Fundamentals of Electromagnetics

Grounding, Bonding, & Shielding

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Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- “Grounding” in the “Real World” (and in “Real Space”)
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
- Summary

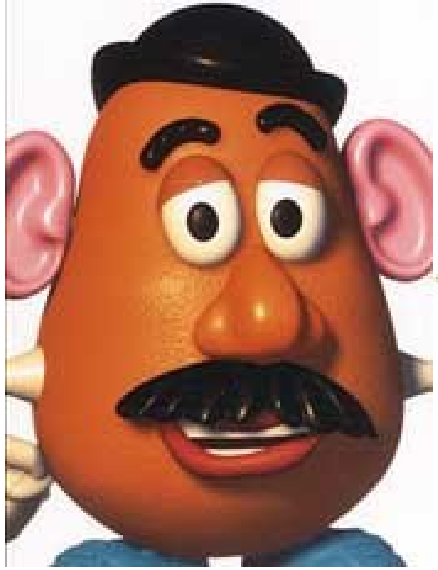
The Ground Mystery - Words of Wisdom

"The search for a 'good ground' is very similar to the search for the Holy Grail in many respects – tales abound about its existence and we all say we want and need it, but we cannot seem to find it."

- Warren H. Lewis

"Ground is a place where potatoes and carrots thrive."

- Dr. Bruce Archambeault

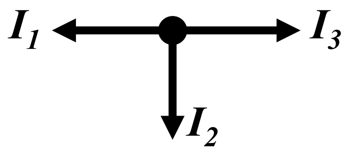


"If your grounding scheme seems overly complicated, it probably is."

- J. McCloskey

The Ground Mystery (cont.)

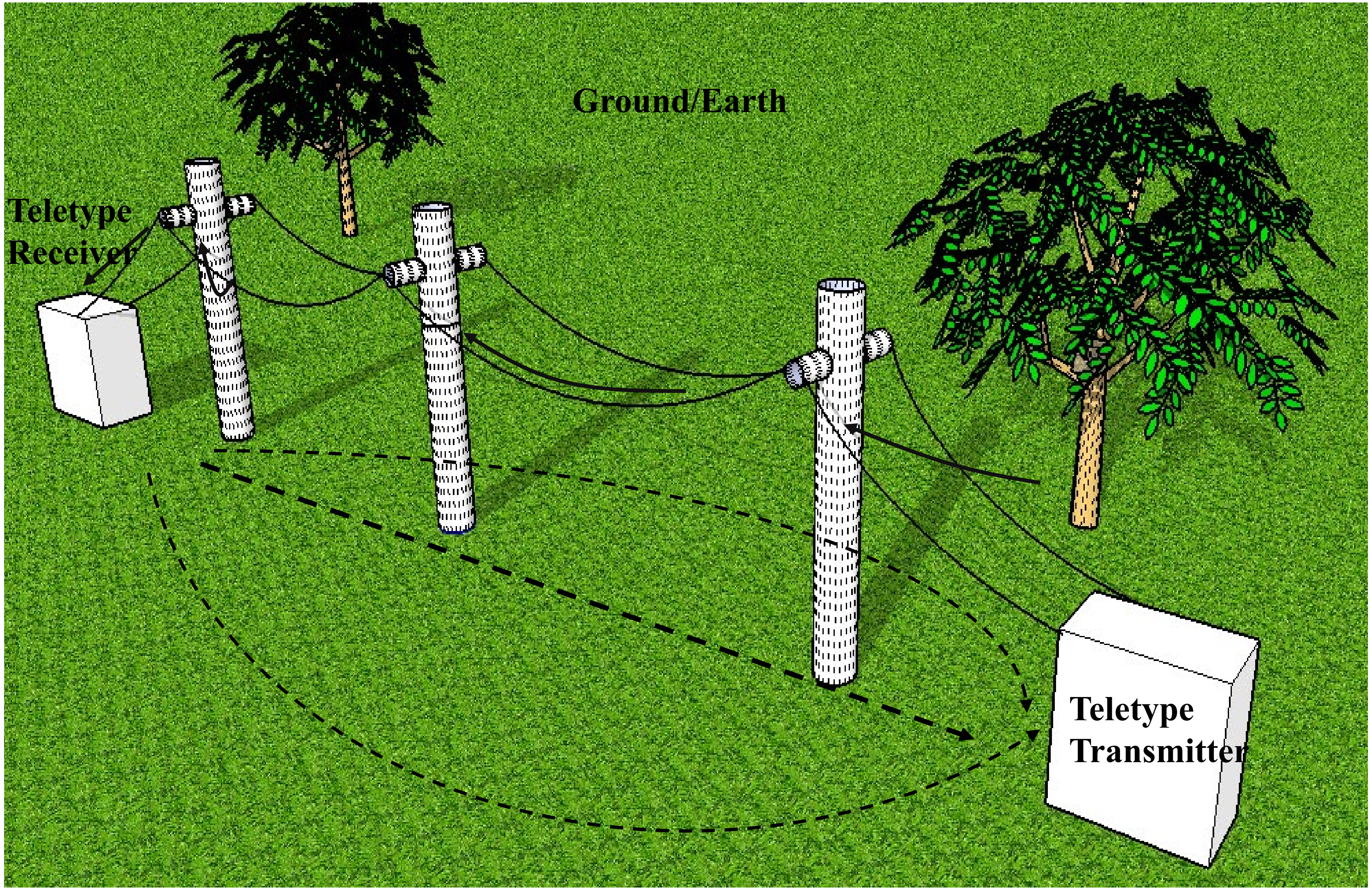
- **"Classic" definition**
  - An equipotential point, plane, or surface that serves as the reference potential for a circuit or system
  - Impossible to achieve in practice
- **More useful definition**
  - Low impedance path for currents to return to their respective sources
  - Kirchoff's current law: All currents return to their sources
    - **Current follows ALL AVAILABLE PATHS**
    - **...in inverse proportion to relative impedances**
    - **NOT ALWAYS PATH OF LEAST RESISTANCE**



$$\Sigma I_n = 0$$

- **Currents do NOT return to "ground"**
  - They may use "ground" as one of many return paths to source, depending on relative impedances

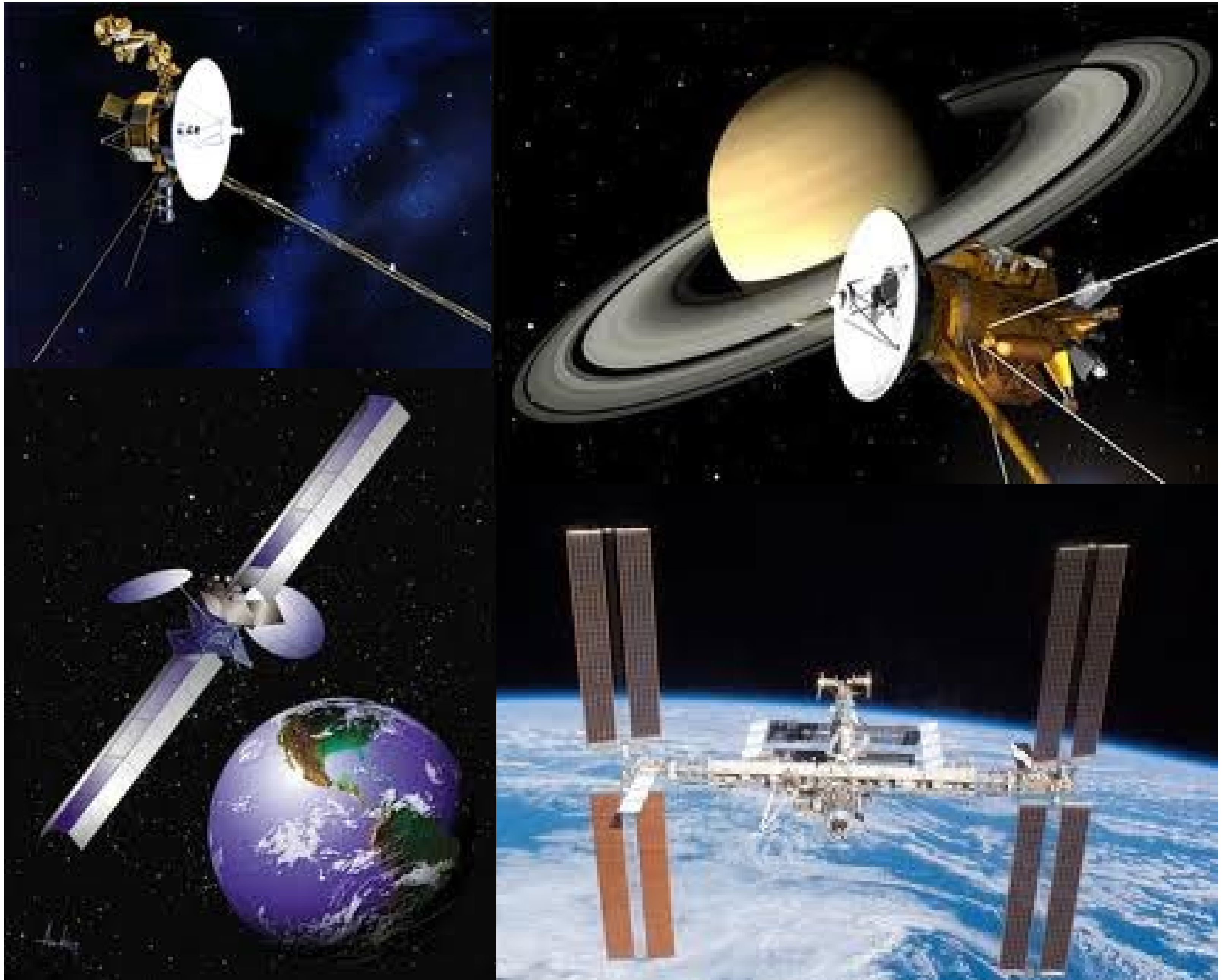
Origin of the Term “GROUND”



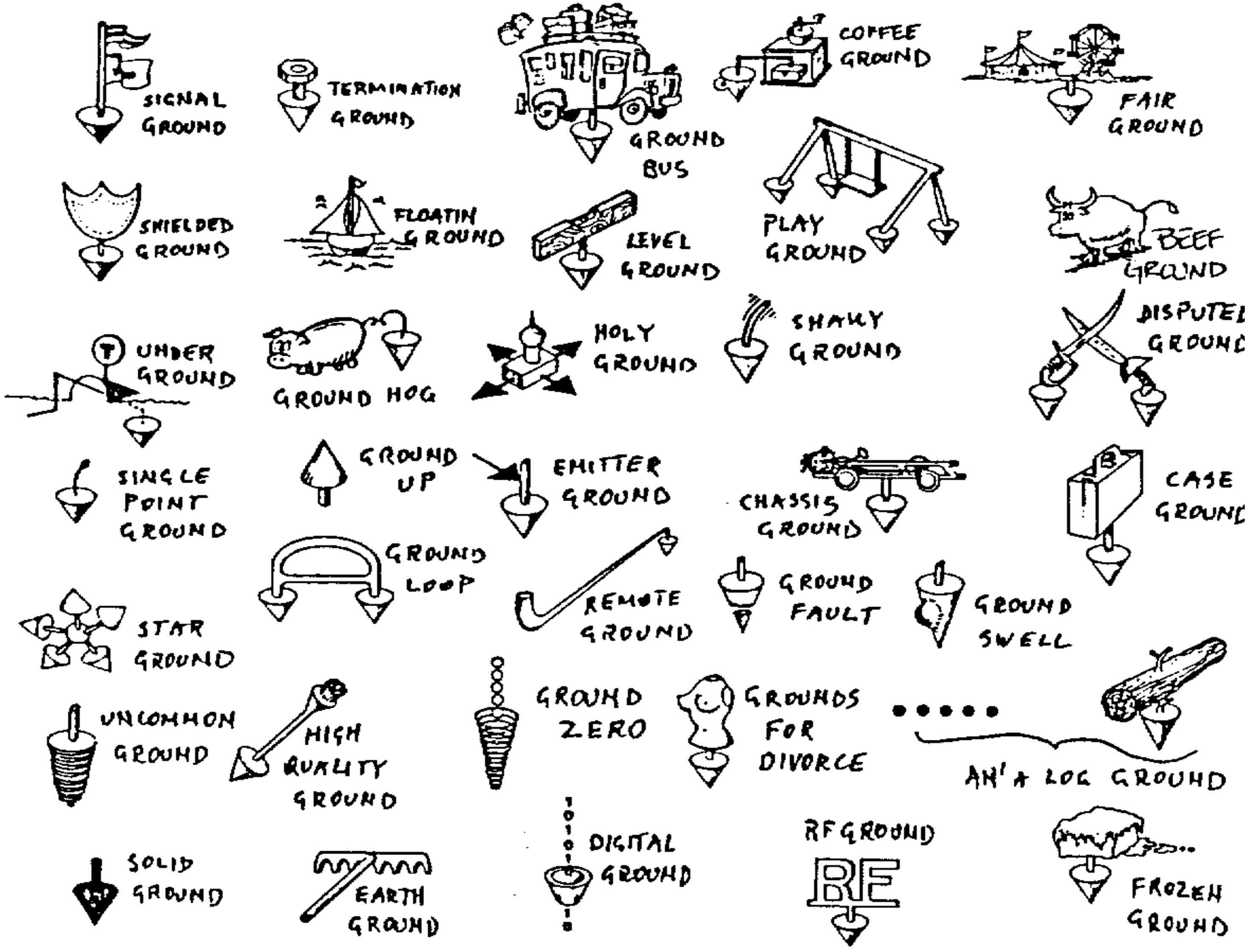
EARTH USED AS CURRENT RETURN PATH

Courtesy of Dr. Bruce Archambeault

“Ground” in Space?



Types of "Grounds"



Courtesy of Dr. Bruce Archambeault

Topics

- Introduction
- **Reasons for "Grounding"**
  - Safety
  - Lightning protection
  - Electrostatic Discharge (ESD) mitigation
  - Common reference potential
  - Current return path
- Ground Bounce
- "Grounding" in the "Real World" (and in "Real Space")
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
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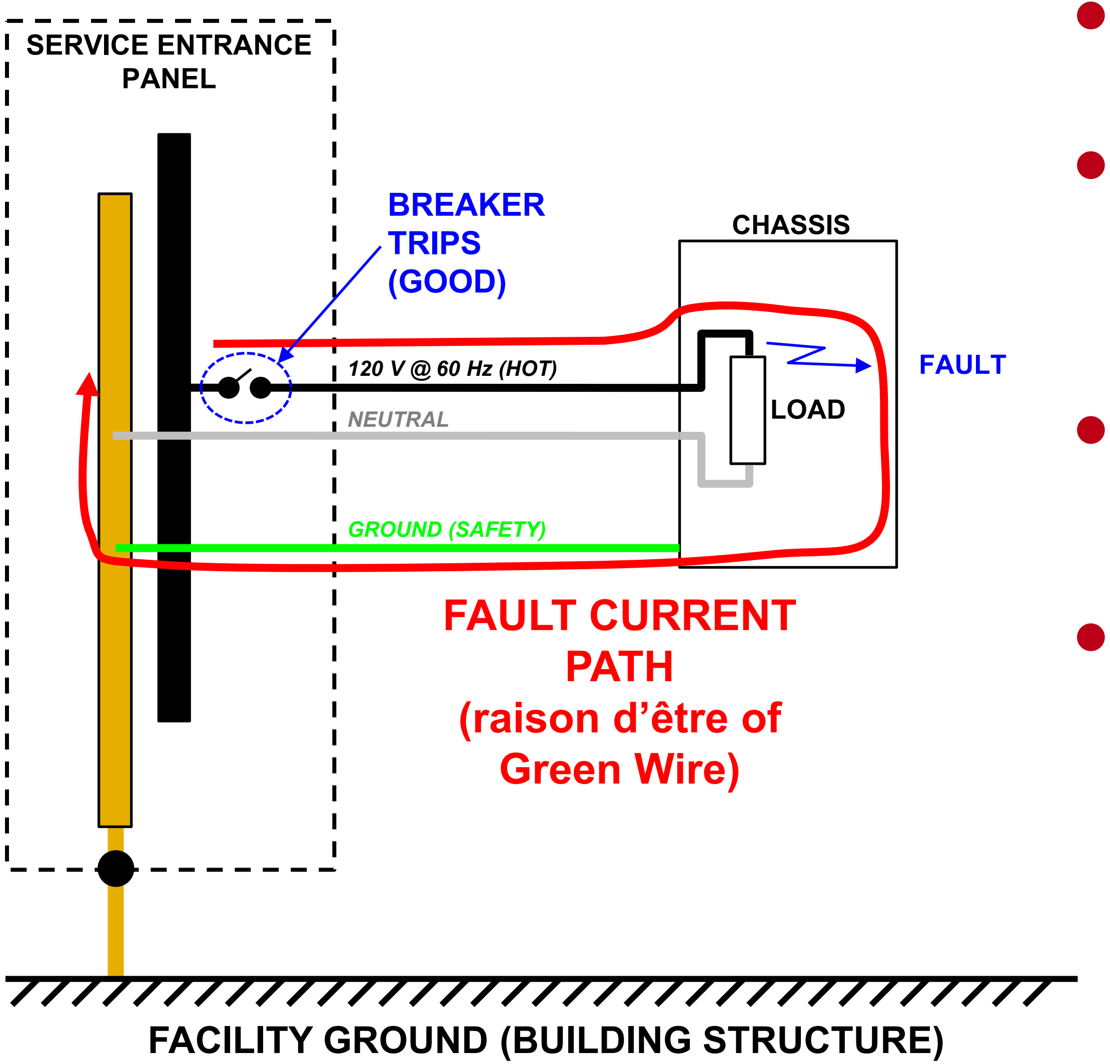
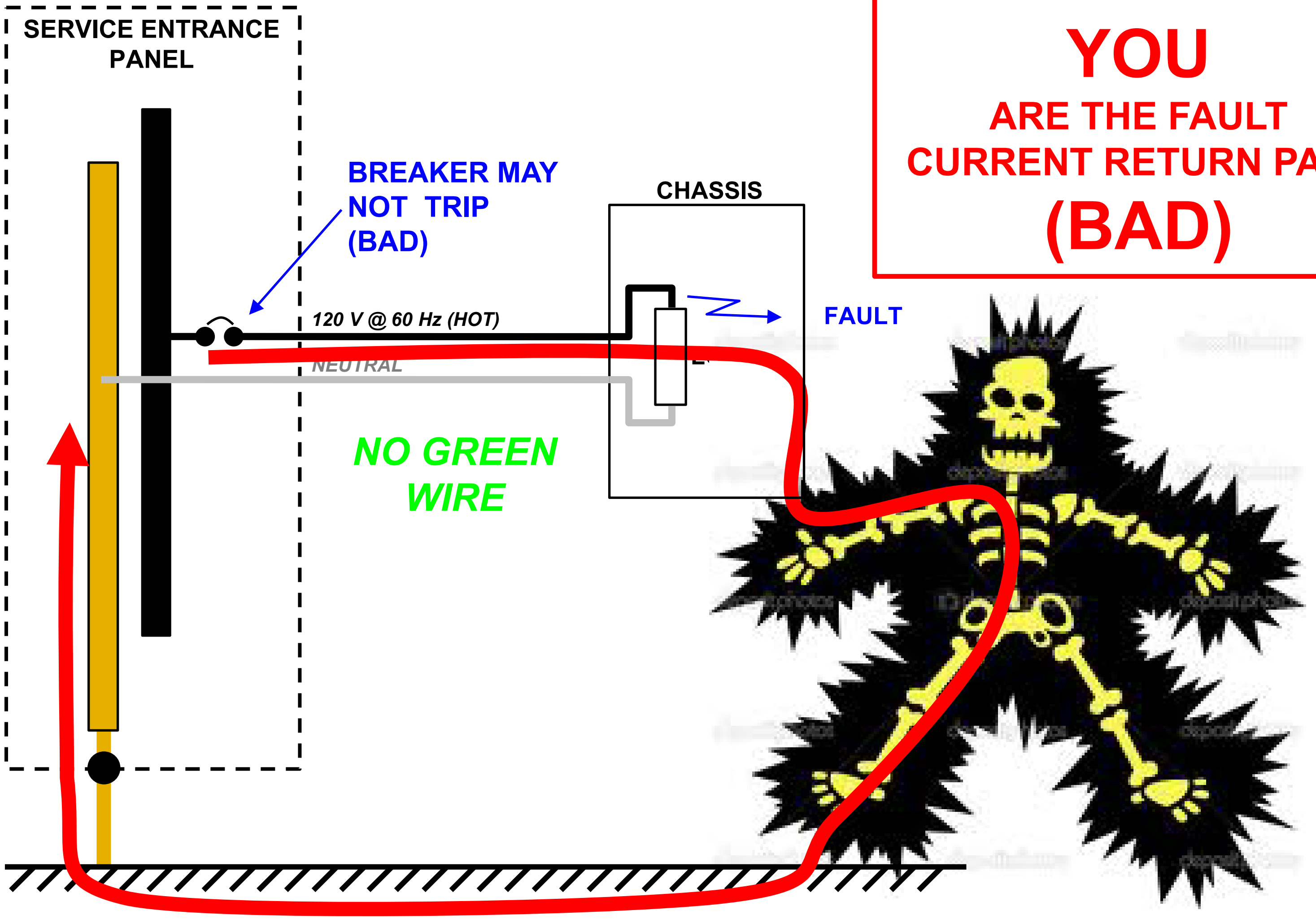
Safety Ground – Facility Power (Green Wire)



- Provides low impedance path for fault currents back to source
- Must have sufficient current capacity for worst-case fault current and to ensure that breaker clears
- Prevents high potential from developing on chassis (shock hazard)
- **Low AWG wire (large cross-sectional area) sufficient; not intended to provide RF benefit**

Safety Ground – Facility Power (cont.)



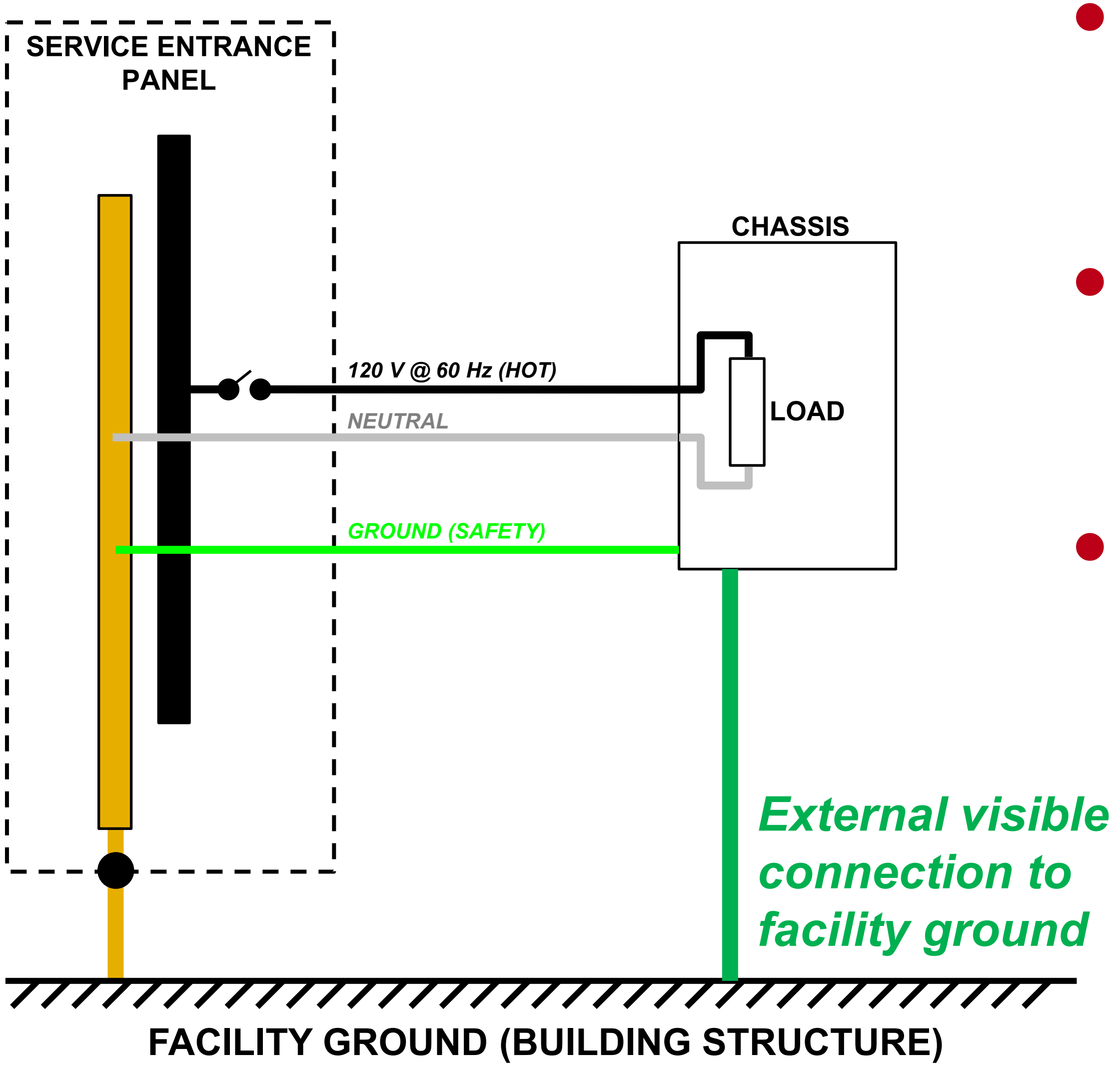
WITHOUT GREEN WIRE:

YOU

ARE THE FAULT CURRENT RETURN PATH

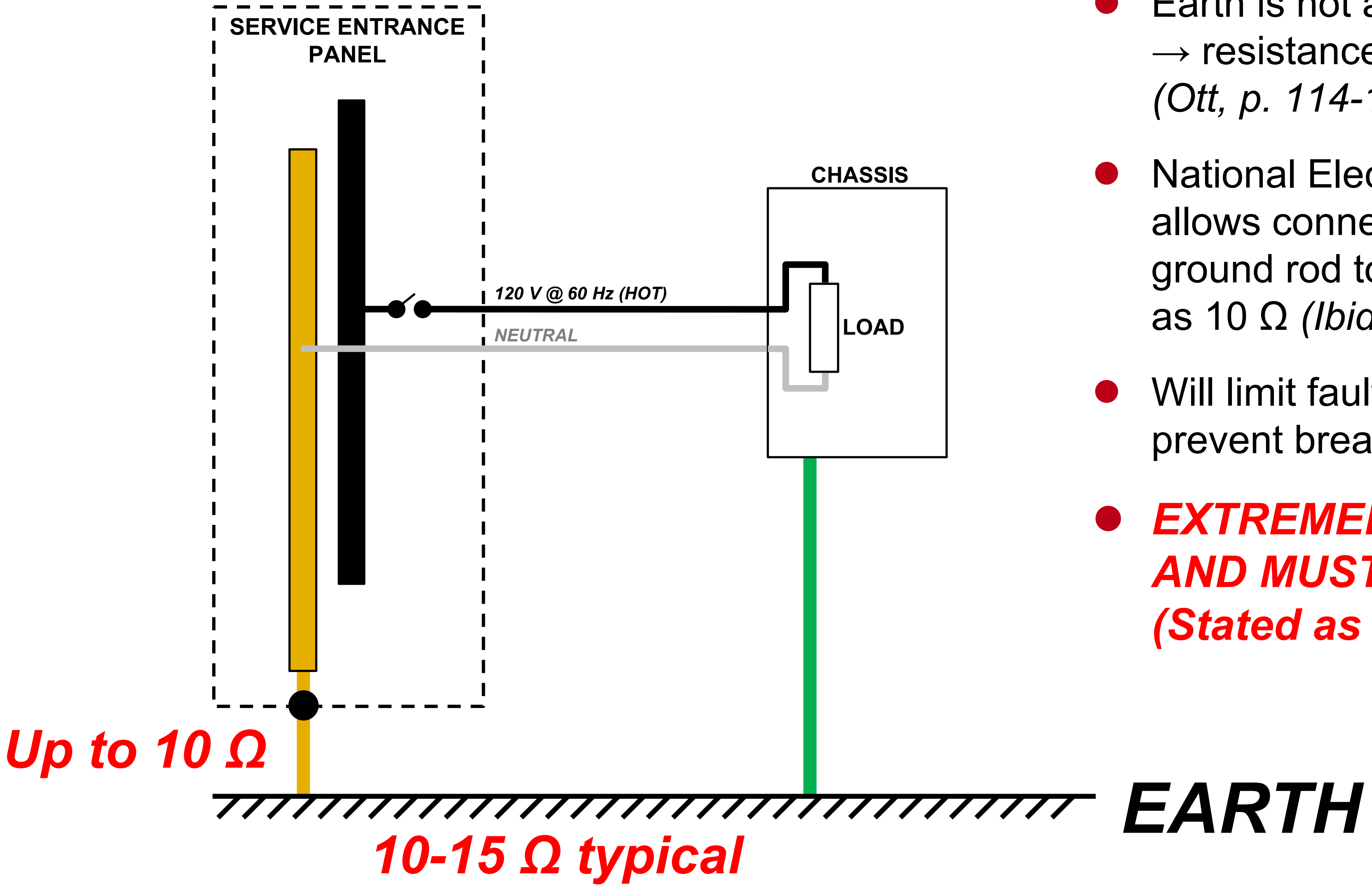
(BAD)

Safety Ground – "Belt and Suspenders" for EGSE



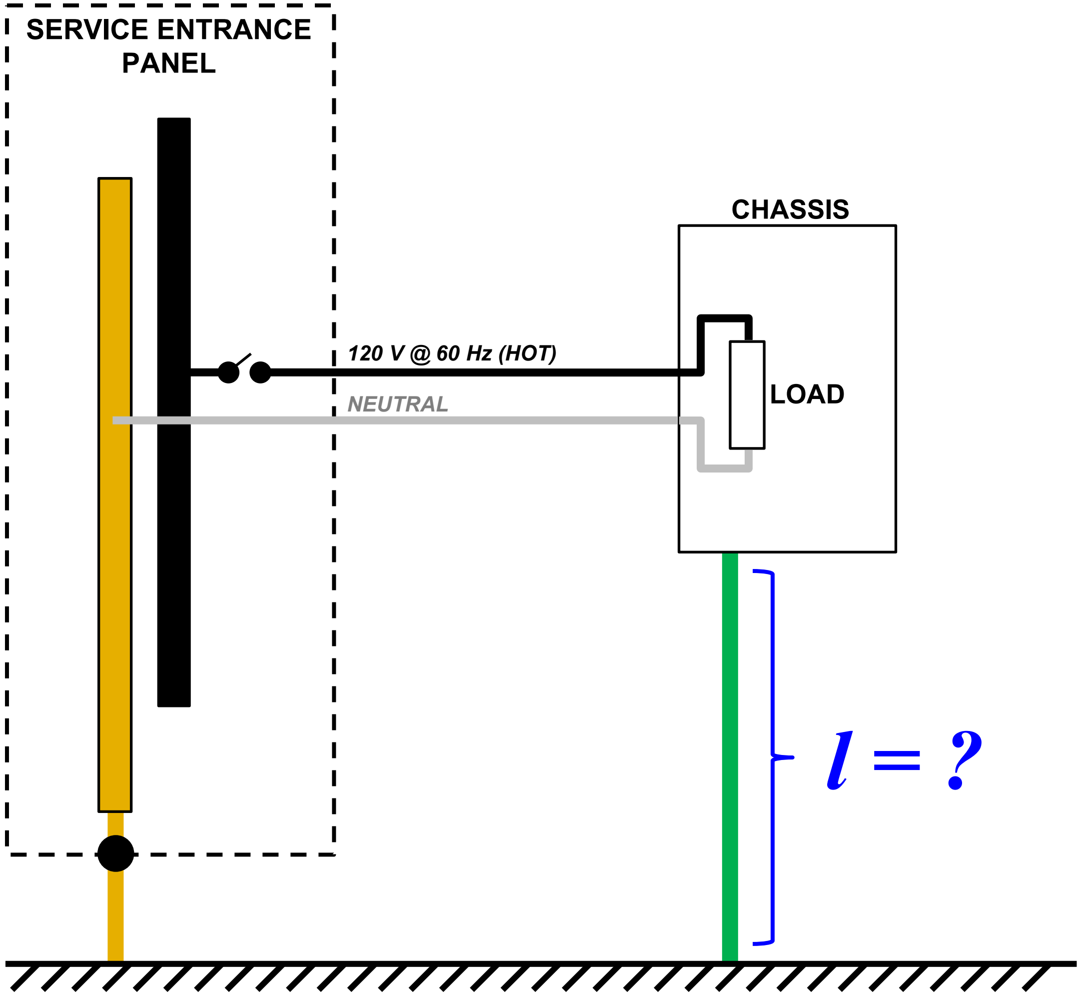
- "Green wire" in power cable provides primary path for EGSE fault currents back to facility power source
- Additional external connection from EGSE rack chassis to facility ground provides readily visible additional connection
- Redundant with green wire in power cable, but can make your pre-test safety inspections go much more smoothly...

Safety Ground – NOT "Earth"!!!



