



WHY and HOW to GROUND ELECTRICAL SYSTEMS



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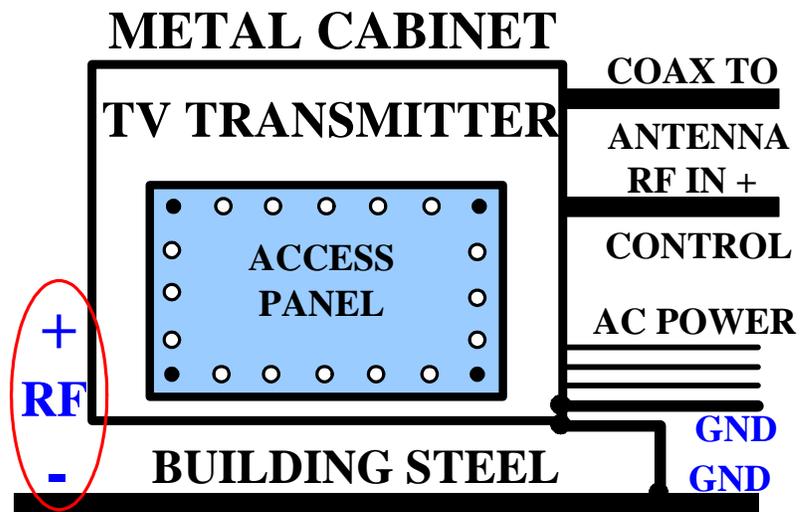


Grounding is a very controversial and misunderstood concept. In the very early days of power distribution and telegraphy the earth (ground) was used as the current return path. Today, for low-voltage (10s of kV) AC power *distribution* the earth is still used as part of the current return path. For high-voltage (100s of kV) AC power *transmission*, the earth is not used as the current return path.

For safety and noise reduction in today's electrical systems, a "grounding connection" does not usually carry intentional current and often has no direct contact with earth. This presentation will explain why and how modern electrical systems are grounded.

THE PROBLEM:
Excessive RF voltage
between cabinet and
building steel.

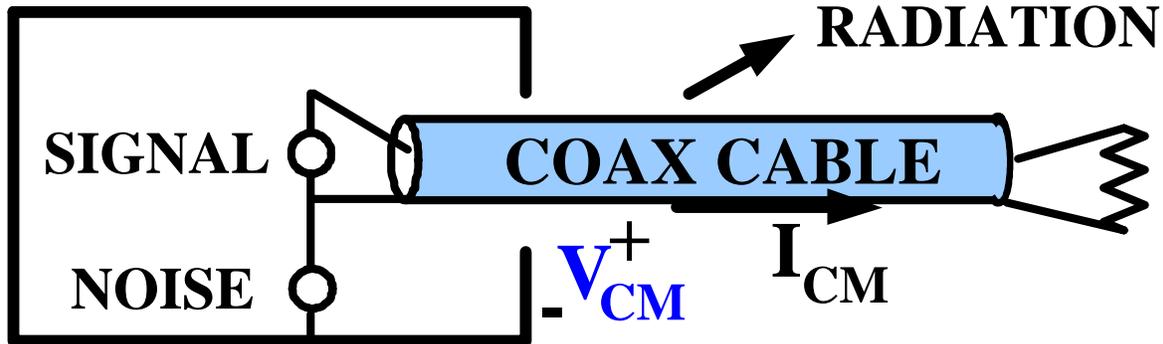
Is problem caused
by inadequate
RF grounding?



A high power TV transmitter was installed on the top floor of a multifloor office building. The transmit antenna was mounted on the roof of the building. Gradually over a period of several years a troublesome RF voltage difference developed between the transmitter cabinet and the surrounding building metal structure. Someone suggested installing a better RF grounding connection between the cabinet and building steel – a “low inductance” wide metal strap. The cabinet already has an adequate AC power safety ground to the building. The inadequate RF grounding is between the access panel and the cabinet. Many of the screws were left off and the gasketing material was damaged during frequent removal of the panel for transmitter maintenance. Replace the screws and the gasketing to recreate the original effective RF grounding connection between the panel and the cabinet.

How can radiated emissions be reduced? 3

METAL ENCLOSURE



The internal NOISE source causes V_{CM} to develop between the coaxial cable outer conductor and the metal enclosure. This voltage difference drives the dipole antenna formed by the cable and the enclosure; and, causes near-and far-field radiation. To reduce these radiated emissions, V_{CM} must be reduced by an effective high-frequency grounding connection between the cable and the enclosure. To be effective, the MUTUAL INDUCTANCE associated with this grounding connection must be minimized. How to build this grounding connection to reduce the mutual inductance will be explained in later figures.

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Misconceptions that can cause EMI:

- Currents go to ground;
- Currents take the path of least resistance;
- **Ground is the signal current return path;**
- A single straight wire has self inductance.

(All of these “concepts” are **often WRONG!!**)

Electromagnetic compatibility is concerned with understanding and controlling the paths of all the currents within a system; the signal currents, the power currents, and the noise currents. It is often thought that currents go to ground taking the path of least resistance. Both of these ideas are usually incorrect. Ground is normally considered to be part of the signal current path. This concept is also usually wrong. A main objective of this presentation is to show that the grounding of a current and the routing of a current are two very important, but entirely different, concepts. Unfortunately, grounding is often thought to be the same concept as routing. Self and mutual inductance concepts are usually misunderstood, but correcting those misconceptions is not part of this presentation.

MAIN TOPICS

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1. Reasons for grounding
2. What is “electrical ground”?
3. Grounding for safety, with examples
4. Grounding to reduce interference
 - Grounding of A/D converter
 - Misunderstanding of “single point” grounding
 - HF grounding at chassis connectors
 - Reducing M of GHz grounding connections

The two reasons for grounding, safety and interference reduction, are defined and described. The characteristics of an electrical ground structure are presented. Several safety grounding examples and grounding to reduce interference examples are discussed. The differences between a current carrying routing connection and a non current carrying grounding connection are emphasized. How to build GHz grounding connections with minimal mutual inductance is shown.

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Reasons for Grounding

To reduce *voltage differences* that might cause:

1. Electrical *Safety* problems; or,
2. Electrical *Interference* problems.

There are two reasons for grounding: safety and noise reduction. The purpose of safety grounding is to reduce voltage differences between exposed conducting surfaces that might become energized and cause a shock hazard. These voltage differences must be kept less than a few volts under worst case conditions, such as lightning and power faults, to reduce the shock hazard for people. In some cases, the voltage difference must be minimized for safety of the equipment. Grounding for noise reduction requires that different parts of the signal system, such as analog and digital circuits, operate at the same voltage reference. A voltage difference between reference points is a source of common mode noise for the system. If two circuits are at the same reference voltage then a conductively coupled interface can be used between them. If two circuits are not at the same reference voltage, then a more complicated isolated interface may be required.

A grounding conductor carries *negligible* signal current under *normal* operating conditions.

A grounding conductor is not a signal current routing conductor!

Grounding is NOT routing.

(Do you detect a “theme” here??)

