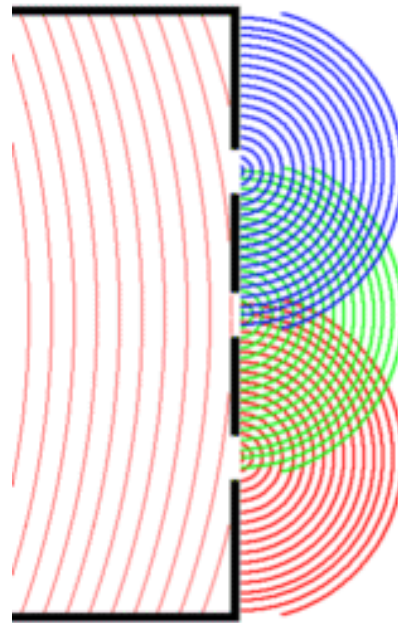
Shield Reflecting



Shield Reflecting,
(with some "parasitic" radiation)



Driven Shield Radiating
(currents in shield create antenna effect)



Leakage of Apertures in Shielded Enclosure
(diffraction apertures act as point sources—
e.g., slot antennas)

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Something to Remember

The area of an aperture is less important than its length (as in seams or joints). The rule of thumb is the maximum dimension of an aperture should not be greater than $1/20$ the wavelength of the highest frequency of interest. Such apertures can act as slot antennas.

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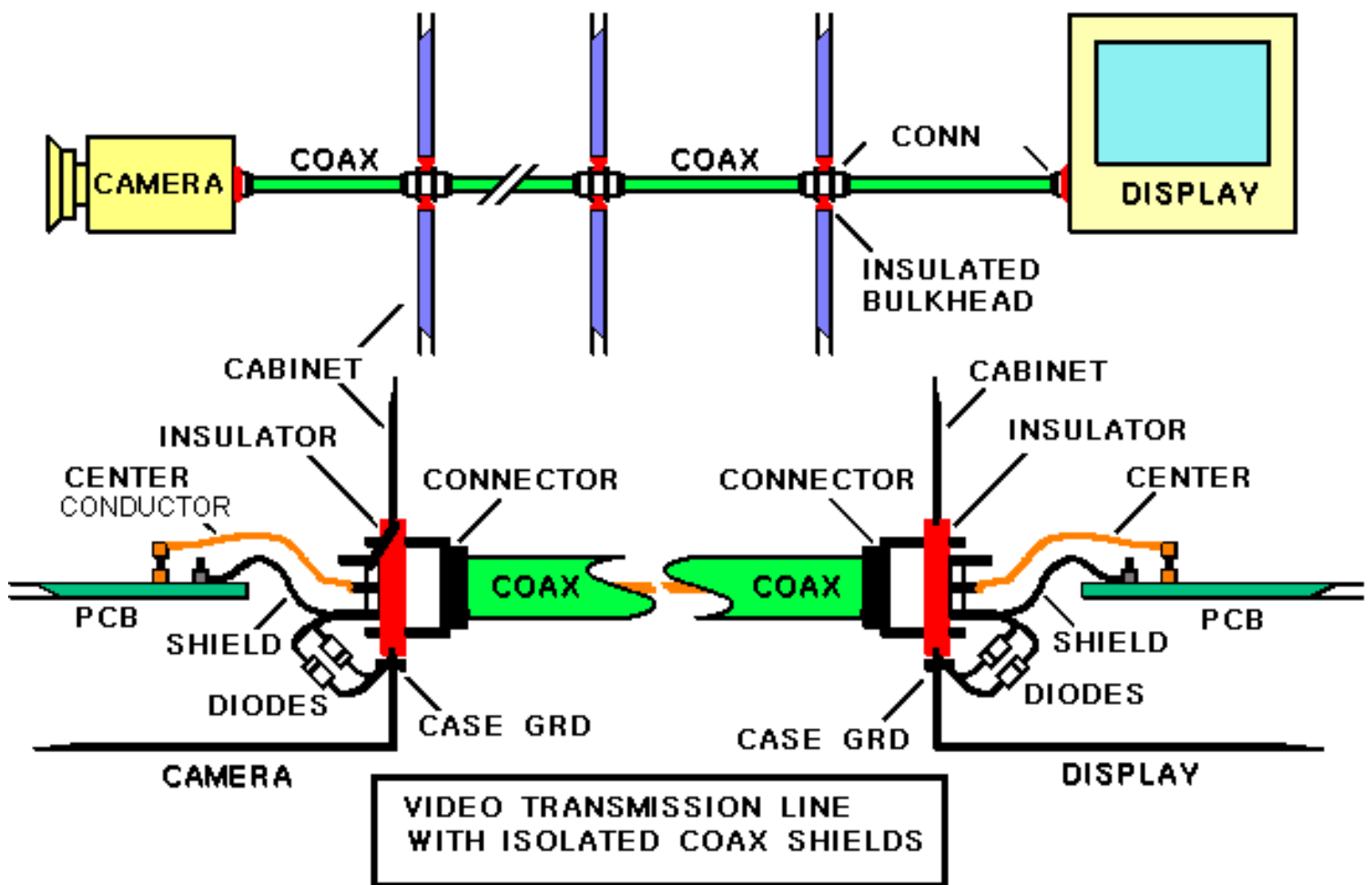
Some Notorious Aperatures I Have Known

- CRTs
- Meter bezels
- Lamps/LEDs
- Switches
- Connectors
- Control knobs (such as volume)
- Sheet metal enclosures
- Cable entrances

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Shielded Cable

Avoid extraneous currents in the coax shield; maintain shield isolation.



