Principle of Path of Least Inductance and its Implications in Circuit, Cable and Grounding Design

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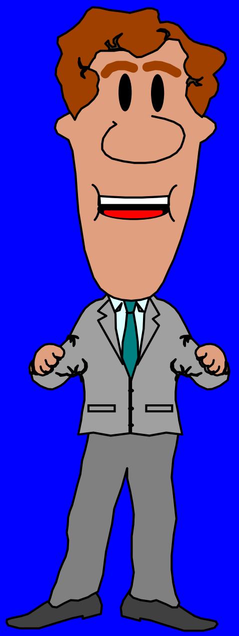
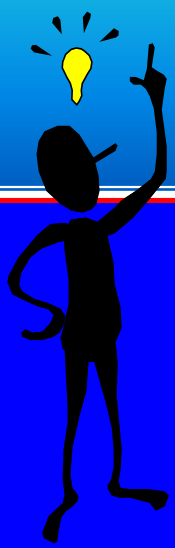
One Rule to bring them all
and in the darkness bind them....

Outline

- Principle of Path of Least Inductance
- Implication of “Path of Least Inductance” in PCB Design
  - Power and Return Circuits on PCBs
  - High Speed Signal and Return Circuits on PCBs
- Implication of “Path of Least Inductance” in Filter Grounding
- Implication of “Path of Least Inductance” in Cable Shield Grounding
  - Shield Grounding
  - Signal vs. Shield Grounding
- Summary

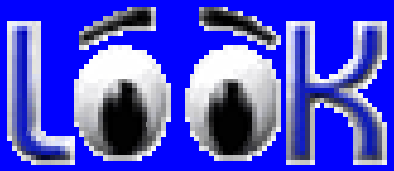


Principle of “Path of Least Inductance”



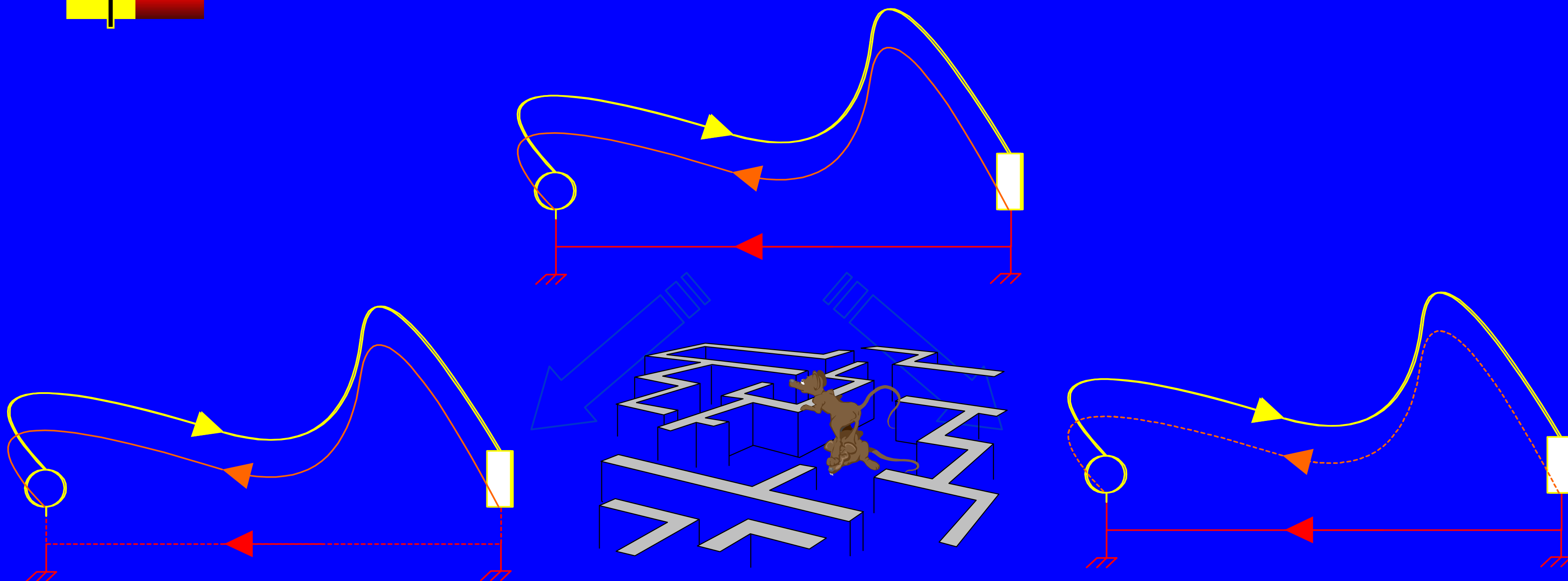
Principle of “Path of Least Inductance”
Visualize Return Currents

- Currents always return…
  - To ground??
  - To battery negative??
  - To their source!!



"Path of Least Inductance" Principle

Which path will the return current follow?



Currents always take the path of least …

- Distance?
- Resistance?
- Impedance!!!

"Path of Least Inductance" Principle

Which path will the return current follow?

$$I_S \cdot (R_S + j\omega L_S) - I_1 \cdot j\omega M = 0$$

$$L_S = M \quad \Downarrow \quad L_S = \frac{\mu}{2\pi} \cdot Ln\left(\frac{4H}{d}\right), \text{ Hy/m}$$

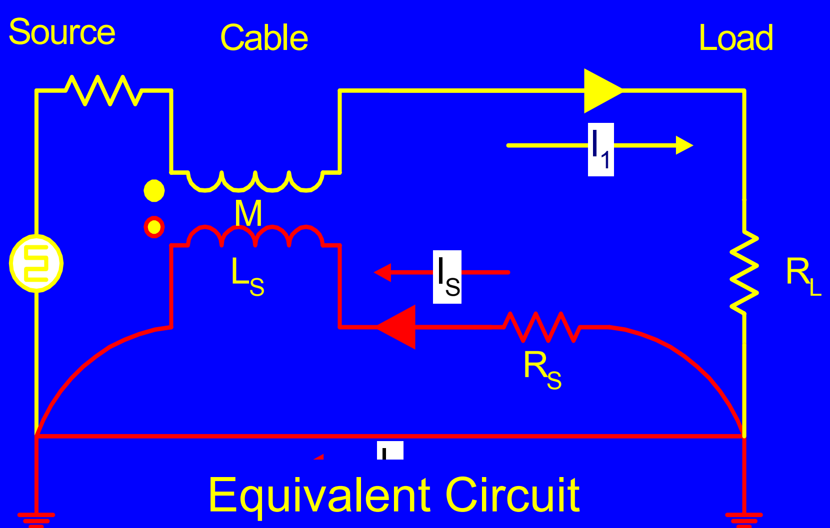
$$\frac{I_1}{I_S} = \frac{j\omega L_S}{R_S + j\omega L_S}$$

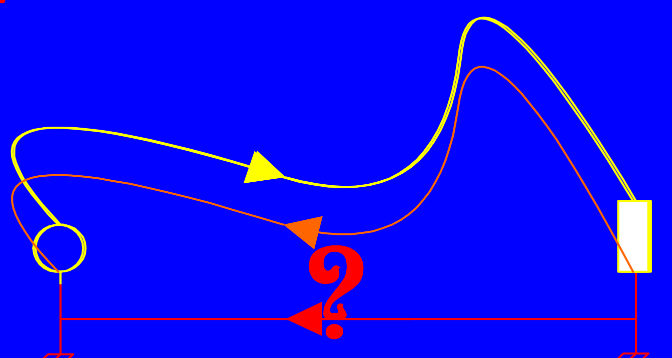
$$\Downarrow$$

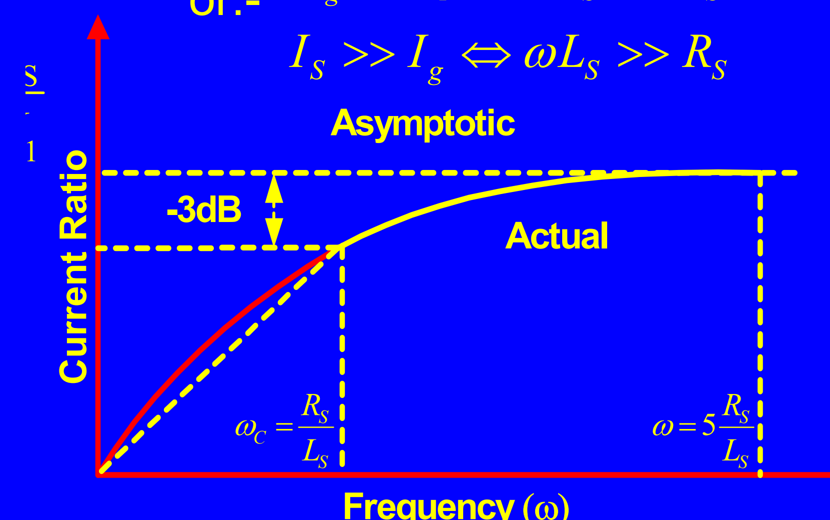
$$I_g << I_1 \Leftrightarrow \omega L_S >> R_S$$

or:-

$$I_S >> I_g \Leftrightarrow \omega L_S >> R_S$$



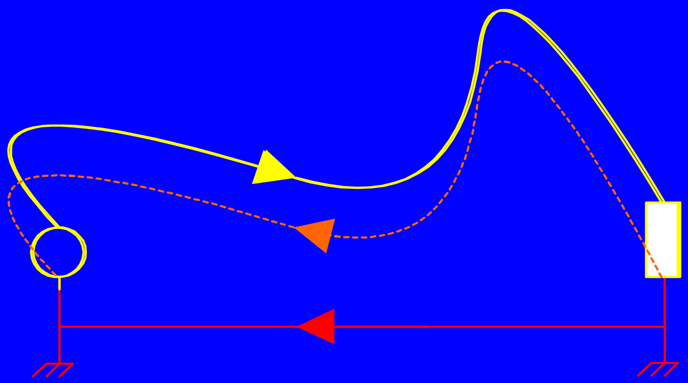


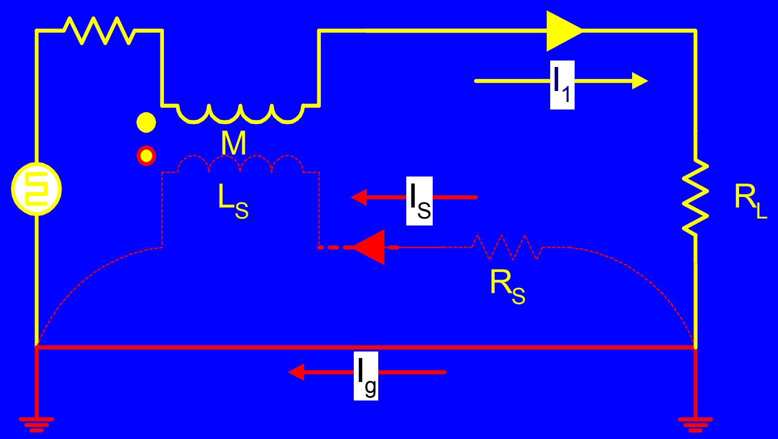


"Path of Least Inductance" Principle

Which path will the return current follow?

- At **LOW FREQUENCIES** (Below 10 kHz in typical copper structures), the current will follow the path of **LEAST RESISTANCE**, via ground (I_G)





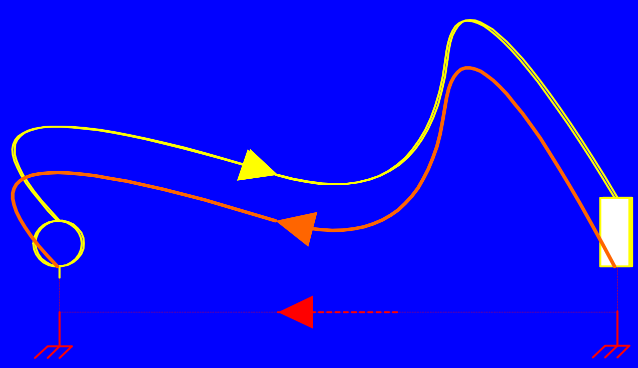
$$Z = R_S + j\omega \cdot M = \begin{cases} |Z| \approx R_S & @\, R_S >> j\omega \cdot L_S \\ |Z| \approx \omega \cdot L_S & @\, \omega \cdot L_S >> R_S \end{cases}$$

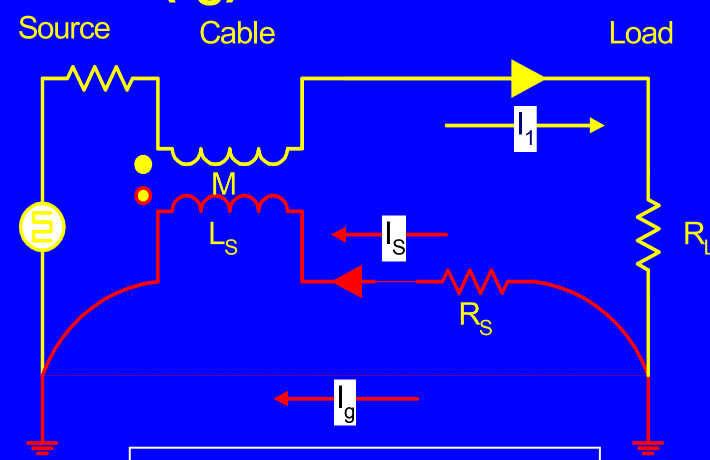
$$I_S = I_1 \cdot \frac{(j\omega)}{(j\omega + R_S / L_S)}$$

“Path of Least Inductance” Principle

Which path will the return current follow?

- At **HIGH FREQUENCIES** (Above 1 MHz (in typical copper structures), the current will follow the path of **LEAST INDUCTANCE**, via the return conductor (I_S)





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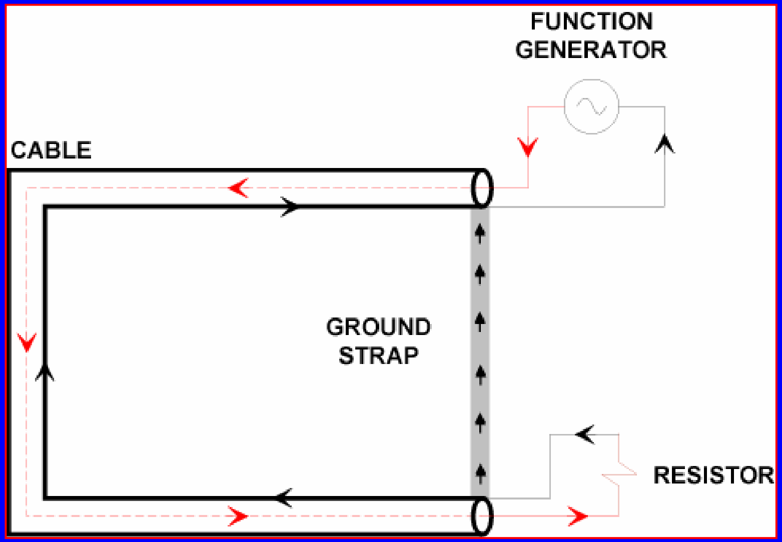
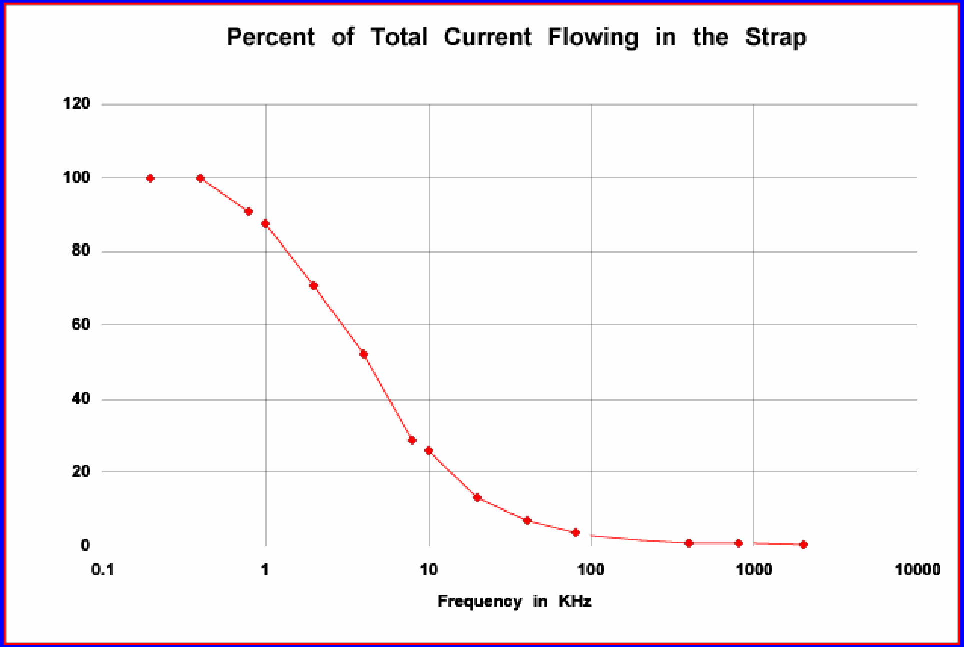
"Path of Least Inductance" Principle

Which path will the return current follow?

