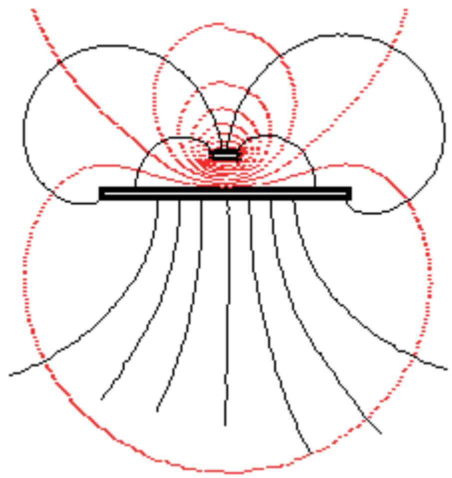
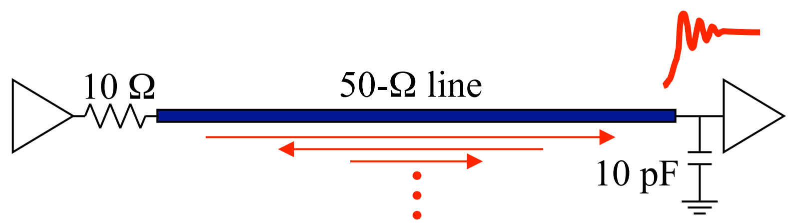
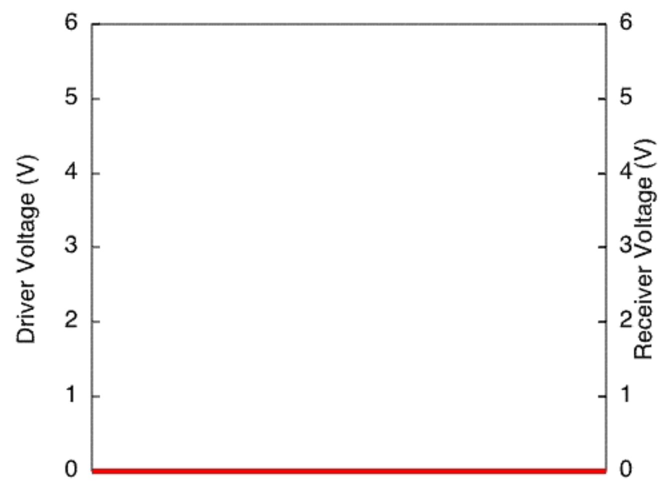
Common Misconceptions about Inductance & Current Return Path







Dr. Cheung-Wei Lam
IEEE EMC Respected Speaker
lam@alum.mit.edu

Outline

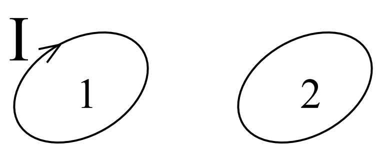
- What are they?

  L = Inductance

  I® = Current Return Path
- Why do we care?
- Common Misconceptions
- How do we control them?
- How do we identify problems?
- Summary

L: What is it?

- Various kinds: ***loop***, ***mutual***, external, internal, kinetic, self, partial, self partial, mutual partial, partial mutual, …
- Definition of inductance for closed loops:



$$L_1 = \frac{\Psi_1}{I_1} \qquad M_{21} = \frac{\Psi_{21}}{I_1}$$

- External, internal, kinetic
- Self, partial, self partial, mutual partial, partial mutual

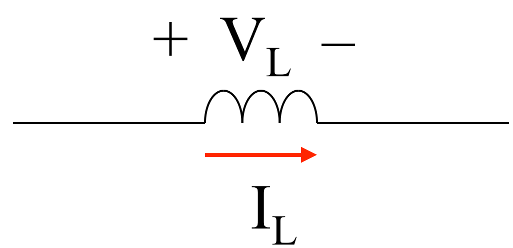
L: What are they exactly?

- Book:
  - Clayton Paul, “Introduction to Electromagnetic Compatibility”
- Paper:
  - Al Ruehli, “Inductance Calculations in a Complex Integrated Circuit Environment,” IBM Journal of R&D, September 1972.
- Articles:
  - Bruce Archambeault, “Decoupling Capacitor Connection Inductance,” IEEE EMCS Newsletter, Spring 2009
  - Bruce Archambeault, “Part II: Resistive vs. Inductive Return Current Paths,” IEEE EMCS Newsletter, Fall 2008

L: Why do we care?

- Affects signal quality, crosstalk, EMI.
- Voltage Drop/Fluctuation

$$V_L = L\frac{dI_L}{dt}$$

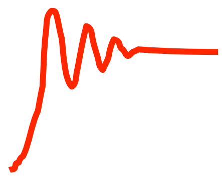


- Crosstalk

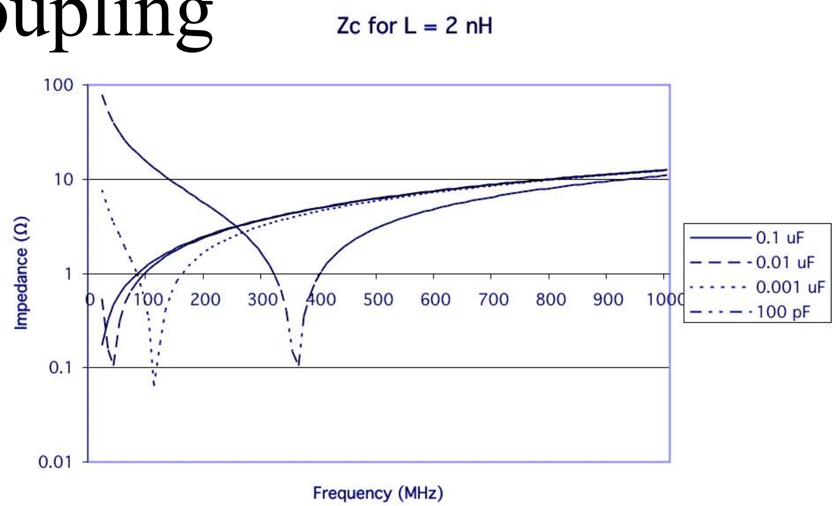
$$V_2 = M_{21}\frac{dI_1}{dt} \qquad M_{21} = L_{21}$$

L: Why do we care?

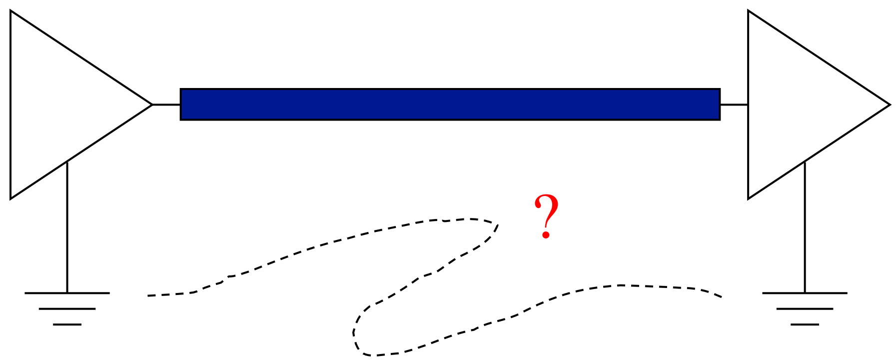
- Transmission Line Discontinuity
  → Signal Ringing



- Filtering & Decoupling
  - $Z_C(f)$
  - $f_o = \dfrac{1}{2\pi\sqrt{LC}}$



I®: What is it?