By definition: the ideal shield has no current flowing through it, and is "grounded" or referenced at only one point.

In the case of shielded cables, the shield is typically referenced or grounded at both ends.

In the case of coax cables the shield acts as both the shield and the return current path for the signal carried on the center conductor. However, with shielded balanced differential pair (sometimes called twisted pair) the shield is just that, a shield. Often this shield can be grounded at either end. However, in the case of EMI suppression, grounding both ends is prudent.

Though coax and shielded twisted pair are used for both audio and higher frequency signals, there can be

differing effects on how the shield is treated. The most difficult case is that of video, where both very low to high frequencies (~ 10 Hz to >4 MHz) are involved.

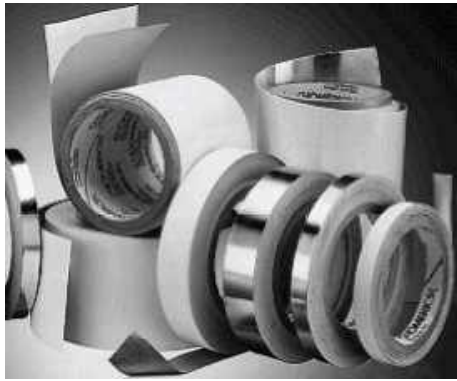
Audio run on coax is subject to "ground loop" noise, i.e., dissimilar ground potentials (especially 60 Hz) which can cause a noise current to flow in the shield, inducing that noise into the protected center conductor. As the frequency of interest increases and the coax gets longer the ground loop problem is diminished; mainly due to the increased inductive reactance (higher Z) of the coax shield.

When long runs are required and/or the environment is noisy, it is best to use shielded twisted pair. The reason is the differential pair's inherent rejection of common mode noise (CMR).

In an extreme case, a remedy might be found in transformer coupling or even optical isolation.

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EMI Protective Arsenal



Metal Foil Tape
(conductive adhesive, and solderable)



Conductive Paint
(copper, nickel, silver, etc.)



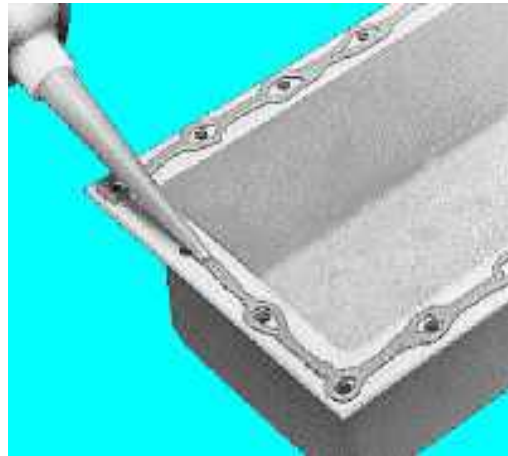
Conductive Plastic Cases



Bronze Finger Stock
(for access panels, doors, drawers, etc.)



Conductive Conformal Gasket Material
(for access panels, etc.)



Conductive Caulking



Custom Conductive Gasket



Solderable & snap-in metal shields



"O" Ring



Conductive ATV



Connector Gaskets

Compressible Gasket

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Additional Shielding Aids

Conductive paint, conductive gasket making silicone (ATV), and assorted conductive gaskets.

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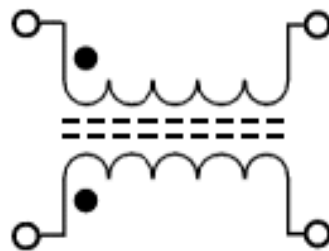
EMI Suppression

Power Line and Data Line EMI Suppression Using Ferrite

Common Mode Noise Suppression



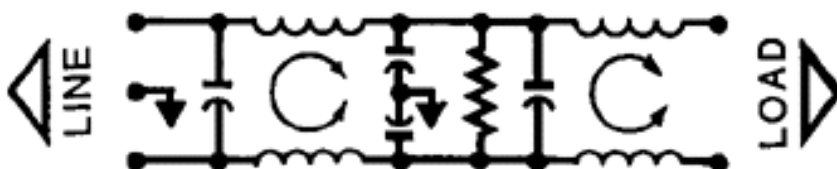
Common Mode Transformers



Common Mode Transformer



Common Mode Transformer



Two Section A.C. Line Filter



A.C. Line Filter
(two section)



A.C. Line Filter



A.C. Line Filter
(built in receptacle)