- Earth is not a very good conductor → resistance of 10-15 Ω typical *(Ott, p. 114-115)*
- National Electrical Code (NEC) allows connection from facility ground rod to earth to be as high as 10 Ω *(Ibid)*
- Will limit fault current and may prevent breaker from tripping
- ***EXTREMELY DANGEROUS AND MUST NOT BE USED (Stated as such in NEC)***

Safety Ground vs. "Quiet Ground"



"Quiet grounds" are not to be used as substitutes for fault current return paths

(especially if they include earth in the path)

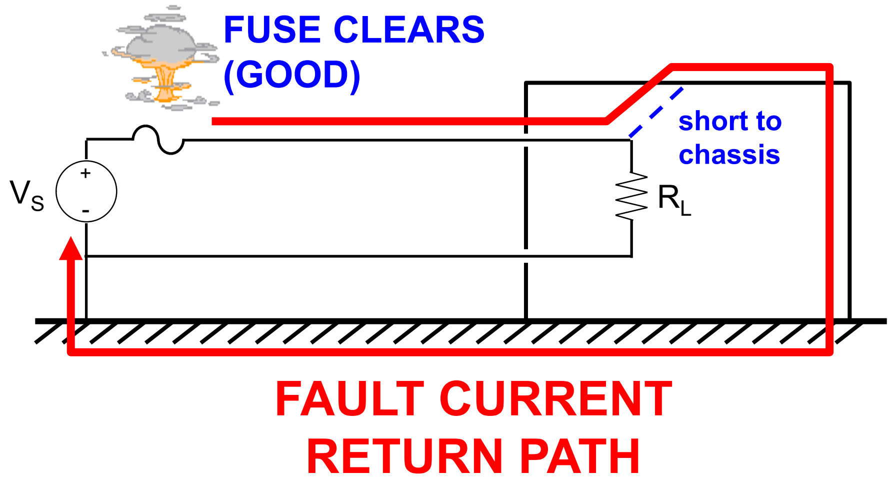
Connection to it generally has some length that eliminates any potential RF or "noise reduction" benefit

"Quiet grounds" frequently introduce more problems than they attempt to solve
(I'm not a fan)

"Quiet Ground"

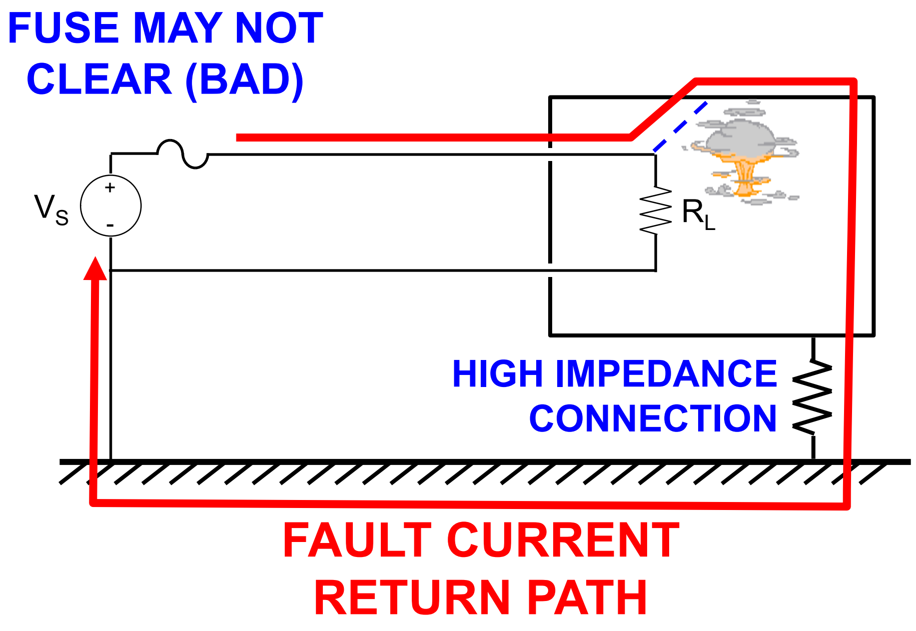
Safety Ground – Spacecraft Power (Structure)

- **On spacecraft, structure provides fault current return path**
  - Performs same function as green wire
  - May also provide RF benefit, but fault current return is primary criterion



Safety Ground – Spacecraft Power (Structure)

- **+28 Vdc may not be a significant shock hazard, but…**
  - A poor (high impedance) connection in fault current return path will limit fault current
  - Hardware can be damaged without blowing fuse (bad)



Safety Ground Summary

- **Safety ground connection MUST be present and verified in ALL configurations:**
  - I&T
  - Flight
  - Bench level
  - Etc.
- **NON-NEGOTIABLE!!!**
- **Purpose is to provide fault current path ONLY**
  - No RF or "noise reduction" benefit
  - Large cross-section (low AWG) wire sufficient (next slide)
- **Earth and/or "Quiet Ground" is NOT to be used as fault current path**

American Wire Gauge (AWG) Sizes and Current Ratings

https://www.engineeringtoolbox.com/wire-gauges-d_419.html

(One of many websites providing this information... search on "AWG" or "American Wire Gauge")

AWG - American Wire Gauge Current Ratings

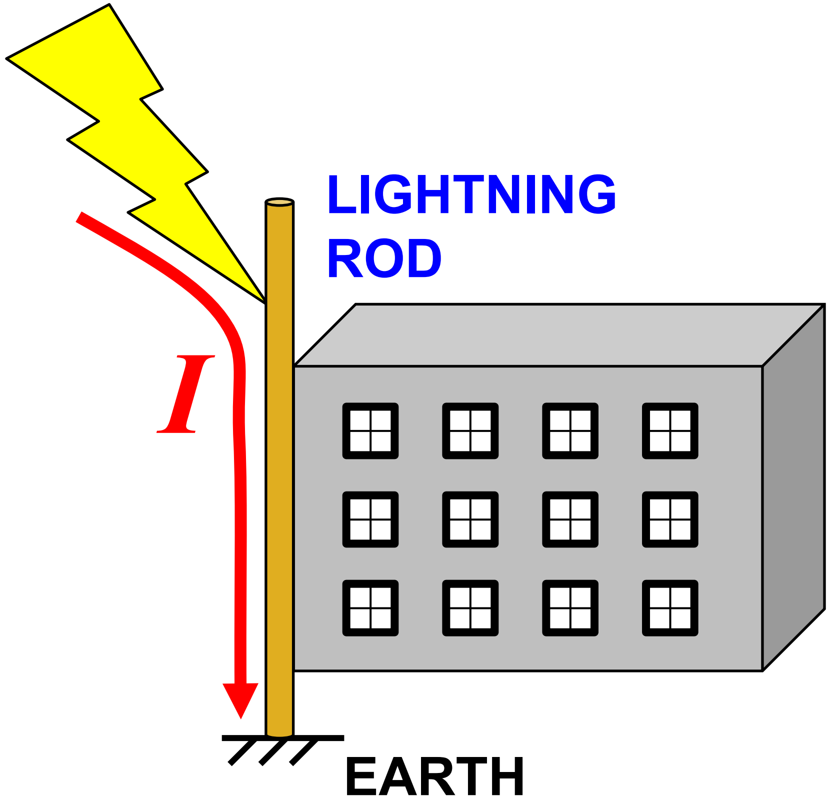
AWG	Diameter *(mm)*	Diameter *(in)*	Square *(mm²)*	Resistance Copper *(ohm/1000m)* (ohm/1000ft)	Resistance Aluminum *(ohm/1000m)* (ohm/1000ft)	Typical Max. Current Load Ratings - Copper *(amps)* 1)					
						Single Core	Multicore				
							up to 3 cores	4 - 6 cores	7 - 24 cores	25 - 42 cores	43 and above
40	0.08	.	0.0050	3448	5300						
39	0.09	.	0.0064	2693	4141						
38	0.10	0.0040	0.0078	2210	3397						
37	0.11	0.0045	0.0095	1810	2789						
36	0.13	0.0050	0.013	1326	2038						
35	0.14	0.0056	0.015	1120	1767						
34	0.16	0.0063	0.020	862	1325						
33	0.18	0.0071	0.026	663	1019						
32	0.20	0.0080	0.031	556	855						
30	0.25	0.010	0.049	352	541						
28	0.33	0.013	0.080	216	331						
27	0.36	0.014	0.096	180	276						
26	0.41	0.016	0.13	133	204						
25	0.45	0.018	0.16	108	166						
24	0.51	0.020	0.20	88	133	3.5	2	1.6	1.4	1.2	1.0
22	0.64	0.025	0.33	52	80	5.0	3	2.4	2.1	1.8	1.5
20	0.81	0.032	0.50	34	53	6.0	5	4.0	3.5	3.0	2.5
18	1.0	0.040	0.82	21	32	9.5	7	5.6	4.9	4.2	3.5
16	1.3	0.051	1.3	13	20	15	10	8.0	7.0	6.0	5.0
14	1.6	0.064	2.1	8.2	13	24	15	12	10	9.0	7.5
13	1.8	0.072	2.6	6.6	10						
12	2.1	0.081	3.3	5.2	8.0	34	20	16	14	12	10
10	2.6	0.10	5.3	3.3	5.0	52	30	24	21	18	15
8	3.3	0.13	8.3	2.1	3.2	75	40	32	28	24	20
6	4.1	0.17	13.3	1.3	2.0	95	55	44	38	33	27
4	5.2	0.20	21.2	0.81	1.3	120	70	56	49	42	35
3			26.7	0.65	0.99	154	80	64	56	48	40
2	6.5	0.26	33.6	0.51	0.79	170	95	76	66	57	57
1	7.4	0.29	42.4	0.41	0.63	180	110	88	77	66	55
0 (1/0)	8.3	0.33	53.5	0.32	0.50	200					
00 (2/0)	9.3	0.37	67.4	0.26	0.39	225					
000 (3/0)	10.4	0.41	85.0	0.20	0.32	275					
0000 (4/0)	11.7	0.46	107	0.16	0.25	325					
250			127			345					
300			152			390					
400			178			415					

Used in 15 A circuits → 14

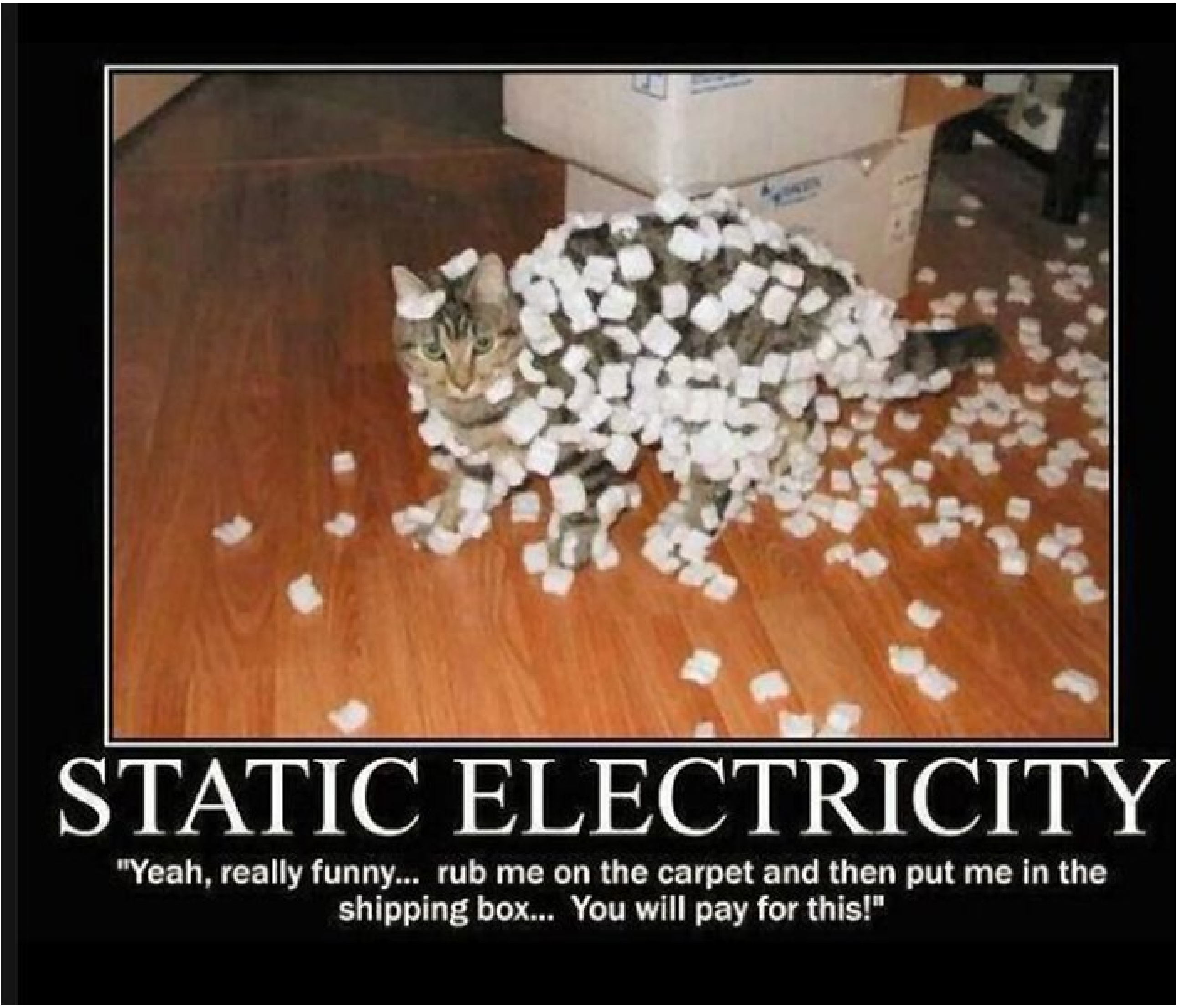
Used in 20 A circuits → 12

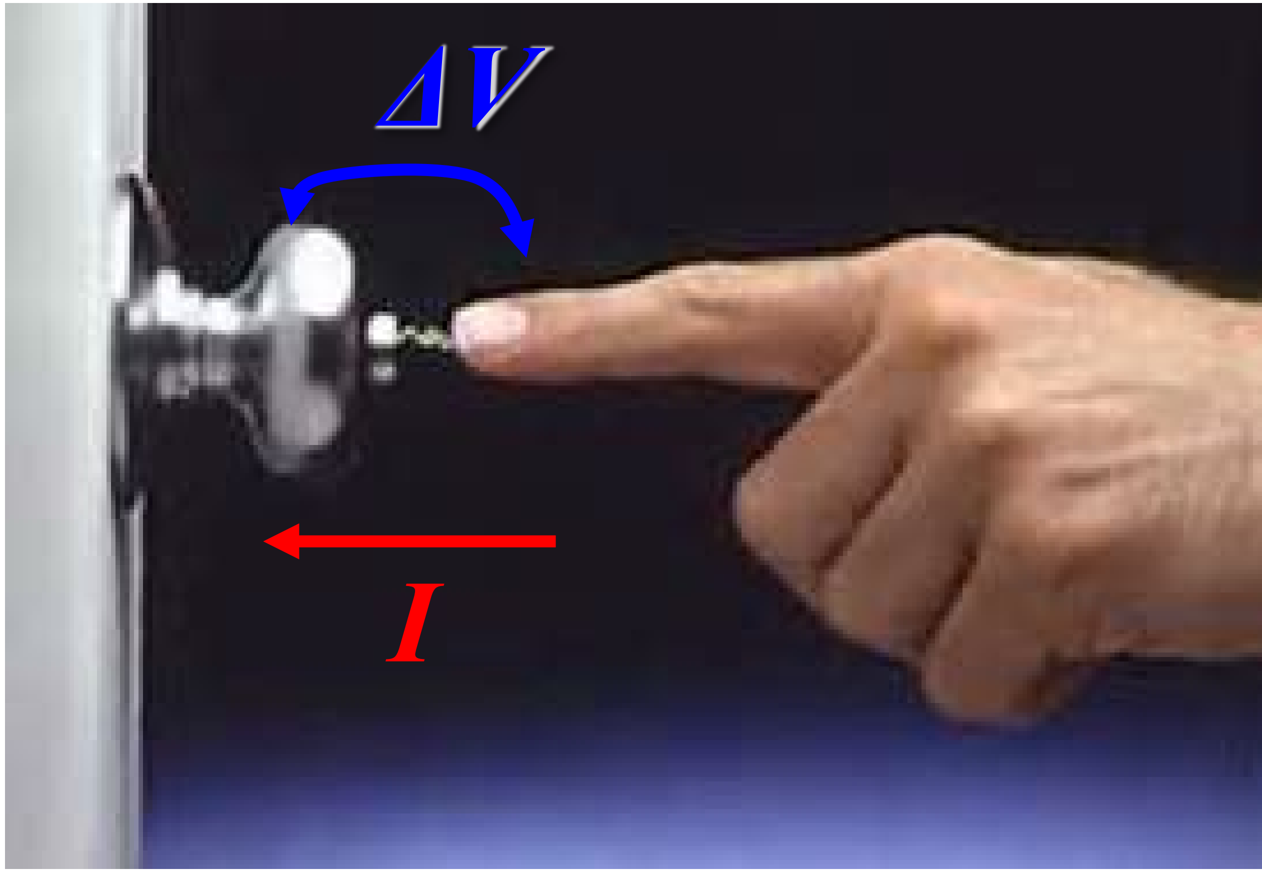
Lightning Protection

- **Lightning rod diverts discharge current to earth**
- **Keeps discharge current away from:**
  - Circuits in building
  - Flammable building parts
- **Primary reason for connection to earth**



Electrostatic Discharge (ESD) Mitigation





ESD Mitigation (cont.)

- **300-PG-8730.6.1A, GSFC Electrostatic Discharge (ESD) Control Plan**

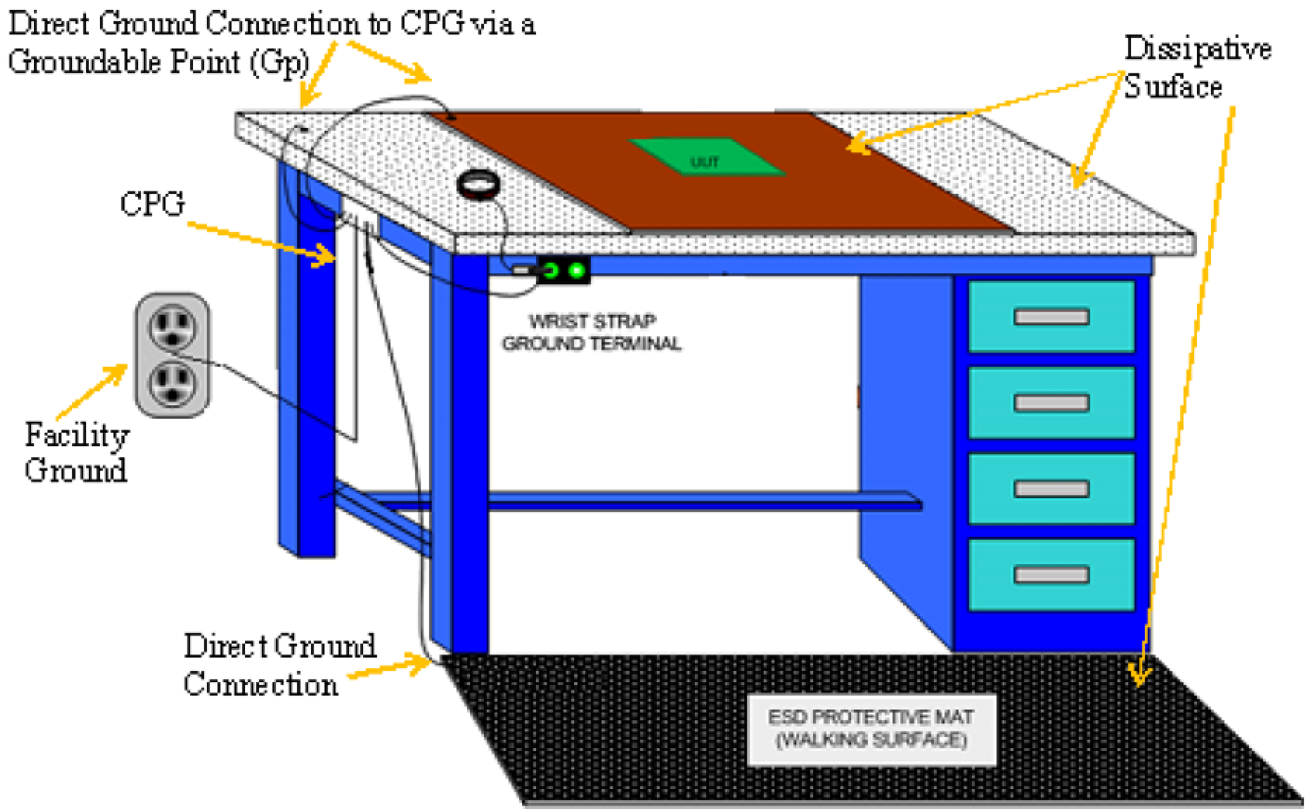
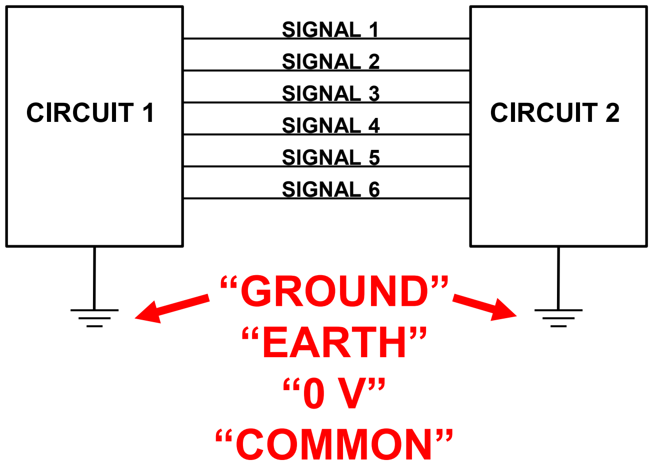


Figure 5-1: Typical ESD Grounded Workstations
(See Table 5-1 for Applicable Requirements and Definitions)

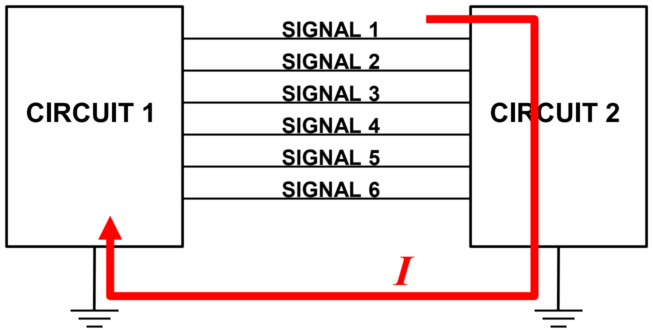
Common Reference Potential

- **Interface signals between 2 circuits need common reference potential in order to work properly**
- **Traditionally called:**
  - Ground
  - Earth
  - Zero volt reference
  - Common



Current Return Path

- **Signal and power currents must return to their respective sources (Kirchoff's Current Law)**
- **Traditionally, "ground" is default return path**
- **Aircraft and automobiles use structure as return path for power feeds**
  - Fewer wires
  - Less mass, less $$$, etc.



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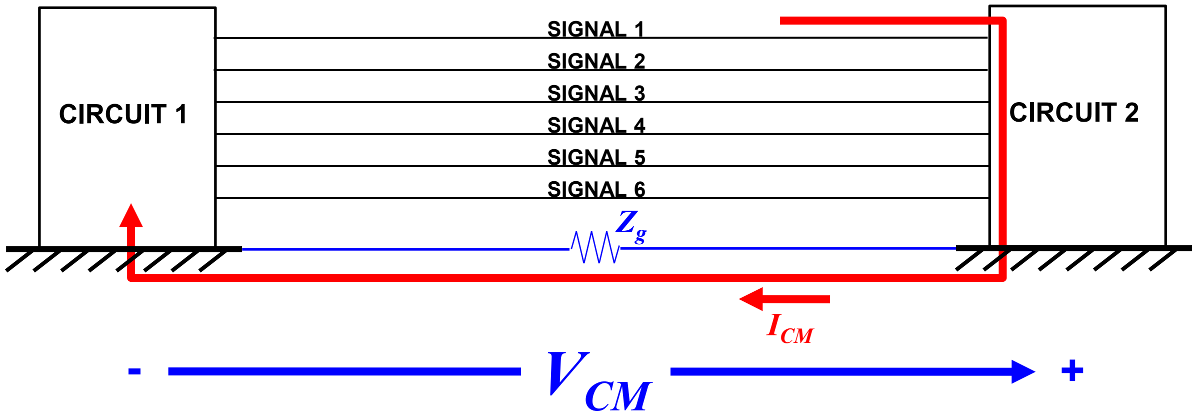
Ground Bounce

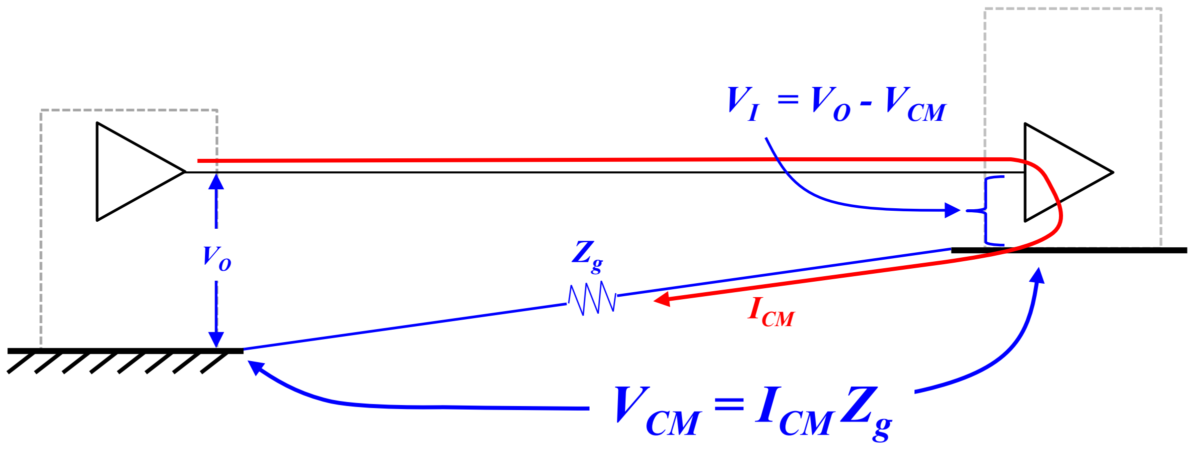
- **Non-ideal "ground"**
  - There is always a non-zero impedance between circuit references
  - Currents on interface signals can induce potential between circuit references that will be seen by all other interface signals
    - Called "common mode noise" or "ground bounce"
    - Common mode currents can induce noise on interface signals (next slides)



SIGNAL 1 RETURN CURRENT CAUSES
COMMON MODE VOLTAGE ON REFERENCE
REFERENCE SEEN BY ALL OTHER SIGNALS

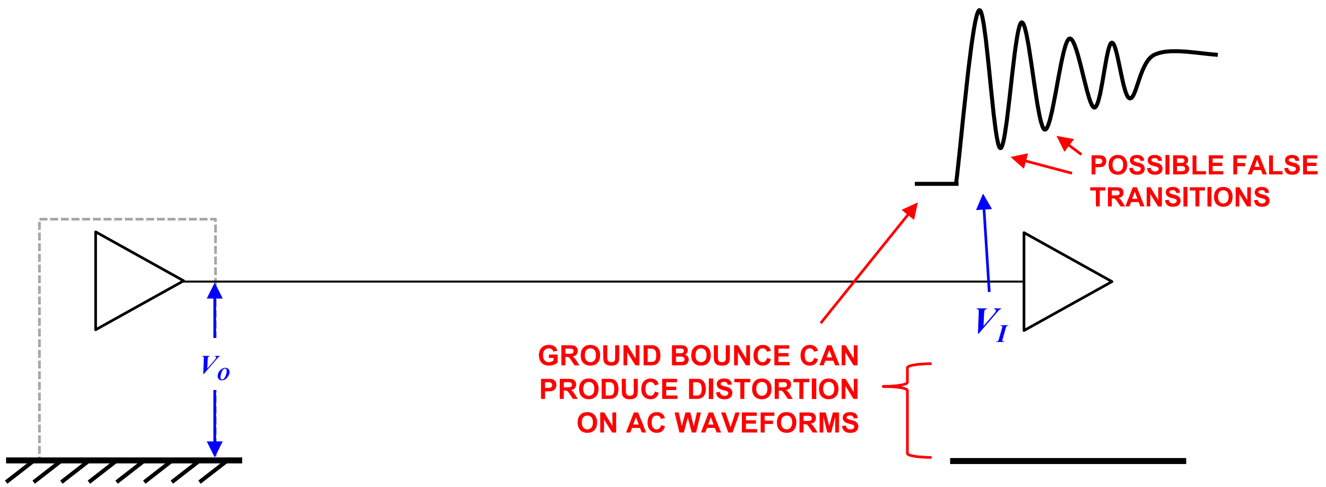
Ground Bounce (cont.)

- **Ground bounce – a DC perspective**
  - Common mode current I_{CM} returns through "ground" impedance Z_g
  - Produces common mode potential difference V_{CM} between circuits
  - Produces common mode (error) voltage V_{CM} in receiver circuit
  - **Minimize V_{CM} by:**
    - **Minimizing common mode current I_{CM} and/or**
    - **Minimizing ground connection impedance Z_g**



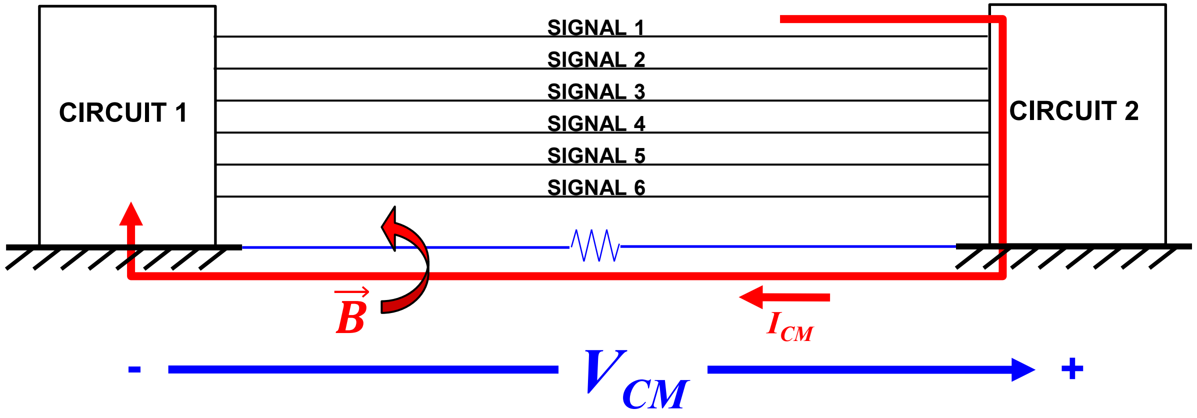
Ground Bounce (cont.)

- **Ground bounce – an AC perspective**
  - Can cause noise on digital signals as well as analog
  - Noise on digital signals can cause false transitions
  - Such noise on a clock line can lock up a state machine
  - **Digital circuits are not immune!!!**



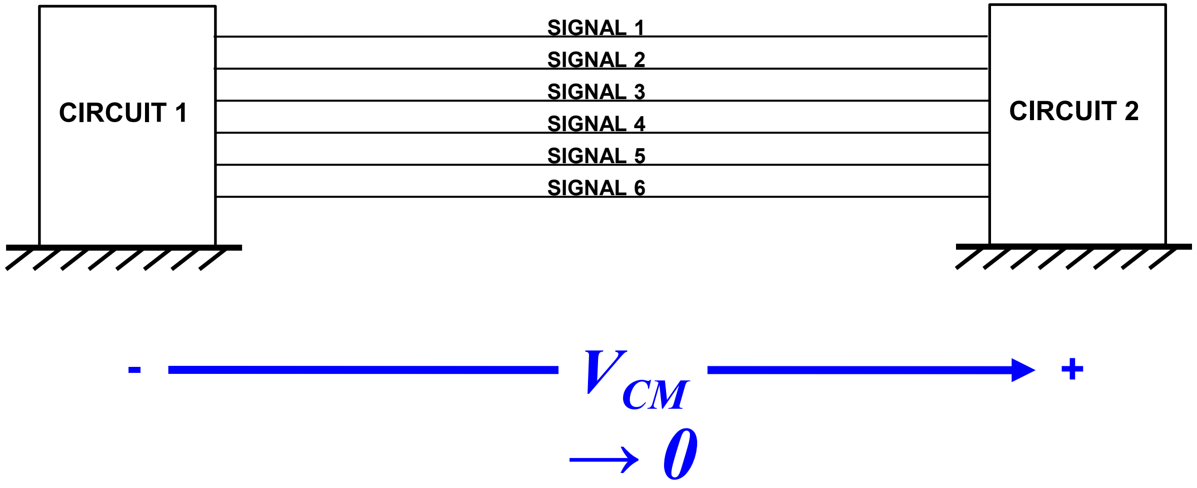
Ground Bounce (cont.)

- **Relying on "ground" as return current path allows currents to flow in large loops**
  - Current creates a magnetic field
  - Common mode voltages can be induced from magnetic fields originating from neighboring circuitry
  - …or from itself



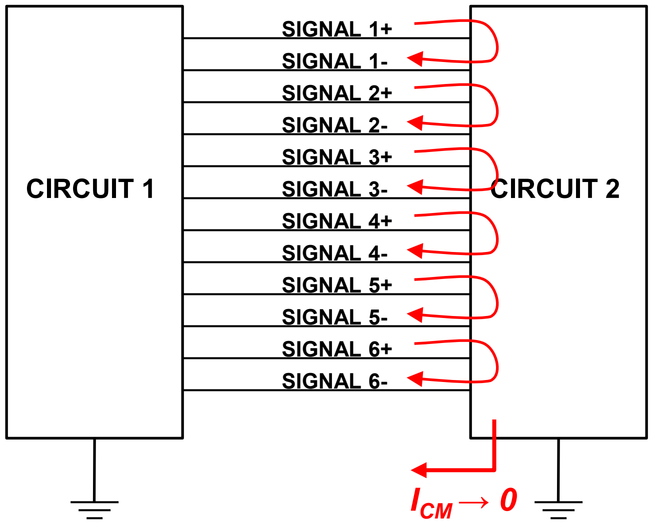
Current Return

- **SOLUTION: Treat "current return" and "ground" (a.k.a. "signal reference") as two separate entities**
- **Purpose of "ground" is:**
  - IDEAL: to provide common reference potential between interfacing circuits
  - PRACTICALLY: To minimize ΔV between circuit references
- **Current return does not need to be (and really should not be) the same thing...**



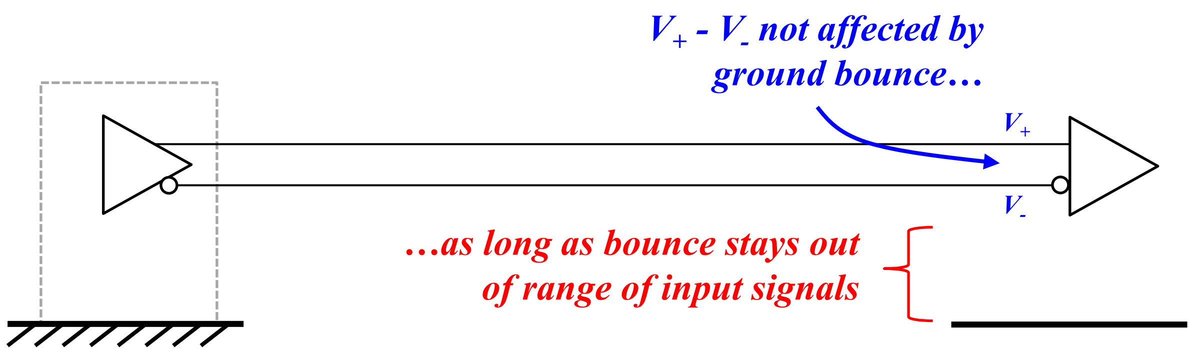
Current Return (cont.)

- Provide differential interfaces for signals → dedicated current return path for each signal
- Doubles number of interface lines, but minimizes common mode currents
- Reduces loop areas (improved magnetic field emissions and susceptibility)
- Much more control over current paths (“follow the current”)
- Less susceptible to ground bounce (next slide)



Current Return (cont.)

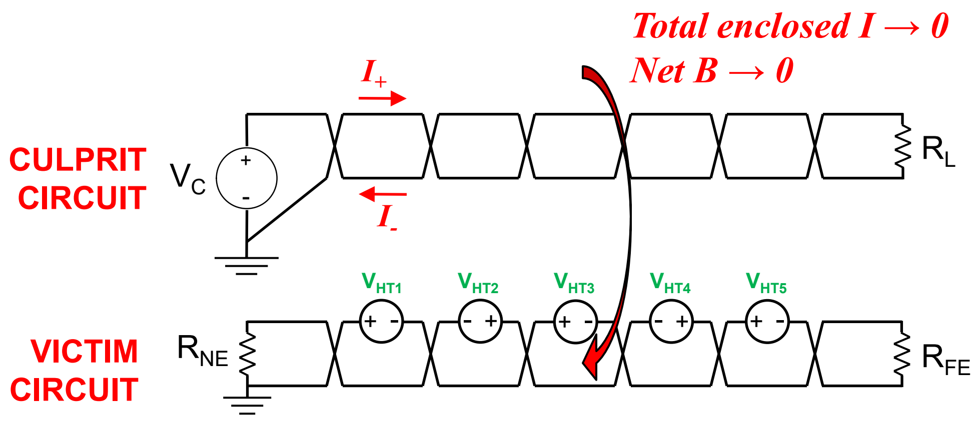
Differential interface circuits are much less susceptible to ground bounce than are single-ended circuits



SpaceWire (LVDS) allows ΔV only up to 1 V between interfacing circuits

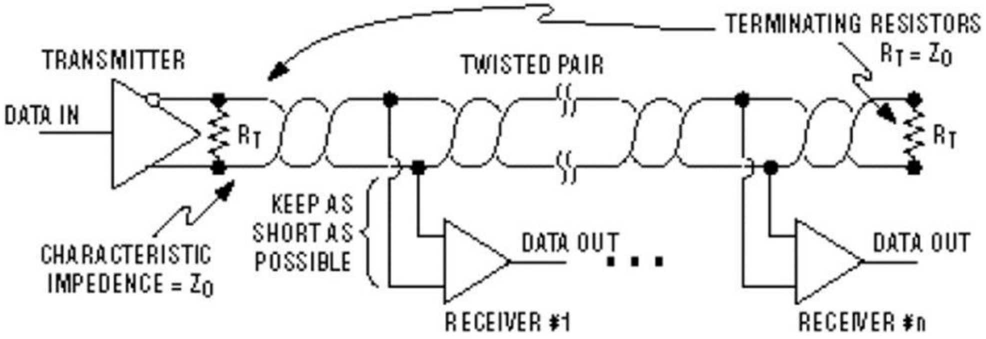
Current Return (cont.)