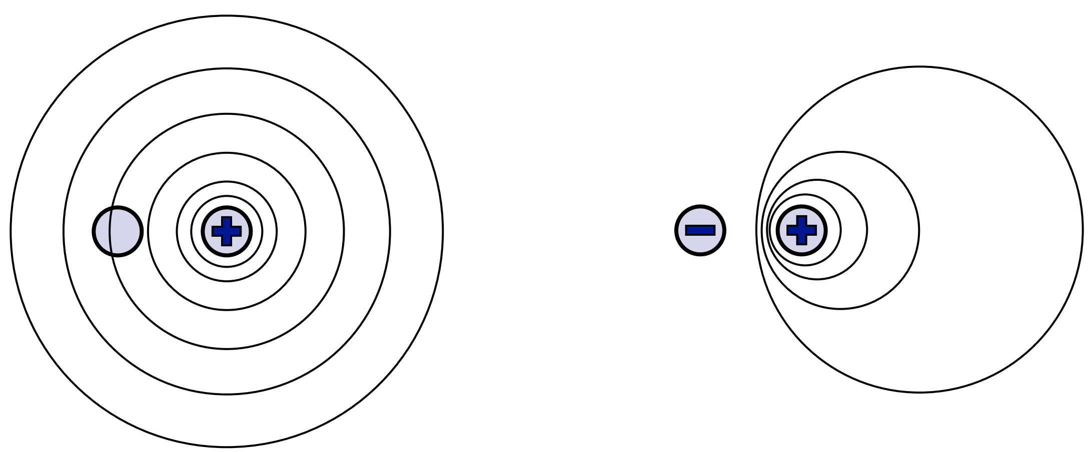
- Is ground a zero-impedance equipotential surface?
  - $V_G = I_G Z_G = I_G(R_G + j\omega L_G) \neq 0$

I®: Why do we care?

- Increases current loop area A
  - **EMI ↑**
- Increases loop inductance L
  - **Signal Quality ↓**
  - **EMI ↑**
- Increases mutual inductance M
  - **Crosstalk ↑**
  - **EMI ↑**
- Increases ground (return) inductance L_G or M_G
  - **EMI ↑**

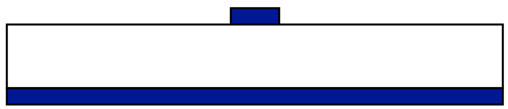
L: Common Misconceptions

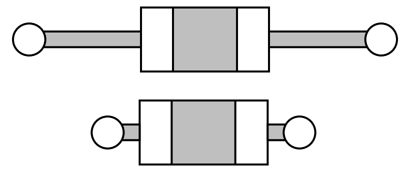
- Mistake loop L as sum of self inductances (L_{self})!?
- Overlook the importance of return proximity!?