Signal current routing conductors provide a conductive path for the signal current. These conductors are intended to carry the majority of the signal current. Grounding conductors are used to reduce voltage differences that might cause a safety hazard or noise interference. Under normal operating conditions negligible current should flow through a grounding conductor. Under abnormal conditions; such as a power fault, lightning, or electrostatic discharge, a grounding conductor might carry a significant amount of current for a short time.

A signal *routing* conductor is NOT a signal *grounding* conductor!

Characteristics of an Electrical Ground Structure

1. A “GOOD” Conductor (usually metal)
2. A “LARGE” Surface Area
3. “CLOSE” to the System

****4. NOT part of the signal current path!**

When a power or signal circuit is connected to “ground”, the ground structure will usually possess these characteristics. (1) A “good” conductor--the ground structure is usually made of metal, except for the Earth. (2) A “large” surface area compared to the size of the system being grounded. (3) “Close” to the system so that the ground structure can have a noticeable effect. This usually means within a distance of a few meters or less. If the ground structure is several hundred meters away, it does not have any effect on the electrical system.

A very important characteristic of a ground structure is that it does **not** carry a significant portion of the signal current. If the structure is supposed to carry the signal current, then it is part of the signal routing path and not part of the grounding structure! The ground structure for one current may be part of the signal path for another current.

Possible Electrical Ground Structures

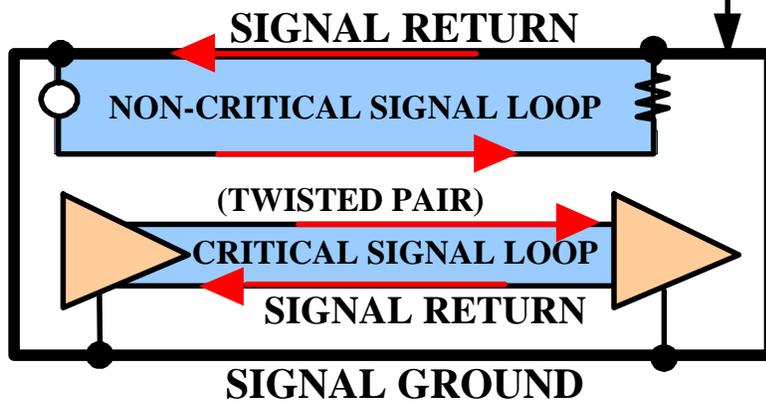
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Metal Equipment Chassis
Building Metal
Metal Vehicle Frame
Earth

Should a metal chassis be a “ground structure” or a “routing structure”? IT DEPENDS!

Typical ground structures are a metal equipment chassis, the metal parts of a building, the metal parts of a vehicle frame, and Earth. A vehicle frame and an equipment chassis may also be part of the intentional current path for some signals. Earth and building steel are rarely ever part of the intended signal current path. The ground structure that is *closest* to the system circuits is usually *the most critical* ground structure because the close proximity allows for more energy coupling. This energy coupling can be good if it helps to control the path of noise currents. This energy coupling can be bad if it provides additional unwanted signal current paths or if some of the noise energy (current) is allowed to couple into the system.

IS THIS *METAL AIRFRAME* GROUND OR RETURN?



The same 10 conductor can be *ground* for one signal and the *return path* for another signal!

This example shows two signals inside the metal frame of a commercial airliner. One signal is critical to the flight of the airplane and the other signal is not. The non-critical signal uses the metal airframe as the current return path, to save the weight of the return conductor. The metal frame is the return path, and not ground, for the non-critical signal.

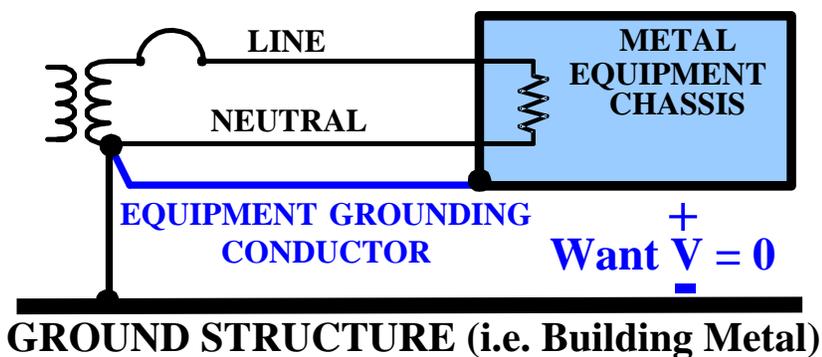
The critical signal uses two dedicated conductors in a twisted pair for the output and return paths. For this current, the metal airframe is; 1) a good conductor, 2) a large surface area, 3) close to the critical signal cable, and 4) not part of the critical signal current path. Therefore, the airframe meets all of the requirements of a ground structure as far as the critical signal is concerned.

Grounding for Safety – Reduces voltage differences between exposed conducting surfaces that might become energized.

Safety grounding requires properly sized and located conductors to reduce voltage differences during lightning or AC power fault conditions.

The purpose of safety grounding is to reduce voltage differences between exposed conducting surfaces that might become energized and cause a shock hazard. The equipment grounding conductor must be of sufficient size to carry the fault current until the fault is cleared by an overcurrent sensing breaker. The grounding conductor must be located next to the phase conductors to minimize the fault path loop inductance. A low impedance fault path results in larger fault current and more rapid tripping of the breaker. For “low” power (<100 kW) AC circuits, a low impedance fault path is much safer than a high impedance fault path.

A Safety Grounding Example



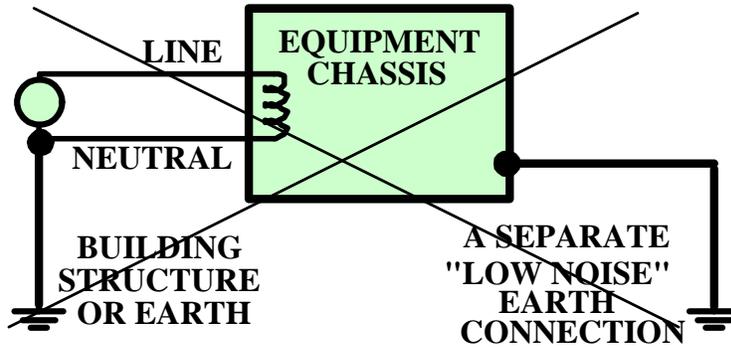
Size – To carry fault current.

Location – To minimize fault path inductance.

The electronic equipment is in a metal chassis and is AC powered. The exposed metal chassis might become energized from the AC power source, and therefore, the chassis should be safety grounded. The **equipment grounding conductor** must be routed with the AC power conductors, to reduce the inductance of the fault path. The grounding conductor must be connected to the metal chassis at the load end, and to the grounded neutral of the AC system at the power source end. The LINE and NEUTRAL are the *current carrying routing* conductors and the EQUIPMENT GROUNDING CONDUCTOR is the *non current carrying grounding* conductor.