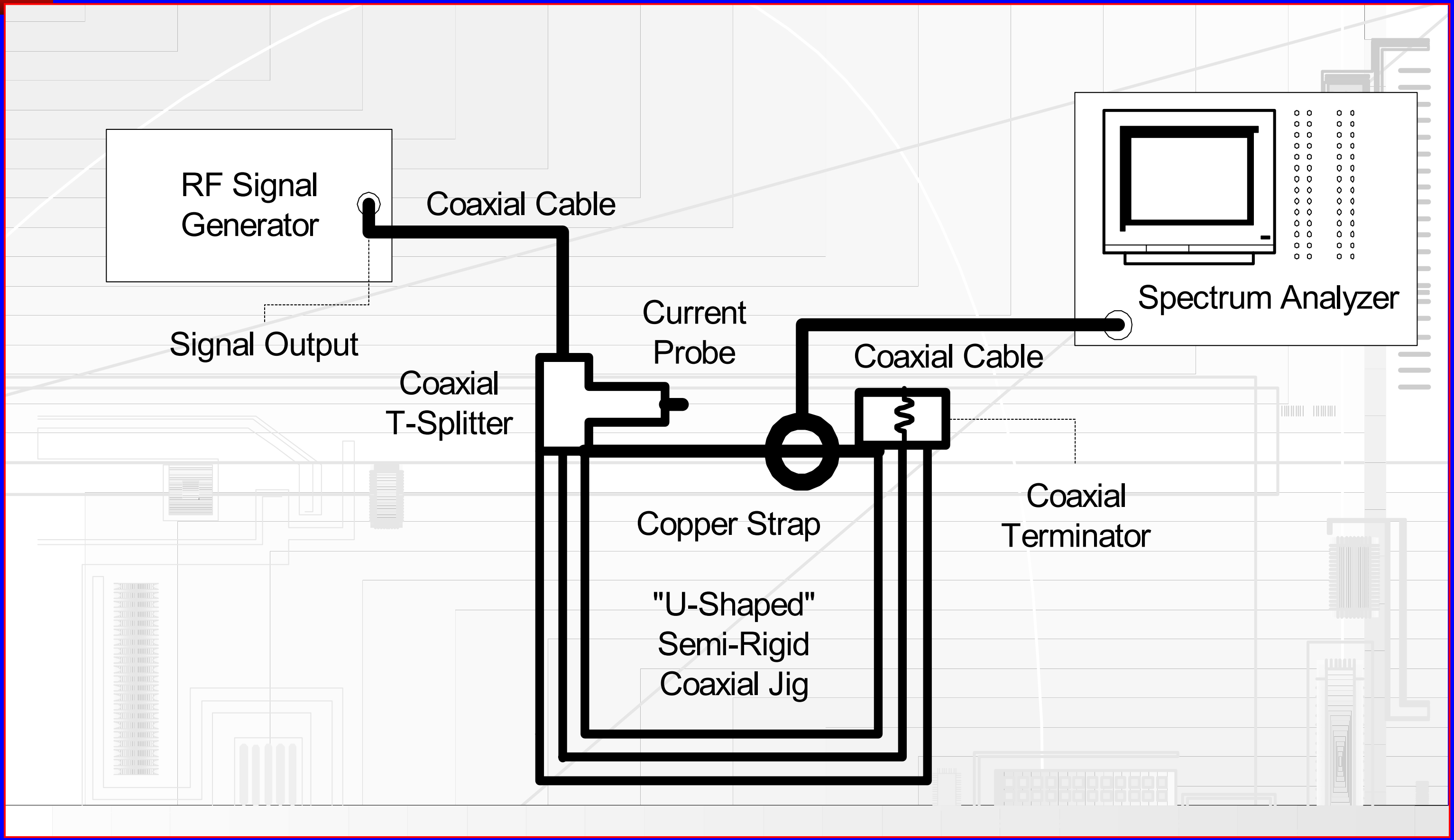




- *Courtesy: Prof. Todd Hubing, UMR*

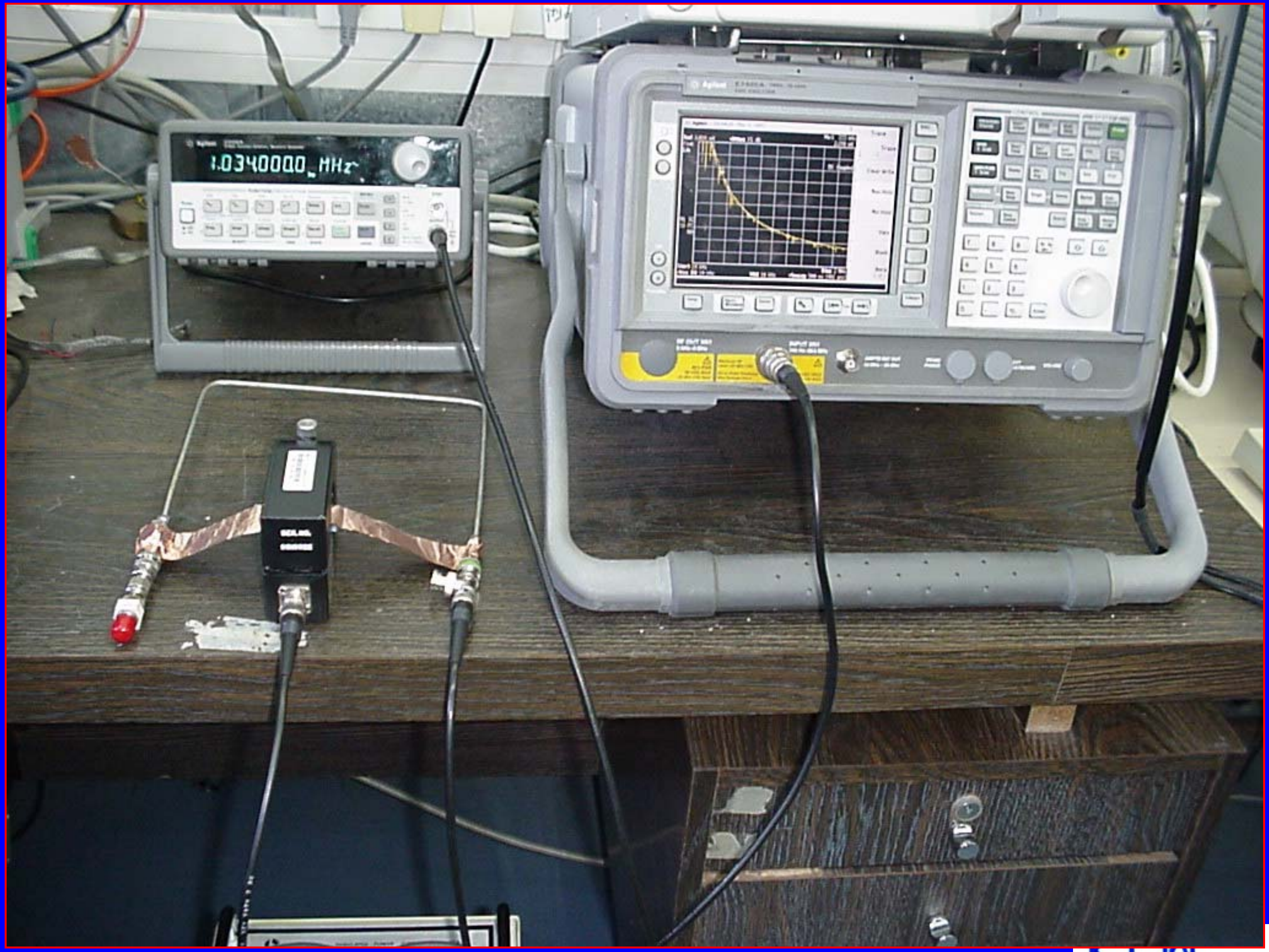
“Path of Least Inductance” Principle

Experiment Set-Up



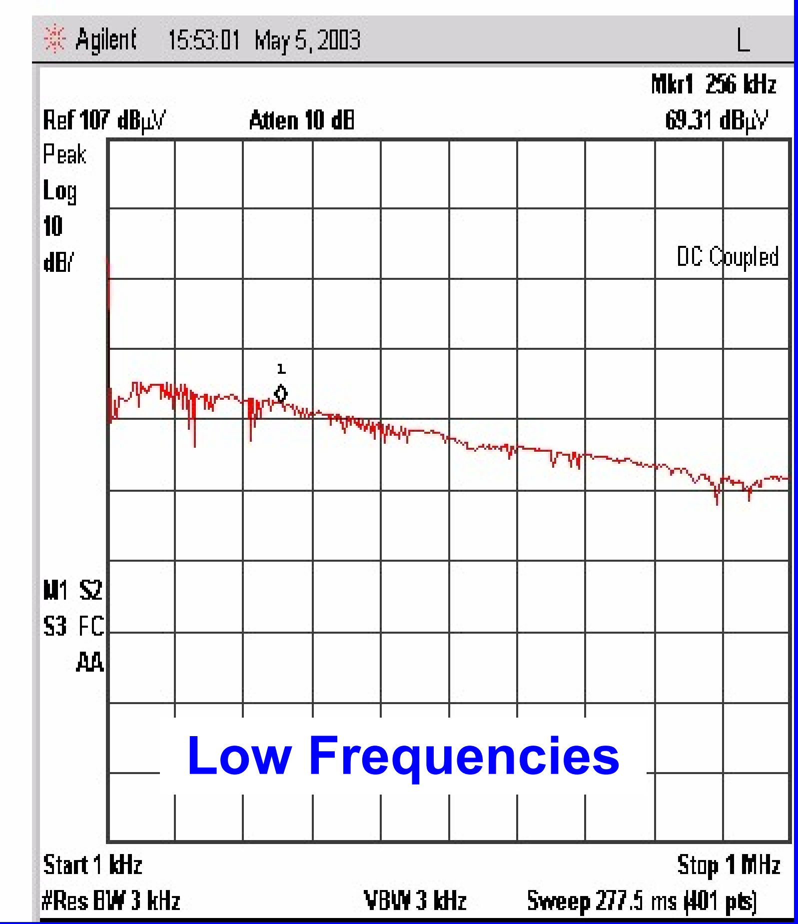
“Path of Least Inductance” Principle

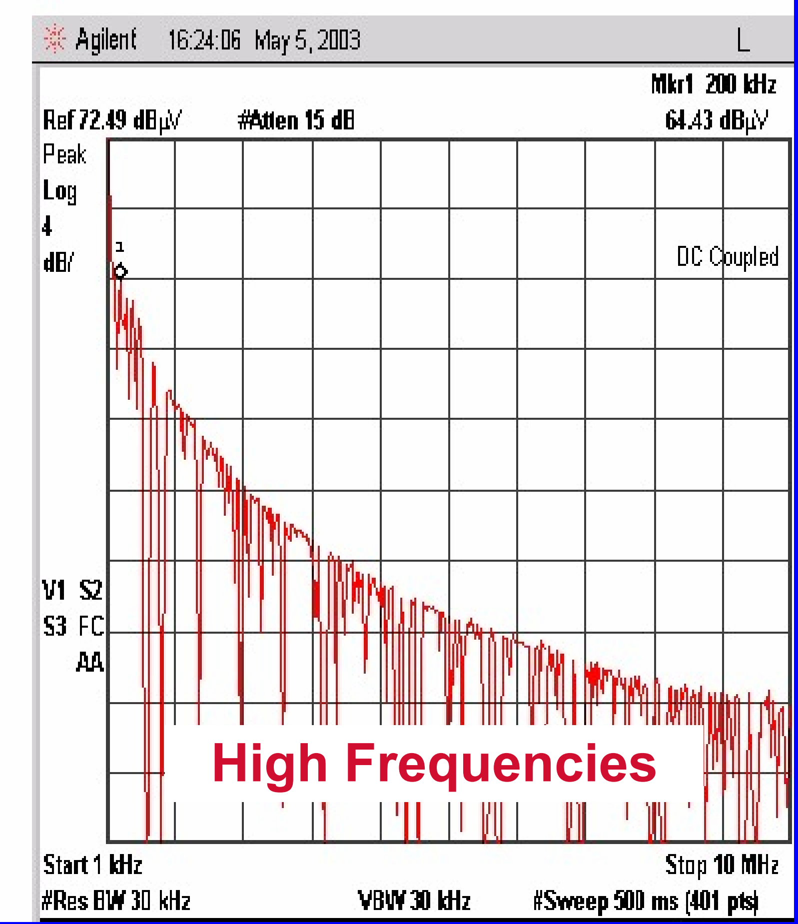
Experiment Set-Up



"Path of Least Inductance" Principle

Experiment Results





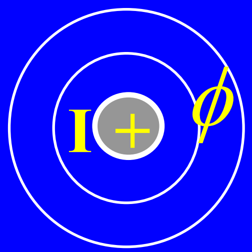
"Path of Least Inductance" Principle

When is Inductance Minimized?

- **Definition of Total Loop Inductance**
- **For I=constant, Φ_{min} implies S_{min}**

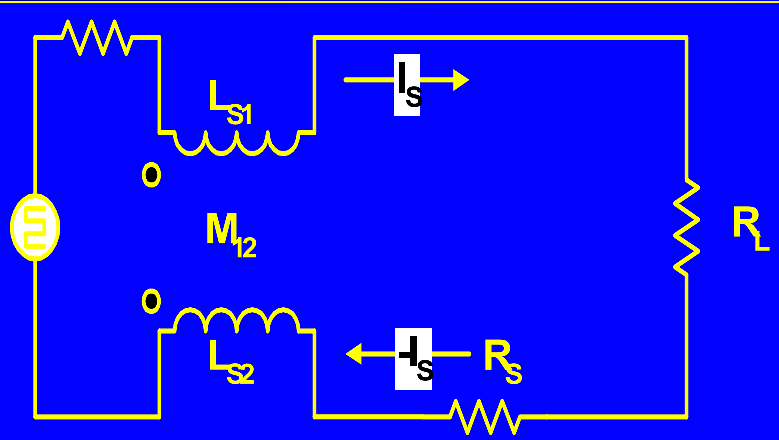
$$L = \frac{\phi}{I} \approx \frac{\int_S B \cdot ds}{I}$$

$$Thus:\ L_{min} \Rightarrow \phi_{min} \Rightarrow S_{min}$$



"Path of Least Inductance" Principle

When is Inductance Minimized?



- **The total inductance of two conductors carrying current in opposite direction (e.g., signal & return leads):**

$$L_{Total} = L_{S1} + L_{S2} - 2M_{12}$$

- **And when the conductors are identical, i.e., $L_{S1}=L_{S2}$:**

$$L_{Total} = 2\left(L_{S1} - M_{12}\right)$$

- **Thus the total inductance depends on the area between the conductors**

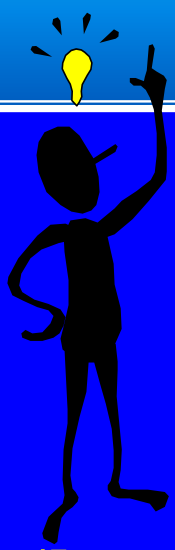
"Path of Least Inductance" Principle

Implication of this Rule?

- The principle of "Path of Least Inductance" will apply, in cable design for EMC, in:
  - –Grounding of cable shields
  - –Transmission line layout and routing on PCBs
  - –Power decoupling on PCBs
  - –Filtering
  - –Circuit grounding topologies

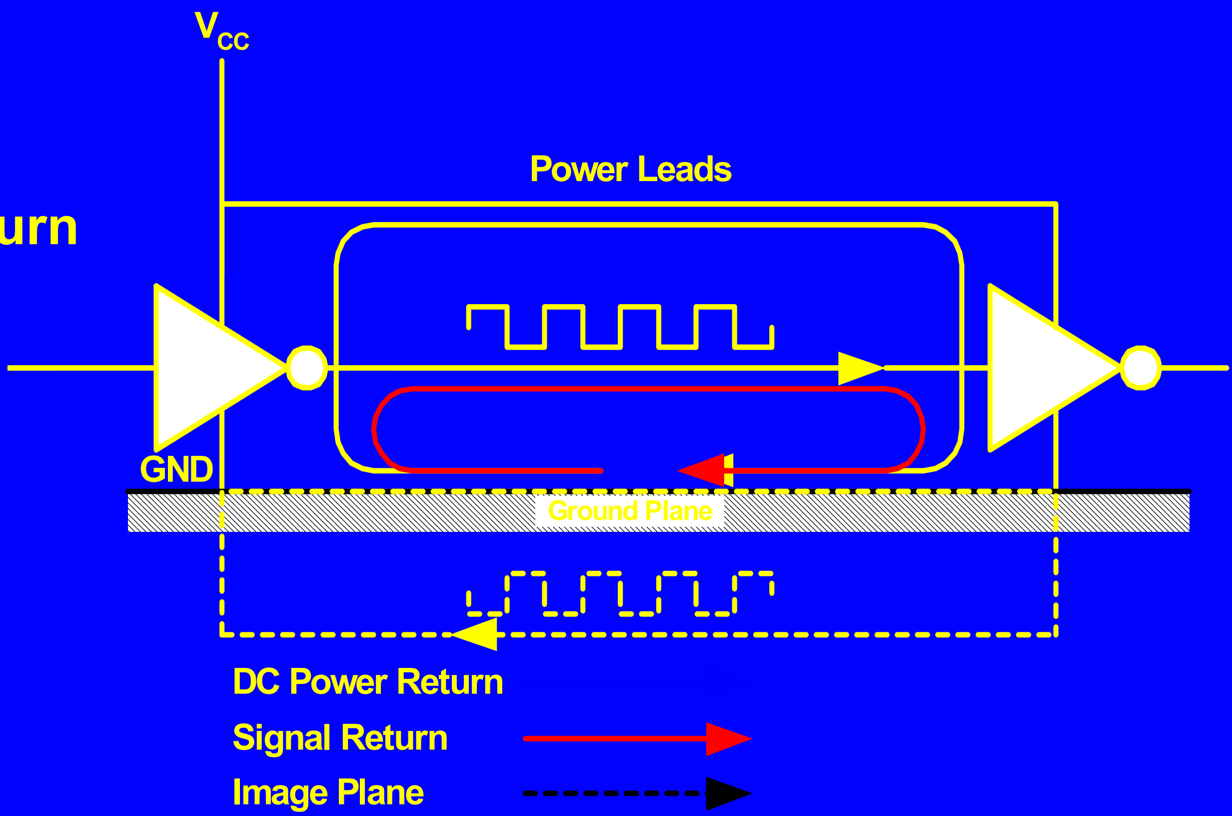
Few principles in EMC are as important as this principle for the understanding and design of shields, filters and return current circuits

Implication of “Path of Least Inductance” in PCBs



Objectives of Grounding in PCBs

- 3 objectives:
  - DC Power Return
  - Signal Return
  - Image Plane

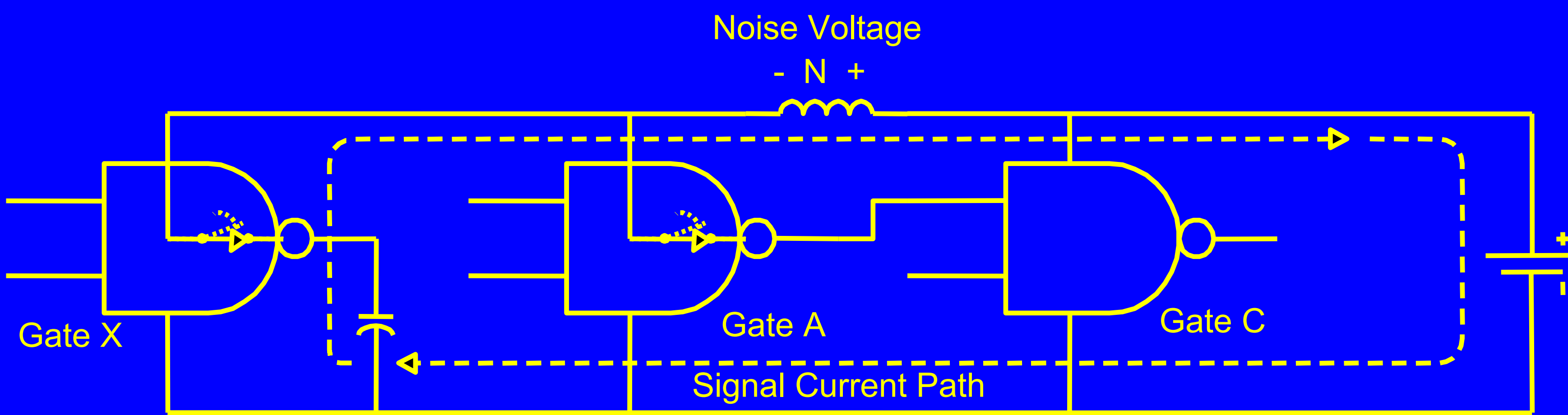


Power and Return Circuits on PCBs

Power and Return Circuits on PCBs

Noise due to Current Switching

- **The battery and its power & return leads must have a very low Z, to maintain stable transmitted signal levels**