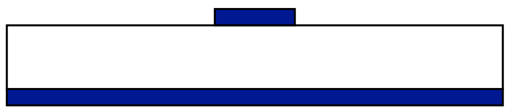
L: Mounting Inductance

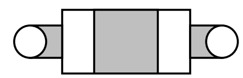
— **Reduce length.**



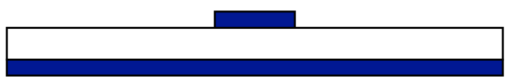


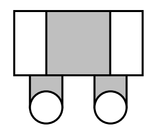
— **Increase width.**





— **Think *return proximity*!**

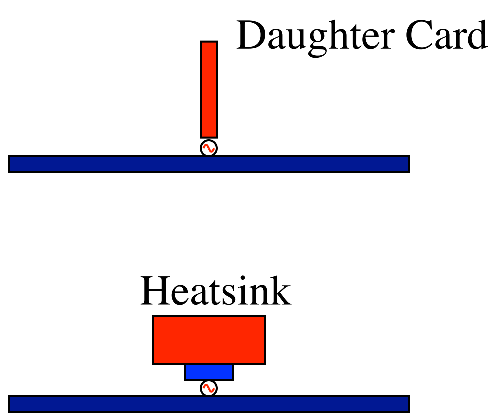


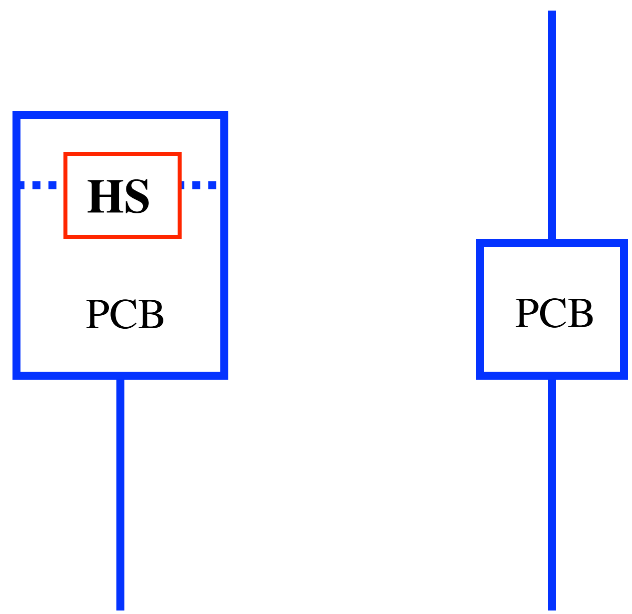


— **Think *loop inductance*!!**

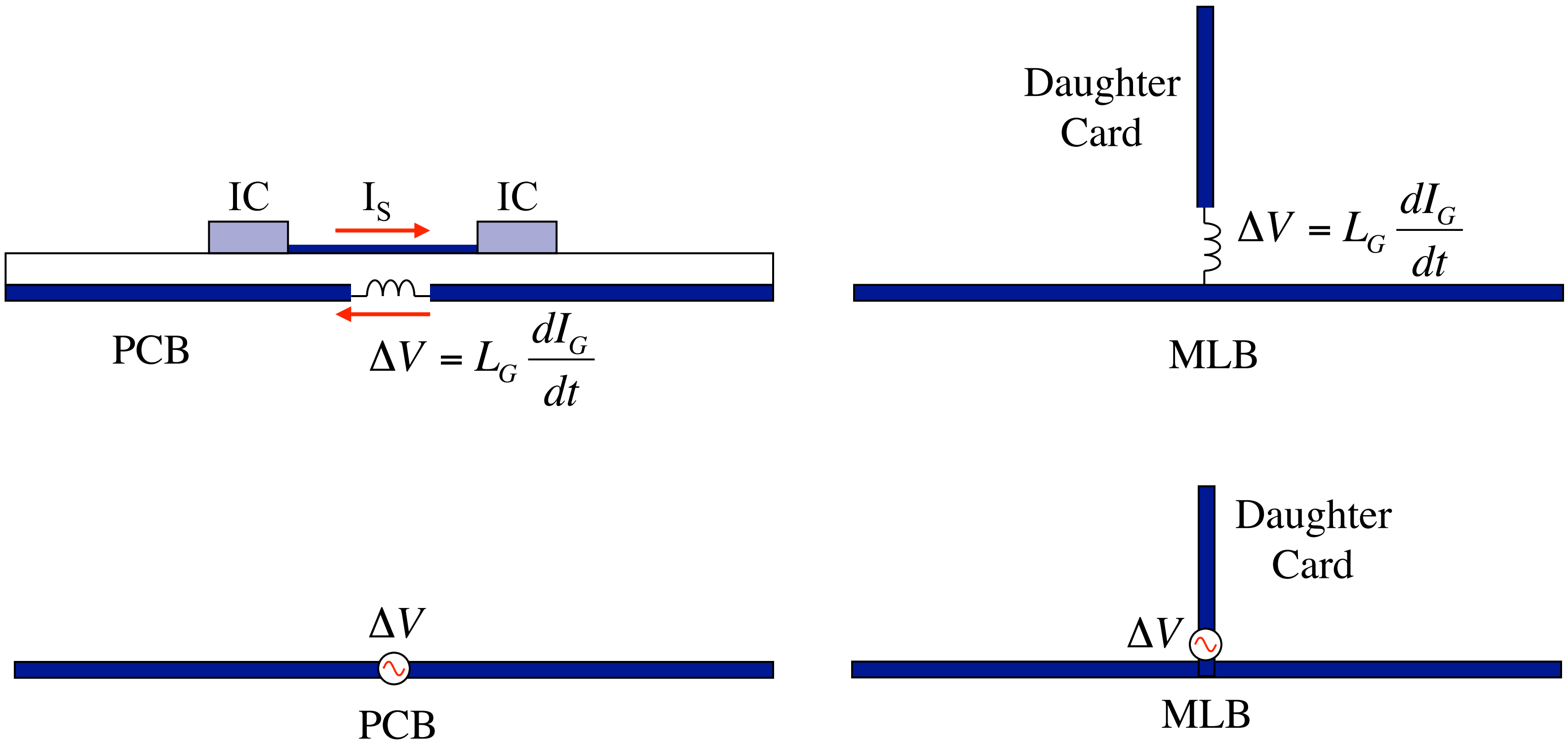
L: Common Misconceptions

- Ground Drop ∝ Self Inductance (L_{Self})!?
  - **Ground Drop is a main source of CM radiation!**
  - $V_G = I_S Z_G = I_S (R_G + j\omega L_G)$



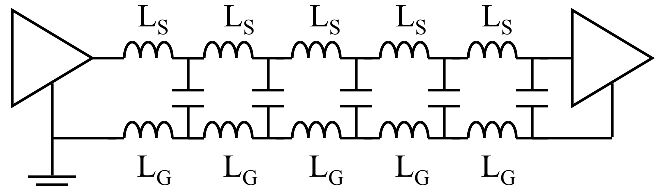


L: $\Delta V = L_G \, dI_G/dt$



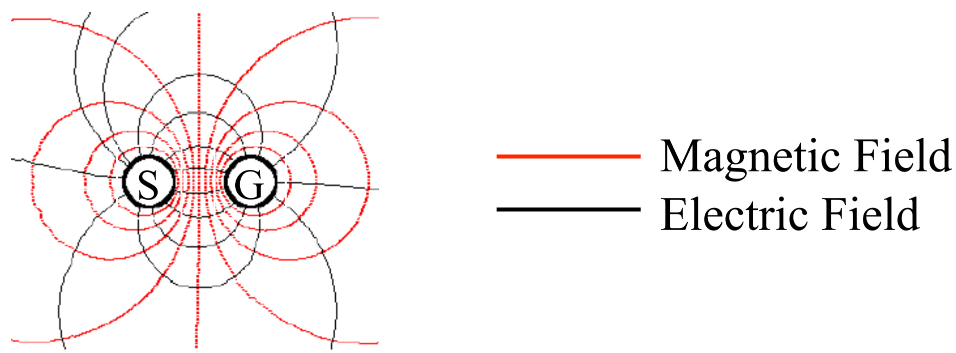
L: Ground Inductance

- Transmission Line: $L_T = L_S + L_G$



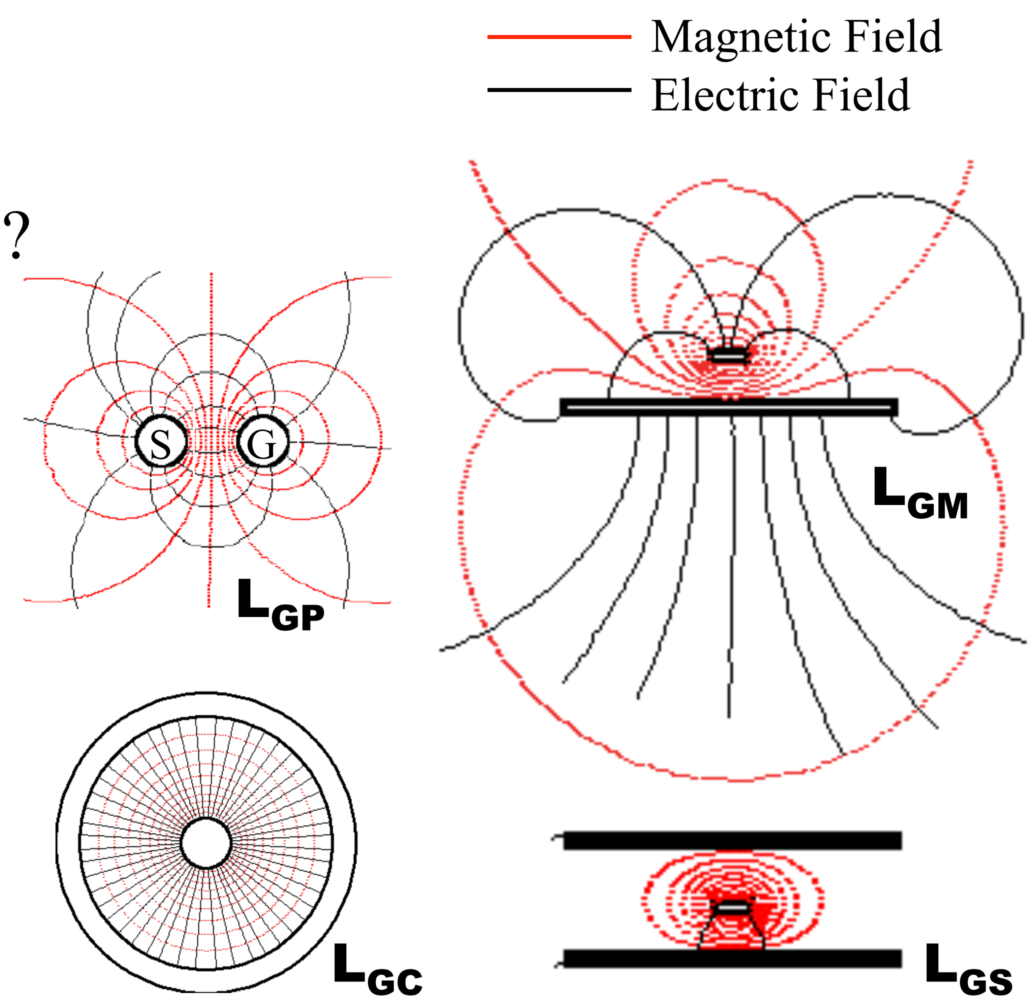
- Ψ_G = magnetic flux around ground conductor