Unsafe Use of “Low Noise” Earth Ground

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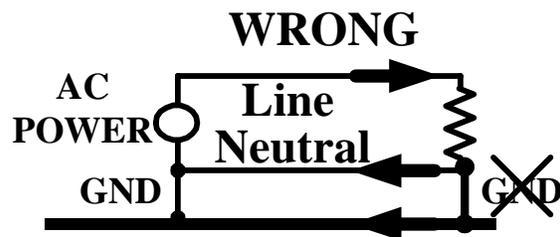
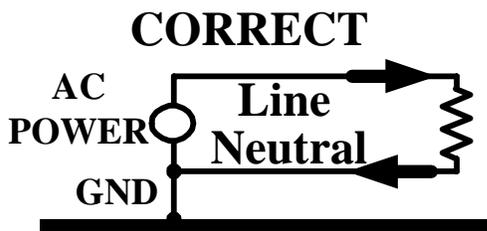
Unsafe because of a high impedance fault path & a possibly large neutral to chassis voltage during lightning.

The fear that the building structure is a source of noise causes some people to not ground their equipment to the building power ground system. Instead they use a separate Earth ground connection as shown in this example. This is a direct violation of the National Electric Code (NEC). Grounding schemes that are labeled “low noise ground”, “instrumentation ground”, or “clean ground” should be carefully checked to see that they satisfy the safety grounding requirements of the NEC. In this example, if a line-to-chassis short occurred there might not be enough fault current to rapidly trip the overcurrent sensing breaker because of the high impedance in the large loop area fault path. Also, lightning induced ground voltage differences could cause large neutral-to-chassis voltage difference.

Inside a building, ground the AC power neutral only once at the source to:

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1. Reduce the Shock Hazard; and,
2. *Control* the AC Current Path.



Grounding the AC power neutral (N) conductor only at the source, as in the figure on the left, forces all of the power current to stay on the line (L) and neutral conductors. Grounding the neutral at both the source and the load, as shown in the figure on the right, allows some of the power current to return to the source using the nearby ground structure (building steel, for example). Currents at frequencies less than a few kHz want to take *all possible paths*.

The neutral conductor for a power line outside of a building is repeatedly connected to ground to provide better lightning protection. Inside a building, the neutral is only connected to ground once to maintain control of the power current path.

An EQUIPMENT GROUNDING CONDUCTOR:

- 1. Must have *Ampacity* to carry the fault current long enough to trip the overcurrent sensing breaker;**
- 2. Must be *positioned next to power conductors* to provide a low impedance fault path;**
- 3. Must carry “*no objectionable*” (negligible) current during normal operation.**

The equipment grounding conductor (the green-wire safety grounding conductor) must have sufficient current carrying capacity (ampacity) to carry the fault current until the overcurrent sensing breaker trips. To allow rapid tripping of the breaker, the fault path impedance (mainly inductance) must be minimized to increase the amount of fault current. Under normal operating conditions; such as no fault current and no lightning current, the equipment grounding conductor should carry “no objectionable” current. The maximum allowed value of current under normal conditions depends on several factors beyond the scope of this discussion.

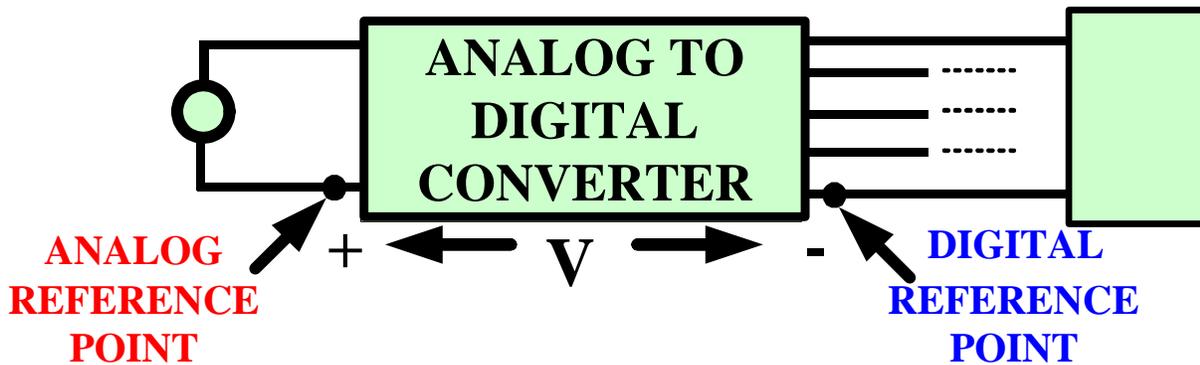
Grounding to Reduce Interference –

Reduces voltage differences that might cause noise emission or susceptibility problems.

***Grounding* to reduce interference is completely different from *routing* to reduce interference.**

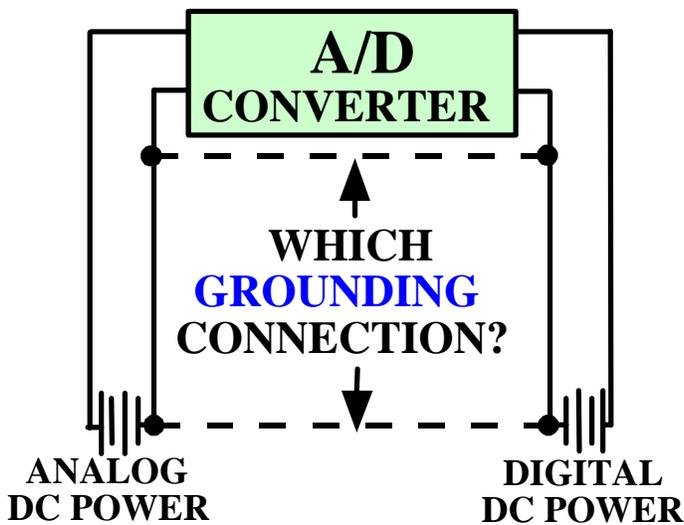
Unnecessary voltage differences between parts of an electronic circuit can cause interference. Using a metallic connection to “short out” these voltage differences that could cause noise emission or susceptibility problems is grounding to reduce electrical interference or noise. Interference can be caused by either improper grounding or improper signal routing, but these are two entirely different problems. Shorting out the voltage difference between analog and digital reference points is a grounding issue and not a signal current routing issue.

Example of Grounding to Reduce Interference 17



Want $V \approx 0$ for Noise Reduction

An analog to digital (A/D) converter is a good example of a signal voltage referencing (grounding) problem. The analog and digital references should be at the same voltage, to reduce the common mode (CM) noise voltage difference applied to the analog input. To reduce the CM voltage, the two references are bonded together by a conductor that should carry no objectionable current under normal operating conditions. A signal grounding conductor is similar to a safety grounding conductor, because both reduce a voltage difference while carrying essentially no current.



