Design of Grounding Systems

(Impedance and Current Path Control)

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GROUNDING CONSIDERATIONS

- Signal Reference Considerations
- Power Current Paths
- System Structure Ground Considerations
- Safety Concerns
- Testing Configuration Concerns
- High Frequency Specific Problems
- Differential & Common Mode Currents
- Low level Signal Concerns
- Ground as a Shield
- Cable Shielding

Definitions

- GROUND
  - Usually the structure of a system, the fundamental electrical reference point for all subsystems and equipment contained therein. May or may not be intentionally current carrying. Used for purposes of safety, EMI and radiation shielding, and overall EMC considerations. Usually common with structure of boxes and equipment.
- RETURN
  - The path by which currents in the power and/or signal systems returns to the source of that power or signal. Often referred to as power return, signal return, primary power return, secondary power return.
    - Primary power return is the return for power currents from the system main power distribution system (and power returns for items not galvanically isolated from it.)
    - Secondary power return is the return for power currents in circuits galvanically isolated from the main power distribution system, usually on the "secondaries" or outputs of power supplies. Often common with the signal return system, since secondary power usually feeds the IC's, which have common signal and power return pins.

Definitions

- REFERENCE
  - The 0 volt reference for any signal. That is, if a signal line is at 0 volts, it is at 0 volts relative to its reference point or line. Note references can be DC, AC or both. CAUTION!!: References at signal sources and signal receiving loads may not be at 0 volts with respect to each other, see COMMON MODE voltage and voltage offset, below. Reference is usually common with the secondary power return and signal return.
- SINGLE POINT GROUND
  - A condition wherein a power or signal return makes contact with the system ground at only one point. Useful for controlling current paths in primary (main) power distribution. Only valid at low frequencies (less than 10 KHz or so).
- MULTI-POINT GROUND
  - A condition wherein a power or signal return makes contact with the system ground at more than one point, sometimes at some distance apart.

Definitions

- GALVANIC ISOLATION
  - A condition in which two circuits or wires within circuits are not connected together. That is, would measure some very high resistance (e.g., 1 Megohm) on a DC ohmmeter, if the ohmmeter was placed between the two points. Can be achieved by two circuits having no common elements (two completely unrelated circuits), or by transformer or optical isolation. (Also by capacitive isolation if capacitors are placed in both signal line and return.) Applicable basically at DC only.
- GALVANIC COMPATIBILITY
  - A condition where the materials forming two conductors can be placed in intimate physical and electrical contact, in the presence of atmospheric moisture, without corrosion of one or both materials taking place. (Two incompatible materials can be made compatible by interposing a plating, shim, etc. of a third material between them, the third material being compatible with each of the two other materials.)

Definitions

- SINGLE-ENDED
  - A signal transmission method in which the references for both signal source and signal receiver are electrically connected together, desirably with both references being a 0 volts with respect to each other. Often characterized by a signal representing one line on a schematic, whose reference on each end is the signal return and/or secondary power return for the source and signal receiver. Voltage offsets between the references can affect single-ended signals.
- DIFFERENTIAL
  - A Signal transmission method having the total signal as two complementary voltage wires (one goes positive with respect to the reference, while the other is simultaneously going negative the same amount) with respect to the source and receiving end references . Differential signals are "balanced", (e.g., one line at +1 volt, while the other is at –1 volt). Or they can be "offset", (e.g., one line at +3 volts while the other is at +1 volt with a + 2 volt reference offset). The signal receiver ignores the offset and voltages between the source and receiver references, considering only the voltage difference between the two differential lines. CAUTION!!: A reference (return) wire <u>must</u> be sent between the source and receiver. It will normally not work with a true open circuit between the source and receiver references.

Definitions

- COMMON MODE VOLTAGE
  - Voltage offset between the source reference (or return), and the receiver reference (or return). May be AC or DC. (Usually used in connection with differential transmission, but applies to single ended, as well). Also, a voltage that appears in the same magnitude and polarity at both receiver inputs (with respect to the receiver reference).
- DIFFERENTIAL MODE VOLTAGE
  - Voltage between the two signal lines of a differential transmission system (Also called "Normal" mode voltage)
- COMMON MODE REJECTION
  - The ratio of the receiver output for a differential mode voltage, and a common mode voltage. A differential receiver that provides 1 volt output for 1 volt of differential input voltage, but would require 1000 volts of common mode voltage to provide the same 1 volt output would have a common mode rejection of 1000:1, or 60 dB

Definitions

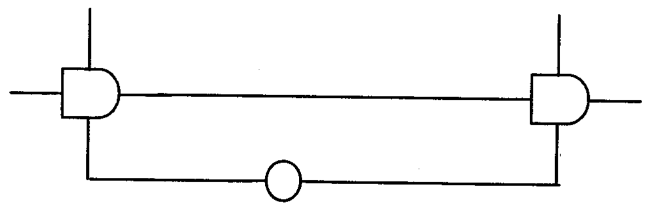
- DIFFERENTIAL MODE CURRENT
  - A current that flows in one direction in one wire of a differential pair, and the opposite direction in the other wire. In the return line (reference), the two currents cancel, providing 0 net current. Can be AC or DC.
- COMMON MODE CURRENT
  - A current that flows in the same direction in both wires of a differential pair, and of the same magnitude. Since both currents flow in the same direction, they add at the receiver, producing twice the current in either line of the differential pair. Can be AC or DC.
  - Power lines of single-point grounded or isolated power systems can also have differential mode currents (the actual current flowing from the power input, and returning on power return), and common mode currents (currents of the same magnitude and polarity in each power line, returning via the structure, or ground, path)

Definitions

- SAFETY GROUND
  - The safety ground system is that system such that, if a human being touches two different points on the grounding system (e.g., a piece of structure and a box external case), he/she will not be exposed to hazardous voltages.
    - NOTE: Human beings are subject to electrocution by touching two items at voltages equal to or more than 60 volts apart!! A2100 POWER SYSTEM VOLTAGES ARE LETHAL TO HUMANS!!
  - Humans or equipment can also be damaged by flying hot metal in an arc formed by separating two conductors that were previously carrying significant current. This condition can exist at voltages as low as 10-12 volts, and currents as low as 0.5 amp.
  - COMPANIES AND INDIVIDUAL ENGINEERS ARE SUBJECT TO LEGAL ACTION, IF SOMETHING THEY DESIGNED INJURES OR KILLS SOMEONE, INCLUDING THEIR OWN EMPLOYEES!!! TAKE HEED!! SAFETY IS EVERYONE'S BUSINESS!!

Signal Reference Issues

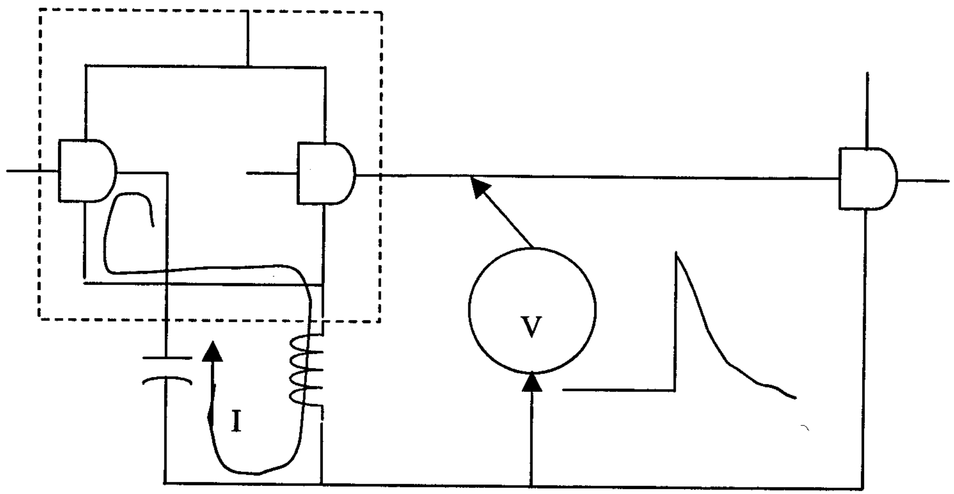
- Voltages between the signal reference ("grounds") of signal sources and loads can cause interference to system functionality (or damage)



- Magnitude of voltage that will cause problems is circuit dependent
  - Smaller signals potentially more vulnerable
  - Concern also dependent on circuit bandpass (sensitivity may be to noise significantly different in frequency than desired signal)

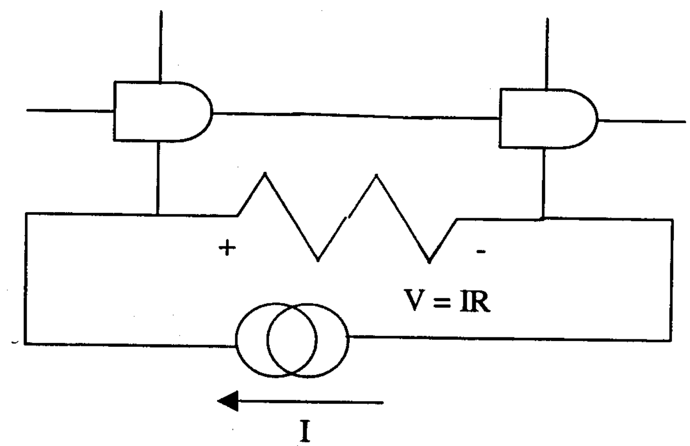
Signal Reference Issues

- So how can we get voltages between sources and loads?
  - Magnetic or Capacitive Coupling (discussed later)
  - Currents flowing in the impedance between source & load
    - Circuit's own currents (e.g., "ground bounce")



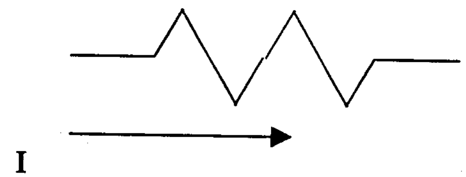
Signal Reference Issues

- So how can we get voltages between sources and loads?
  - Currents flowing in the impedance between source & load
    - Current generated by other circuits
    - Called "Common Impedance" coupling



Signal Reference Issues

- So how can we get the voltages between source & load small enough?



$$V = I \bullet Z$$

- V→ 0 if:
  - I→ 0 or
  - Z→ 0
  - Or both
- So either prevent "bad" currents from flowing (minimize overall current magnitude), or minimize the impedance
  - What's a "bad" current?– Any unnecessary current, particularly if it doesn't support the function of the circuit in question!!

Impedance Minimization

- In low impedance systems (like power lines, signal references), Z is dominated by R and L:

- At low frequencies, the reference is resistive
  - Minimize by making the wire or trace large cross-section area:

$$R = \frac{\rho l}{A}$$

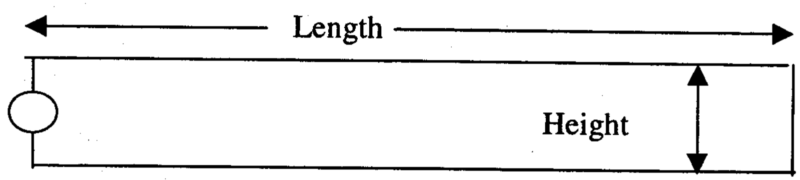
  - Or by paralleling a quantity (n) of wires or traces:

$$R_t = \frac{R}{n}$$

    - A ground plane is like a large number of parallel wires or traces

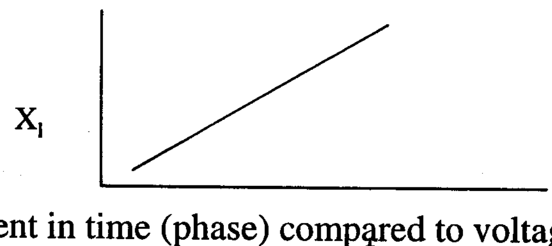
Impedance Minimization

- At high frequencies, impedance is a combination of resistance & inductance
- The current must flow in a closed path that has inductance.



$$L = \mu_r \mu_o 10.16 \bullet 10^{-9} \bullet [l \bullet \ln(\frac{2w}{d}) + w \bullet \ln(\frac{2l}{d})]$$

  - μ_r and μ_o are material properties (permeability), μ_r=1 for non-magnetic materials
  - l is length of the path
  - w is width (or height) of the path
  - d is diameter of wire (or largest dimension of rectangular wire)
  - Inductance has an impedance (reactance) that increases with frequency
    - $X_l = 2\pi \times f \times L$



    - X_l delays current in time (phase) compared to voltage so currents are not in phase with applied voltage (usually indicated by symbol j, the complex imaginary symbol) $X_l = j\, 2\pi \times f \times L$
- Inductance typically begins to dominate in the 1's Khz-10's KHz region

Skin Effect

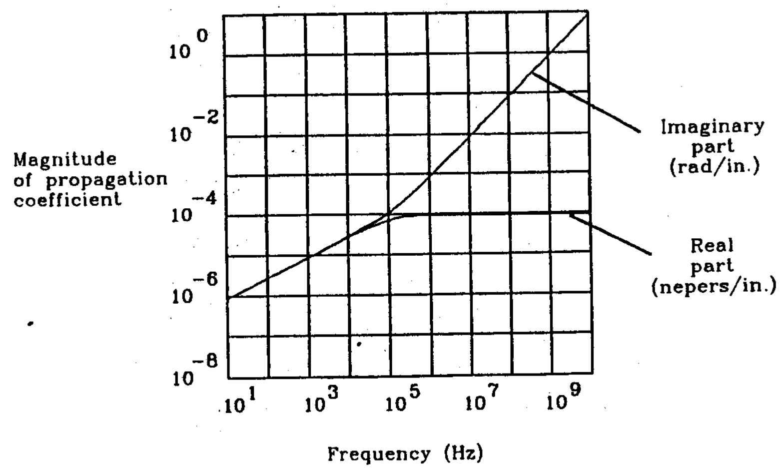


Figure 4.9 Propagation of a cable with fixed series resistance (no skin effect).

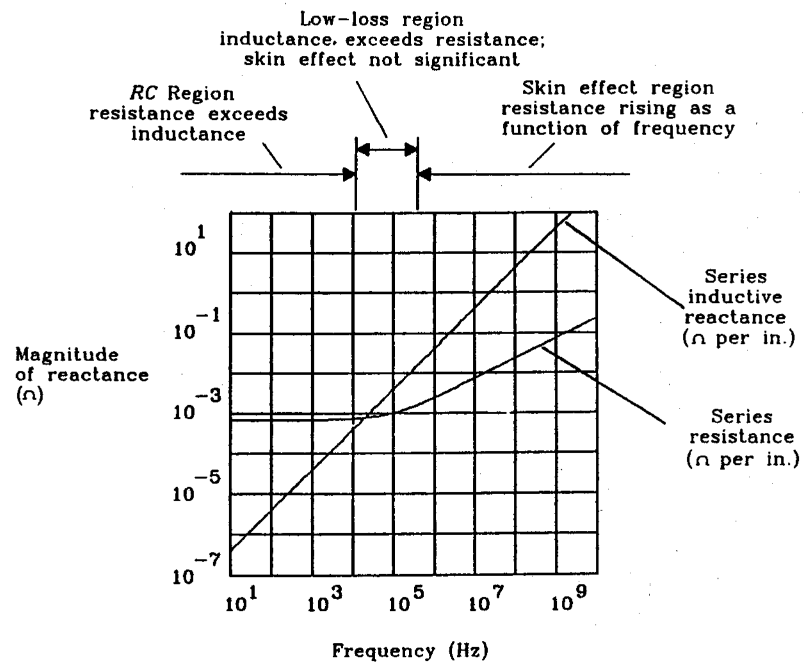


Figure 4.10 Series resistance and series inductive reactance of RG-58/U coax versus frequency.

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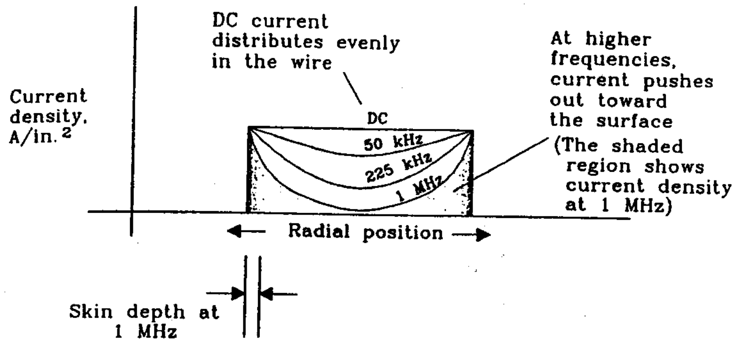
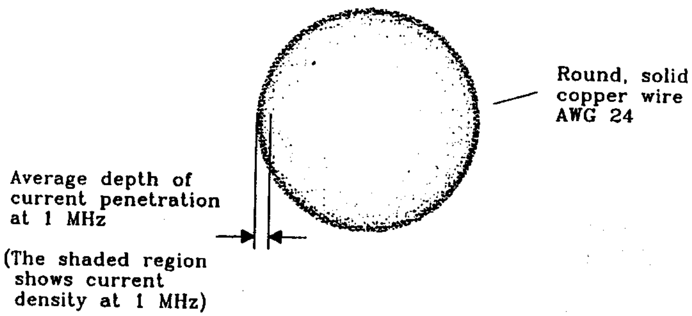
Skin Effect

Current density versus radial position



Cross section of wire



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Skin Effect

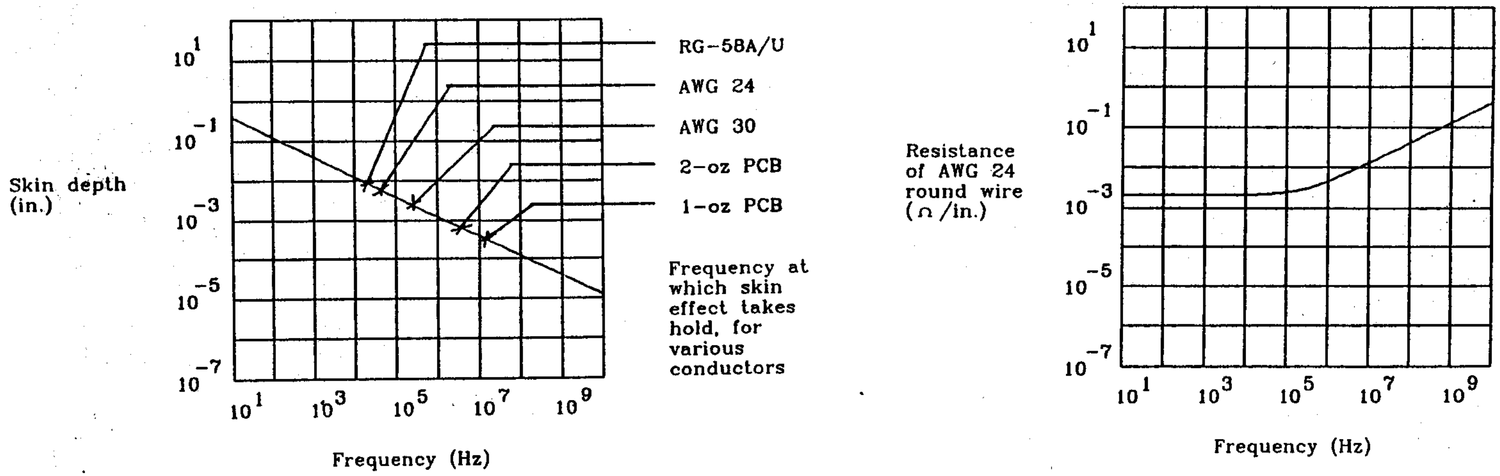

Figure 4.13 Skin effect in copper versus frequency.

TABLE 4.1 SKIN-EFFECT FREQUENCIES FOR CONDUCTORS

Round conductors	Radius	Skin-effect frequency (KHz)
RG-58/U	0.017	21
AWG 24	0.010	65
AWG 30	0.005	260
Printed circuit trace	**Copper weight (oz)**	**Skin-effect frequency (MHz)**
0.010 width	2	3.5
0.005 width	2	3.5
0.010 width	1	14.0
0.005 width	1	14.0

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IMPEDANCE OF STRAIGHT CIRCULAR COPPER WIRES

	AWG#=2, D=6.54mm				AWG#=10, D=2.59mm				AWG#=22, D=.64			
FREQ.	ℓ=1cm	ℓ=10cm	ℓ=1m	ℓ=10m	ℓ=1cm	ℓ=10cm	ℓ=1m	ℓ=10m	ℓ=1cm	ℓ=10cm	ℓ=1m	ℓ=10m
10Hz	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	529μ	5.29m	52.9m	529m
20Hz	5.14μ	52.0μ	532μ	5.50m	32.7μ	328μ	3.28m	32.8m	529μ	5.29m	53.0m	530m
30Hz	5.15μ	52.8μ	555μ	5.94m	32.8μ	328μ	3.28m	32.9m	529μ	5.30m	53.0m	530m
50Hz	5.20μ	55.5μ	624μ	7.16m	32.8μ	329μ	3.30m	33.2m	530μ	5.30m	53.0m	530m
70Hz	5.27μ	59.3μ	715μ	8.68m	32.8μ	330μ	3.33m	33.7m	530μ	5.30m	53.0m	530m
100Hz	5.41μ	66.7μ	877μ	11.2m	32.9μ	332μ	3.38m	34.6m	530μ	5.30m	53.0m	530m
200Hz	6.20μ	99.5μ	1.51m	20.6m	33.2μ	345μ	3.67m	39.6m	530μ	5.30m	53.0m	530m
300Hz	7.32μ	137μ	2.19m	30.4m	33.7μ	365μ	4.11m	46.9m	530μ	5.30m	53.0m	531m
500Hz	10.1μ	219μ	3.59m	50.3m	35.3μ	425μ	5.28m	64.8m	530μ	5.31m	53.2m	533m
700Hz	13.2μ	303μ	5.01m	70.2m	37.7μ	500μ	6.66m	84.8m	530μ	5.32m	53.4m	537m
1kHz	18.1μ	429μ	7.14m	100m	42.2μ	632μ	8.91m	116m	531μ	5.34m	53.9m	545m
2kHz	35.2μ	855μ	14.2m	200m	62.5μ	1.13m	16.8m	225m	536μ	5.48m	56.6m	589m
3kHz	52.5μ	1.28m	21.3m	300m	86.3μ	1.65m	25.0m	336m	545μ	5.71m	60.9m	656m
5kHz	87.3μ	2.13m	35.6m	500m	137μ	2.72m	41.5m	559m	571μ	6.39m	72.9m	835m
7kHz	122μ	2.98m	49.8m	700m	189μ	3.79m	58.1m	783m	609μ	7.28m	87.9m	1.04Ω
10kHz	174μ	4.26m	71.2m	1.00Ω	268μ	5.41m	82.9m	1.11Ω	681μ	8.89m	113m	1.39Ω
20kHz	348μ	8.53m	142m	2.00Ω	533μ	10.8m	165m	2.23Ω	1.00m	15.2m	207m	2.63Ω
30kHz	523μ	12.8m	213m	3.00Ω	799μ	16.2m	248m	3.35Ω	1.39m	22.0m	305m	3.91Ω
50kHz	871μ	21.3m	356m	5.00Ω	1.33m	27.0m	414m	5.58Ω	2.20m	36.1m	504m	6.48Ω
70kHz	1.22m	29.8m	498m	7.00Ω	1.86m	37.8m	580m	7.82Ω	3.04m	50.2m	704m	9.06Ω
100kHz	1.74m	42.6m	712m	10.0Ω	2.66m	54.0m	828m	11.1Ω	4.31m	71.6m	1.00Ω	12.9Ω
200kHz	3.48m	85.3m	1.42Ω	20.0Ω	5.32m	108m	1.65Ω	22.3Ω	8.59m	142m	2.00Ω	25.8Ω
300kHz	5.23m	128m	2.13Ω	30.0Ω	7.98m	162m	2.48Ω	33.5Ω	12.8m	214m	3.01Ω	38.7Ω
500kHz	8.71m	213m	3.56Ω	50.0Ω	13.3m	270m	4.14Ω	55.8Ω	21.4m	357m	5.01Ω	64.6Ω
700kHz	12.2m	298m	4.98Ω	70.0Ω	18.6m	378m	5.80Ω	78.2Ω	30.0m	500m	7.02Ω	90.4Ω
1MHz	17.4m	426m	7.12Ω	100Ω	26.6m	540m	8.28Ω	111Ω	42.8m	714m	10.0Ω	129Ω
2MHz	34.8m	853m	14.2Ω	200Ω	53.2m	1.08Ω	16.5Ω	223Ω	85.7m	1.42Ω	20.0Ω	258Ω
3MHz	52.3m	1.28Ω	21.3Ω	300Ω	79.8m	1.62Ω	24.8Ω	335Ω	128m	2.14Ω	30.1Ω	387Ω
5MHz	87.1m	2.13Ω	35.6Ω	500Ω	133m	2.70Ω	41.4Ω	558Ω	214m	3.57Ω	50.1Ω	646Ω
7MHz	122m	2.98Ω	49.8Ω	700Ω	186m	3.78Ω	58.0Ω	782Ω	300m	5.00Ω	70.2Ω	904Ω
10MHz	174m	4.26Ω	71.2Ω	1.00kΩ	266m	5.40Ω	82.8Ω	1.11kΩ	428m	7.14Ω	100Ω	1.29kΩ
20MHz	348m	8.53Ω	142Ω	2.00kΩ	532m	10.8Ω	165Ω	2.23kΩ	857m	14.2Ω	200Ω	2.58kΩ
30MHz	523m	12.8Ω	213Ω	3.00kΩ	798m	16.2Ω	248Ω	3.35kΩ	1.28Ω	21.4Ω	301Ω	3.87kΩ
50MHz	871m	21.3Ω	356Ω	5.00kΩ	1.33Ω	27.0Ω	414Ω	5.58kΩ	2.14Ω	35.7Ω	501Ω	6.46kΩ
70MHz	1.22Ω	29.8Ω	498Ω	7.00kΩ	1.86Ω	37.8Ω	580Ω	7.82kΩ	3.00Ω	50.0Ω	702Ω	9.04kΩ
100MHz	1.74Ω	42.6Ω	712Ω	10.0kΩ	2.66Ω	54.0Ω	828Ω	11.1kΩ	4.28Ω	71.4Ω	1.00kΩ	12.9kΩ
200MHz	3.48Ω	85.3Ω	1.42kΩ	20.0kΩ	5.32Ω	108Ω	1.65kΩ	22.3kΩ	8.57Ω	142Ω	2.00kΩ	25.8kΩ
300MHz	5.23Ω	128Ω	2.13kΩ	30.0kΩ	7.98Ω	162Ω	2.48kΩ	33.5kΩ	12.8Ω	214Ω	3.01kΩ	38.7kΩ
500MHz	8.71Ω	213Ω	3.56kΩ	50.0kΩ	13.3Ω	270Ω	4.14kΩ	55.8kΩ	21.4Ω	357Ω	5.01kΩ	64.6kΩ
700MHz	12.2Ω	298Ω	4.98kΩ	70.0kΩ	18.6Ω	378Ω	5.80kΩ	78.2kΩ	30.0Ω	500Ω	7.02kΩ	90.4kΩ
1GHz	17.4Ω	426Ω	7.12kΩ		26.6Ω	540Ω	8.28kΩ		42.8Ω	714Ω	10.0kΩ	