- **Twisted Pairs**
  - Emissions
    - Provides return current path to cancel culprit current
    - Reduced net current reduces net emitted magnetic field
  - Susceptibility
    - Current return on adjacent wire minimizes loop area
    - Voltages induced on adjacent half-twist loops cancel
    - Worst case net induced voltage is that induced on loop area of single half-twist

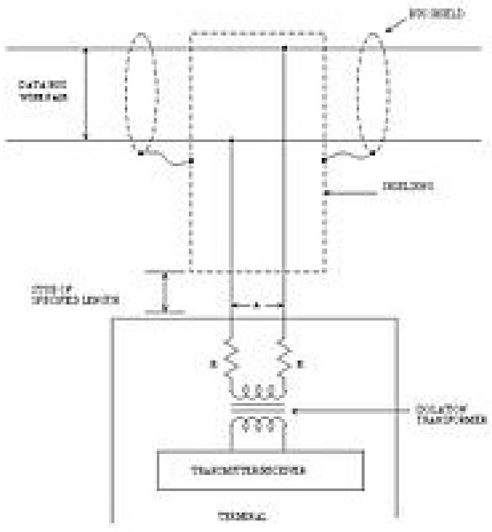


Differential Twisted Pair Interface Examples

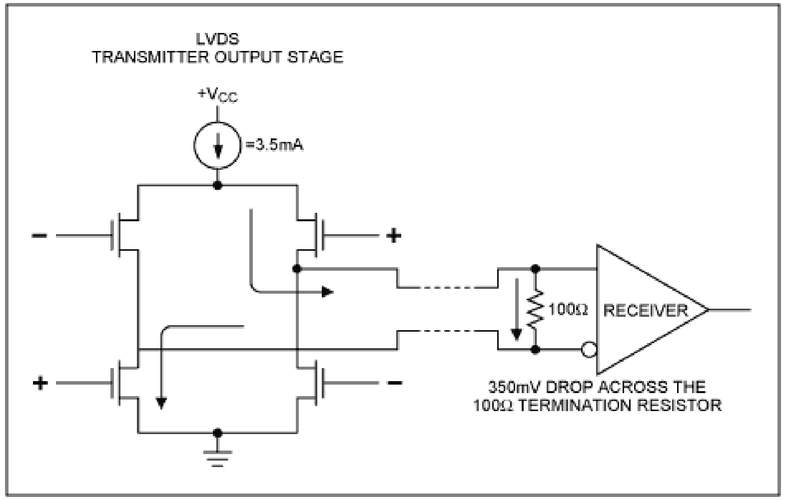
RS-422



MIL-STD-1553B



Low Voltage Differential Signal (LVDS → SpaceWire)

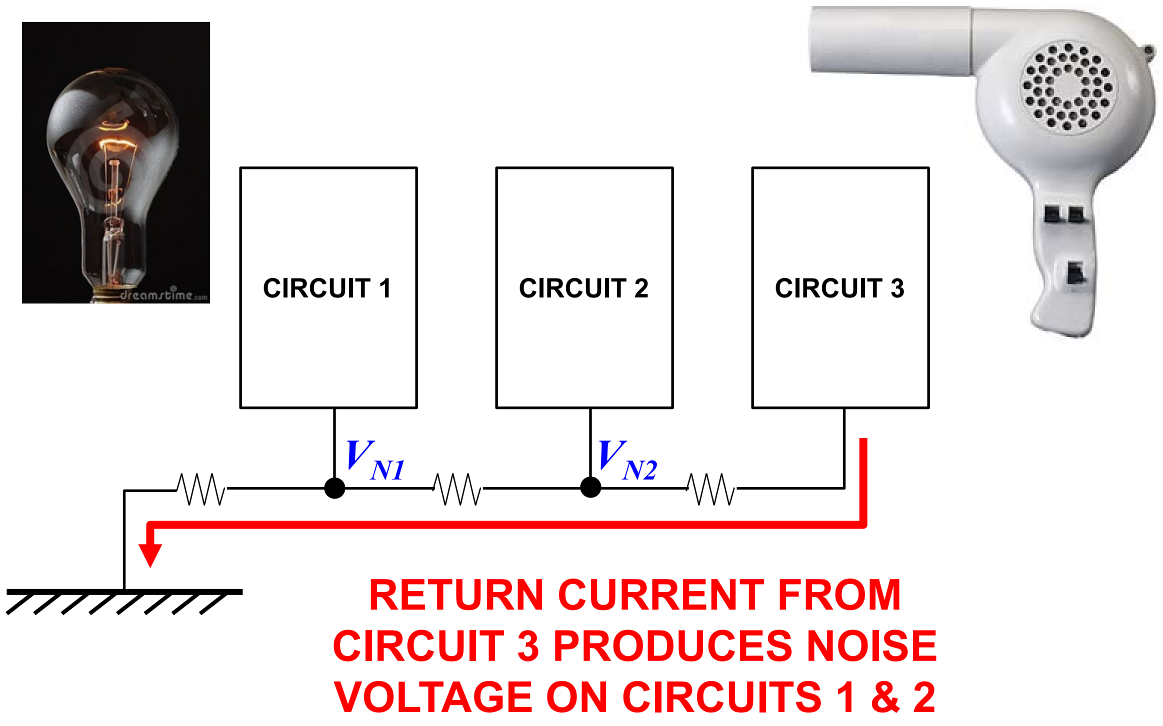


Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- **“Grounding” in the “Real World” (and in “Real Space”)**
  - Single-Point vs. Multi-Point
  - Virtual Demonstration: Current Return Path
  - Ground Plane and "Ohms per Square What?"
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
- Summary

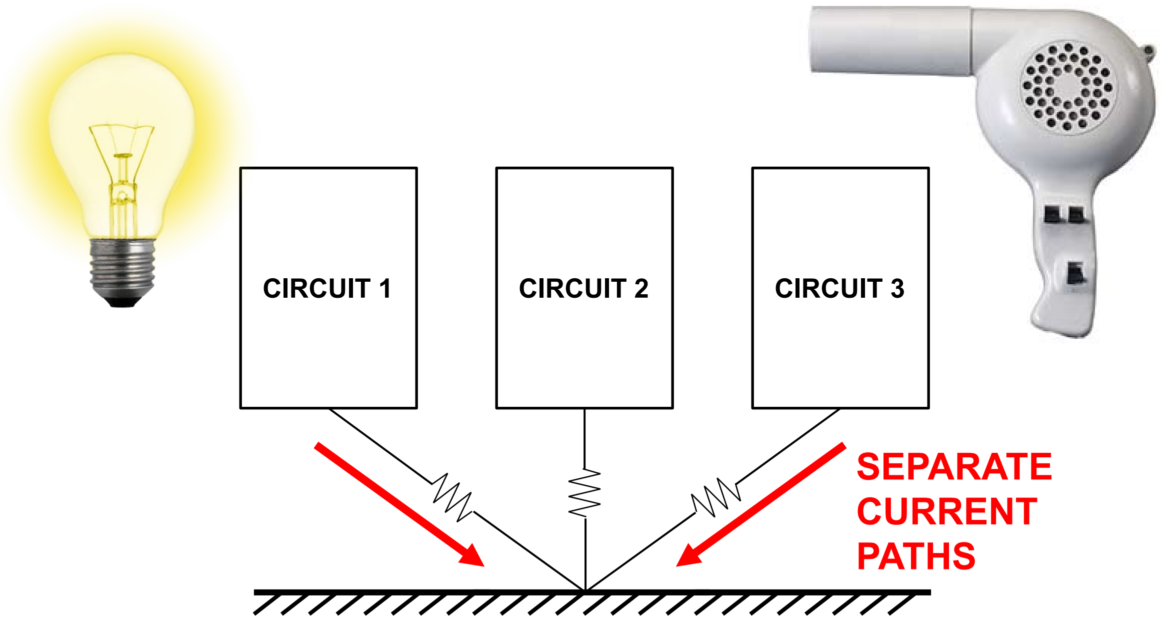
Single Point Ground

- "Daisy Chained" connections (not recommended)
- Very susceptible to common impedance coupling



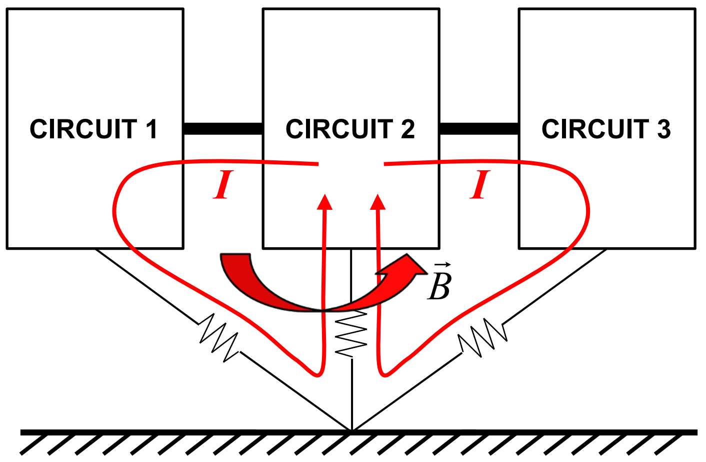
Single Point Ground (cont.)

- Single point “star” ground (better)
- Return currents separate
- Less susceptible to common impedance coupling



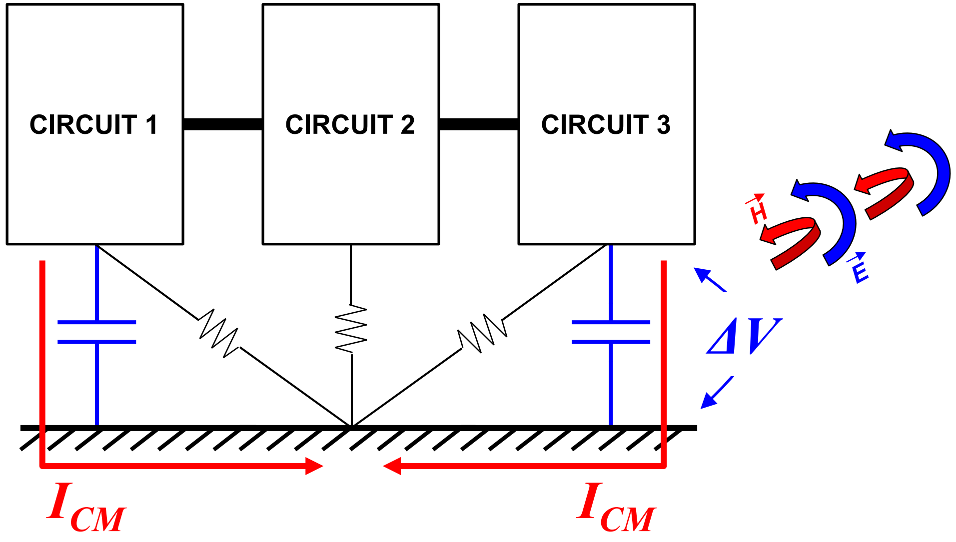
Single Point Ground (cont.)

- Single point excellent for truly isolated circuits (no interconnections)
- Interconnections complicate the situation
- Introduce possibility of:
  - Current loops
  - Magnetic coupling



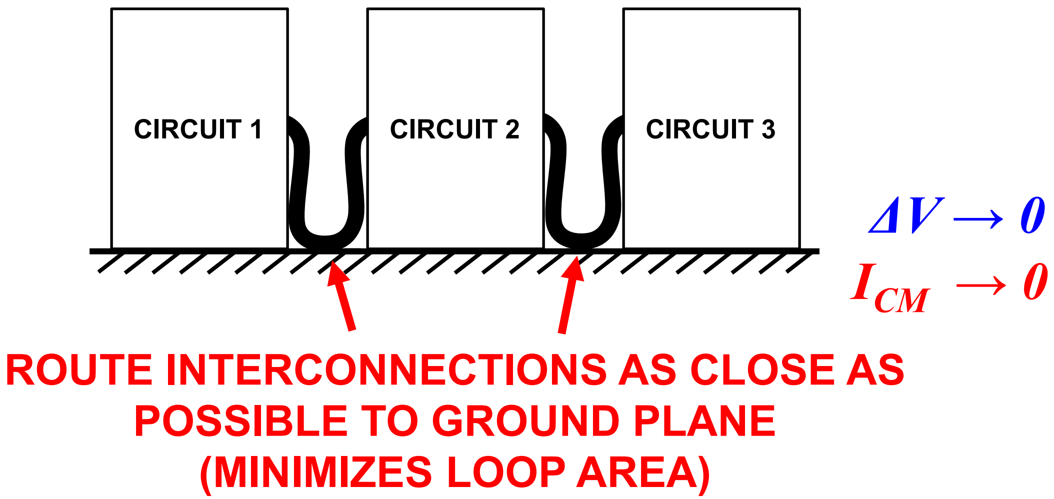
Single Point Ground (cont.)

- **"Isolation" allows potential difference to form between conductors**
  - Allows common mode current to flow across stray capacitance
  - Causes radiated fields that couple into neighboring circuitry
- **"Single point ground" is ineffective and impractical at high frequencies!!!**

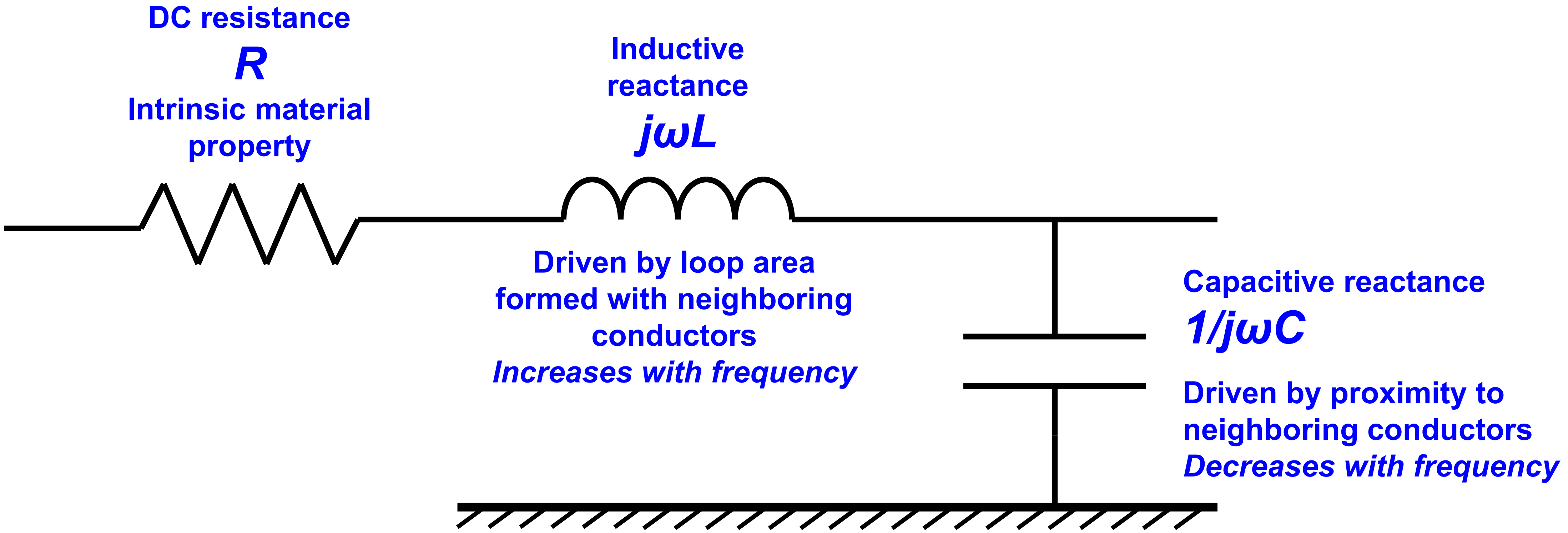


Multi-Point Ground

- **“Multi-point” ground is most effective at high frequencies**
  - Connect to common ground plane or structure
  - Reduces potential difference between conductors
  - Reduces common mode currents
  - Reduces radiated fields and susceptibility

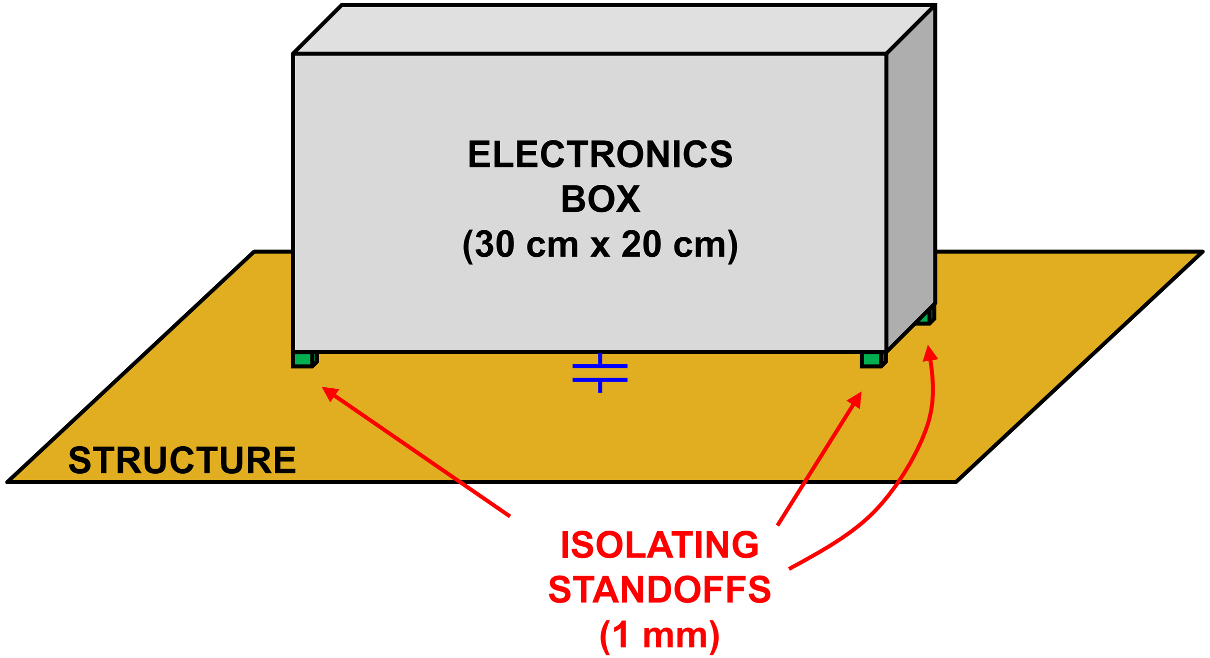


Grounding Connection Impedances (“Hidden Schematic”)



GROUNDING CONNECTION IMPEDANCE IS A FUNCTION OF FREQUENCY

Capacitance Example



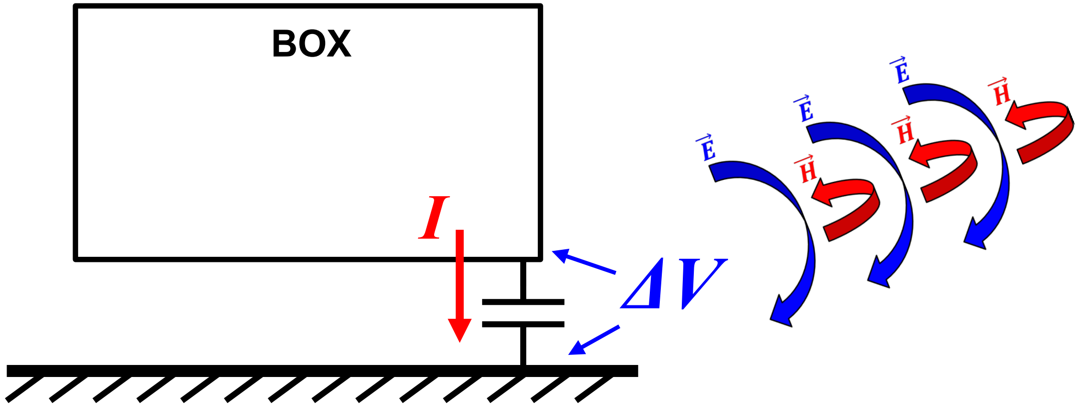
Parallel plate capacitor:

$$C = \frac{\varepsilon_0 A}{d} = \frac{(8.84 \times 10^{-12}\ F/m)(0.3\ m)(0.2\ m)}{0.001\ m} \approx 500\ pF$$

$$|X_C(10\ MHz)| = \frac{1}{2\pi f C} = \frac{1}{2\pi(10 \times 10^6\ Hz)(500 \times 10^{-12}\ F)} \approx \underline{32\ \Omega}$$

CAPACITIVE REACTANCE (IMPEDANCE) DECREASES WITH FREQUENCY

Capacitance Example (cont.)



...producing radiated fields that can couple into neighboring circuitry

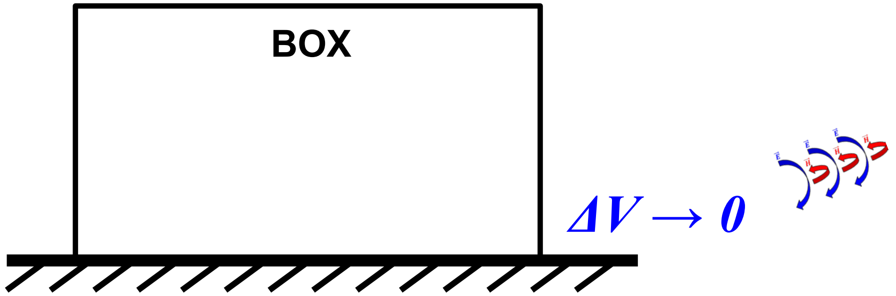
High frequency currents will find these capacitive paths...

...producing a high frequency potential between the conductors...

Capacitance Example (cont.)

"Isolation" frequently introduces more problems than it attempts to solve

Not effective for high frequency currents



...minimizing radiated fields

Providing low impedance connection...

...minimizes potential between the conductors...

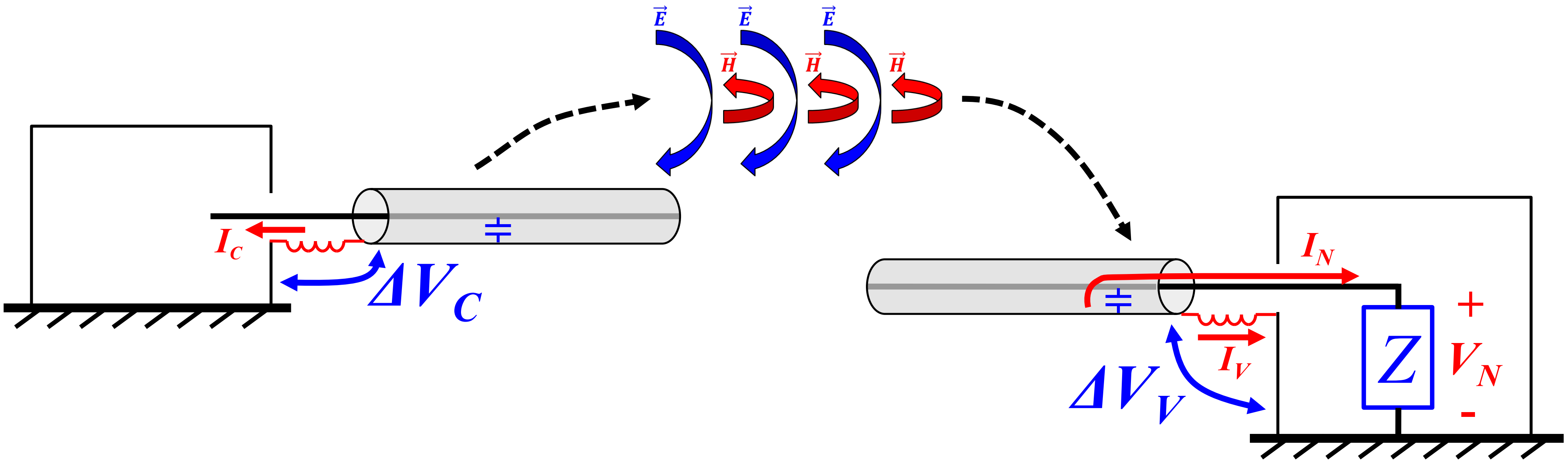
"Single-point ground" is losing battle at high frequencies

STOP PHIGHTING PHYSICS!

Sneak Preview: Cable Sheild Terminations

HINT (not terribly subtle):

This is also precisely why we yell and scream about cable shield terminations…



Current Return (cont.)

- **DEMO: Current Return: The Path of Least IMPEDANCE**
  - Video posted on NESC Academy website:
    - http://nescacademy.nasa.gov/
  - Has some errors in the details; basic message still holds
  - Updated summary on following slides

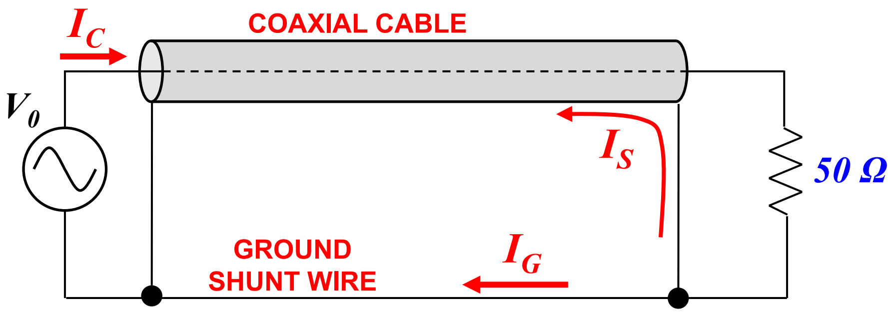
Kirchhoff's Current Law

- **All currents return to their sources following all available paths**
  - In inverse proportion to relative **IMPEDANCES**
  - NOT always path of least resistance
- **Currents do NOT return to "ground"**
  - They may use "ground" as one of many available return paths, depending on relative impedances

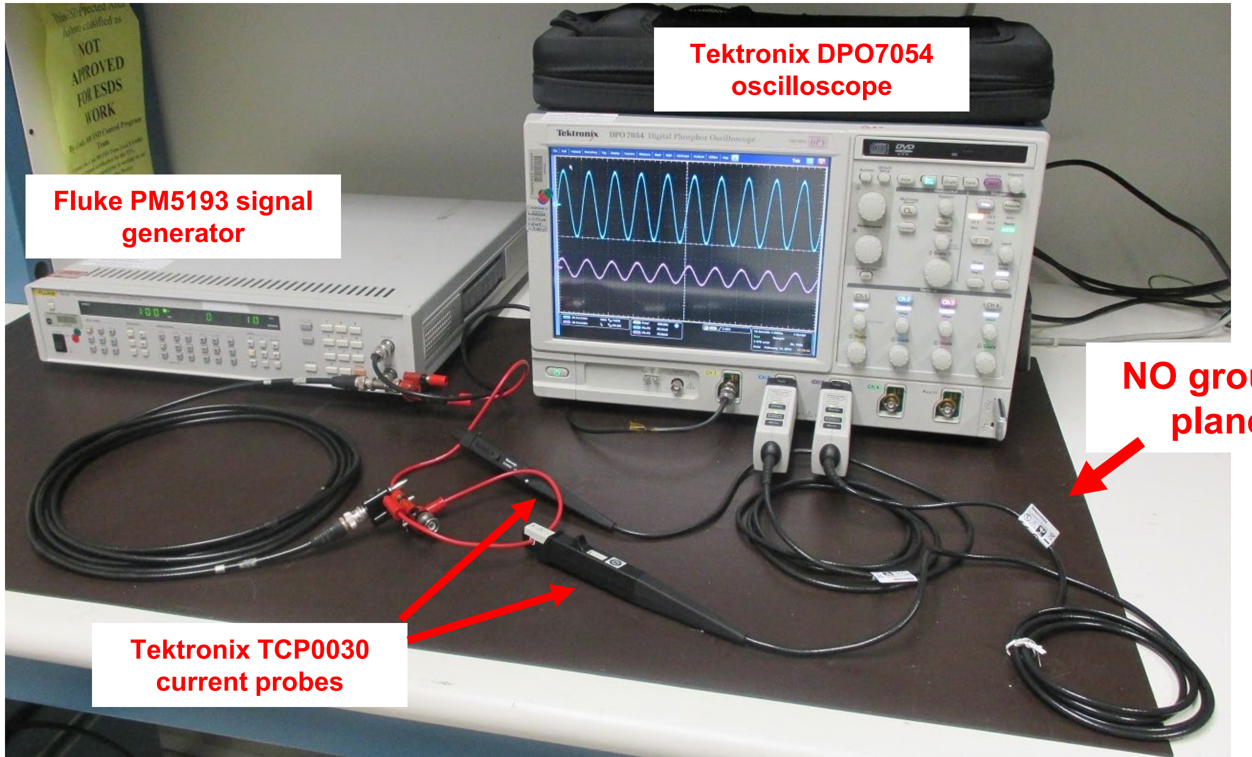
BIG Rule of Thumb for EMC: "Follow the current"

Virtual Demonstration: Current Return Path

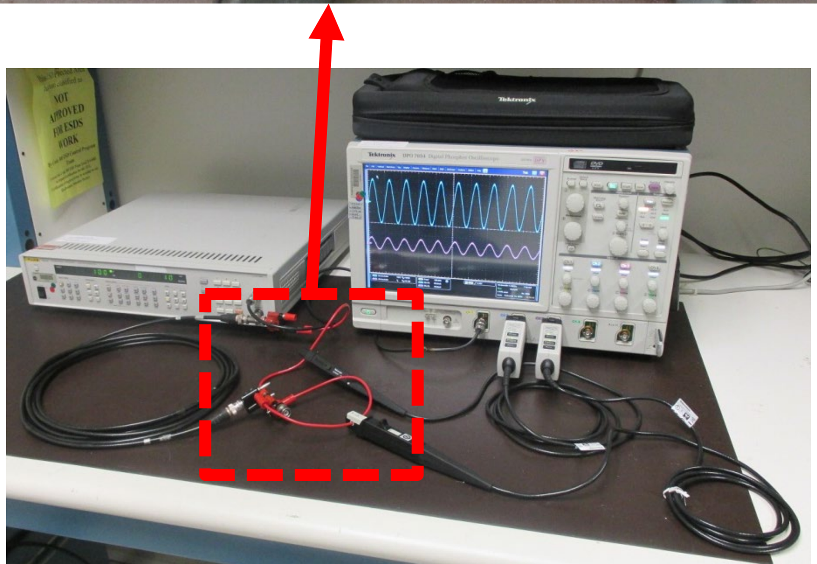
Which path will the return current take?



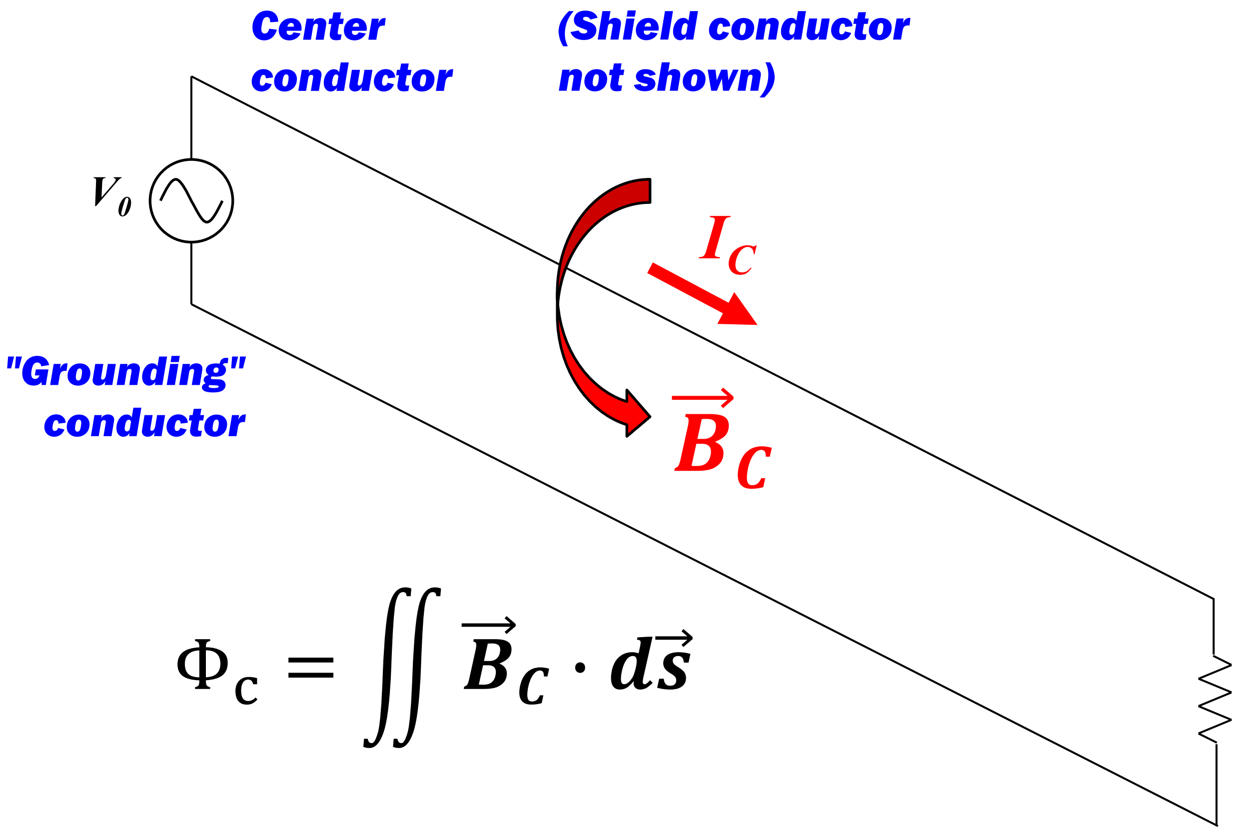
I_C = center conductor current
I_S = shield return current
I_C = ground shunt wire return current



Current Return Path (cont.)

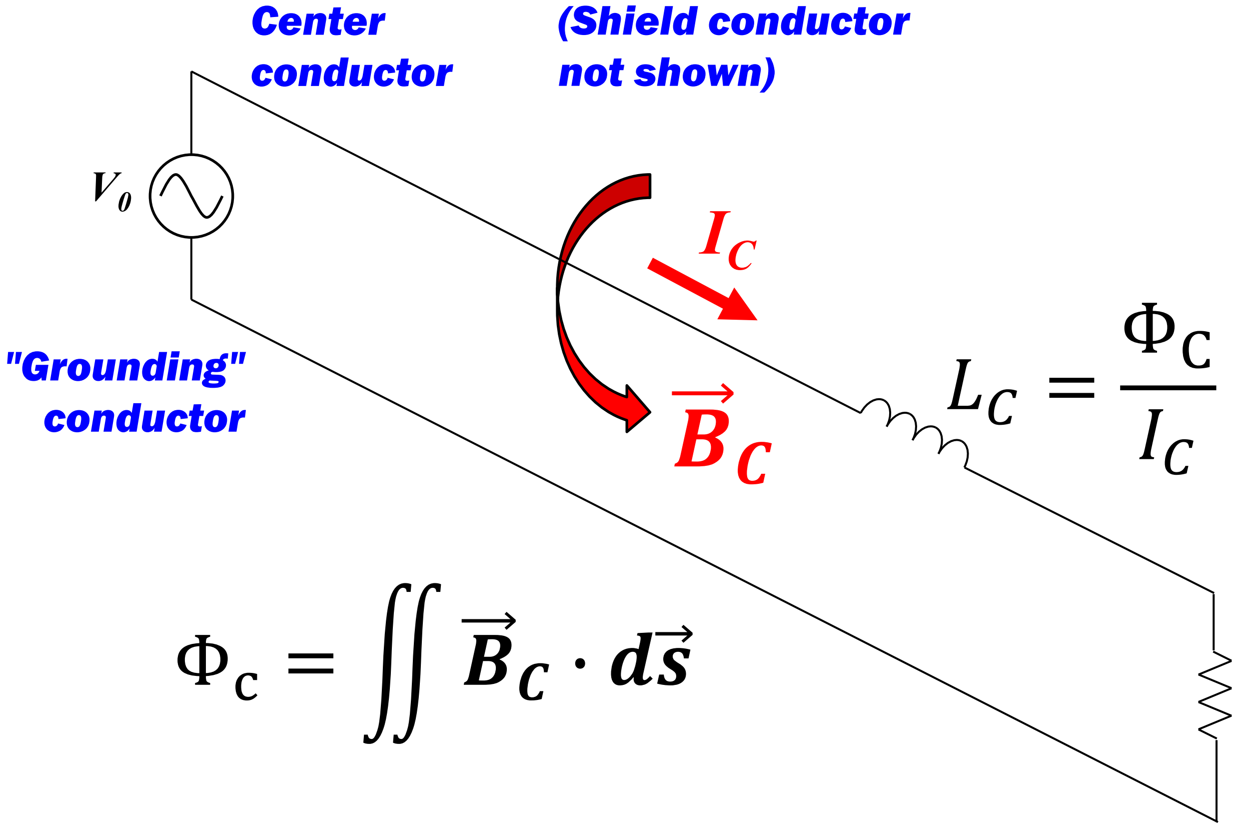


Inductances



$$\Phi_c = \iint \vec{B}_C \cdot d\vec{s}$$

Inductances (cont.)