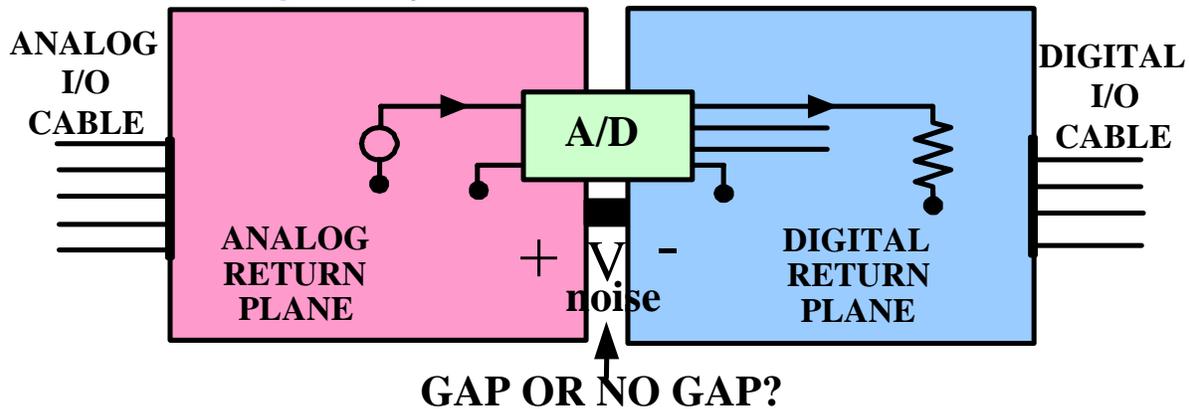
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Place the noise reduction grounding connection where it will do the most good!

Should the interference reduction grounding connection be placed close to the analog to digital (A/D) converter or close to the DC power supplies? The two DC power supplies do not need to operate at the same reference potential. However, the A/D converter needs the analog and digital circuits at the same reference potential to minimize the common mode noise applied to the analog input side of the converter. So the reference connection must be placed close to the A/D converter.

Would a second reference connection near the DC supplies be helpful? NO! If two or more connections exist between the analog and digital circuits, then the low frequency (kHz) currents can flow between the two circuits using these two connections. Too many signal grounding connections can result in loss of control of the low frequency (kHz) current paths.

The *Wrong* Way to Ground an A/D Converter 19



Move connector locations & use one solid return plane!

A grounding (reference) connection is usually required at the location of each analog to digital converter. Should this connection be one continuous plane or a narrow conductor with a gap between the planes, as shown above? One continuous plane should be used, if the noise frequencies of concern are in the MHz range. This low-impedance connection reduces the CM voltage available to drive the two cables as a dipole antenna. At MHz frequencies, the digital return currents should stay on the digital side of the board, even when there is one continuous plane. In very rare situations a gap may be necessary to keep kHz digital noise currents from flowing onto the analog side of the board.

No signal traces whose current returns in the plane should be allowed to cross any gap in the return plane!

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A single point connection of grounding conductors – might be good.

A single point connection of current routing conductors – is usually very bad.

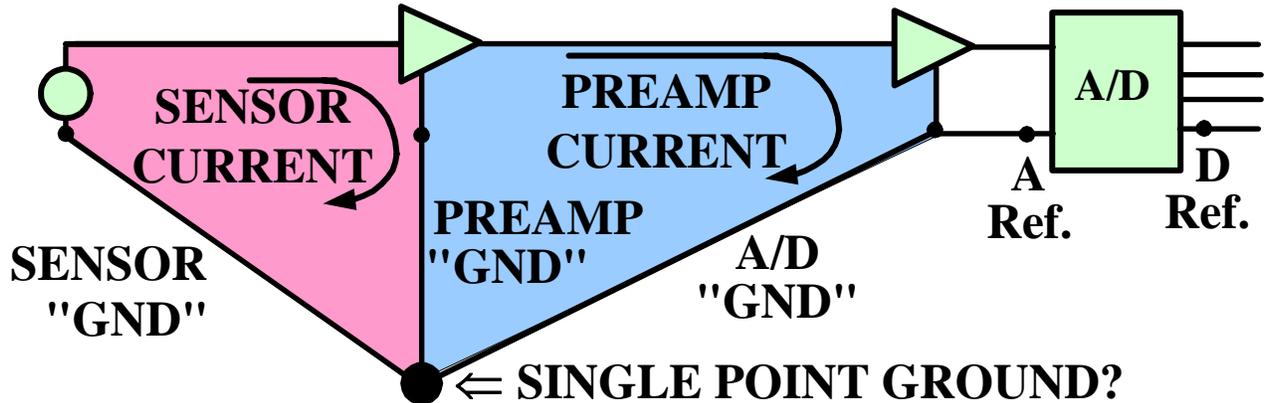
The current return path is often incorrectly labeled as a grounding conductor!

Connecting all grounding conductors to a single point, to avoid connecting to voltage differences in the ground structure, can be a good grounding technique. Connecting signal return conductors to a single point is not usually a good idea, because this increases the signal loop area. There is serious confusion between these two situations, because the signal return conductor is often incorrectly labeled as the grounding conductor.

Carefully check all “single point grounding” schemes to make sure that only grounding conductors are involved.

Why is this not single point grounding?

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This is not single point grounding. The three conductors labeled “GND” each carry a significant amount of signal current and therefore these are routing conductors and not grounding conductors. This arrangement increases both the sensor current and the preamp current loop areas. For single point grounding to be effective, the grounding conductors must not carry any significant amount of the signal currents. The focus in this example should not be on grounding, but should be on signal routing to minimize loop areas.

The only place in this figure where a grounding connection is needed is between the analog reference (A Ref.) and the digital reference (D Ref.) of the A/D converter.

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Should signal return be connected to an external metal chassis?

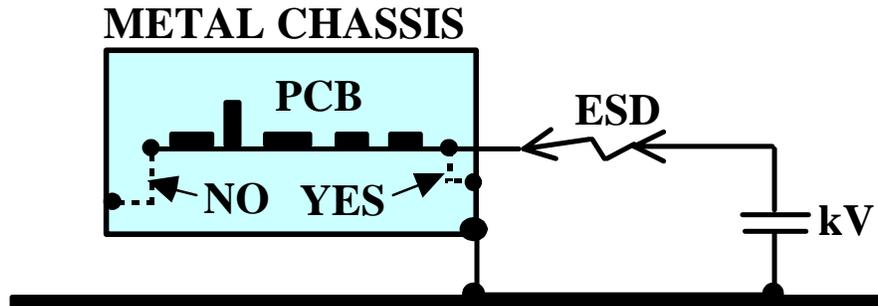
If yes, then where and at what frequencies?

Some Issues: Safety, HF susceptibility, HF emission, & Ground loop avoidance.

If signal circuits are inside a metal enclosure, should the signal reference be electrically connected to the external chassis? This is a more complicated question than it might seem, because several competing requirements may have to be met. The issues of safety, susceptibility, emissions and ground loops effect the decision of where and at which frequencies the signal return should be connected to the chassis. The topic is discussed in the next few figures.

“Ground” signal return to chassis at the connector to reduce MHz-GHz susceptibility.

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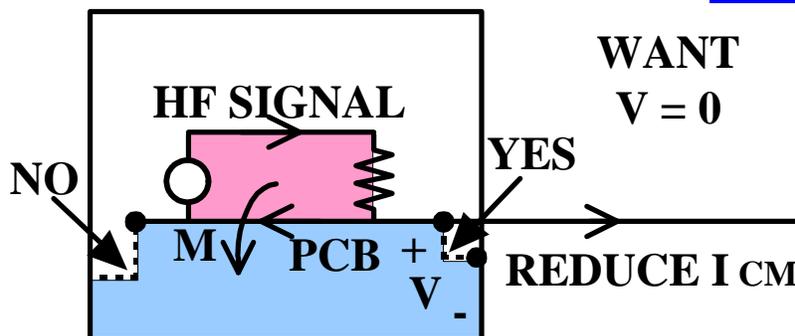


Which dashed connection is preferred? Why?