* AWG = American Wire Gage
D = wire diameter in mm
ℓ = wire length in cm or m
μ = microhms
m = milliohms
Ω = ohms

Non-Valid Region for which ℓ ≥ λ/4

10/28/02 wgi

IMPEDANCE OF PRINTED CIRCUIT BOARD WIRING

	w=1mm, t=0.03mm				w=3mm, t=0.03mm			w=10mm, t=0.03mm	
FREQ.	l=10mm	l=30mm	l=100mm	l=300mm	l=30mm	l=100mm	l=300mm	l=100mm	l=300mm
10Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
20Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
30Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
50Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
70Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
100Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
200Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
300Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.74m	17.2m
500Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.75m	17.2m
700Hz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.4m	5.75m	17.2m
1kHz	5.74m	17.2m	57.4m	172m	5.74m	19.1m	57.5m	5.76m	17.3m
2kHz	5.74m	17.2m	57.4m	172m	5.75m	19.1m	57.6m	5.81m	17.5m
3kHz	5.74m	17.2m	57.5m	172m	5.76m	19.2m	57.8m	5.89m	18.0m
5kHz	5.75m	17.2m	57.5m	172m	5.78m	19.3m	58.4m	6.15m	19.2m
7kHz	5.75m	17.2m	57.6m	173m	5.82m	19.5m	59.4m	6.52m	21.0m
10kHz	5.76m	17.3m	57.9m	174m	5.89m	20.0m	61.4m	7.23m	24.4m
20kHz	5.81m	17.5m	59.2m	180m	6.32m	22.4m	72.1m	10.5m	38.6m
30kHz	5.89m	17.9m	61.4m	189m	6.97m	26.0m	87.1m	14.4m	54.7m
50kHz	6.14m	19.2m	67.9m	215m	8.74m	35.1m	123m	22.7m	88.3m
70kHz	6.51m	21.0m	76.6m	250m	10.8m	45.5m	163m	31.3m	122m
100kHz	7.21m	24.3m	92.5m	311m	14.3m	62.0m	225m	44.4m	174m
200kHz	10.4m	38.5m	155m	545m	26.9m	119m	440m	88.2m	346m
300kHz	14.3m	54.4m	224m	795m	39.9m	177m	657m	132m	519m
500kHz	22.5m	87.8m	367m	1.30Ω	66.1m	295m	1.09Ω	220m	866m
700kHz	31.1m	121m	510m	1.82Ω	92.4m	413m	1.52Ω	308m	1.21Ω
1MHz	44.0m	173m	727m	2.59Ω	131m	590m	2.18Ω	440m	1.73Ω
2MHz	87.5m	344m	1.45Ω	5.18Ω	263m	1.17Ω	4.36Ω	880m	3.46Ω
3MHz	131m	516m	2.17Ω	7.76Ω	395m	1.76Ω	6.54Ω	1.32Ω	5.19Ω
5MHz	218m	861m	3.62Ω	12.9Ω	659m	2.94Ω	10.9Ω	2.20Ω	8.66Ω
7MHz	305m	1.20Ω	5.07Ω	18.1Ω	922m	4.12Ω	15:2Ω	3.08Ω	12.1Ω
10MHz	437m	1.72Ω	7.25Ω	25.8Ω	1.31Ω	5.89Ω	21.8Ω	4.40Ω	17.3Ω
20MHz	874m	3.44Ω	14.5Ω	51.7Ω	2.63Ω	11.7Ω	43.6Ω	8.80Ω	34.6Ω
30MHz	1.31Ω	5.16Ω	21.7Ω	77.6Ω	3.95Ω	17.6Ω	65.4Ω	13.2Ω	51.9Ω
50MHz	2.18Ω	8.61Ω	36.2Ω	129Ω	6.59Ω	29.4Ω	109Ω	22.0Ω	86.6Ω
70MHz	3.05Ω	12.0Ω	50.7Ω	181Ω	9.22Ω	41.2Ω	152Ω	30.8Ω	121Ω
100MHz	4.37Ω	17.2Ω	72.5Ω	258Ω	13.1Ω	58.9Ω	218Ω	44.0Ω	173Ω
200MHz	8.74Ω	34.4Ω	145Ω	517Ω	26.3Ω	117Ω	436Ω	88.0Ω	346Ω
300MHz	13.1Ω	51.6Ω	217Ω	776Ω	39.5Ω	176Ω	654Ω	132Ω	519Ω
500MHz	21.8Ω	86.1Ω	362Ω	1.29kΩ	65.9Ω	294Ω	1.09kΩ	220Ω	866Ω
700MHz	30.5Ω	120Ω	507Ω	1.81kΩ	92.2Ω	412Ω	1.52kΩ	308Ω	1.21kΩ
1GHz	43.7Ω	172Ω	725Ω	2.58kΩ	131Ω	589Ω	2.18kΩ	440Ω	1.73kΩ
2GHz	87.4Ω	344Ω	1.45kΩ	5.17kΩ	263Ω	1.17kΩ	4.36kΩ	880Ω	3.46kΩ
3GHz	131Ω	516Ω	2.17kΩ	7.76kΩ	395Ω	1.76kΩ	6.54kΩ	1.32kΩ	5.19kΩ
5GHz	218Ω	861Ω	3.62kΩ	12.9kΩ	659Ω	2.94kΩ	10.9kΩ	2.20kΩ	8.66kΩ
7GHz	305Ω	1.20kΩ	5.07kΩ	18.1kΩ	922Ω	4.12kΩ	15.2kΩ	3.08kΩ	12.1kΩ
10GHz	437Ω	1.72kΩ	7.25kΩ	25.8kΩ	1.31kΩ	5.89kΩ	21.8kΩ	4.40kΩ	17.3kΩ

* Wiring dimensions are width x thickness in mm

l = wiring length in mm
m = milliohms
μ = microhms
Ω = ohms

Non-Valid Region for which $l \geq \lambda/4$

METAL GROUND PLANE IMPEDANCE IN OHMS / SQUARE

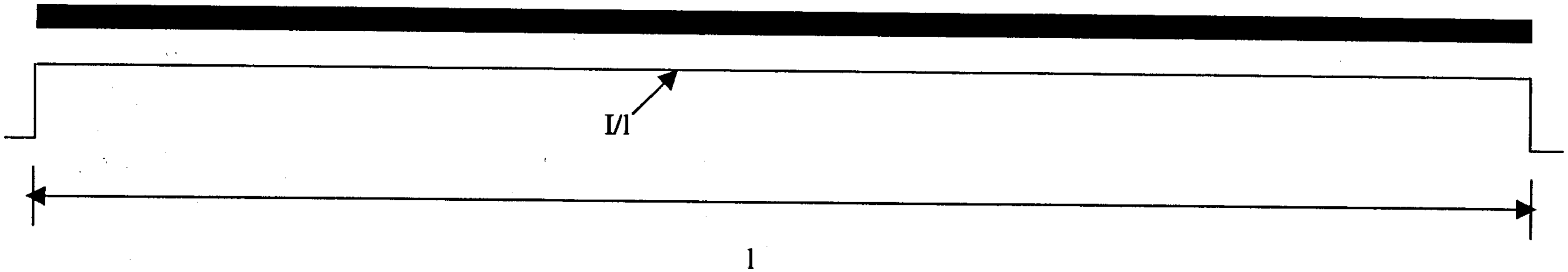
	COPPER. COND-1, PERM-1						STEEL. COND-.17, PERM-200					
Freq.	t=.03	t=.1	t=.3	t=1	t=3	t=10	t=.03	t=.1	t=.3	t=1	t=3	t=10
10Hz	574u	172u	57.4u	17.2u	5.74u	1.75u	3.38m	1.01m	338u	101u	38.5u	40.3u
20Hz	574u	172u	57.4u	17.2u	5.75u	1.83u	3.38m	1.01m	338u	102u	49.5u	56.6u
30Hz	574u	172u	57.4u	17.2u	5.75u	1.95u	3.38m	1.01m	338u	103u	62.3u	69.3u
50Hz	574u	172u	57.4u	17.2u	5.76u	2.30u	3.38m	1.01m	338u	106u	86.2u	89.6u
70Hz	574u	172u	57.4u	17.2u	5.78u	2.71u	3.38m	1.01m	338u	110u	105u	106u
100Hz	574u	172u	57.4u	17.2u	5.82u	3.35u	3.38m	1.01m	338u	118u	127u	126u
200Hz	574u	172u	57.4u	17.2u	6.04u	5.16u	3.38m	1.01m	340u	157u	179u	179u
300Hz	574u	172u	57.4u	17.2u	6.38u	6.43u	3.38m	1.01m	342u	199u	219u	219u
500Hz	574u	172u	57.4u	17.3u	7.36u	8.27u	3.38m	1.01m	350u	275u	283u	283u
700Hz	574u	172u	57.4u	17.3u	8.55u	9.77u	3.38m	1.01m	362u	335u	335u	335u
1kHz	574u	172u	57.4u	17.5u	10.4u	11.6u	3.38m	1.01m	385u	403u	400u	400u
2kHz	574u	172u	57.5u	18.3u	16.1u	16.5u	3.38m	1.02m	495u	566u	566u	566u
3kHz	574u	172u	57.5u	19.5u	20.3u	20.2u	3.38m	1.03m	623u	693u	694u	694u
5kHz	574u	172u	57.6u	23.0u	26.2u	26.1u	3.38m	1.06m	862u	896u	896u	896u
7kHz	574u	172u	57.8u	27.1u	30.9u	30.9u	3.38m	1.10m	1.05m	1.06m	1.06m	1.06m
10kHz	574u	172u	58.2u	33.5u	36.9u	36.9u	3.38m	1.18m	1.27m	1.26m	1.26m	1.26m
20kHz	574u	172u	60.4u	51.6u	52.2u	52.2u	3.40m	1.57m	1.79m	1.79m	1.79m	1.79m
30kHz	574u	172u	63.8u	64.3u	63.9u	63.9u	3.42m	1.99m	2.19m	2.19m	2.19m	2.19m
50kHz	574u	173u	73.6u	82.7u	82.6u	82.6u	3.50m	2.75m	2.83m	2.83m	2.83m	2.83m
70kHz	574u	173u	85.5u	97.7u	97.7u	97.7u	3.62m	3.35m	3.35m	3.35m	3.35m	3.35m
100kHz	574u	175u	104u	116u	116u	116u	3.85m	4.03m	4.00m	4.00m	4.00m	4.00m
200kHz	575u	183u	161u	165u	165u	165u	4.95m	5.66m	5.66m	5.66m	5.66m	5.66m
300kHz	575u	195u	203u	202u	202u	202u	6.23m	6.93m	6.94m	6.94m	6.94m	6.94m
500kHz	576u	230u	262u	261u	261u	261u	8.62m	8.96m	8.96m	8.96m	8.96m	8.96m
700kHz	578u	271u	309u	309u	309u	309u	10.5m	10.6m	10.6m	10.6m	10.6m	10.6m
1MHz	582u	335u	369u	369u	369u	369u	12.7m	12.6m	12.6m	12.6m	12.6m	12.6m
2MHz	604u	516u	522u	522u	522u	522u	17.9m	17.9m	17.9m	17.9m	17.9m	17.9m
3MHz	638u	643u	639u	639u	639u	639u	21.9m	21.9m	21.9m	21.9m	21.9m	21.9m
5MHz	736u	827u	826u	826u	826u	826u	28.3m	28.3m	28.3m	28.3m	28.3m	28.3m
7MHz	855u	977u	977u	977u	977u	977u	33.5m	33.5m	33.5m	33.5m	33.5m	33.5m
10MHz	1.04m	1.16m	1.16m	1.16m	1.16m	1.16m	40.0m	40.0m	40.0m	40.0m	40.0m	40.0m
20MHz	1.61m	1.65m	1.65m	1.65m	1.65m	1.65m	56.6m	56.6m	56.6m	56.6m	56.6m	56.6m
30MHz	2.03m	2.02m	2.02m	2.02m	2.02m	2.02m	69.4m	69.4m	69.4m	69.4m	69.4m	69.4m
50MHz	2.62m	2.61m	2.61m	2.61m	2.61m	2.61m	89.6m	89.6m	89.6m	89.6m	89.6m	89.6m
70MHz	3.09m	3.09m	3.09m	3.09m	3.09m	3.09m	106m	106m	106m	106m	106m	106m
100MHz	3.69m	3.69m	3.69m	3.69m	3.69m	3.69m	126m	126m	126m	126m	126m	126m
200MHz	5.22m	5.22m	5.22m	5.22m	5.22m	5.22m	179m	179m	179m	179m	179m	179m
300MHz	6.39m	6.39m	6.39m	6.39m	6.39m	6.39m	219m	219m	219m	219m	219m	219m
500MHz	8.26m	8.26m	8.26m	8.26m	8.26m	8.26m	283m	283m	283m	283m	283m	283m
700MHz	9.77m	9.77m	9.77m	9.77m	9.77m	9.77m	335m	335m	335m	335m	335m	335m
1GHz	11.6m	11.6m	11.6m	11.6m	11.6m	11.6m	400m	400m	400m	400m	400m	400m
2GHz	16.5m	16.5m	16.5m	16.5m	16.5m	16.5m	566m	566m	566m	566m	566m	566m
3GHz	20.2m	20.2m	20.2m	20.2m	20.2m	20.2m	694m	694m	694m	694m	694m	694m
5GHz	26.1m	26.1m	26.1m	26.1m	26.1m	26.1m	896m	896m	896m	896m	896m	896m
7GHz	30.9m	30.9m	30.9m	30.9m	30.9m	30.9m	1.06Ω	1.06Ω	1.06Ω	1.06Ω	1.06Ω	1.06Ω
10GHz	36.9m	36.9m	36.9m	36.9m	36.9m	36.9m	1.26Ω	1.26Ω	1.26Ω	1.26Ω	1.26Ω	1.26Ω

* t is in units of mm
μ = microhms
m = milliohms
Ω = ohms

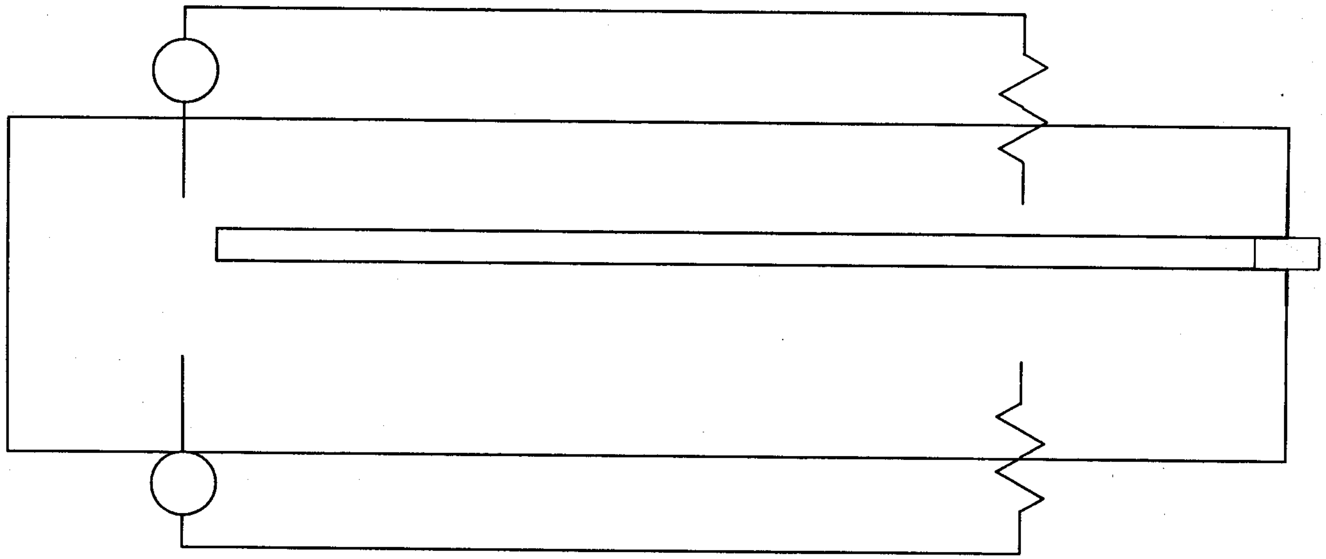
NOTE: Do not use table at frequencies in MHz above $15/L_m$ since the separation distance in meters, L_m, of two grounded equipments will exceed 0.05λ where error becomes significant.

Keeping Out "Bad" Currents

- At low frequencies Current distributes approximately uniformly along a group of parallel wires or a wide trace (e.g., a ground plane)

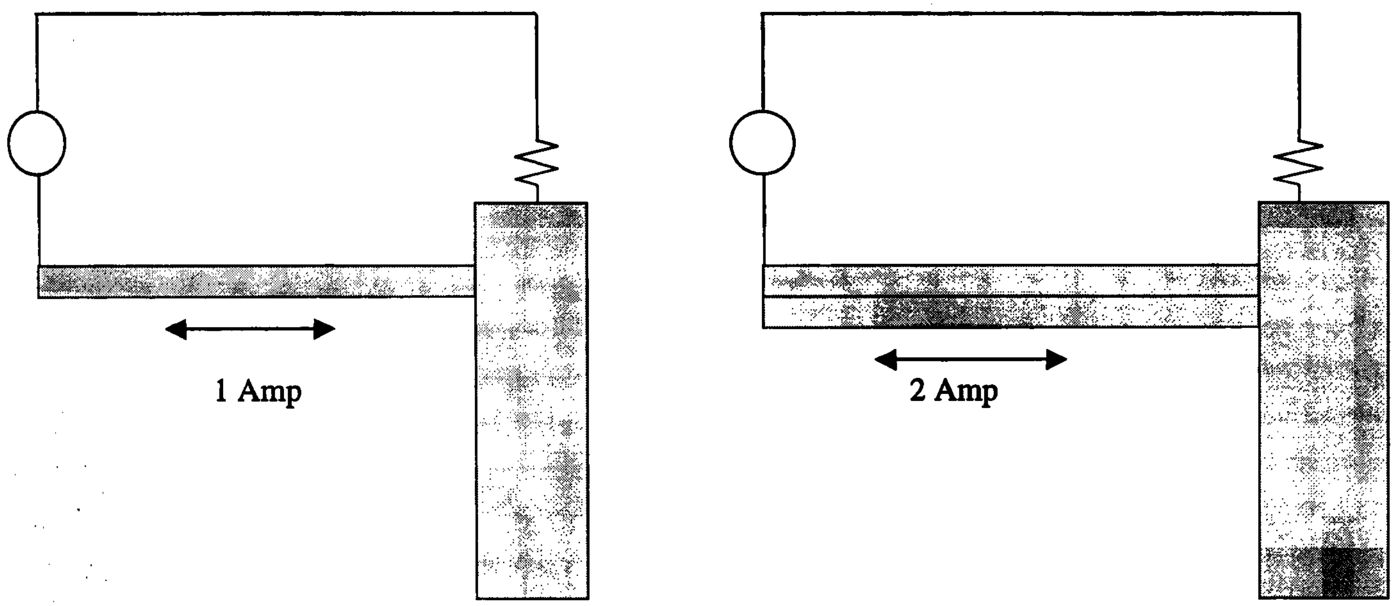


- Only way to prevent current flow is to interrupt conductor



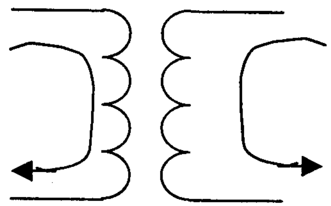
Choices of Ground Approaches

- Which of these is a better design choice?