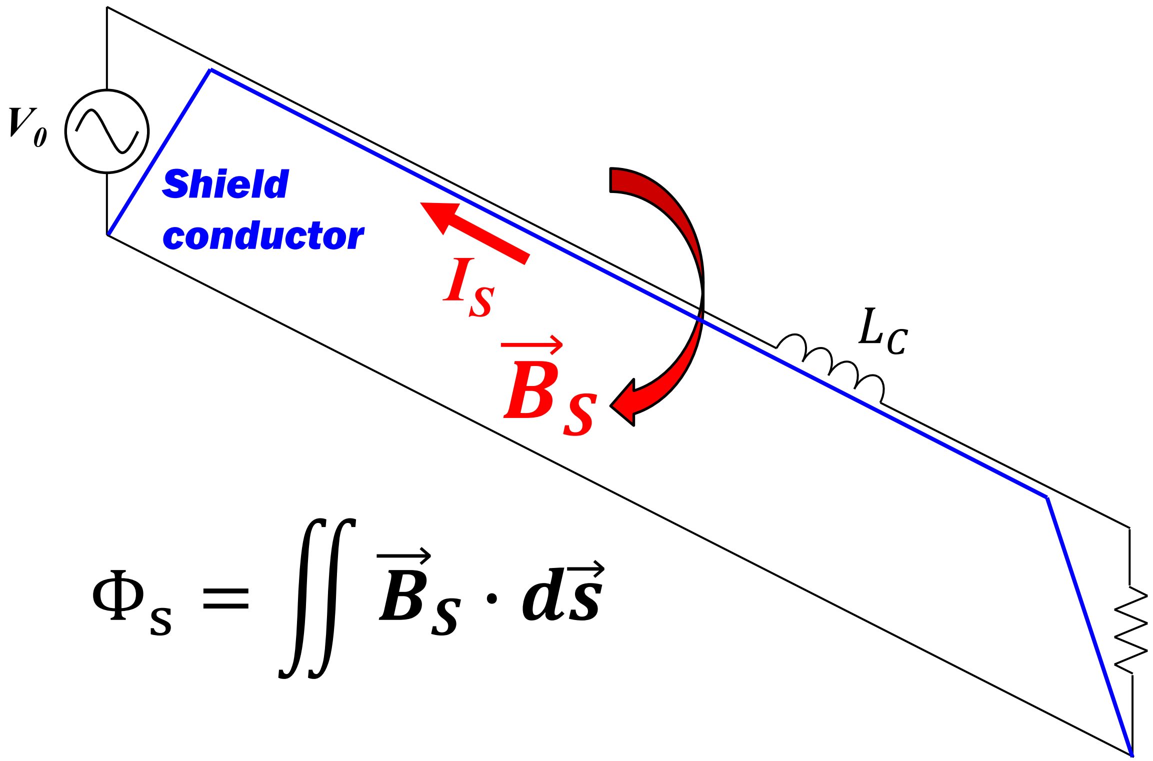


$$L_C = \frac{\Phi_C}{I_C}$$

Partial self-inductance of center conductor
(w.r.t. grounding conductor)

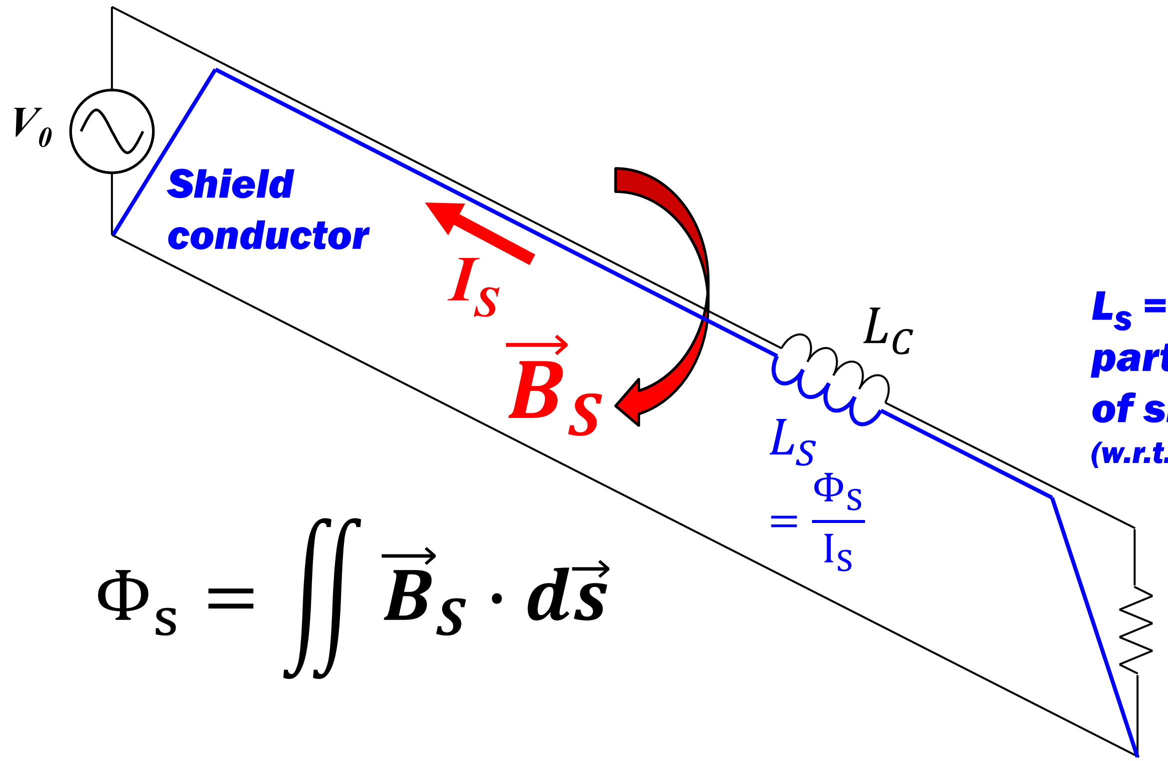
$$\Phi_c = \iint \vec{B}_C \cdot d\vec{s}$$

Inductances (cont.)



$$\Phi_s = \iint \vec{B}_S \cdot d\vec{s}$$

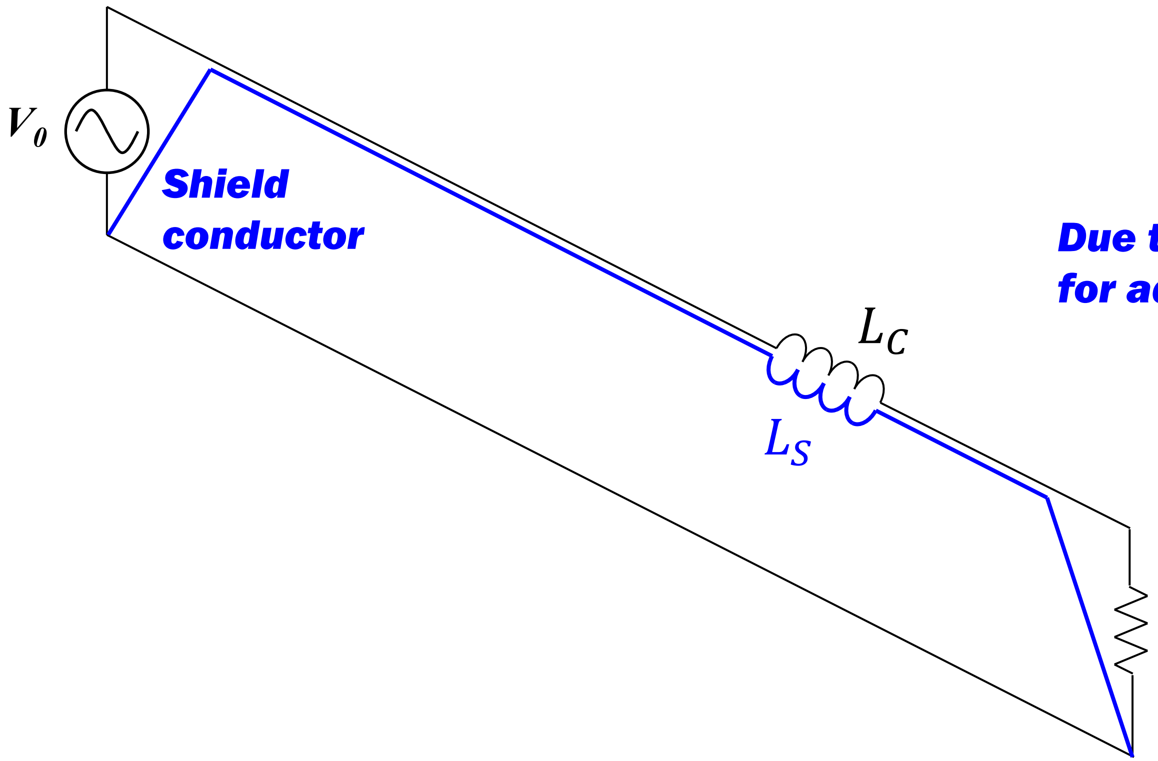
Inductances (cont.)



$$\Phi_s = \iint \vec{B}_S \cdot d\vec{s}$$

L_s =
partial self-inductance of shielding conductor
(w.r.t. grounding conductor)

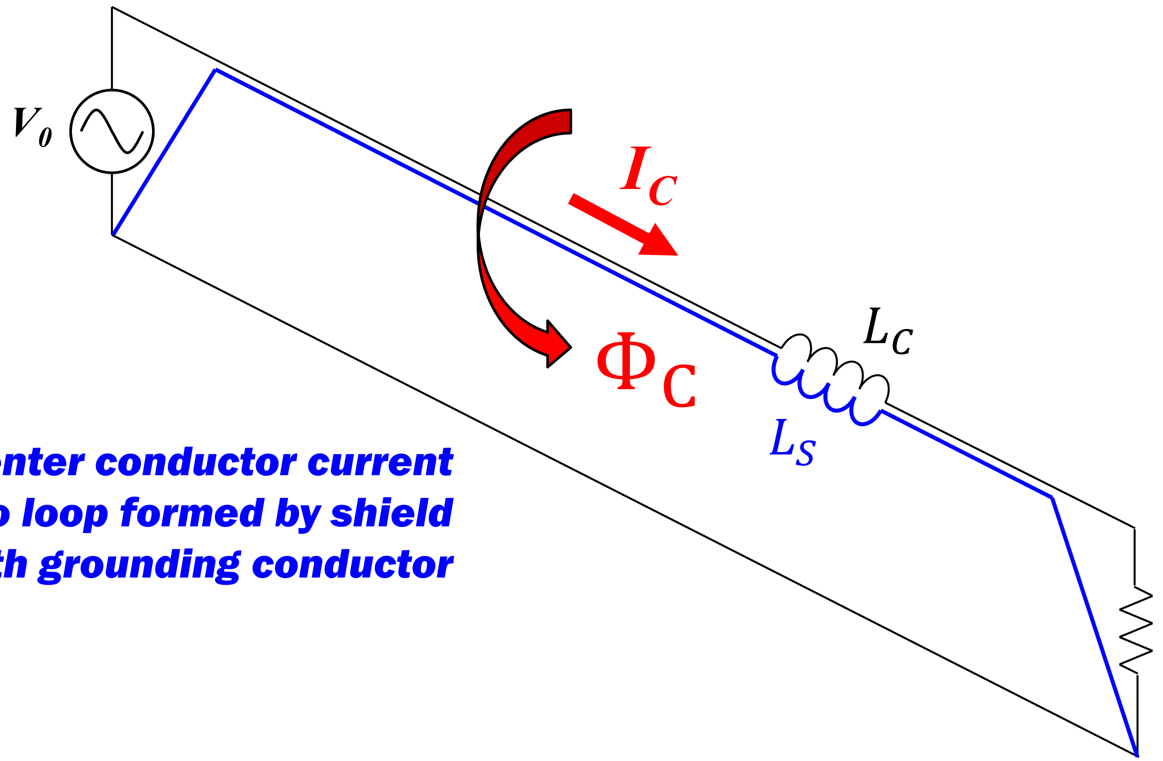
Inductances (cont.)



Due to similar geometry for adjacent conductors:

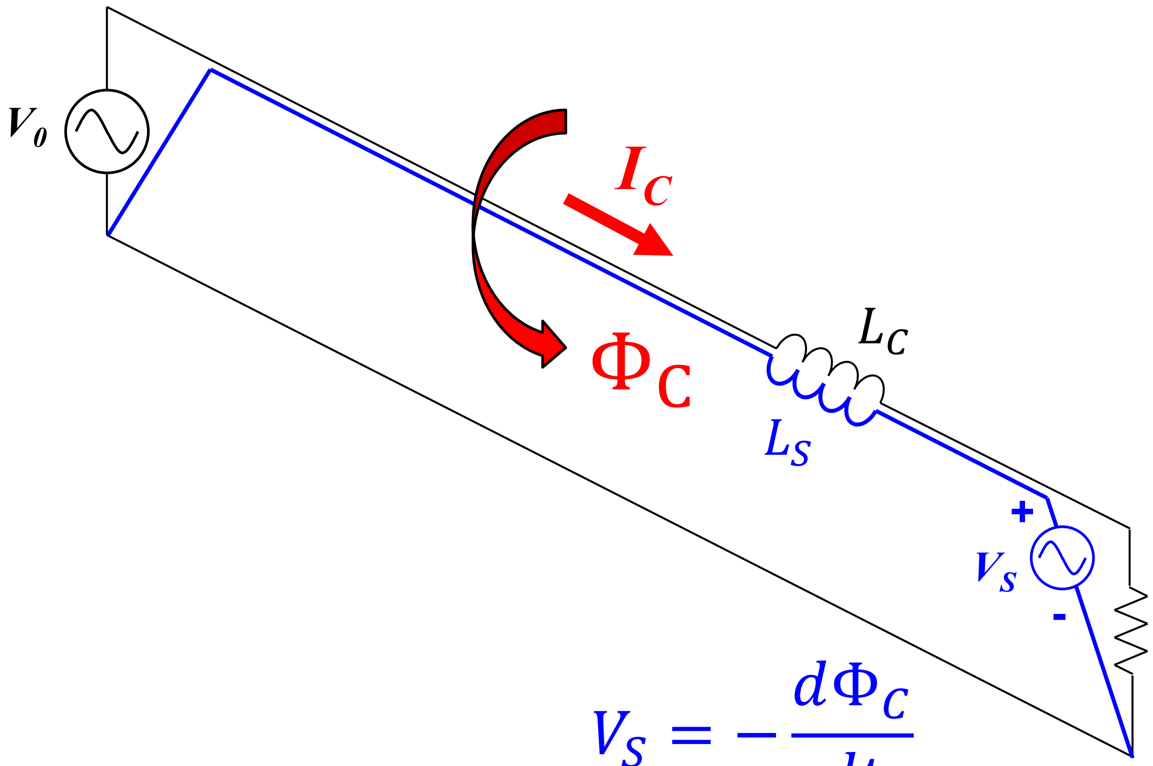
$$L_C \approx L_S$$

Inductances (cont.)



All flux from center conductor current couples into loop formed by shield conductor with grounding conductor

Inductances (cont.)



$$V_S = -\frac{d\Phi_C}{dt}$$

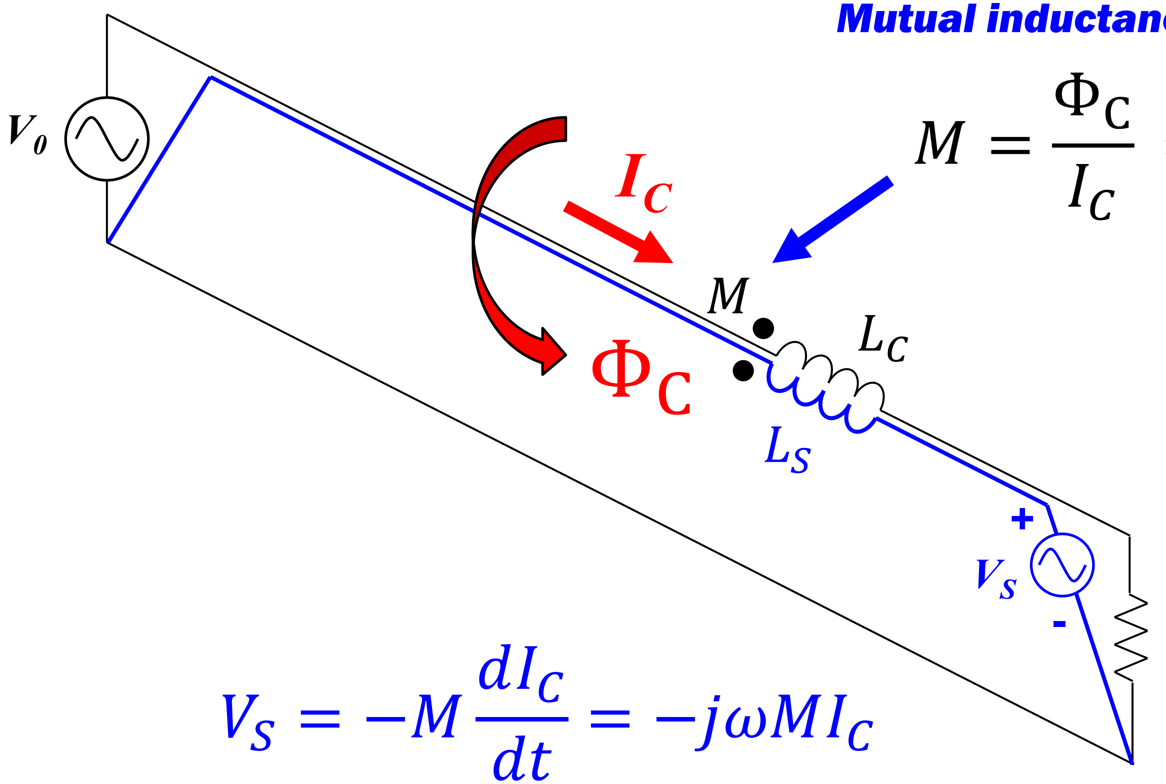
Per Faraday's and Lenz's Laws, potential (emf) is induced in shield loop to oppose (impede) incident flux

Inductances (cont.)

Mutual inductance

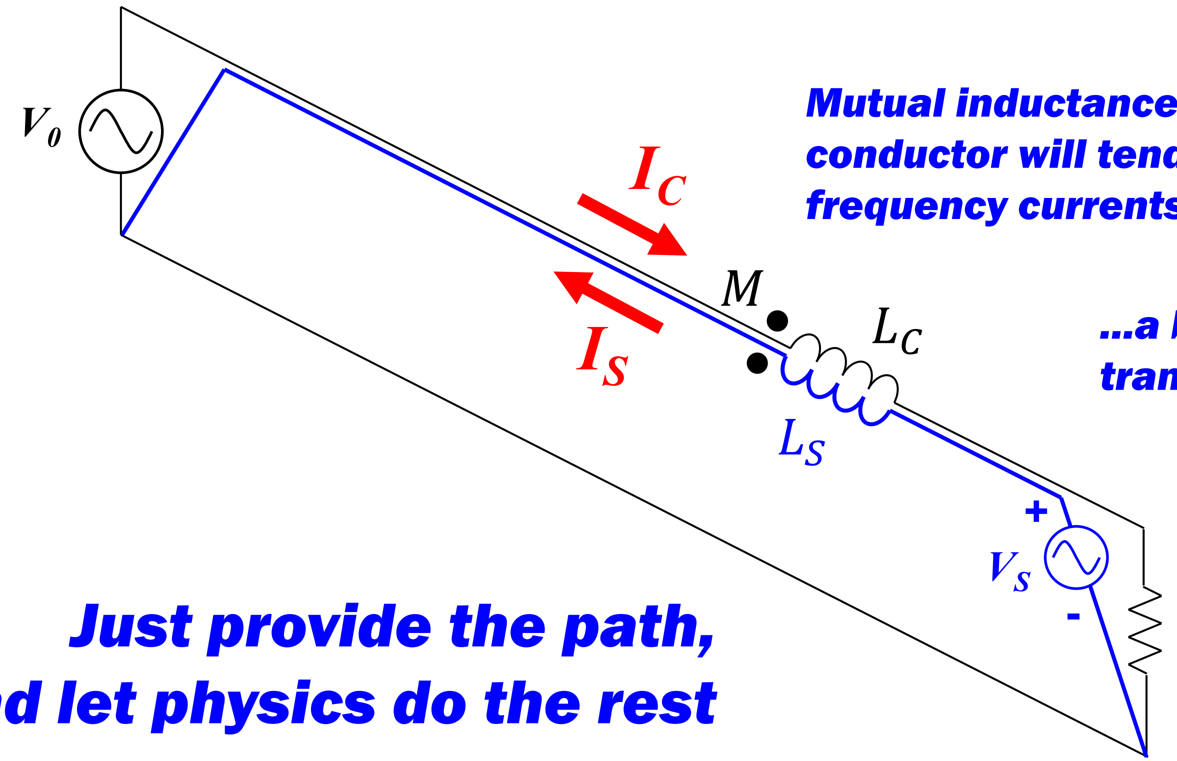
$$M = \frac{\Phi_C}{I_C} \approx L_C \approx L_S$$

Same flux, same current for adjacent conductors



$$V_S = -M\frac{dI_C}{dt} = -j\omega M I_C$$

Inductances (cont.)

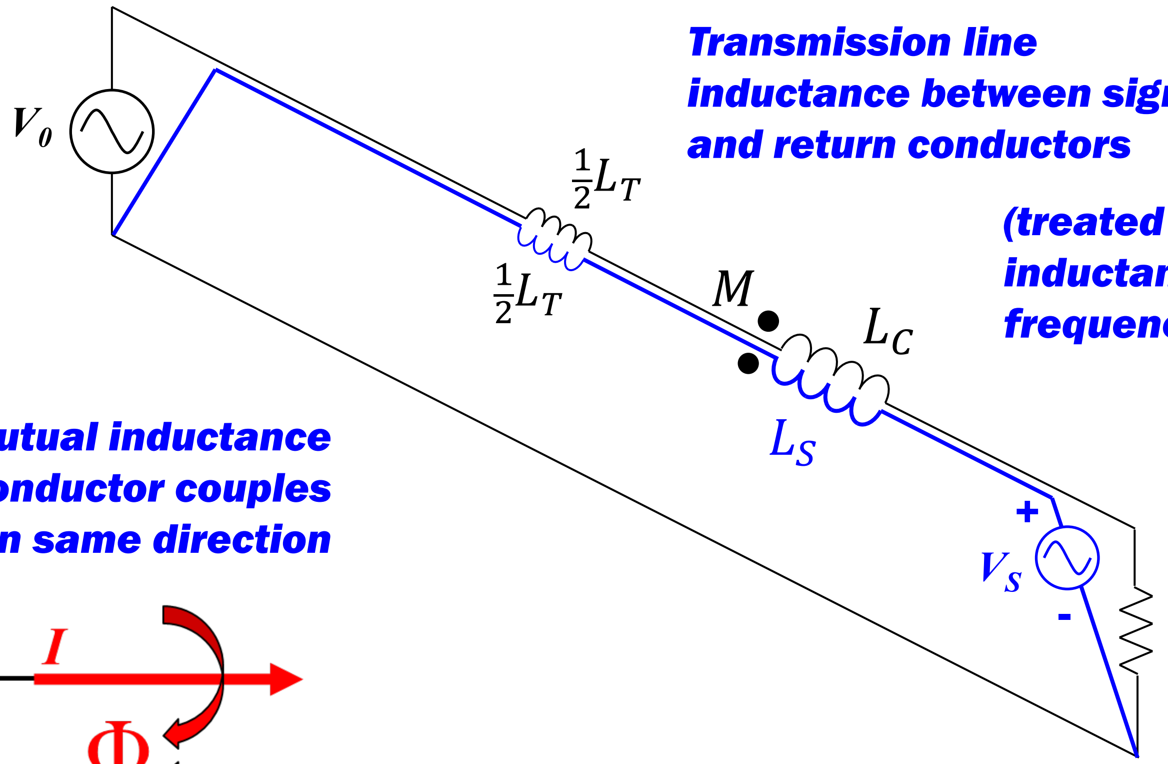


Mutual inductance to nearby return conductor will tend to force high frequency currents to return on it

…a bit like a transformer…

Just provide the path, and let physics do the rest

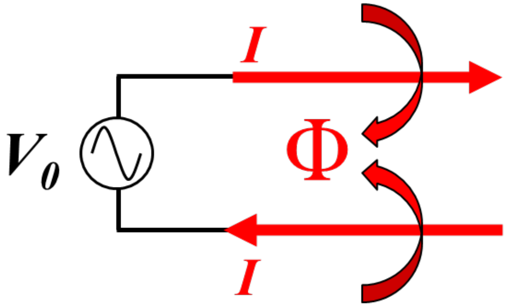
Inductances (cont.)



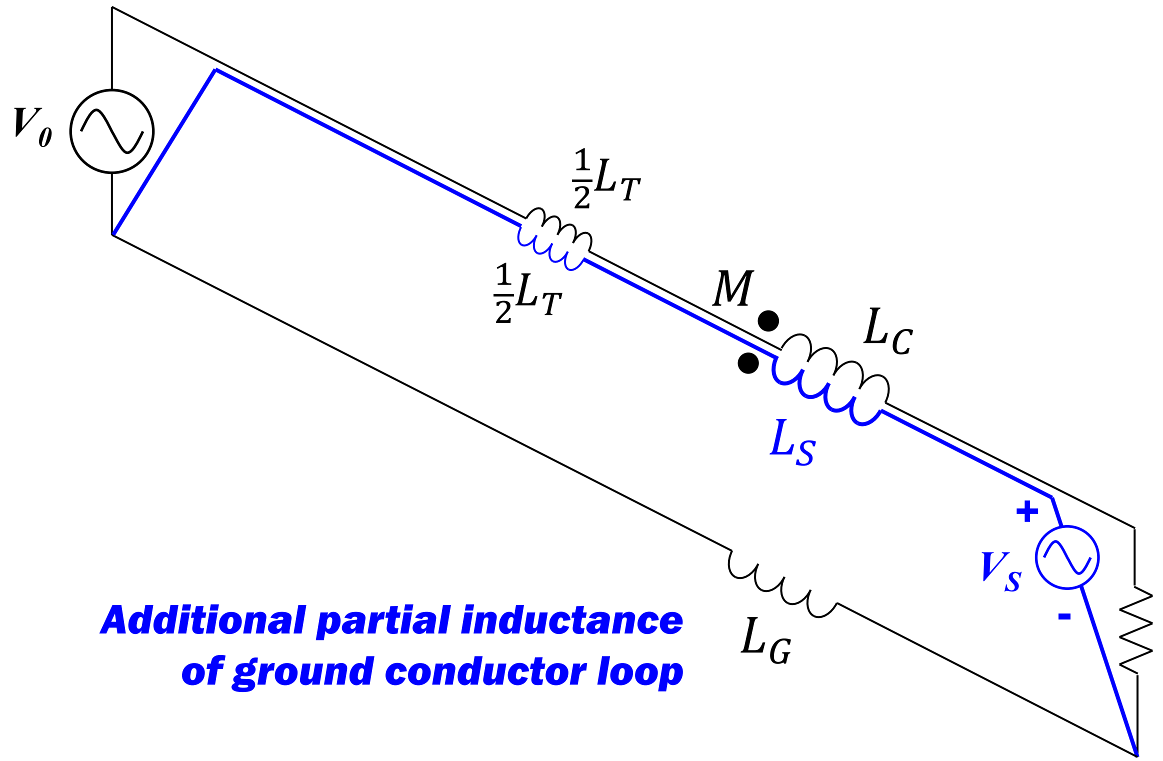
Transmission line inductance between signal and return conductors

(treated as lumped inductance at low frequencies)

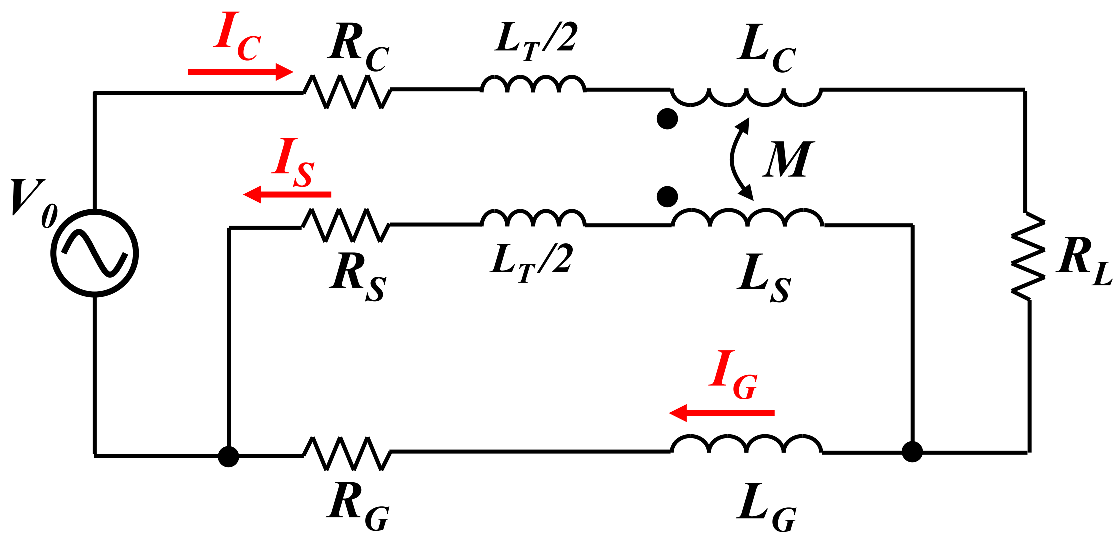
NOT mutual inductance
Flux from each conductor couples through loop in same direction



Inductances (cont.)



Equivalent Circuit



R_C = *center conductor resistance*

R_S = *shield return resistance*

R_G = *ground wire resistance*

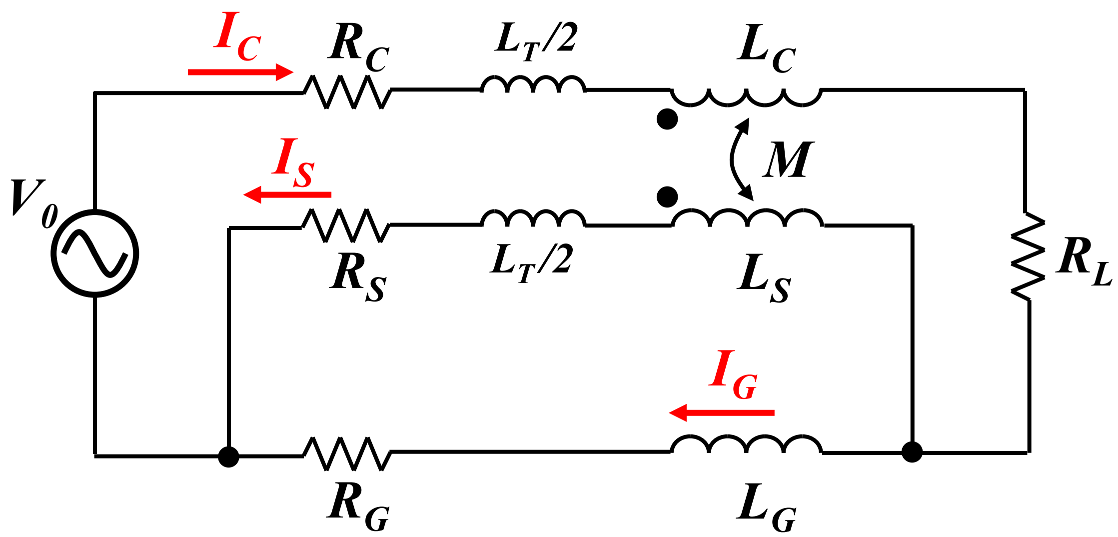
I_C = *center conductor current*

I_S = *shield return current*

I_G = *ground wire return current*

$$I_C = I_S + I_G$$

Circuit Analysis



Center conductor shield loop

$$V_0 = I_C(R_C + j\omega\, L_T/2 + j\omega L_C) - I_S(j\omega M) + I_S(R_S + j\omega\, L_T/2 + j\omega L_S) - I_C(j\omega M)$$

Center conductor ground wire loop

$$V_0 = I_C(R_C + j\omega\, L_T/2 + j\omega L_C) - I_S(j\omega M) + I_G(R_G + j\omega L_G)$$

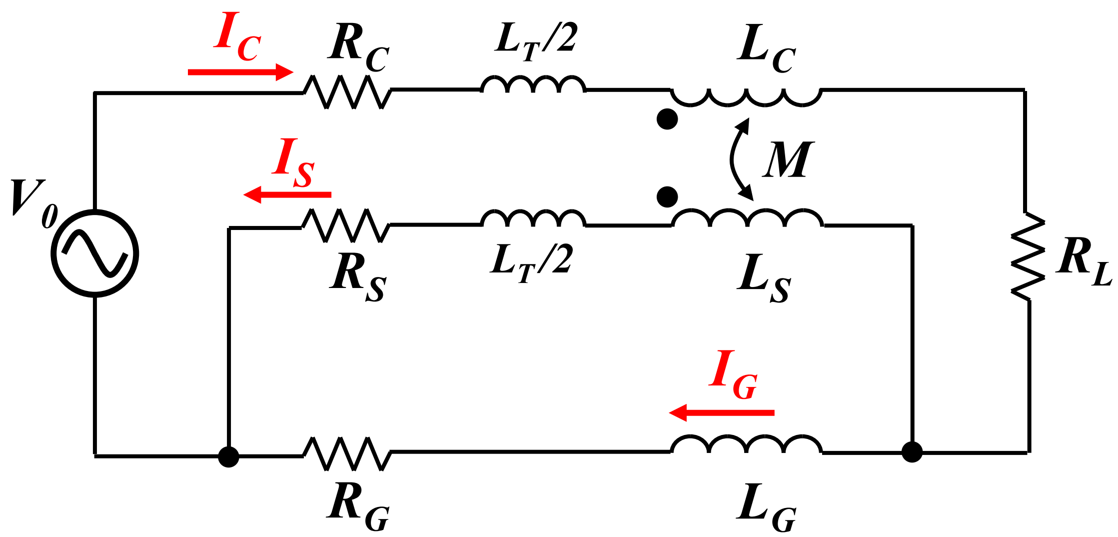
Subtract

$$0 = I_S(R_S + j\omega\, L_T/2 + j\omega L_S) - I_C(j\omega M) - I_G(R_G + j\omega L_G)$$

$$I_S(R_S + j\omega\, L_T/2 + j\omega L_S) = I_C(j\omega M) + I_G(R_G + j\omega L_G)$$

$$I_C = I_S + I_G \qquad M = L_C = L_S$$

Circuit Analysis (cont.)



Solving for I_S/I_C:

$$I_S(R_S + j\omega\, L_T/2 + j\omega L_S) = I_C(j\omega L_S) + (I_C - I_S)(R_G + j\omega L_G)$$

$$I_S[(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)] = I_C[R_G + j\omega(L_S + L_G)]$$

$$I_S[(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)] = I_C[R_G + j\omega(L_S + L_G)]$$

$$\frac{I_S}{I_C} = \frac{R_G + j\omega(L_S + L_G)}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

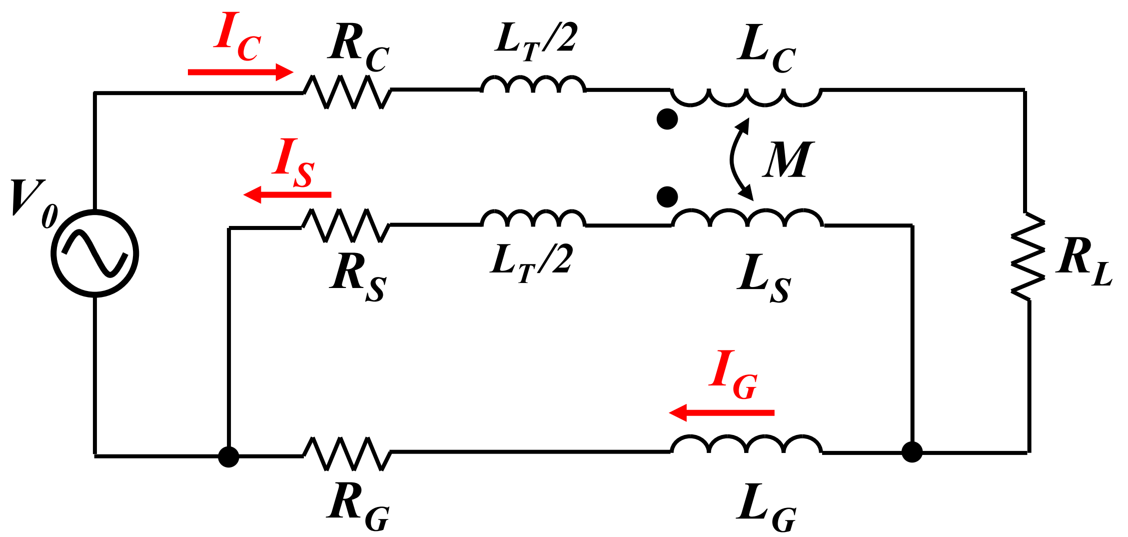
Solving for I_G/I_C:

$$(I_C - I_G)(R_S + j\omega\, L_T/2 + j\omega L_S) = I_C(j\omega L_S) + I_G(R_G + j\omega L_G)$$

$$I_C(R_S + j\omega\, L_T/2) = I_G[(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)]$$

$$\frac{I_G}{I_C} = \frac{R_S + j\omega\, L_T/2}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

Circuit Analysis (cont.)



Higher MUTUAL inductance between signal and return conductors → higher fraction of return current returning on return conductor (due to "transformer action")

Shield return current:

$$\frac{I_S}{I_C} = \frac{R_G + j\omega(L_S + L_G)}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

Ground wire return current:

$$\frac{I_G}{I_C} = \frac{R_S + j\omega L_T/2}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

At low frequencies (resistive divider)

$$\frac{I_S}{I_C} \approx \frac{R_G}{R_S + R_G} \qquad \frac{I_G}{I_C} \approx \frac{R_S}{R_S + R_G}$$

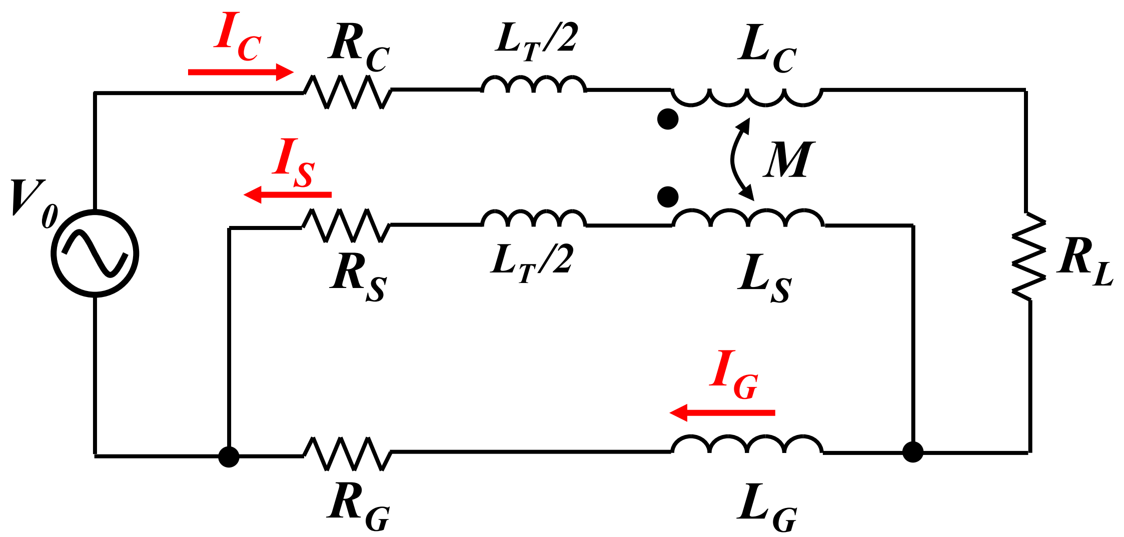
At high frequencies (inductive divider)

$$\frac{I_S}{I_C} \approx \frac{L_S + L_G}{L_T/2 + L_S + L_G} \qquad \frac{I_G}{I_C} \approx \frac{L_T/2}{L_T/2 + L_S + L_G}$$

$L_S + L_G \gg L_T/2$

$$\frac{I_S}{I_C} \approx 1 \qquad \frac{I_G}{I_C} \approx 0$$

Circuit Analysis (cont.)