When gate X switches Hi, current from battery charges the load capacitance

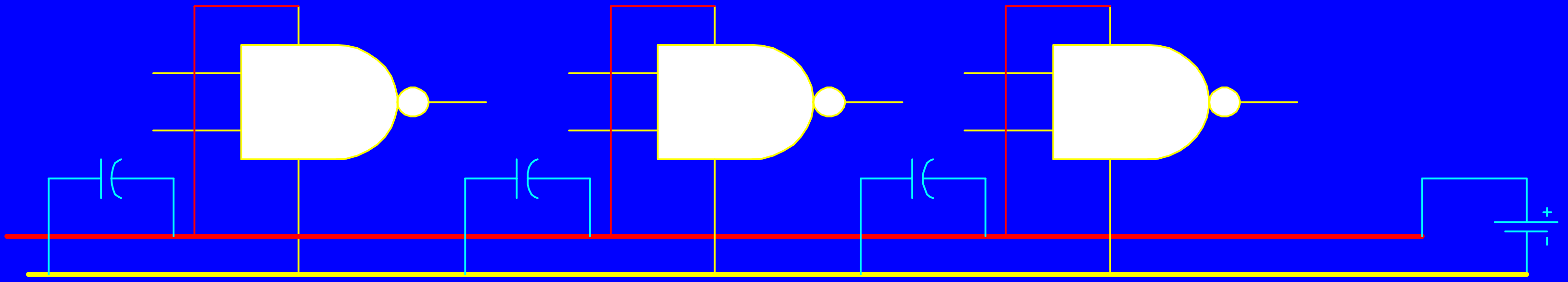
When gate A switches Hi, it connects its output to the (+) terminal of the supply. Any noise there transfers to its output

- **Alternative, low-Z paths between power and ground should be provided**

Power and Return Circuits on PCBs

Noise due to Current Switching

- **Rule #1:** Use low impedance ground connections between gates
- **Rule #2:** The impedance between power pins on any two gates should be just as low as the impedance between ground pins
- **Rule #3:** A low impedance path must be provided between power and ground

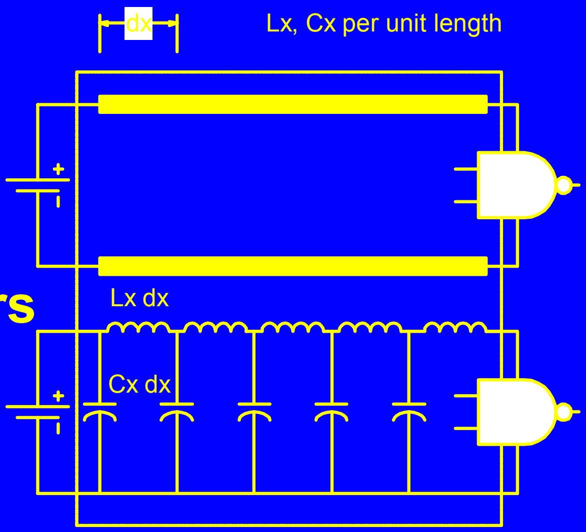


Power and Return Circuits on PCBs
Reduction of Power Distribution Impedance

- For high switching current transients, the power distribution system can be represented by a two conductor transmission line
- Amplitude of power supply transients is directly proportional to the characteristic impedance of the power distribution system, Z_0:
- Reduction of Z_0 mandates:
  - Reduction of inductance
  - Increase in capacitance

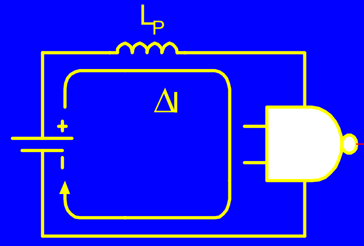
$$Z_0 = \sqrt{\frac{L}{C}}$$

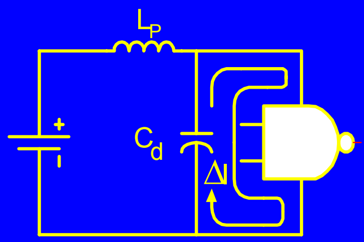
- Both are achieved by:
  - Reduction of loop area between conductors
  - Placing conductors as closely as possible
  - Increase of conductors' width



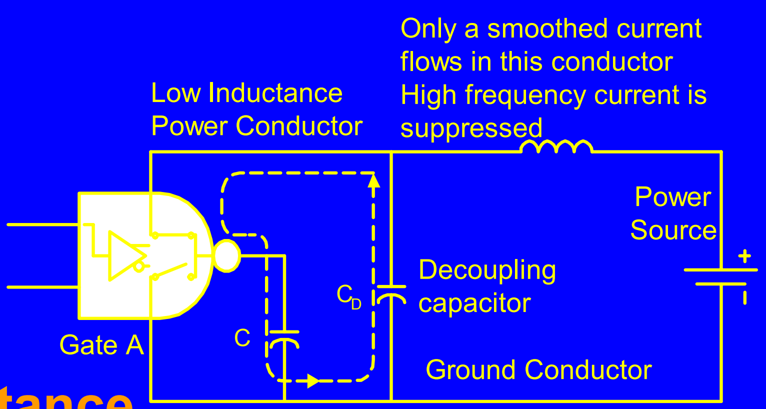
Power and Return Circuits on PCBs
Power Supply System Decoupling

- **Further Improvement: Decoupling Capacitors**
  - **Reduce Inductance of power lead**
  - **Reduce radiating loop area**
  - **Reduce transient current drawn from P.S.**
  - **Provide a transient current source near device**



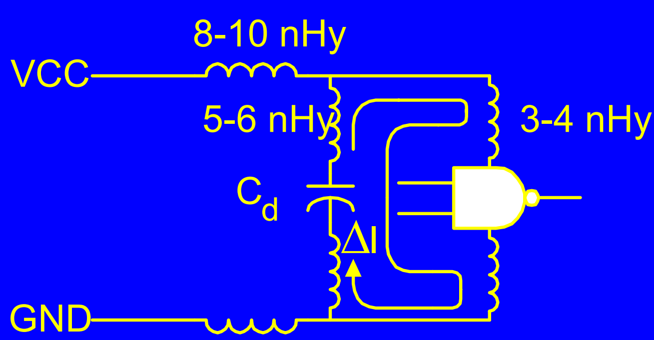


- **How does it work?**
  - **Low-F current provided directly from power source**
  - **High-F current provided by decoupling capacitor**
  - **High-F current ONLY provided from capacitor via the path of least inductance**



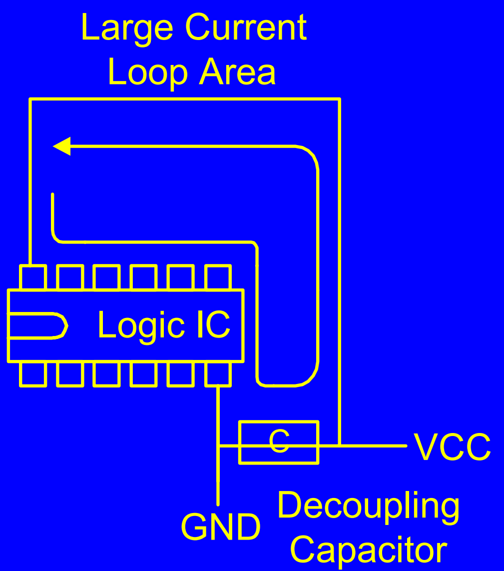
Power and Return Circuits on PCBs
Installation of Decoupling Capacitors

- **Decoupling capacitors must be installed as near as possible to the decoupled device, or else...**



Bad Installation!

Loop inductance still dominates, defeating the decoupling

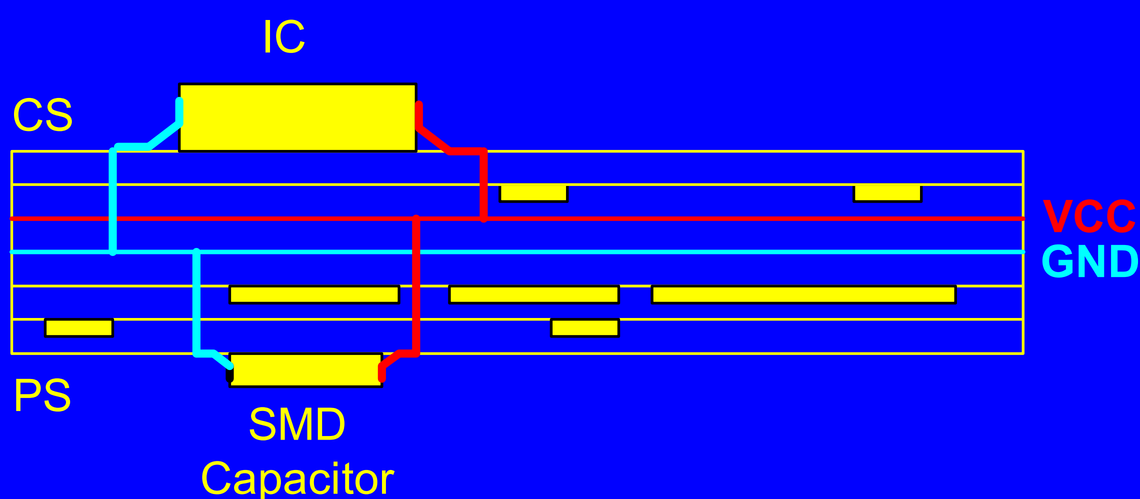


only half work is done...! The current is forced to flow through a high inductance!

Power and Return Circuits on PCBs
Installation of Decoupling Capacitors

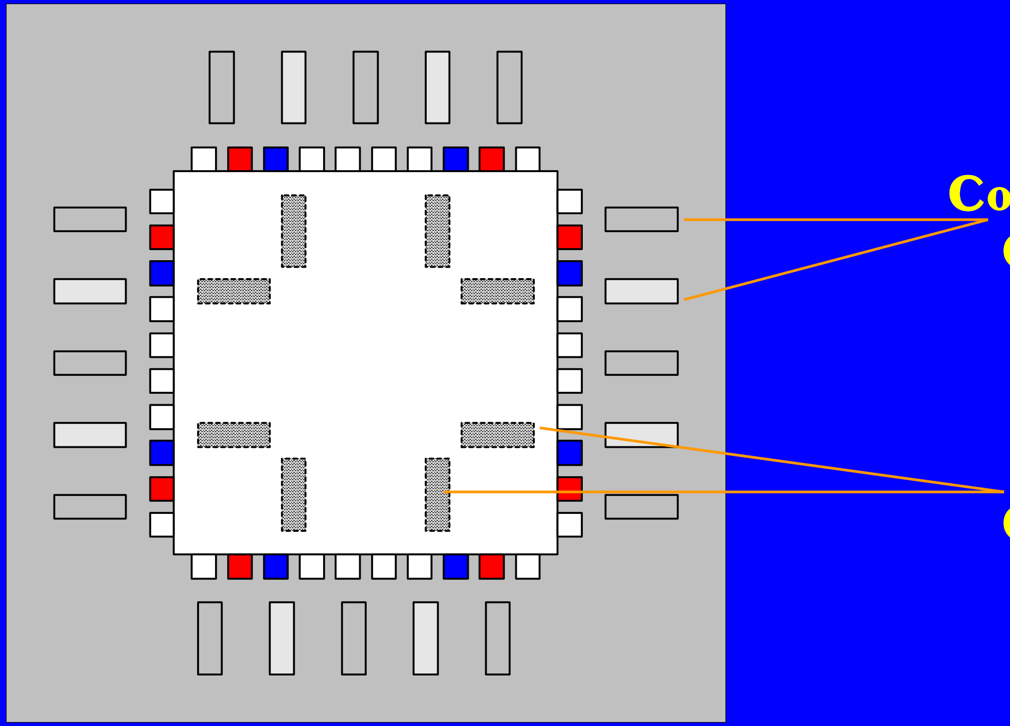
Good Installation!

Loop inductance minimized



Power and Return Circuits on PCBs
Installation of Decoupling Capacitors

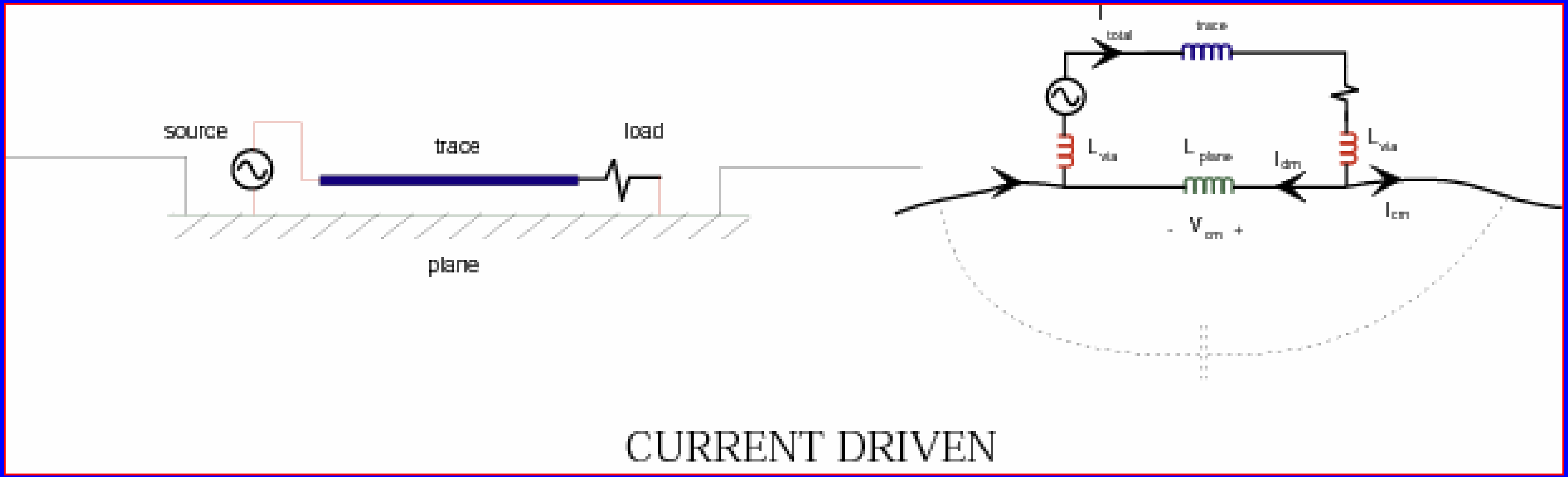
Pin Grid Arrays (PGA), e.g. memories, require multiple capacitors, due to high current consumption at refresh cycles



High Speed Signal and Return Circuits on PCBs

High Speed Signal and Return Circuits on PCBs

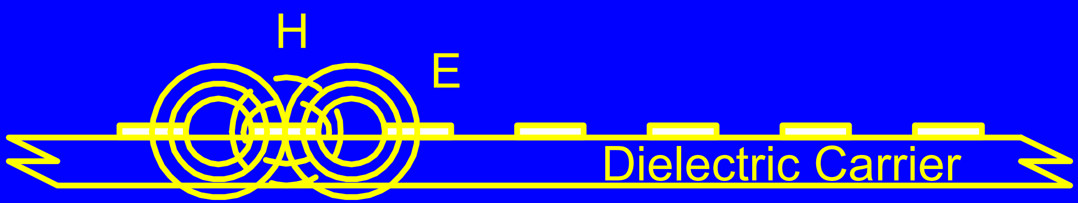
- **Loop inductance dominates EMI from high speed signal propagation and signal integrity**



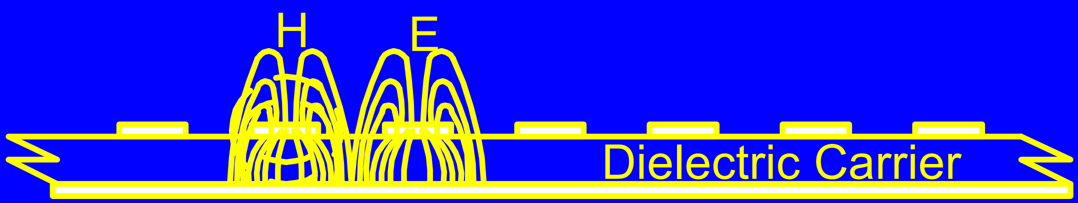
- ***Courtesy: Prof. Todd Hubing, UMR***

High Speed Return Signals on PCBs
Topologies for Signal Returns

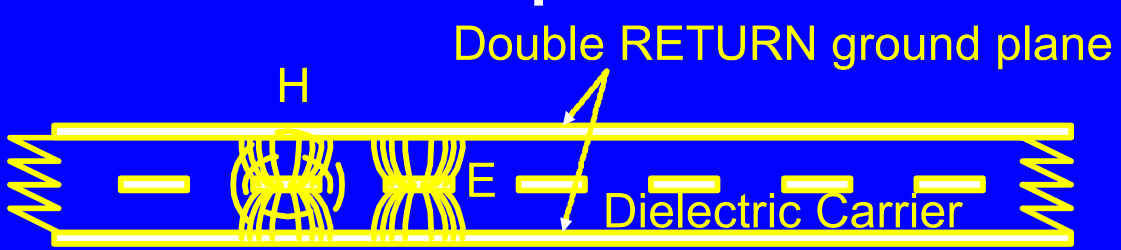
- Exposed traces over a PCB with no ground plane



- Traces routed as “microstrip”

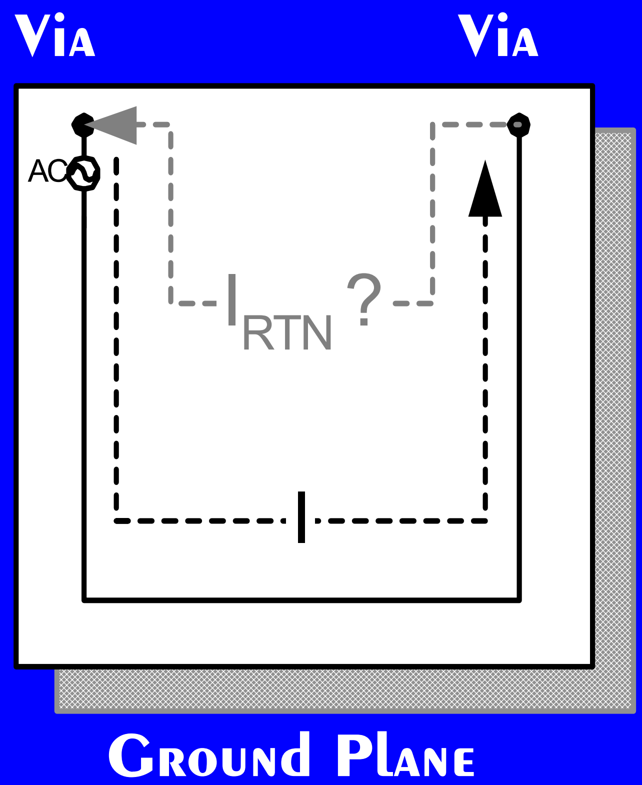


- Traces routed as “stripline”