$$L_G = \frac{\Psi_G}{I_G}$$



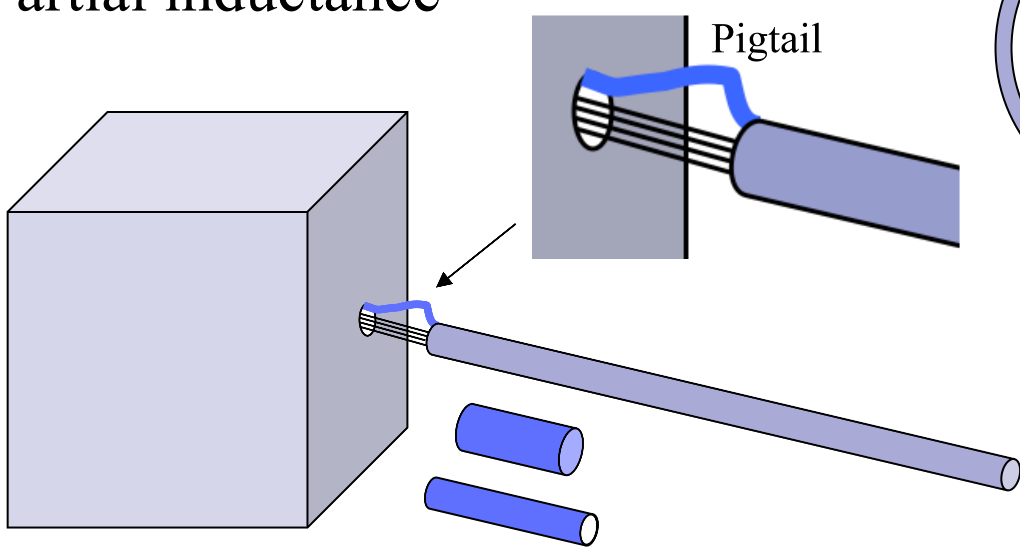
L: L_G = ?

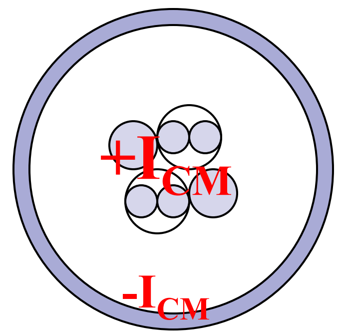
- L_G = self inductance!?
  - **L_G = M_G (DM→CM)**
    - Partial inductance
  - **Pairs (S, P, V, W)**
    - $L_{GP} = L_T/2$
  - **Microstrip**
    - $L_{GM} \ll L_T$
  - **Stripline**
    - $L_{GS} \ll L_{GM}$
  - **Coaxial**
    - $L_{GC} \approx 0$



L: Common Misconceptions

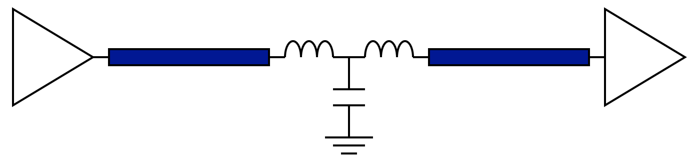
- Pigtail termination is bad because of its L_{Self}!?
  - — **M_P (inner→outer) (DM→CM)**
    - Partial inductance



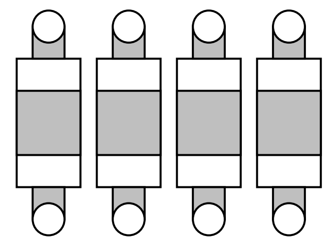


L: Common Misconceptions

- Smaller is always better!?
  - — **Excess capacitance causes reflections!**



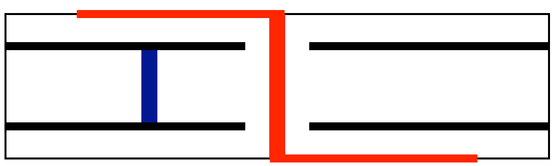
- Inductance parallels down like resistors!?
  - — **Don't forget M!**
  - — **Spread out decoupling capacitors!**
  - — **Alternate power/ground pins!**

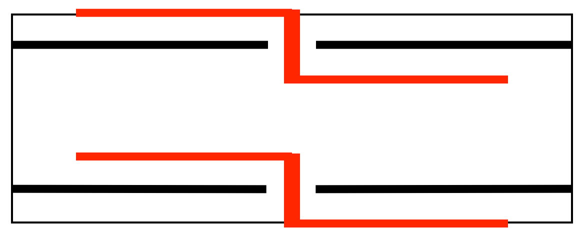


- Overlook mounting inductance vs. component inductance!?
  - — **Don't spend on expensive low-L filters unless layout has already been optimized.**

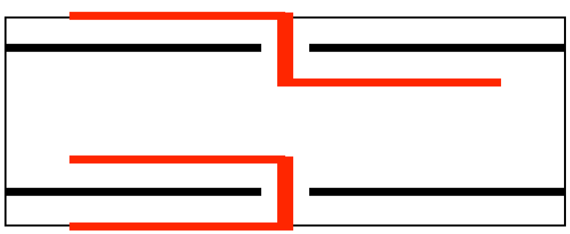
L: Common Misconceptions

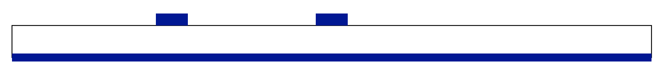
- Via Inductance = L_{Self}!?
  - **Think *loop inductance*!**





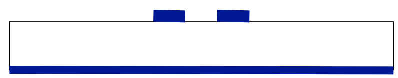
- Overlook the dependence on current distribution!?
  - **Current distribution affects inductance!**