If the signal return is connected to the chassis at an internal location, as shown by the dashed line on the left, then externally injected high frequency currents have to cross the printed circuit board (PCB) in order to reach the metal chassis. These transient noise currents could interfere with or damage the circuits on the board. If the signal return is connected to the chassis at the connector, the dashed line on the right, then most of the external noise current can be transferred to the chassis without passing across the circuit board. To reduce high frequency susceptibility, the signal return should have a low *mutual* inductance connection to the chassis at the connector location. To achieve a low mutual inductance the entire width of the PCB must be connected to the chassis along the edge where the connector is located.

“Ground” signal return to chassis at the connector to reduce MHz-GHz emission.

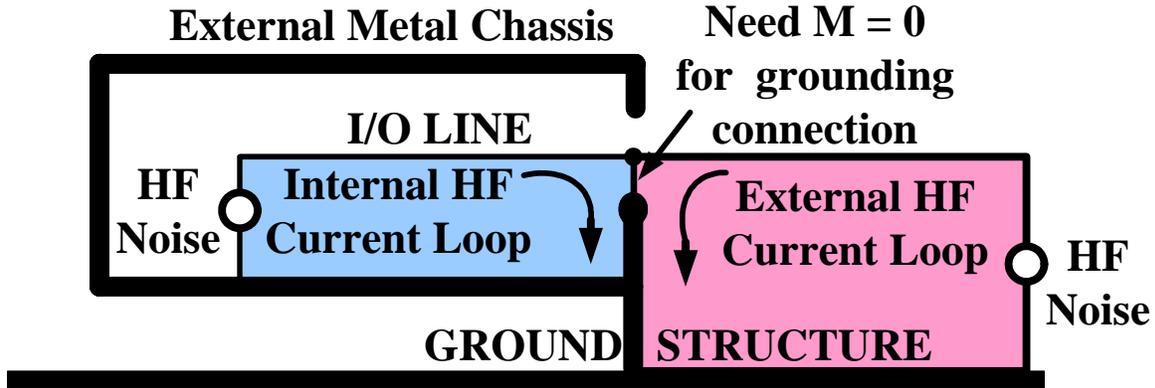
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Which dashed connection is preferred? Why?

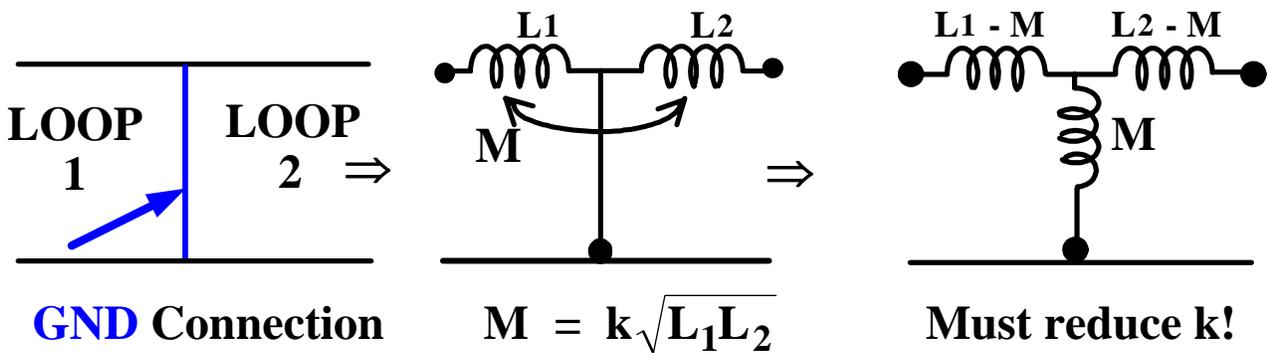
An external wire and a metal chassis form a monopole antenna. If the wire connects to a circuit board that is isolated from the chassis, then a voltage difference might exist to drive the monopole antenna. If the circuit board is connected at some internal point to the chassis, then magnetic coupling (M) can induce a voltage to drive the antenna. The most effective way to reduce the antenna drive voltage is to connect the signal return (ground) plane of the circuit board to the chassis by a low mutual inductance connection at the connector. This effectively shorts out the voltage source that is attempting to drive the antenna.

Provide a HF current diversion path at the connector (a grounding connection) with minimal M!



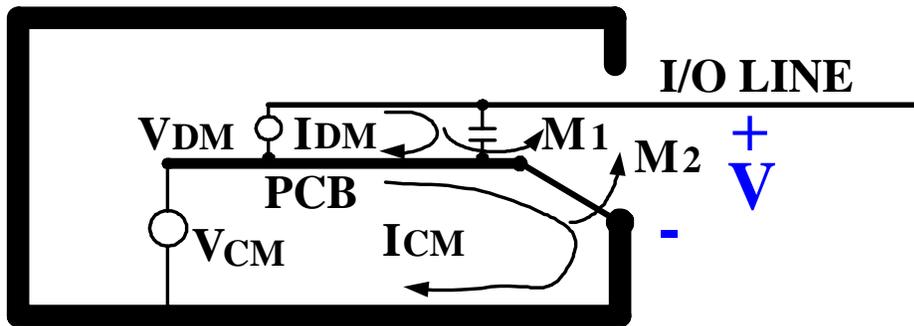
To prevent unintended high frequency (HF) currents from either entering or leaving the metal enclosure, it is necessary to provide an effective diversion or bypass path from each I/O signal line to the chassis. This connection must have minimal resistance (R) and minimal mutual inductance (M). Direct metal-to-metal bonding or a shunt capacitor with low equivalent series resistance (ESR) usually easily satisfies the $R \approx 0$ requirement. **Minimizing the mutual inductance is the most important and most difficult requirement for an effective MHz-GHz grounding connection.**

Reduce Mutual Inductance of Grounding Connection (Reduce the common boundary between the two loops)



The mutual inductance between LOOP 1 and LOOP 2 is what limits the effectiveness of this grounding connection. Noise coupling from LOOP 1 to LOOP 2 or vice versa increases at 20 dB per decade with increasing frequency due to $2\pi fM$. An effective high frequency grounding connection (current diverting path) requires a minimal value of mutual inductance between the two loops. The “common boundary” shared by the two loops is the main geometrical feature that causes the mutual inductance. Minimum common boundary means minimum M!