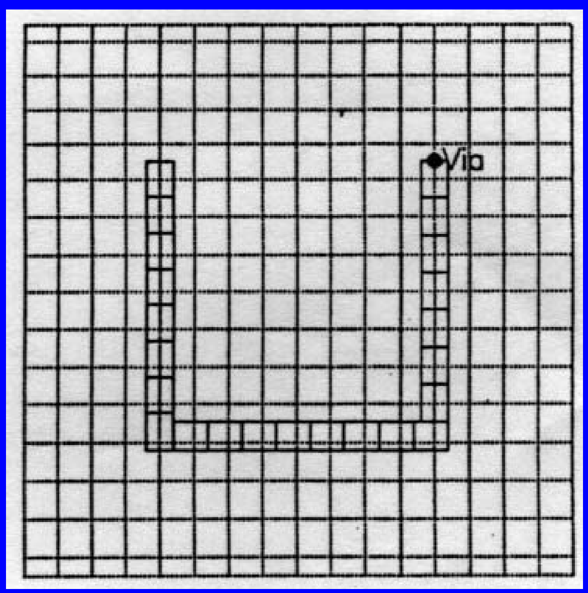


High Speed Return Signals on PCBs
Return Current Flow in Ground Planes

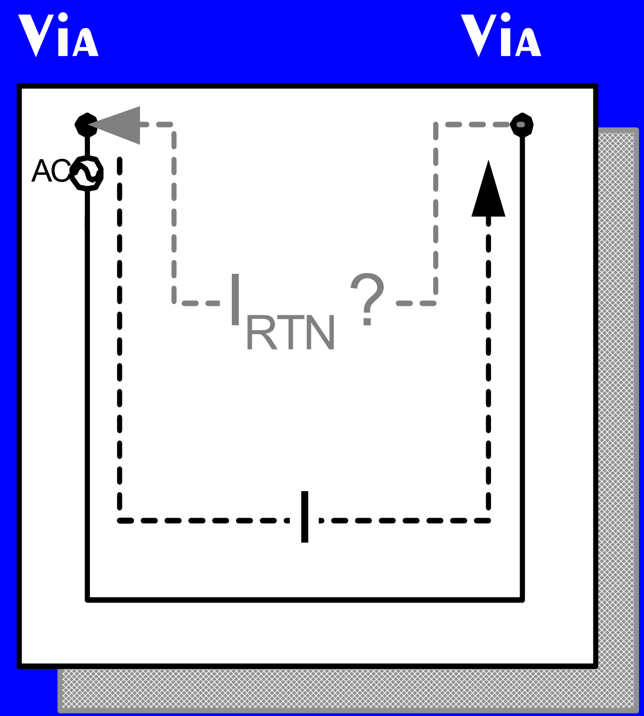
- How will the return current flow?
  - Will it take the shortest path?
  - Will it take the path with the lowest resistance?
  - Will it take the path with the lowest impedance?



High Speed Return Signals on PCBs
Return Current Flow in Ground Planes

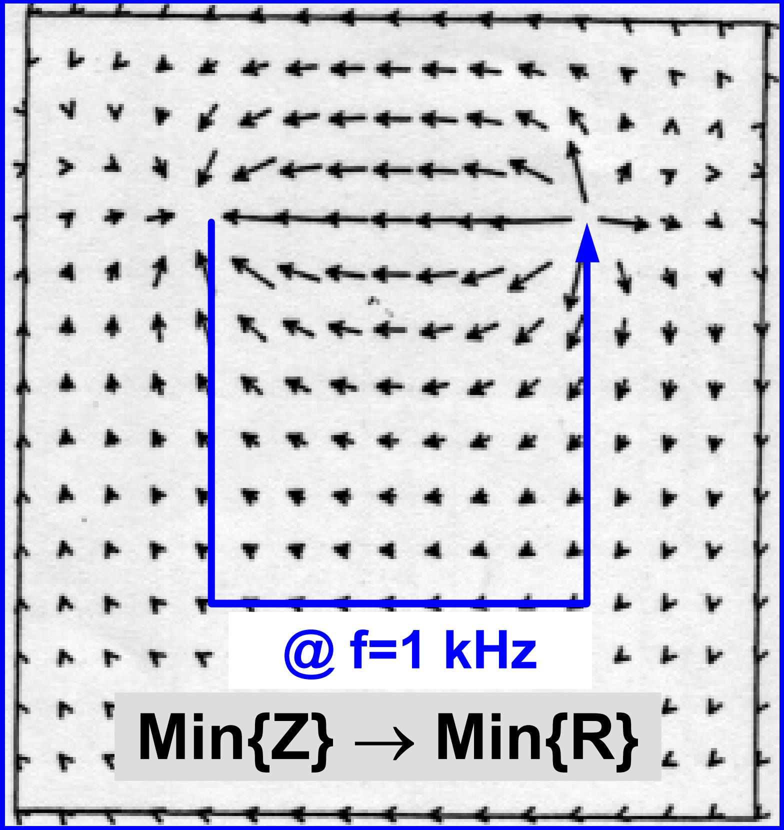


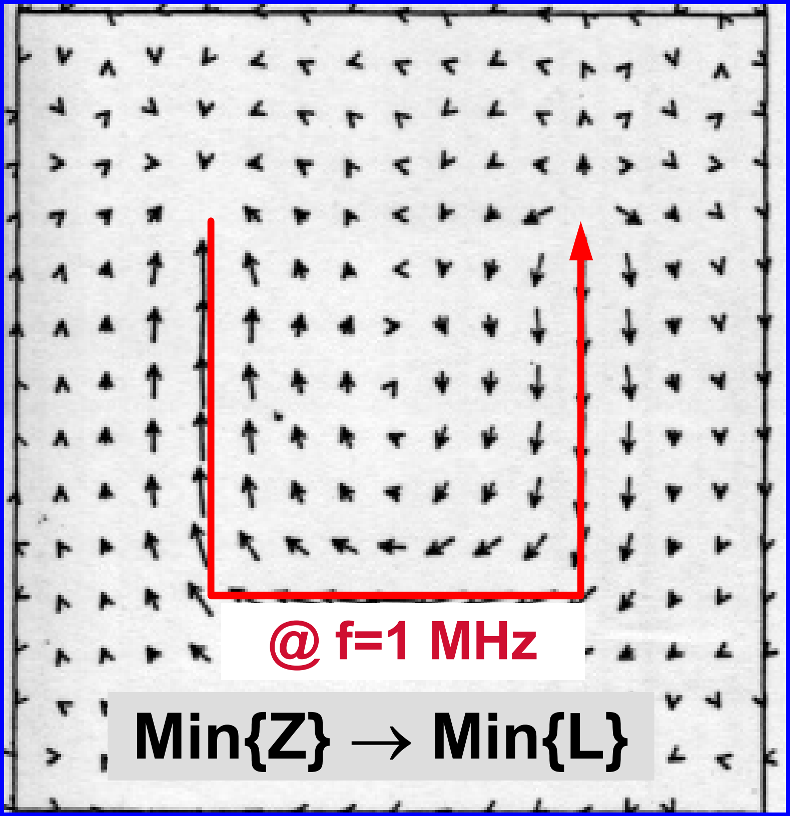
MoM Simulation
Model



Ground Plane

High Speed Return Signals on PCBs
Return Current Flow in Ground Planes



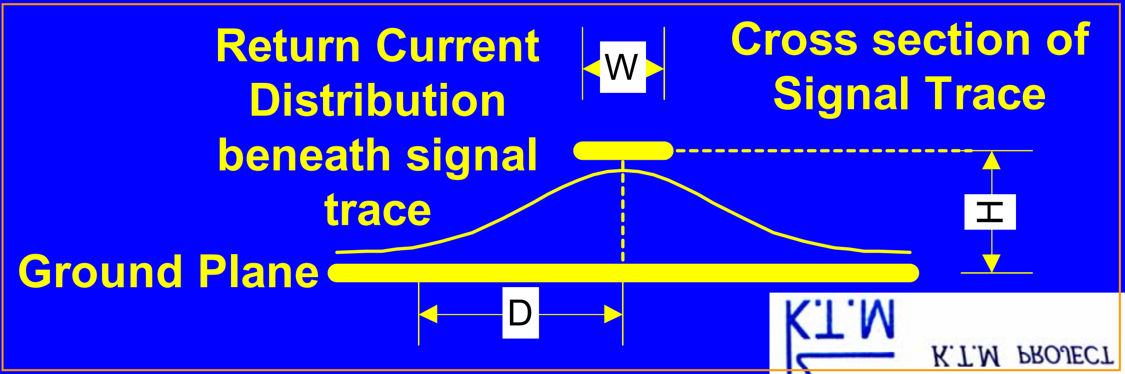


High Speed Return Signals on PCBs

Return Current Flow in Ground Planes

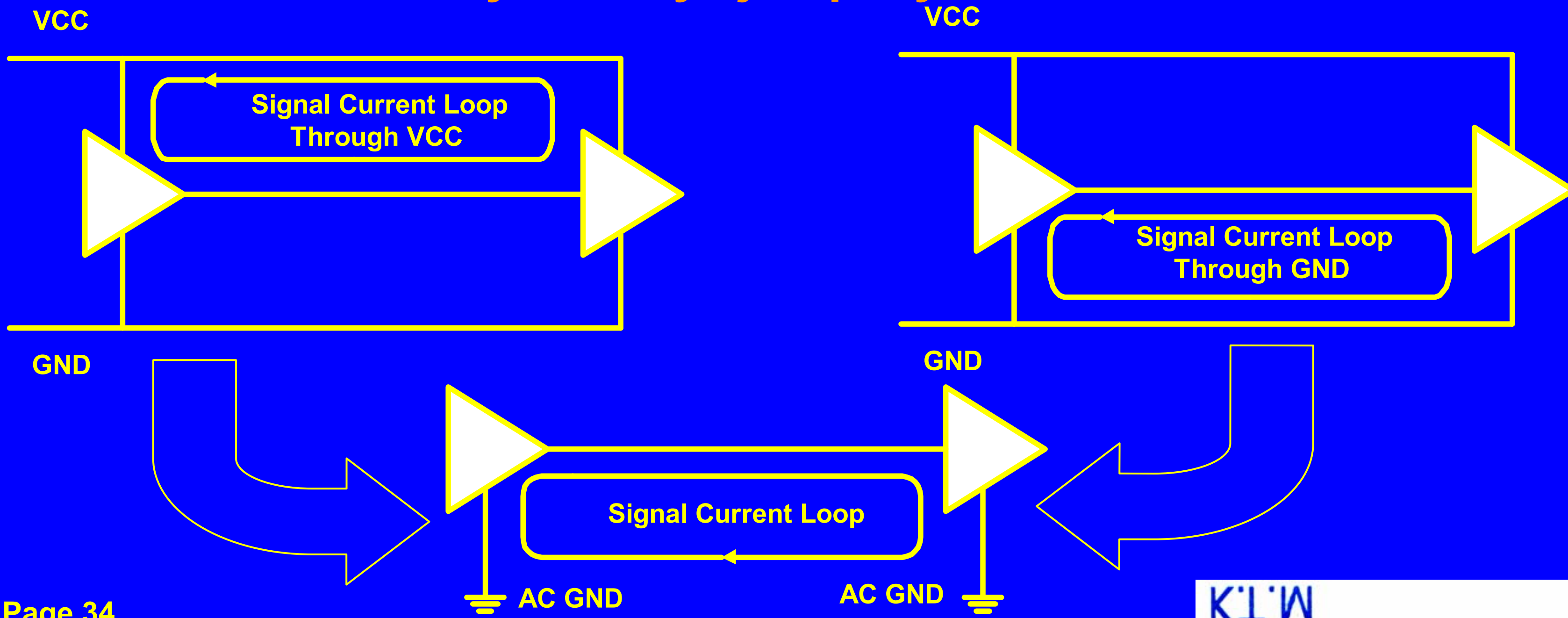
- **The current distribution balances to opposing forces:**
  - **If the return current is concentrated immediately below the trace, it would have a higher inductance**
    - **A skinny conductor has a higher inductance than a wide conductor**
  - **If the return current is spread farther apart from the trace, the loop inductance will increase,** violating the path of least inductance
    - **Loop inductance is proportional to the current path loop area**

$$i(D)_{A/m} = \frac{I_0}{\pi H} \cdot \frac{1}{1+\left(D/H\right)^2}$$

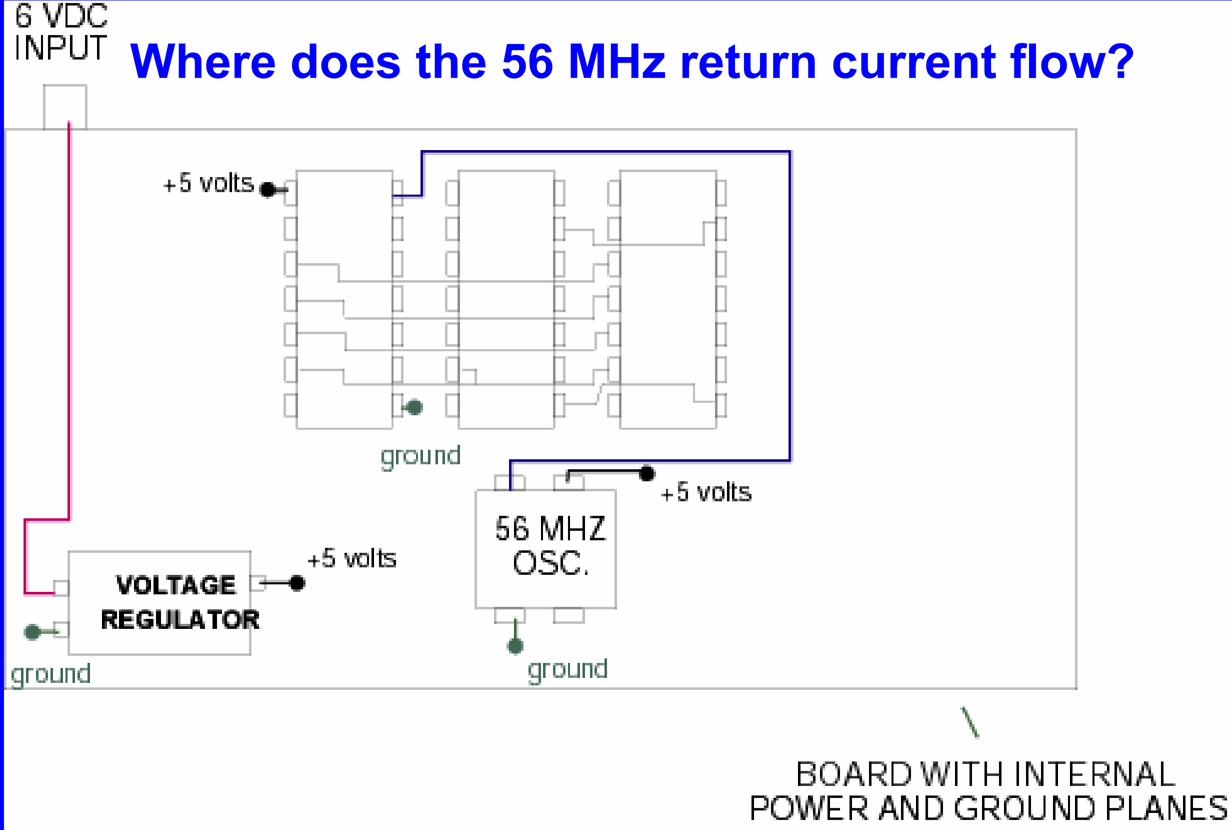


High Speed Return Signals on PCBs
Return Current Flow in Ground Planes

- **The return current may flow either through Ground (GND) or Power (VCC) layers**
  - It will "choose" the path of… lower inductance
  - If necessary - it may "jump layers"



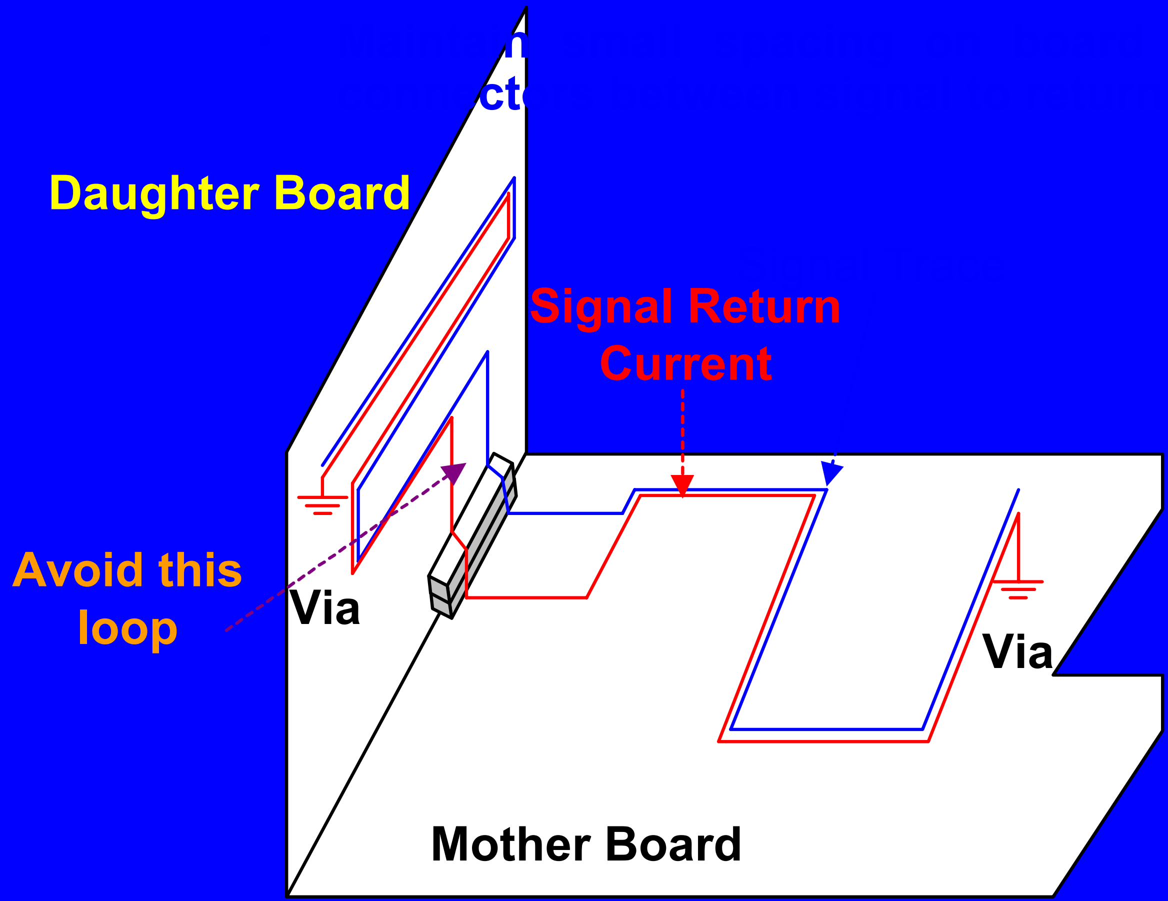
High Speed Return Signals on PCBs
Return Current Flow in Ground Planes