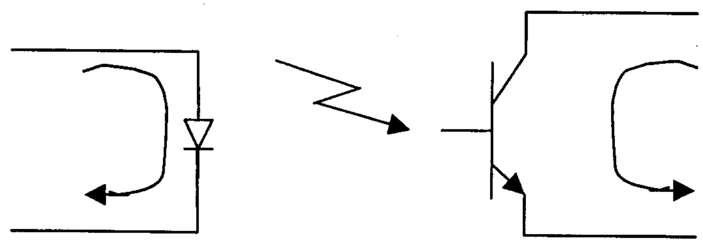


Keeping Out "Bad" Currents

- How else can I keep undesired low frequency currents out of a path?
  - Transformer coupling:
    - Requires either AC signal or conversion to AC & back



  - Opto-isolation
    - Poor current transfer ratio, non-linear, high life/radiation drift



- Note: High frequencies can couple around the isolation if not careful

NSIDERATIONS

low frequency AC) are large and

ver System tend to be concentrated

box power supplies

ically tolerate sizable voltage drops
s >=2% of distribution voltage)

nited bandwidth and lots of filtering

dary) power/signal references
ed (notable exceptions--high power
ge ASIC or FPGA)

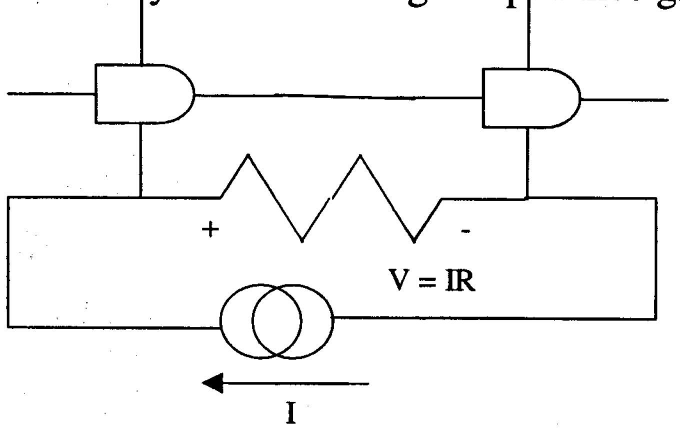
rate significant voltage differences

n very wide bandwidth

ndary (load) power/signal grounding
lifferent "needs"

GROUNDING CONSIDERATIONS

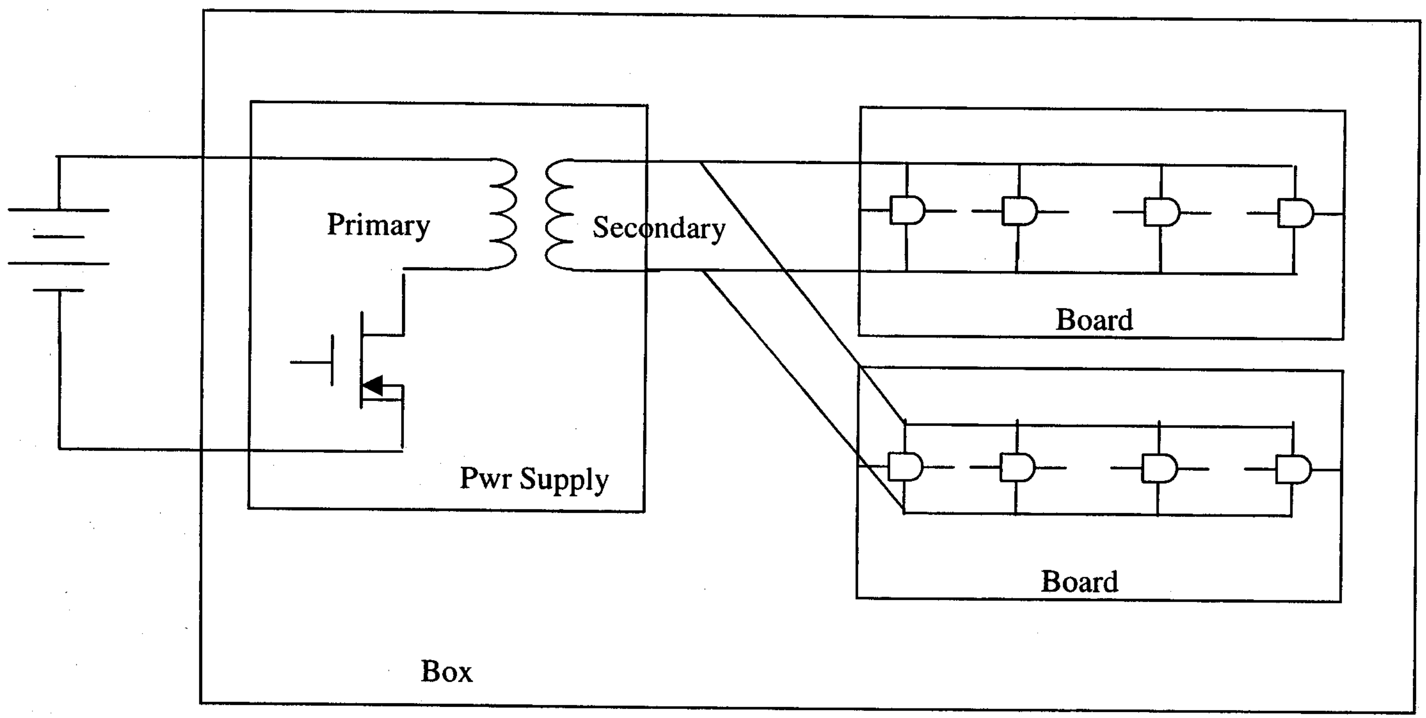
- Secondary (load) power and signal circuits cannot be isolated from each other
  - Ground pins are shared between power to IC and signal reference
- Signal circuits cannot tolerate stray voltages between source and load
  - Stray currents in high impedance ground paths cause voltage errors



- This kind of coupling of circuits is called "common impedance coupling"
- Message--
  - Keep impedances in load power/signal references low (at AC and DC)
  - Keep unnecessary large currents out of signal ground references

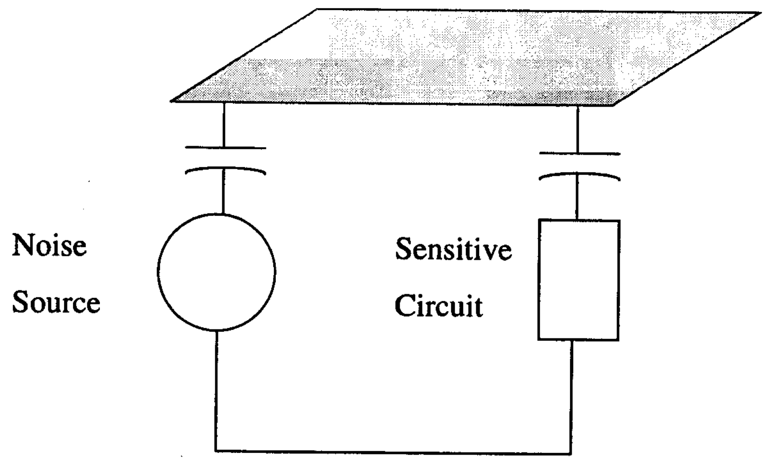
So How to handle Input Power vs. Secondary Power/Signals?

- Use transformer isolated DC/DC converters as power supplies



Handling Secondary Power/Signal Returns

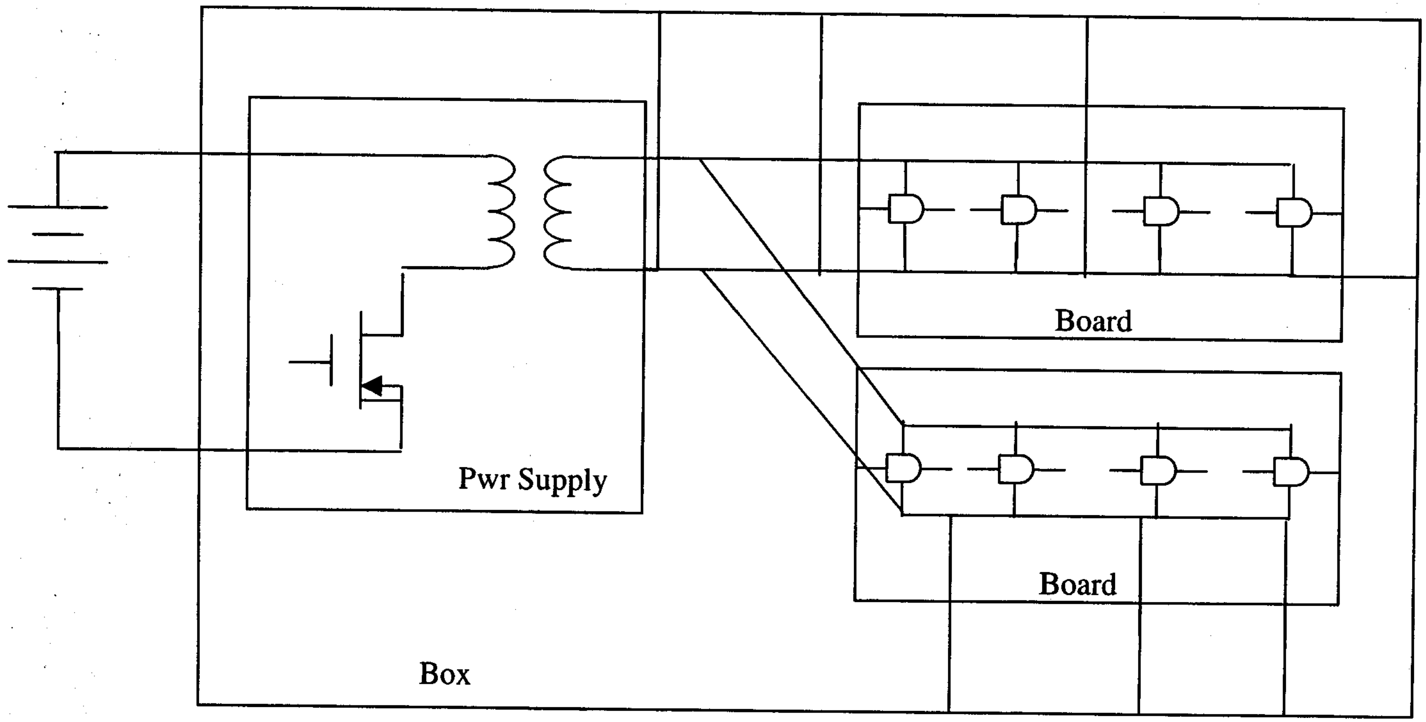
- But secondary (load side) power & signal returns often have to handle high frequency currents (so low impedance is important).
- And box chassis, if not at the same potential as the signal reference is a noise coupling mechanism.



- So how do I deal with this situation?

Handling Secondary Power/Signal Returns

- Tie the secondary power returns to box chassis ("ground") in a manner effective at high frequencies
  - Tie at every conceivable point (use ground planes where possible)

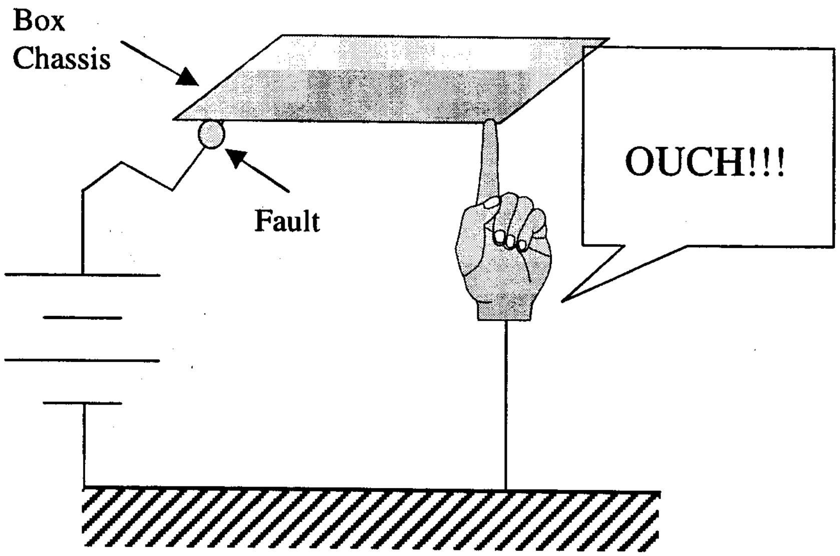


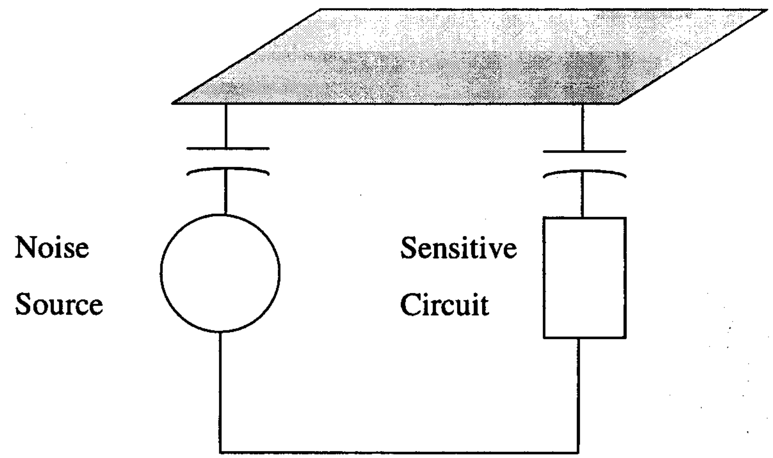
Primary/Secondary Relationships (Primary Grounding)

- But can I let the primary power system float with respect to chassis?
  - **NO!!!!!**
    - Safety and EMI Considerations indicate can't do that
      - What happens if I get 50, 100, 300, 1000 volts between primary/secondary?
        - » Something eventually blows up, arcs over, etc.
      - I could get hit by lightning or Electrostatic discharge
      - I may need to sense the primary power system with a piece of secondary side electronics
      - DC/DC Converters generate lots of high frequency EMI

GROUNDING CONSIDERATIONS

- Box/System Chassis Ground is <u>Always</u> part of your circuit.
  - If it floats it can be a hazard, or an EMI problem



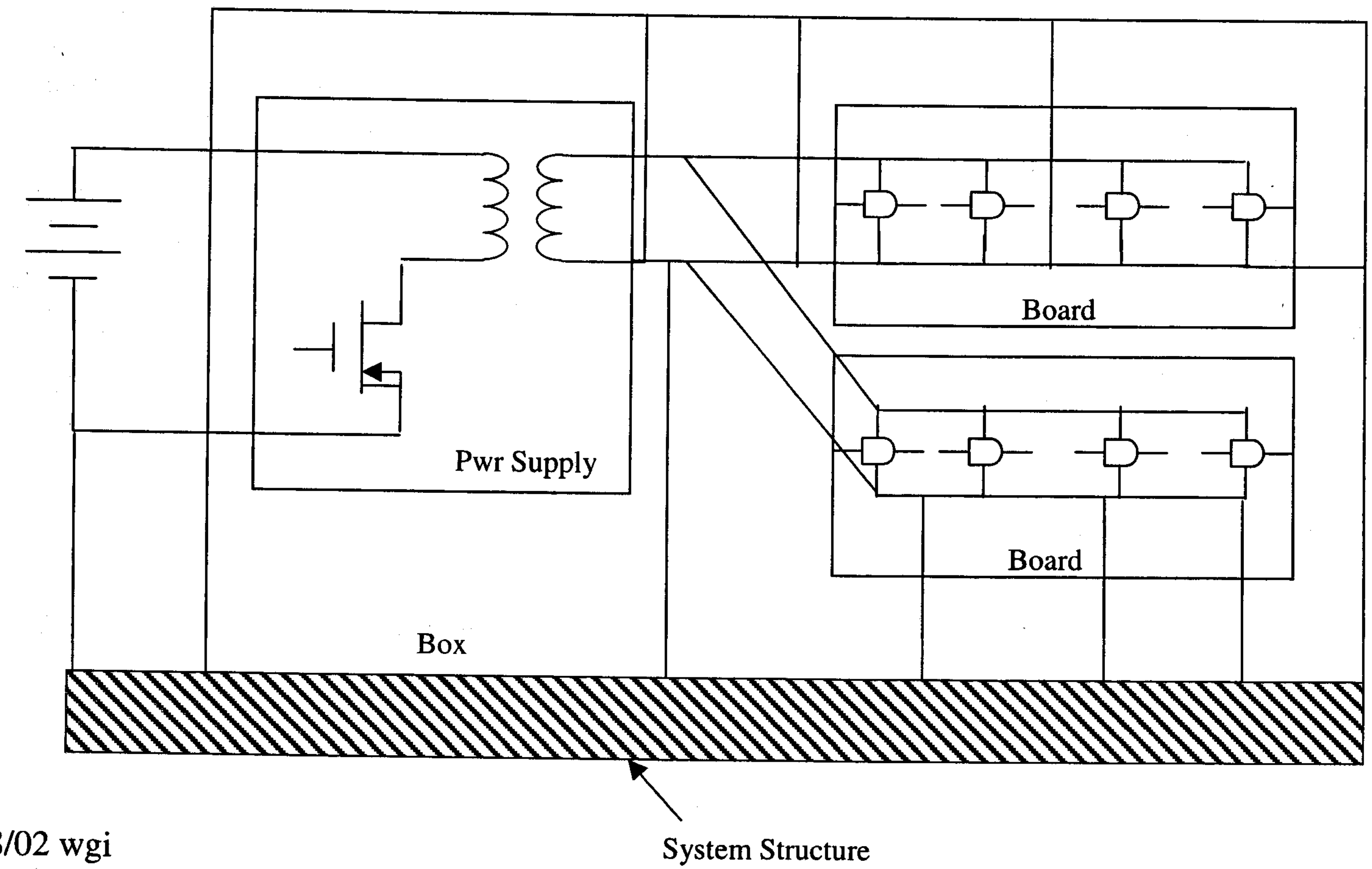


- Message--Make the chassis a known potential with respect to your circuit

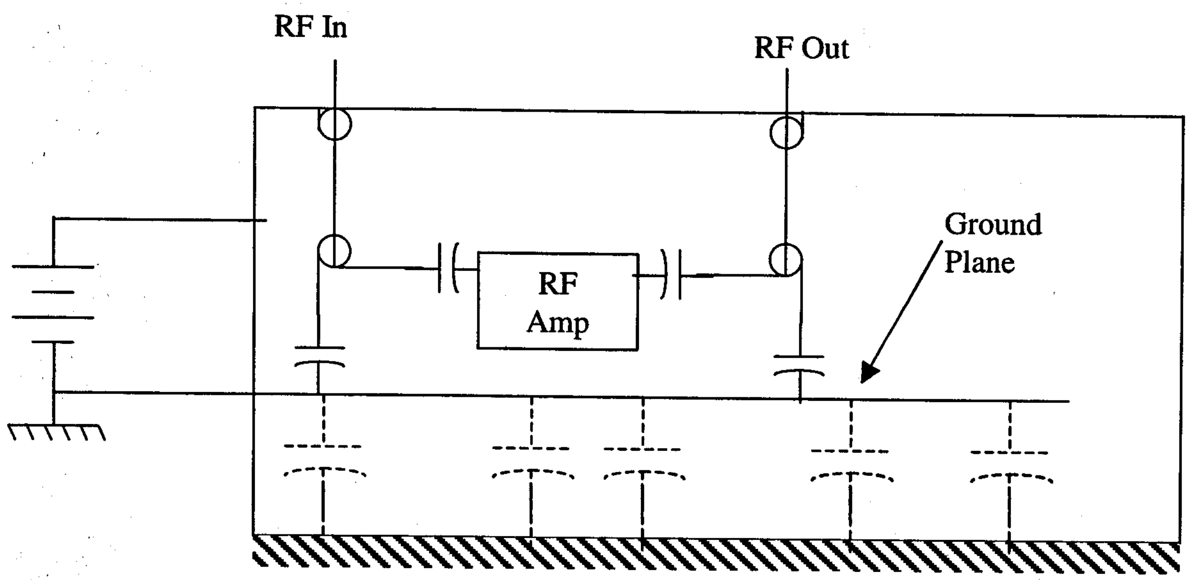
(Preferably a ground reference voltage)

Chassis Ground tie the power system only at the source

- "Single-point power grounding" concept



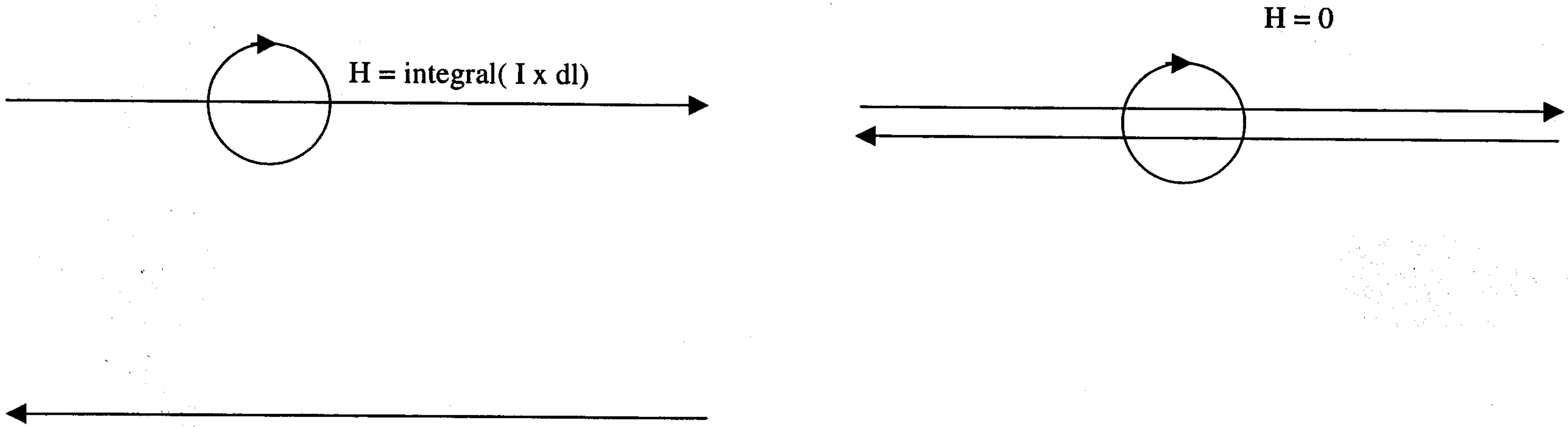
Single Point Power Input Ground on RF Amplifier



9/16/03 wgi

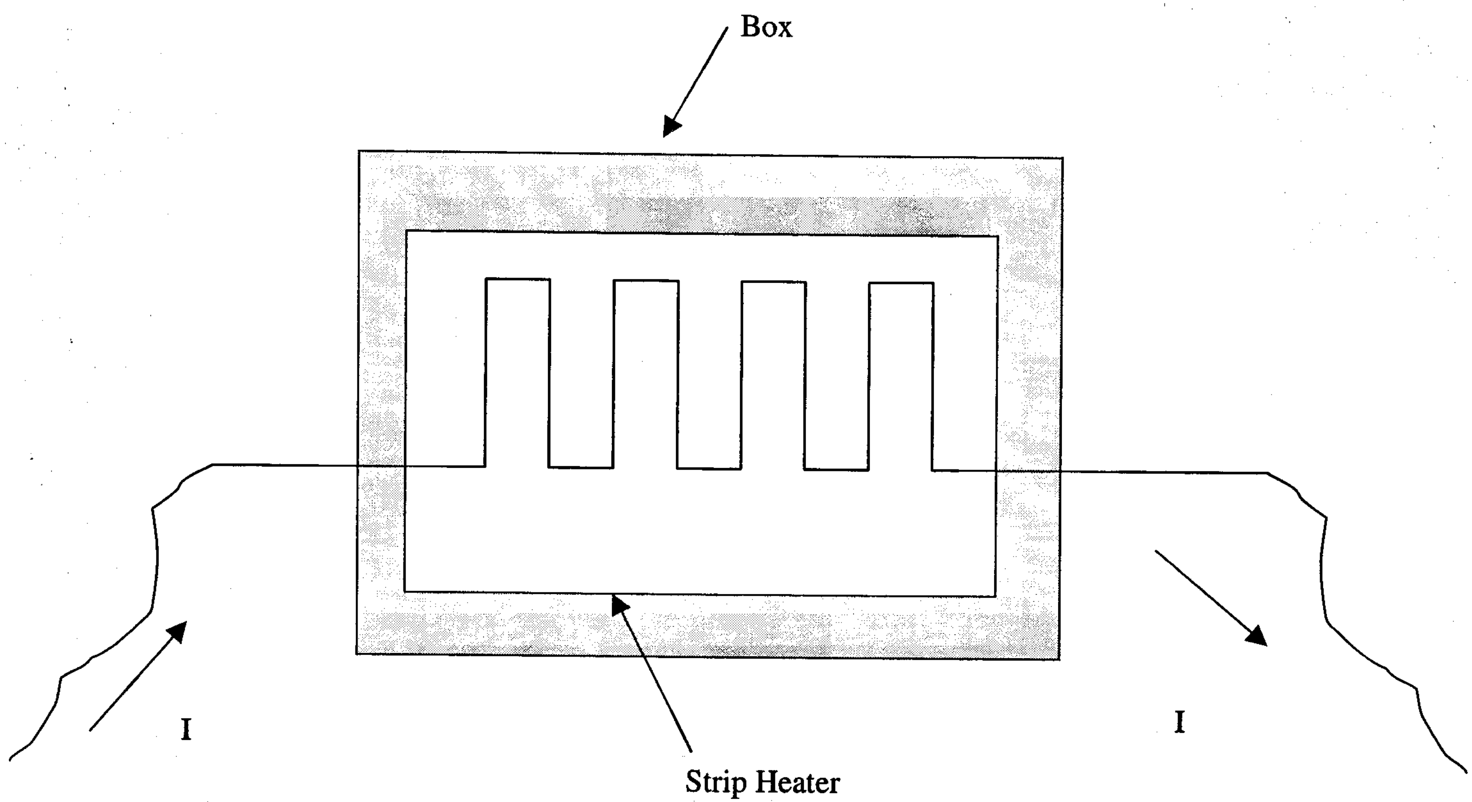
Another Reason for Single Point Grounding

- Current carrying paths that do not route with their returns generate stray magnetic fields:



- Message--Route wires that carry significant current (like DC power) together (Desirably as twisted Pairs)
  - Don't share Power lines or Power returns between units