Shield return current:

$$\frac{I_S}{I_C} = \frac{R_G + j\omega(L_S + L_G)}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

Ground wire return current:

$$\frac{I_G}{I_C} = \frac{R_S + j\omega\, L_T/2}{(R_S + R_G) + j\omega(L_T/2 + L_S + L_G)}$$

Ratio of shield current to ground wire current:

$$\frac{I_S}{I_G} = \frac{R_G + j\omega(L_S + L_G)}{R_S + j\omega\, L_T/2}$$

$I_S = I_G$ when:

$$\sqrt{R_G^2 + \omega^2(L_S + L_G)^2} = \sqrt{R_S^2 + \omega^2(L_T/2)^2}$$

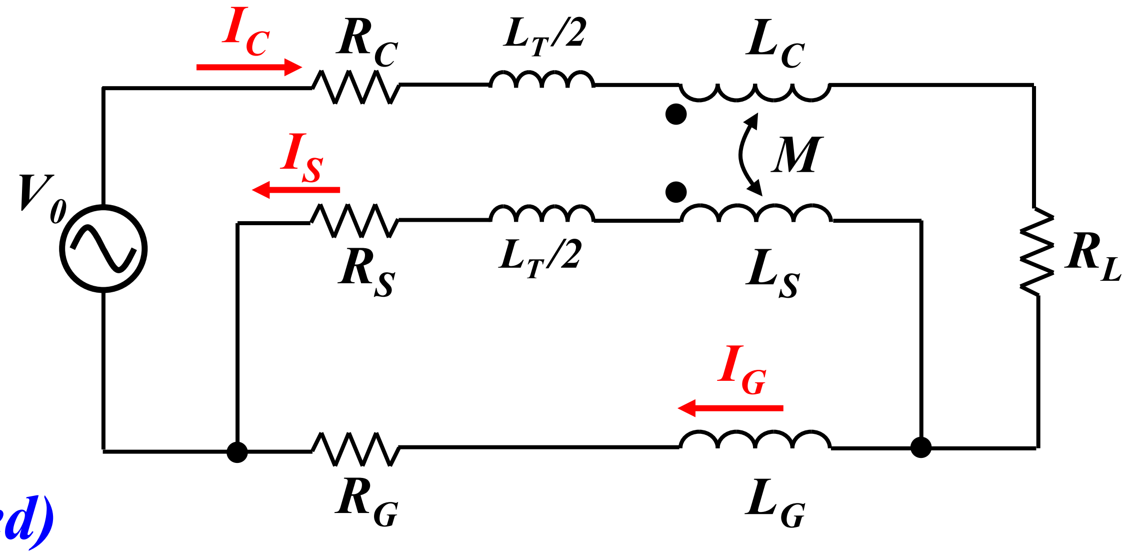
$$\omega^2[(L_S + L_G)^2 - (L_T/2)^2] = R_S^2 - R_G^2$$

$$\omega = \sqrt{\frac{R_S^2 - R_G^2}{(L_S + L_G)^2 - (L_T/2)^2}}$$

$$f_c = \frac{1}{2\pi}\sqrt{\frac{R_S^2 - R_G^2}{(L_S + L_G)^2 - (L_T/2)^2}}$$

$$f_c \approx \frac{\sqrt{R_S^2 - R_G^2}}{2\pi(L_S + L_G)} \qquad L_S + L_G \gg L_T/2$$

Setup Parameters



$L_T/l = 0.25\ \mu H/m$
(from RG-58 coaxial cable datasheet)

$l = 4.8\ m$

$L_T = 1.2\ \mu H$

$L_C = L_S = 23.8\ \mu H$

$L_G = 0.6\ \mu H$

(next slides)

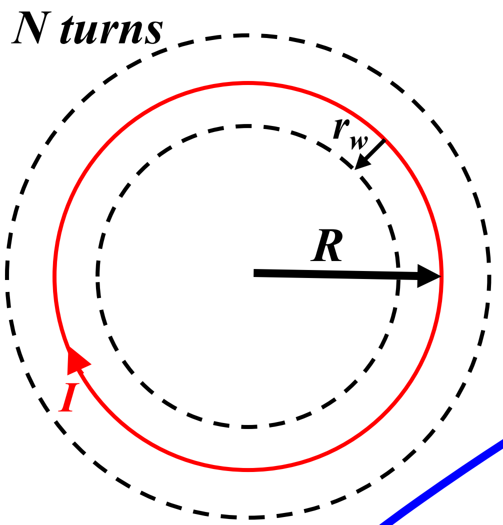
$R_S = 96\ m\Omega$ *(measured)*

$R_G = 15\ m\Omega$ *(measured)*

$R_L = 50\ \Omega$

Inductance of Circular Loop

- **From Missouri University of Science and Technology inductance calculator**
  - http://emclab.mst.edu/inductance/



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

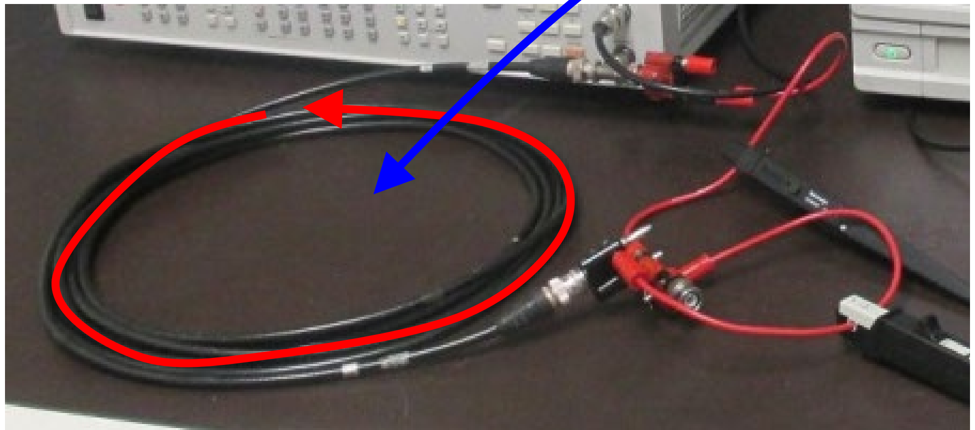
$N = \sim 5.5$

$\mu_r = 1$

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$R = 6$ inches $= 15$ cm

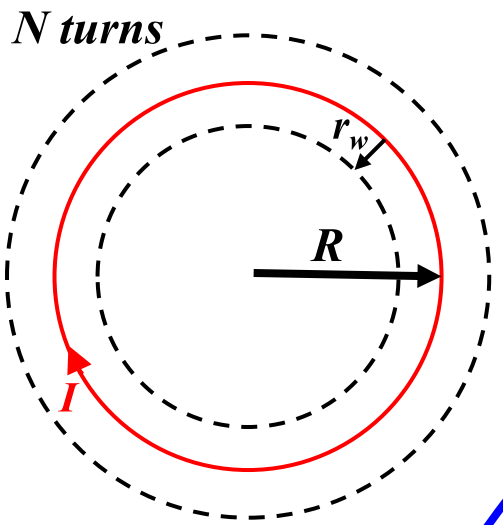
$r_w = 0.25$ cm (shield radius)



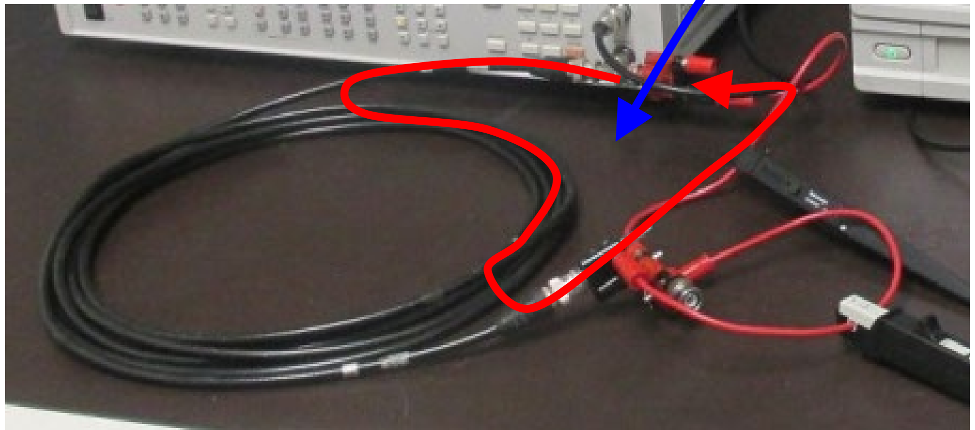
$L_C = L_S = \sim 23.8\ \mu H$

Inductance of Circular Loop (cont.)

- **Coiled cable in series with loop completing connections to signal generator:**



$$L_{loop} \approx N^2 \mu_r \mu_0 R\left(\ln\frac{8R}{r_w} - 2\right)$$



$N = 1$

$\mu_r = 1$

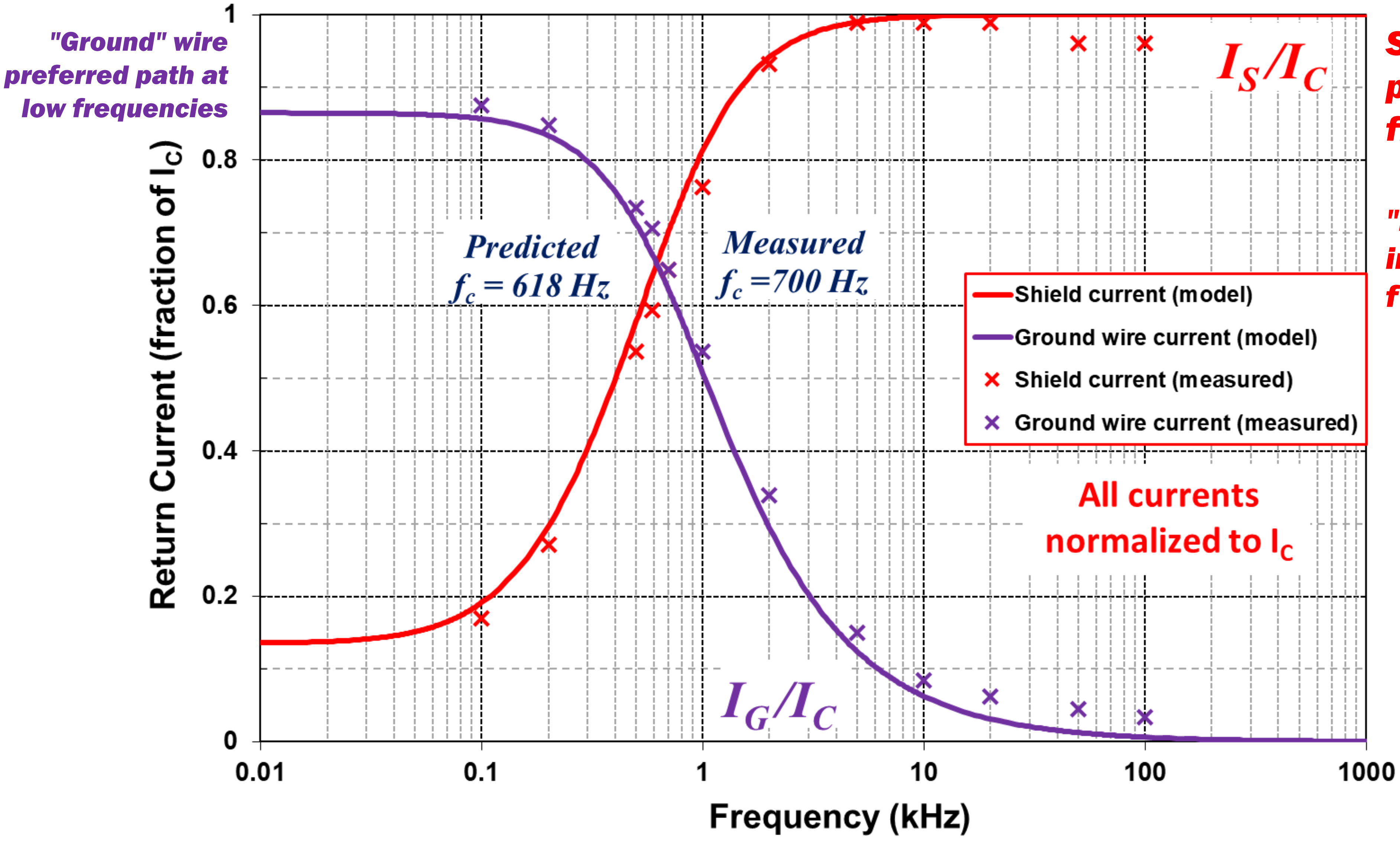
$\mu_0 = 4\pi \times 10^{-7}$ H/m

$R_{eff} = 12$ cm

$r_w = 0.25$ cm (shield radius)

$L_G = \sim 0.6\ \mu H$

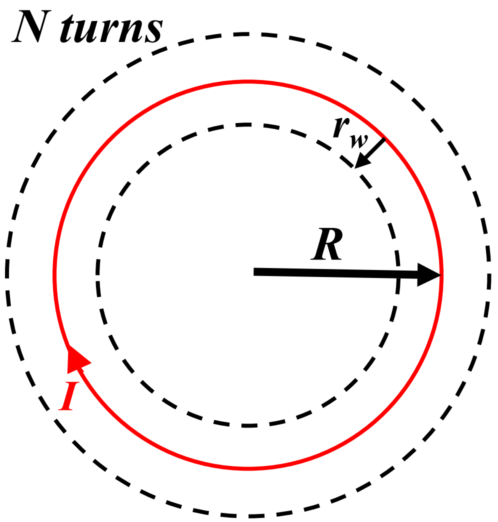
Measured Data vs. Model



Shield preferred path at high frequencies

"High" frequencies in this example: f > 700 Hz

Single-Turn Loop



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

$N = 1$

$\mu_r = 1$

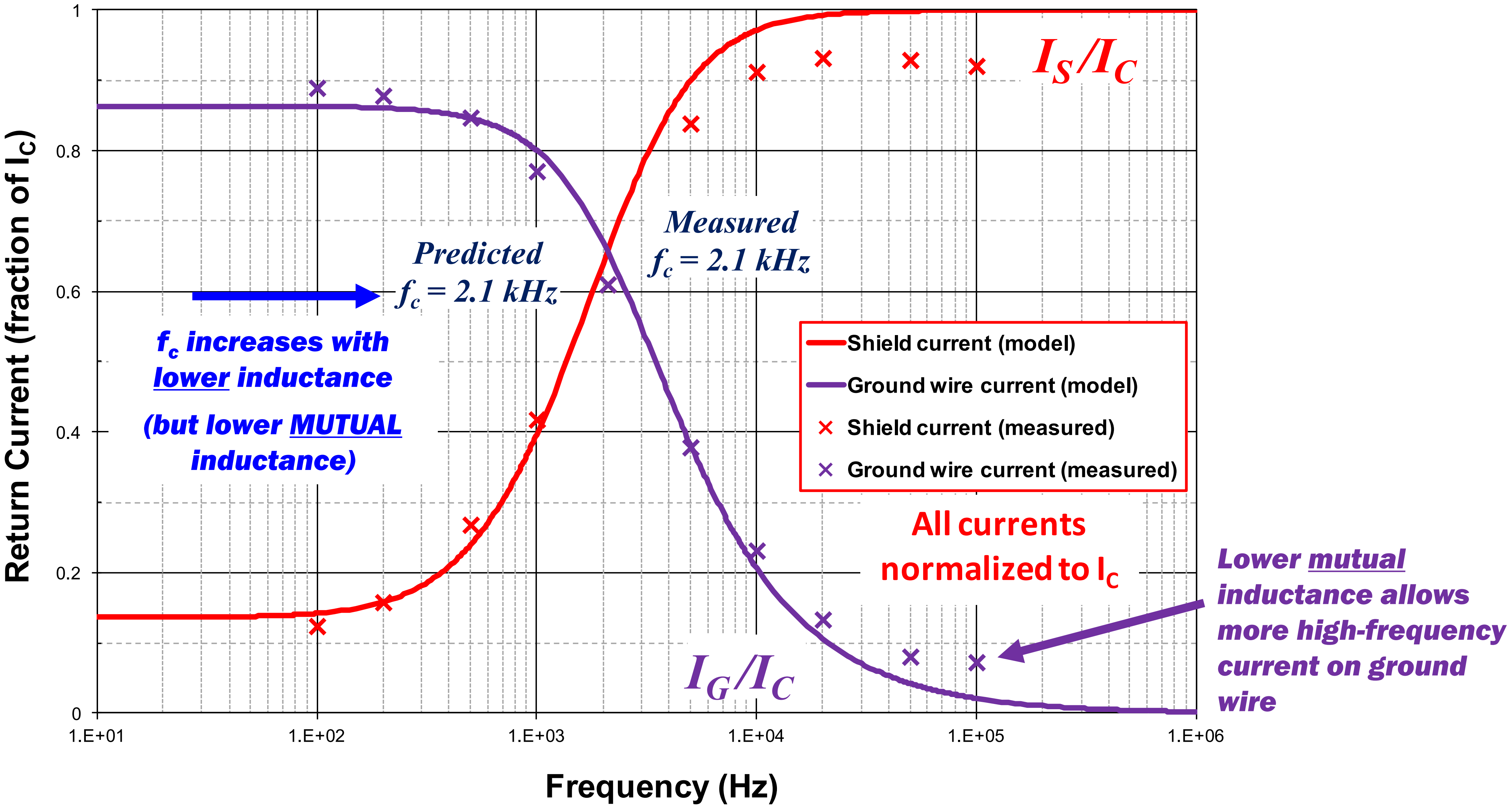
$\mu_0 = 4\pi \times 10^{-7}$ H/m

$R_{eff} = 5\ m / 2\pi = \sim 80\ cm$

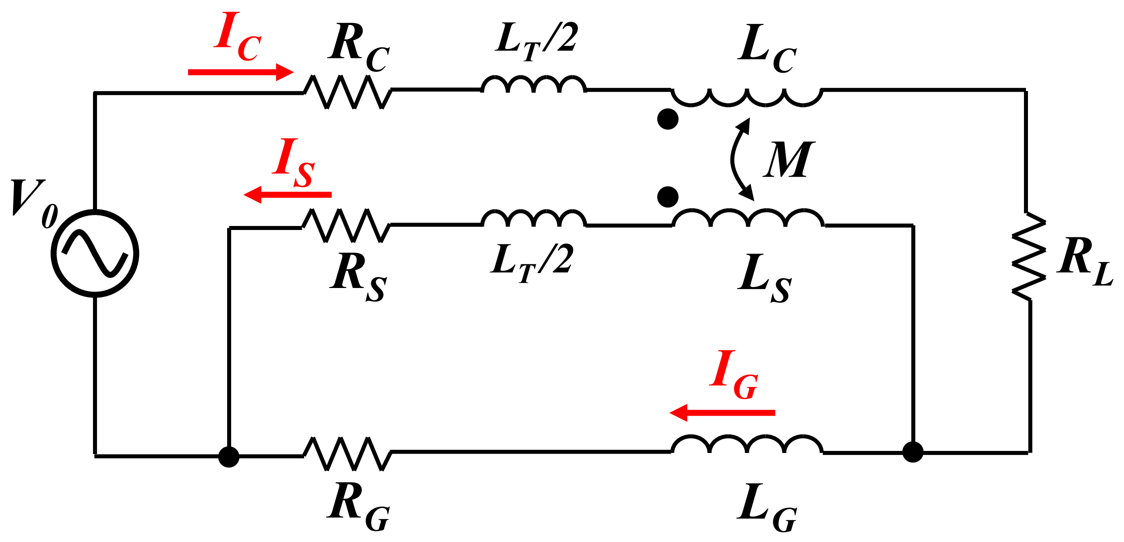
$r_w = 0.25\ cm$ (shield radius)

$$L_C = L_S = 5.9\ \mu H$$

Single-Turn Loop: Measured vs. Model

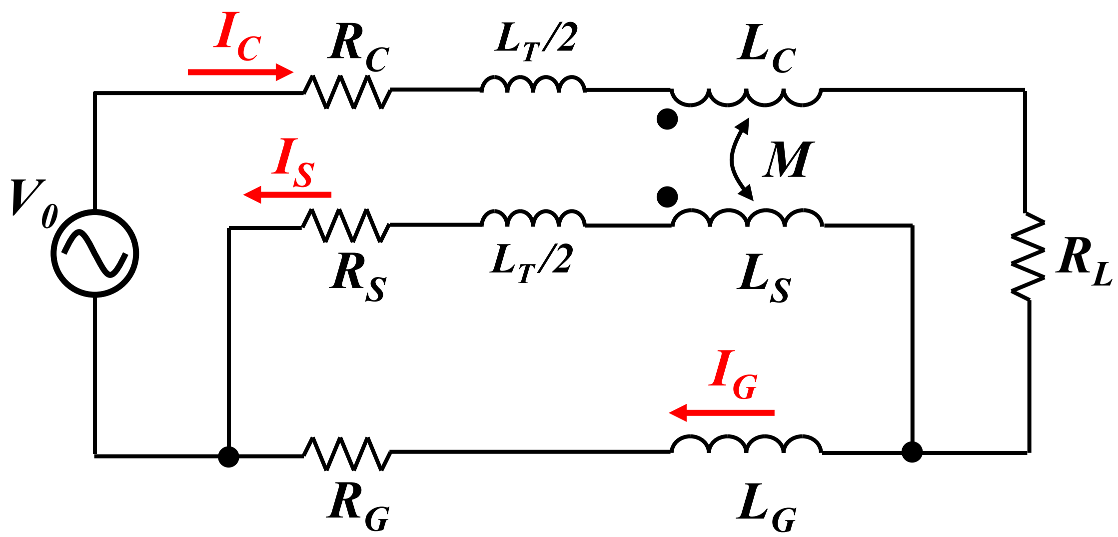


Current Return Path Observations



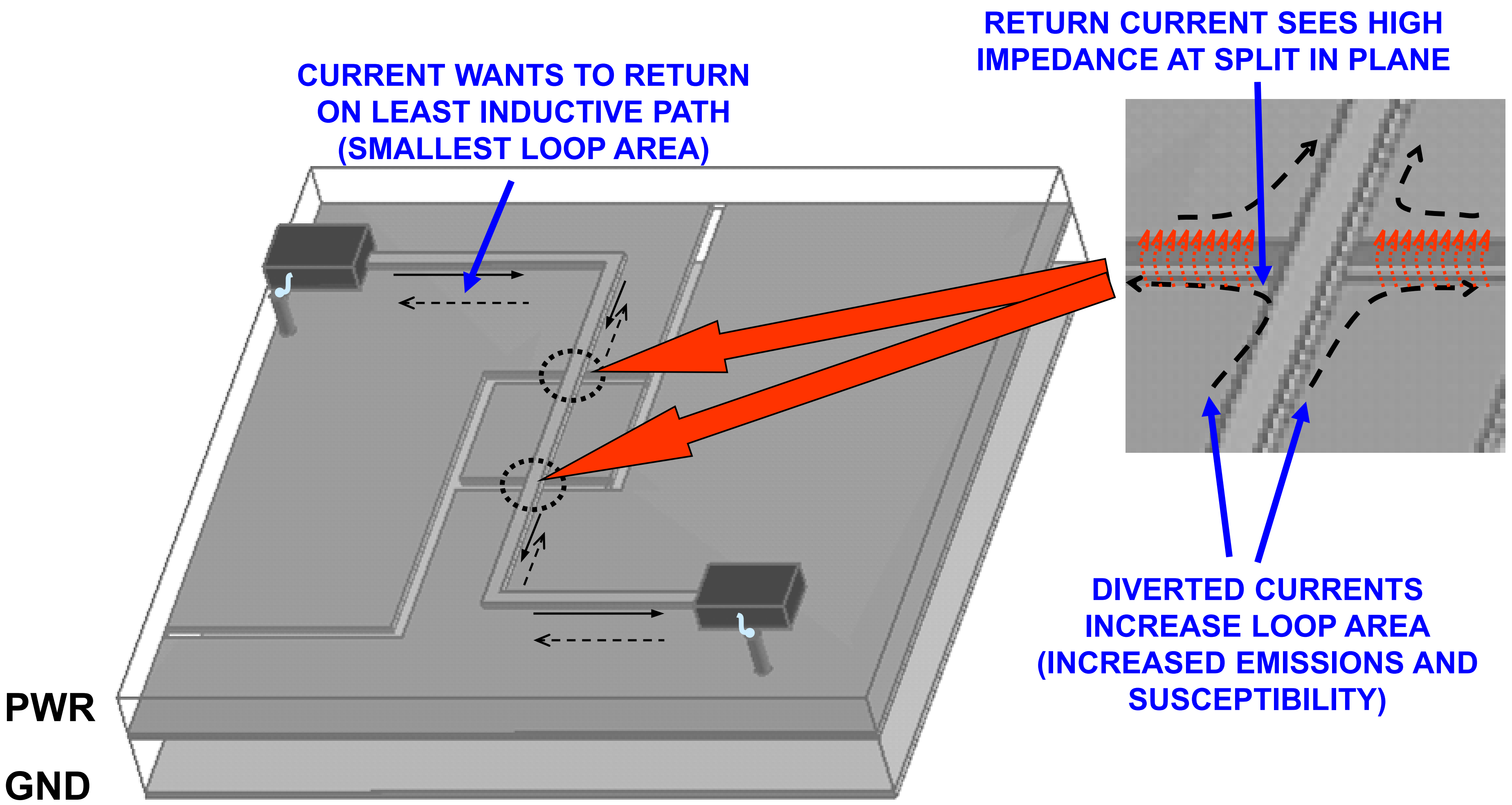
- **CURRENT RETURN PATH IS FREQUENCY DEPENDENT!**
- **Low frequency currents follow paths defined by resistive dividers**
- **High frequency currents will find their way back to source using most efficient available path**
  - NOT "path of least resistance" or, strictly speaking, "path of least inductance"
  - High mutual inductance between adjacent send and return paths forces current to return on adjacent path ("transformer action")
  - Simply provide the path and let nature do the work for you
  - “Ground loops” less of a concern at these frequencies
  - **Open-circuited shield at one end to avoid "ground loop" misses the point by a long shot**

Current Return Path Observations



- **Practical implications for circuit and system design:**
  - Cabling
    - Twisted pairs, coax
    - Terminate bundle shields at both ends to ensure low impedance path back to source for high frequency currents **(do NOT leave open for sake of avoiding "ground loop")**
  - PC board: return (-) traces/vias immediately adjacent to send (+) traces/vias
  - If using ground plane as return path, avoid routing traces over splits in ground plane
  - **SPLIT GROUND PLANES NOT RECOMMENDED**

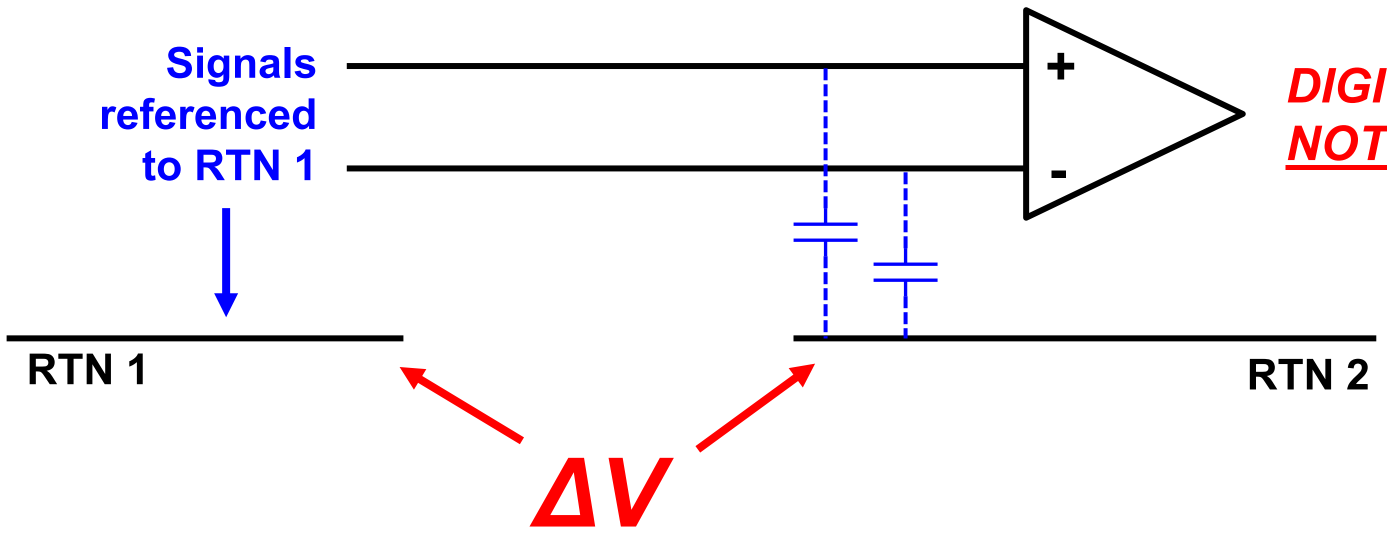
Split Reference Plane



AVOID RUNNING TRACES OVER SPLITS IN GROUND PLANE

Courtesy of Dr. Bruce Archambeault

Unbalanced capacitances to (+) and (-) lines can (will) distort waveform seen by receiver circuit

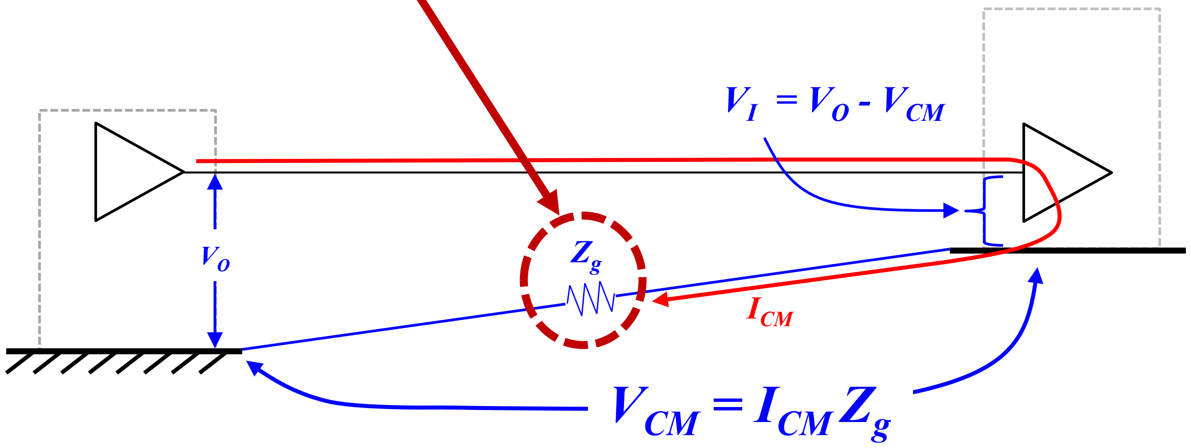


DIGITAL CIRCUITS NOT IMMUNE!

Noise potential between return planes can (will) couple onto traces routed over gap

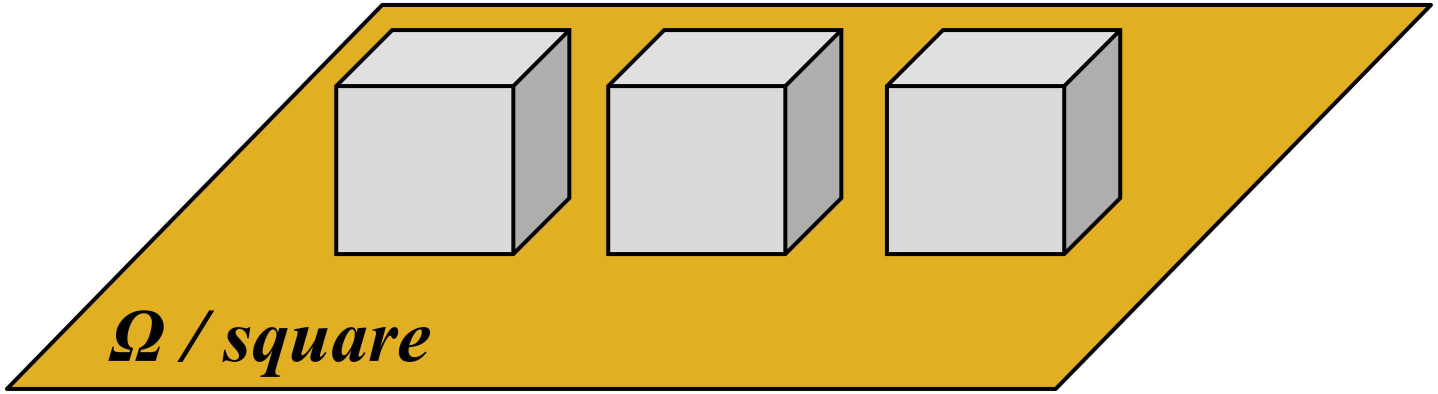
Minimize "Ground" Impedance

- **Recall: Minimize V_{CM} (ground bounce) by:**
  - Minimizing common mode current I_{CM} and/or
  - **Minimizing "ground" impedance Z_g**



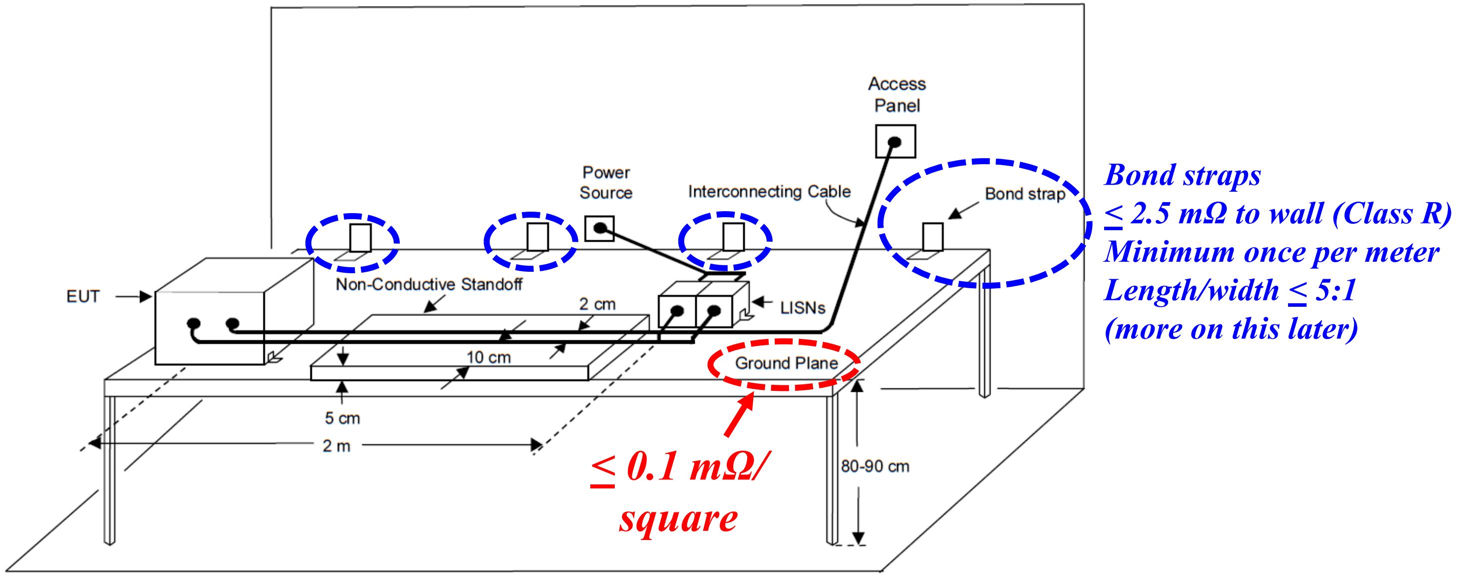
Ground Plane

- Ground plane provides lowest impedance ground connection
- Surface resistance typically specified in terms of “ohms per square”
- "Ohms per square what?"

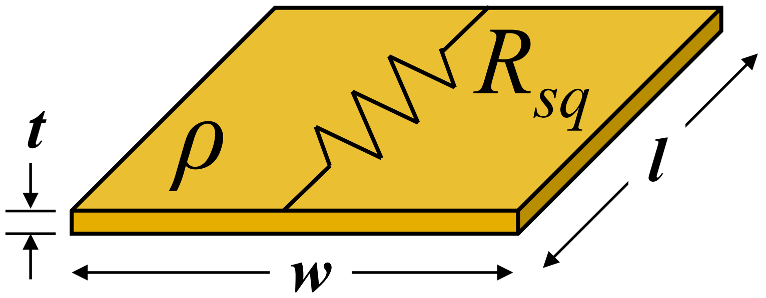


Ground Plane (cont.)

- **MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, section 4.5.3.1:**
  - The ground plane shall have a surface resistance no greater than **0.1 milliohms per square**.
  - The DC resistance between metallic ground planes and the shielded enclosure shall be 2.5 milliohms or less.
  - The metallic ground planes shall be electrically bonded to the floor or wall of the basic shielded room structure at least once every 1 meter. The metallic bond straps shall be solid and maintain a five-to-one ratio or less in length to width.



"Ohms Per Square What?"



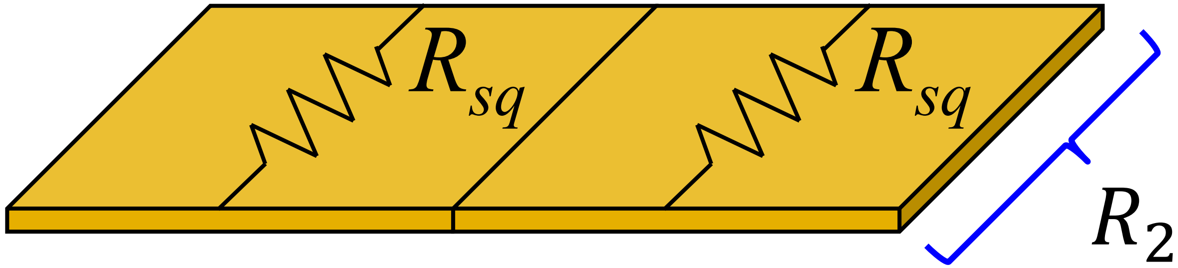
(For square: $w = l$)

$$R_{sq} = \frac{\rho l}{A}$$

ρ = resistivity of material

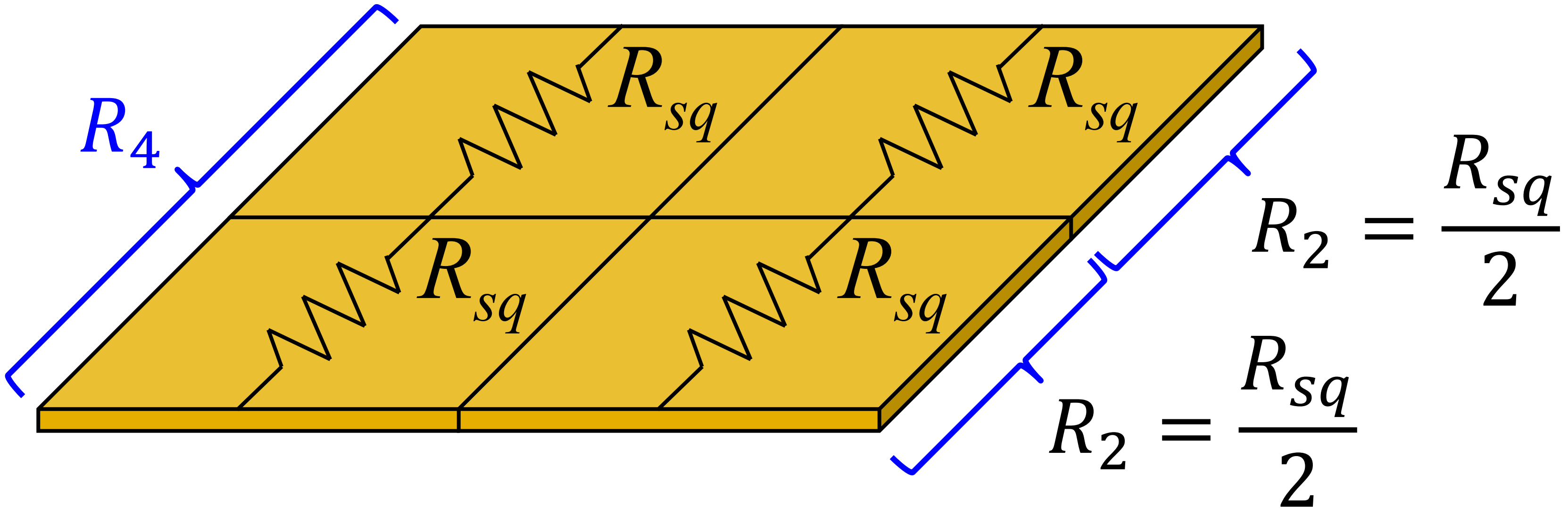
Cross-sectional area: $A = wt$

"Ohms Per Square What?" (cont.)



$$R_2 = \frac{R_{sq}}{2}$$

"Ohms Per Square What?" (cont.)