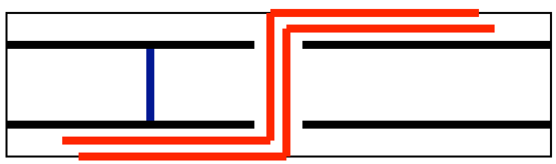




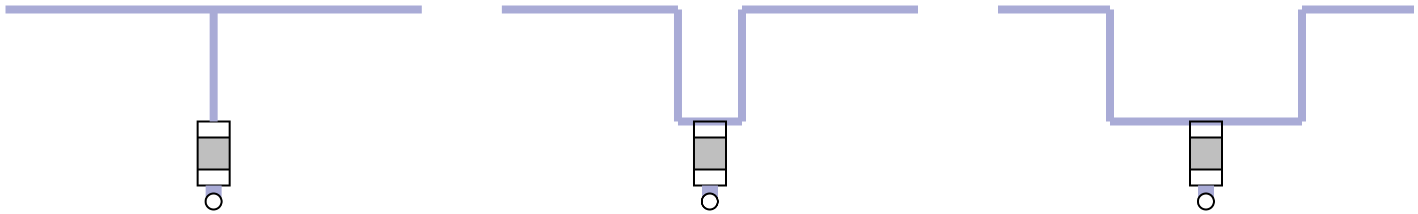
M: Common Misconceptions

- Overlook the importance of return proximity!?
  - **Think separation.**
  - **Think *return proximity*!**



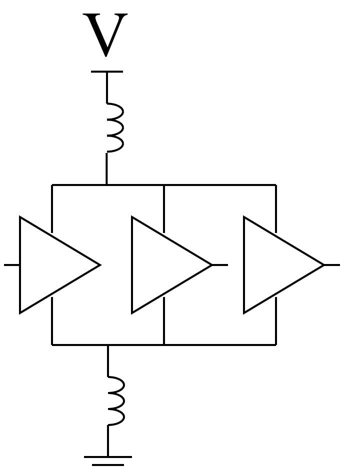


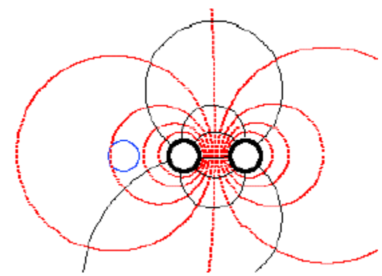
- L_{Self} degrades capacitor performance!?
  - **Think mutual inductance!**

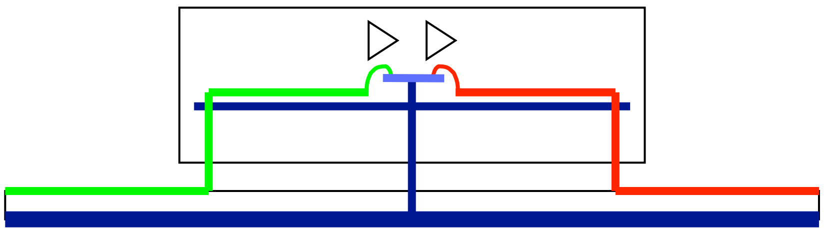


M: Common Misconceptions

- Ground Bounce & Power Noise $\propto L_{Self}$ (L_P) of Pin!?
  - **Think *loop-to-loop mutual inductance*!**







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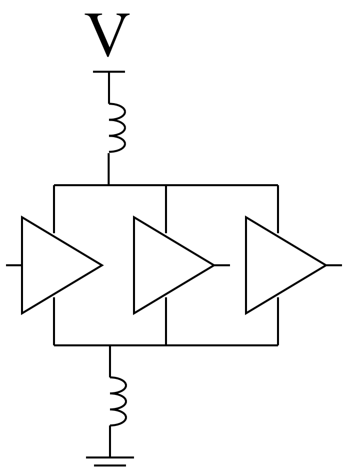

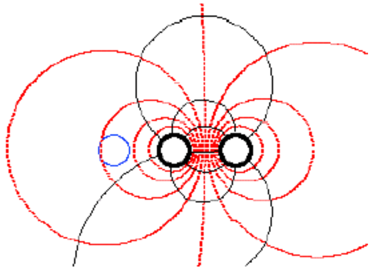

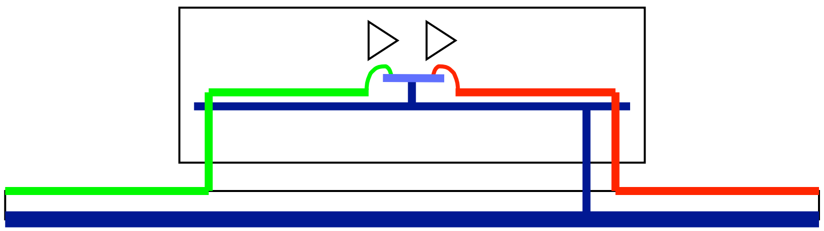

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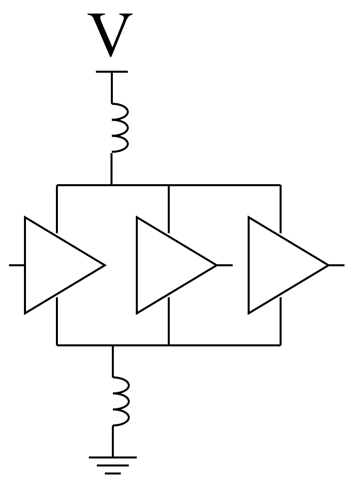

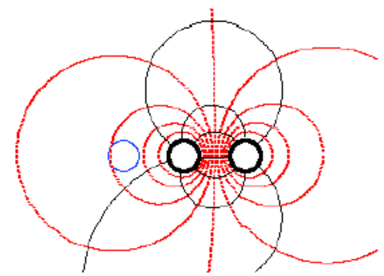

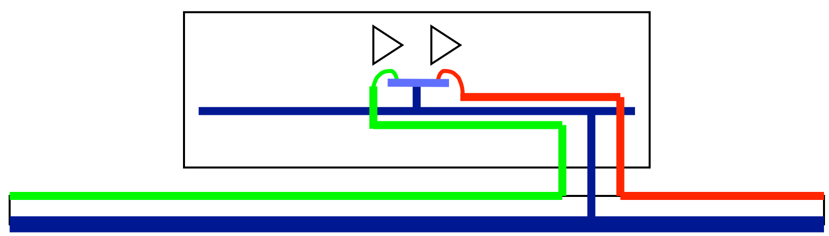

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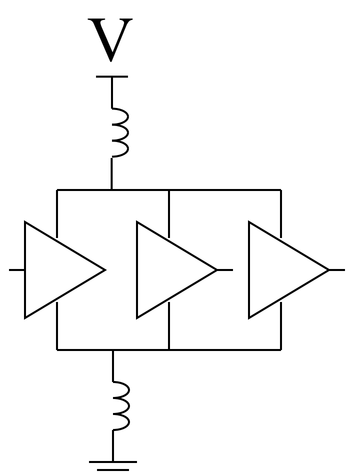
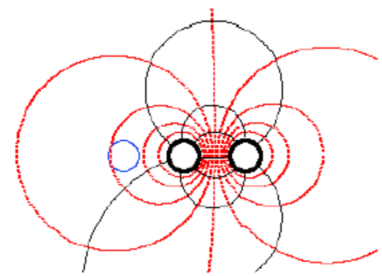
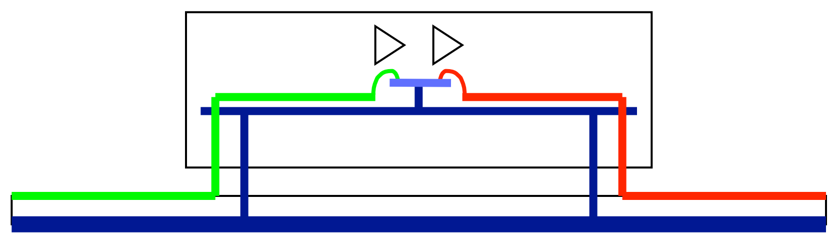
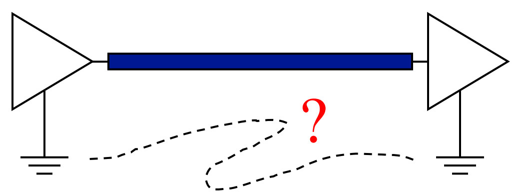