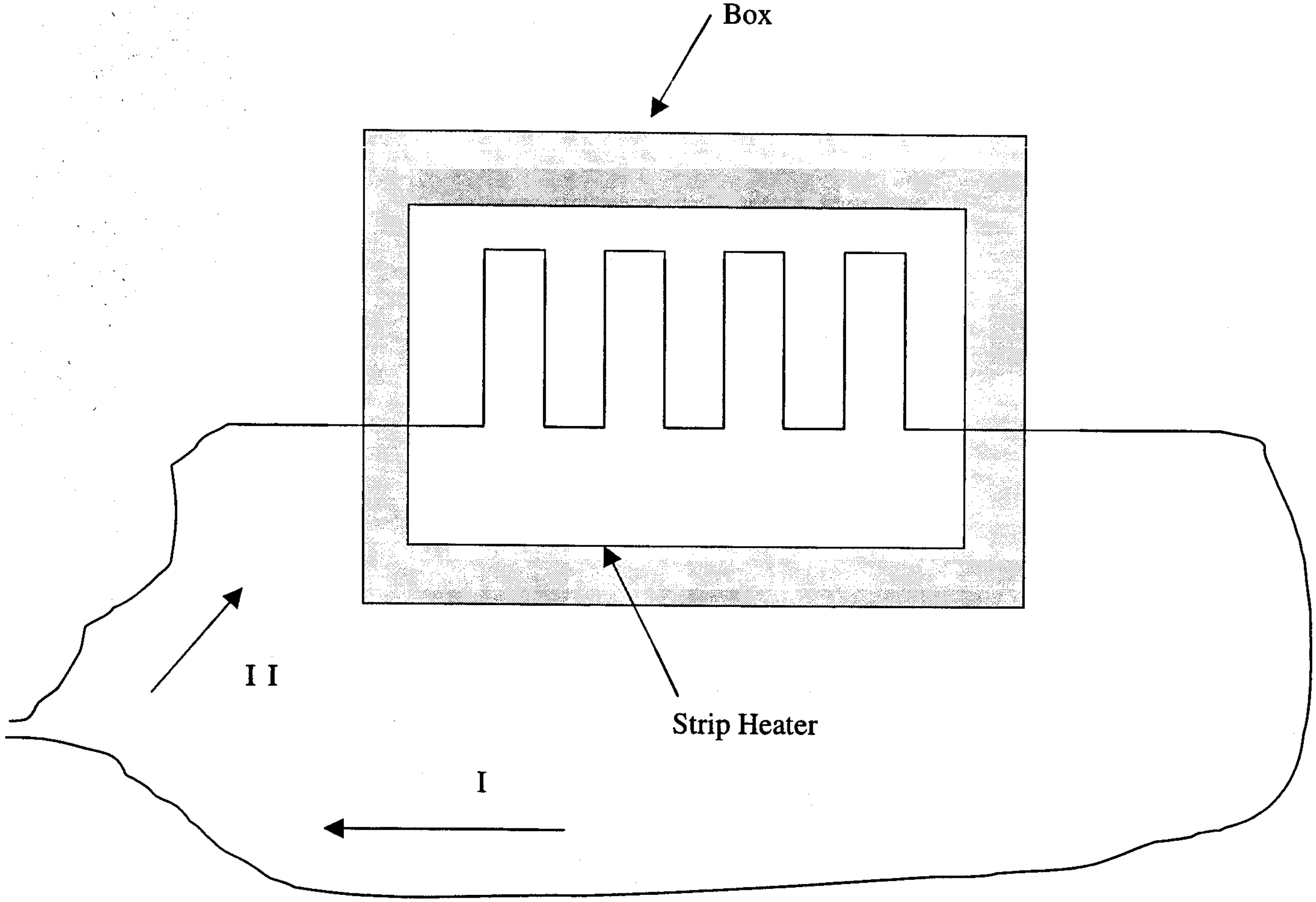
Heater Power Lines



• Un-cancelled Magnetic Fields make this a bad design approach

8/25/03 wgi

Heater Power Lines Concept #2



• Better—but still large un-cancelled loop

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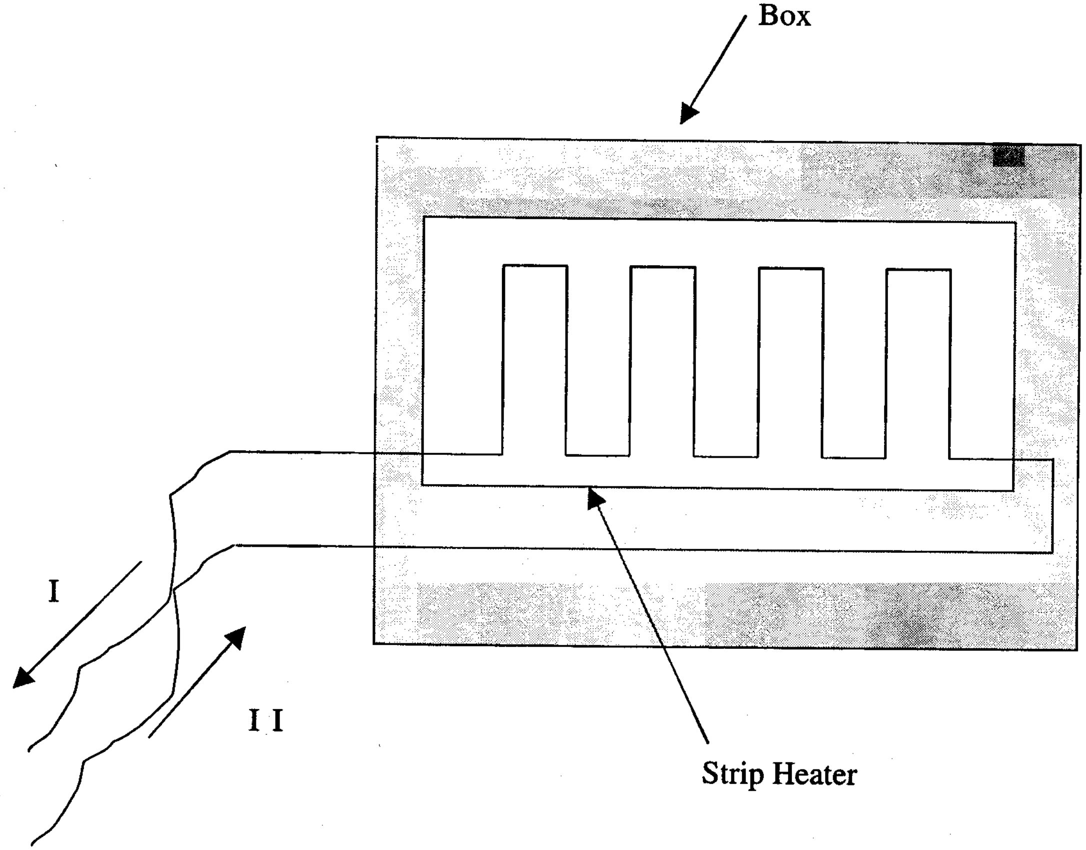
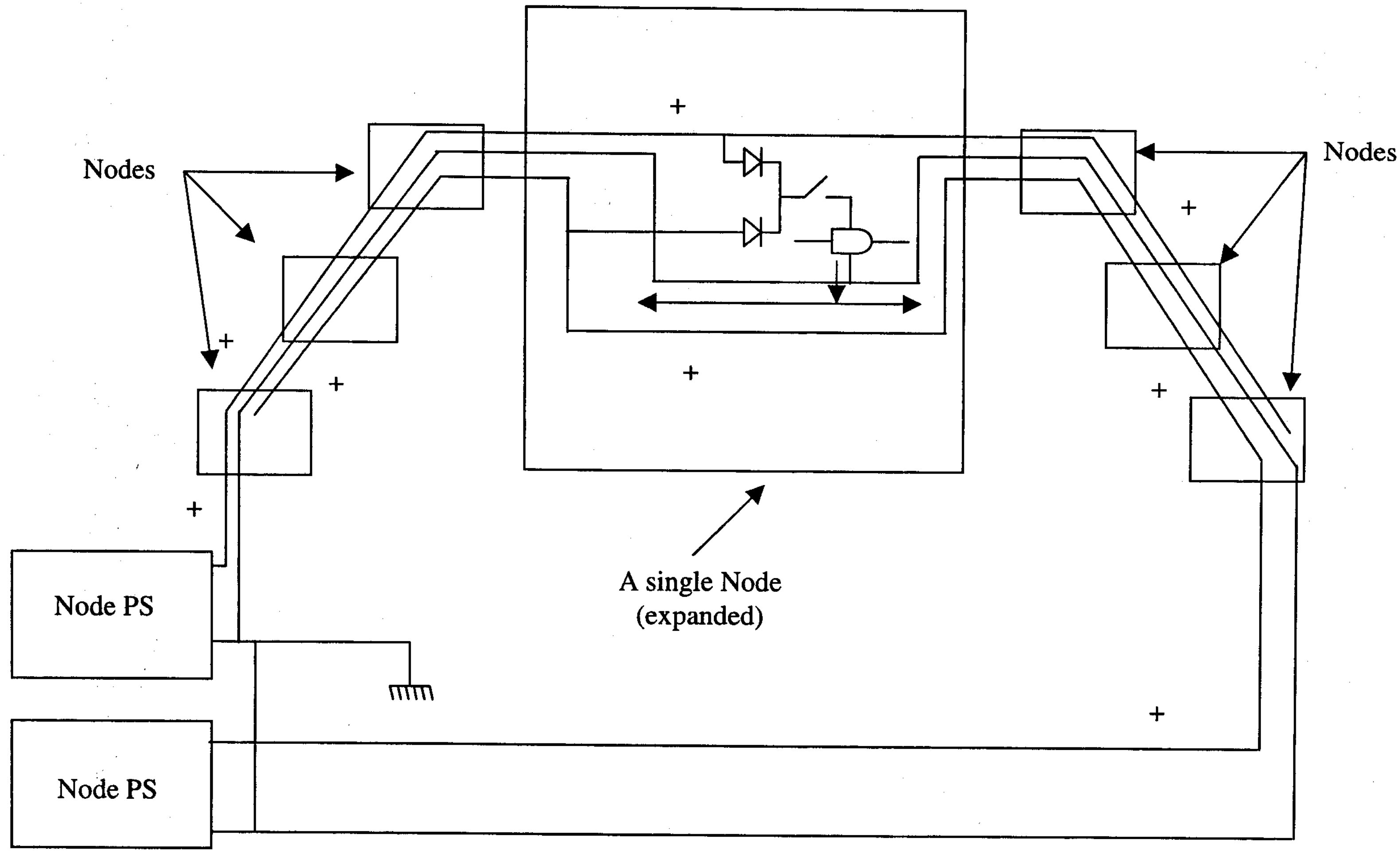
Heater Power Lines Concept #3



• Looping power line back immediately adjacent to heater and routing lines together provides efficient H-Field cancellation

8/25/03 wgi

IEEE-1394 (Firewire) Node Loop Power

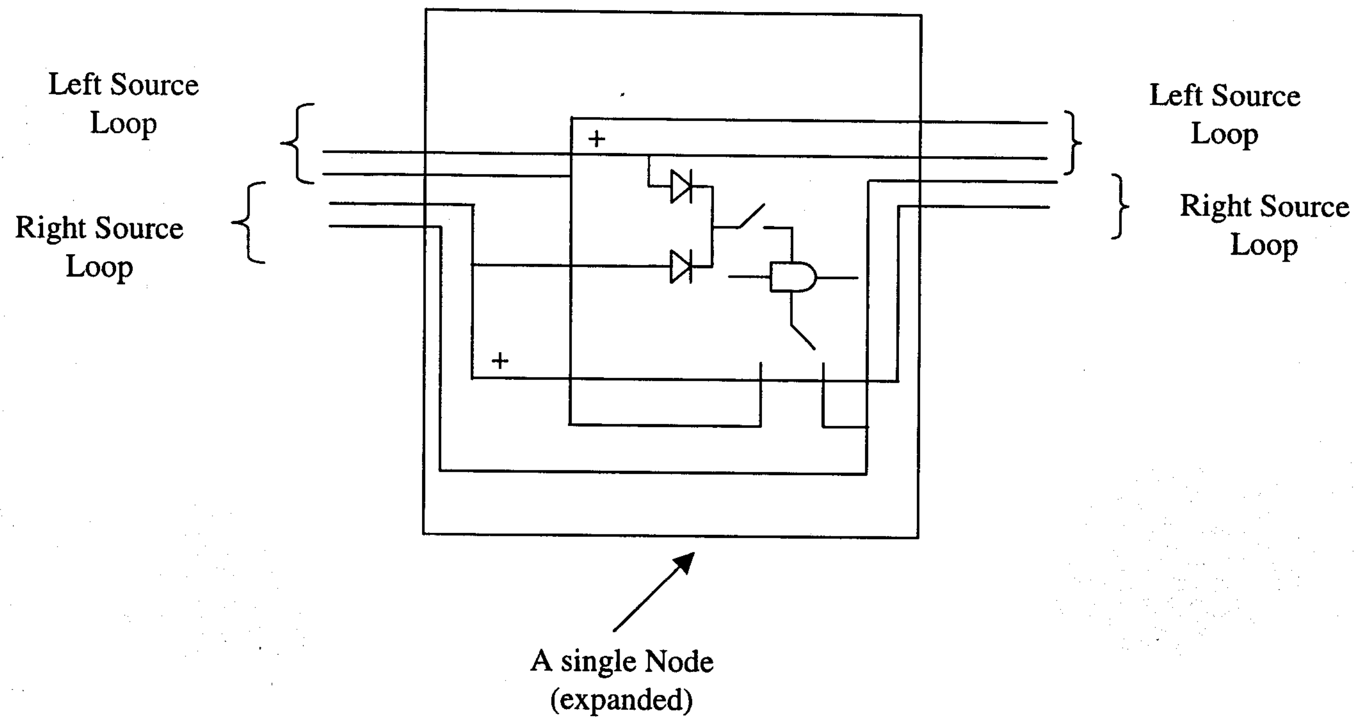


• Current return path splits between two loops—
Un-cancelled H-Field formed

8/25/03 wgi

25d

IEEE-1394 Split Returns Solves Problem



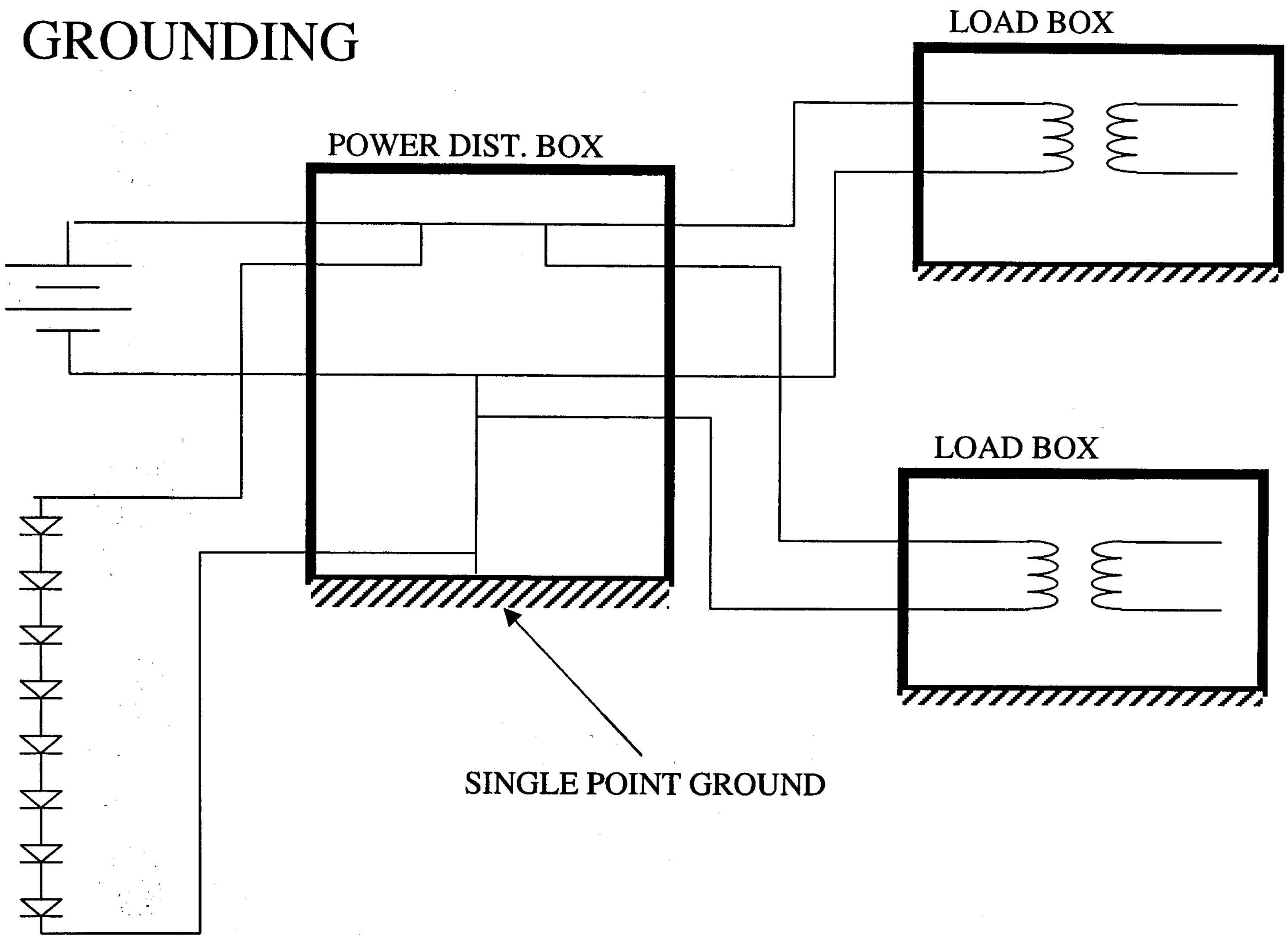
- Several possible methods exist to split returns

  Solid State or electromechanical switches at source or at node

  Isolated converter inputs

8/25/03 wgi

PRIMARY POWER GROUNDING

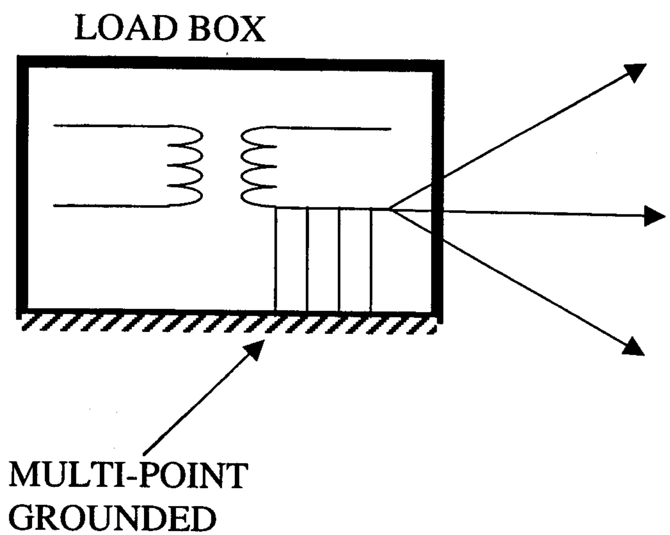


Multi-Point Grounded Power

- Can I successfully build a system that grounds power input lines to the system structure (chassis) at both sources and loads?
  - Yes, it can be done. And at least one major aerospace company does it.
    - The fact that the large power currents flow through the same paths as the signal circuit references requires an increased emphasis on return-to-box structure, box structure to system structure, and system structure resistance because of "common impedance" coupling between power currents and signal circuits
    - The grounding system in this case cannot take advantage of the larger voltage drops possible in the power return system (the signal system can't tolerate it)
  - Most aerospace companies (including LM) almost exclusively use single point grounded power systems

SECONDARY POWER GROUNDING

(POWER USED INTERNALLY ONLY)

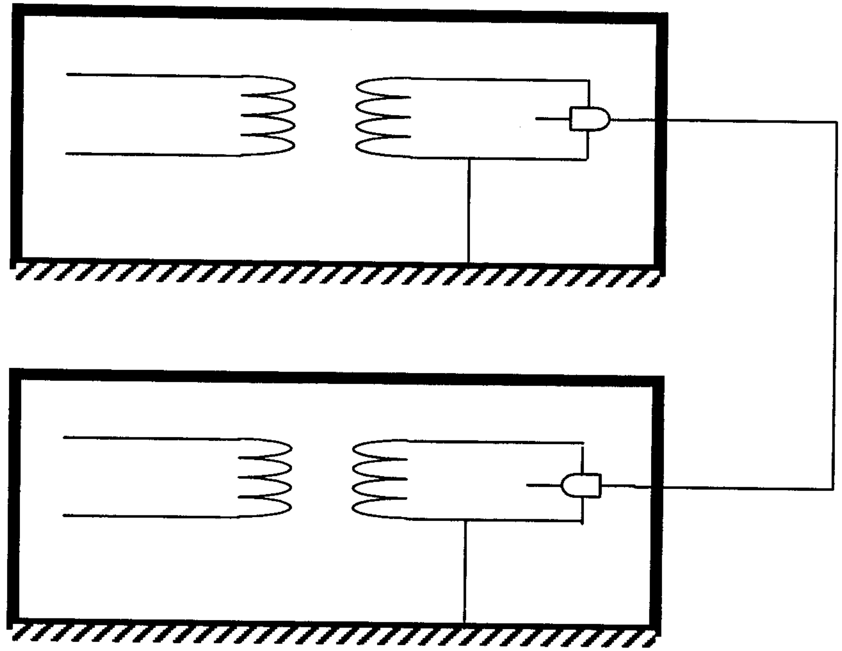


SIGNAL REFERENCES TO OTHER UNITS

(NO POWER TRANSFER)

(OTHER BOXES DESIGNED SAME WAY)

But Signal Circuits Have to Communicate between boxes

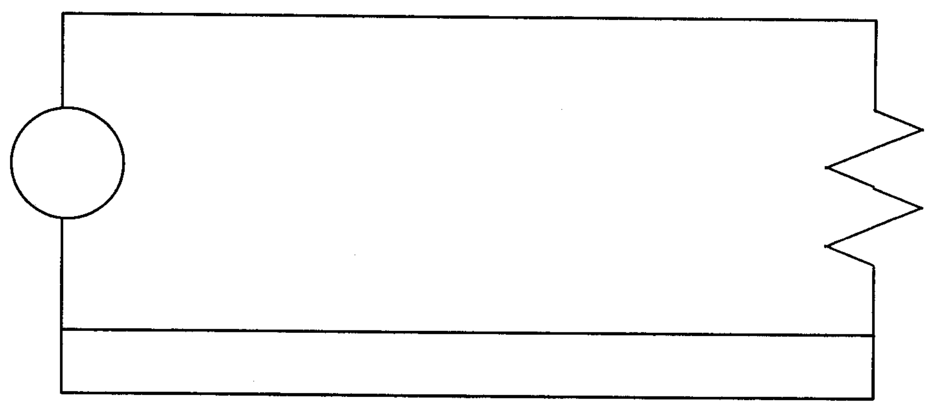


- Note: We normally don't want to depend upon the system structure to pass current. Always include a wire path.
- If the signal return system in both boxes is multipoint grounded to box chassis, and the boxes are grounded to system structure, doesn't that create the dreaded "GROUND LOOP"?