Minimize M_1 & M_2 for HF “Grounding” of I/O Line



$$V \approx \omega_1 M_1 I_{DM} + \omega_2 M_2 I_{CM}$$

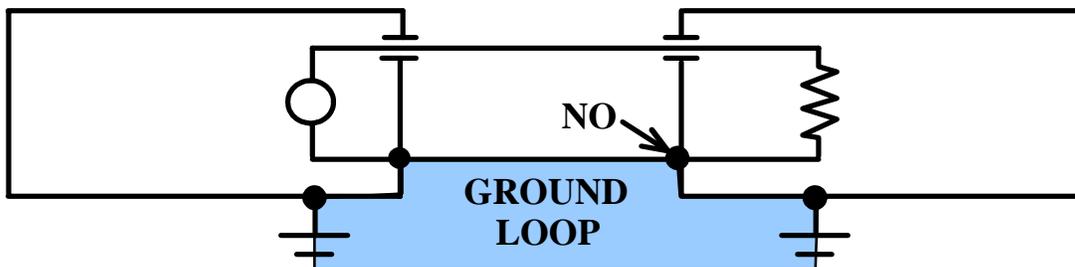
NEED
 $V \approx 0!$

The shunt capacitor provides a bypass path for HF DM currents, thus reducing the unintended current leaving the chassis on the I/O Line. The mutual inductance M_1 between input and output loops must be minimized. The common boundary through the capacitor that is shared by the two loops must be minimized.

The CM current is shunted to the inside of the metal enclosure through the direct bond of the circuit board edge to the chassis. The mutual inductance M_2 of this connection must be minimized.

Effective HF bonding (or grounding) usually requires minimizing a mutual inductance rather than minimizing a self inductance.

No, don't connect the signal return to chassis at DC on both ends to avoid a kHz ground loop.

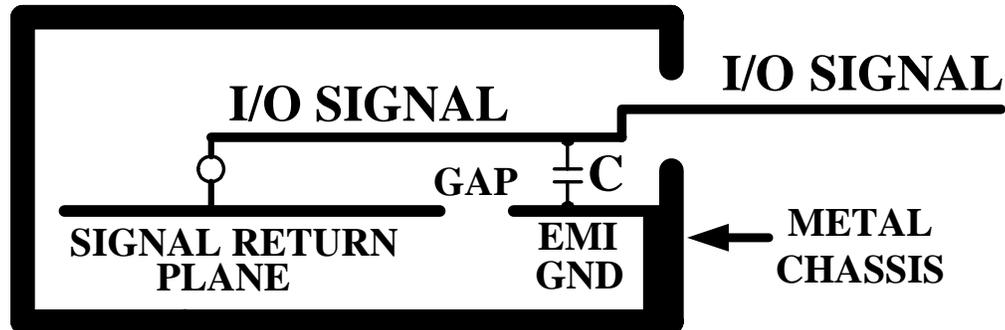


Remove one of the DC signal-to-chassis connections.

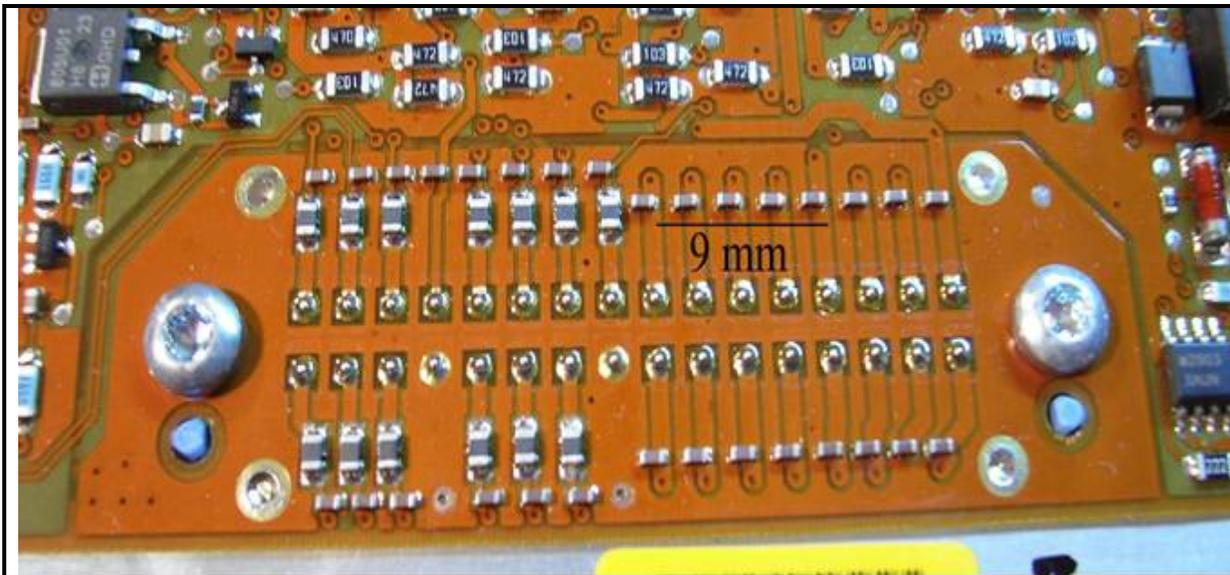
In this system the signal return has been connected to both external metal chassis at each end of the interconnecting cable. This reduces the transmission and reception of high frequency (MHz) noise along the return conductor. But, a low frequency (kHz) ground loop might bring conductively coupled or magnetically coupled noise into the system. To avoid a ground loop, the signal return should be directly bonded to the chassis at only one end of the signal path. On the other end, the return wire should be capacitively decoupled to the chassis to reduce high frequency noise.

The out going signal wire has been capacitively decoupled to the chassis on both ends, to reduce the emission and reception of MHz noise.

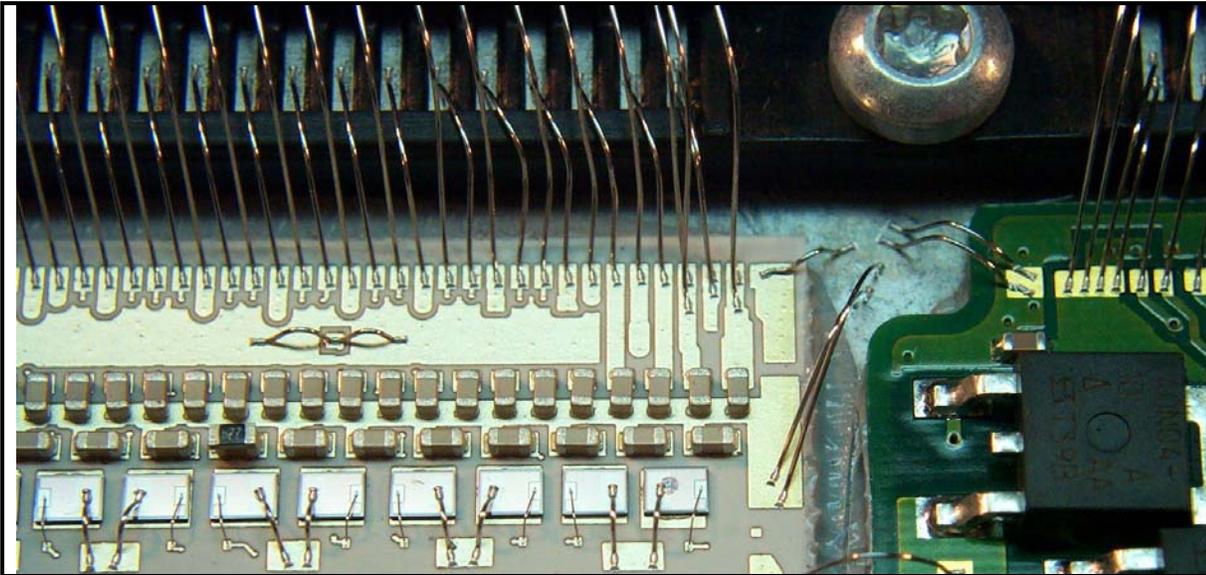
When signal return must be isolated from chassis at DC, use an “EMI GND” on PCB bonded to chassis.