I®: Common Misconceptions

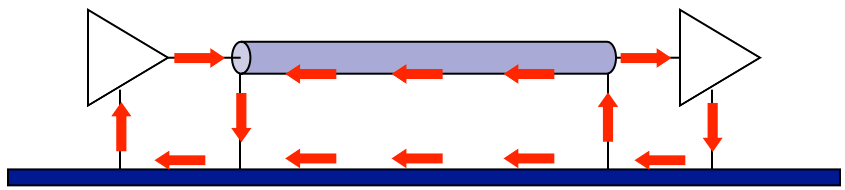
- Signal ground is a current source/sink!?



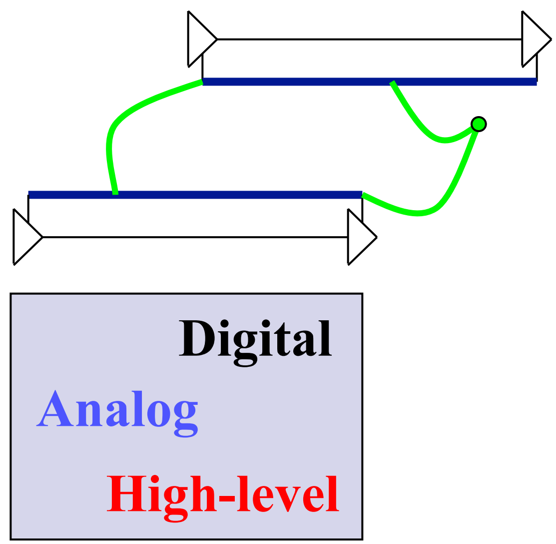
- Ground plane is a zero-impedance equipotential surface!?
  - $V_G = I_G Z_G = I_G(R_G + j\omega L_G) \neq 0$
  - At kHz: $R_G \gg j\omega L_G$
    - IR drop causes common-impedance coupling.
  - At MHz/GHz: $R_G \ll j\omega L_G$
    - I® affects A, L, M, SI, EMI.

I®: Common Misconceptions

- Current takes the least resistance path!?
  - $Z_G = R_G + j\omega L_G$
  - Think R at f ≤ kHz.
  - Think L at f ≥ MHz!

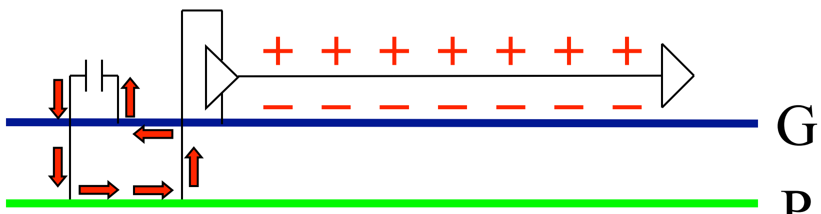


- Current returns along intended paths!?
  - IR drop → common-Z coupling.
  - Current spreads out at f ≤ kHz.
  - Single-point grounding used for:
    - Low-level analog subsystems,
    - High-level noisy subsystems, e.g. motor drivers.

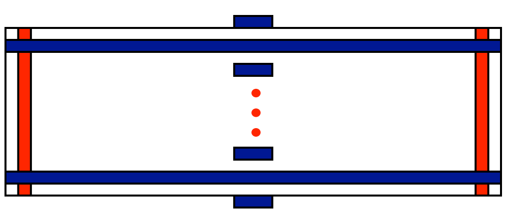


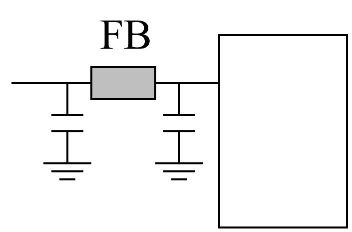
I®: Common Misconceptions

- Current returns through ground but not power!?



- Ground and power planes are interchangeable!?
  - **Ground is connected to chassis, but not power.**
  - **Power isolation breaks the symmetry.**





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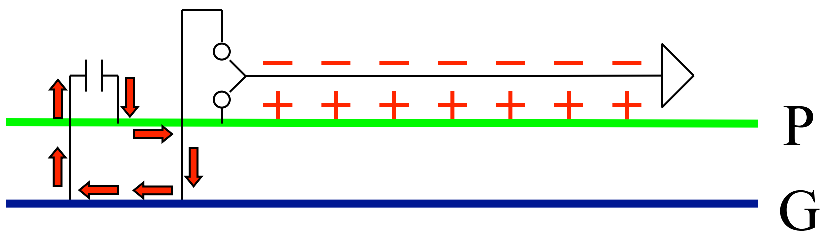

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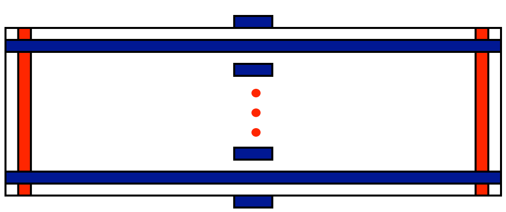
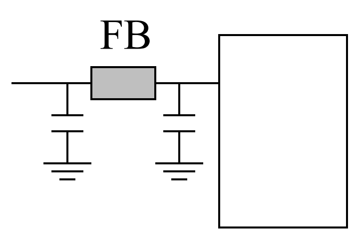
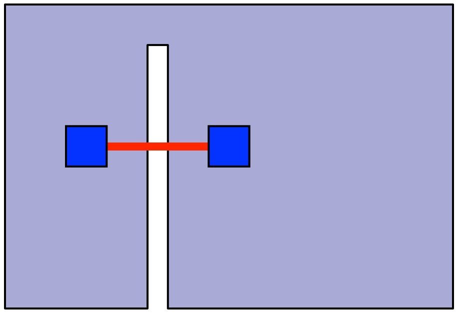
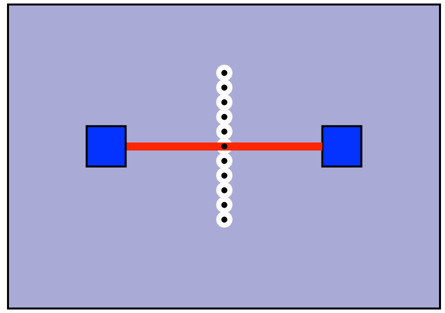




I®: Common Misconceptions

- Overlook horizontal return path!?