GROUNDING CONSIDERATIONS

- Ground "Loops" are not always bad!!!
  - They can be good if they lower the impedance of the associated circuit

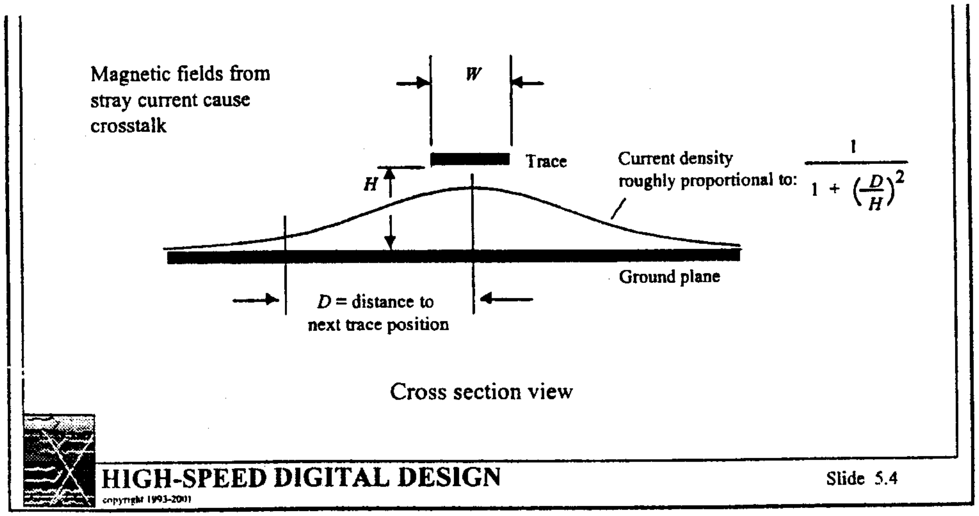
    (A Ground plane on a board or a conductive box chassis is the ultimate in a, usually good, ground loop)



  - Ground loops are bad if they allow large currents to flow through undesired paths (like sensitive signal circuits) or generate large magnetic fields

Ground Loops are not always Bad

- If the big power currents are kept out of the ground loop the small signal currents don't create a lot of potential difference
- If the structure is a good ground plane (highly conductive, large cross-sectional area) there's not a lot of impedance there.
- At high frequencies the currents don't flow out everywhere
  - they concentrate in the ground underneath the associated signal line



Handling "Bad" Chassis Paths

- OK, I've got a nonconductive structure, like composite or fiberglass, now what?
  - Several options exist:

  a. If composite, grab conductive fibers in it to use as a ground path
     - Requires non-standard processes, necessitates use of continuous fibers or ways to assure fibers make contact, etc.
     - Not an especially good conductor (high V drop at big currents)

  b. If supported by a conductive honeycomb structure, make contact to honeycomb via hardware mounting inserts
     - Requires non-standard processes, necessitates assuring continuous contact of honeycomb material, conductive contact to inserts, and conductive inserts

  c. Put a layer of conductive material on top of it (e.g., "Astrostrike")
     - Signal reference paths do not require Large volumes of conductive materials (a thin, wide plane is adequate at high frequencies)
     - Does require additional processing—Standard processes do exist
     - Requires bonding straps at structure joints to maintain electrical contact

Handling “Bad” Chassis Paths

- OK, I’ve got a nonconductive structure, like composite or fiberglass, now what? (continued)
  - Several options exist (continued):

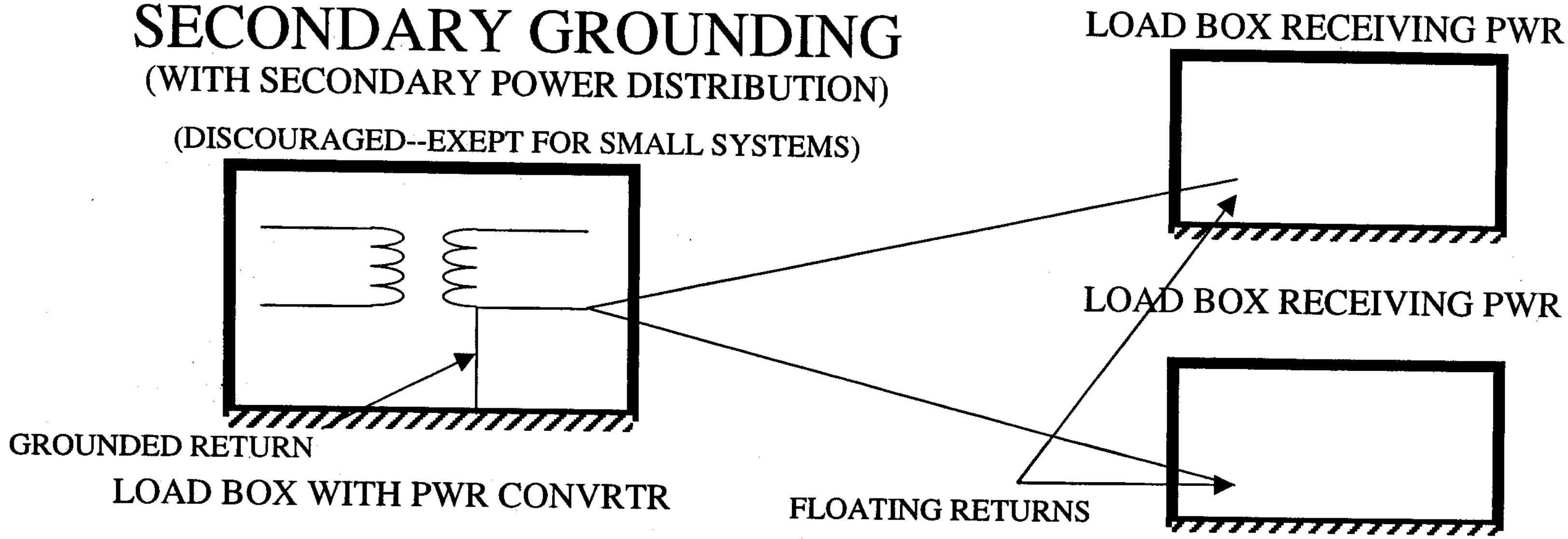
  d. Use bond straps (wide, large surface area flat straps)
    - Necessary for high frequency performance
    - Usually require width >= length/5 for small inductance
    - Still not useful at frequencies >= $\lambda/20$, because look like transmission line
      - (Long ground wires do not provide low impedance at high frequencies)
    - Requires additional labor at installation & has potential for error
    - Unless large cross-sectional area—not capable of high currents

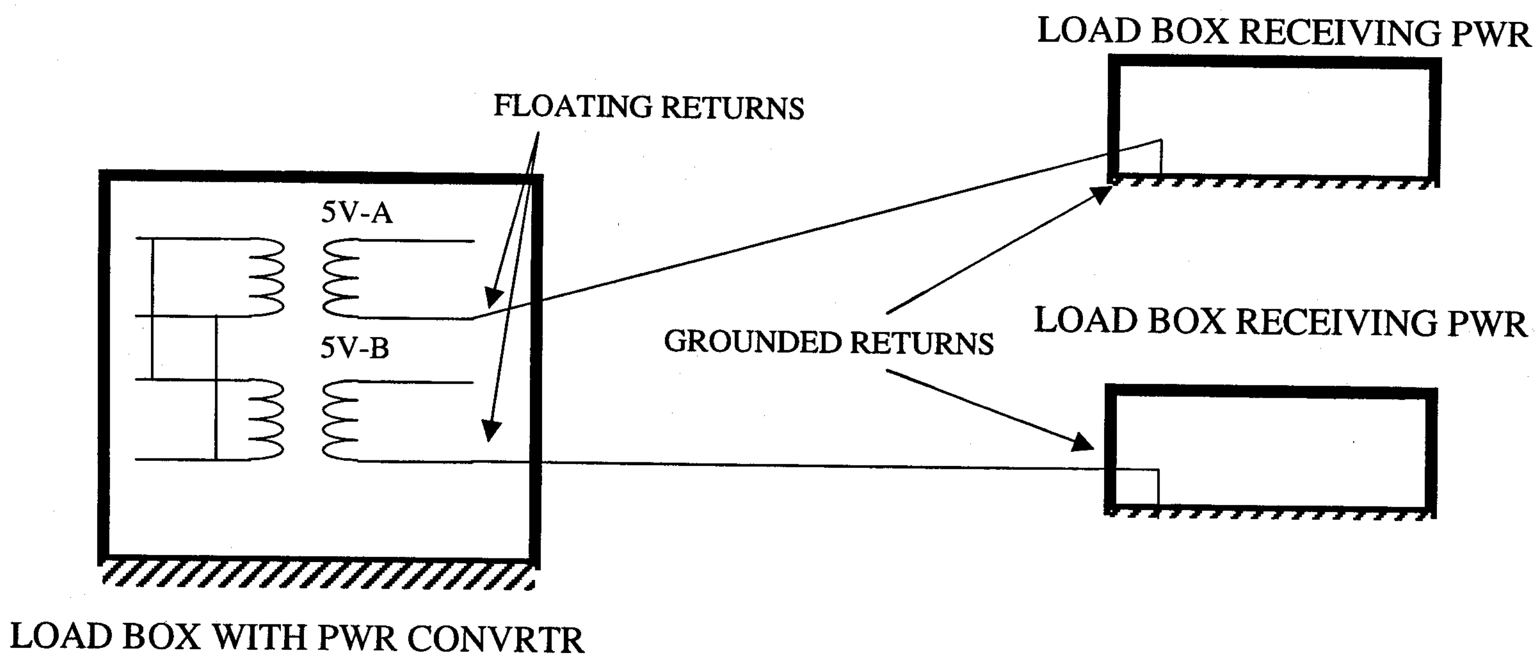
  e. Use bonding jumpers (e.g., round wires)
    - Low frequency performance (or safety) only
    - Requires additional labor at installation & has potential for error
    - Unless large cross-sectional area—not capable of high currents

SECONDARY GROUNDING

(WITH SECONDARY POWER DISTRIBUTION)

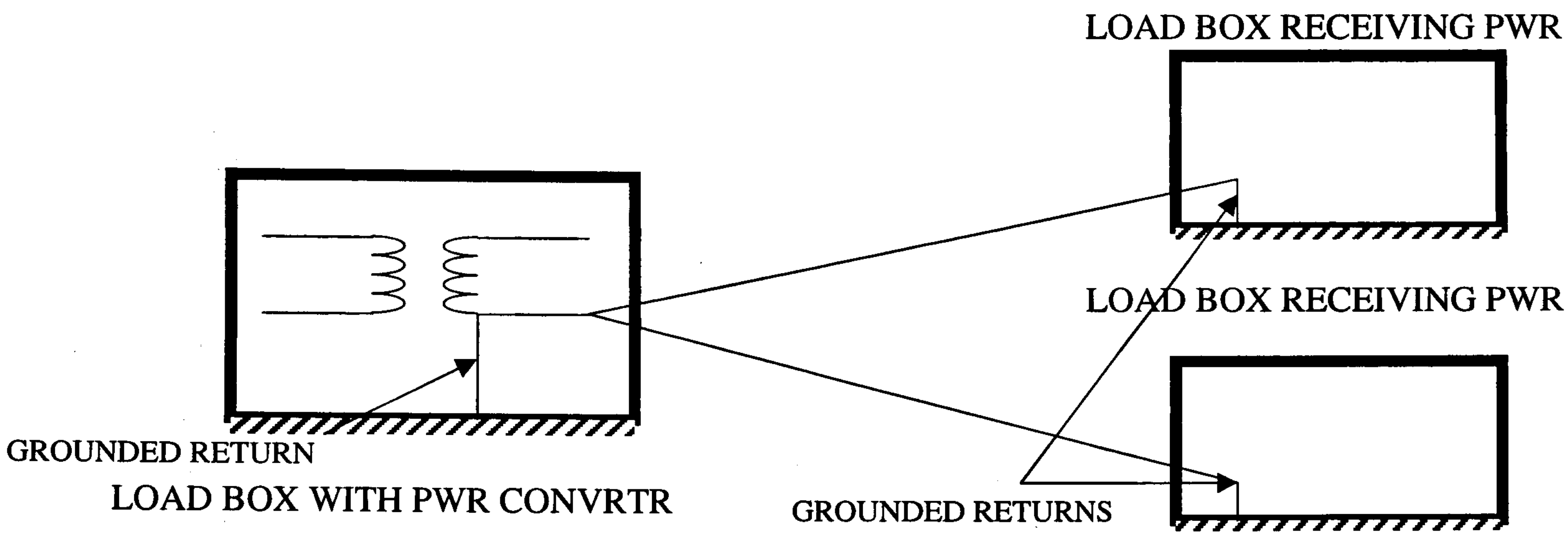
(DISCOURAGED--EXEPT FOR SMALL SYSTEMS)





SECONDARY GROUNDING
(WITH MULTI-GROUNDED POWER DISTRIBUTION)

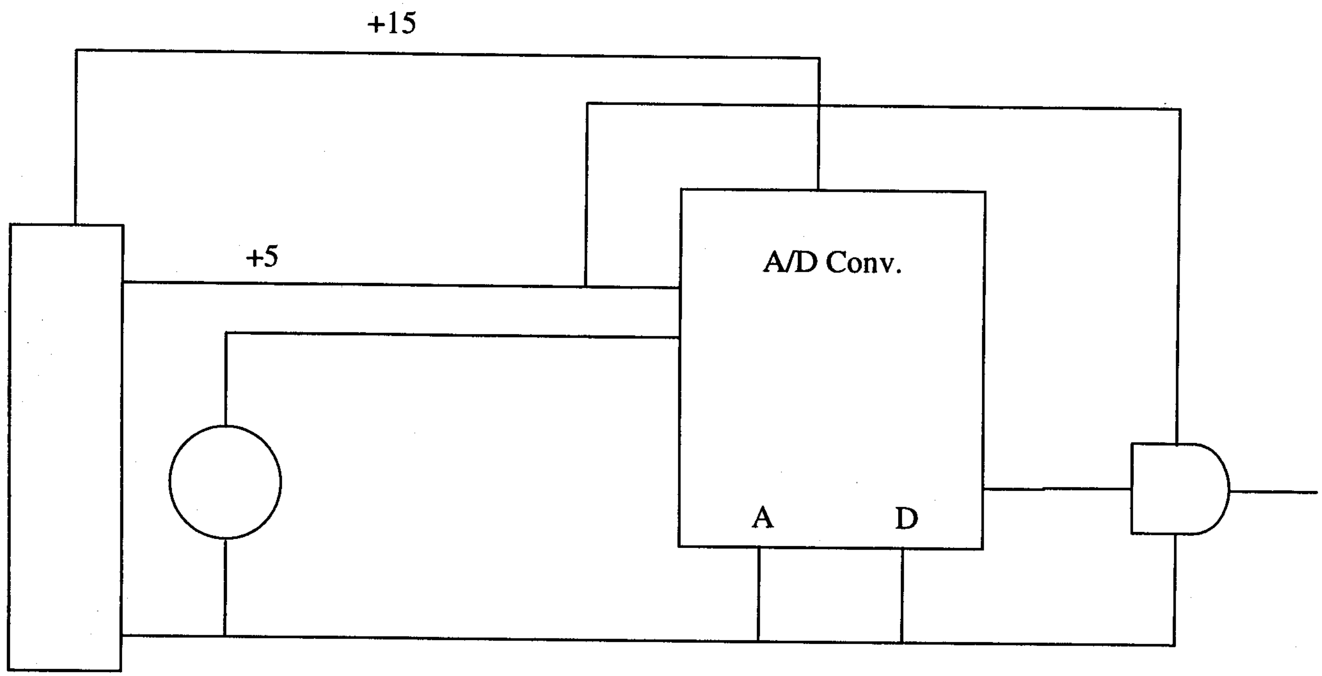
(EVEN MORE DISCOURAGED--EXEPT FOR SMALL SYSTEMS)



- If necessary to use—limit to use on a single small panel
- Requires adherence to cautions about multi-grounded power lines (from slide 27)

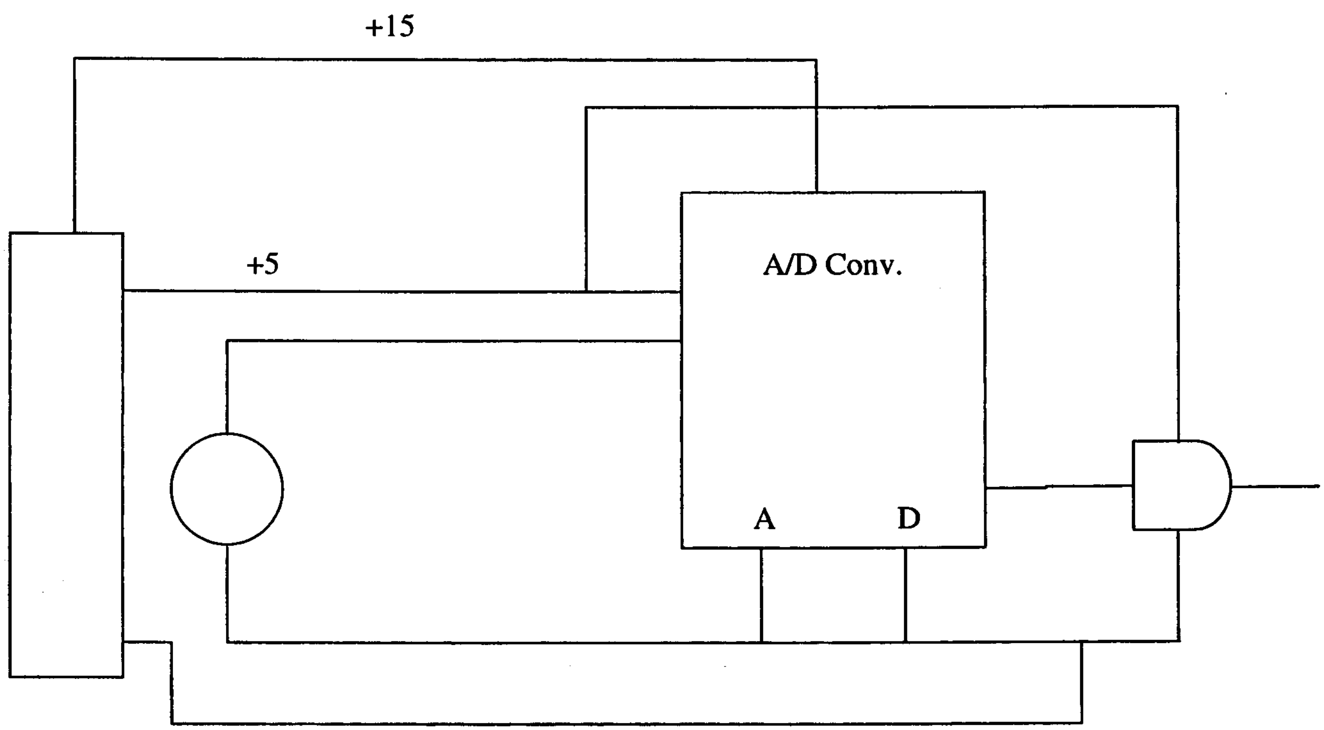
Sensitive Signal Interface References

- OK, I've got a 16 bit high speed A/D converter in my digital box, and the digital system noise from "common impedance" coupling will drive that sensitive analog system nuts, what can I do?



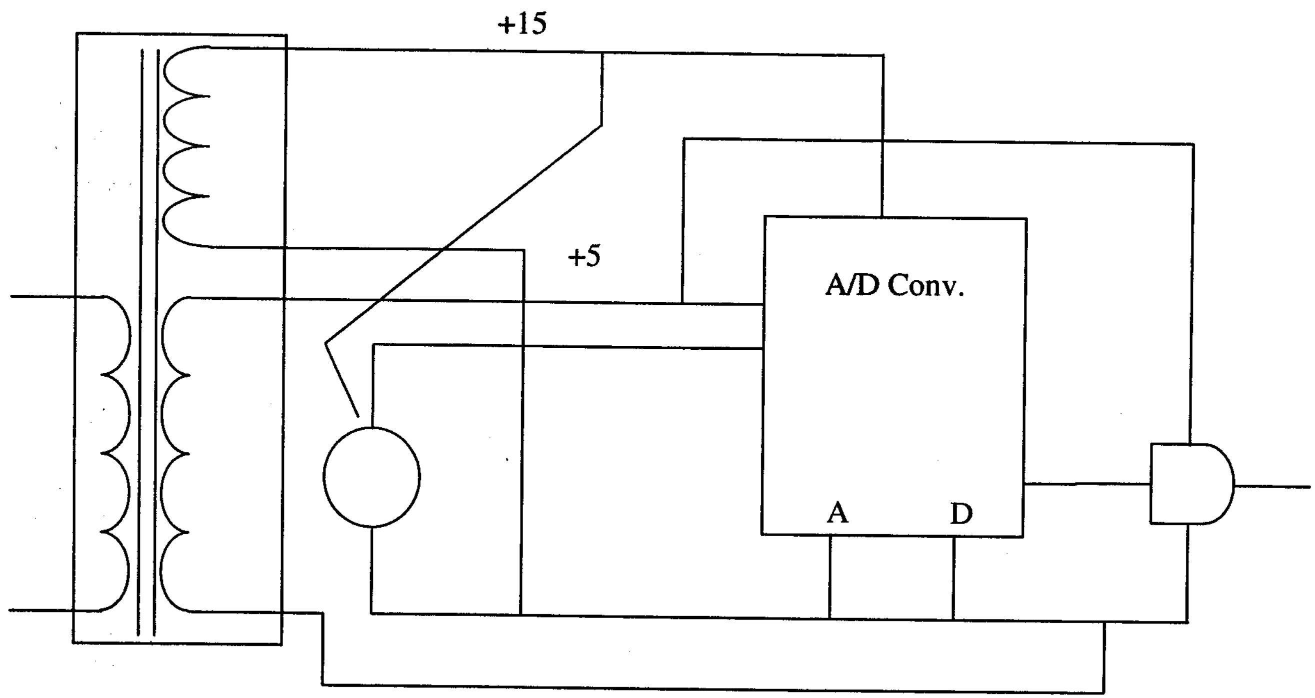
Sensitive Signal Interface References

- Use the slotted reference from chart 15:



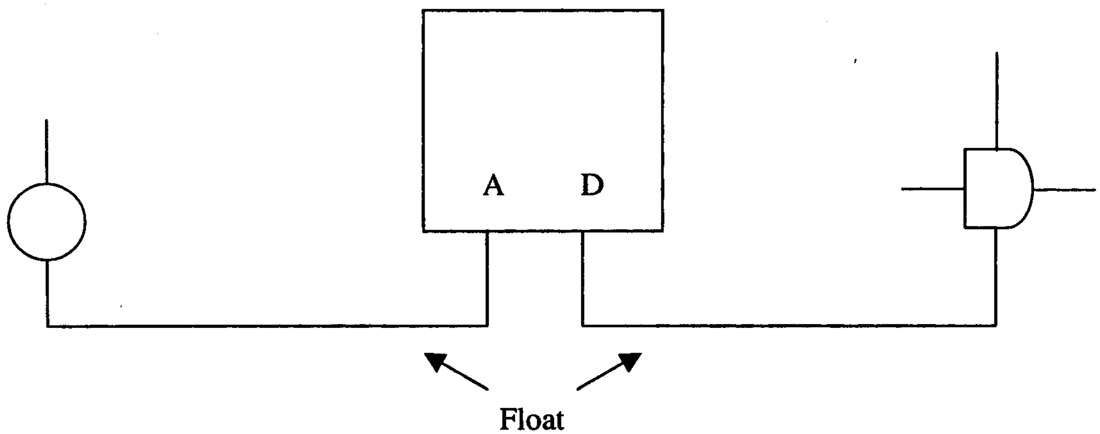
Sensitive Signal Interface References

- OK, but the previous chart still has the noise from the digital power lines imposed on the analog power I/F, what can I do about that?
  - Use transformer-isolated windings for the analog +15 volt power & the +5 volt digital power



Sensitive Signal Interface References

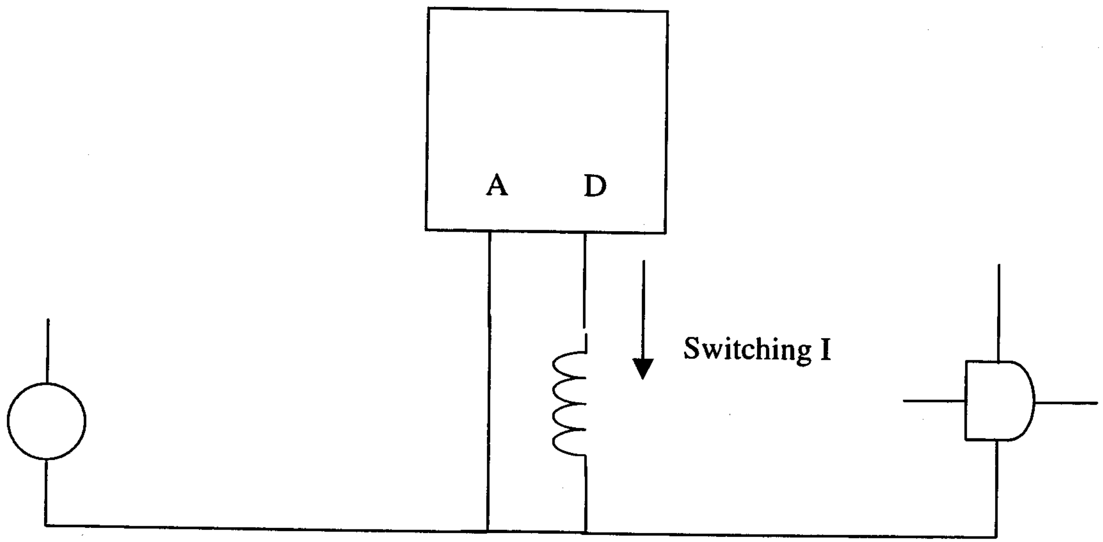
- Incidentally, ever wonder why the A/D has two ground pins (A & D)?
  - It's <u>not</u> so you can do this!!!! (Although you might be able to do it)



- Risk is that common mode voltages between A & D systems could kill the device or cause noise problems