In some situations the signal return plane must be kept DC isolated from the external metal enclosure. In this situation it may be necessary to have an EMI ground (GND) metal surface area on the circuit board. All low frequency I/O lines can be capacitively connected to this surface. The EMI GND must be bonded to the chassis along the entire edge of the circuit board. This type of bonding connection results in a mutual inductance $M \approx 0$. Minimal mutual inductance requires a very short (mm) and wide (several cm) connection between EMI ground and metal chassis.



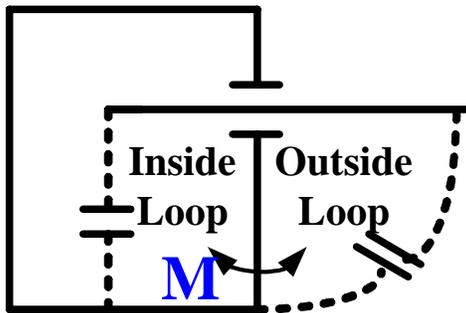
This is a polyimide circuit board glued to a metal base plate. The metal plate is part of a surrounding metal chassis. A connector that attaches to an external cable is mounted in this area of the board. The ends of the connector pins are visible in the photo. Intentional signals with bandwidths between DC and 1 MHz pass through this connector. A shunt capacitor is mounted between each connector pin and the metal base plate (chassis). The purpose of the shunt capacitor is to direct internal high-frequency currents back to the inside of the metal chassis and to direct external high frequency currents back to the outside of the chassis. The distance from signal line through capacitor to metal plate is several centimeters in all cases. This common boundary results in excessive mutual inductance between internal and external loops. These shunt mounted capacitors do not provide effective filtering above a few MHz due to excess mutual inductance.



The EMI GND strip on the top of this ceramic circuit board is connected by several wire bonds to the metal plate beneath. Each of the I/O signal lines is capacitively connected to this EMI GND strip. The entire distance from each signal line through a shunt capacitor to the GND strip and then to the metal plate is excessively long for every connection. The length of the HF grounding connection from each I/O signal line to the metal plate must be reduced to less than a few mm in order to reduce the mutual inductance and, thereby, make each grounding connection effective to several hundred MHz.

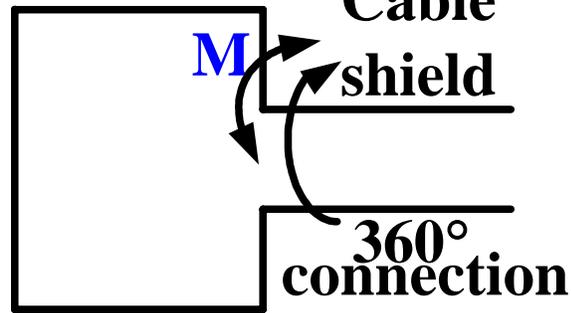
Reduce M by eddy current magnetic shielding 32

Metal Box



$M = 0$ for feed thru capacitor

Metal Box



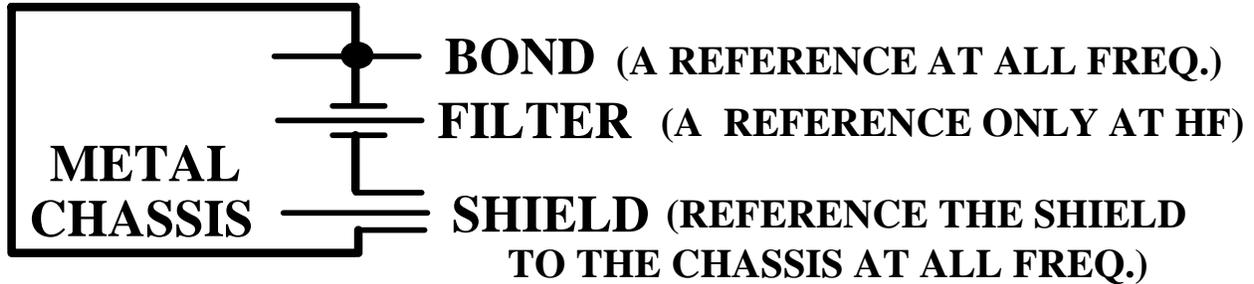
$M = 0$ for shield connection

A feed-thru capacitor mounted in the wall of a metal enclosure eliminates the mutual inductive coupling between the inside and the outside loops because of the eddy current magnetic shielding provided by the metal wall. The eddy current shielding is effective from about 100 kHz to daylight!

A “pigtail” style connection between a cable outer shield and a metal enclosure allows a mutual inductance to exist between the interior and the exterior loops. A 360° connection of the cable shield to the metal enclosure, created by the use of metal connector shells, eliminates the mutual inductance by eddy current magnetic shielding just as in the feed-thru capacitor example.

Reduce voltage between external wires and a metal chassis by bonding, filtering, or shielding. 33

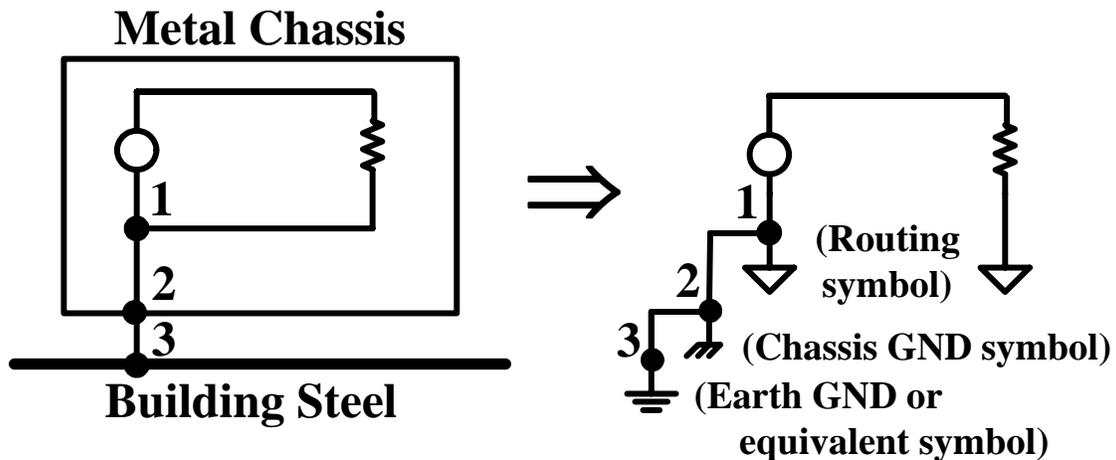
Reducing this voltage is a **GROUNDING** function!



To reduce MHz emission and susceptibility, all metal that exits a metal enclosure must be at the same RF potential as the enclosure. This requires that all signal wires either be metallurgically bonded to the enclosure, capacitively decoupled to the enclosure, or surrounded by a metal shield that is connected to the enclosure.