- *Courtesy: Prof. Todd Hubing, UMR*

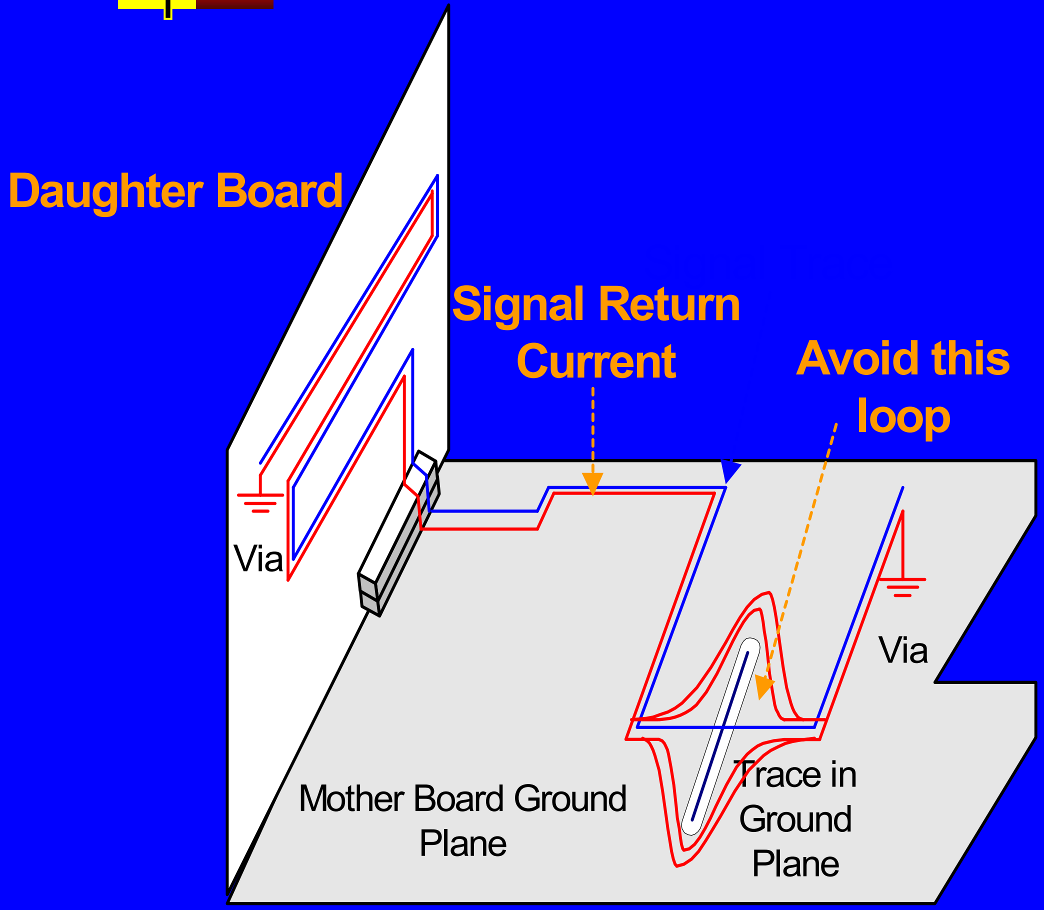
High Speed Return Signals on PCBs

Return Current Flow in Ground Planes

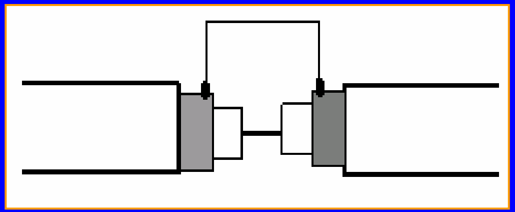


High Speed Return Signals on PCBs

How do the Signal Return Currents Flow… with slots in the ground plane?



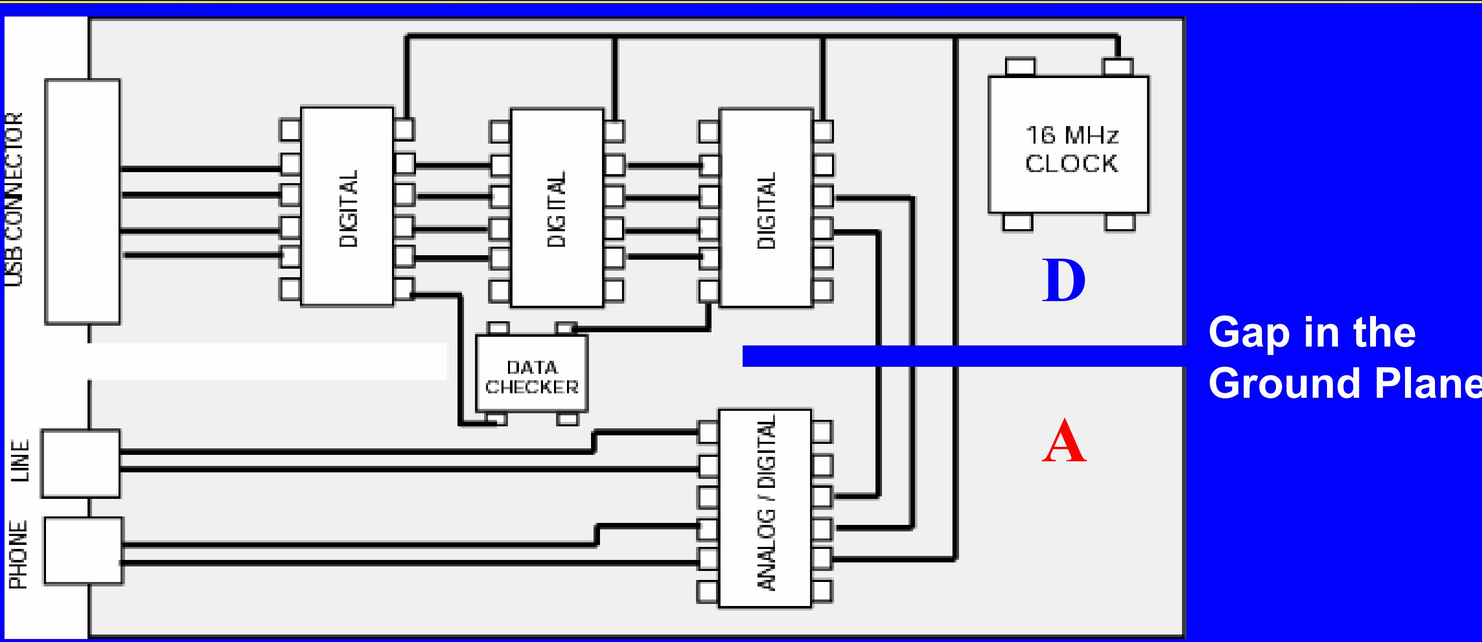
- A "Trace in the ground plane" diverts the return currents
- Signal+Return loop area increases
- Loop inductance increases
- Crosstalk, Radiation



- Effect similar to splicing a coaxial cable

High Speed Return Signals on PCBs

(Almost) Never gap a solid ground plane!!!

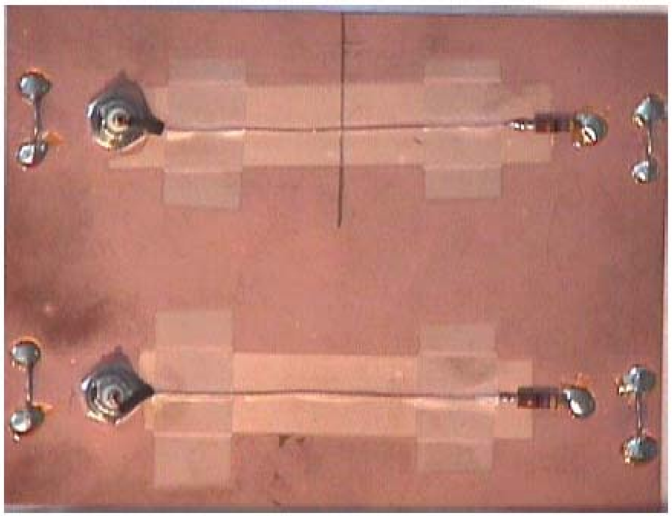


- *Courtesy: Prof. Todd Hubing, UMR*

- **Enhances potential differences in ground**
- **Usually creates more problems than it solves**
- **Except… when necessary to prevent common-impedance coupling at frequencies below 100 kHz**

High Speed Return Signals on PCBs

Effects of slots in the ground plane Illustrated

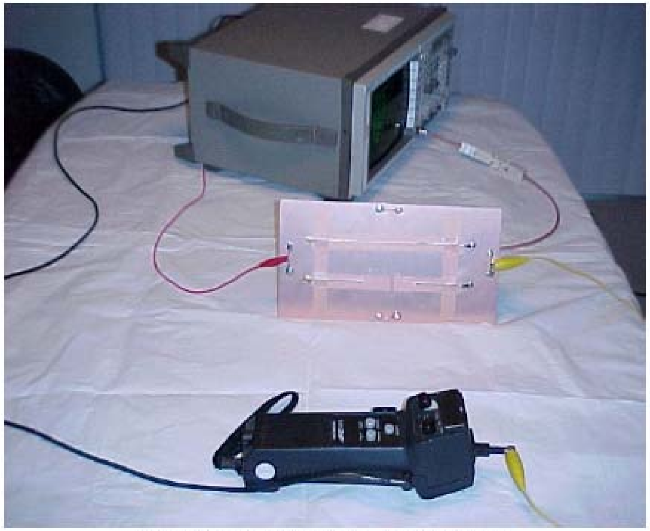


Split Ground Plane Test Board

From: “ESD and EMI Effects in Printed Wiring Boards”

Courtesy of Douglas C. Smith

- **1kV ESD injected onto PCB with and without split**
- **Noise coupled into a test circuit was measured**

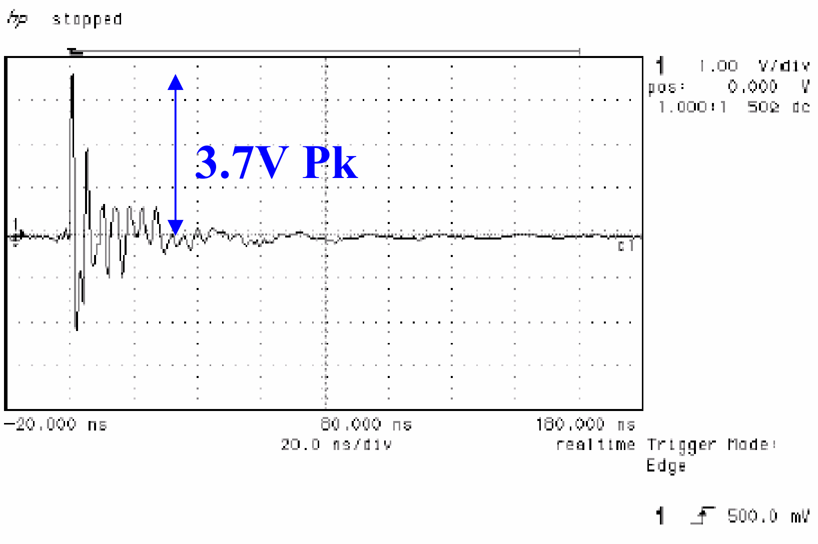


Overall Test Setup - Front View

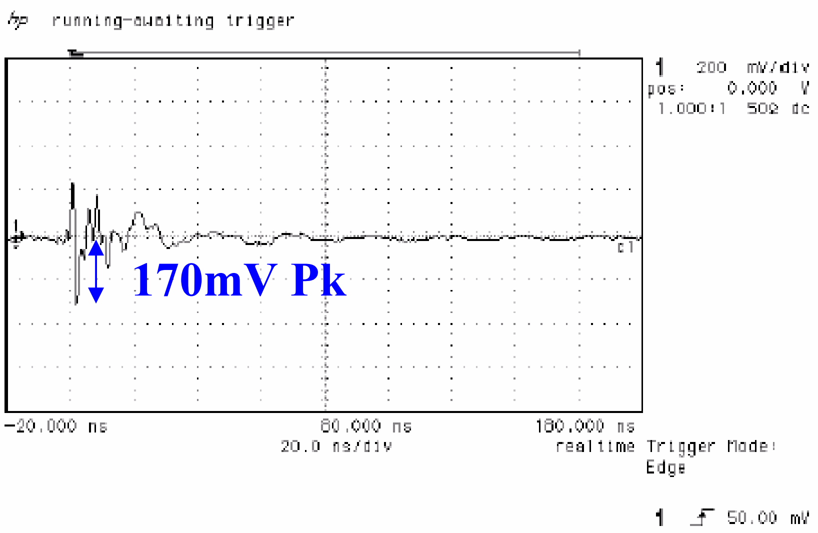
High Speed Return Signals on PCBs

Effects of slots in the ground plane Illustrated

- Increased current loop size increased noise coupling
- Violation of the Path of Least Inductance



EMI: Split Ground Plane Path (1 kV ESD)



EMI: Continuous Ground Plane Path (1 kV ESD)

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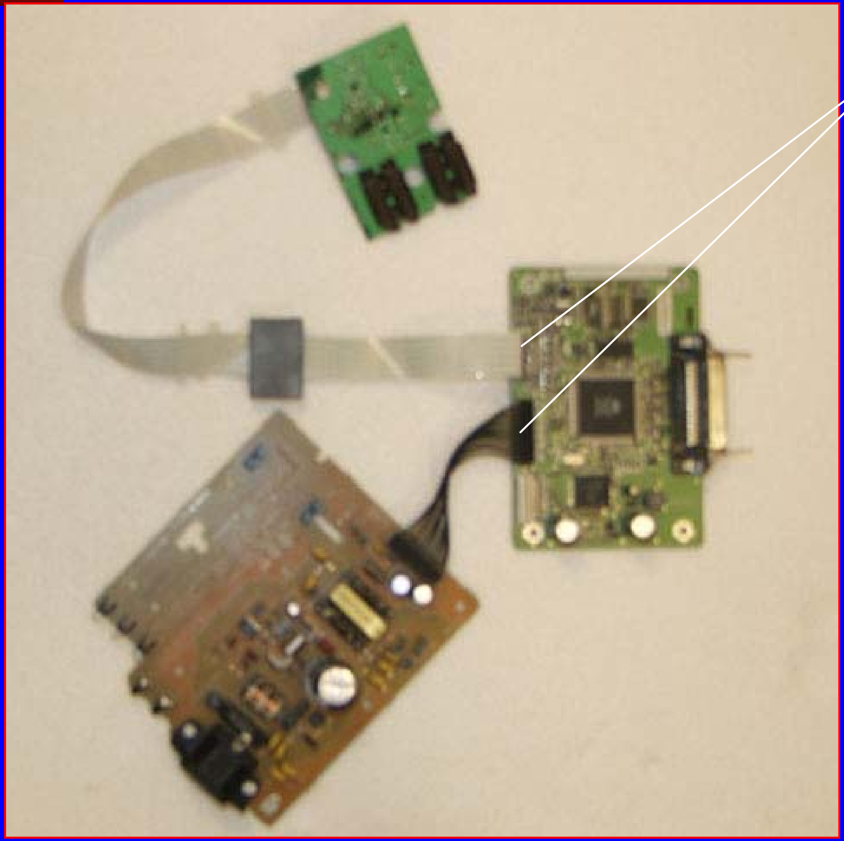
Some PCB Design Recommendations
Put connectors on one side of the board

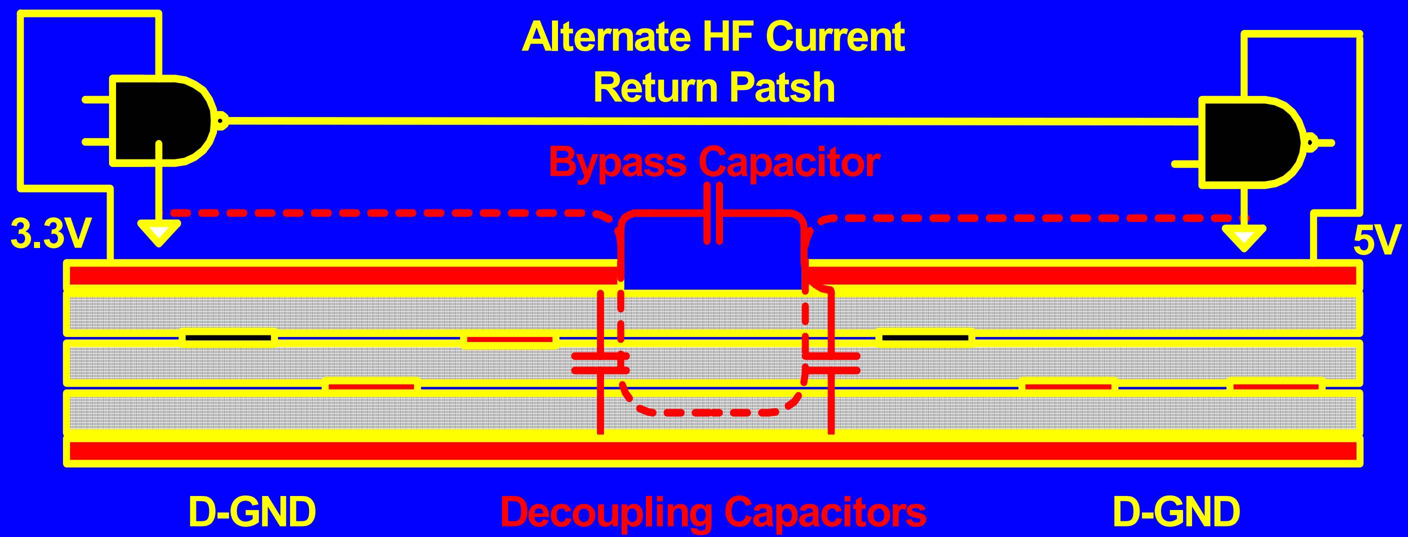


- Put connectors on one side of the PCB to reduce the loop area between I/O conductors
  - Reducing loop are of traces on PCB

- *Courtesy: Prof. Todd Hubing, UMR*

Some PCB Design Recommendations

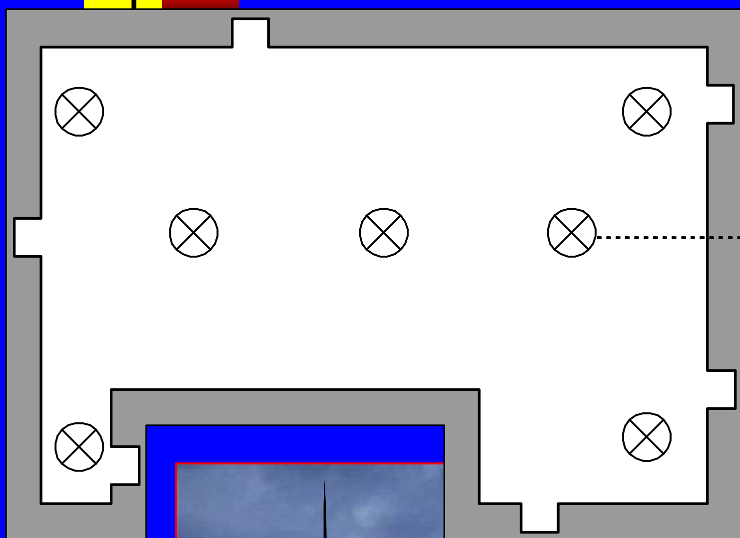
Bypassing Power Planes when Crossed by High Speed Signals