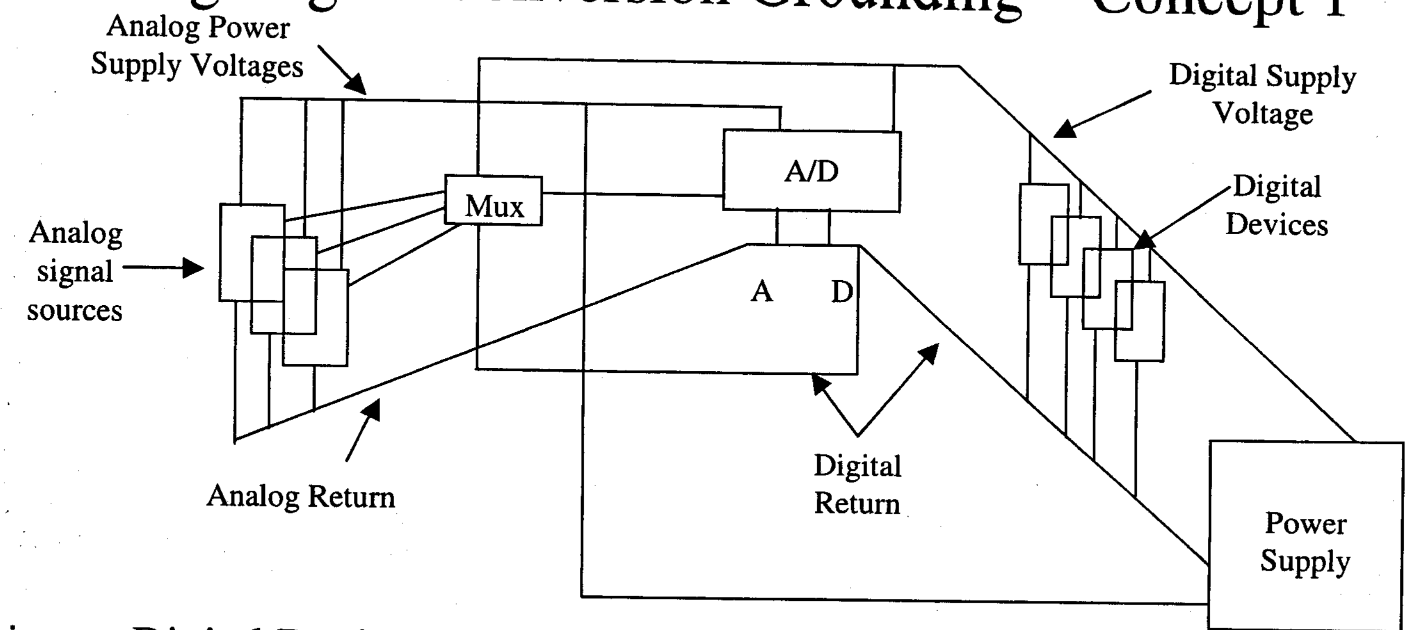
Sensitive Signal Interface References

- Here's why:

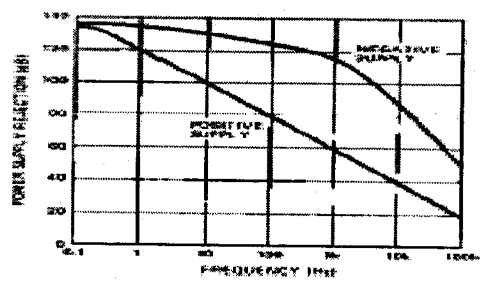


  - Ground "bounce" in digital interfaces (chart 4) doesn't appear as noise source between the analog source and the A/D analog input

Analog-Digital Conversion Grounding—Concept 1



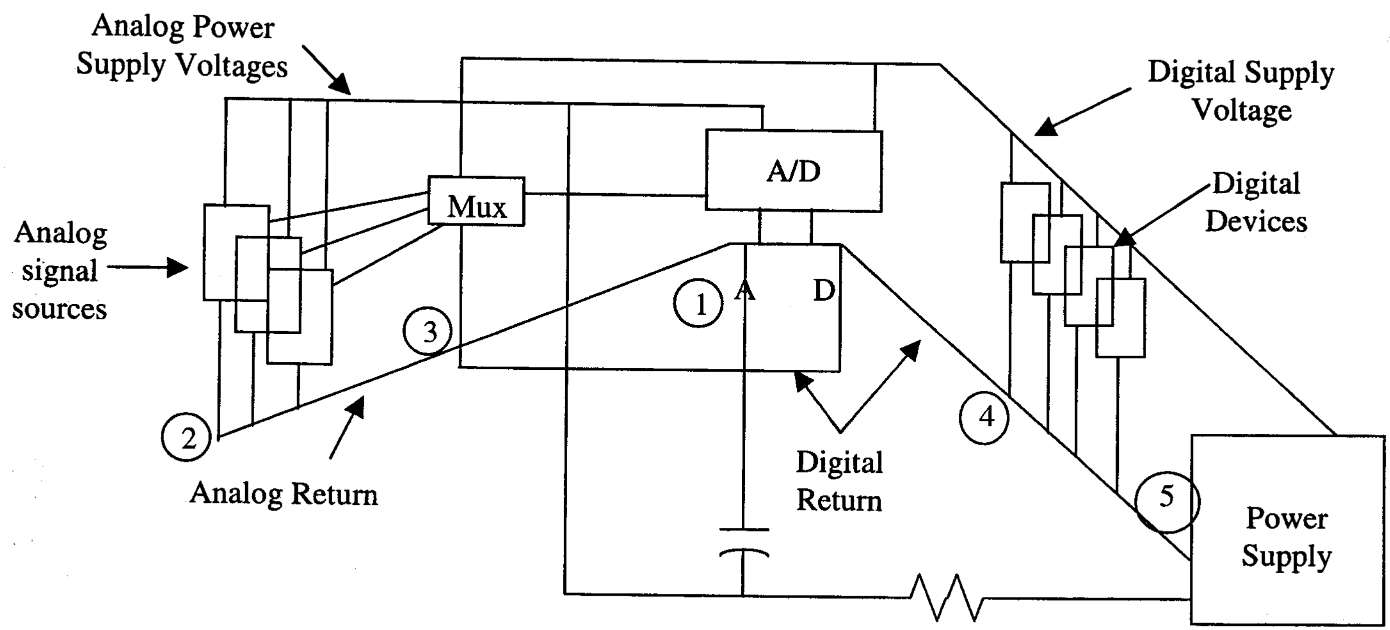
- Eliminates Digital Device Currents in paths between sources & A/D
  - Digital currents still affect analog device power supply voltage interfaces
    - Often acceptable since analog device power supply rejection is good—be careful, may only be good at low frequencies



TPC 12. Power Supply Rejection vs. Frequency

- Analog power currents create offsets in A/D inputs—Make analog return large area and paths short in length

Analog-Digital Conversion Grounding—Concept 2



- Adding filtering can help reduce digital noise on analog device lines
  - NOTE: Capacitor grounding is best done to point (1) above
    - Also note that local device bypass capacitors ground to point (2) above.
- Digital noise still appears as common mode noise on analog signal and power interfaces

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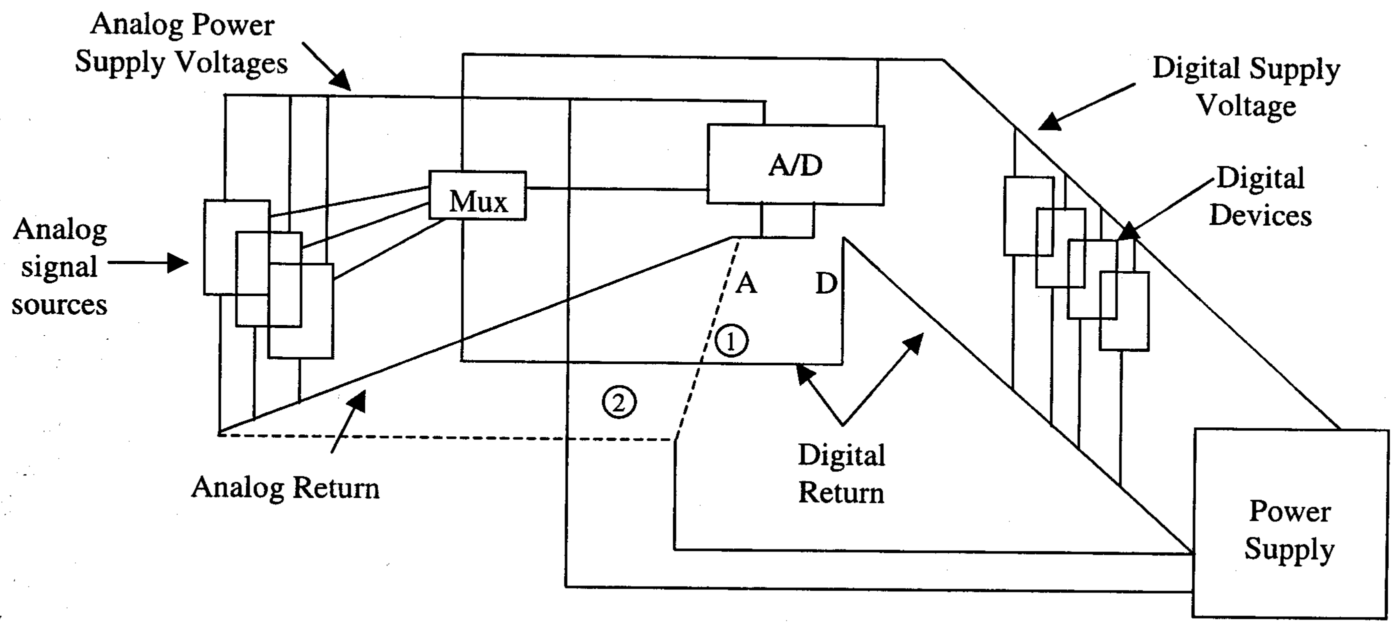
Analog-Digital Conversion Grounding—Concept 3



- Eliminates effect of digital devices on analog signal and power interfaces
- May eliminate or minimize analog device power supply currents on analog signals—(tie point 1)
- Possible Problem: A/D Digital currents may flow in analog paths (tie point 2)—is time correlated to A/D converter operations

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Sensitivity to Ground Offsets and Noise—A/D Conversion

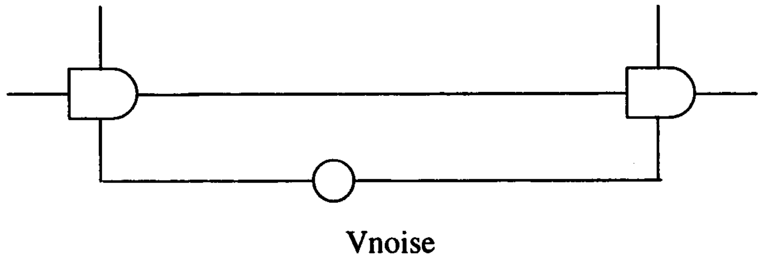
- Sensitivity of A/D conversion process increases significantly as number of bits increases:
  - For a 5 volt full scale signal:

Number of Bits	Value of LSB
8	19.5 mV
12	1.22 mV
16	76.3 uV
20	4.77 uV
24	0.3 uV

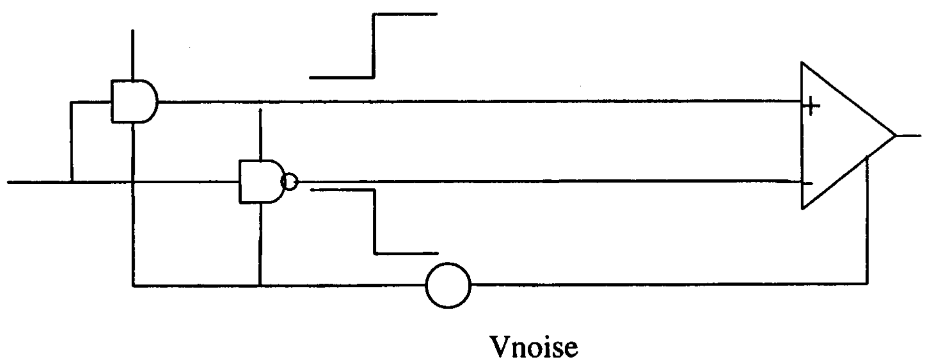
- Effect of ground offsets and noise can be reduced by:
  - Locating the A/D converter right next to the analog source
  - Reducing impedance of the ground path
  - Reducing the current flowing in the ground path
  - Employing differential transmission methods

Single-Ended vs. Differential Transmission

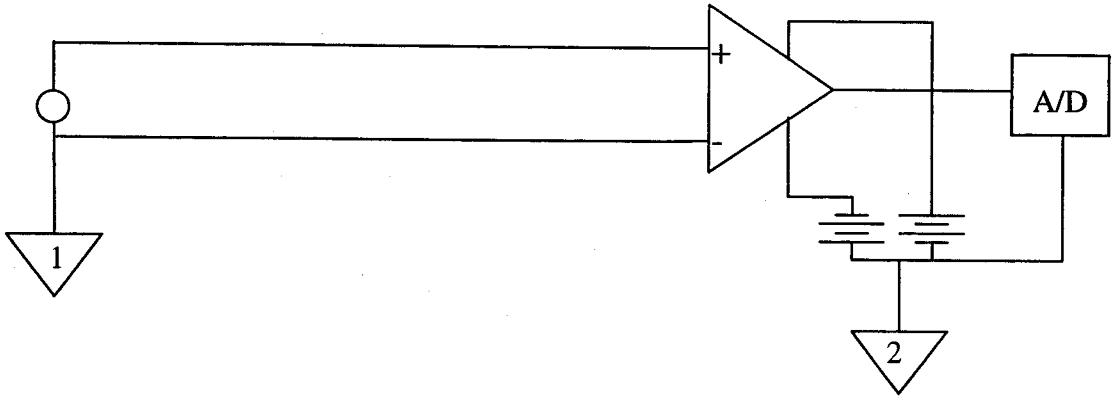
- Single ended (trace over ground) transmission is sensitive to ground voltage offsets and noise, and crosstalk from other lines.
  - Wide bandwidth of digital circuits means they are sensitive to frequencies far below (maybe above) the signal you are transmitting (including DC)
  - Analog circuits often sensitive to small magnitudes of noise



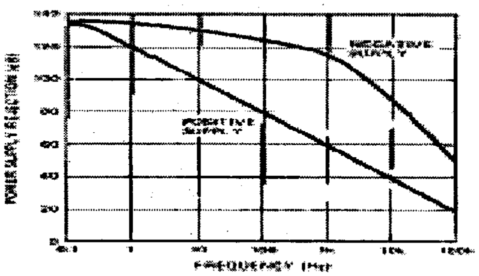
- Differential transmission reduces these concerns.



Using Differential Interfaces to Reduce Offsets & Noise

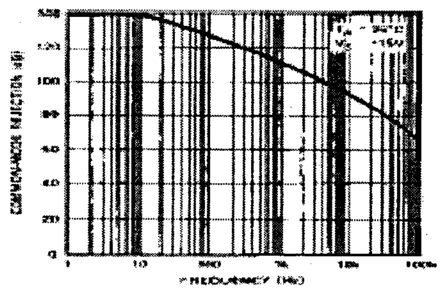


- Ability of this configuration to help depends on:
  - Common Mode Rejection Ratio of Differential Amp
  - Power Supply Rejection Ratio of Differential Amp
  - Magnitude and Spectral Content of Common mode or Power Supply voltage



TPC 12. Power Supply Rejection vs. Frequency

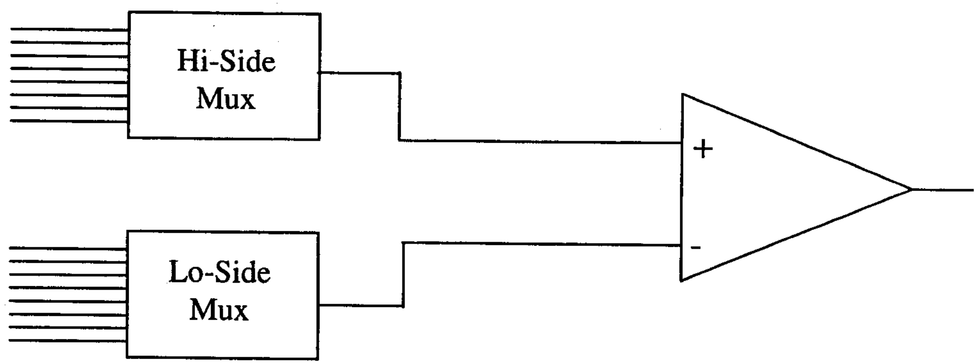
Number of Bits	Value of LSB	Common Mode or Power Supply Rejection Ratio for 1 V source
8	19.5 mV	34 dB
12	1.22 mV	58 dB
16	76.3 uV	82 dB
20	4.77 uV	106 dB
24	0.3 uV	130 dB



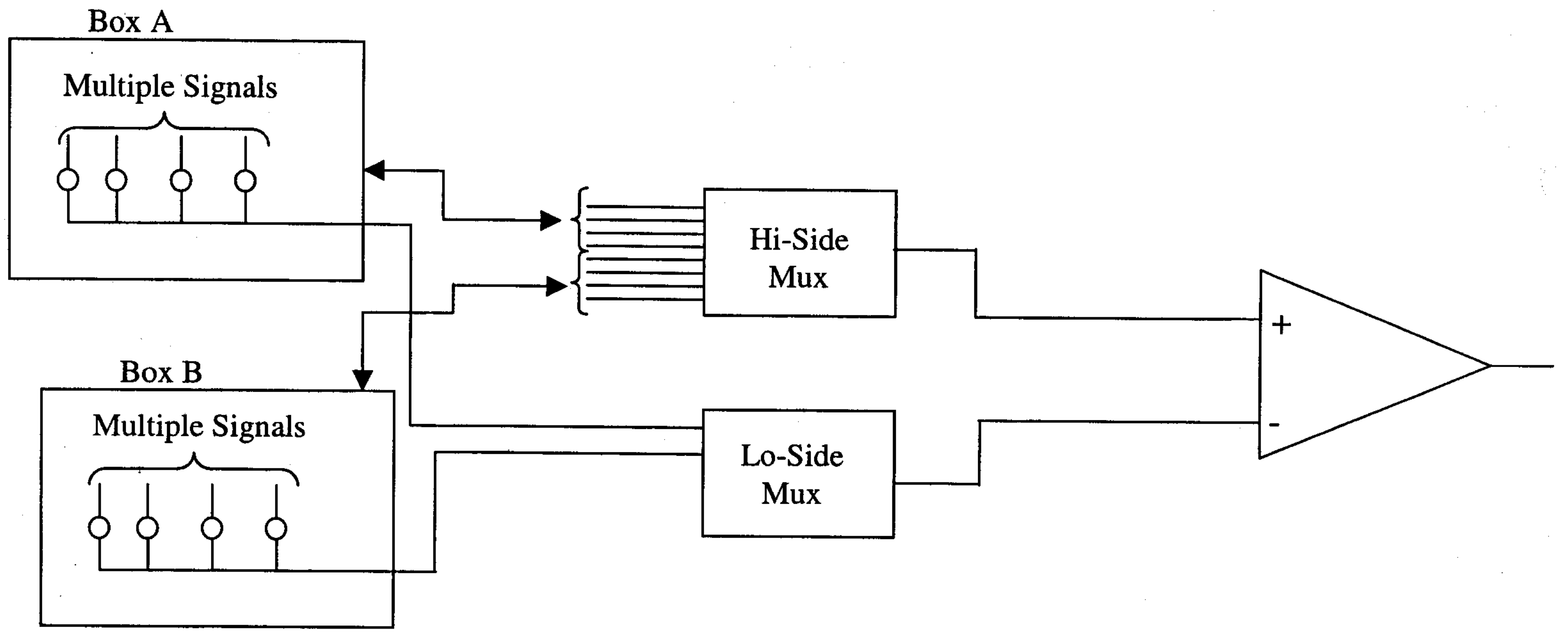
TPC 6. Common-Mode Rejection vs. Frequency

Issues with Differential Interfaces on Multiplexed Inputs

- Using one differential amplifier per input on multiplexed inputs requires many amplifiers, a sizeable real-estate and power penalty
- Similar, but somewhat less of a problem if one differential amplifier is used with both high side and low side multiplexers
  - Lots of multiplexers required (2 x number of inputs)
  - Multiplexers are smaller and consume less power than amplifiers



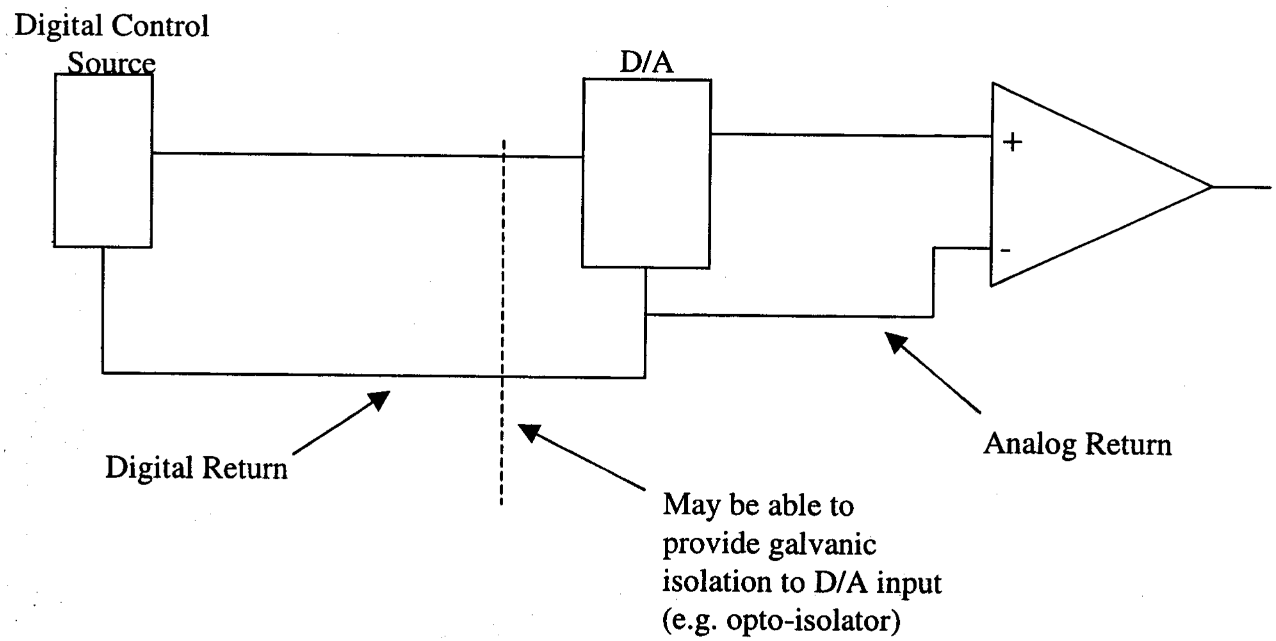
Reducing the Impact with "Pseudo-Differential" Interfaces



- Quantity of Lo-Side Multiplexers can be reduced many-fold by combining returns and using "Pseudo-Differential" Connections
  - Sometime a single "box" may contain two or more different ground domains (e.g., unregulated power return and analog signal return)— In such cases use separate lo-side mux for each different return

D/A Grounding considerations

- Locate the D/A as close as possible to the analog system it serves.
  - Return the D/A return(s) to the analog ground
    - Reduces return voltage between the D/A and the analog system
    - Possible problem: Introduces D/A digital power and signal currents into the analog system return
      - Advantage: D/A digital I/F typically are small currents—not driving long lines or high fanout



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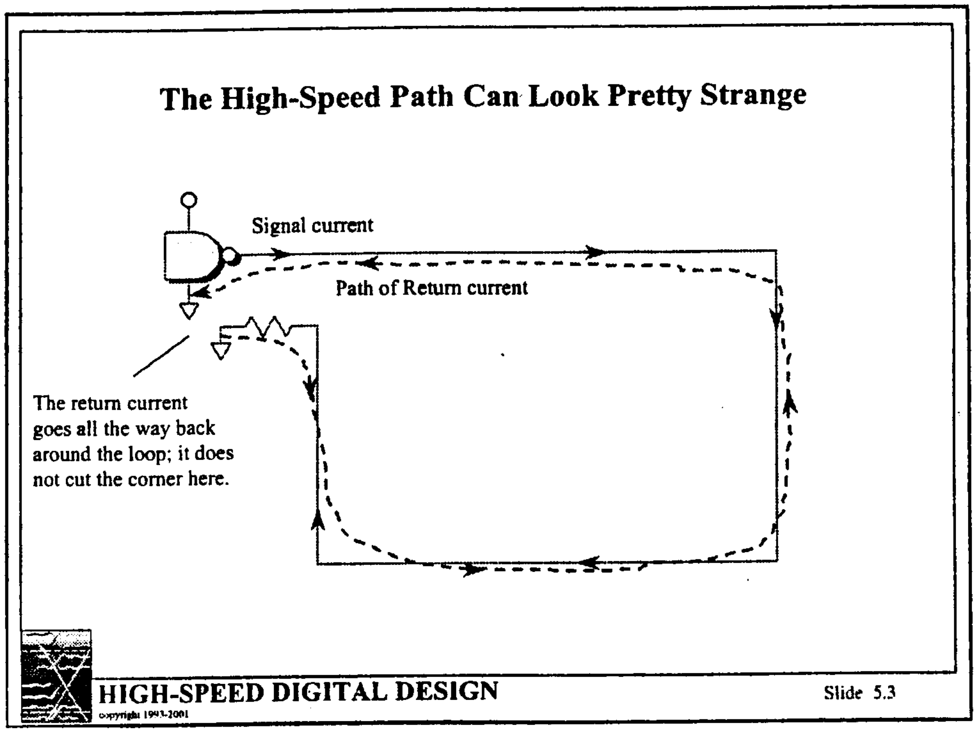
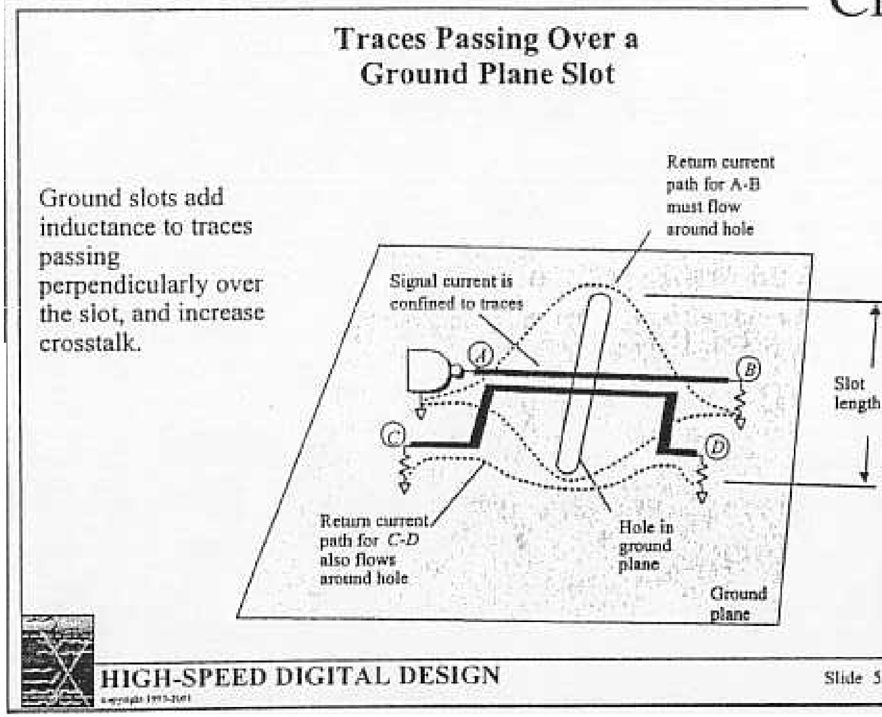
• If must separate D/A and analog system—use differential interface