For a coaxial cable, the inside surface of the outer conductor is the signal return path. The outside surface is the noise current carrying shield. The outer surface must have a 360° connection to the metal chassis for effective high-frequency shielding and grounding.

IEEE Defined Routing & Grounding Symbols 34



IEEE Standard 315 defines the symbols that are to be used to designate routing and grounding functions. Unfortunately, these symbols are rarely used as defined by the standard.

White & black triangles are current routing symbols. These refer to connections that carry current.

⏏ refers to a non current carrying grounding connection to a surrounding metal chassis. This is a grounding symbol.

⏏ represents a non current carrying grounding connection to earth or its equivalent. This is a grounding symbol. Large conducting surfaces near the system can be the equivalent of “earth”.

SUMMARY

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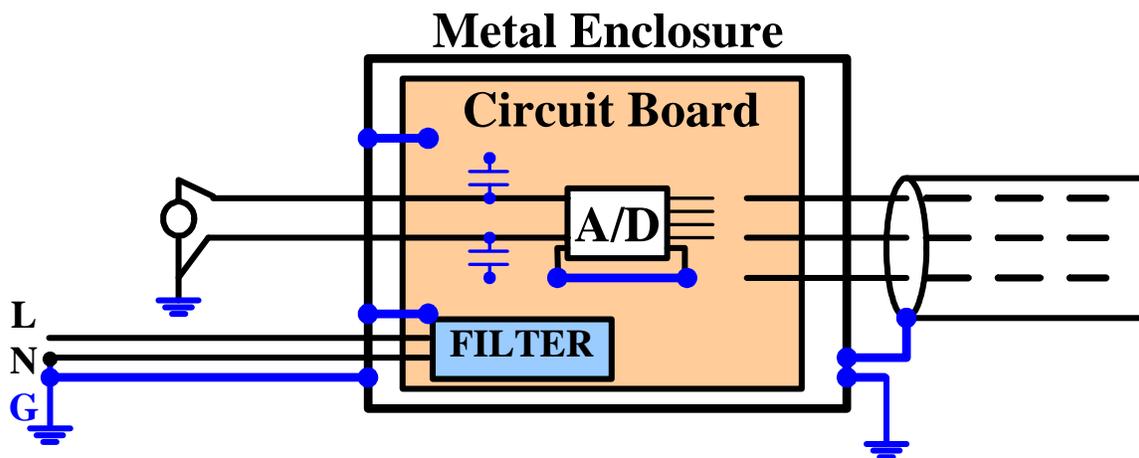
Grounding is for Safety or Noise Reduction**Grounding is NOT Routing****A Grounding conductor carries negligible current****Reduce M of MHz-GHz Grounding Connections****by reducing common boundary or using eddy current shielding of a solid metal barrier.****Dr. Tom Van Doren****vandoren@mst.edu****emc-education.com**

The reason for making a grounding connection is to reduce a voltage difference that could cause a personnel shock hazard or an electrical interference problem. A grounding connection carries negligible current during normal operating conditions. A grounding connection is NOT a current carrying routing connection.

Many grounding connections to reduce interference must be effective at frequencies from MHz to GHz. To reduce mutual inductance, reduce the length of the common boundary shared by the two loops.

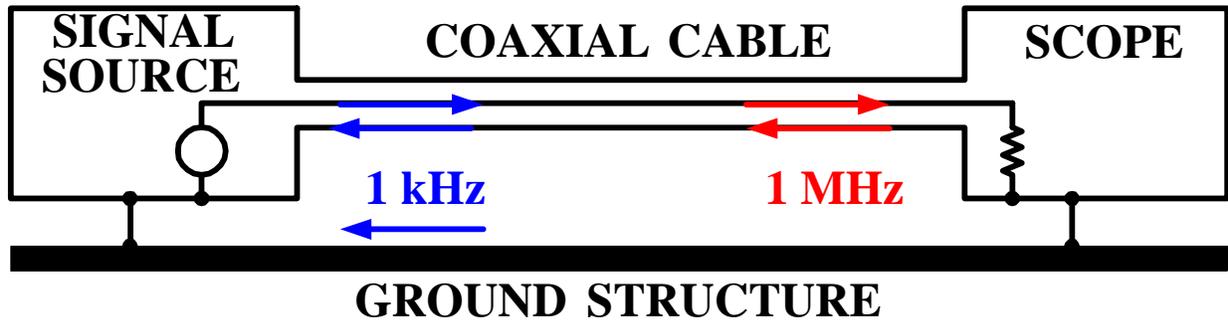
Identify the Grounding Connections

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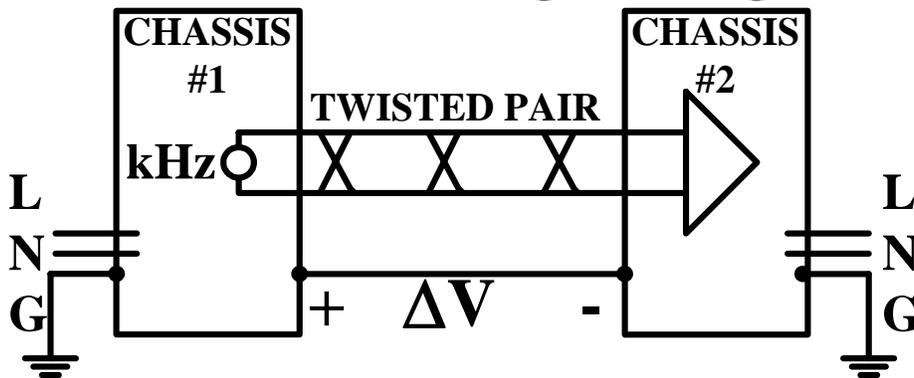
The grounding connections in this figure are highlighted in blue. Some of these connections are mandated by electrical safety and some are needed to reduce noise emission or susceptibility. Some are not in the best physical location and some are not effective above a few MHz. It is important to know which are the non current carrying grounding connections and which are the current carrying routing connections.

What is the signal current *return* path for $f = 1 \text{ kHz}$ and $f = 1 \text{ MHz}$?



This example shows the “classic” ground loop problem caused by a grounded signal source connected by a coaxial cable to a grounded scope. At 1 kHz, part of the signal current returns to the source on the outer conductor of the coaxial cable and part of the current returns on the ground structure. The large signal current loop allows both magnetic field emission and reception. At 1 MHz the current returns on the inside surface of the outer conductor of the coaxial cable and the magnetic field is completely contained inside the coaxial cable (perfect self shielding).

A System Grounding Example How should the kHz signal be grounded?



A kHz signal is routed on a twisted pair between two metal enclosures. Each enclosure uses AC power at a voltage greater than 50 V, therefore each enclosure is safety grounded using a conductor of the proper size that is routed with the AC power line conductor and grounded at the power service entrance to the facility. A conductor is connected between the two metal chassis to reduce the voltage difference ΔV that might be a common-mode noise source for the kHz signal. If the receiver of the kHz signal is differential, the signal source might be grounded to the chassis on the left. Shunt capacitors may be required between each signal line and the corresponding metal enclosure, to reduce the emission or reception of high-frequency noise.