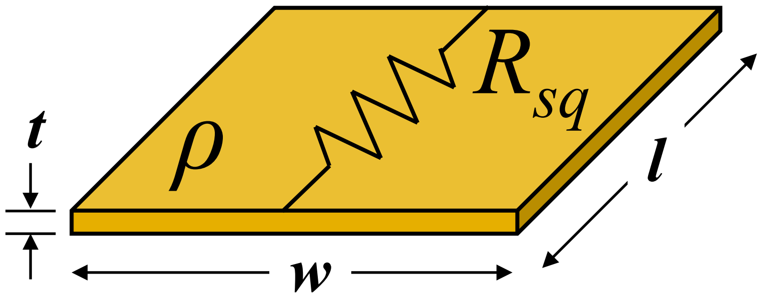


$$R_4 = 2R_2 = 2\frac{R_{sq}}{2} = R_{sq}$$

Resistance is independent of size of square

"Ohms per square," Q.E.D.

"Ohms Per Square What?" (cont.)



(For square: $w = l$)

ρ = resistivity of material

Cross-sectional area: $A = wt$

$$R_{sq} = \frac{\rho l}{A} = \frac{\rho l}{wt} = \frac{\rho}{t}$$

Example: $t = 1\,mm$

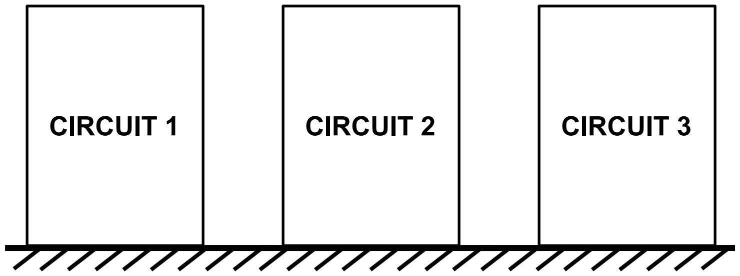
$$\rho_{Cu} = 1.68 \times 10^{-8}\ \Omega \cdot m$$
$$\left(R_{sq}\right)_{Cu} = 0.0168\ \text{m}\Omega/square$$

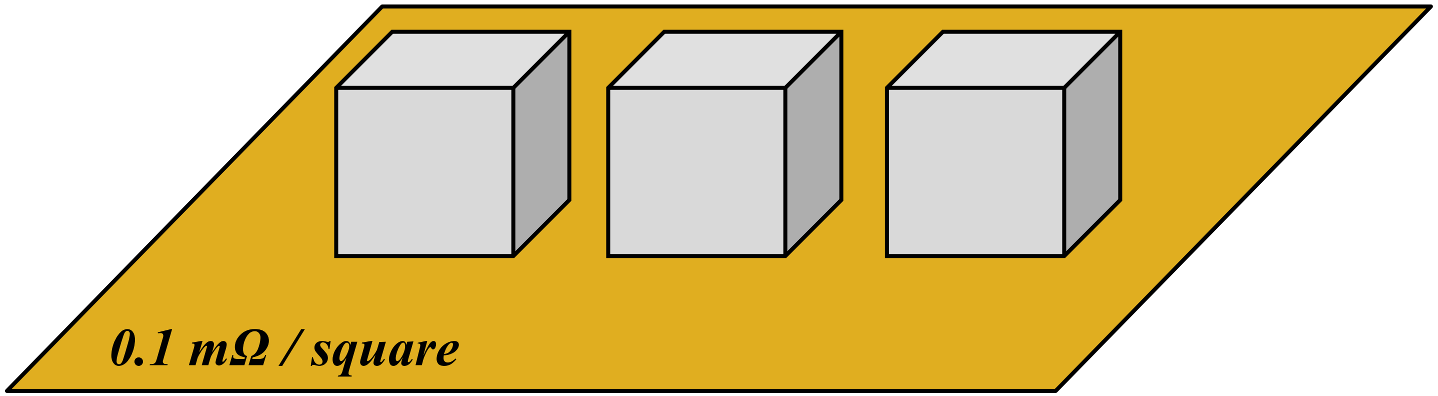
$$\rho_{Al} = 2.82 \times 10^{-8}\ \Omega \cdot m$$
$$\left(R_{sq}\right)_{Al} = 0.0282\ \text{m}\Omega/square$$

Not terribly difficult to meet ≤ 0.1 mΩ/square

"Ohms Per Square What?" (cont.)

- "Multi-point" ground scheme implemented by mounting enclosures directly to ground plane (structure)





"Ohms Per Square What?" (cont.)

- **Surface resistance measurement**
  - Specific locations of probes does not matter
  - …as long as they enclose a square portion of the surface

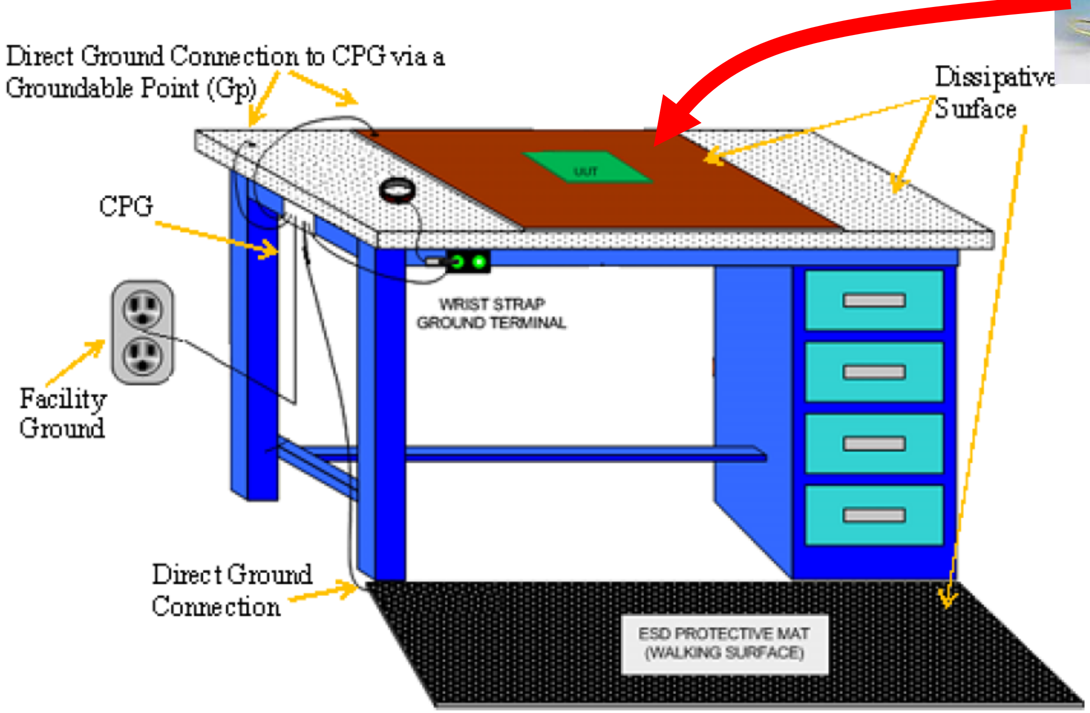


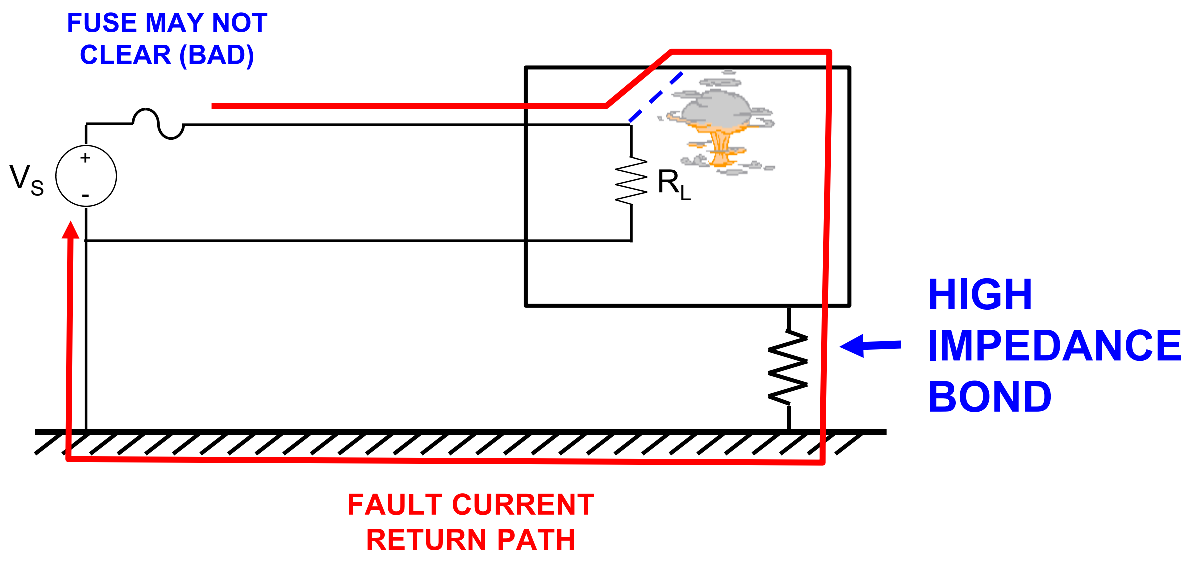
Figure 5-1: Typical ESD Grounded Workstations
(See Table 5-1 for Applicable Requirements and Definitions)

Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- “Grounding” in the “Real World” (and in “Real Space”)
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
- Summary

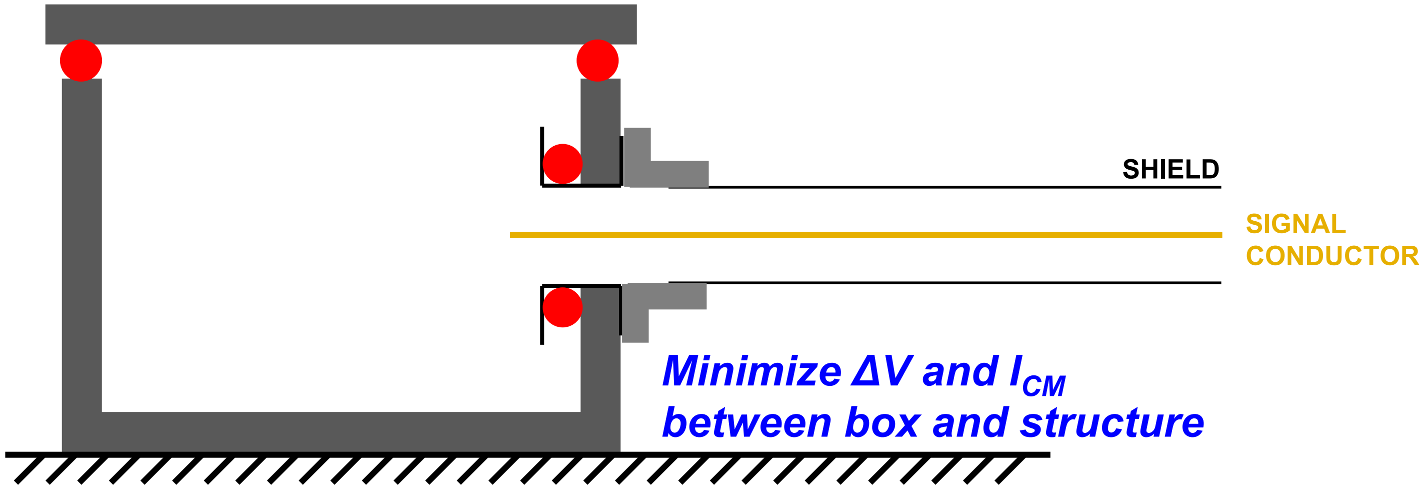
Bonding

- Bond is important part of grounding architecture
- Poor (high impedance) bond will limit fault current
- Hardware can be damaged without blowing fuse (bad)



Bonding (cont.)

- Good metal-to-metal contact is essential to minimize ΔV and I_{CM} between surfaces
- Non-conductive coatings must be avoided
- Must be considered in conjunction with thermal requirements



Bonding - NASA-STD-4003

Table 1—Summary of Electrical Bonding Classes

	POWER RETURN	SHOCK HAZARD	RADIO FREQUENCY	LIGHTNING	ELECTROSTATIC CHARGE
BOND CLASS	CLASS C	CLASS H	CLASS R	CLASS L	CLASS S
PURPOSE OF BOND	Reduces power and voltage losses at the bonding interfaces. Applies to equipment and structure, which are required to return intentional current through structure.	Protects against fire or shock to personnel. Applies to equipment and structure that may be required to carry fault current in case of a short to case or structure.	Protects equipment from RF emissions. Applies to equipment that could generate, retransmit, or be susceptible to RF. Includes antenna mounts and cable shield connections. Covers wide frequency range.	Protects equipment from lightning effects. Applies to equipment or structure that would carry current resulting from a lightning strike.	Protects against electrostatic discharge. Applies to any item subject to electrostatic charging.
BOND REQMT.	Requires low impedance and low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Requires low impedance and low voltage across joints to prevent shock hazard or fire due to short. Jumpers and straps acceptable.	Requires low RF impedance at high frequency. Direct contact preferred. No jumpers. Short, wide strap may be used as last resort.	Requires low impedance at moderate frequency. Bonding components are required to withstand high current without arcing. Straps and jumpers are required to withstand high magnetic forces.	Allows moderate impedance. Jumpers and straps acceptable.
DC BOND RESISTANCE REQMT.	Bonding resistance requirement depends on current.	Bonding resistance requirement, 0.1 ohm or less. Special requirements when near flammable vapors.	Bonding resistance requirement, 2.5 milliohms or less. Low inductance required.	Bonding resistance requirement depends on current. 500 volts or less across any joint. Low inductance required.	Typical bonding resistance requirement, 1.0 ohm or less.
FREQ. REQMT.	Low	Low	High	High	Low
CURRENT REQMT.	High	High	Low	High	Low

Low frequency bonds allow use of straps and jumpers.
High frequency bonds require low inductance paths. Short straps are sometimes acceptable.
High current bonds require large cross-sectional areas.
Low current bonds allow use of small contact areas.

Full document available at:

https://standards.nasa.gov/

Click on:

- ***NASA Technical Standards***
- ***4000 - Electrical and Electronics Systems, Avionics/Control Systems, Optics***
- ***NASA-STD-4003***

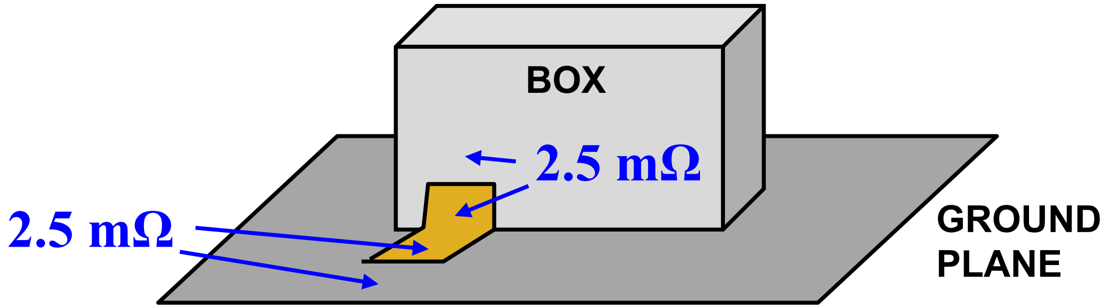
Bonding – Class H (Shock and Fault Protection)

- **From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:**
  - 4.2 Shock and Fault Protection (Class H) – excerpts:
    - All electrically conductive equipment cases that may develop potentials due to short circuits shall be electrically bonded to structure.
    - Bonding of structural joints in the fault current return path shall provide for the maximum current that may be delivered by the power supply until the fuse or circuit breaker disconnects.
    - Exposed cases or chassis of electrical or electronic equipment shall be bonded to structure with a resistance of **0.1 ohm or less.**

Bonding – Class R (Radio Frequency)

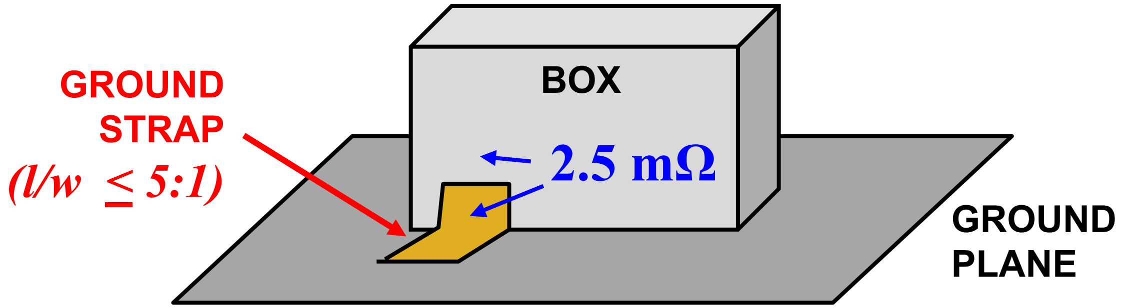
- **From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:**
  - 4.3 Electromagnetic Interference or Radio Frequency (Class R) – excerpts:
    - RF bonding is required between all conductive basic structural components of the vehicle.
    - **The dc resistance across each joint shall not exceed 2.5 milliohms**.
    - **The dc resistance from equipment case to structure shall not exceed 2.5 milliohms**.

2.5 mΩ applies to each individual metal-to-metal junction (NOT to full series of junctions)



Bonding – Class R (cont.)

- **From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:**
  - <u>6.4 Electromagnetic Interference or Radio Frequency (Class R):</u>
    - There is no RF design basis for the historical 2.5-milliohm requirement except to ensure a good metal-to-metal contact that can be expected to be consistent.
    - If the use of bond straps for RF bonds is unavoidable, strap length should always be limited to a length to width ratio of 5 to 1.
    - The 2.5-milliohm, dc resistance requirement is good for a standard, but one should not assume a good RF bond exists just because the dc resistance is less than 2.5 milliohms. Also, extra effort need not be made just to satisfy the dc requirement if the RF impedance is much higher due to the inductance of the configuration. Look at the whole configuration to get the lowest impedance possible at the frequencies of interest to produce a good RF bond.

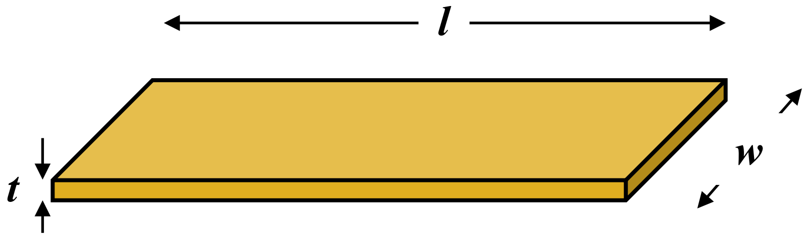


Bonding Summary

- **Class H**
  - Shock and Fault Protection
  - 0.1 ohm
  - Must have current capacity to withstand worst-case fault current
- **Class R**
  - Radio Frequency (RF)
  - 2.5 milliohms
  - Direct metal-to-metal contact preferred
  - If a strap is used, use maximum length-to-width ratio of 5:1
    - Much less inductance than wire
    - Multiple parallel straps recommended (one on each face of box)
  - Article on origins of 2.5 mΩ requirement:
    - Ken Javor, "Lightning and RF Electrical Bonding," IN Compliance magazine, May 2021
    - *https://incompliancemag.com/lightning-and-rf-electrical-bonding/*

Self-Inductance of Rectangular Strap vs. Wire

RECTANGULAR STRAP



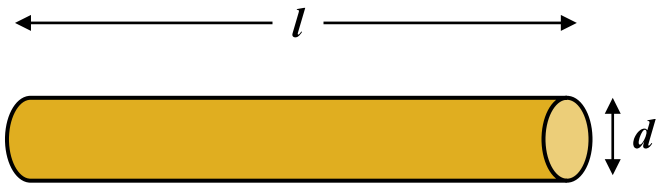
From Ott: $L_{strap} = 0.002l\left[ln\left(\frac{2l}{w+t}\right) + 0.5 + 0.2235\left(\frac{w+t}{l}\right)\right]$

For w >> t:

$$L_{strap} \approx 0.002l\left[ln\left(\frac{2l}{w}\right) + 0.5 + 0.2235\left(\frac{w}{l}\right)\right]$$

Dependence on l as well as l/w
(the shorter, the better)

WIRE



$$L_{wire} = 0.002l\left[ln\left(\frac{4l}{d}\right) - 1\right]$$

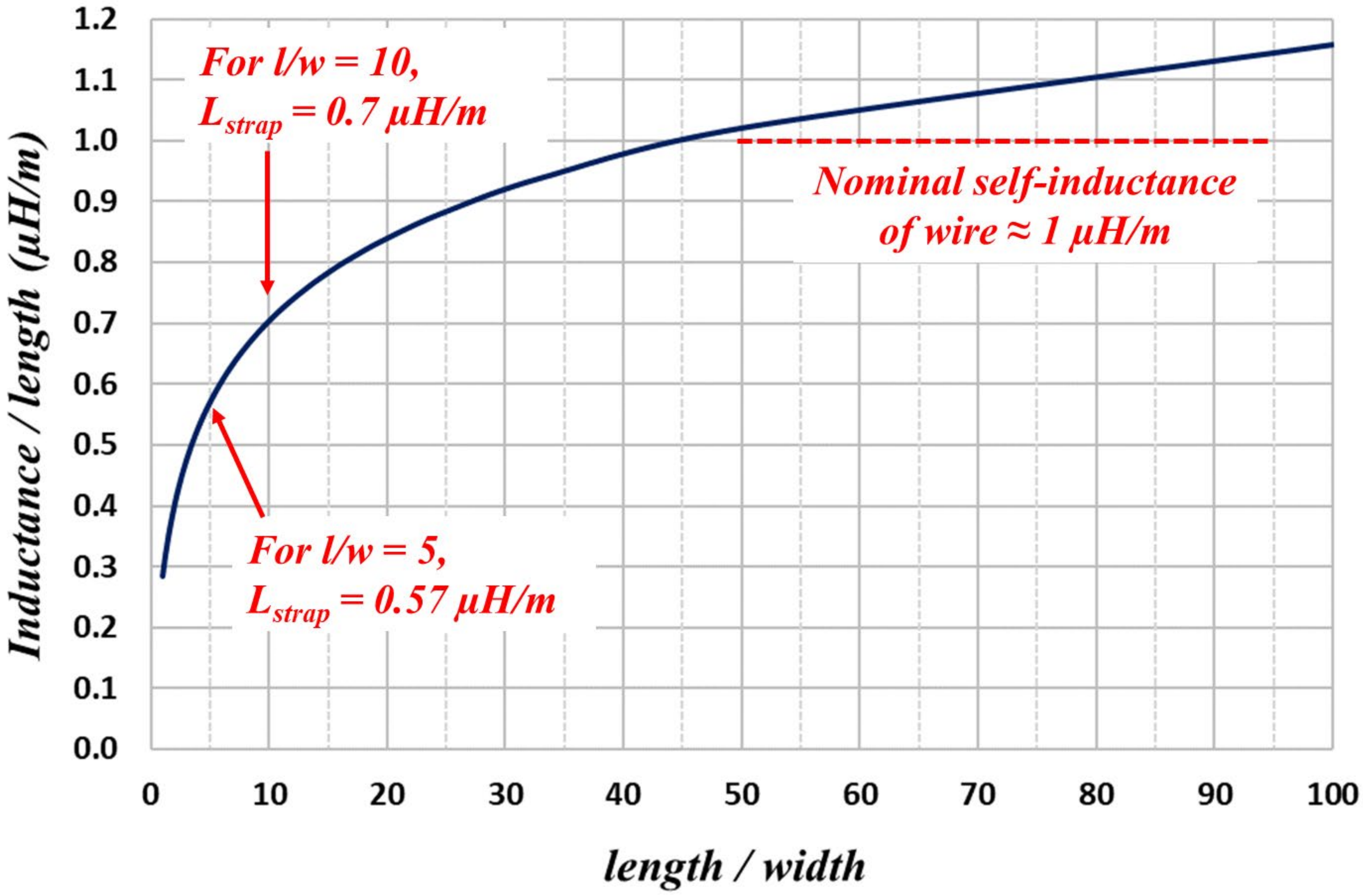
Nominal
$L_{wire} \approx 10$ nH/cm
≈ 1 µH/m

(We'll see this again...)

Inductances in µH

All dimensions in cm

Self-Inductance of Rectangular Strap vs. Wire (cont.)



Self-Inductance of Rectangular Strap vs. Wire (cont.)

- **Purpose of rectangular strap is to minimize inductance of RF bond**
- **5:1 "maximum" length-to-width (l/w) ratio provides inductance < 60% that of wire**
- **If 5:1 l/w ratio cannot be maintained, bond will have higher inductance determined by logarithmic relationship (does not just suddenly stop working)**
- **For l/w > 50, may be preferable to use beefy wire and consider it Class H bond for fault current**
- **Rectangular strap may also provide fault current path**
  - Ensure that cross-sectional area is sufficient to carry worst-case fault current
  - Compare to cross-sectional area of AWG used for power service in question
  - Example: Copper strap, w = 25.4 mm (1 inch), t = 0.5 mm
    - Cross-sectional area = 12.5 mm^2
    - Comparable to AWG 8 with 75 A capacity (per table on earlier slide)
    - *(Not difficult; just don't leave it to guesswork)*

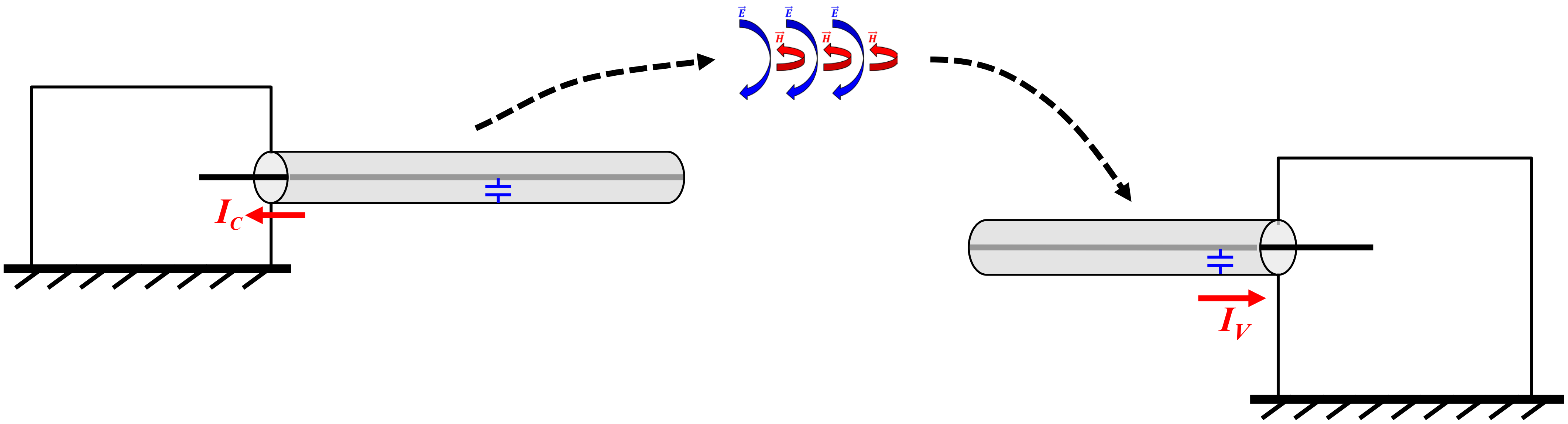
Discussion: OSAM-1 Example

Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- “Grounding” in the “Real World” (and in “Real Space”)
- Bonding
- **Shielding**
  - Why Do We Shield?
  - Skin Depth
  - Enclosure Shielding
  - Cable Shielding
- Anatomy of a Grounding Scheme
- Summary

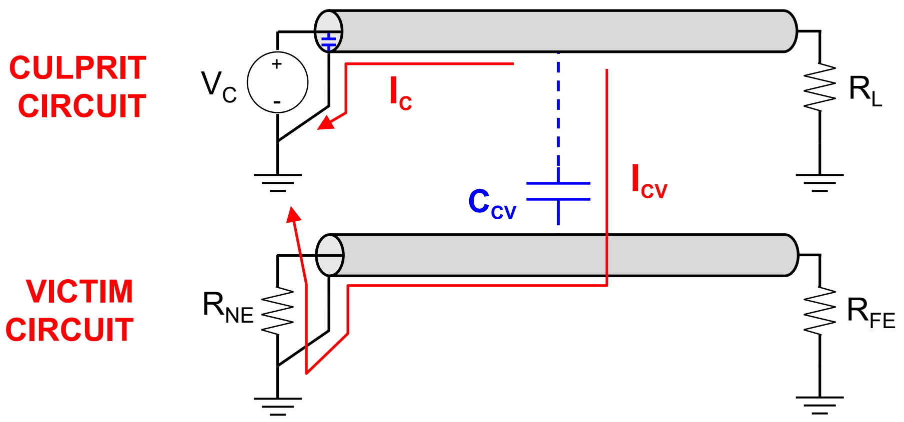
Why Do We Shield?

- **Raisons d'être for shielding:**
  - Contain emissions from noisy circuits
  - Protect signal carrying conductors from interference
  - Provide return current path to **SOURCE** over lowest impedance (most desirable) path possible

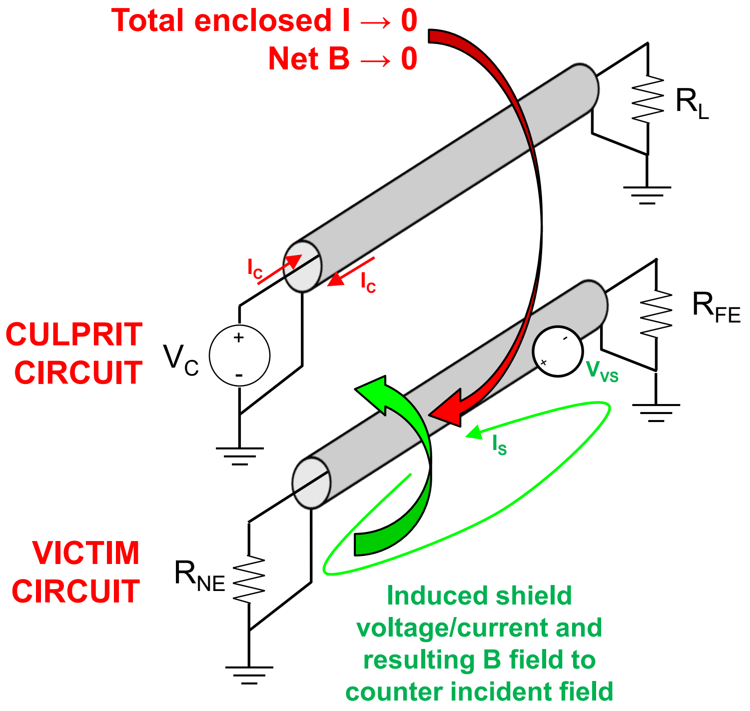


Cable Shielding - Capacitive Coupling

- **Emissions**
  - Culprit current couples to its own shield and returns to its source
- **Susceptibility**
  - Any remaining current that makes its way to victim couples to victim's shield and gets shunted back to source (via "ground"), protecting victim signal wire
- **Shields must provide low impedance path back to source**
  - Includes shield terminations, connector to chassis connections, reference plane to chassis connections, etc.



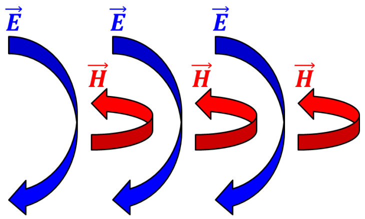
Cable Shielding - Inductive Coupling

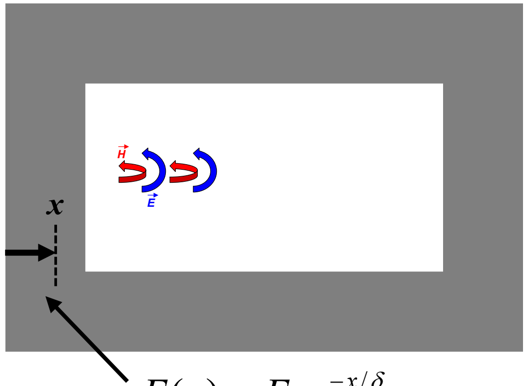


- **Emissions**
  - Provides return current path to cancel culprit current
  - Reduced net current reduces net magnetic field
- **Susceptibility**
  - Reduced loop area
  - Any remaining B field induces V and I in shield to counter incident field
  - Shield must be terminated at both ends to allow current to flow
  - Drawback: Can induce secondary coupling onto victim wire
  - Internal twisted pairs recommended for additional magnetic field protection

SHIELDING CAN HELP MITIGATE INDUCTIVE COUPLING, BUT IT IS GENERALLY NOT SUFFICIENT (INTERNAL TWISTED PAIRS RECOMMENDED FOR ADDITIONAL PROTECTION)

Skin Depth

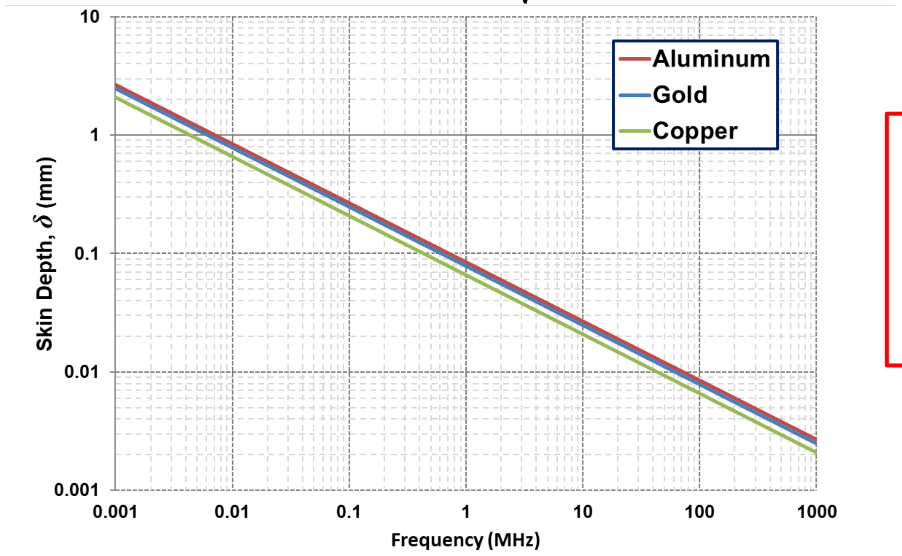




$$E(x) = E_{in} e^{-x/\delta}$$
$$H(x) = H_{in} e^{-x/\delta}$$

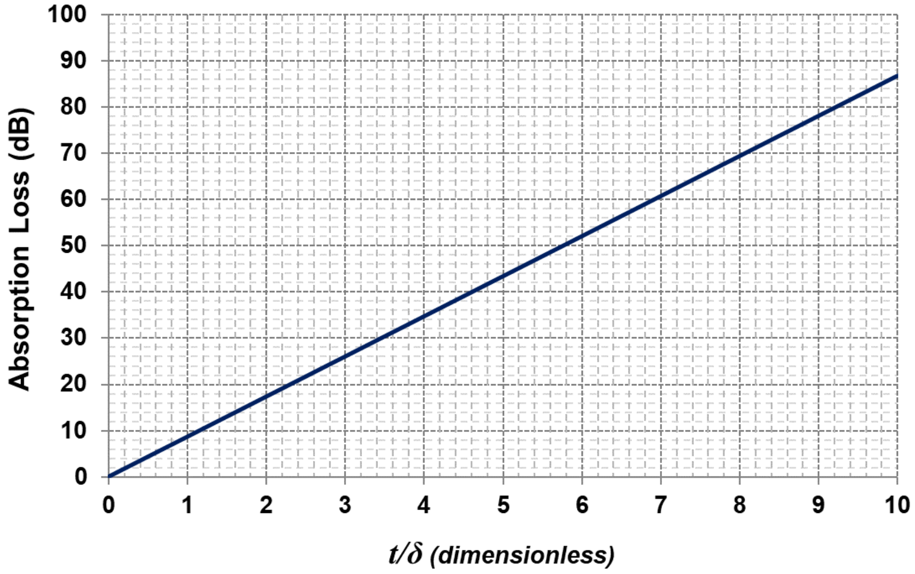
$$AL_{dB} = 20\log_{10} e^{-t/\delta}$$
$$= \left(-\frac{t}{\delta}\right) 20\log_{10} e$$
$$= -8.67\left(\frac{t}{\delta}\right)$$