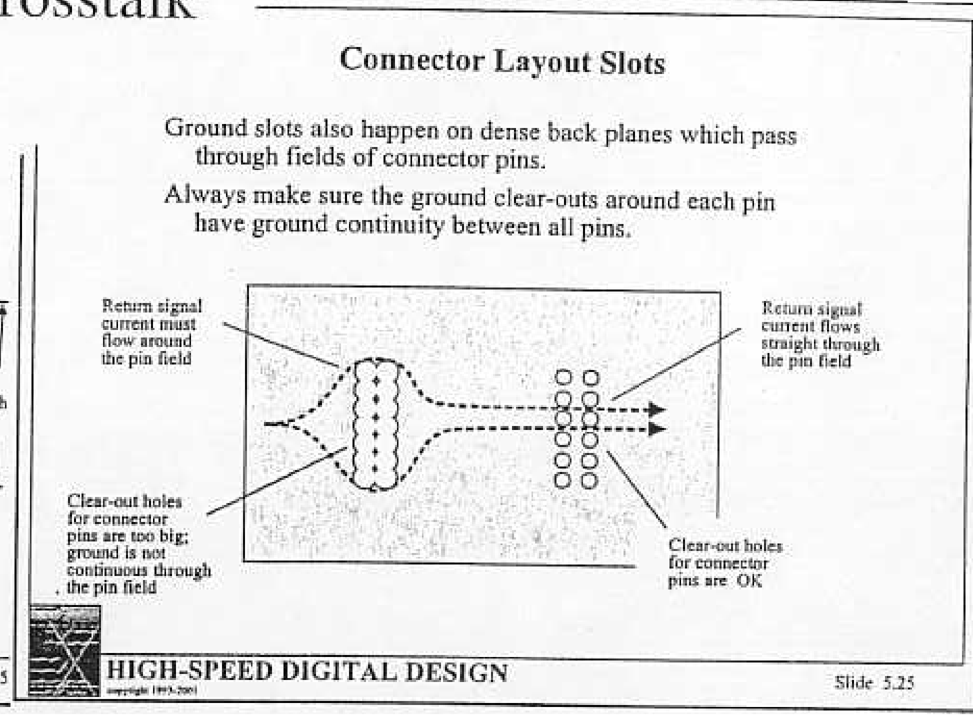
Effects of Ground Slots at High Frequencies

- Inductive effects causing concentration of current paths make the return current follow the outgoing path.

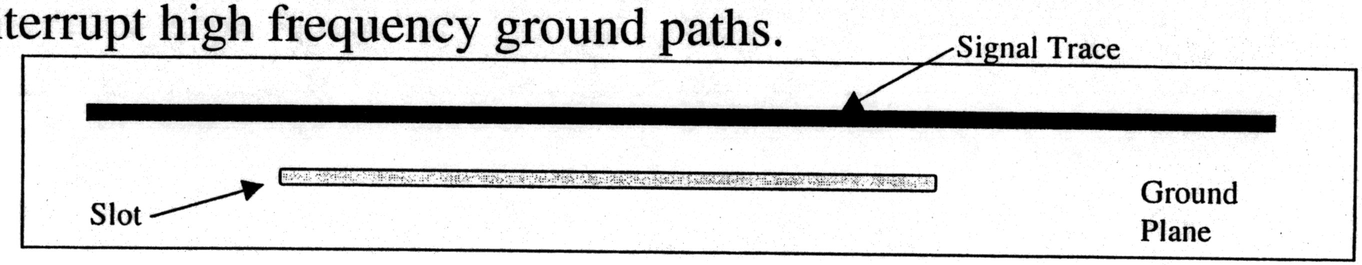


Slots in Groundplane can cause Impedance Discontinuities & Crosstalk



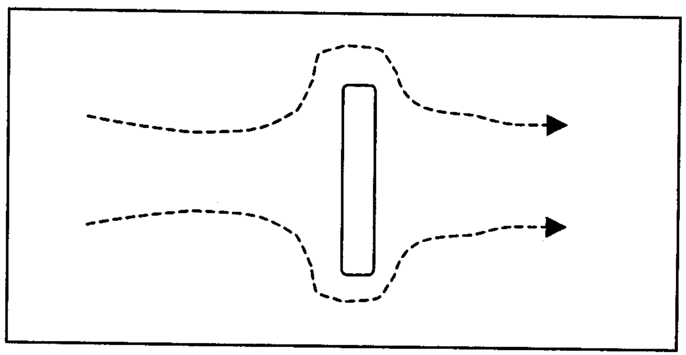


- If ground plane is to be broken or slotted, make sure slots do not interrupt high frequency ground paths.

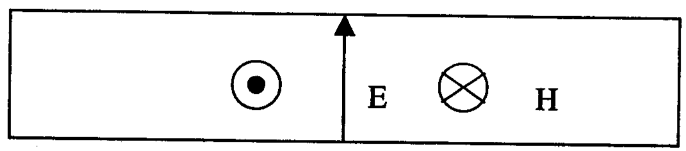


Another Effect of Slots

- A resonant slot in the plane (at high frequencies) can set up a high-Q resonant cavity
  - High electric and magnetic fields inside
  - Potent noise source for any circuit between planes



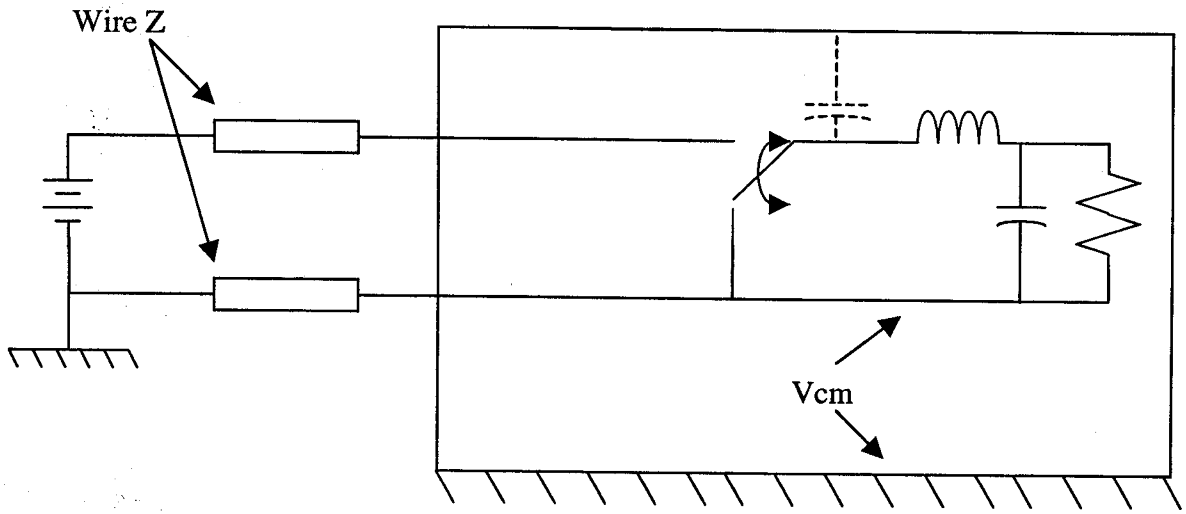
Top View



Side View

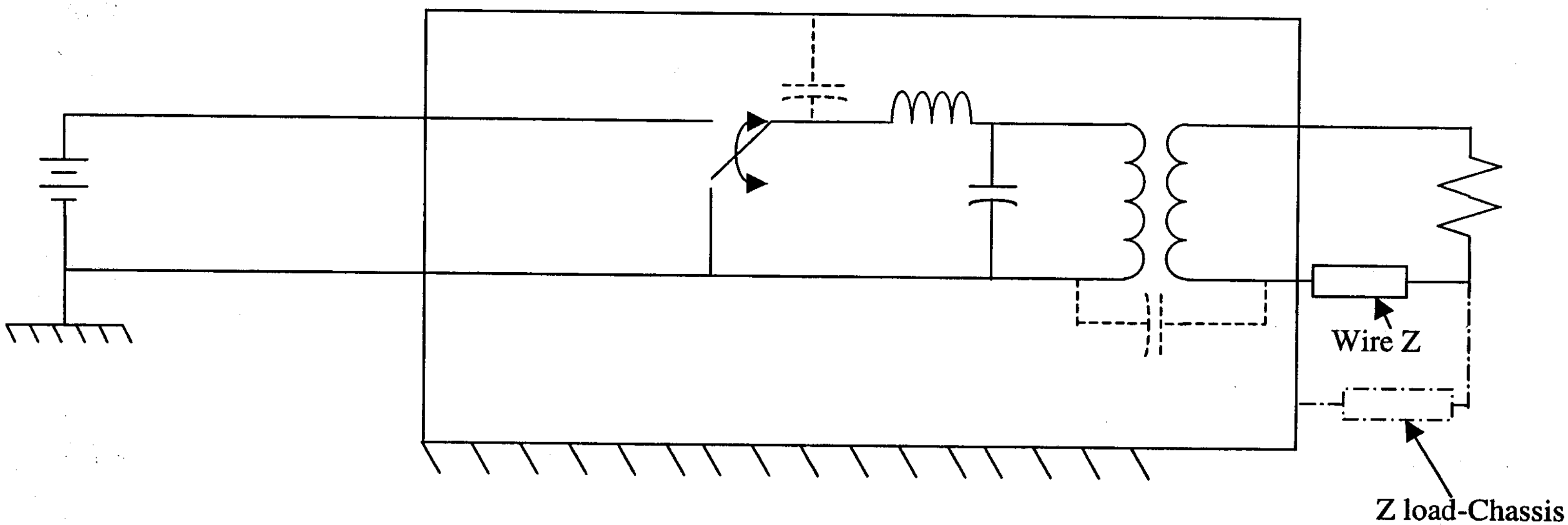
  - Only way to stop is to have ties between the planes at small intervals
    - (<=3 inches is resonant at about 300 MHz)

Generation of Common-Mode Voltages/Currents in Power Supplies



- Capacitance to Structure causes currents in input positive line when switch goes high and in input negative line (return) when switch goes low
  - Noise current in input lines causes EMI to the system and other loads
- Because these currents flow through the wiring impedance, this generates common mode voltages for the load

Transformer Isolation may not eliminate the noise applied to the load



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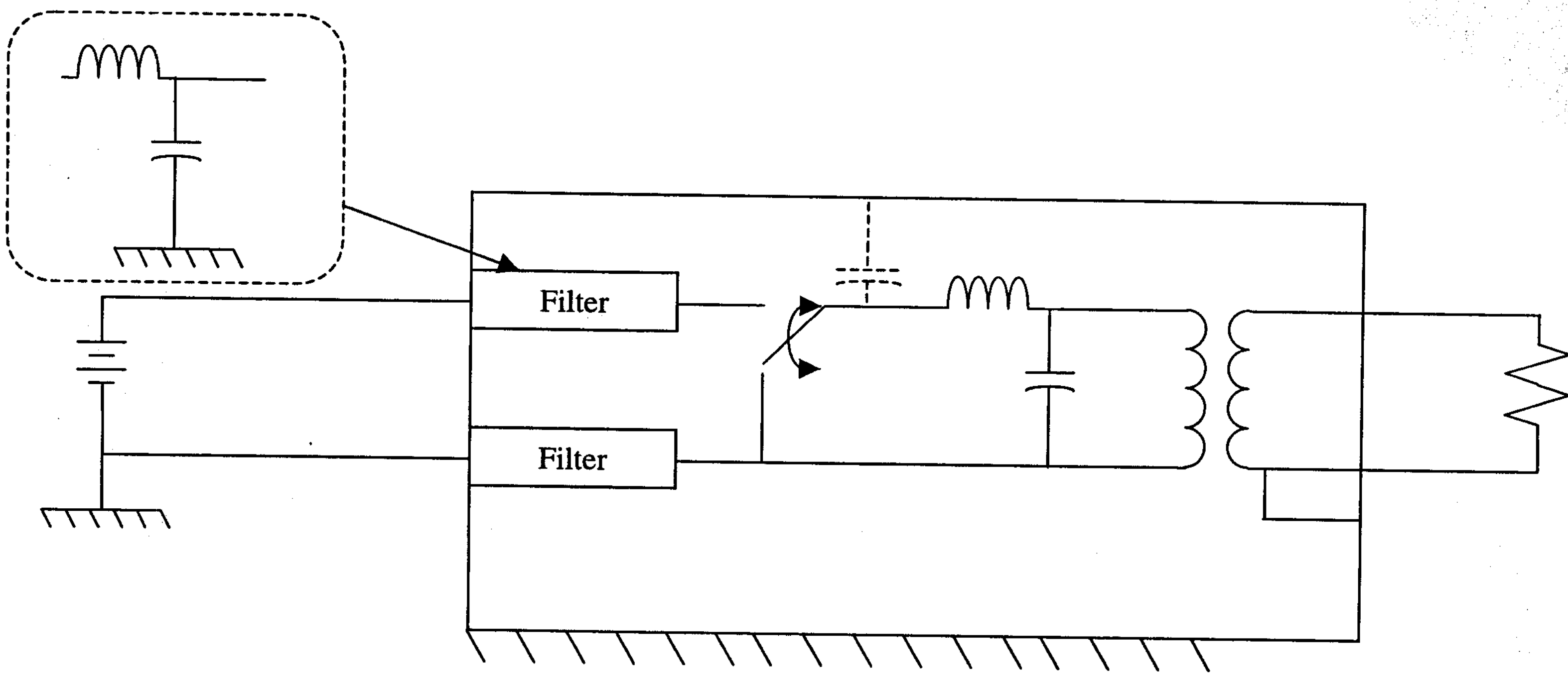
Solution for Common Mode Noise



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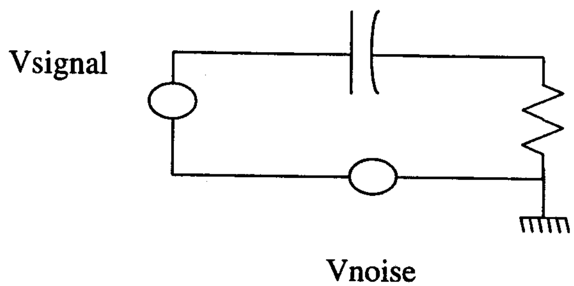
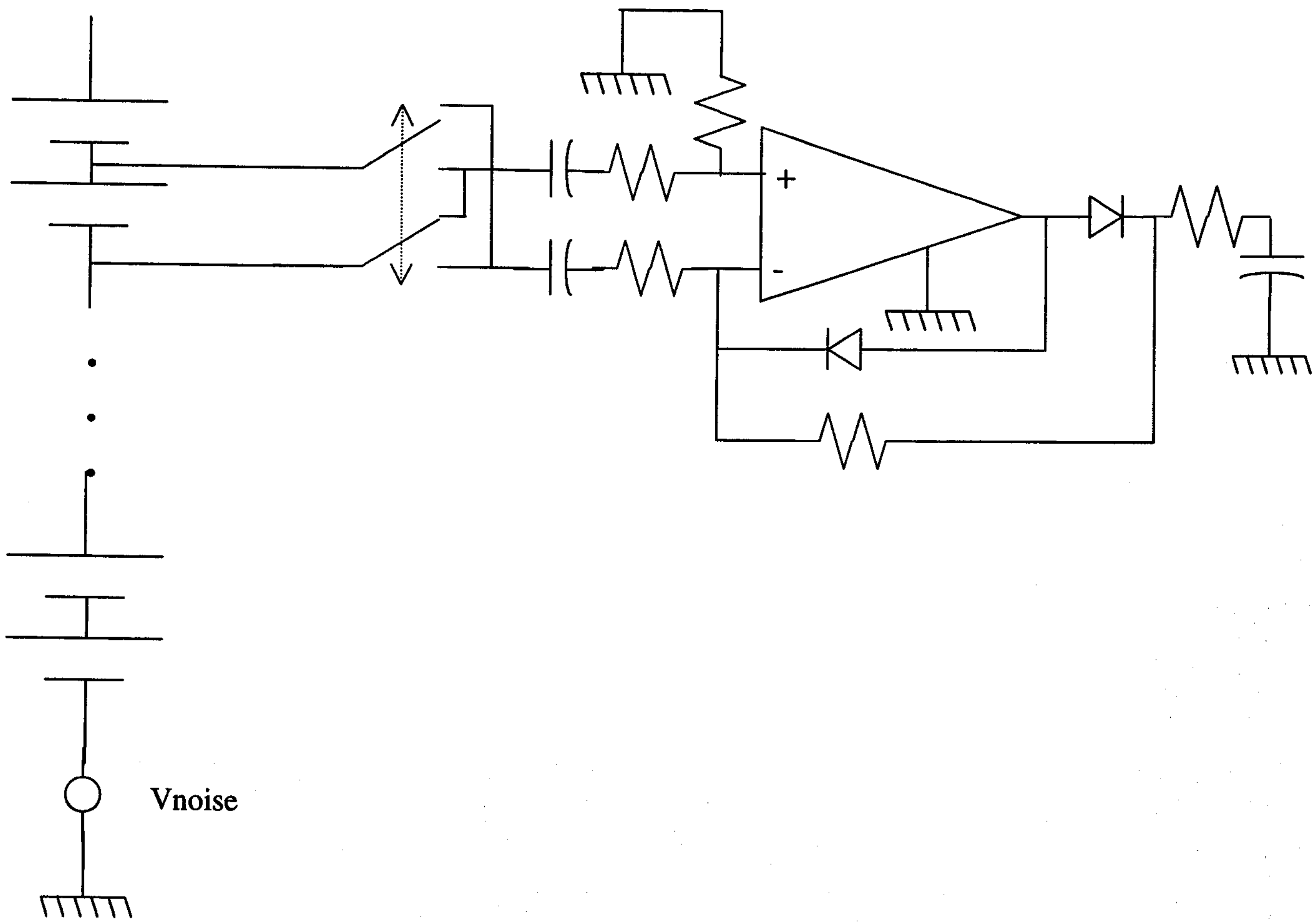
Charge-Coupled Devices Do Not Correct Grounding Problems

- Does capacitive coupling in a circuit eliminate ground voltage difference concerns?



- Only works for low frequency noise voltages
  - (Measured noise dependent upon how far below the cutoff frequency of the circuit the noise frequency is)

Charge-Coupled Devices Do Not Correct Grounding Problems



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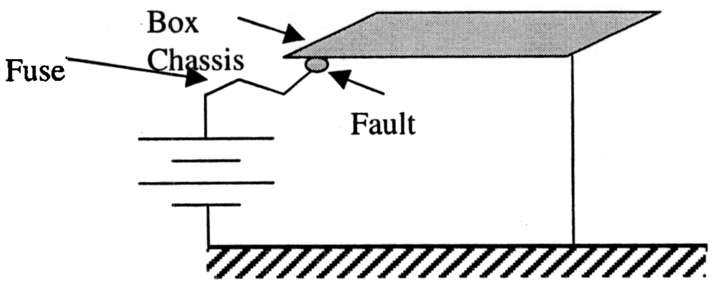
45e

GROUNDING SYSTEM FAULT PROVISIONS

- Faults to box structure require the structure path to be capable of large currents
  - Efficient power distribution requires low resistances in cabling to boxes (typically 2% of voltage dropped at maximum box load and minimum bus voltage--0.5 VDC for 28 volt systems, 1/2 of that in plus lead)

  (Translation--Max. fault can be big, up to 500 Amp for 250W, 30V load!)
  - Fault protectors typically sized for 2-3 times maximum current (they only clear the fault, they don't limit the current!!)
    - Typical protectors blow in something like 5 seconds at 2x protector rating
    - We want the fault protector to open, not the structure path or wire



- Conductive, metallic structures usually have no problem safely passing fault currents
- Composite structures often have difficulty passing fault currents.--may need supplemental fault current wire grid.