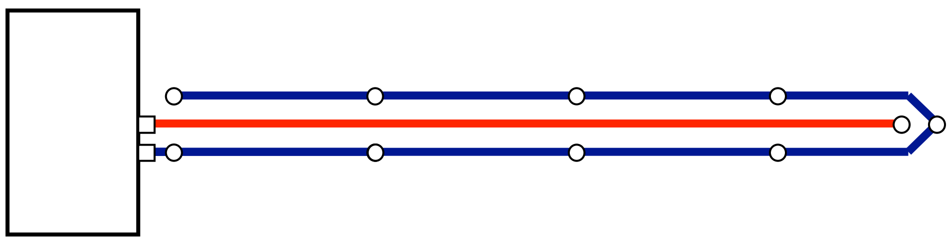




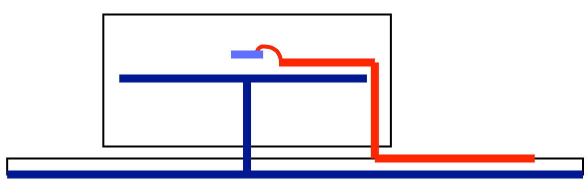
- Traces crossing plane cuts
  - **Avoid ground plane cuts.**
  - **Route around plane cuts.**
  - **Use stitching capacitors.**
- Overlapping via antipads
  - **Stagger vias.**
  - **Space vias apart.**

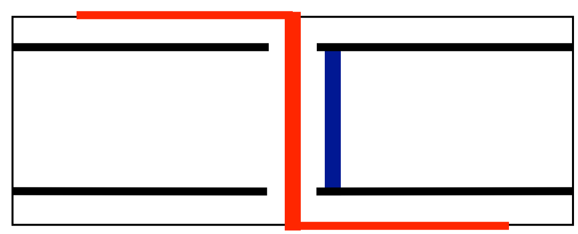
I®: Common Misconceptions

- Overlook vertical return path!?
  - **Trace to Plane**



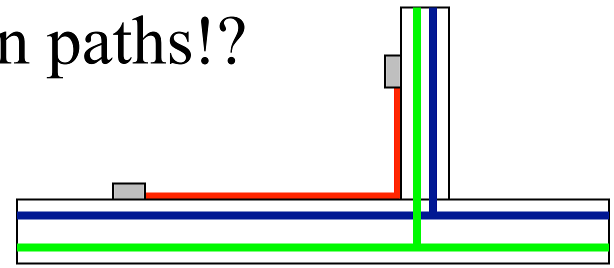
  - **Plane to Plane**



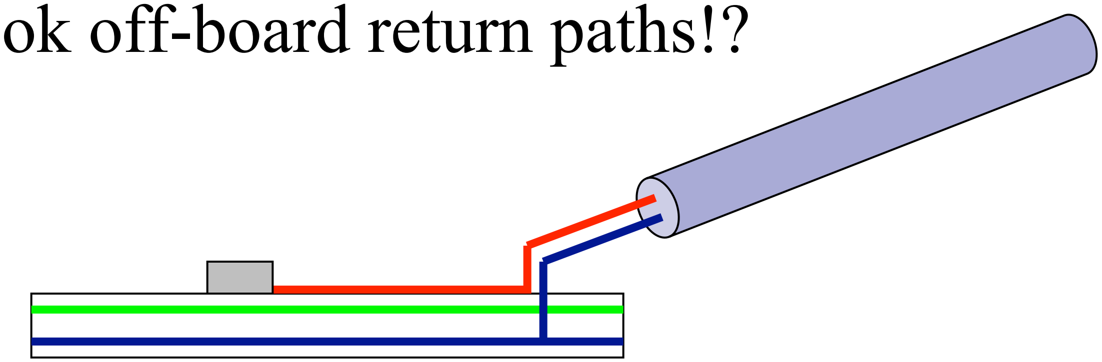


I®: Common Misconceptions

- Overlook cross-board return paths!?
  - **Avoid discontinuity.**
  - **Provide capacitors.**

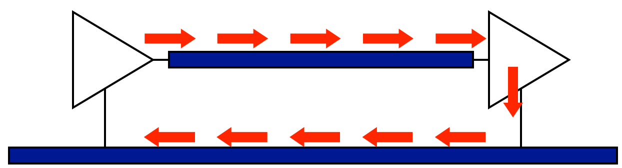


- Overlook off-board return paths!?

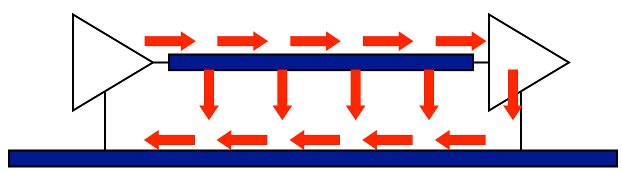


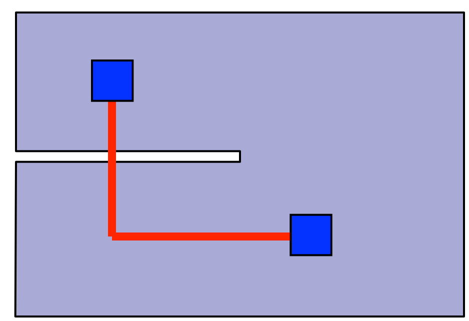
I®: Common Misconceptions

- Current flows in loops.
  - **Think of signal path and return path separately!?**



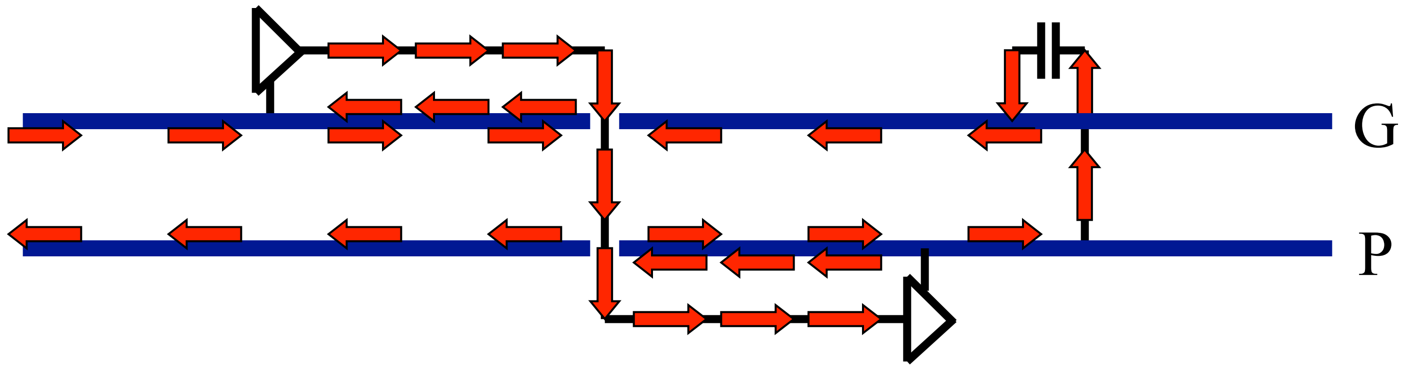
  - **Current flows in loops, but not this way.**
  - **Current flows in pairs!**
    - Signal and return go hand-in-hand.