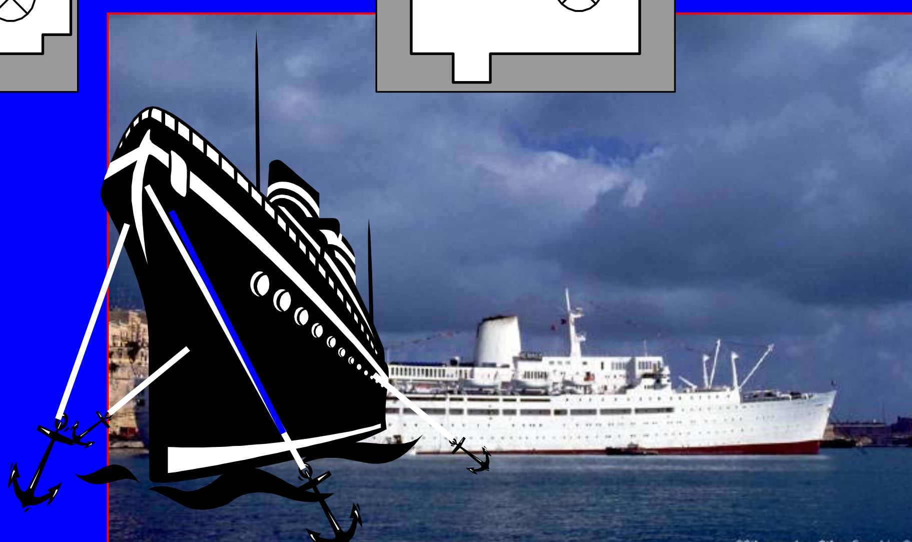


Although a solid ground plane is present, the RETURN current must seek its way through when the upper power planes are slotted/split to guarantee the path of least inductance

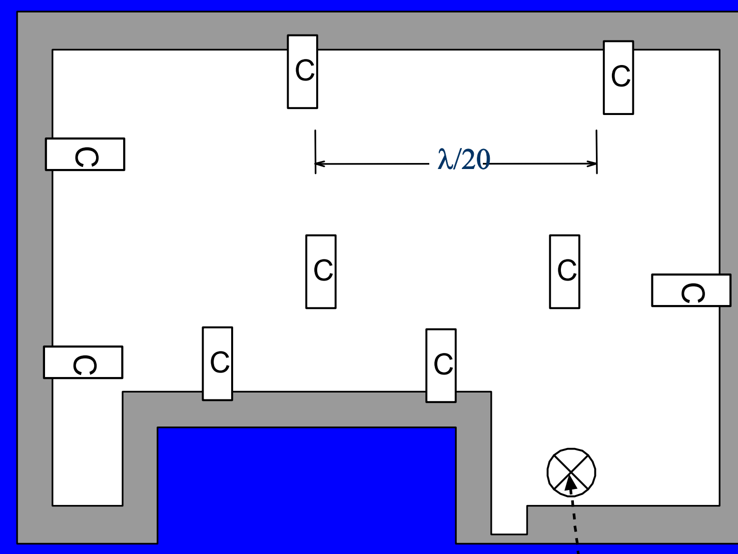
High Speed Return Signals on PCBs

Chassis Ground Connections/"Stitches"





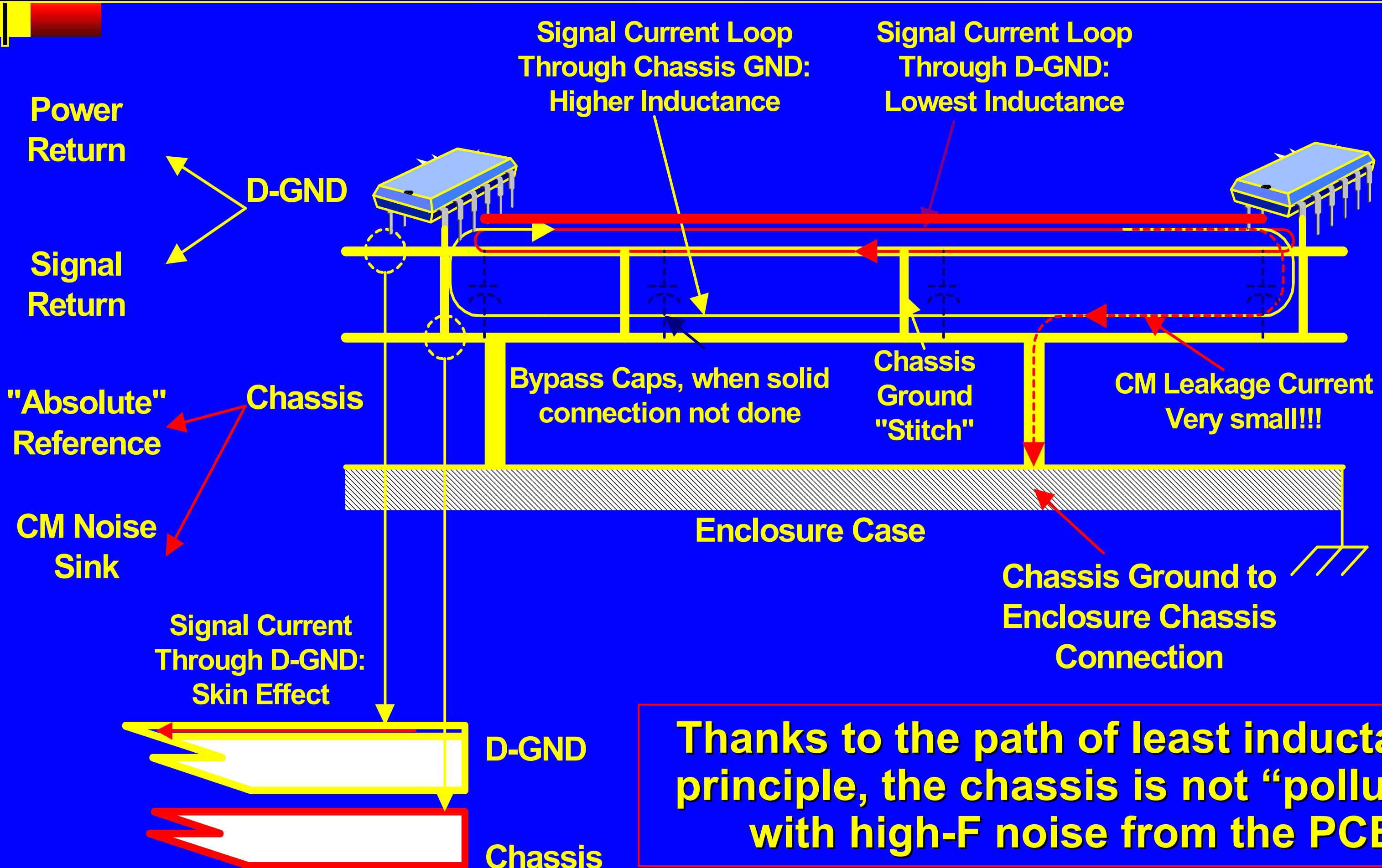
Use caps when safety requirements prohibit direct bonds



"Ground Stitches":

"Anchors" for the Circuit…?

High Speed Return Signals on PCBs
Chassis Ground Connections/"Stitches": A Problem?

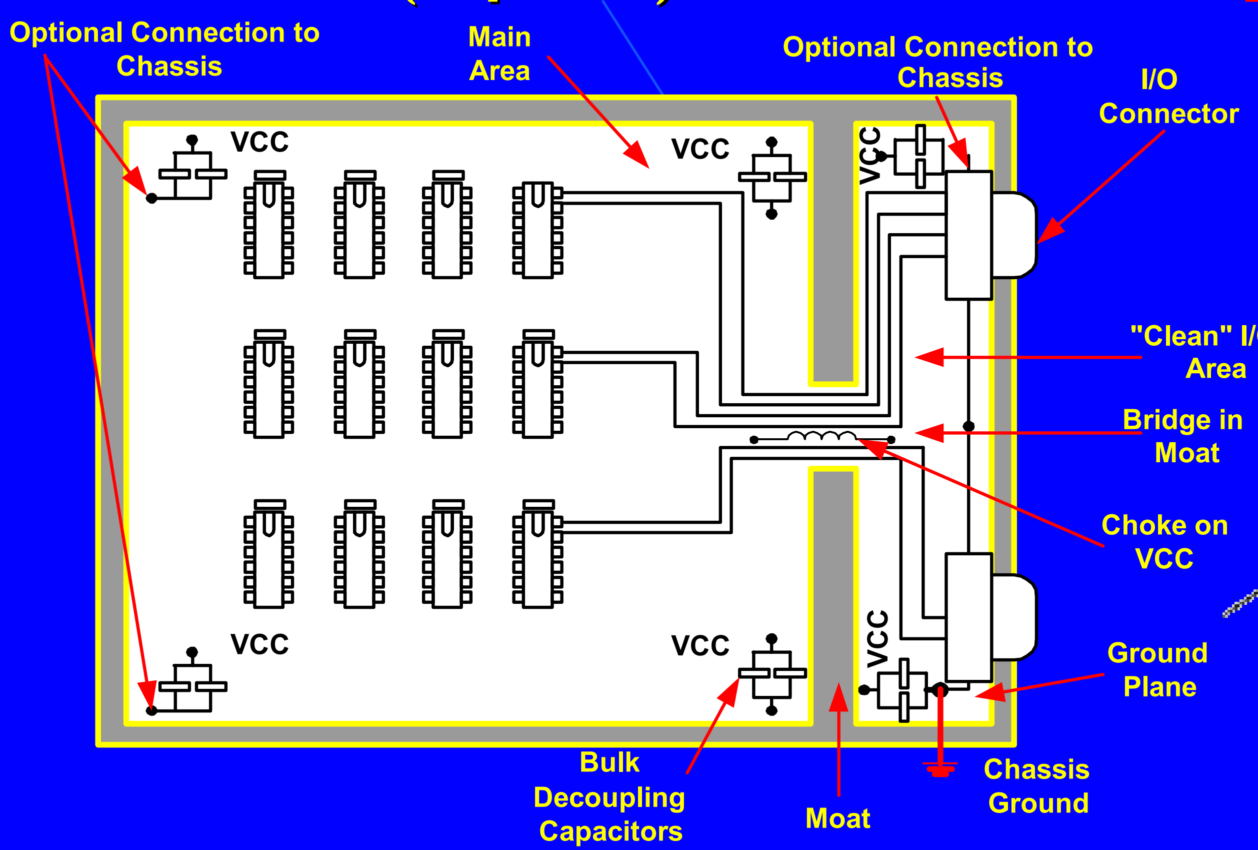


Thanks to the path of least inductance principle, the chassis is not "polluted" with high-F noise from the PCB

High Speed Return Signals on PCBs

Moats/Barriers

The "bridge" acts as a choke on the GND (& power) Planes



Himeji-Jo Castle, Japan

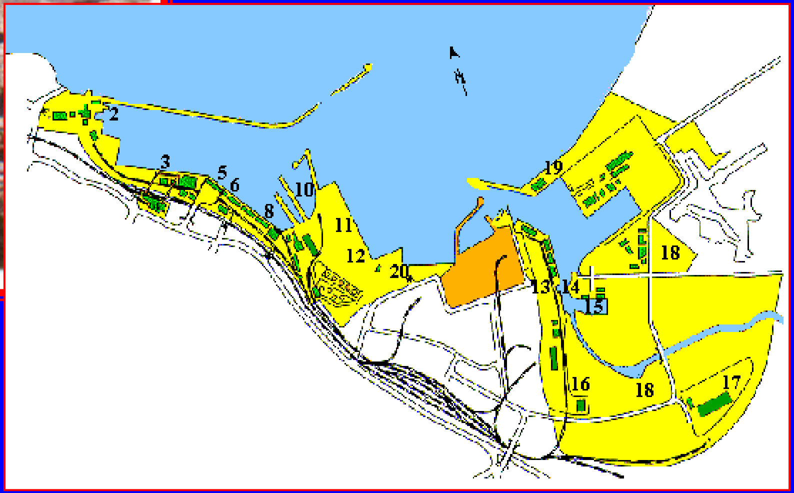
High Speed Return Signals on PCBs

Moats/Barriers

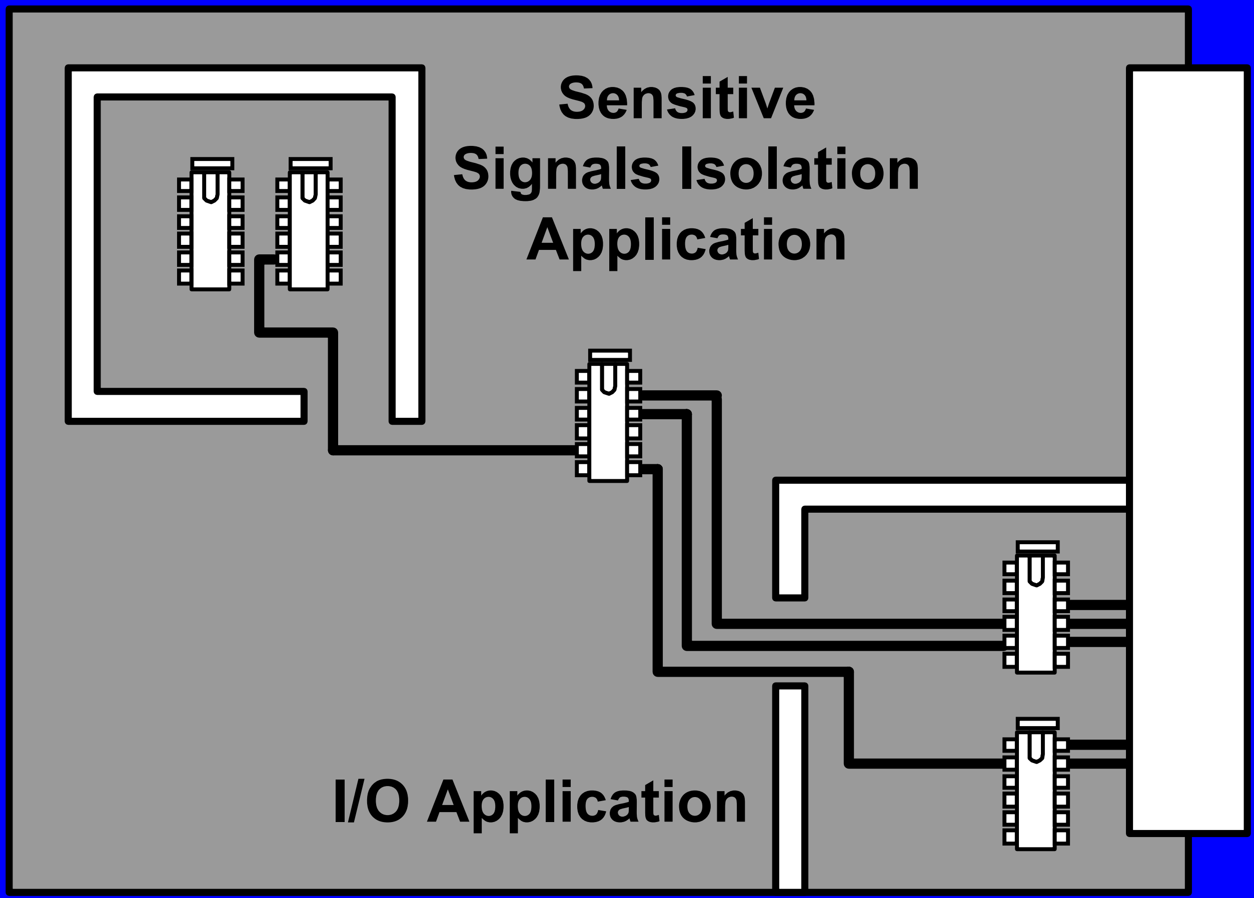
An Protected Harbor in a Rough Sea

- Keeping the rough seas outside, but letting the ships in...