WIRE RATINGS FOR FAULT GROUND PROVISIONS

- Approximate Fusing Currents of Copper Wire:

	DIA. (IN.)	RESISTANCE (milli-ohms/ft)	FUSING CURRENT (AMPS)
20	0.032	10	58
16	0.05	4	117
12	0.08	1.6	235
8	0.128	0.62	472
6	0.162	0.4	668
0	0.324	0.1	1900

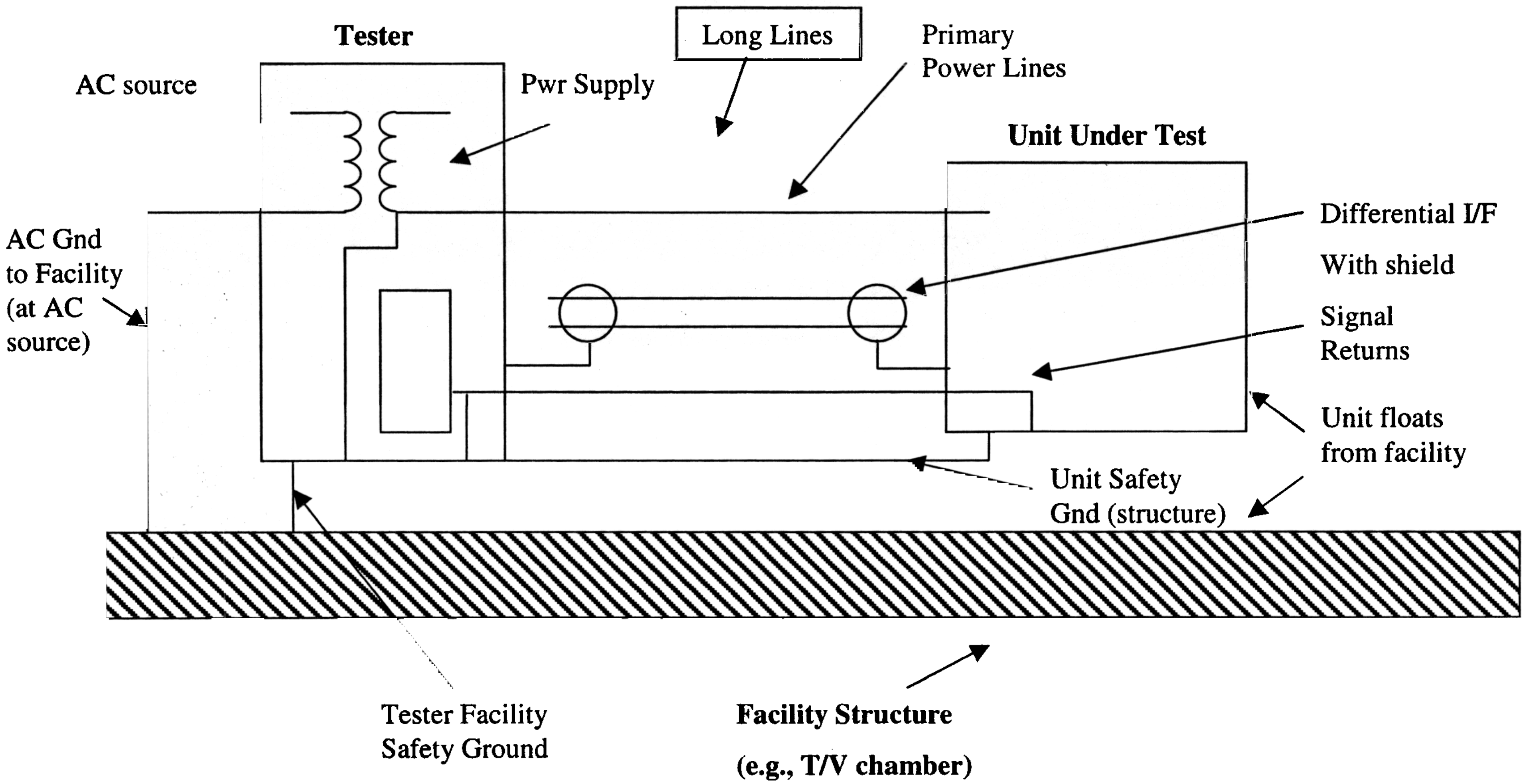
- Must also be concerned about voltage which can occur along structure path at high fault currents

  A large fault current through the structure can create a voltage between source box and load box that exceeds the voltage capability of the devices on the load interfaces

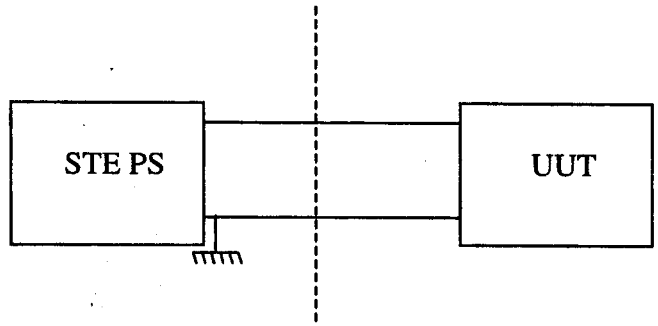
  - Differential devices help (because of CMRR)
  - Must be careful or voltage can exceed device absolute maximum damage ratings

How to Configure Testing Systems

- Ground paths between test consoles & units under test <u>major concerns</u>

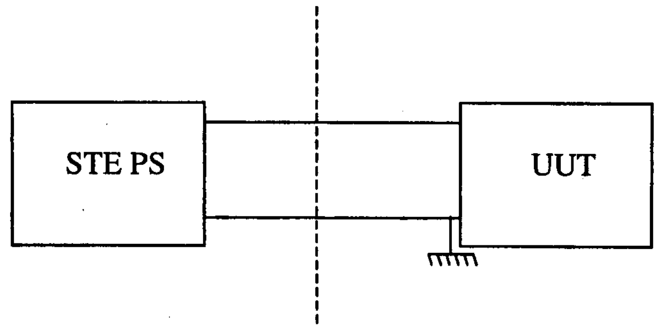


Testing Grounded EPS Boxes vs. Other Boxes



• Other Boxes-

Ground return at power source



• Grounded EPS Boxes—
Ground return at UUT, float at source

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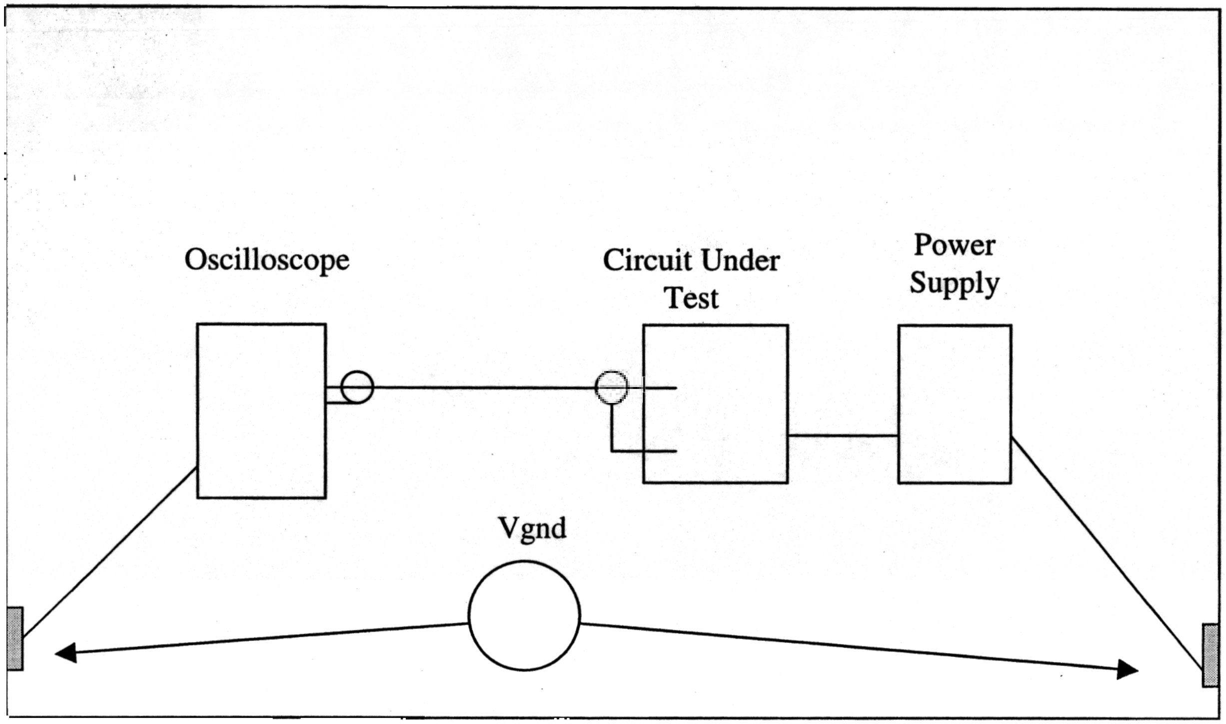
Testing Problems (AC Power System Ground Noise)



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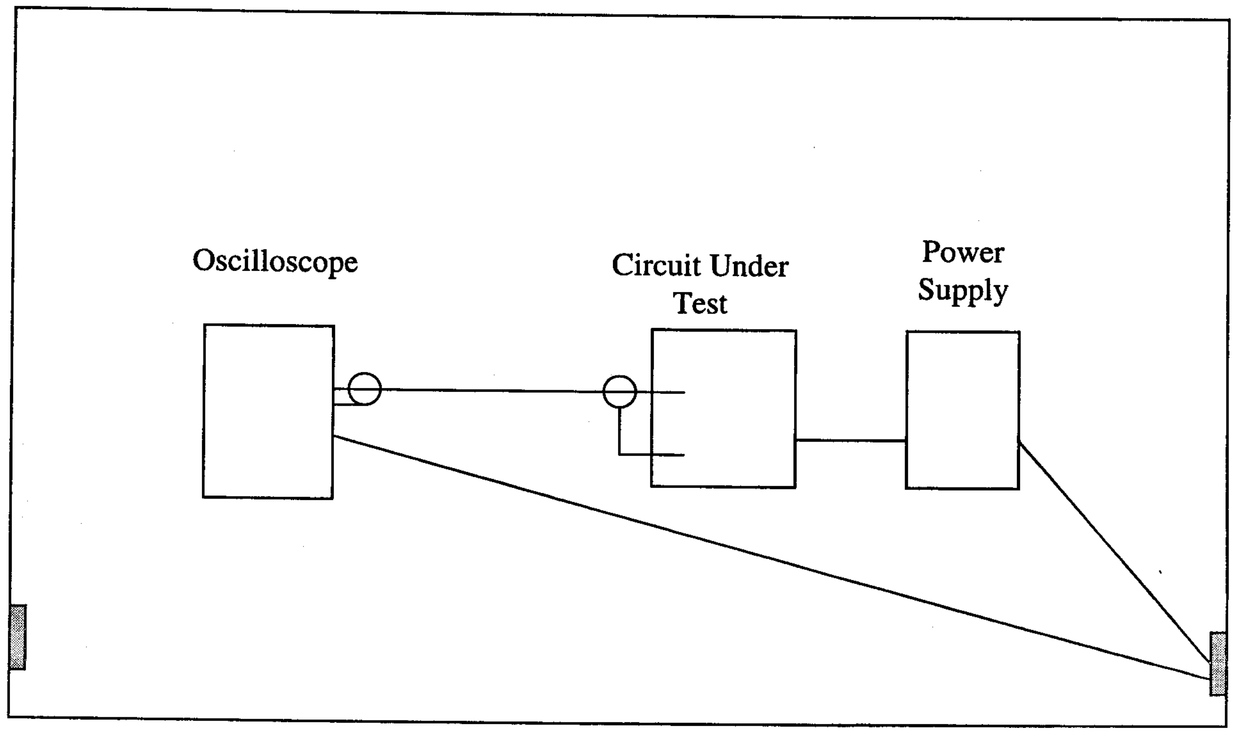
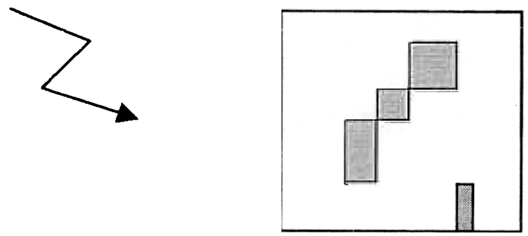
Avoiding Test Ground Noise Problems

- Could use a differential input 'scope amplifier
- Could put the 'scope on an isolation transformer (safety?)
- Here's another way:

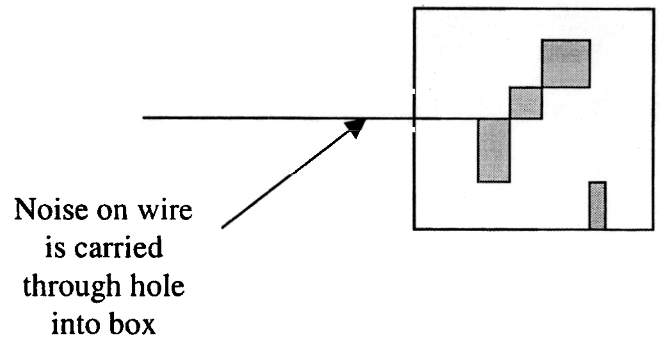


Grounds as a Shield

- A circuit totally contained within a conductive "box" is shielded from the outside world (even if things inside float from the box)

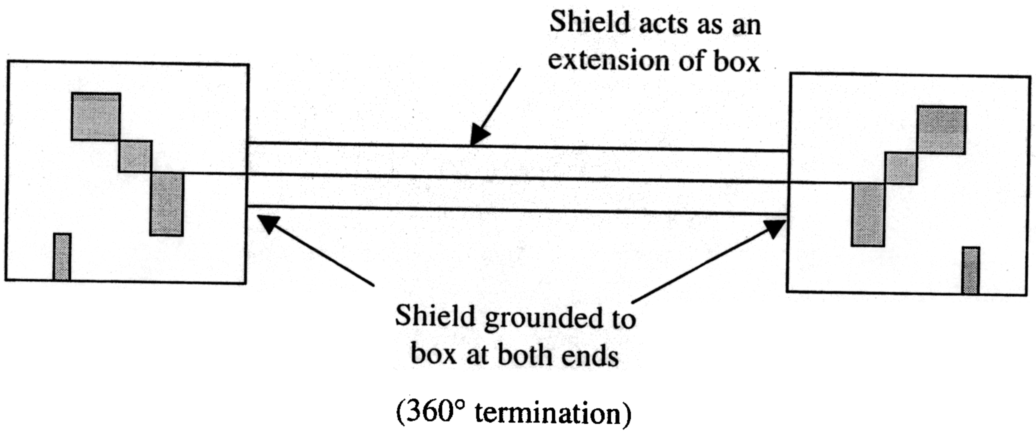


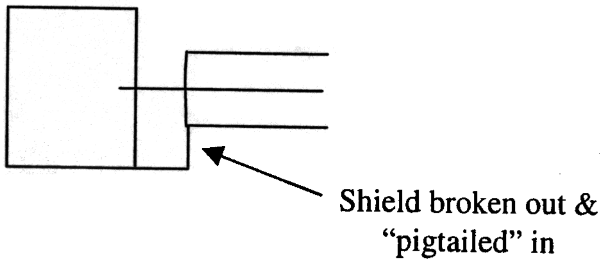
- Wires that penetrate the box degrade shielding



Wire Shields

- Adding a double end grounded shield to wires (with good peripheral terminations) extends box shielding.

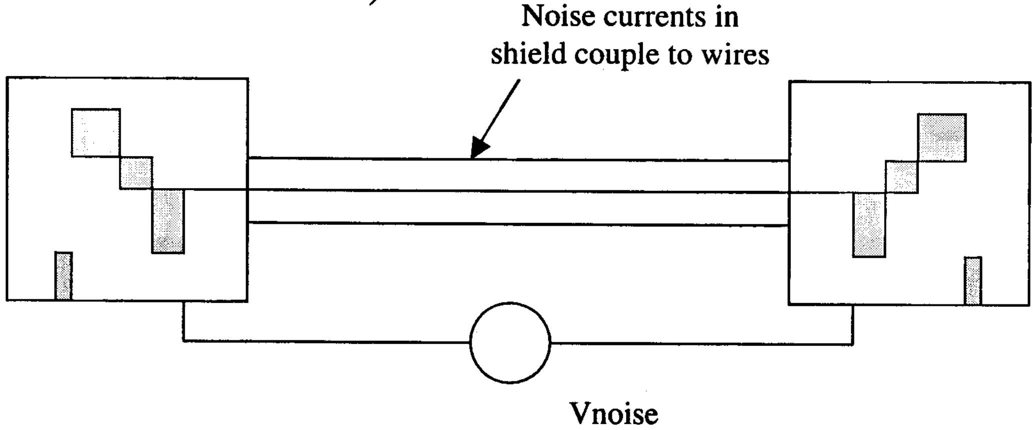




"pigtailed" shields not useful > 5 MHz

Wire Shields

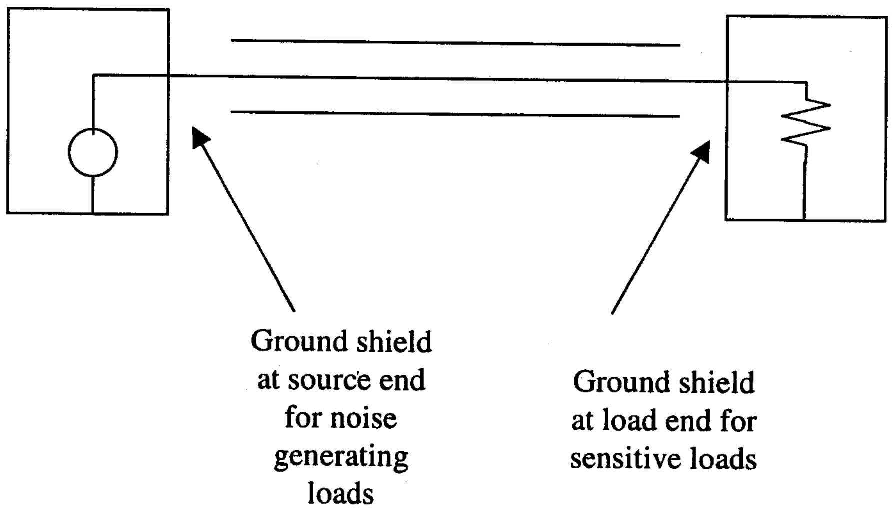
- Usually double-end grounded shields preferred (work at low and high frequencies)
- Sometimes boxes not at same low frequency potential, or low frequency contained common mode currents couple to shields (creating structure currents)



- In such cases, a single-ended shield ground <u>may</u> be preferable

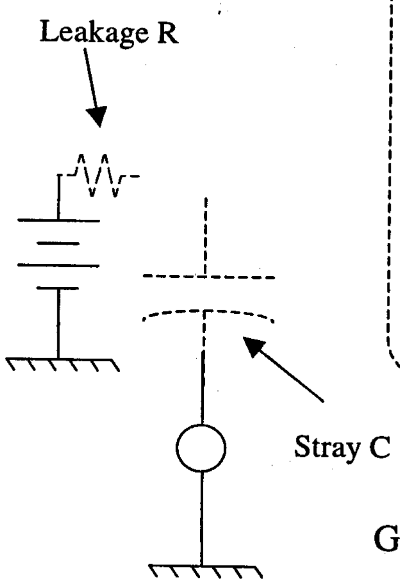
Wire Shields

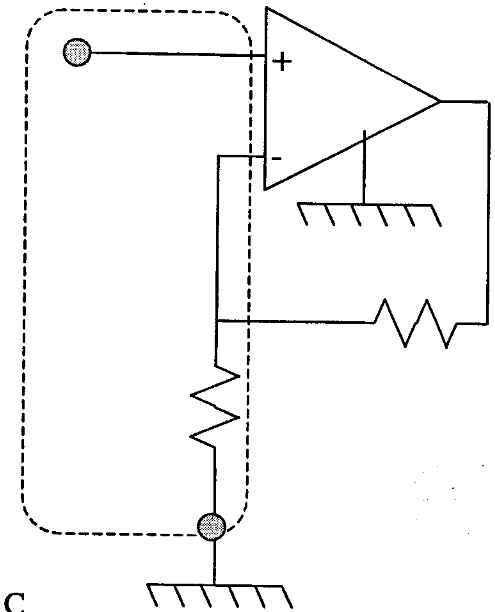
- If single end grounding of shields desirable:



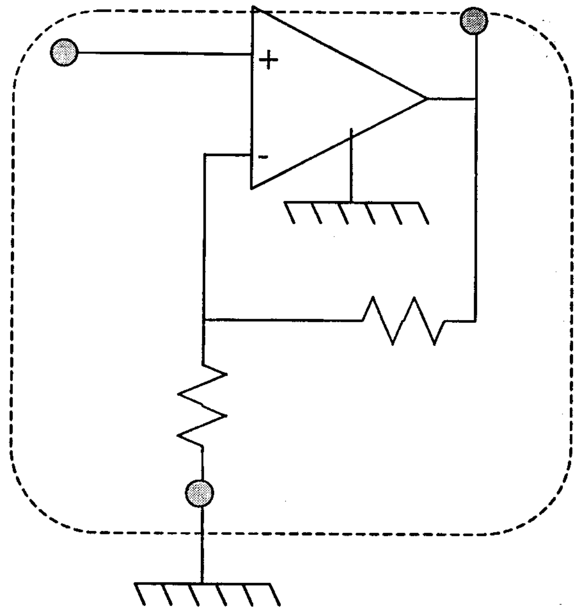
- This type of shielding will not work at high frequencies
  - May need two shields, inner single end grounded, outer double grounded

Guard Rings





Guard Ring at Ground Potential



Guard Ring not at Ground Potential

Note: Guard Rings must appear on all board layers

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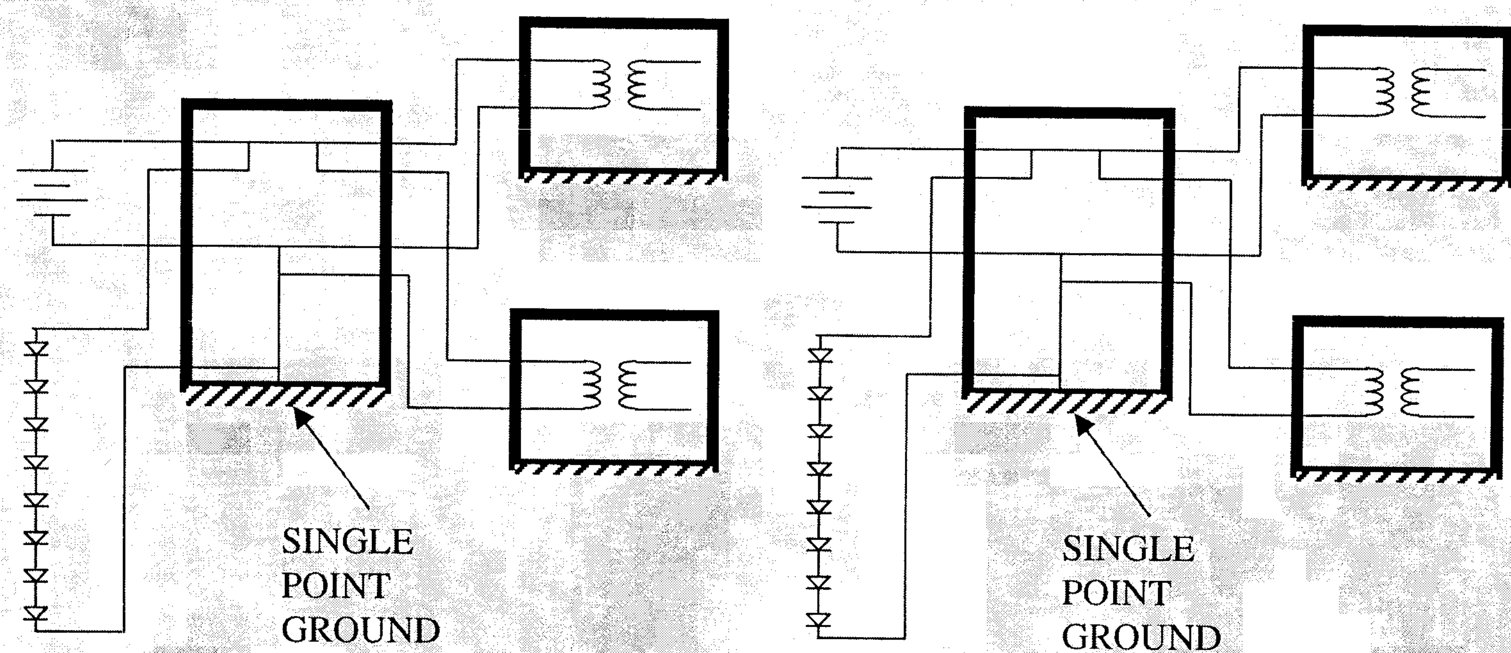
Is this a violation of Single Point Primary Power Grounding?



Overall System

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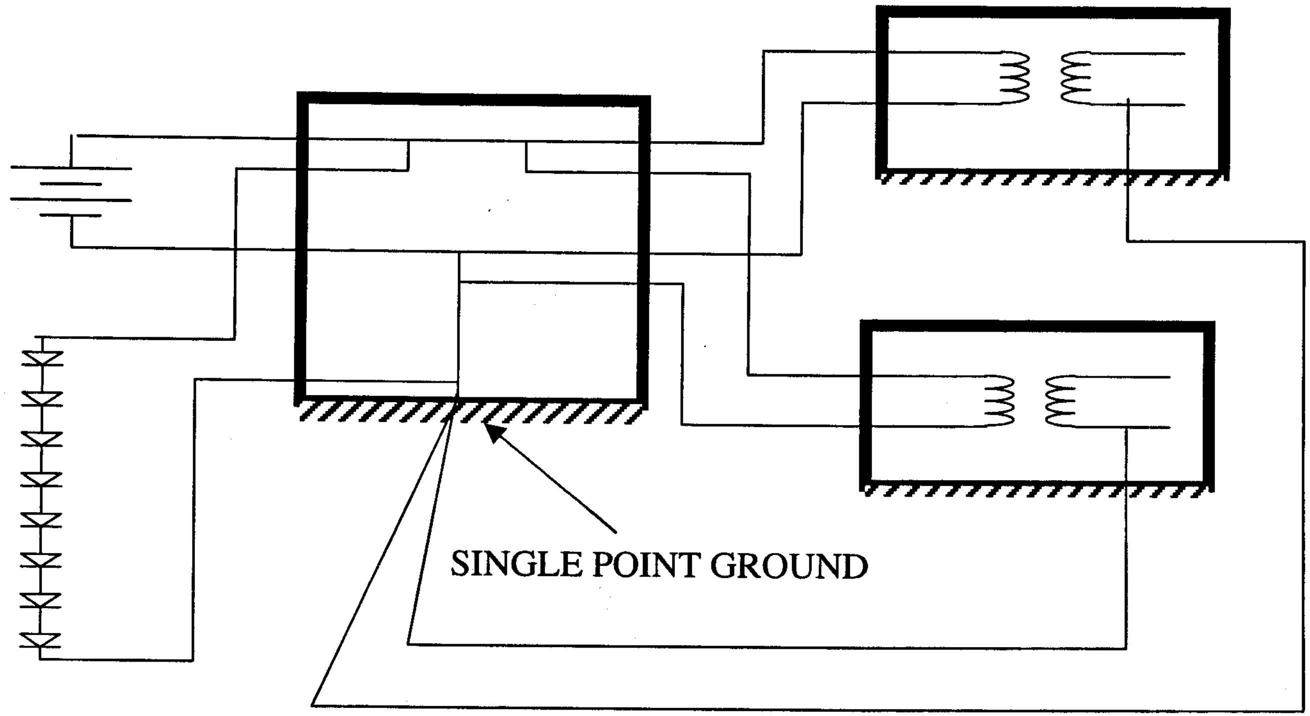
Please Don't Do This



52c

10/22/02 wgi