SKIN DEPTH $\delta = \dfrac{1}{\sqrt{\pi f \mu \sigma}}$



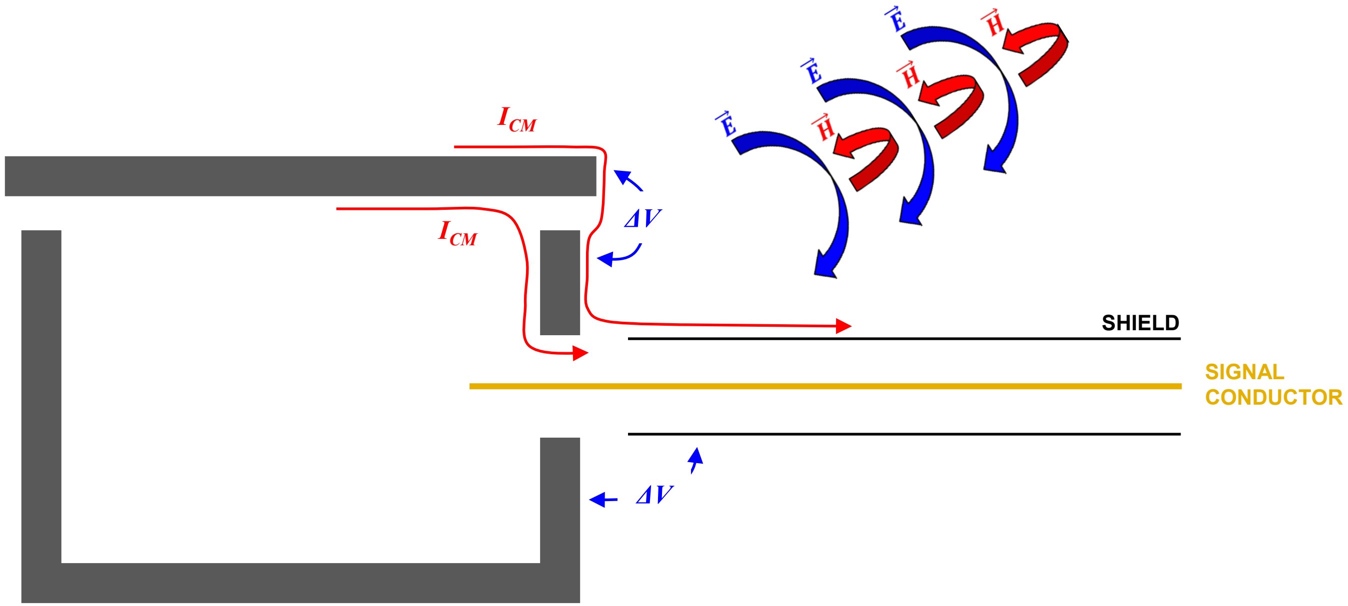
100 mils (2.54 mm) of aluminum provides > 80 dB attenuation above 100 kHz

ABSORPTION LOSS (ATTENUATION)



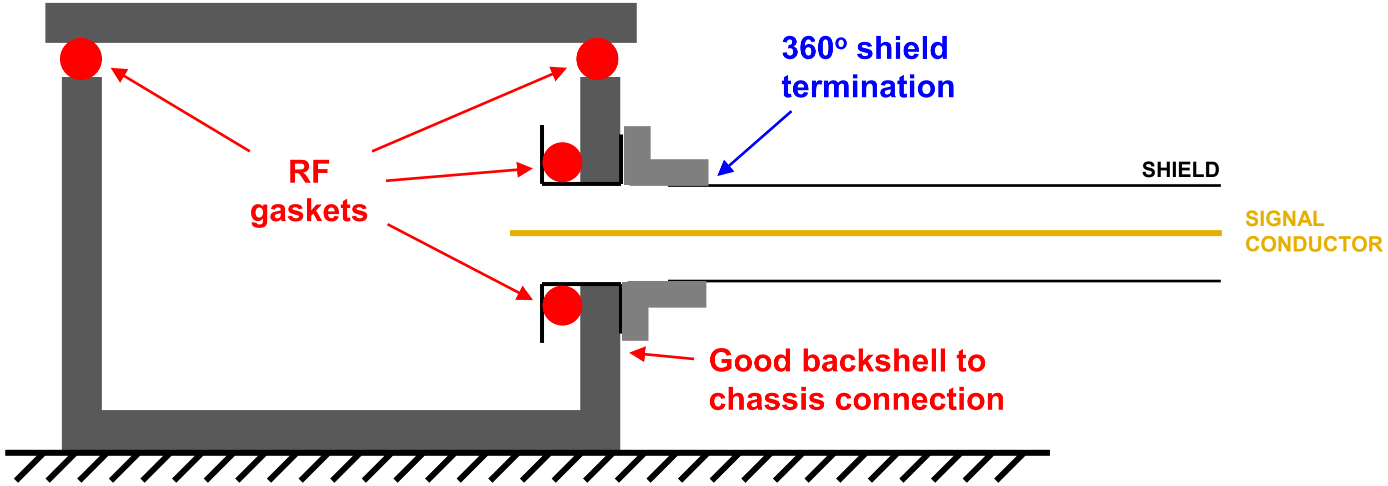
Enclosure Shielding - Seams and Penetrations

- **Metal chassis provides darned good shielding (previous slide)**
- **Weak point always comes at seams and penetration points**
  - Poor connections allow ΔV between conductors (antenna)
  - ΔV induces common mode current (I_{CM}) across connection impedance
  - I_{CM} induces radiated fields



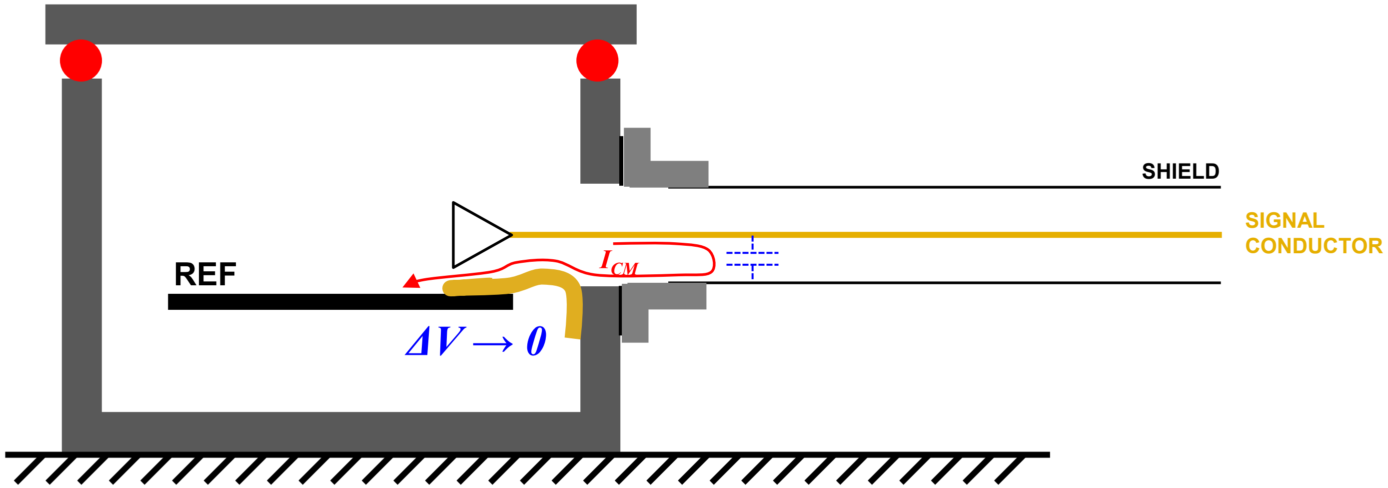
Enclosure Shielding - Seams and Penetrations (cont.)

- **Good metal-to-metal contact is essential**
  - RF gaskets on all seams and penetrations
  - 360º termination of shield to backshell **(NO PIGTAILS!!!)**
  - Good metal-to-metal contact between backshell and chassis
  - **Class R bonds**



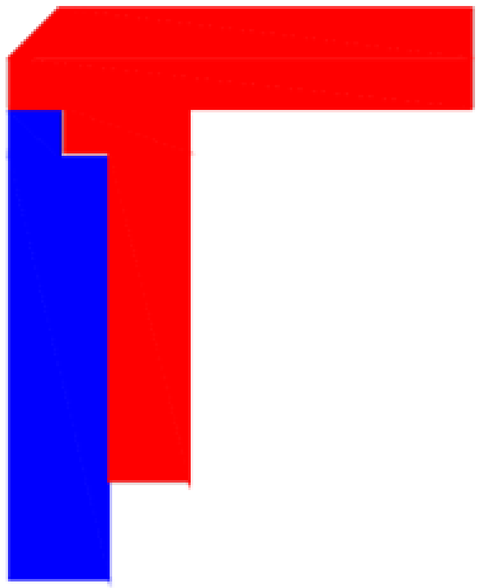
Enclosure Shielding - Seams and Penetrations (cont.)

- **Reference planes should be bonded to chassis at I/O connector(s)**
  - Provide low impedance path for currents to return to **SOURCE**
  - Minimize ΔV between reference plane and chassis
  - Reduce radiated emissions



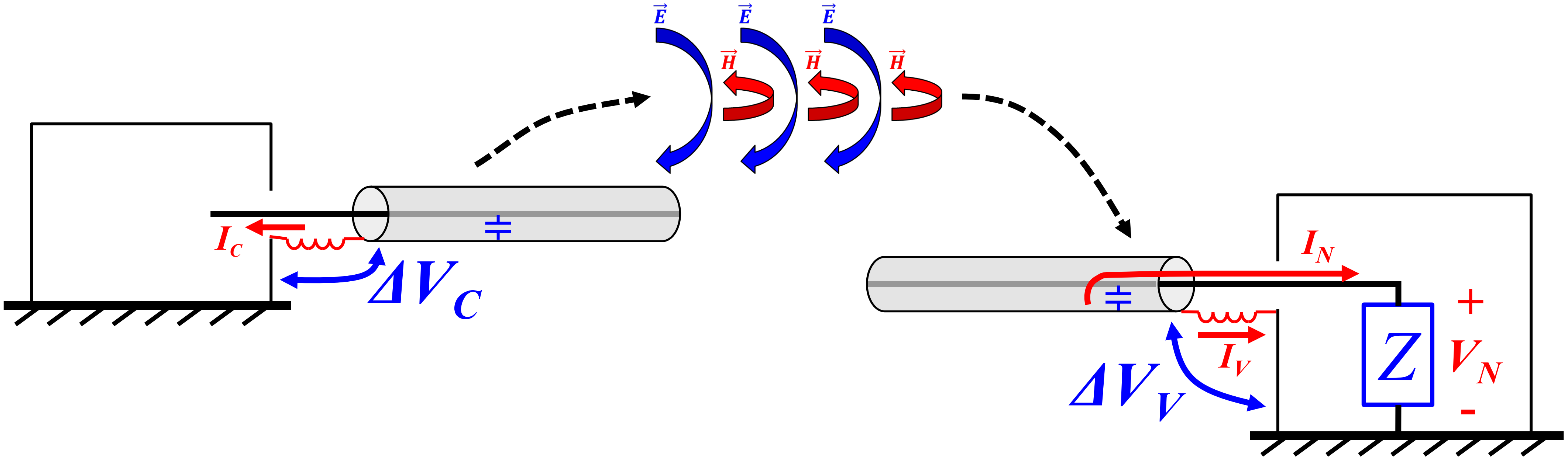
Enclosure Shielding - Seams and Penetrations (cont.)

- **Alternative for panel-to-panel seams**
  - Minimum of 2 right angle turns (“labyrinth”)
  - Electromagnetic energy has to “work” harder to get through seam

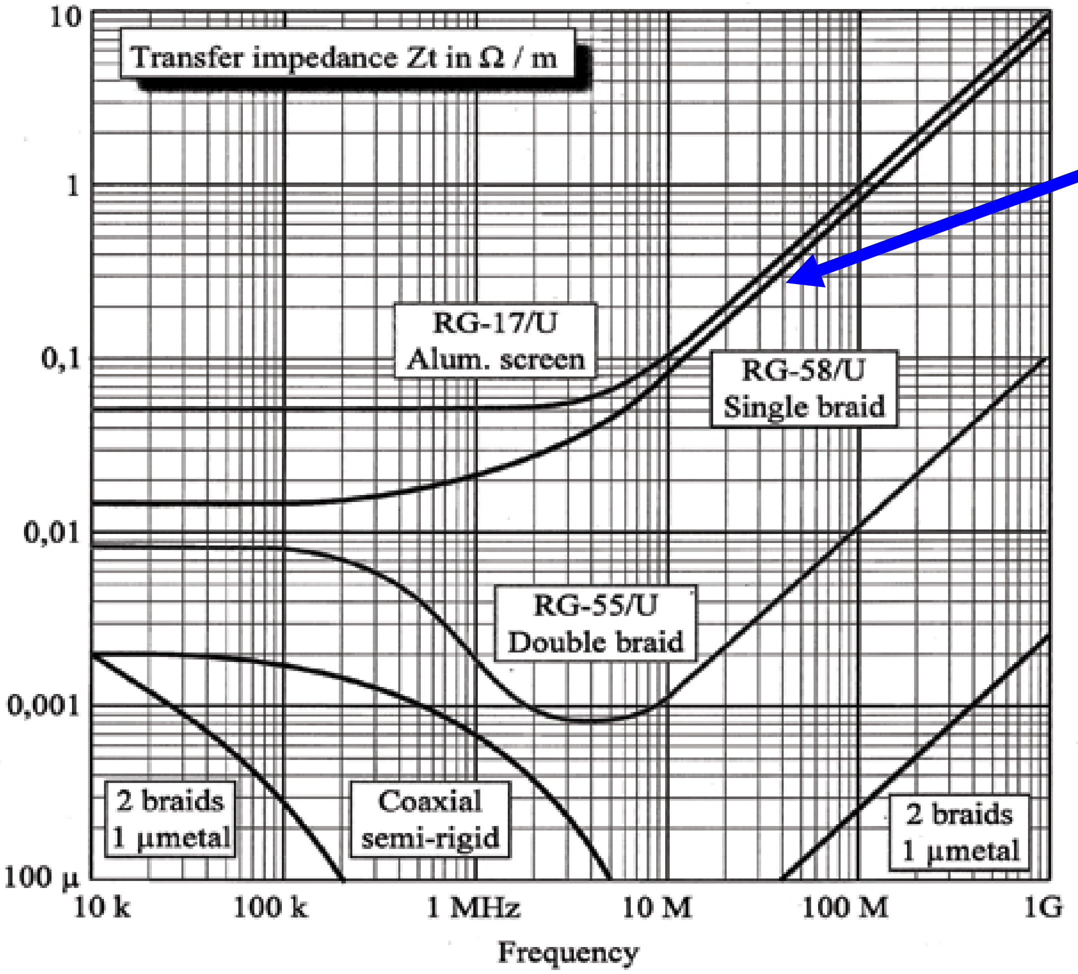


Cable Shield Terminations

- "Pigtail" termination has significant inductance (next slide)
- Allows ΔV between conductors (antenna)
- ΔV induces common mode current (I_{CM}) across connection impedance → inducing radiated fields
- Poor termination on victim shield allows noise current to flow into victim circuitry



Braided Shield Transfer Impedance and Pigtail Inductance



RG-58 braid transfer impedance above 10 MHz corresponds to inductance of ~1 nH/m

Recall:
Wire has self-inductance of ~1 μH/m

Pigtail termination has ~1000x higher inductance than braid

Cable Shield Terminations (cont.)

- **Requested verbiage to be added to NASA-STD-8739.6, section 10.5 - Shield Termination:**
  - The preferred method of terminating overall cable bundle shields is to provide complete 360^o coverage with a mechanical termination to the connector or backshell following the guidelines in IPC/WHMA-A-620C section 15.3 (excerpts below).

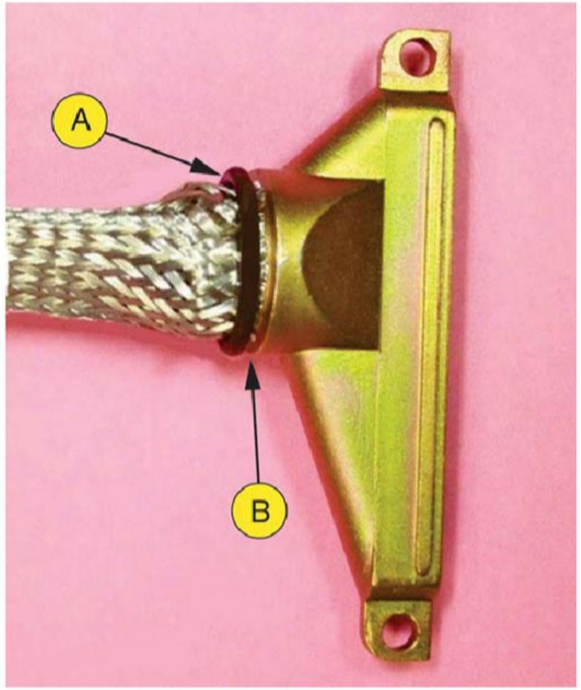


Figure 15-33

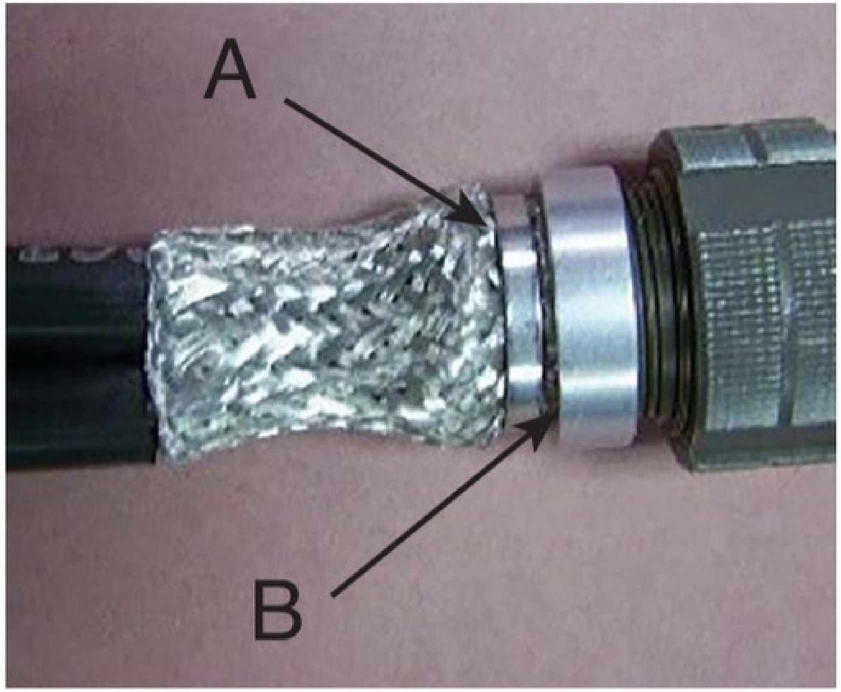


Figure 15-35

Cable Shield Terminations (cont.)

- **Requested verbiage to be added to NASA-STD-8739.6, section 10.5 - Shield Termination (cont.):**
  - The preferred method of terminating individual inner shields is to provide a soldered, tied, and/or taped connection to an overall braid following the guidelines in IPC/WHMA-A-620C section 15.4. The overall braid should be connected to the connector or backshell following the guidelines in section IPC/WHMA-A-620C section 15.3 (excerpts below).

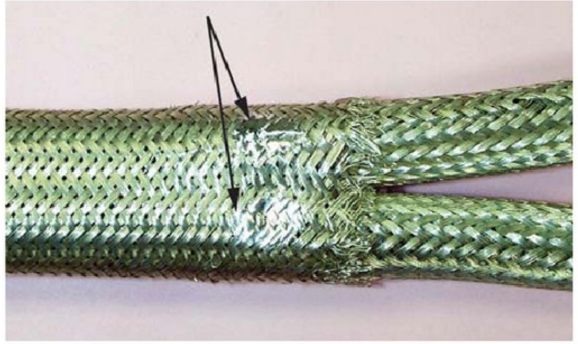


Figure 15-44

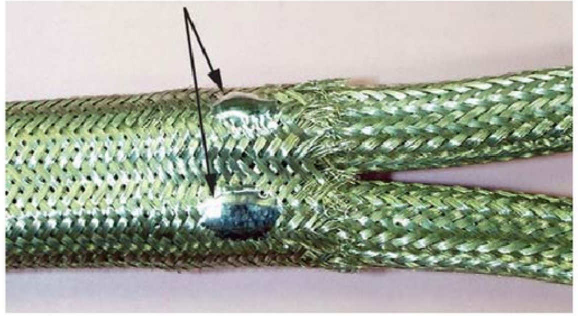


Figure 15-45

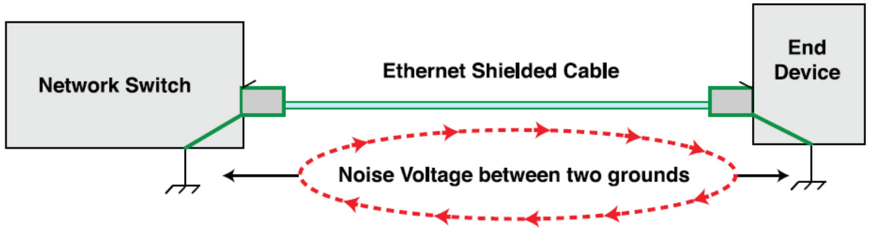
Figure 15-49

Cable Shield Terminations (cont.)

- **Requested verbiage to be added to NASA-STD-8739.6, section 10.5 - Shield Termination (cont.):**
  - Terminating shields with a wire (a.k.a "pigtail") should be avoided wherever possible. Where use of a terminating wire is unavoidable, it is permitted only when contained completely within an outer shield that is properly terminated with complete 360^{o} coverage as described above and when its length is minimized.
  - **Neither inner nor outer shields should be terminated to connector pins.**

Ethernet Cable

- *https://www.panduit.com/content/dam/panduit/en/website/solutions/applications/documents/shielded-cable-for-ethernet-applications.pdf*



If the shield connections are not close in proximity, there could be a significant ground potential difference and hence a ground current could flow!

Different building locations can develop large ΔV at facility power frequency (60 Hz)

→ *FIRE HAZARD*

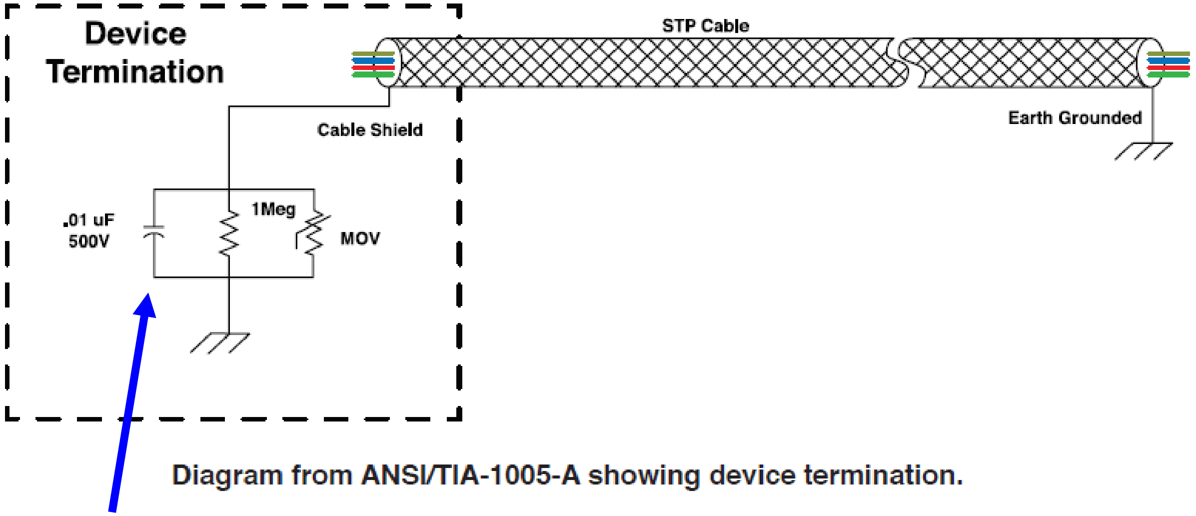


Diagram from ANSI/TIA-1005-A showing device termination.

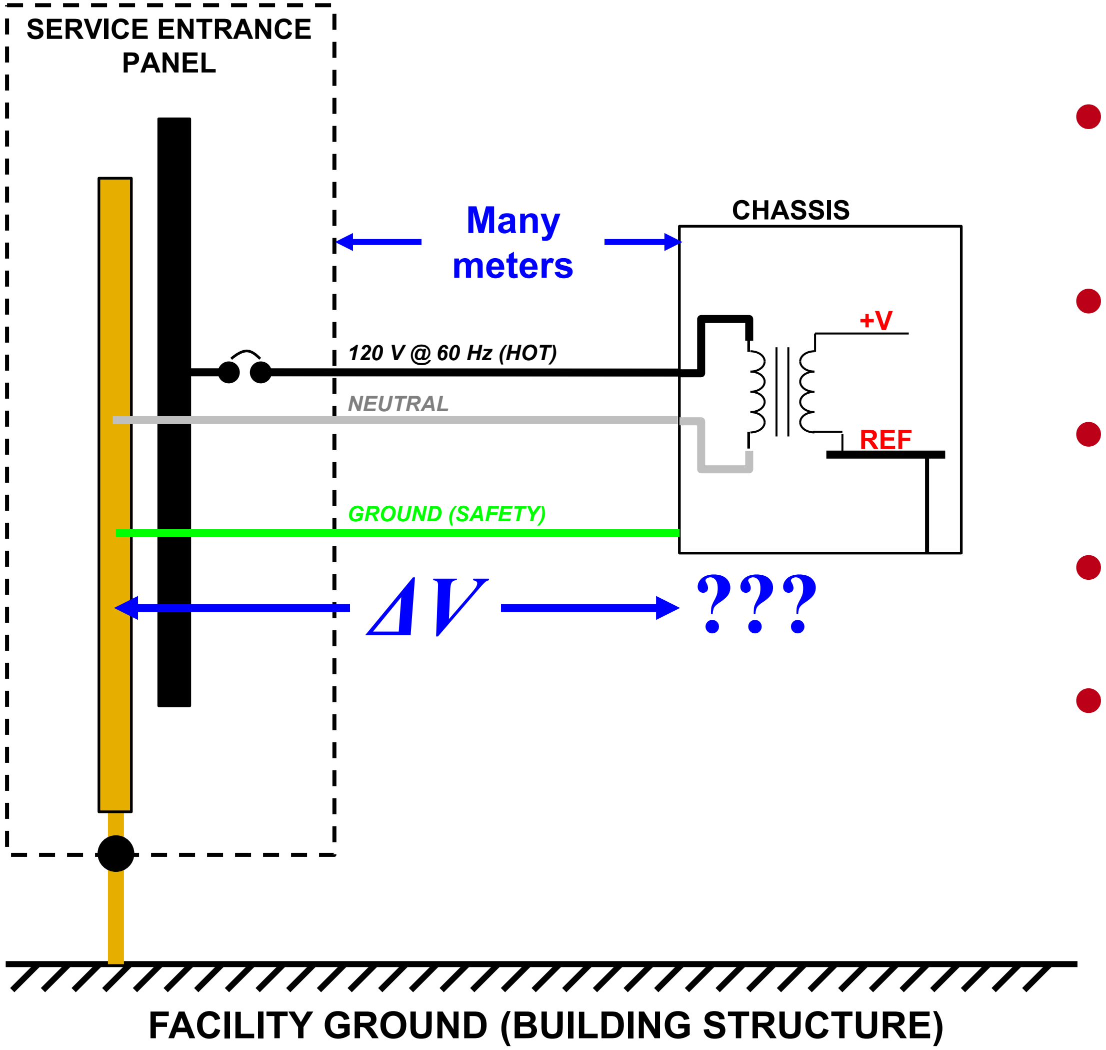
Shield terminated through capacitor to provide path for high frequency noise currents while blocking 60 Hz power currents

BY DESIGN

Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- “Grounding” in the “Real World” (and in “Real Space”)
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
- Summary

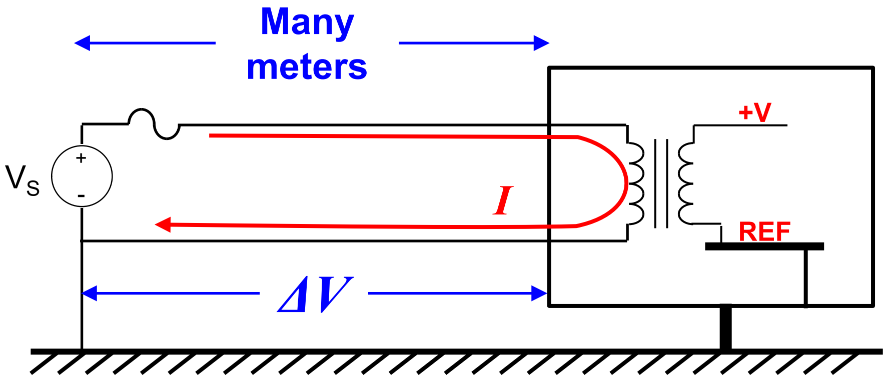
Anatomy of a Grounding Scheme



- Load may be 10s of meters from service panel entrance
- "Ground" at service panel has no meaning at load; large ΔV can develop between load and power source reference
- Load must provide its own regulated local voltages and reference(s)
- Less dependant on ΔV between load and power source reference
- Depends primarily on differential potential between (+) and (-) power leads
- ***REMEMBER: CONNECTION TO FACILITY GROUND IS PRIMARILY FOR FAULT CURRENT RETURN AND PROVIDES NO RF BENEFIT***

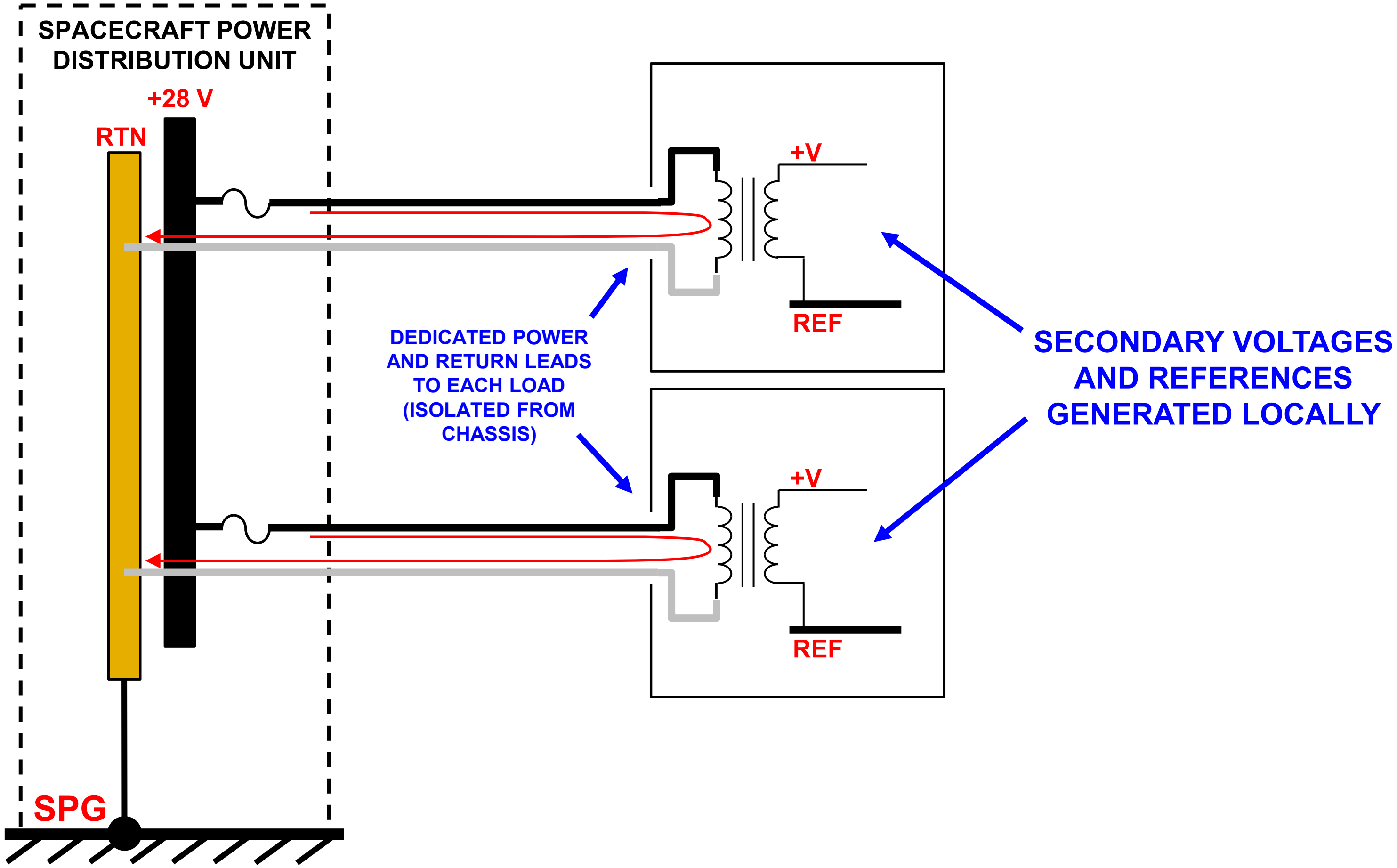
Anatomy of a Grounding Scheme (cont.)

- **Similar deal on spacecraft**
  - Load must provide its own regulated voltages and reference(s)
  - Less dependant on ΔV between load and power source

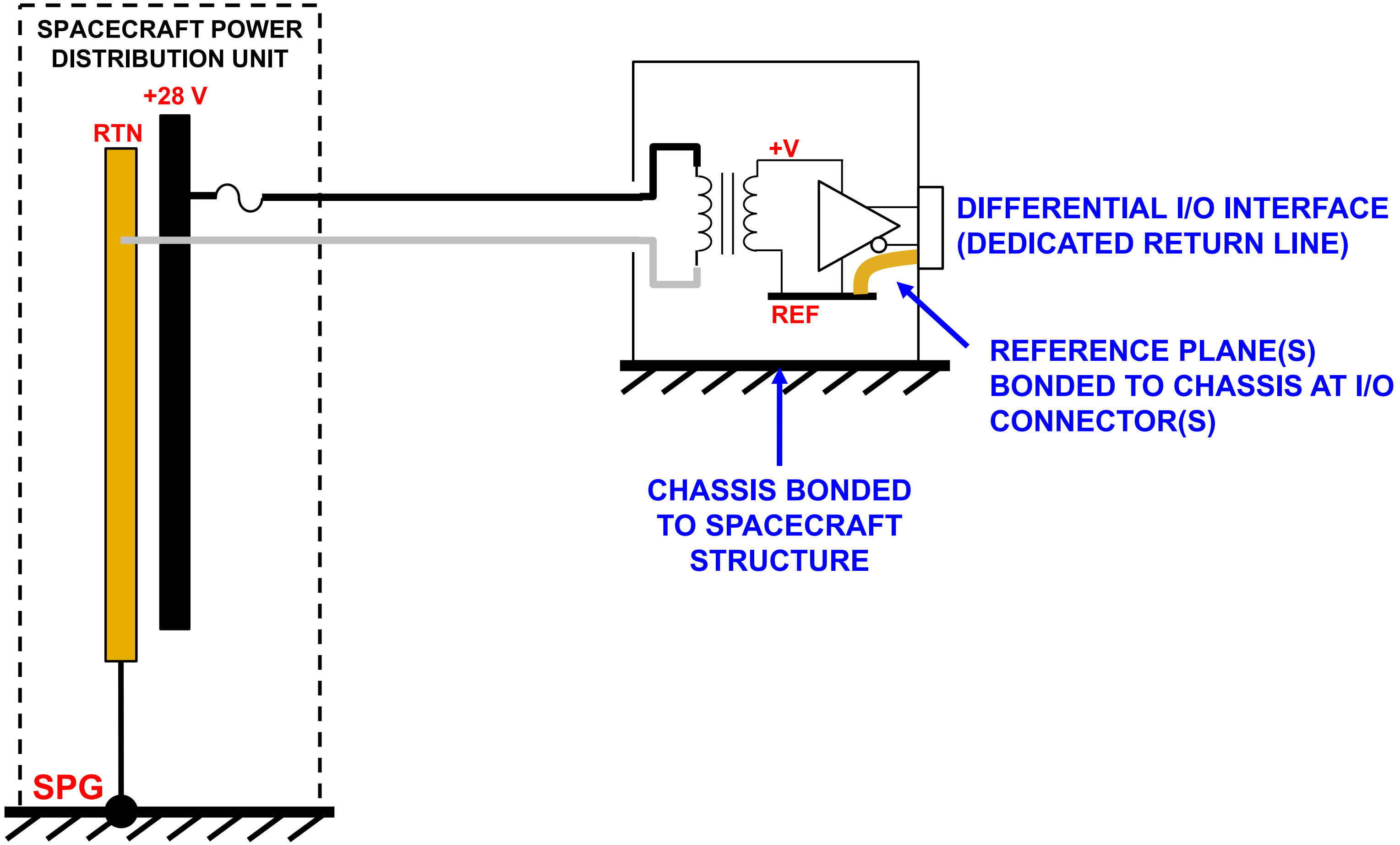


Anatomy of a Grounding Scheme (cont.)

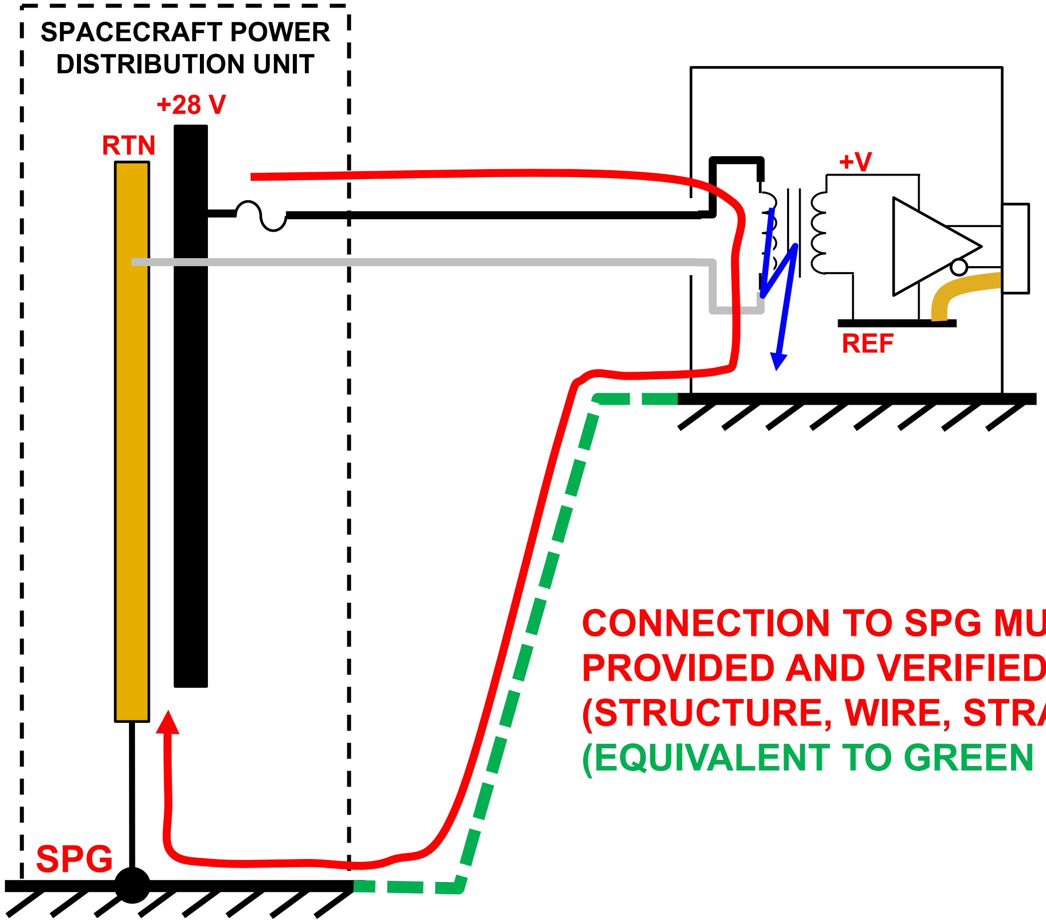
- Single point ground (SPG) applied to power distribution only



Anatomy of a Grounding Scheme (cont.)