The Breakwater in Haifa Port, Northern Israel



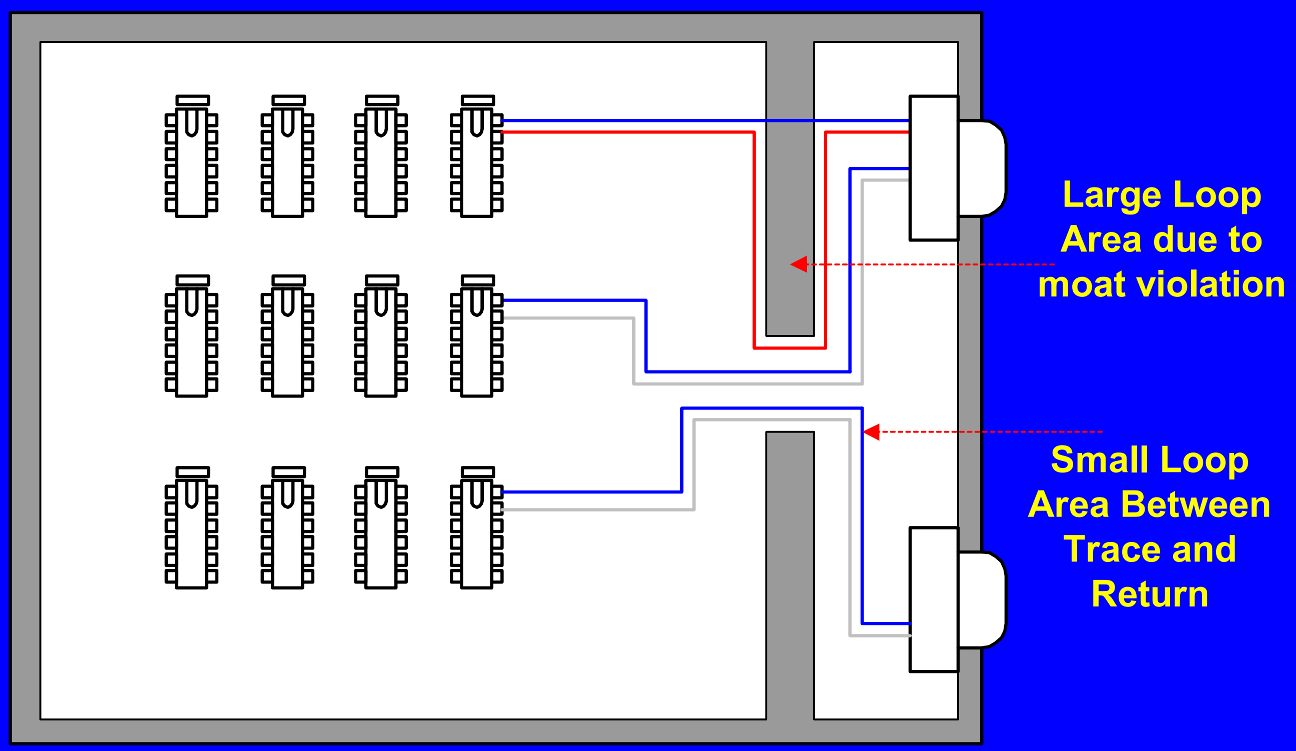
High Speed Return Signals on PCBs
Moats/Barriers Applications



High Speed Return Signals on PCBs

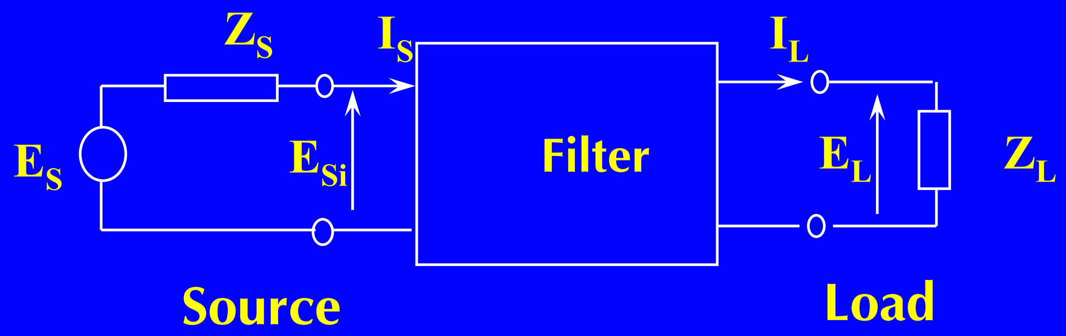
Moat Violation

Violation of the Path of Least Inductance



Implication of “Path of Least Inductance” in Filter Grounding

EMI Filters: Definition



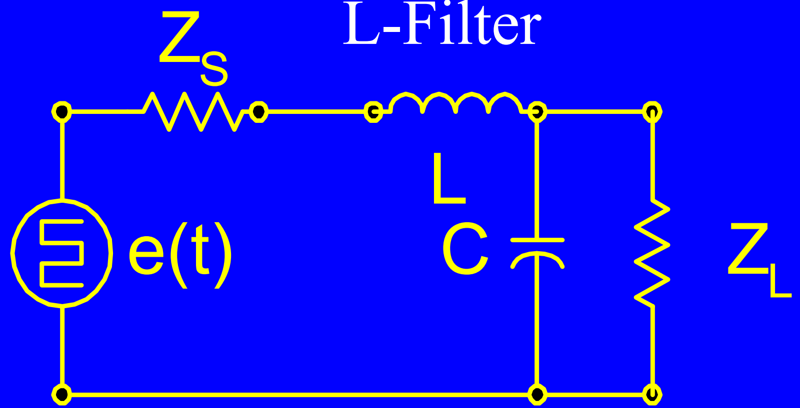
- **A filter is simply a two-port device, characterized by its Insertion Loss function:**

$$IL(\mathrm{f}) = 20 \cdot Log \frac{E_{L1}(\mathrm{f})}{E_{L2}(\mathrm{f})} = 20 \cdot Log \frac{E_L(\mathrm{f})\ \mathrm{w/\ Filter\ Inserted}}{E_L(\mathrm{f})\ \mathrm{w/o\ Filter\ Inserted}}$$

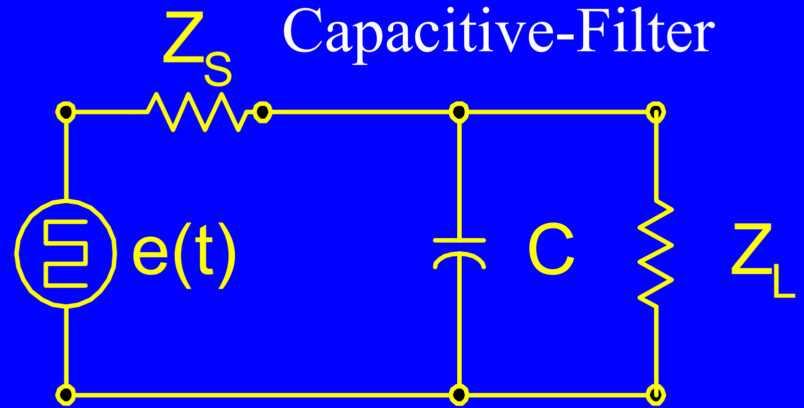
- **A filter is a simple method for attenuating conducted (and subsequently - radiated) emissions and**

Filter Topologies

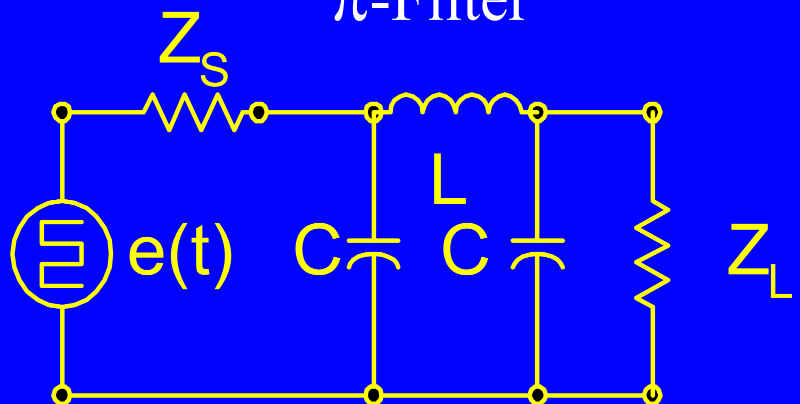
L-Filter



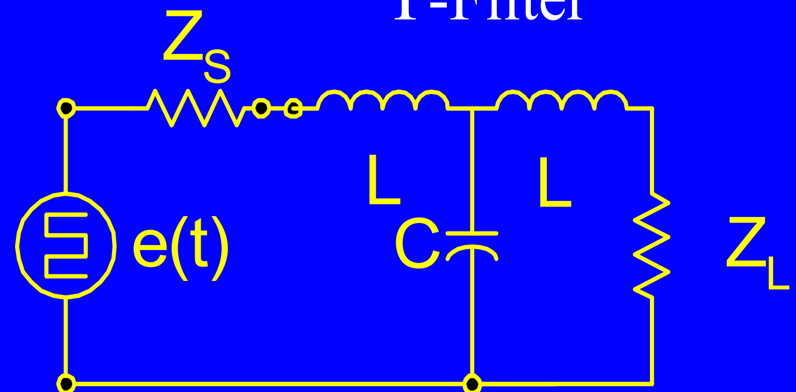
Capacitive-Filter



π-Filter

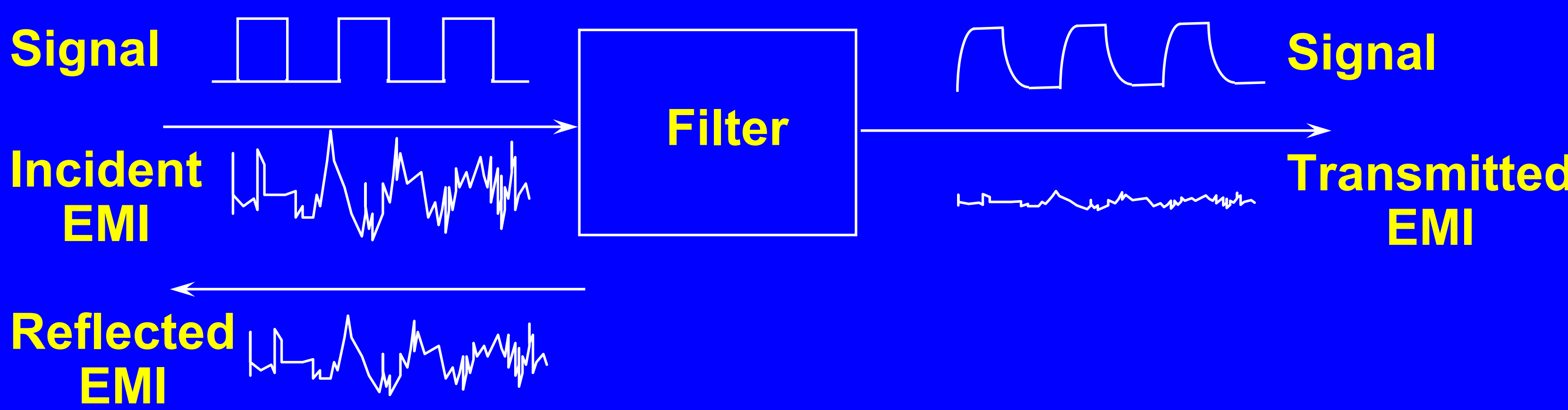


T-Filter

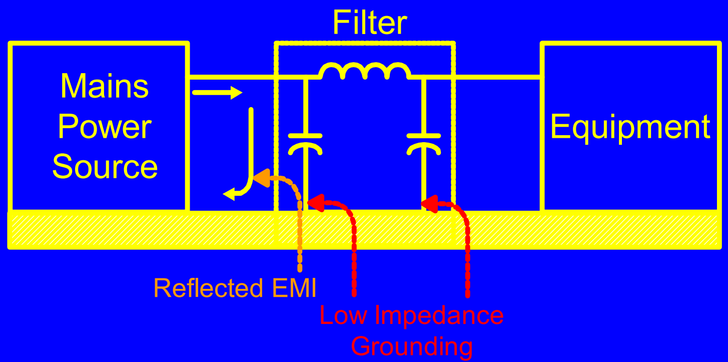


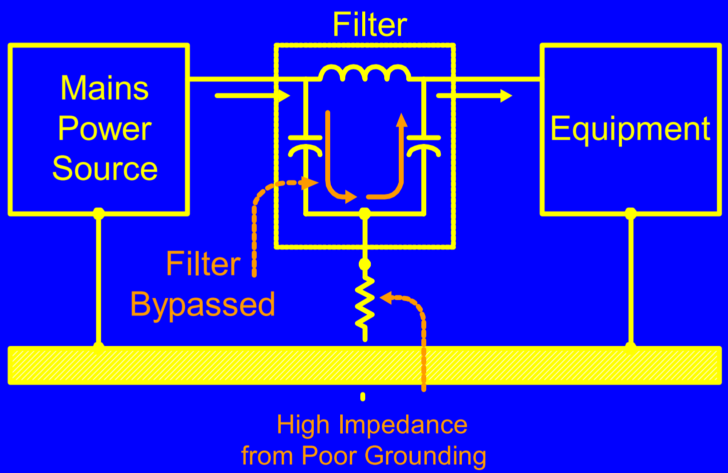
Filter Performance

- T, L & π filters are reflective filters
  - “Losses” are due to the mismatch between the noise source interference and filter’s impedance
  - Interference shunted to ground/reflected back to the source



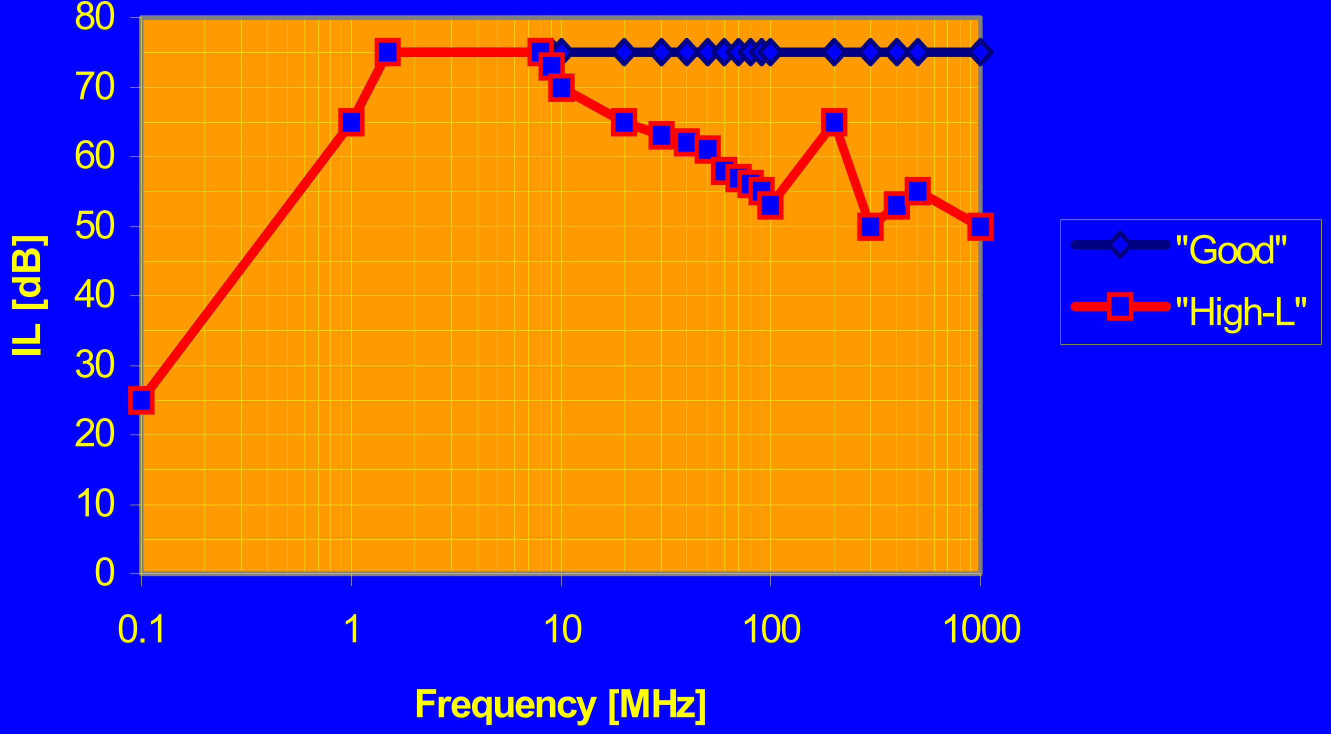
Effective Filter Performance – Dependant on Filter Grounding





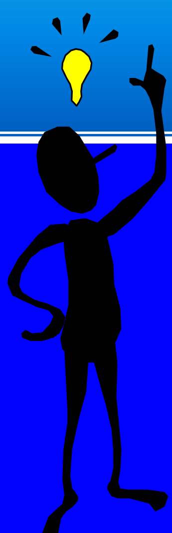
- **A well-grounded filter will reflect the high frequency EMI back to the source**
  - **HF EMI follows the path of least inductance back to the source**
- **When improperly grounded – the EMI may “bypass” the filter**
  - **Due to the high inductance of the filter grounding, the EMI bypasses the filter**

Effective Filter Performance – Dependant on Filter Grounding



Effect of bad filter grounding on Insertion Loss

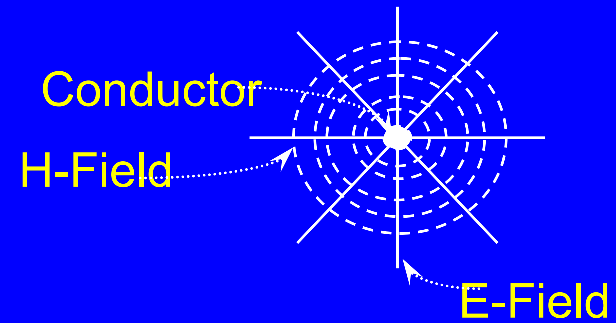
Implication of “Path of Least Inductance” in Cable Shield Grounding



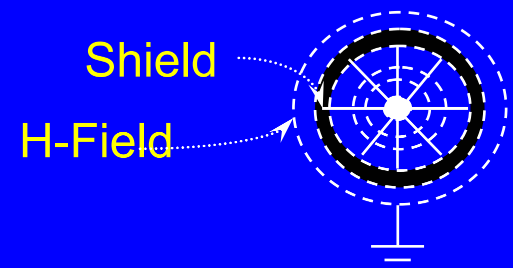
Shield Grounding

How Does the Cable Shield Work ?

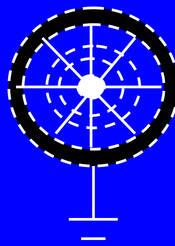
- **In a non-shielded cable:-**



- **In a shielded cable, grounded at one end:-**
  - **E-field terminates at the shield (@ *Low F*)**
  - **H-field penetrates the shield**

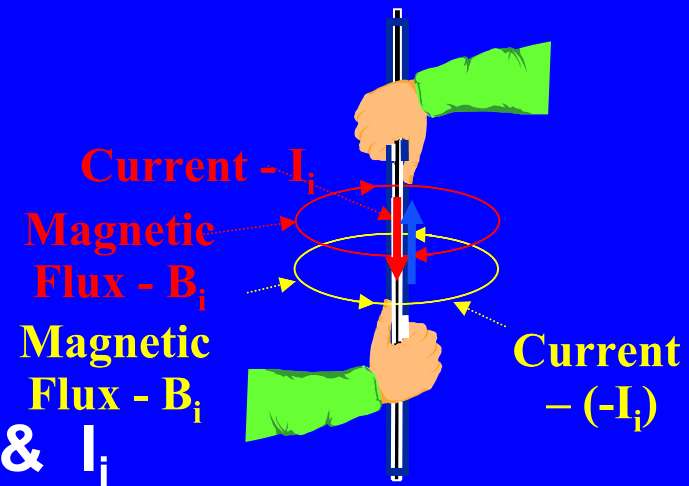


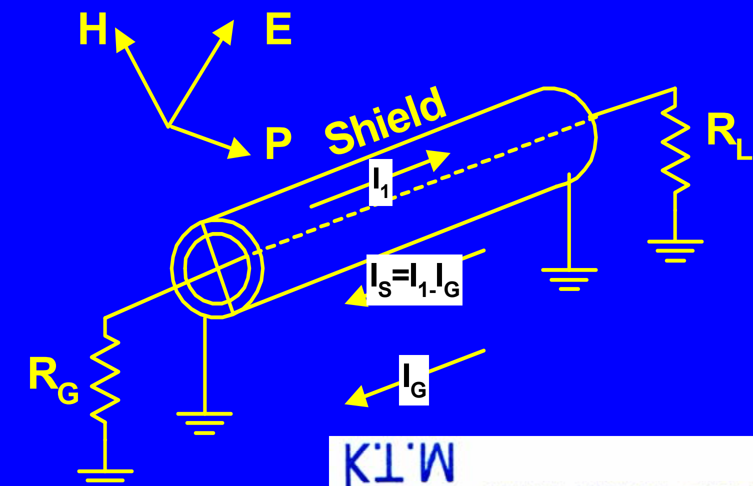
- **In a shielded cable, grounded at both ends:-**
  - **E-field terminates at the shield (@ *Low & hi F*)**
  - **H-field cancelled by opposite shield currents**



How Does The Shield Prevent H-Field Radiation ?

- Design goal:-
  - Cancellation of magnetic flux emerging from
    - Internal conductor current
    - Shield current
  - Magnetic flux from currents I_S & I_i will cancel out
- Goal achieved by:
  - Limiting ground current I_G





How Does The Shield Prevent H-Field Radiation ?

$$I_S \cdot (R_S + j\omega L_S) - I_i \cdot j\omega M = 0$$

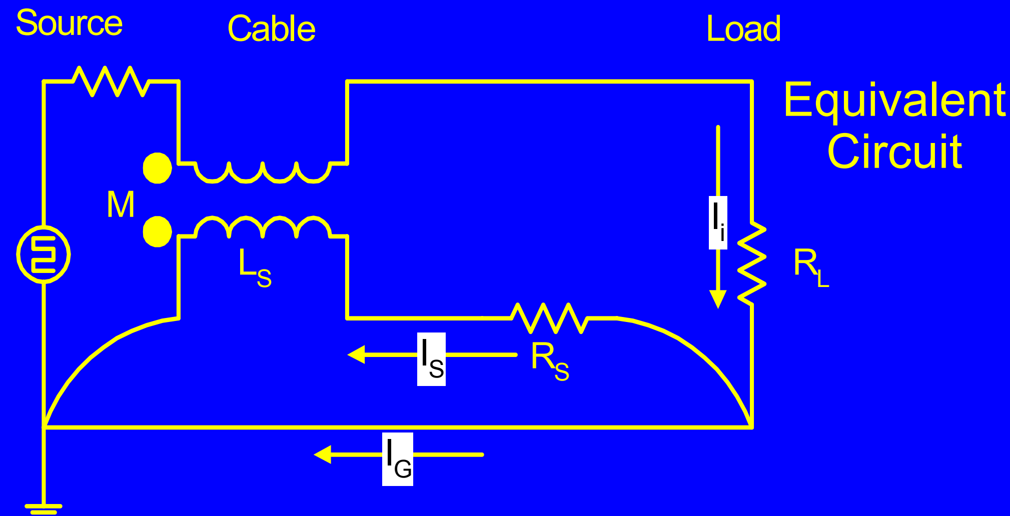
$$L_G = M$$

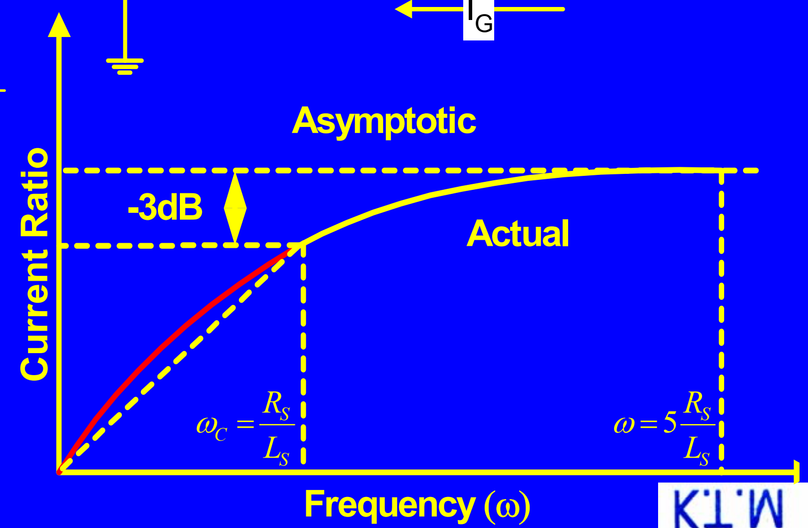
$$\frac{I_i}{I_S} = \frac{j\omega M}{R_G + j\omega L_S} = \frac{j\omega L_S}{R_S + j\omega L_S}$$

or:-

$$I_G << I_i \Leftrightarrow \omega L_S >> R_S$$

$$I_S << I_G \Leftrightarrow \omega L_S >> R_S$$



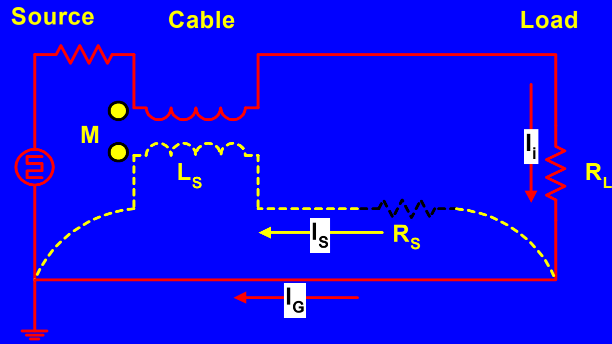


How Does The Shield Prevent H-Field Radiation ?

$$Z = R_S + j\omega \cdot M = \begin{cases} |Z| \approx R_S & @\, R_S >> j\omega \cdot L_S \\ |Z| \approx \omega \cdot L_S & @\, \omega \cdot L_S >> R_S \end{cases}$$

- At low frequencies, the current will take the **path of least resistance**, via ground (I_G)
  - Design goal not achieved

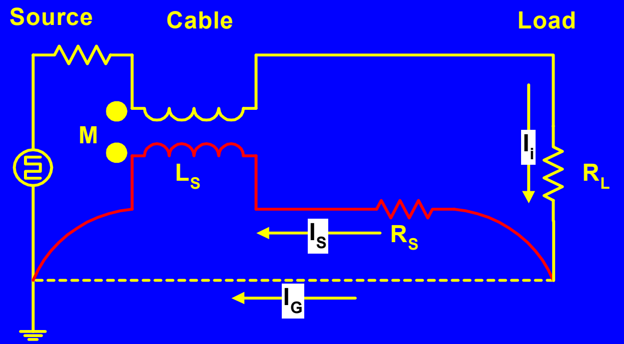
$$\frac{I_i}{I_S} \approx \frac{j\omega L_S}{R_S + j\omega L_S} \xrightarrow{R_S >> j\omega L_S} \frac{I_i}{I_S} \approx \frac{j\omega L_S}{R_S} \approx 0$$



How Does The Shield Prevent H-Field Radiation ?

$$Z = R_S + j\omega \cdot M = \begin{cases} |Z| \approx R_S & @\, R_S >> j\omega \cdot L_S \\ |Z| \approx \omega \cdot L_S & @\, \omega \cdot L_S >> R_S \end{cases}$$

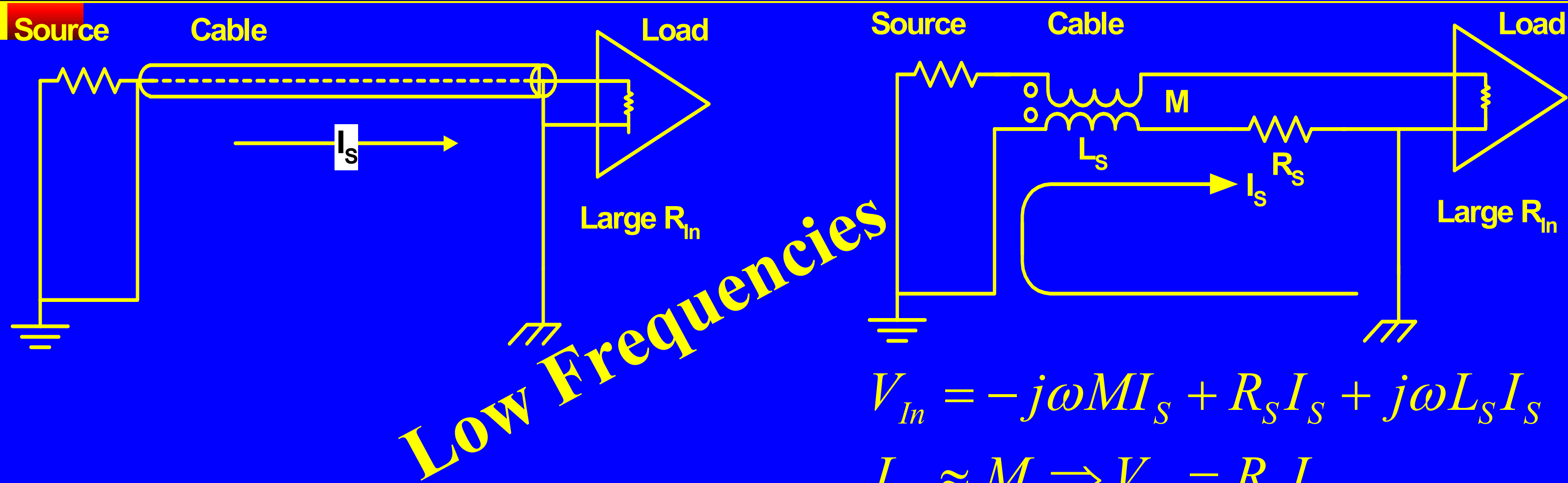
- **At high frequencies, inductance dominates the current paths**
  - **Since Inductance⇔f{Loop area}, the current will flow through the shield, if grounded properly**



Path of Least Inductance dominates at high frequencies

This is how a coaxial cable works!!!

How Does The Shield Prevent H-Field Radiation ?



$$V_{In} = -j\omega M I_S + R_S I_S + j\omega L_S I_S$$

$$L_S \approx M \Rightarrow V_{In} = R_S I_S$$

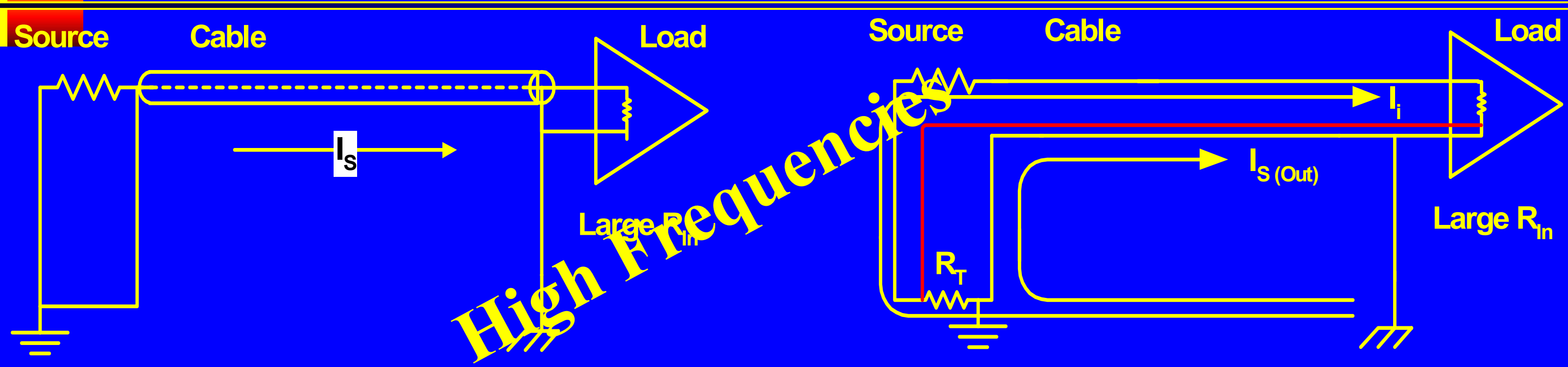
Whenever shield current flows – a noise voltage is produced in the shield due to the $I_S R_S$ voltage drop

Even if the shield is grounded one end only, noise current may flow via capacitive coupling

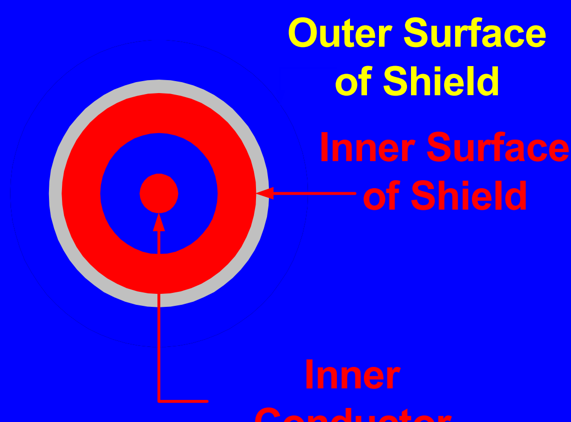
Thus:

- For low-frequency noise protection, the shield should not be one of the signal conductors
- One end of the circuit must be isolated from the ground

How Does The Shield Prevent H-Field Radiation ?



- At HF, a coaxial cable contains 3 “isolated” conductors:
  - Center Conductor
  - Inner surface of shield conductor
  - Outer surface of shield conductor
- The inner and outer surfaces of the shield are effectively isolated (large R_T) due to skin effect
- Noise coupling does not occur because:
  - Signal current flows on inner surface
  - Noise current flows on outer surface
  - No common impedance

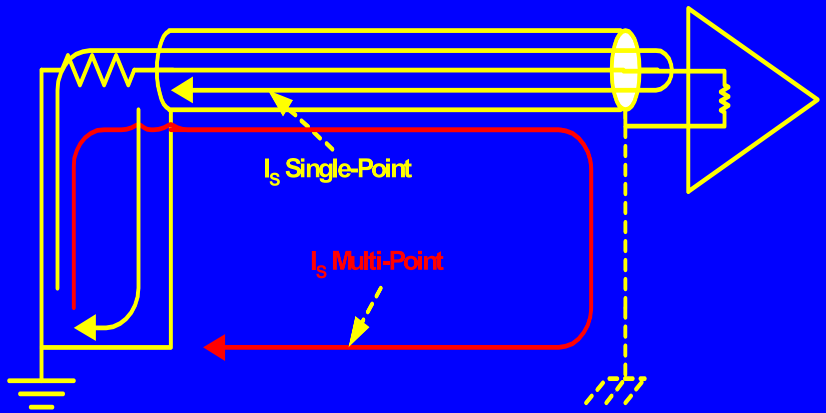


Signal vs. Shield Grounding

Signal Cable vs. Shield Grounding

Low Frequencies: Unbalanced Shielded Line

- **Unbalanced (single ended) shielded line**
  - **If single-point grounded:**
    - **Return current flows through the shield only**
    - **Effective low frequency magnetic flux cancellation**

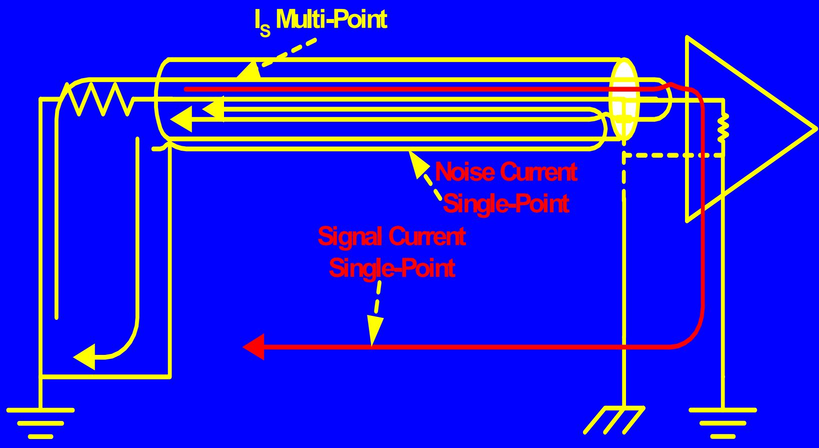


  - **If multi-point grounded**
    - **Return current splits between ground and shield**
    - **Skin effect insignificant**
    - **Ineffective Low frequency magnetic flux cancellation**
  - In low frequencies the shield forms part of the circuit path of single-ended lines leading to noise coupling into the circuit
  - Unbalanced (single ended) shielded lines should be avoided in low frequencies

Signal Cable vs. Shield Grounding

High Frequencies: Unbalanced Shielded Line (coax)

- Unbalanced shielded line
  - If single-point grounded:
    - Return current flows through chassis only
    - Ineffective high frequency magnetic flux cancellation
    - Noise may couple into circuit via shield to cable capacitance
  - If multi-point grounded
    - Return current flows primarily through inner skin of the shield
      - "Path of least inductance"
    - Interference current flows through outer skin of the shield
      - Skin effect is very significant

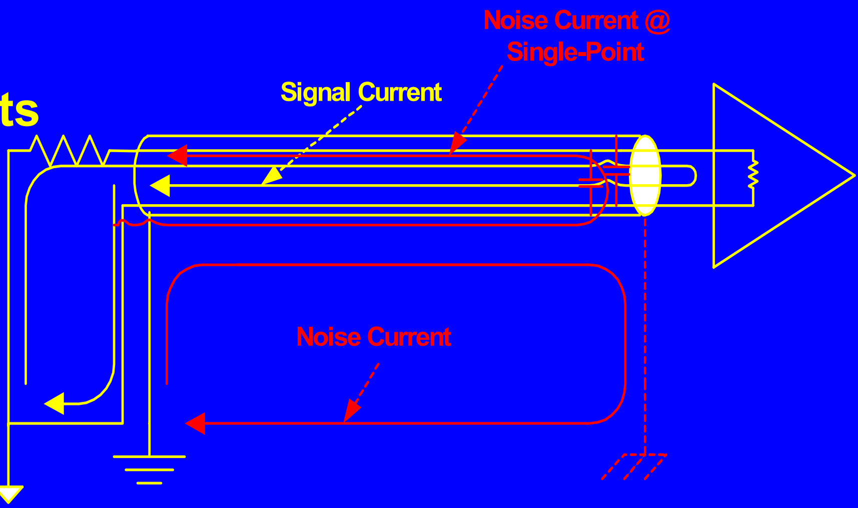


- In high frequencies the shield has two "isolated" current paths:
  - Inner skin
  - Outer layer
- Grounding both ends is MANDATORY for effective shielding and flux cancellation
- Coax and similar single-ended lines are effective

Signal Cable vs. Shield Grounding

Low & High Frequencies: Balanced Shielded Line

- Balanced shielded line
  - Return current flows through return conductor and not through the shield
  - The shield is used strictly for its purpose – shielding!
  - If shield is single-point grounded:
    - Effective low frequency E-field shielding
    - Ineffective low frequency H-field shielding
    - Ineffective high-frequency E-field shielding
  - If the shield is multi-point grounded
    - Effective high frequency shielding (both E & H fields)
  - Grounding of the shield has no impact on the circuit grounding
  - Shielding at high frequencies is effective ONLY when shield grounded at both ends



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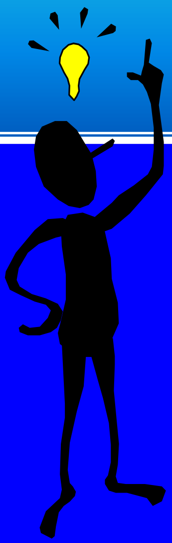
Summary



Summary

- "Path of least inductance" is a principle of utmost importance for understanding EMI phenomena and application of design rules for:
  - Cable shield grounding
  - PCB trace routing
  - Decoupling and bypassing
  - Filtering
- In your design, therefore, remember:
  - Visualize signal current paths
  - Common sense is still permitted…

Few EMC design principles of as such importance as the principle of "Path of Least Inductance"