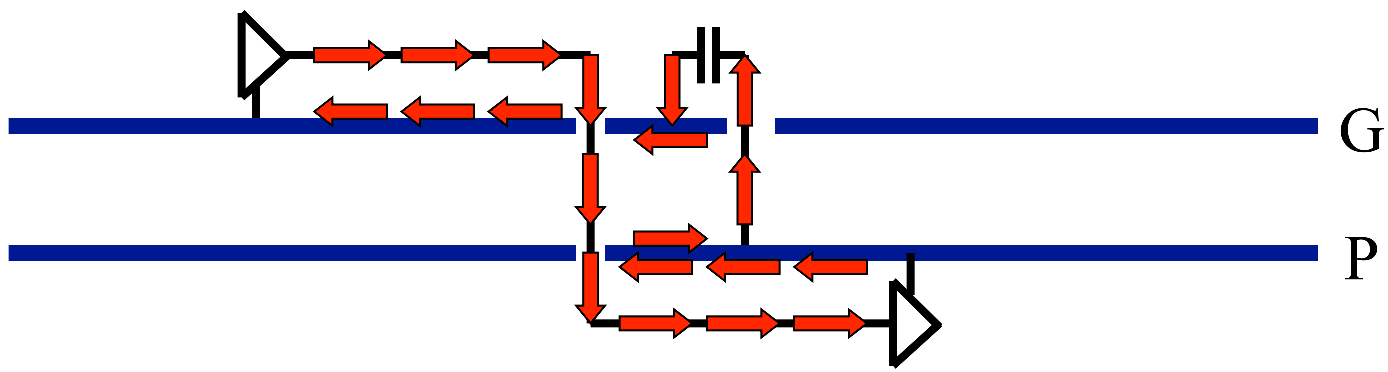
I®: Exercise

- Trace out the current return path.



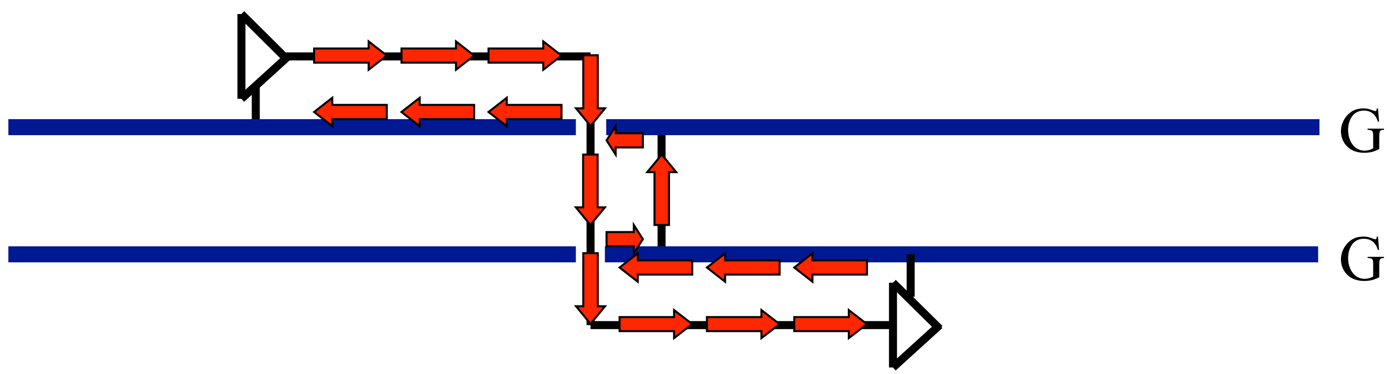
I®: Exercise

- Trace out the current return path.



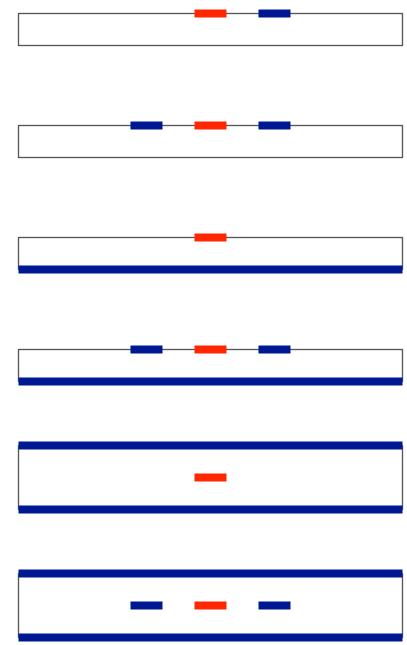
I®: Exercise

- Trace out the current return path.



L: How do we control them?

- $L \rightarrow$ Signal Ringing
  - **Small loop (adjacent return, short, wide).**
- $M_{21} \rightarrow$ Crosstalk (Inductive Coupling)
  - **Separation, return proximity, twisting, shielding.**
- L_G (M_G) $\rightarrow$ Ground Drop $\rightarrow E_{CM}$
  - **Coaxial, stripline, microstrip.**
  - **Small H, large W, away from edge, guard traces.**
- $L_C \rightarrow$ Decoupling
  - **Small loop (short wide traces, adjacent vias).**
  - **Use multiple capacitors and spread them out.**
- $M_C \rightarrow$ Filtering
  - **Minimize M (eliminate stub, short trace to ground).**



I®: How do we control them?

- At kHz: $R_G \gg j\omega L_G$
  - **Low-level analog or high-level noisy subsystems**
    - Single-point grounding prevents common-Z coupling.
- At MHz/GHz: $R_G \ll j\omega L_G$
  - **Horizontal return**
    - Use ground planes/grids instead of ground traces.
    - Avoid traces crossing plane cuts.
  - **Vertical return**
    - Provide adjacent return pins for noisy or susceptible pins.
    - Provide adjacent vias, stitching capacitors as return bridges.
    - Provide sufficient vias for guard traces.

L & I®: How do we identify problems?

Options	Pros	Cons
Fix when Fail	Less design time	Risks: time, cost, …
Layout Review	Identify problems early	Labor intensive
Layout Checking Tool	Identify problems quickly Less labor intensive	Report 100's of violations Require expertise & time to identify critical violations
Automated & Customized Layout Checking Tool	Identify problems quickly No setup required Report critical violations	Require automation and customization development

Summary

- L & I® affects signal quality, crosstalk and EMI.
- Inductance (L)
  - **Forget self inductance.**
  - **Think loop inductance and mutual inductance!**
  - **Think return proximity!**
- Current Return Path (I®)
  - **Low f: Current spreads out as R_G » $j\omega L_G$.**
  - **High f: Trace out I® to identify discontinuities.**