Assorted EMI Suppression Devices Using Ferrites



Assorted Ferrites



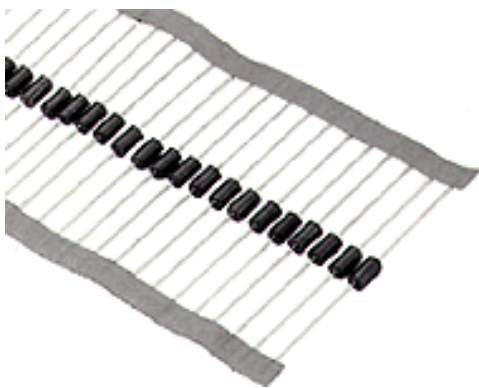
Ferrite Snap-in



Balun (ferrite core)



Tubular & Toroidal Ferrite



Ferrite Beads
Axial Leads



Multilayer Ferrite Chip Beads



SMT Ferrite Beads



"DB" Data-Connector



Flat Cable Ferrite Cores

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Summary

Transmission Lines

Be careful of high SWR (Standing Wave Ratio) on all transmission lines such as twisted pair, coax, PCB traces, etc.. If not terminated correctly, or if there are discontinuities (e.g., unterminated stubs, damaged cable, etc.) they can radiate.

Properly terminated, differentially driven and received shielded twisted pair offer the best performance.

Bypass & Decouple

- Bypass all active devices!
- Remember that bypass capacitors are self resonant.
- Connect capacitors using the shortest leads!

Voltage regulators offer the best decoupling.

Caution: voltage regulators will generate parasitic oscillations if not properly bypassed.

Groundplane

Every signal should have its own ground return.

Shielding

By definition, real shields have no current flowing through them. They are grounded (referenced) at only one point.

Enclosures

Leakage Apertures

Diffraction: openings or apertures in enclosures appear as point sources, and radiate their venomous exhaling.

Area of the apertures is less important than the longest dimension, e.g., seams and joints; greater than $\sim 1/20$ wavelength of the highest frequency of interest. They start looking like slot antennas.

Some Apertures

- CRTs
- lamps/LEDs
- switches
- connectors

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EMI Reduction Check List

Suppression of Emitter EMI

1. Enclose noise sources in a shielded enclosure.
 2. Filter all leads leaving a noisy environment.
 3. Limit pulse rise and fall times.
 4. Relay coils should have surge damping.
 5. Shield and/or twist noisy leads.
- B. 6. Ground both ends of shields used to suppress radiated interference (shield should be insulated).

Reducing Noise Coupling

1. Twist low-level signal leads.
2. Place low-level leads near chassis (especially if the circuit impedance is high).
3. Twist and shield signal leads (coaxial cable may be used at high frequencies).
4. Shielded cables used to protect low frequency, low-level signal leads should be grounded at only one end (coaxial cable may be used at high frequencies with shield grounded at both ends).
5. Insulate shield on signal leads.
6. When low-level signal leads and noisy leads are in the same connector, separate them and place the ground leads between them.
7. Carry shield on signal leads through connectors on a separate pin.
8. Avoid common ground leads between high-level and low-level equipment.
9. Keep hardware grounds separate from circuit grounds.
10. Keep ground leads as short as possible.
11. Use conductive coatings in place of nonconductive coatings for protection of metallic surfaces.
12. Separate noisy and quiet leads.
13. Ground low frequency, low-level circuits at one point only (high frequencies and digital logic

are exceptions).

14. Avoid questionable or accidental grounds.
 15. For very sensitive applications, operate source and load balanced to ground.
 16. Place sensitive equipment in shielded enclosures.
 17. Filter or decouple any leads entering enclosures containing sensitive equipment.
 18. Keep the length of sensitive leads as short as possible.
 19. Keep the length of leads extending beyond cable shields as short as possible.
 20. Use low impedance power distribution lines.
 21. Avoid ground loops in low frequency, low-level circuits.
 22. Consider using the following devices for breaking ground loops:
 - a. isolation transformers
 - b. common-mode chokes
 - c. optical couplers
 - d. differential amplifiers
 - e. guarded amplifiers
 - f. balanced circuits
 - g. hybrid ground
- C.

Receiver Noise Reduction

1. Use only necessary bandwidth.
 2. Use frequency selective filters when applicable.
 3. Provide proper power supply decoupling.
 4. Bypass electrolytic capacitors with small, high-frequency capacitors.
 5. Separate signal, noisy, and hardware grounds.
 6. Use shielded enclosures.
 7. When using tubular capacitors, connect the outside foil end to ground.
- D.

Controlling Digital System Emissions

1. Minimize ground inductance by using a ground plane or ground grid.
2. Locate bypass capacitors next to each IC in the system (use shortest leads possible).
3. Use the smallest value decoupling capacitor that will do the job.
4. Use a bulk decoupling capacitor to recharge the individual IC decoupling capacitors.
5. Clock signal loop areas should be kept as close to zero as possible.
6. All cables should be treated to minimize their common-mode current.
7. All unused inputs on logic gates should be connected to either power or ground.
8. I/O drivers should be located near where the cables leave the system.
9. Use the lowest frequency clock and slowest rise time that will do the job.
10. Keep clock circuits and leads away from the I/O cables.

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