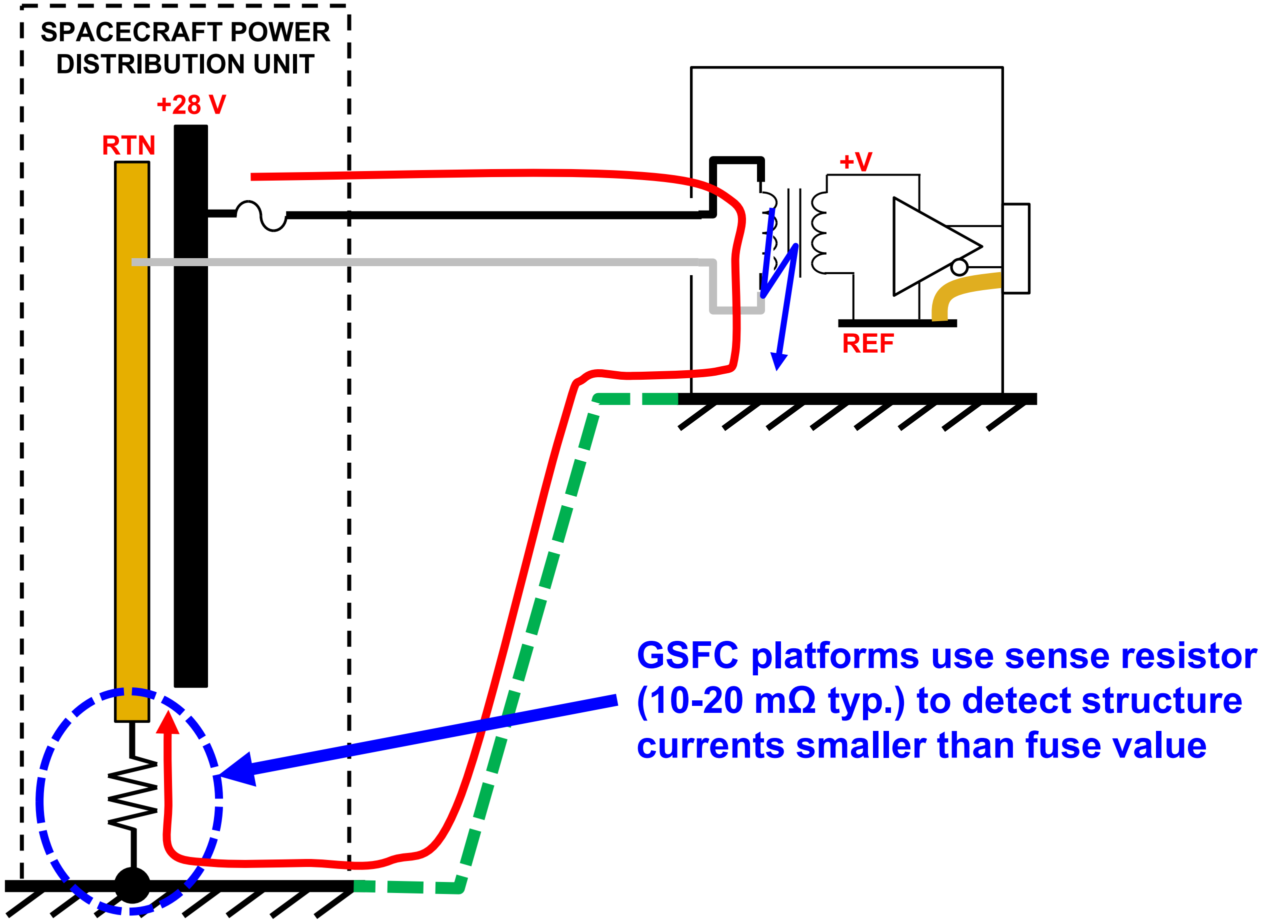
Anatomy of a Grounding Scheme (cont.)



CONNECTION TO SPG MUST BE PROVIDED AND VERIFIED (STRUCTURE, WIRE, STRAP, ETC.) (EQUIVALENT TO GREEN WIRE)

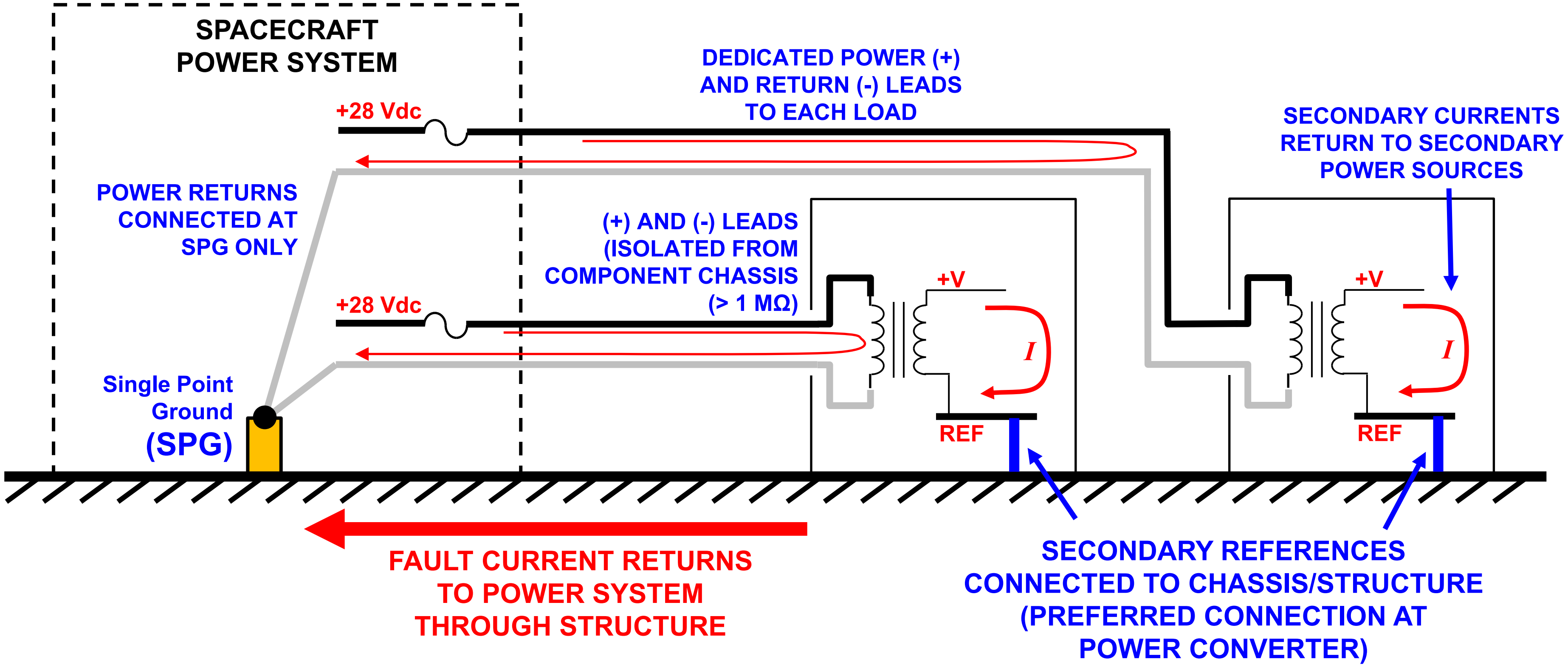
Anatomy of a Grounding Scheme (cont.)

- **Isolation/sense resistor between spacecraft power return and structure**
  - See NASA-HDBK-4001, Section 4.2.2



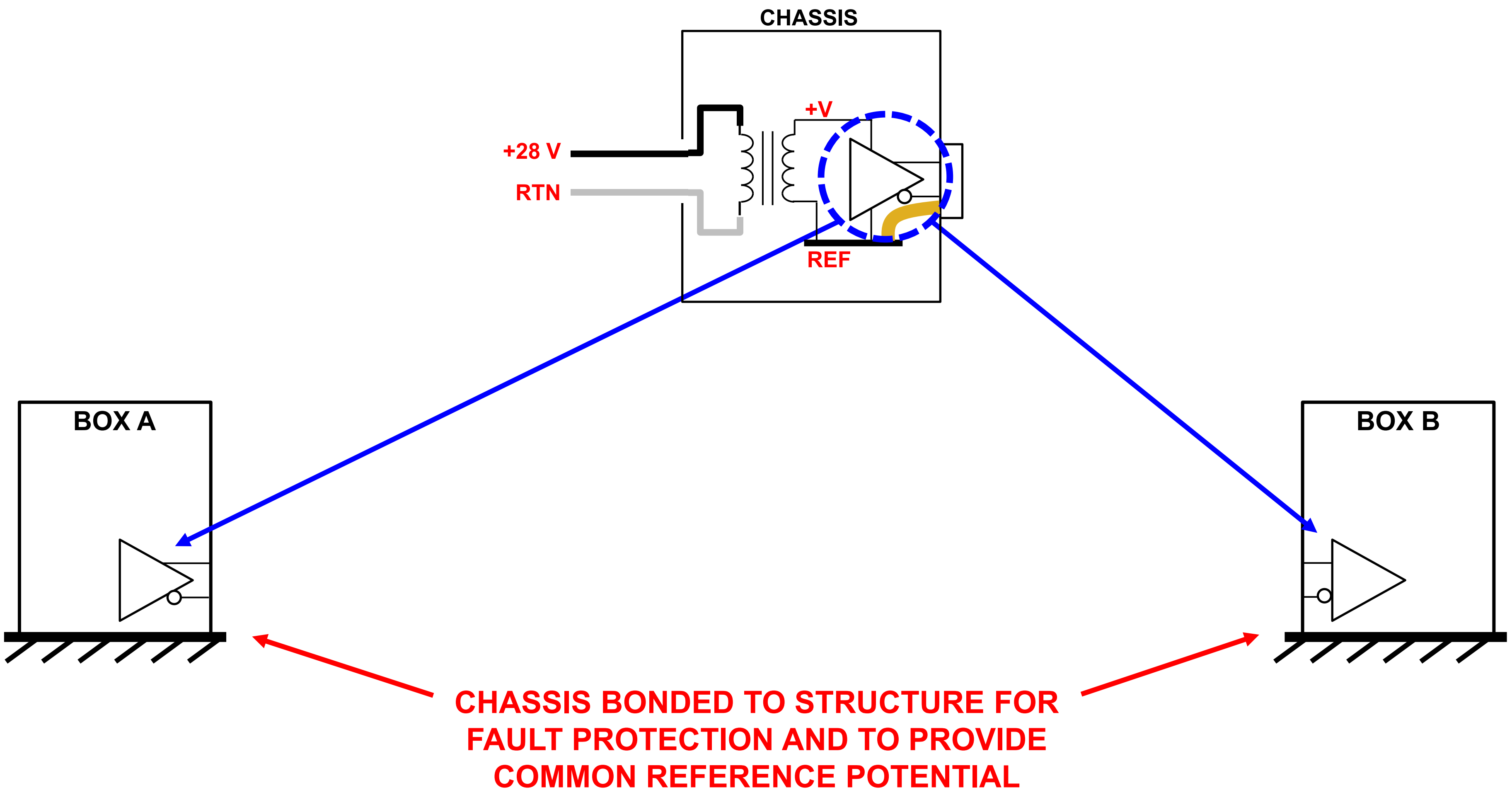
Anatomy of a Grounding Scheme (cont.)

- **Single point ground (SPG) scheme for primary power distribution**
  - Effective for low frequencies where resistance dominates (e.g. DC power and 60 Hz facility power)
  - SPG ineffective and undesirable at RF (next slides)

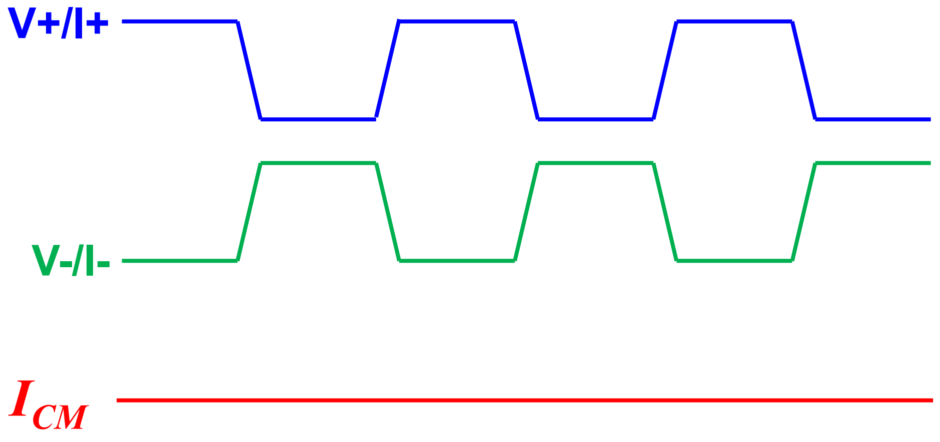


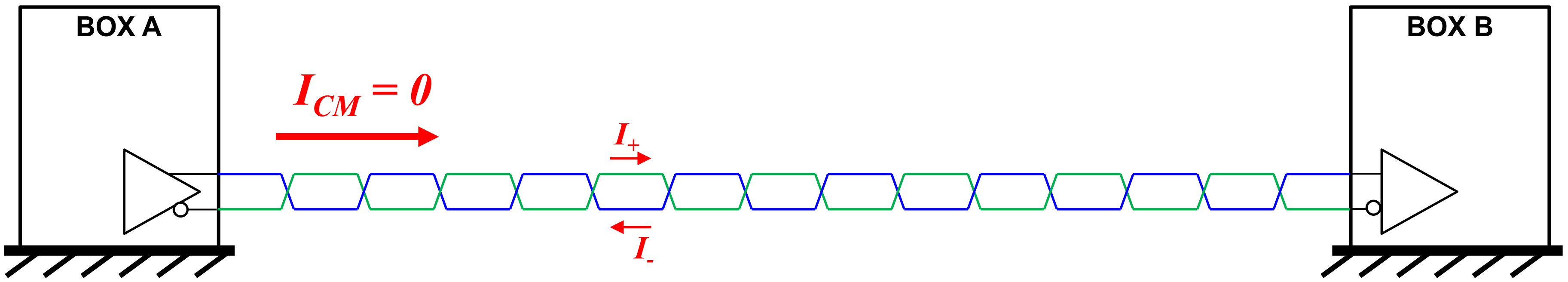
Anatomy of a Grounding Scheme (cont.)

- Signal returns must be well defined at system level to control EMI



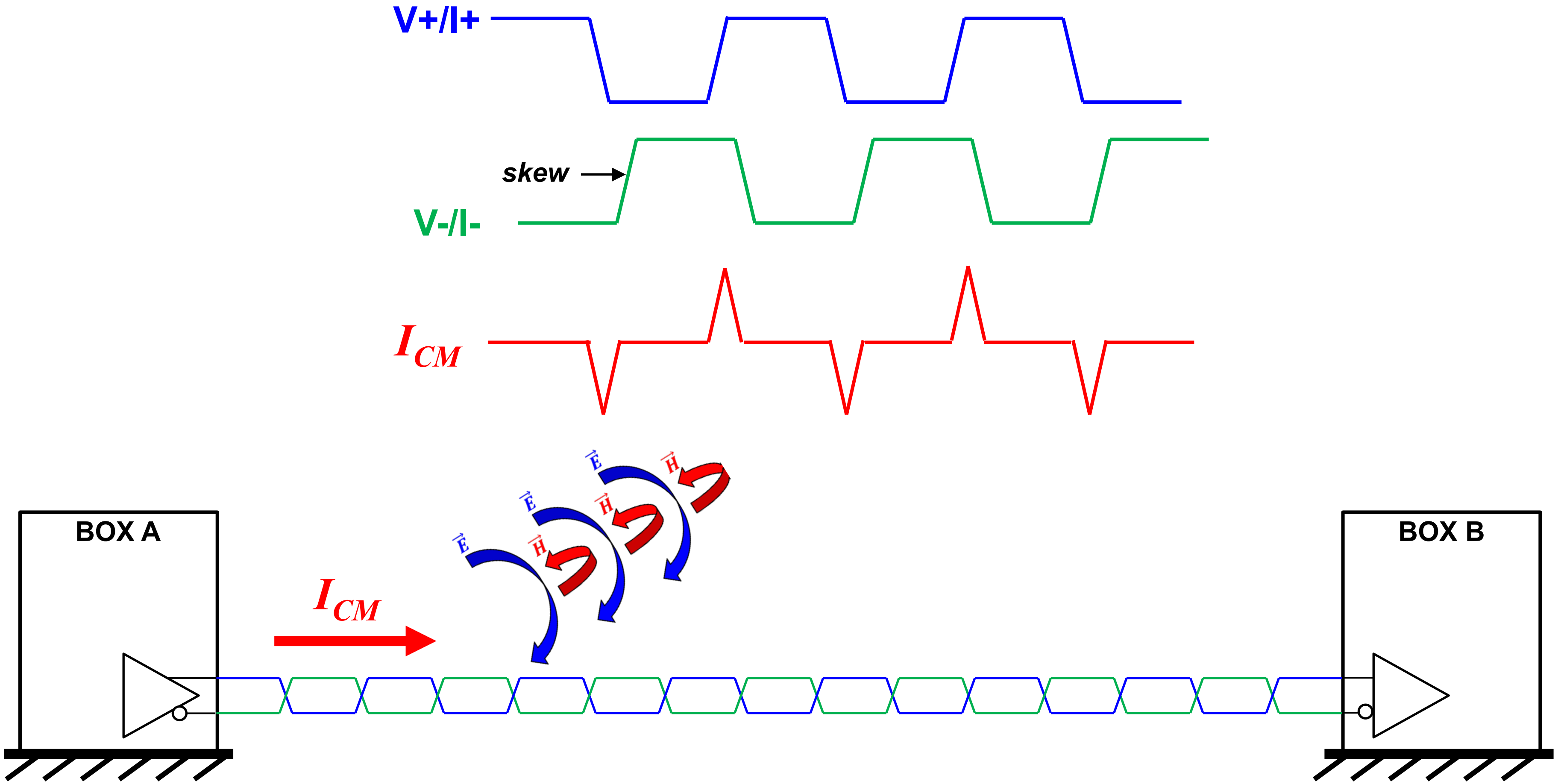
Anatomy of a Grounding Scheme (cont.)





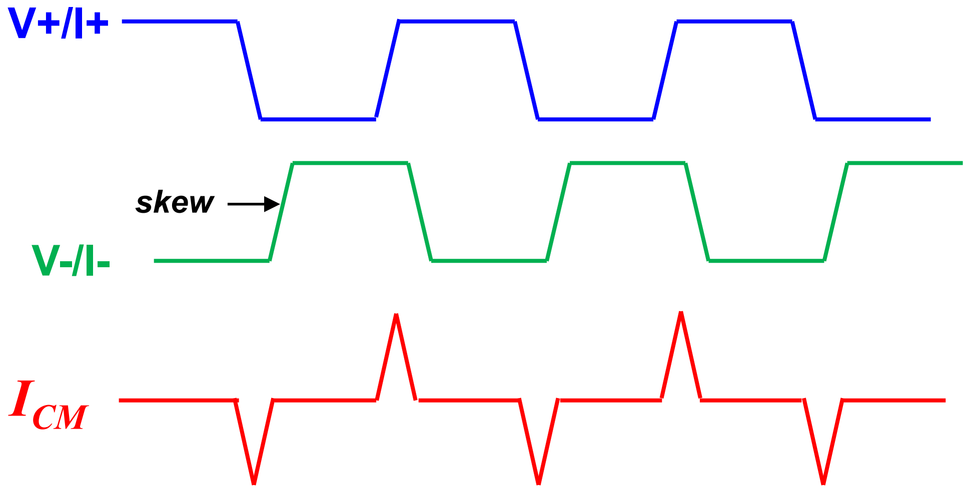
DIFFERENTIAL I/O SIGNALS ROUTED ON TWISTED PAIRS FOR CURRENT CANCELLATION

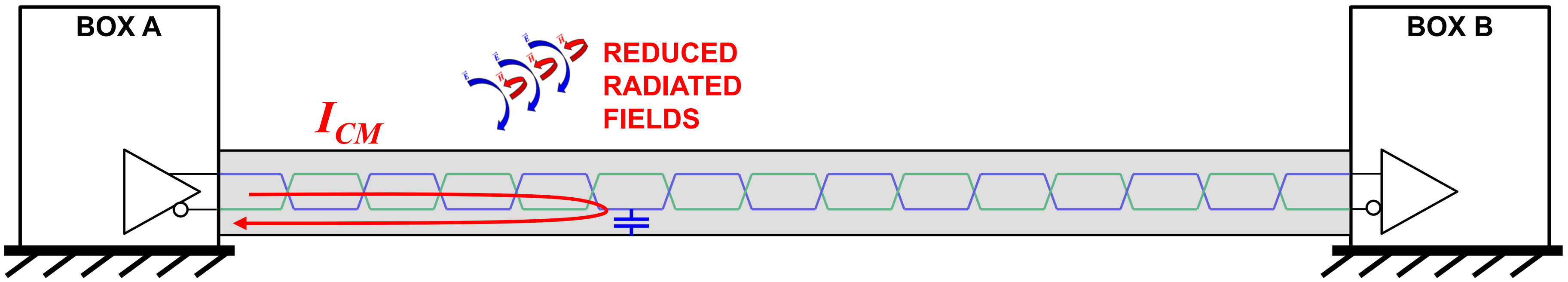
Anatomy of a Grounding Scheme (cont.)



CURRENT IMBALANCE PRODUCES COMMON MODE CURRENTS THAT PRODUCE RADIATED FIELDS

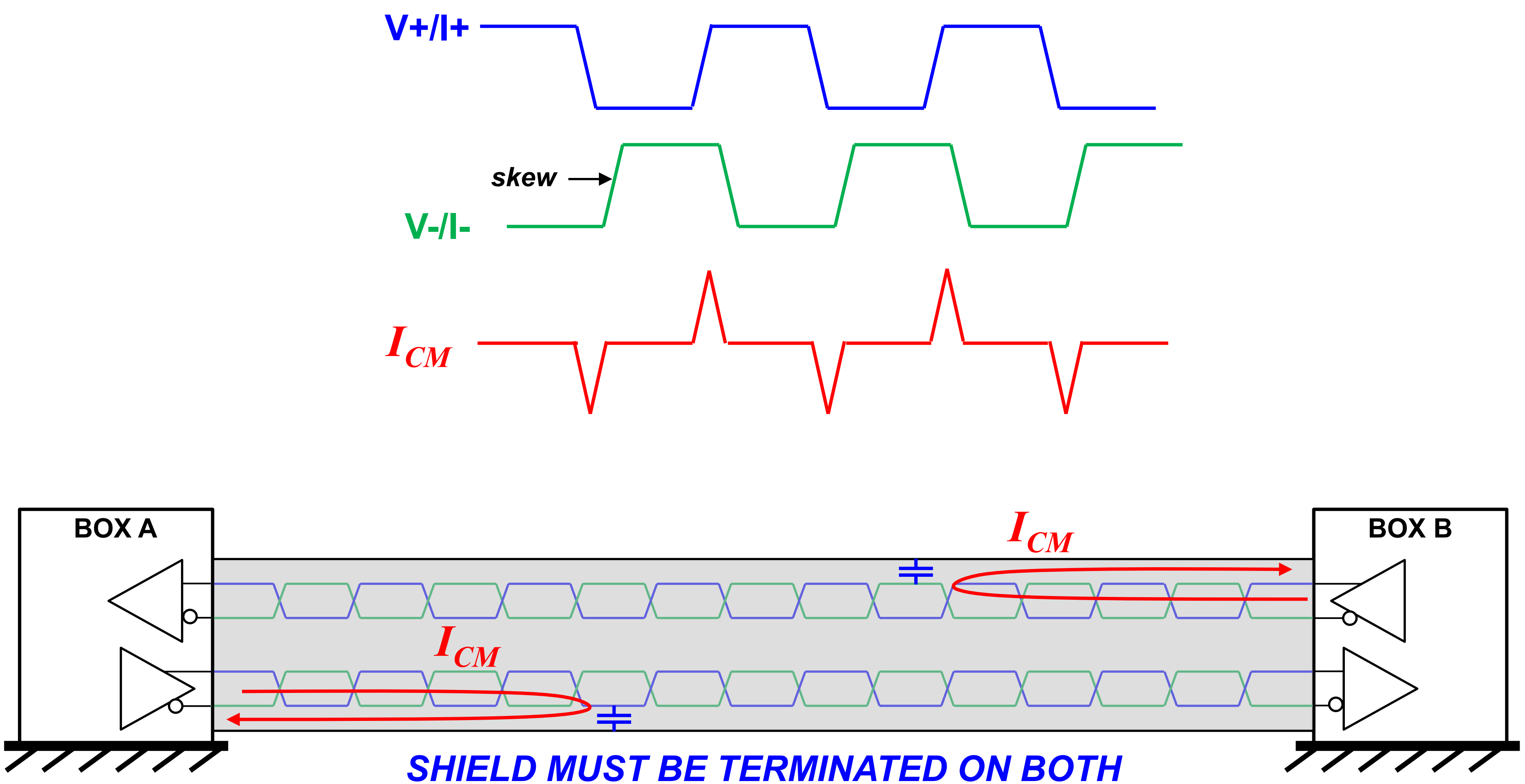
Anatomy of a Grounding Scheme (cont.)





COMMON MODE CURRENT CAPACITIVELY COUPLES TO SHIELD AND RETURNS TO SOURCE

Anatomy of a Grounding Scheme (cont.)

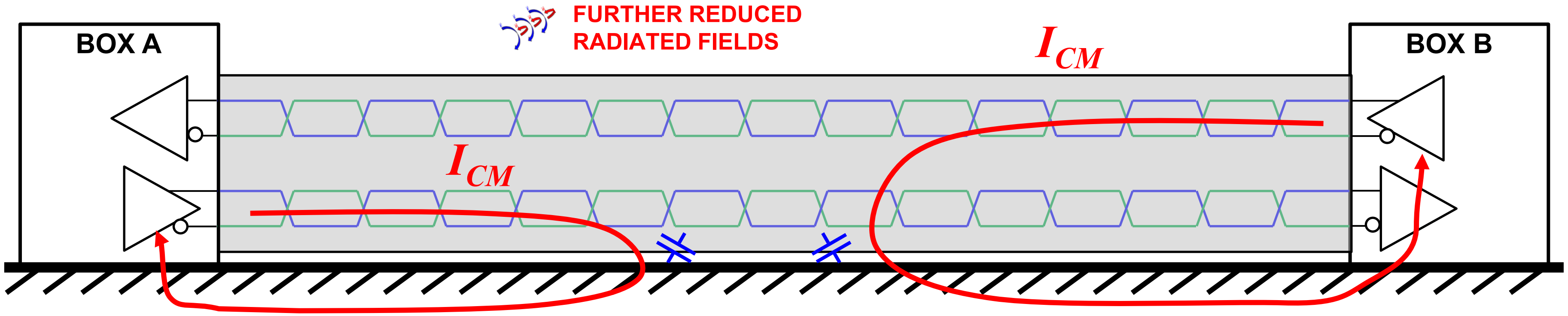


SHIELD MUST BE TERMINATED ON BOTH SIDES TO PROVIDES LOW IMPEDANCE PATH IN BOTH DIRECTIONS

Anatomy of a Grounding Scheme (cont.)

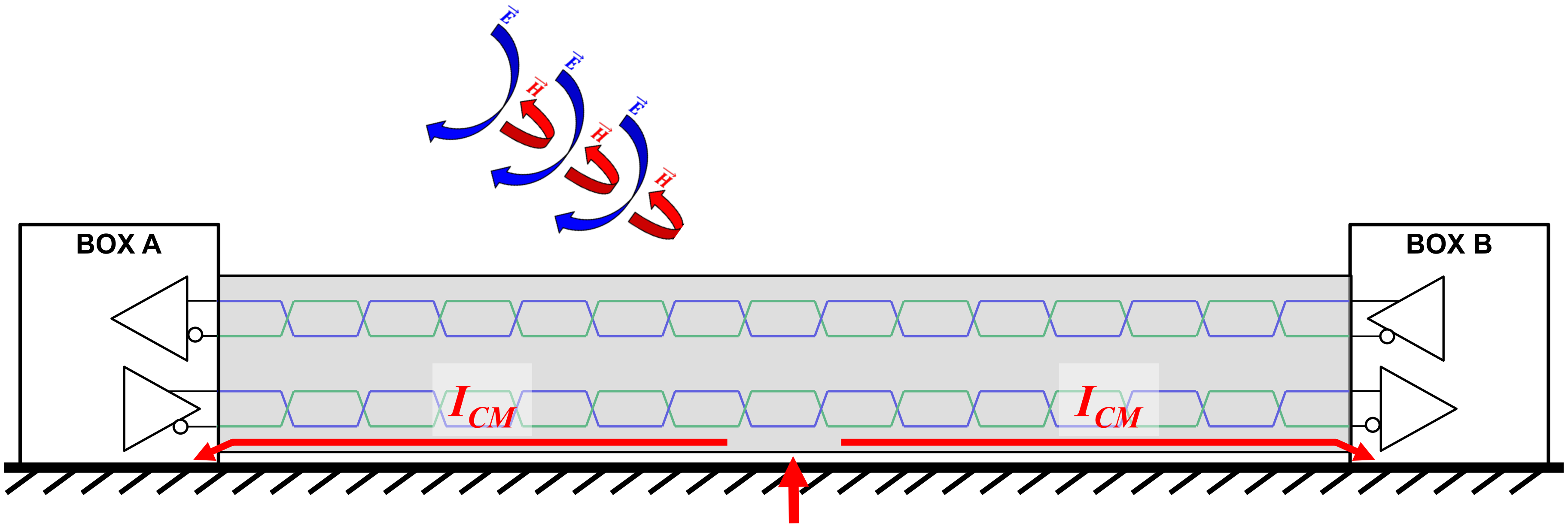
ROUTING CABLES OVER GROUND PLANE (STRUCTURE) PROVIDES ADDITIONAL LOW IMPEDANCE RETURN PATH FOR ANY RESIDUAL COMMON MODE CURRENTS ON SHIELD

(CAPACITIVE COUPLING BETWEEN SHIELD AND GROUND PLANE)



Anatomy of a Grounding Scheme (cont.)

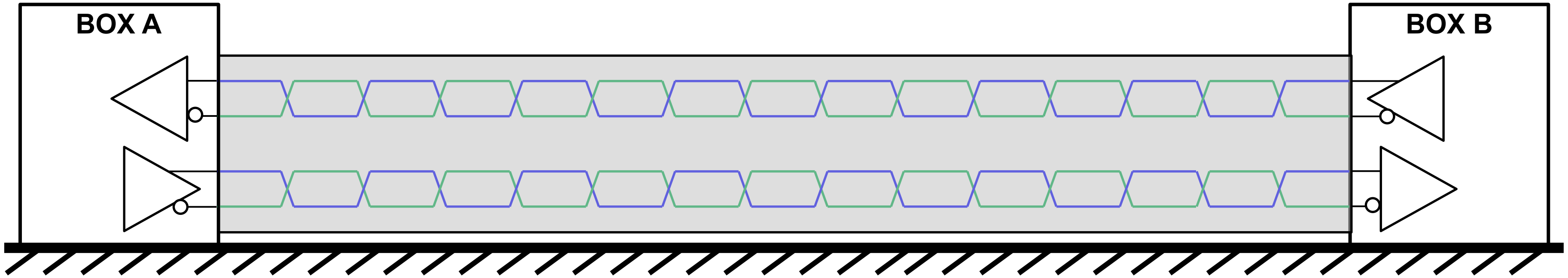
INCIDENT FIELDS INDUCE COMMON MODE CURRENTS ON SHIELD AND ARE SHUNTED AWAY FROM SIGNAL CARRYING CONDUCTORS



MINIMIZE LOOP AREA FOR MAGNETIC COUPLING

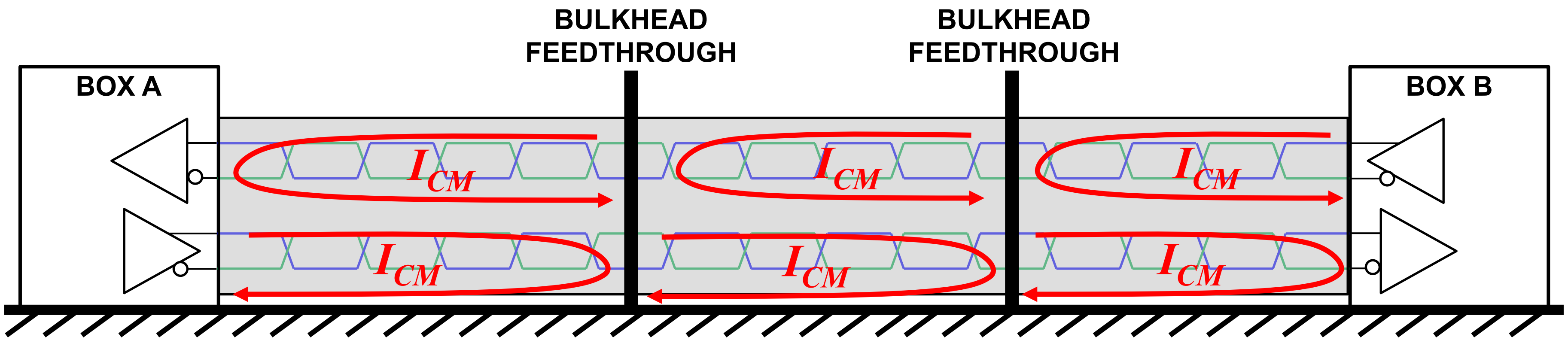
Anatomy of a Grounding Scheme (cont.)

While fully enclosed "Faraday Cage" provides best shielding benefits, simply routing cables over ground plane/structure still provides significant protection for both emissions and susceptibility



Anatomy of a Grounding Scheme (cont.)

- **Shields must be terminated at all bulkhead feedthroughs**
  - Keeps common mode currents localized
  - Minimizes loop areas
- **Applies to bulkheads on:**
  - Spacecraft in flight configuration
  - I&T configurations (EMI chamber, thermal vacuum chamber, etc.)
- **ISOLATING SHIELDS AT BULKHEAD FEEDTHROUGHS "TO AVOID GROUND LOOPS" MISSES THE POINT…**
- **…AND AN OPPORTUNITY TO SHUNT NOISE CURRENTS AWAY FROM SIGNAL-CARRYING CONDUCTORS!!!**



Topics

- Introduction
- Reasons for “Grounding”
- Ground Bounce
- “Grounding” in the “Real World” (and in “Real Space”)
- Bonding
- Shielding
- Anatomy of a Grounding Scheme
- Summary

Summary (1 of 2)

- **"Grounding" need not and should not be complicated (simpler is better)**
- **Primary reasons for grounding:**
  - Safety (fault protection, lightning)
  - Common reference potential
- **“Signal return” must be treated separately from “ground”**
  - Kirchoff’s current law: All currents return to their **SOURCES** following all available paths in inverse proportion to relative impedances
  - Consider inductance and capacitance in all possible return paths
  - Provide low impedance return path by design; let nature do the work
- **Structure "ground" should be avoided as intentional signal return path**
- **Should be used only as return path for fault and noise currents**

Summary (2 of 2)

- Single point ground should be used only at low frequencies (< 100 kHz)
- Multi-point ground should be used at high frequencies (> 100 kHz)
- Beware of isolation – it could be doing more harm than good
- ESPECIALLY WITH CABLE SHIELDS - TERMINATE THEM PLEASE!!!
- **FOLLOW AND CONTROL THE CURRENT!!!**

References (1 of 2)

- **Textbooks:**
  - Dr. Bruce Archambeault, “PCB Design for Real-World EMI Control”
  - Elya B. Joffe, Kai-Sang Lock, “Grounds for Grounding”
  - Henry Ott, “Electromagnetic Compatibility Engineering,” Chapter 3
  - Paul, Clayton, "Introduction to Electromagnetic Compatibility"
  - Paul, Clayton, "Inductance: Loop and Partial"

- **Article:**
  - Ken Javor, "Lightning and RF Electrical Bonding," IN Compliance magazine, May 2021
  - *https://incompliancemag.com/lightning-and-rf-electrical-bonding/*

References (2 of 2)

- NASA-HDBK-4001, Electrical Grounding Architecture for Unmanned Spacecraft
- NASA-HDBK-4002A, Mitigating In-Space Charging Effects - a Guideline
- NASA-STD-4003, Electrical Bonding For NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment
- NASA-HDBK-419A, Volumes 1 & 2, Grounding, Bonding, and Shielding for Electronic Equipments And Facilities
- IEEE STD 1100™-2005, IEEE Recommended Practice for Powering and Grounding Electronic Equipment
- NASA-HDBK-8739.21, Workmanship Manual for Electrostatic Discharge Control
- Marshall Space Flight Center Electromagnetic Compatibility Design and Interference Control (MEDIC) Handbook
- MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment