Electromagnetics for the Working EMC Engineer

Dr. Bruce Archambeault

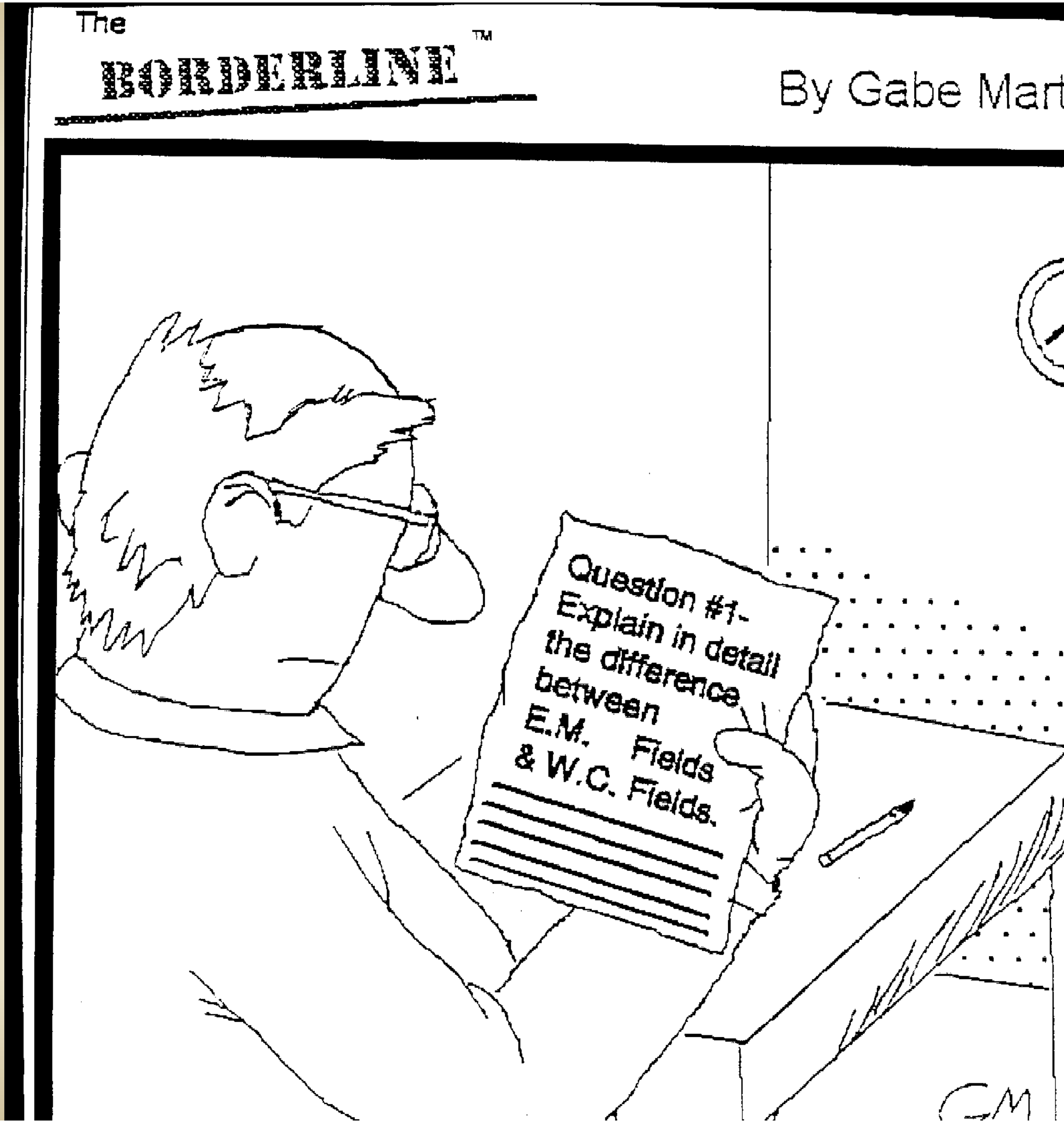
Missouri S&T EMC Lab

bruce@brucearch.com

June 2022

Introduction

- Electromagnetics can be scary
  - Universities *LOVE* messy math
- EM is not hard, unless you want to do the messy math
- Goal:
  - Intuitive understanding
  - Understand the basic fundamentals
  - Understand how to read the math


The BORDERLINE™
By Gabe Mart
Question #1-
Explain in detail
the difference
between
E.M. Fields
& W.C. Fields.
GM

Overview

- What does the derivative mean?
- What does integration mean?
- Weird vector notation
- In the beginning – Faraday and Maxwell
- Inductance
- “Ground”

Derivative

- How fast is *something* changing?

$$\frac{d}{dt}\left[something\right]$$

Changing with respect to time

$$\frac{d}{dx}\left[something\right]$$

Changing with respect to position (x)

Partial Derivative

- How fast is *something* changing for one variable?

$$\frac{\partial}{\partial t}\left[something(t,x)\right]$$

Changing with respect to time (as ‘x’ is constant)

$$\frac{\partial}{\partial x}\left[something(t,x)\right]$$

Changing with respect to position (x) (as time is constant)

Vector Notation

Dot, Gradient, Curl

- Dot Product
  - How much of something is going in a specified direction?

Direction only

Size = 1

Vector Notation – Dot Product

- Suppose we have an electric field that varies in x, y, z

$$\overrightarrow{E} = E_x + E_y + E_z$$

$$\vec{E} \cdot \hat{i} = E_x$$

$$\vec{E} \cdot \hat{j} = E_y$$

$$\vec{E} \cdot \hat{k} = E_z$$

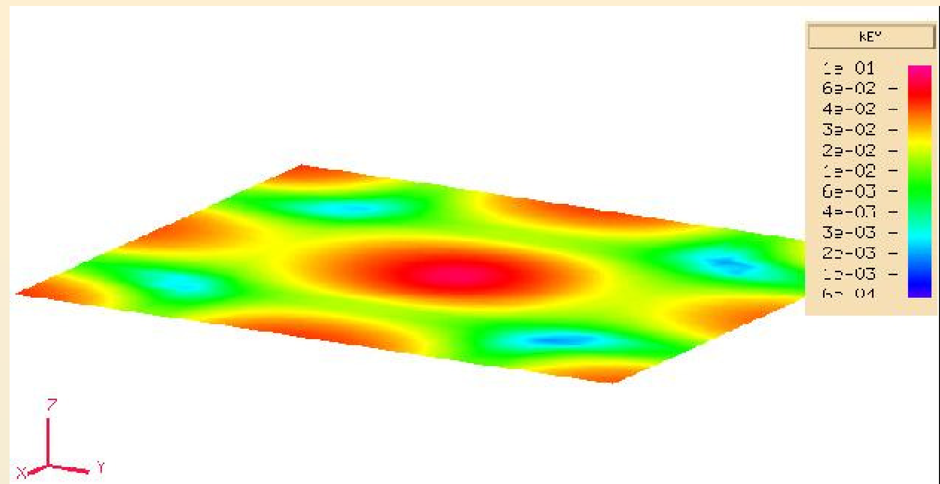
Vector Notation -- Gradient

- How fast is something changing, and in what direction is this change?

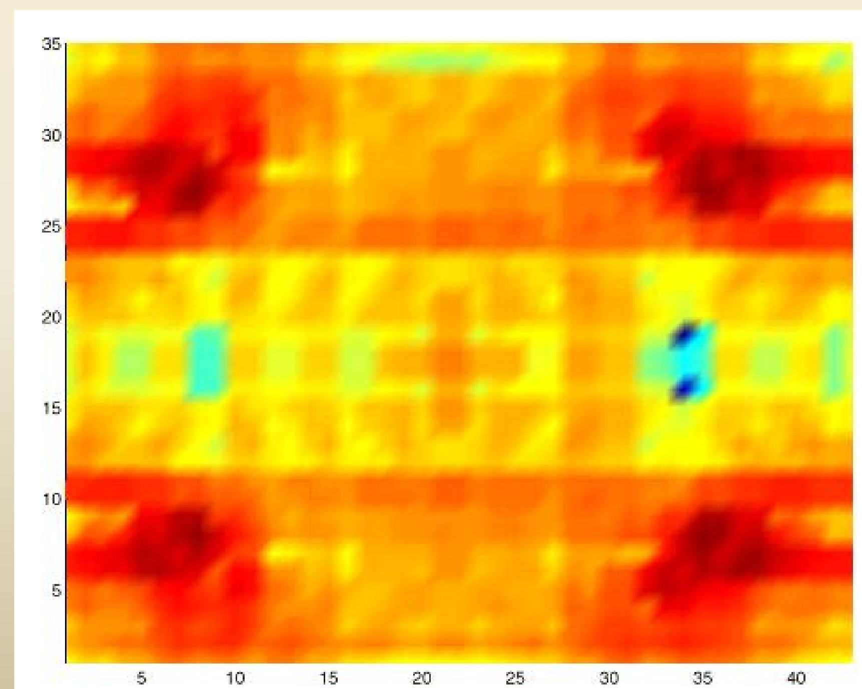
$$\nabla \vec{E} = \left(\hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y} + \hat{k}\frac{\partial}{\partial z} \right) \vec{E}$$

Gradient -- Example

- Voltage Distribution between power/gnd planes on printed circuit board
  - Standing wave due to resonance at 800 MHz



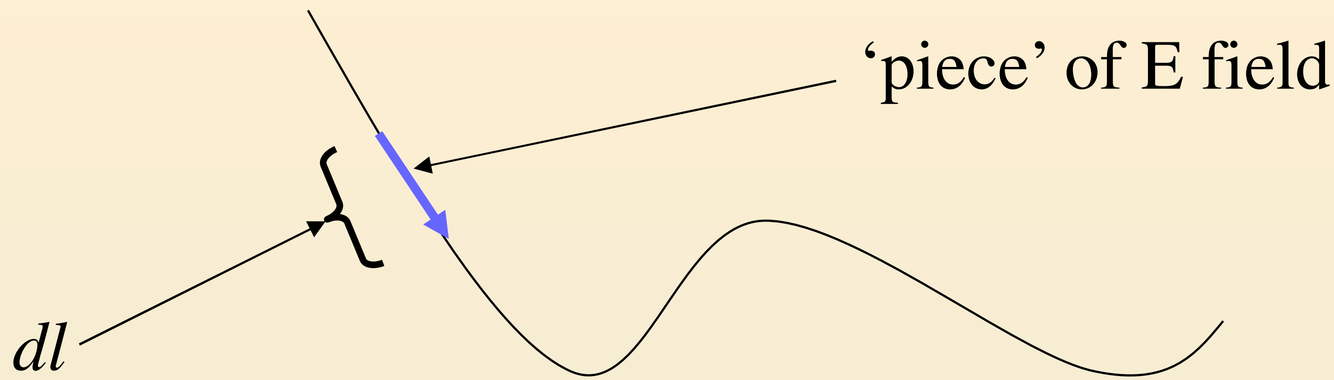
- Voltage Gradient
  - How fast is the voltage between plates changing?



Integration

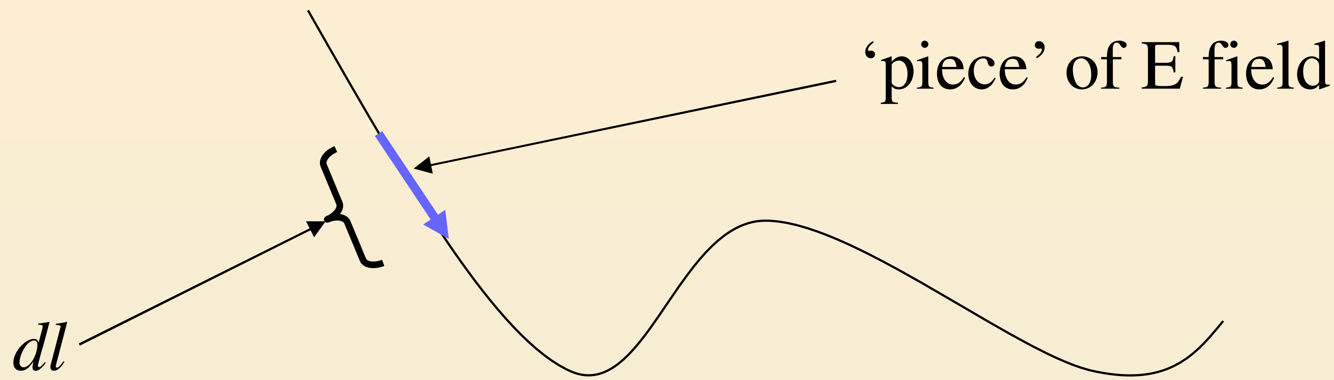
- Simply the sum of parts (when the parts are very small)
  - Line Integral --- sum of small line segments
  - Surface Integral -- sum of small surface patches
  - Volume Integral -- sum of small volume blocks

Line Integral
(find the length of the path)



$$V = -\int_{start}^{stop} (\vec{E} \bullet dl)$$

Line Integral

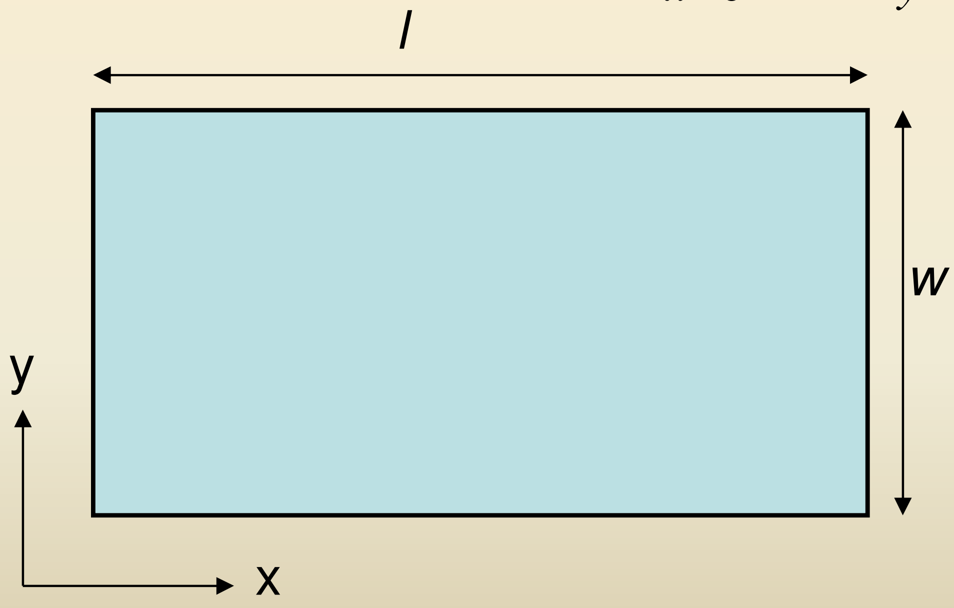


$$V = -\int_{start}^{stop} \left[\; (E_x * dx) + (E_y * dy) \; \right]$$

Line Integral -- Closed

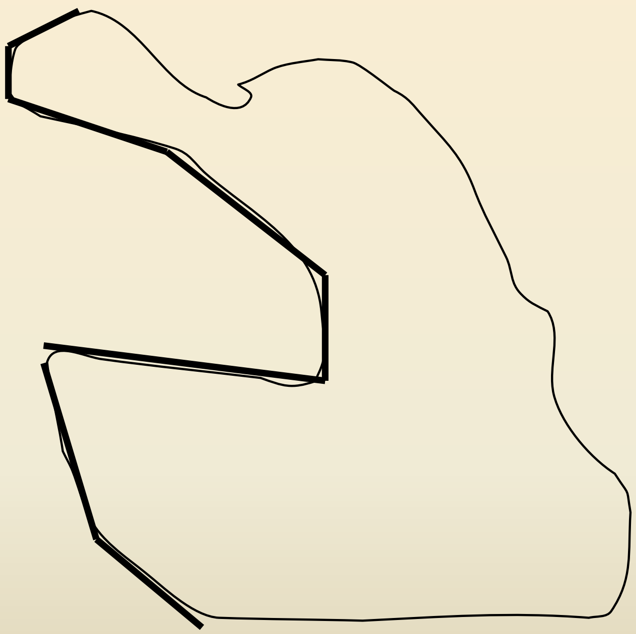
$$Circumference = \oint path\ around\ box$$

$$= \int_{x=0}^{x=l} dx + \int_{y=0}^{y=w} dy + \int_{x=l}^{x=0} dx + \int_{y=w}^{y=0} dy$$

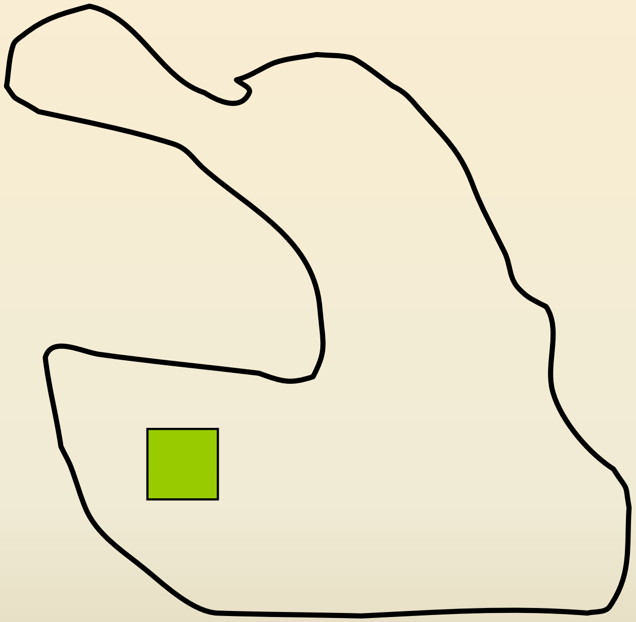


Line Integral -- Closed

- Closed line integrals find the path length
- And/or the amount of some quantity along that closed path length



Surface Integral
(find the area of the surface)



$$Area = \int da$$

$$da = dx * dy$$

$$Area = \iint dx * dy$$

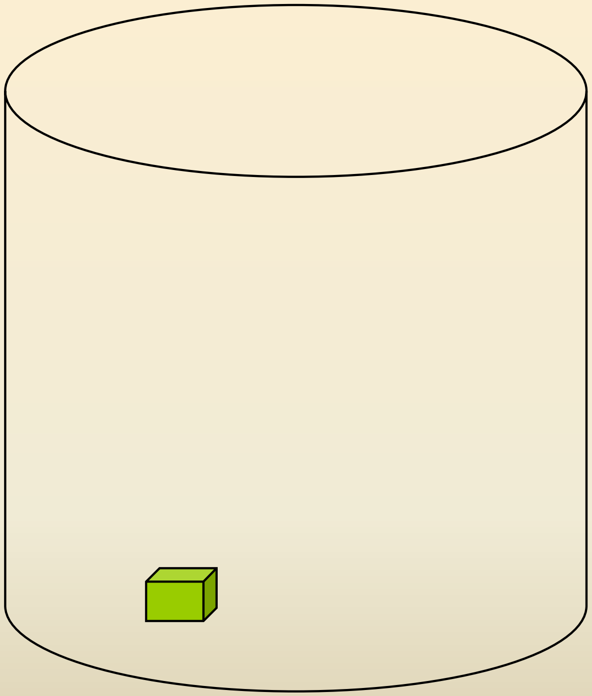
As *dx* and *dy* become smaller and smaller, the area is better calculated

Closed Surface Integral

- Find the surface area of a closed shape

$$\oint\!\!\oint shape\ da$$

Volume Integral (find the volume of an object)



$$Volume = \int dv$$

$$dv = dx * dy * dz$$

$$Volume = \iiint [dx * dy * dz]$$

Electromagnetics

In the Beginning

- Electric and Magnetic effects not connected
- Electric and magnetic effects were due to ‘action from a distance’
- Faraday was the 1st to propose a relationship between electric lines of force and time-changing magnetic fields
  - Faraday was very good at experiments and ‘figuring out’ how things work

Maxwell

- Maxwell was impressed with Faraday’s ideas
- Discovered the mathematical link between the “electro” and the “magnetic”
- Scotland’s greatest contribution to the world (next to Scotch)

Maxwell’s Equations are NOT Hard!

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

Maxwell's Equations are not Hard!

- Change in H-field across space Change in E-field (at that point) with time
- Change in E-field across space Change in H-field (at that point) with time
- (Roughly speaking, and ignoring constants)

Current Flow

- Most important concept of EMC
- Current flow through metal changes as frequency increases
- DC current
  - Uses entire conductor
  - Only resistance inhibits current
- High Frequency
  - Only small part of conductor (near surface) is used
  - *Resistance* is small part of current inhibitor
  - ***<u>Inductance</u>*** is major part of current inhibitor

Skin Depth

- High frequency current flows only near the metal surface at high frequencies

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Frequency	**Skin Depth**	**Skin Depth**
60 Hz	260 mils	8.5 mm
1 KHz	82 mils	2.09 mm
10 KHz	26 mils	0.66 mm
100 KHz	8.2 mils	0.21 mm
1 MHz	2.6 mils	0.066 mm
10 MHz	0.82 mils	0.021 mm
100 MHz	0.26 mils	0.0066 mm
1 GHz	0.0823 mils	0.0021 mm

Inductance

- Current flow through metal => inductance!
- Fundamental element in EVERYTHING
- Loop area first order concern
- Inductive impedance increases with frequency and is MAJOR concern at high frequencies

Impedance from inductance ⟶ $$X_L = 2\pi f L$$

Current Loop => Inductance

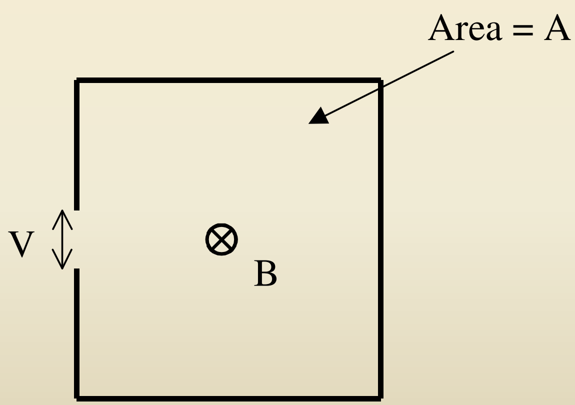
Courtesy of Elya Joffe

Inductance Definition

- Faraday's Law

$$\oint \overline{E} \cdot dl = -\iint \frac{\partial \overline{B}}{\partial t} \cdot d\overline{S}$$

- For a simple rectangular loop



$$V = -A \frac{\partial B}{\partial t}$$

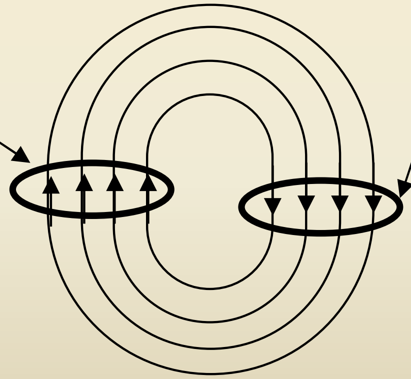
The minus sign means that the induced voltage will work against the current that originally created the magnetic field!

Mutual Inductance

$$\Phi_2 = M_{21} I_1$$

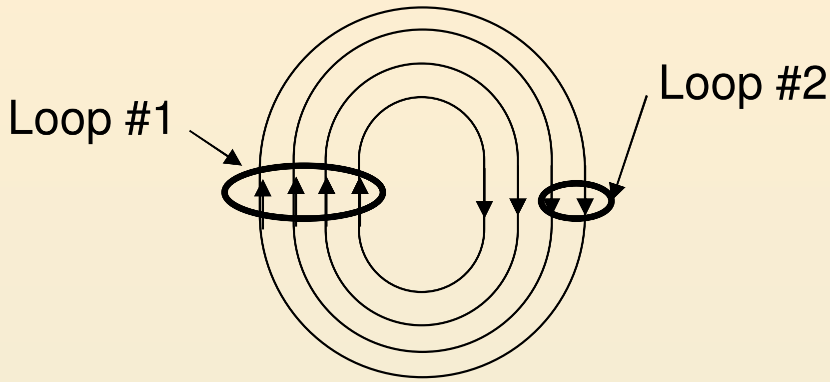
$$M_{21} = \frac{\Phi_2}{I_1}$$

How much magnetic flux is induced in loop #2 from a current in loop #1?

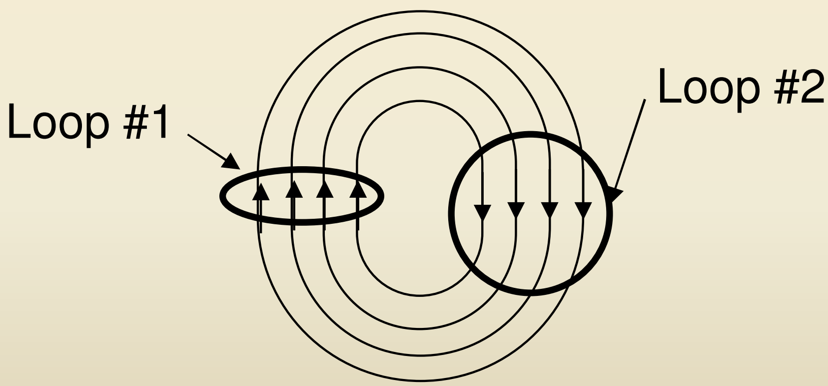


$$\Phi_2 = \int_{S_2} \vec{\mathrm{B}}_1(\mathrm{r}) \cdot \hat{n}\, \mathrm{dS}_2$$

Mutual Inductance



Less loop area in loop #2 means less magnetic flux in loop #2 and less mutual inductance



Less loop area perpendicular to the magnetic field in loop #2 means less magnetic flux in loop #2 and less mutual inductance

Self Inductance

- Isolated circular loop

$$L \approx \mu_0 a \left(\ln \frac{8a}{r_0} - 2 \right)$$

- Isolated rectangular loop

$$L = \frac{2\mu_0 a}{\pi} \left(\ln \frac{p + \sqrt{1 + p^2}}{1 + \sqrt{2}} + \frac{1}{p} - 1 + \sqrt{2} - \frac{1}{p} \sqrt{1 + p^2} \right)$$

Note that inductance is directly influenced by loop ***AREA*** and only less influenced by conductor size!

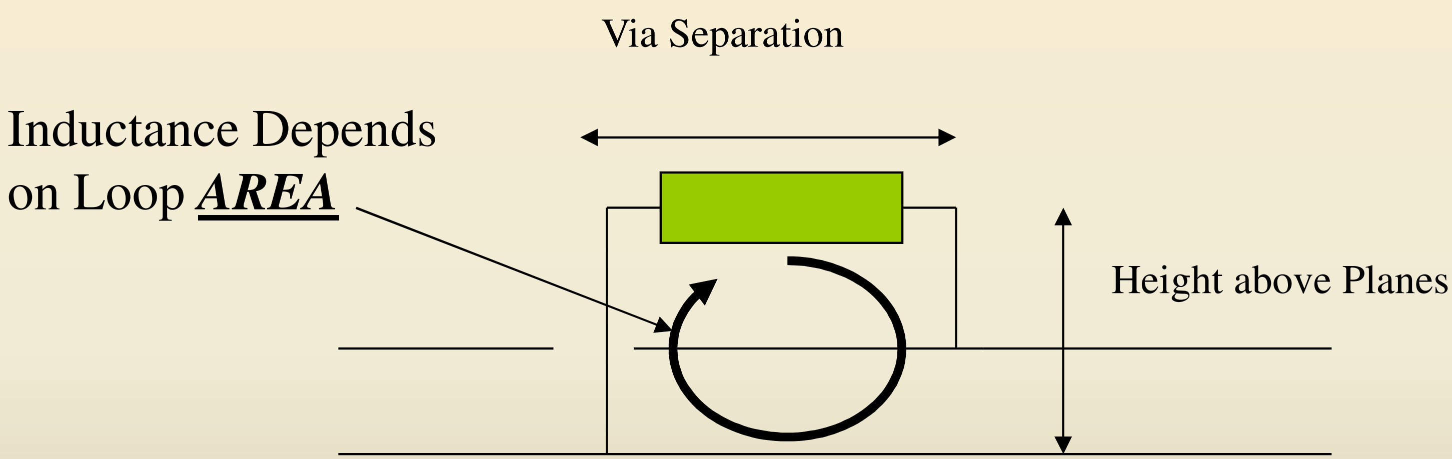
$$p = \frac{\textit{length of side}}{\textit{wire radius}}$$

Important Points About Inductance

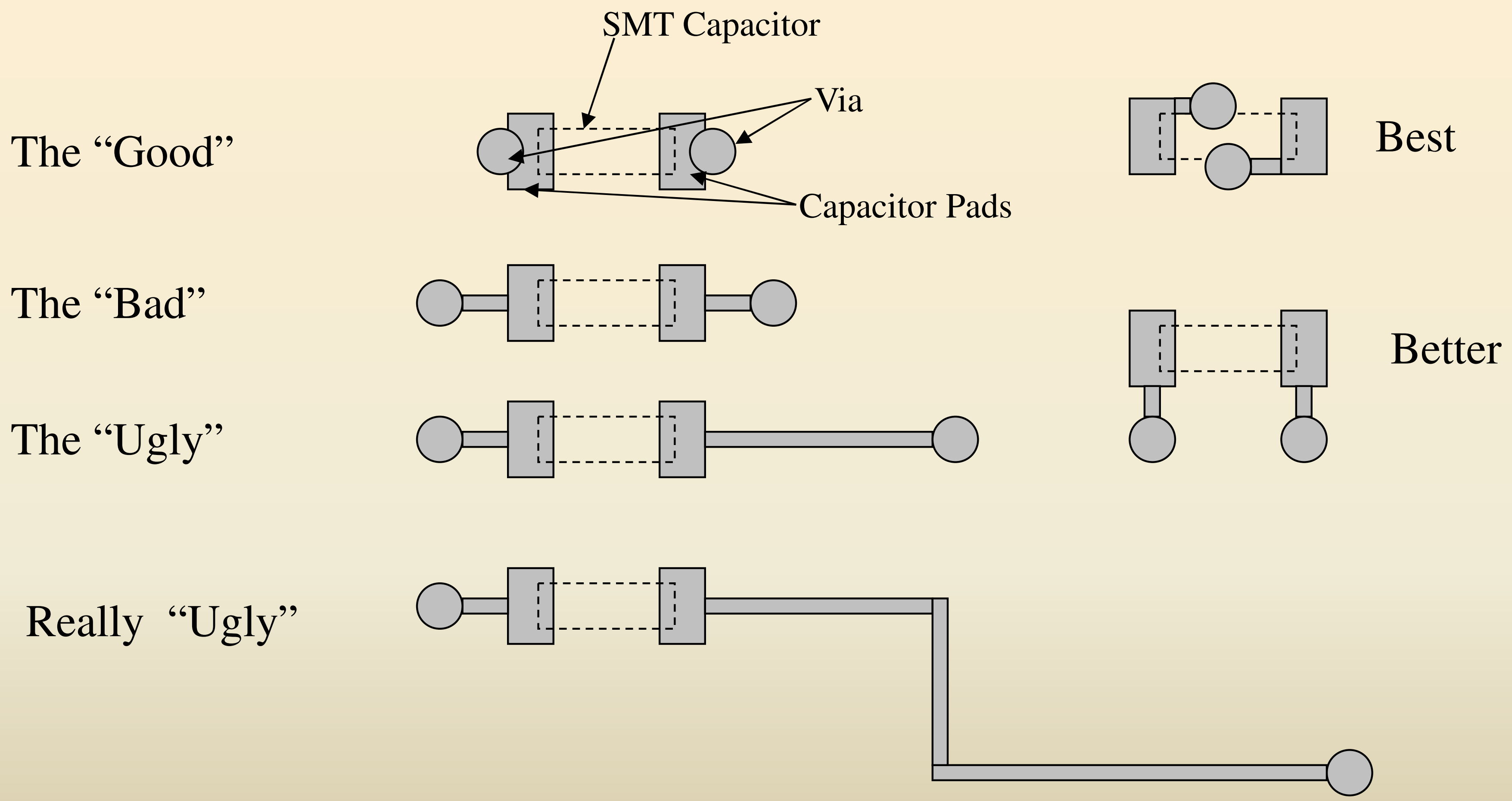
- Inductance is everywhere
- Loop area most important
- Inductance is everywhere

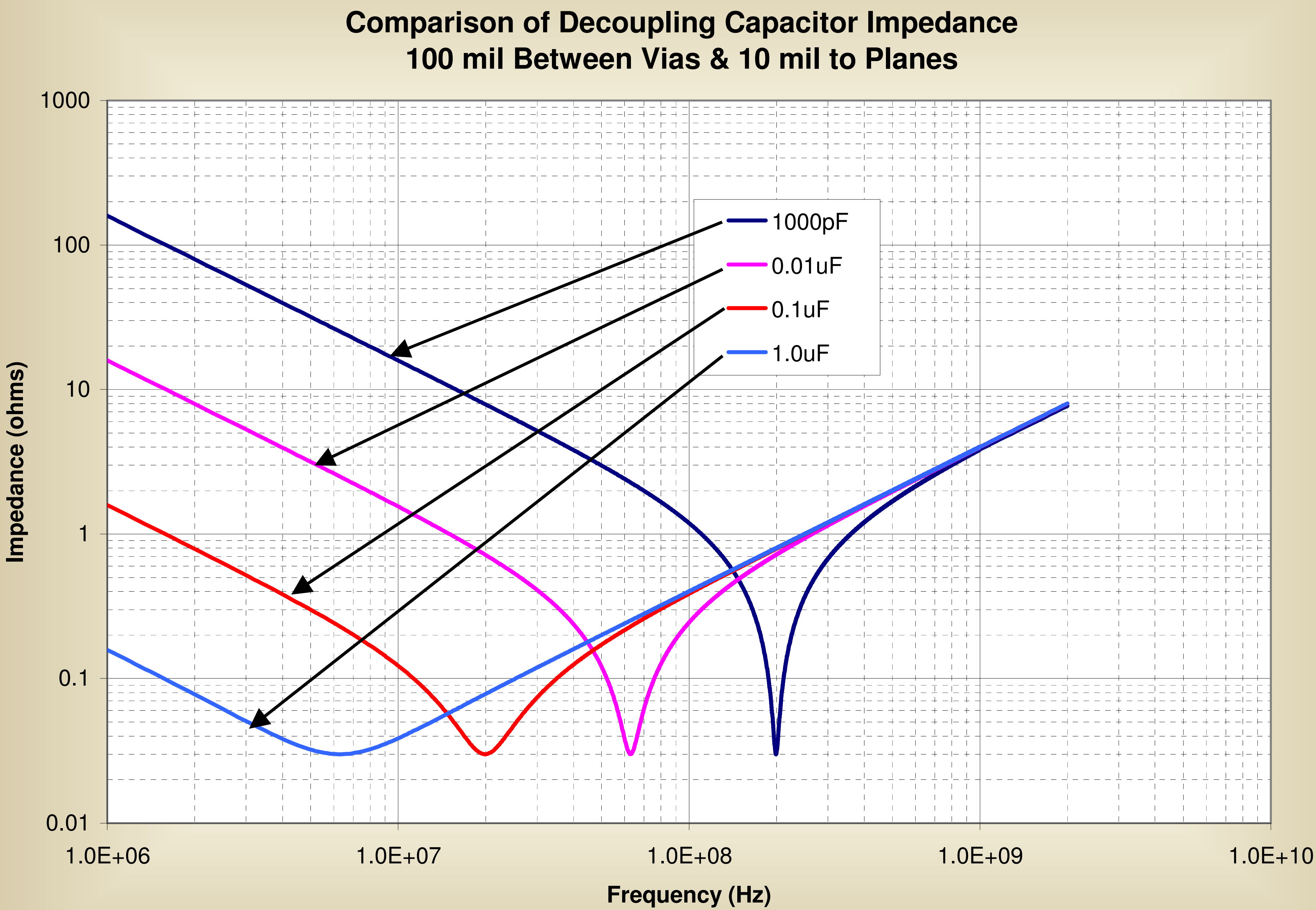
Decoupling Capacitor Mounting

- Keep as to planes as close to capacitor pads as possible

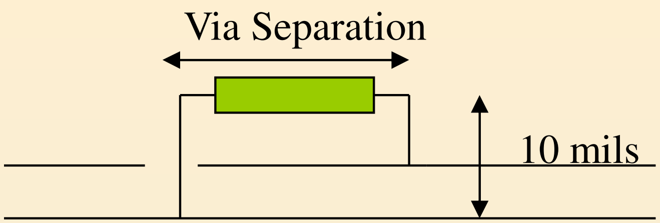


Via Configuration Can Change Inductance




Comparison of Decoupling Capacitor Impedance
100 mil Between Vias & 10 mil to Planes
Impedance (ohms)
1000
100
10
1
0.1
0.01
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
Frequency (Hz)
1000pF
0.01uF
0.1uF
1.0uF

Comparison of Decoupling Capacitor Via Separation Distance Effects

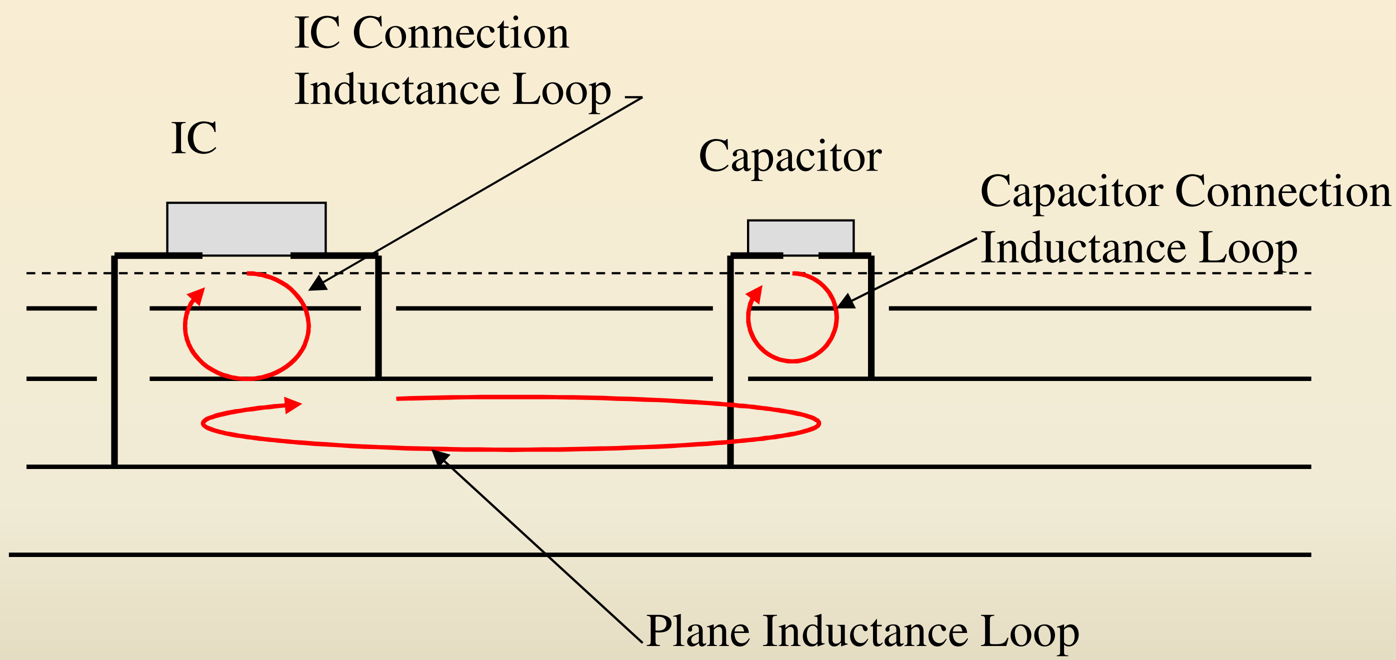


0.1 uF Capacitor

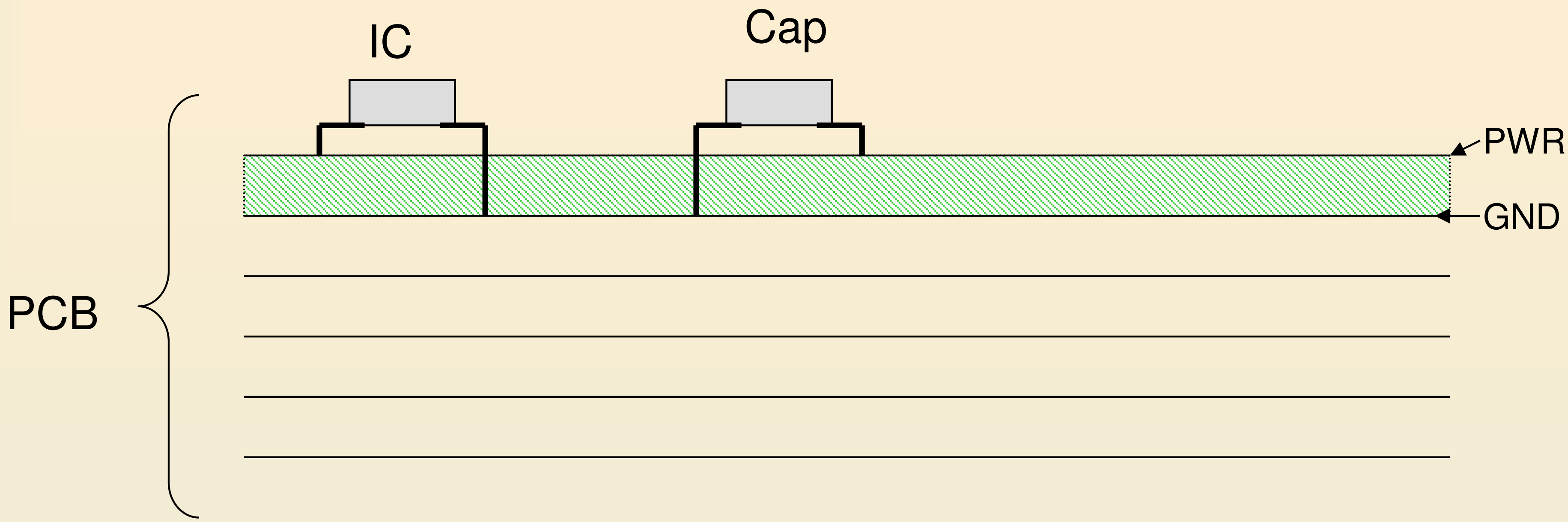
Via Seperation (mils)	Inductance (nH)	Impedance @ 1 GHz (ohms)
20	.06	.41
40	0.21	1.3
60	0.36	2.33
80	0.5	3.1
100	0.64	4.0
150	1.0	6.23
200	1.4	8.5
300	2.1	12.69
400	2.75	17.3
500	3.5	21.7

Decoupling Capacitor Mounting

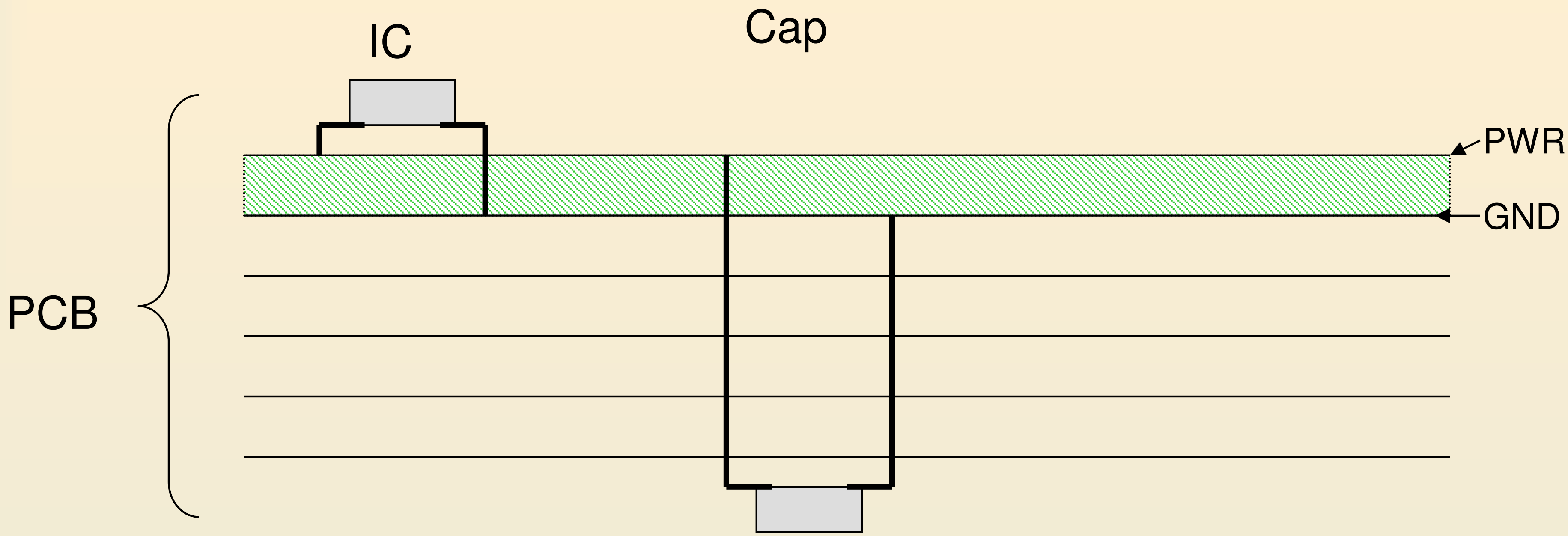
- Keep as to planes as close to capacitor pads as possible



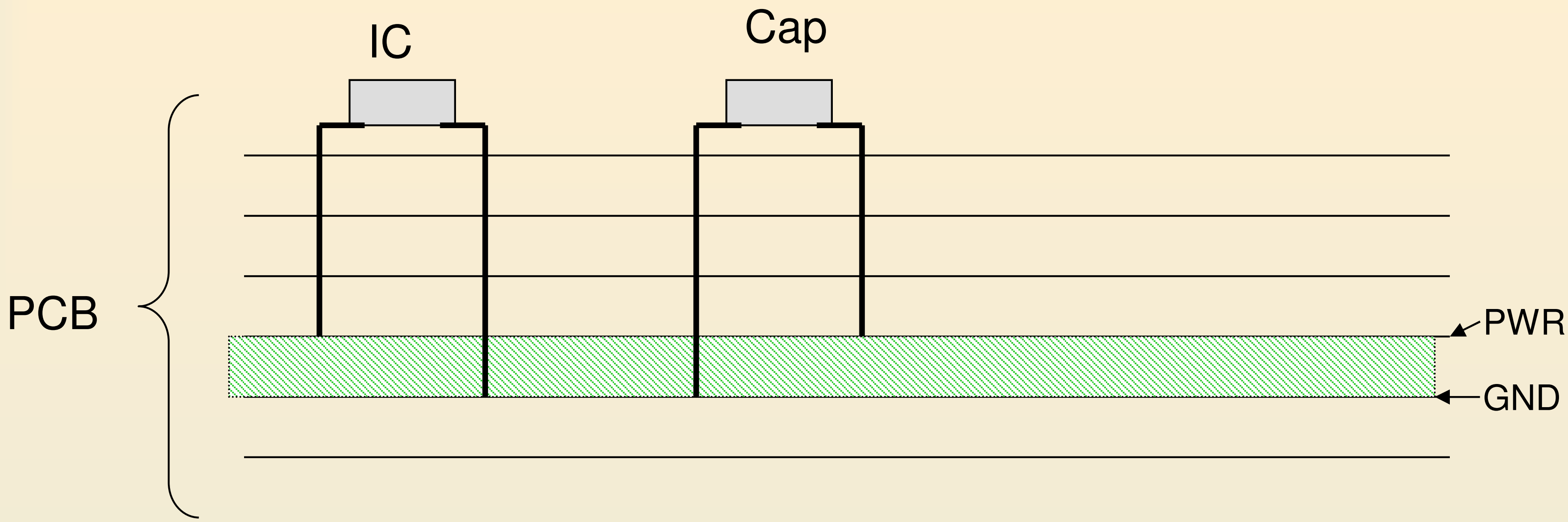
Example #1
Low Cap Connection Inductance



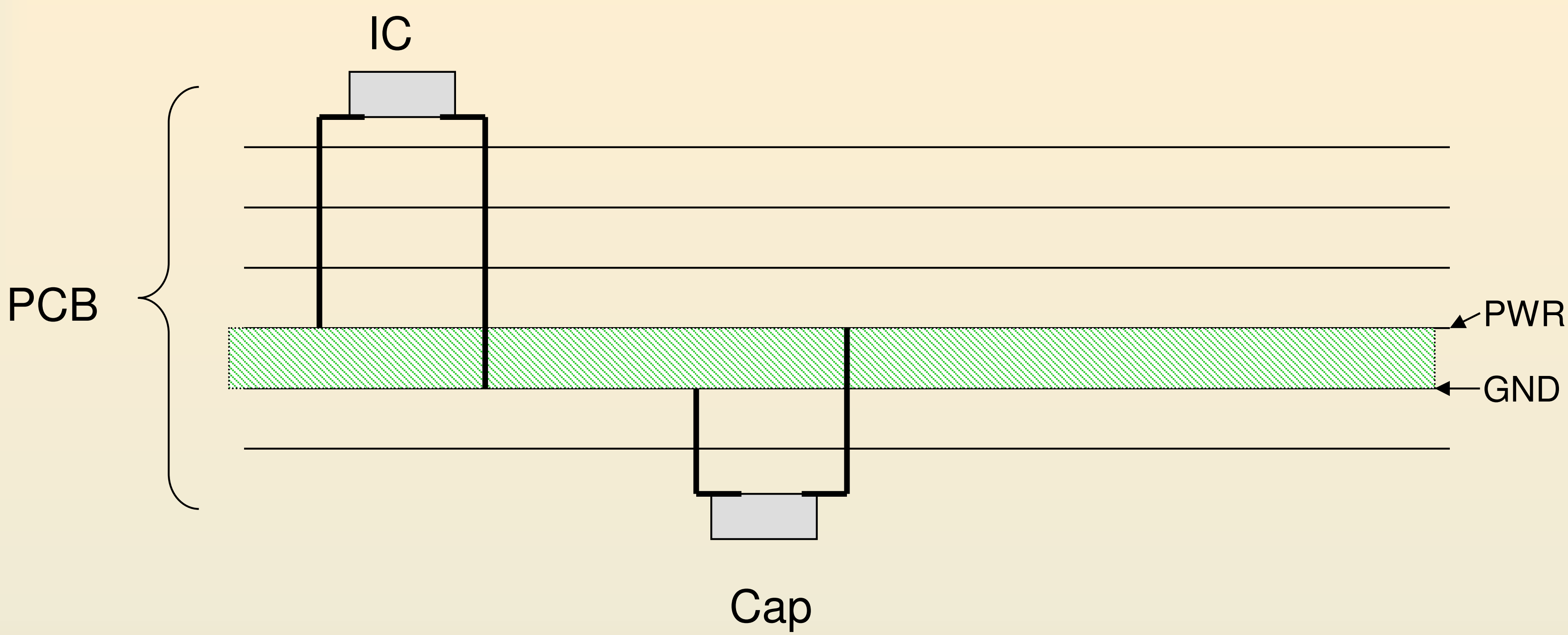
Example #2
High Cap Connection Inductance



Example #1
Hi Cap Connection Inductance



Example #1
Lower Cap Connection Inductance



‘Ground’

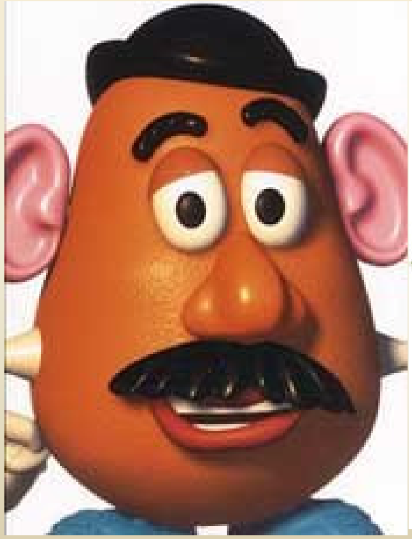
- **Ground is a place where potatoes and carrots thrive!**
- ‘Earth’ or ‘reference’ is more descriptive
- Original use of “GROUND”
- Inductance is everywhere

$$X_L = 2\pi f L$$

‘Ground’

- **Ground is a place where potatoes and carrots thrive!**
- ‘Earth’ or ‘reference’ is more descriptive
- Original use of “GROUND”
- Inductance is everywhere

$$X_L = 2\pi f L$$



What we Really Mean when we say ‘Ground’

- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

‘Ground’ is NOT a Current Sink!

- Current leaves a driver on a trace and must return (somehow) to its source
- This seems basic, but it is often forgotten, and is most often the cause of EMC problems

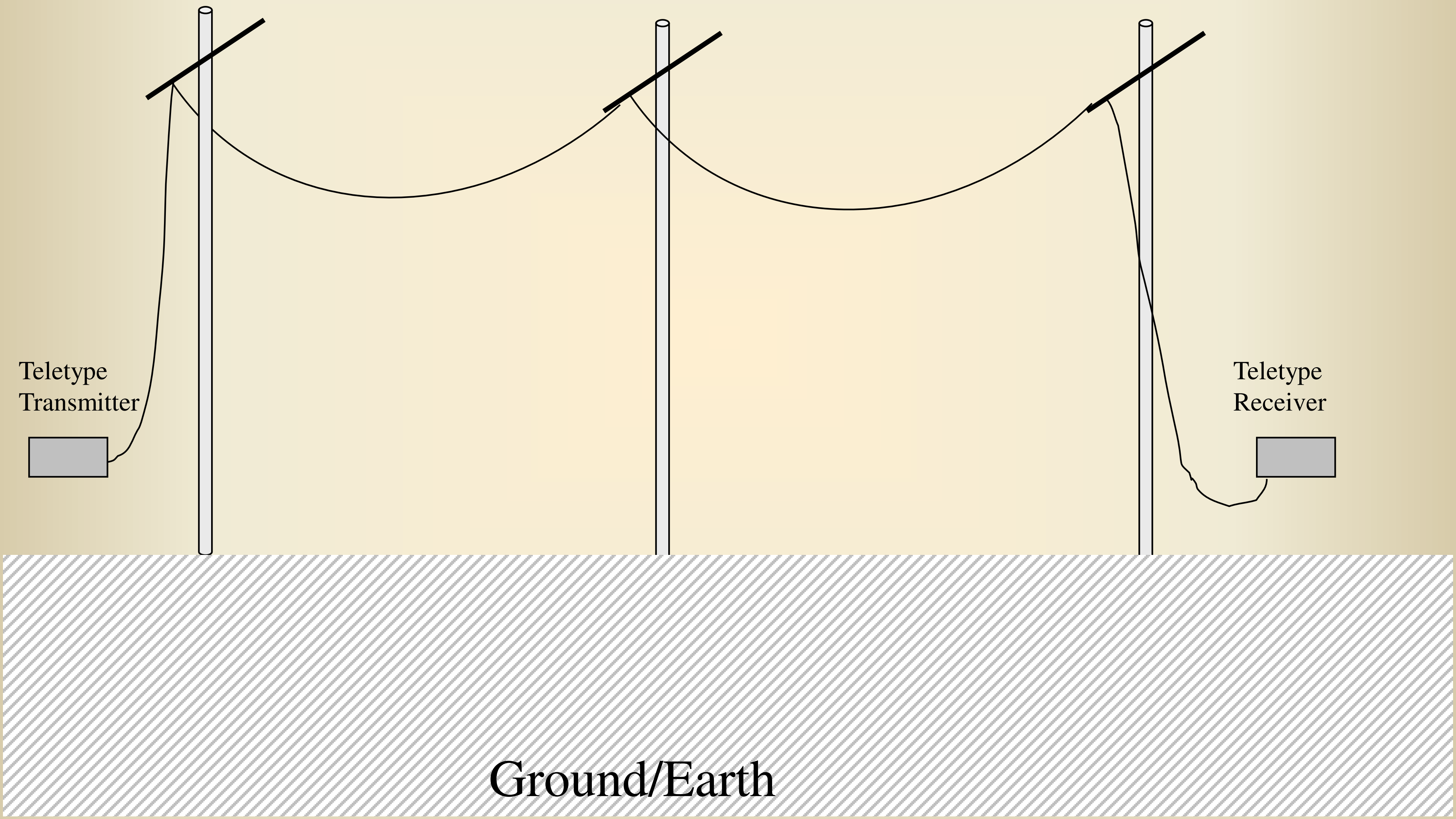
‘Grounding’ Needs Low Impedance at Highest Frequency

- Steel Reference Plate
  - 4 milliohms/sq @ 100KHz
  - 40 milliohms/sq @ 10 MHz
  - 400 milliohms/sq @ 1 GHz
- A typical via is about 2 nH
  - @ 100 MHz Z = 1.3 ohms
  - @ 500 MHz Z = 6.5 ohms
  - @ 1000 MHz Z = 13 ohms
  - @ 2000 MHz Z = 26 ohms

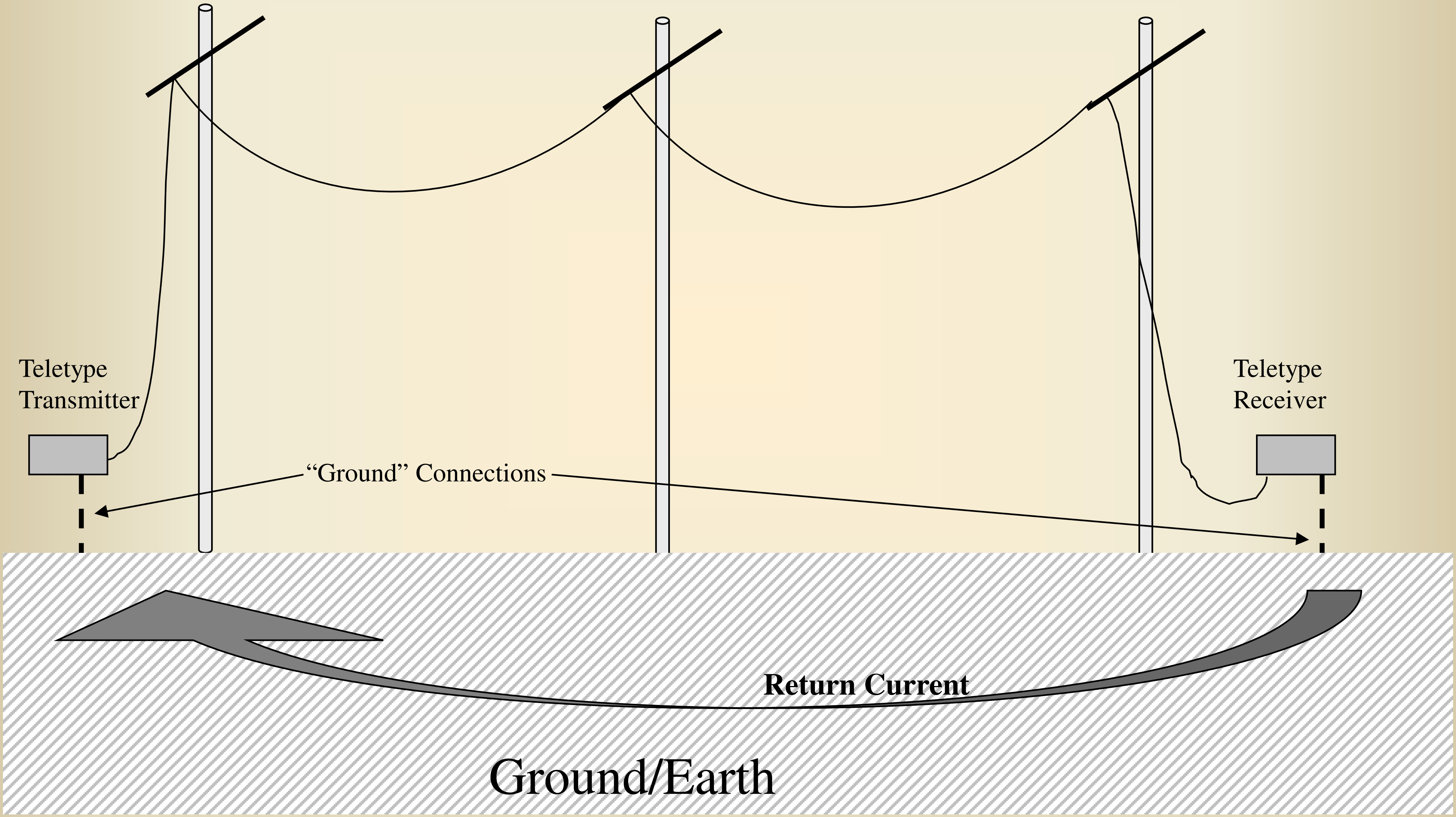
Where did the Term “GROUND” Originate?

- Original Teletype connections
- Lightning Protection

Original Teletype System Example

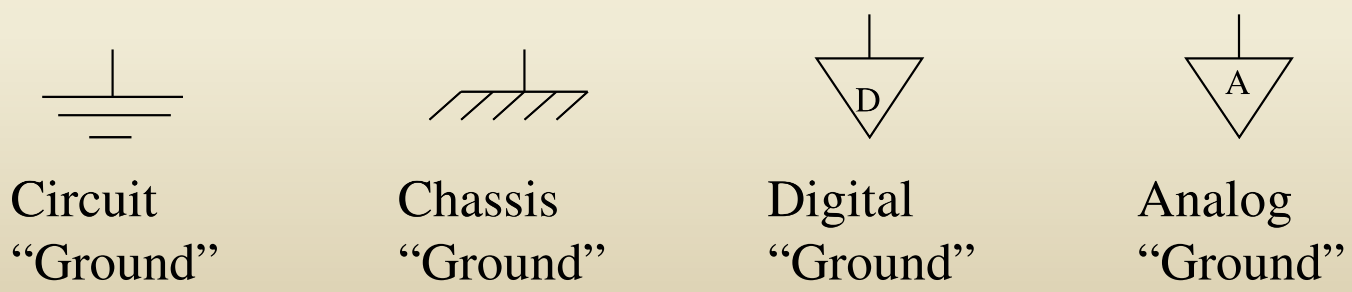


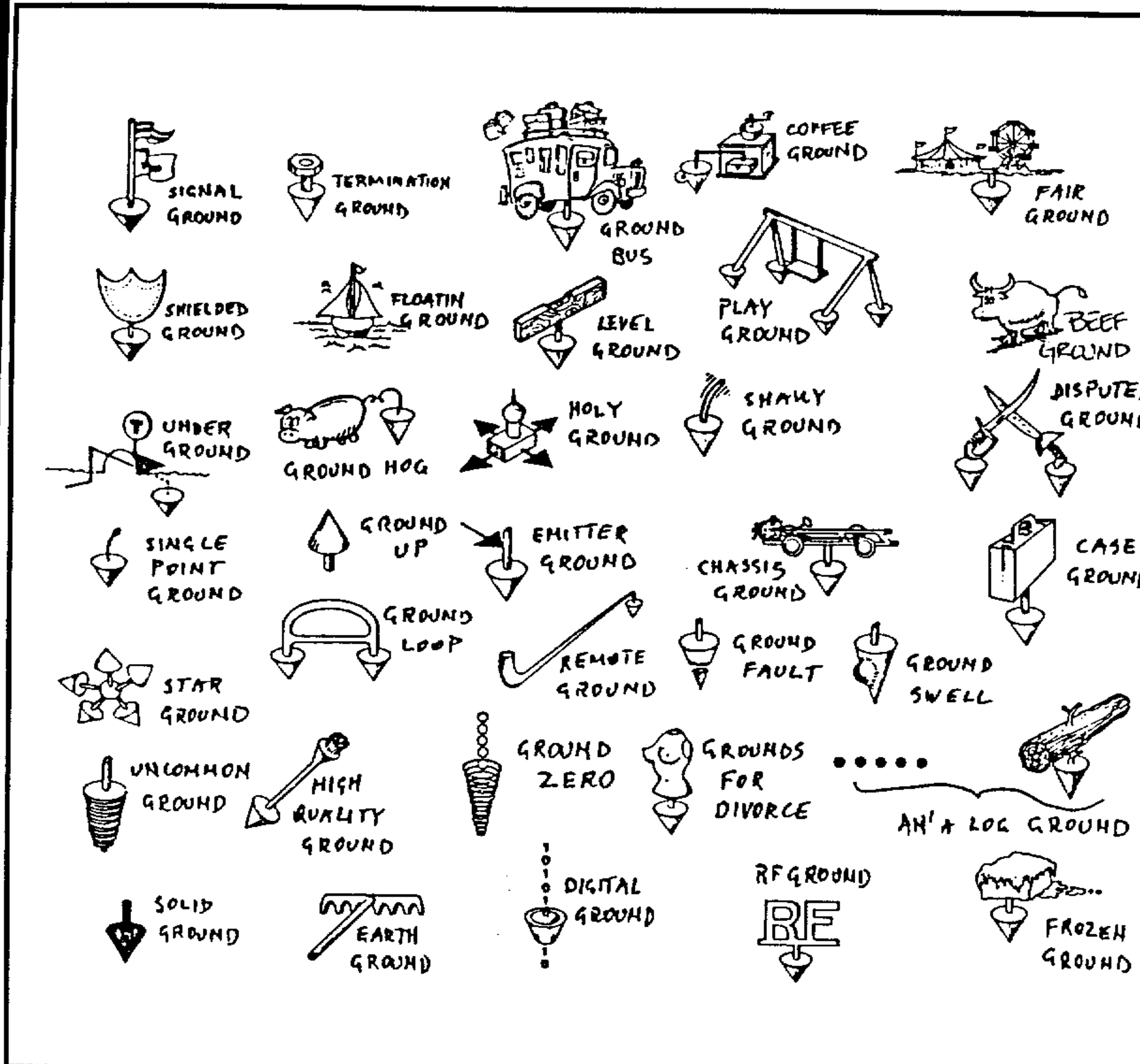
Original Teletype System Example



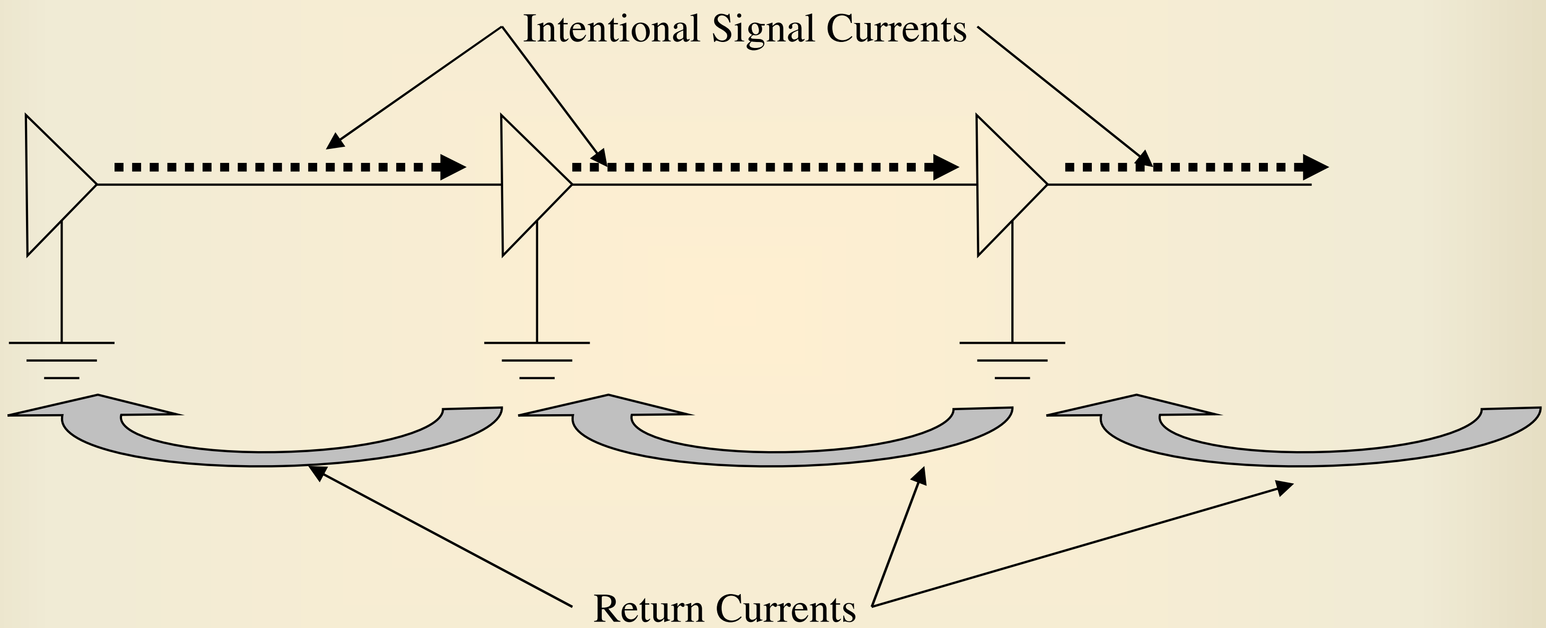
What we Really Mean when we say ‘Ground’

- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

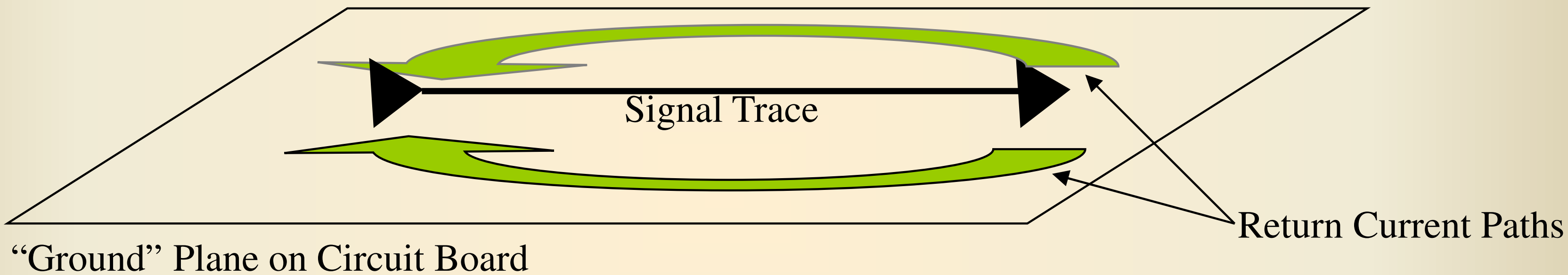



SIGNAL GROUND
TERMINATION GROUND
GROUND BUS
COFFEE GROUND
FAIR GROUND
SHIELDED GROUND
FLOATIN GROUND
LEVEL GROUND
PLAY GROUND
BEEF GROUND
UNDER GROUND
GROUND HOG
HOLY GROUND
SHAKY GROUND
DISPUTED GROUND
SINGLE POINT GROUND
GROUND UP
EMITTER GROUND
CHASSIS GROUND
CASE GROUND
GROUND LOOP
REMOTE GROUND
GROUND FAULT
GROUND SWELL
STAR GROUND
UNCOMMON GROUND
HIGH QUALITY GROUND
GROUND ZERO
GROUNDS FOR DIVORCE
AN' A LOG GROUND
SOLID GROUND
EARTH GROUND
DIGITAL GROUND
RF GROUND
RF
FROZEN GROUND

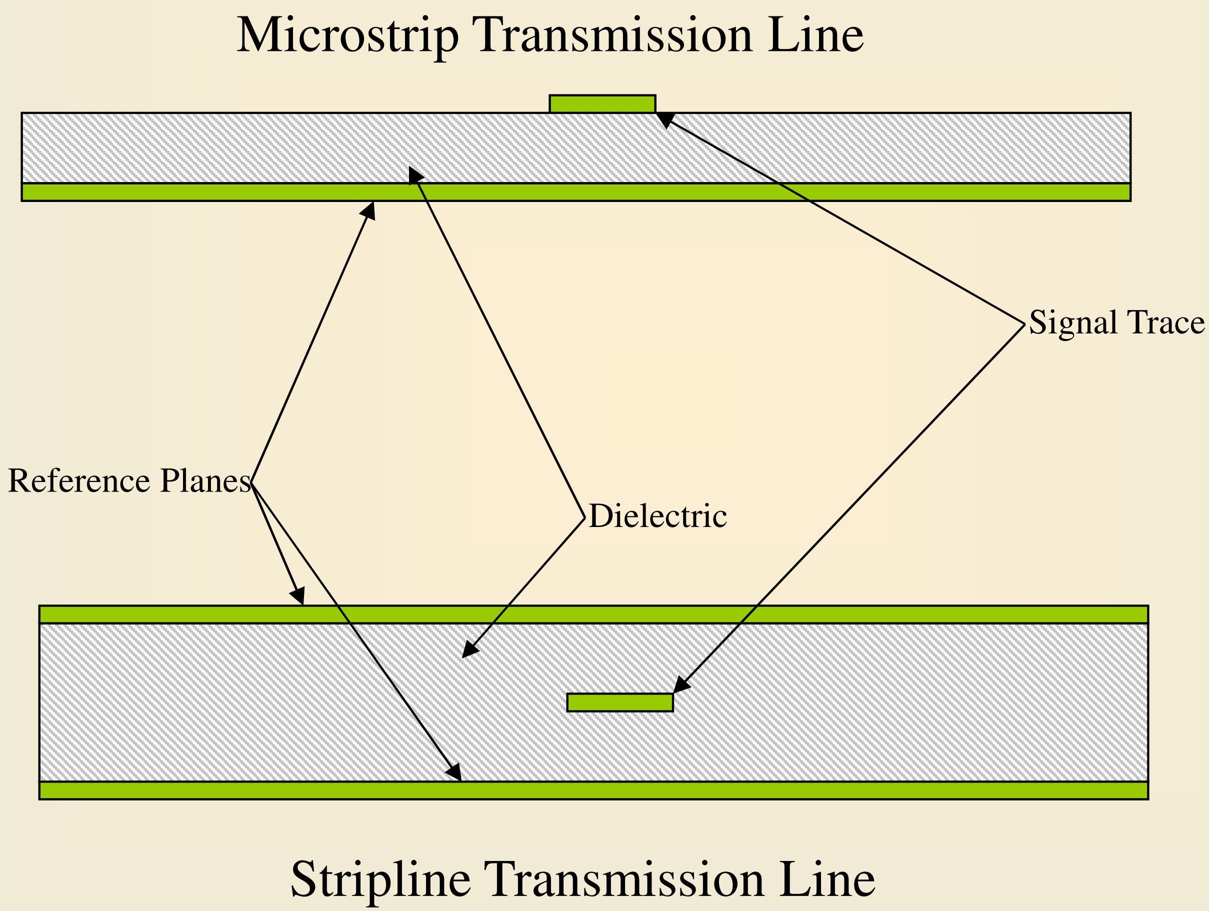
“*Ground*” as Signal Reference



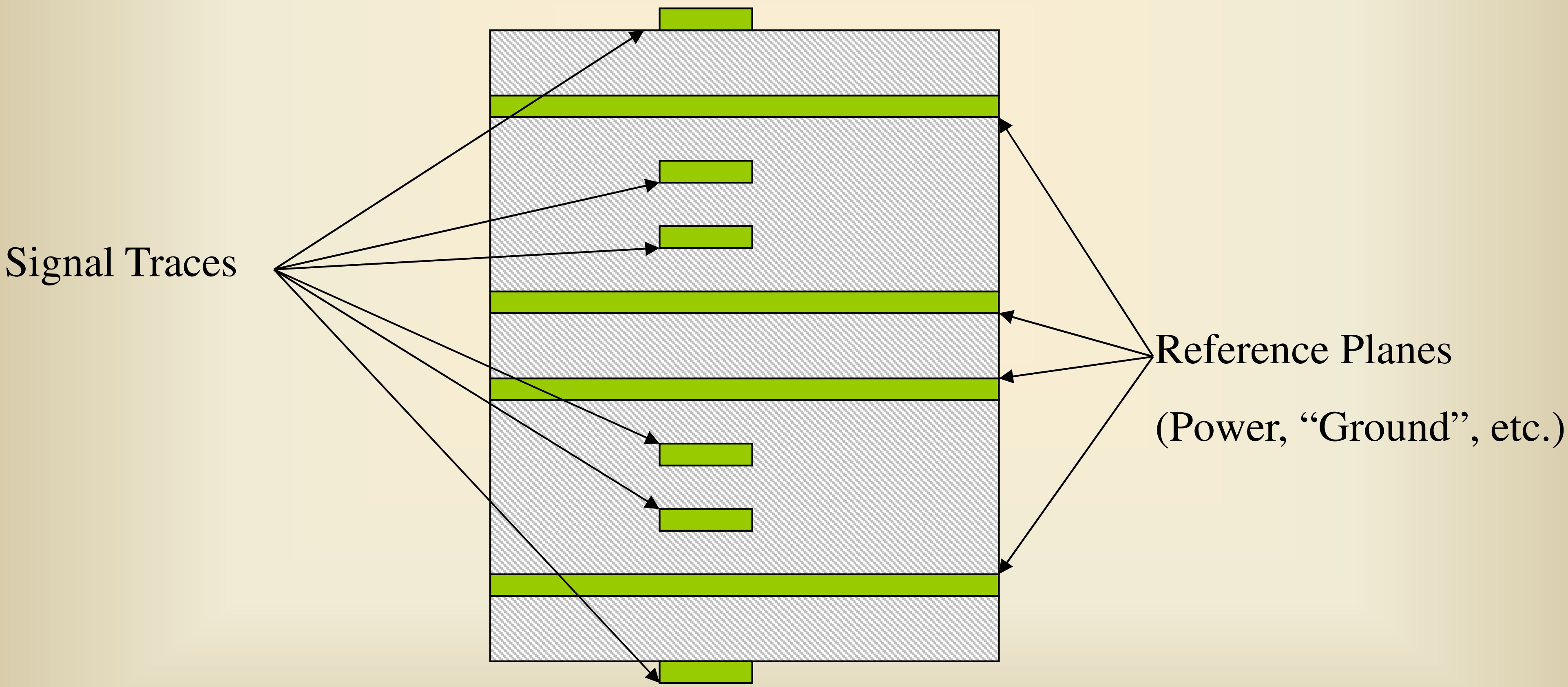
“*Ground*” as Signal Reference



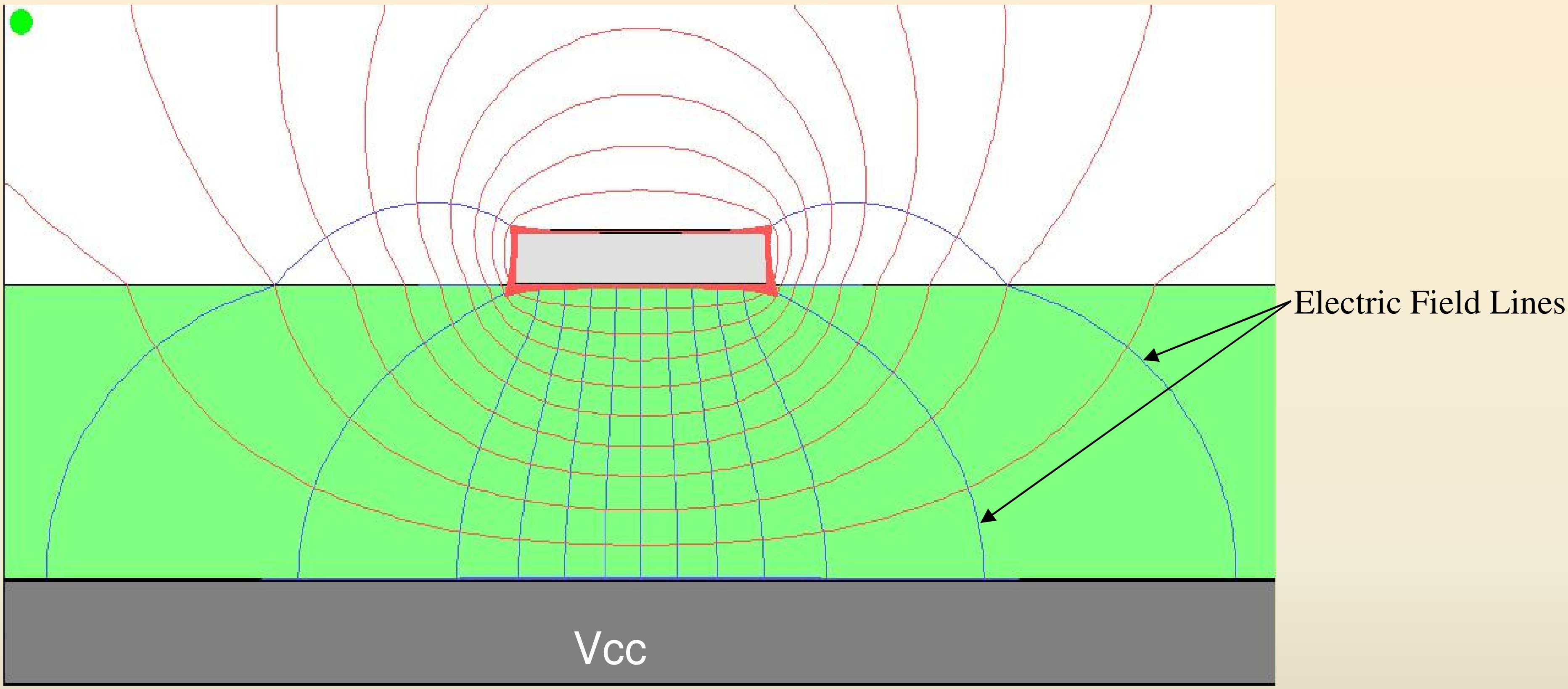
Traces/nets over a Reference Plane



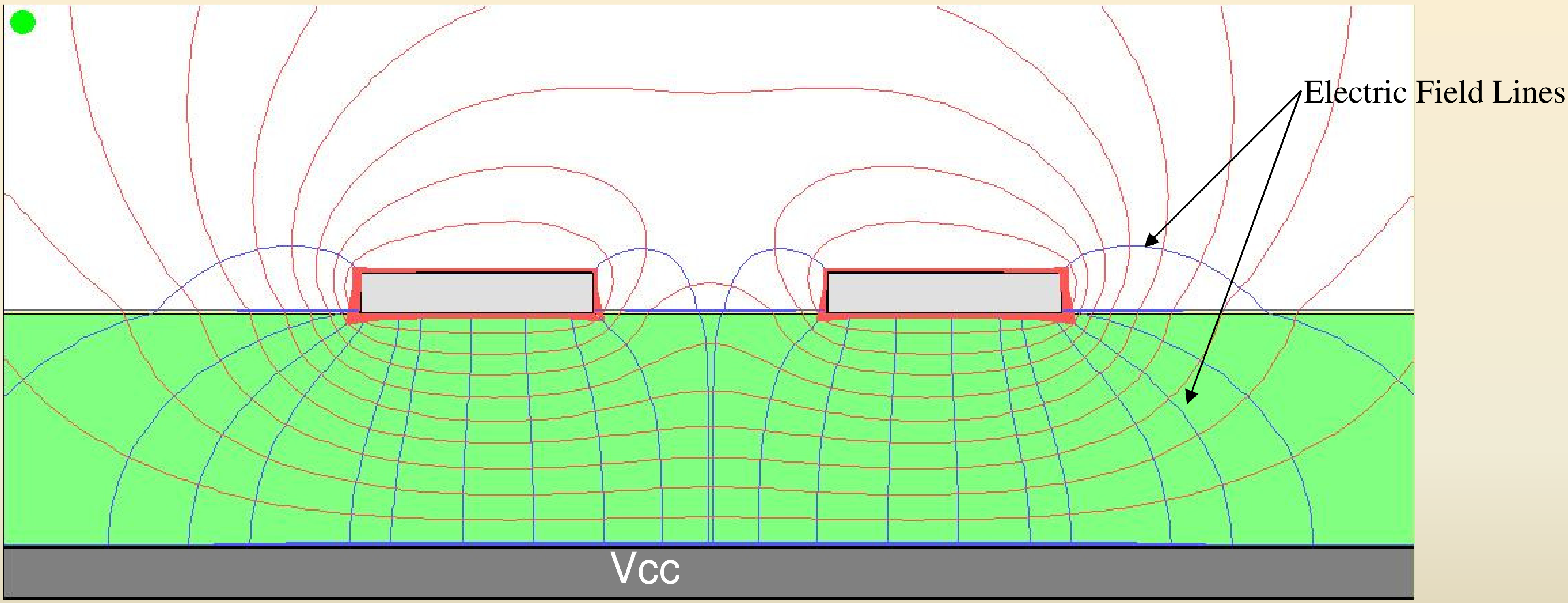
Traces/nets and Reference Planes in Many Layer Board Stackup



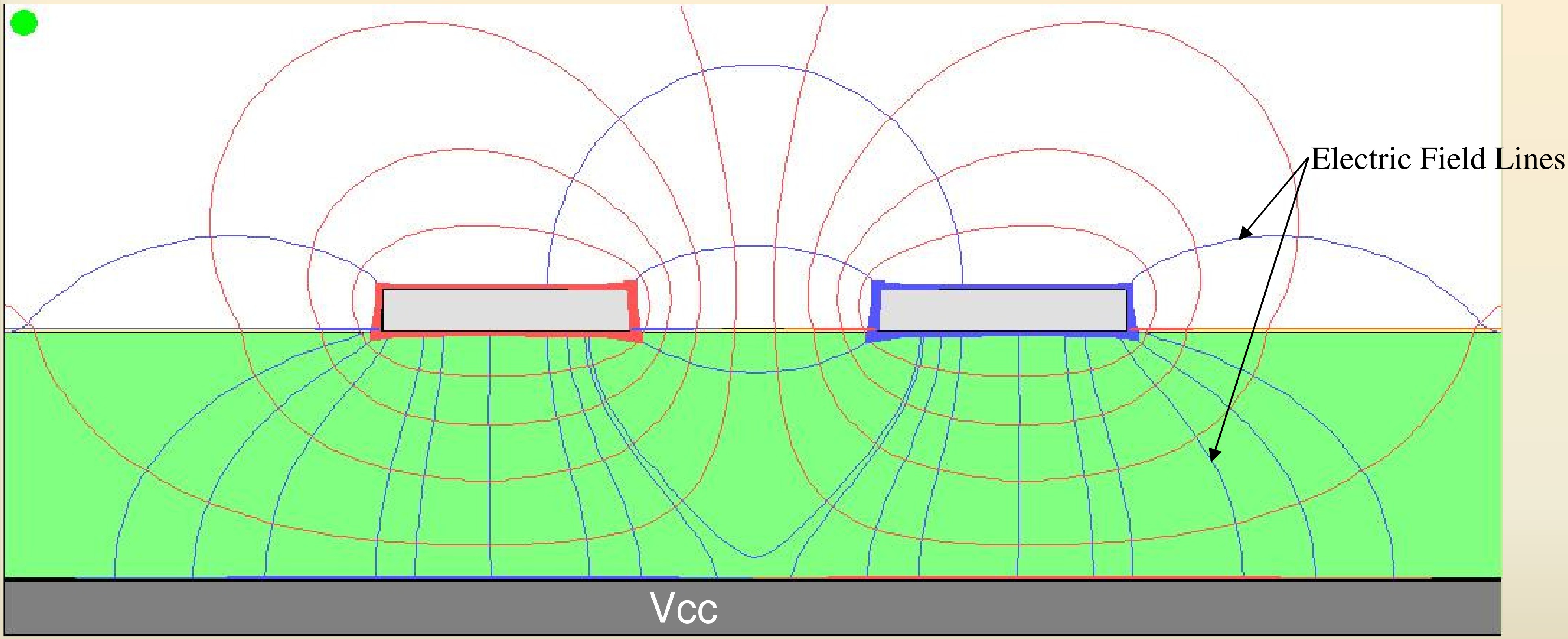
Microstrip Electric/Magnetic Field Lines
(8mil wide trace, 8 mils above plane, 65 ohm)



Microstrip Electric/Magnetic Field Lines
Common Mode
8 mil wide trace, 8 mils above plane, 65/115 ohm)

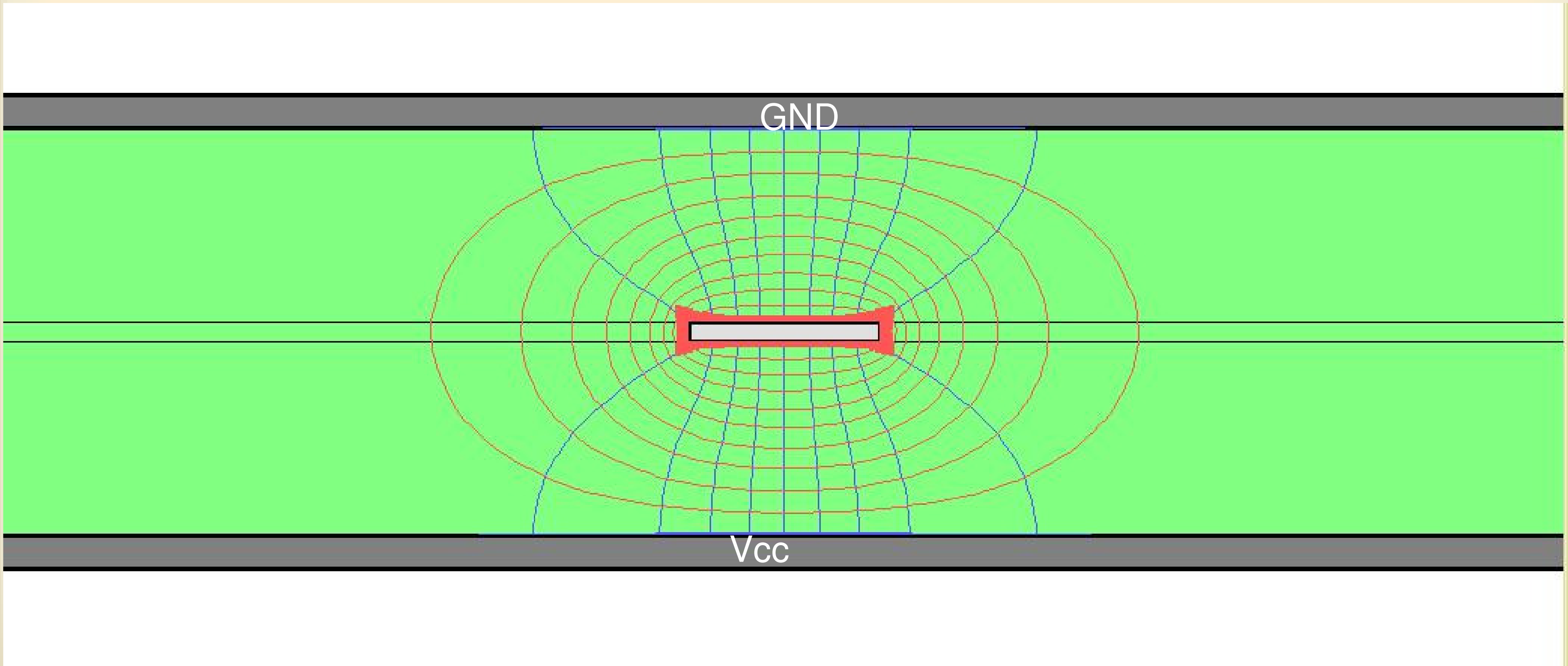


Microstrip Electric/Magnetic Field Lines
Differential Mode
8 mil wide trace, 8 mils above plane, 65/115 ohm)

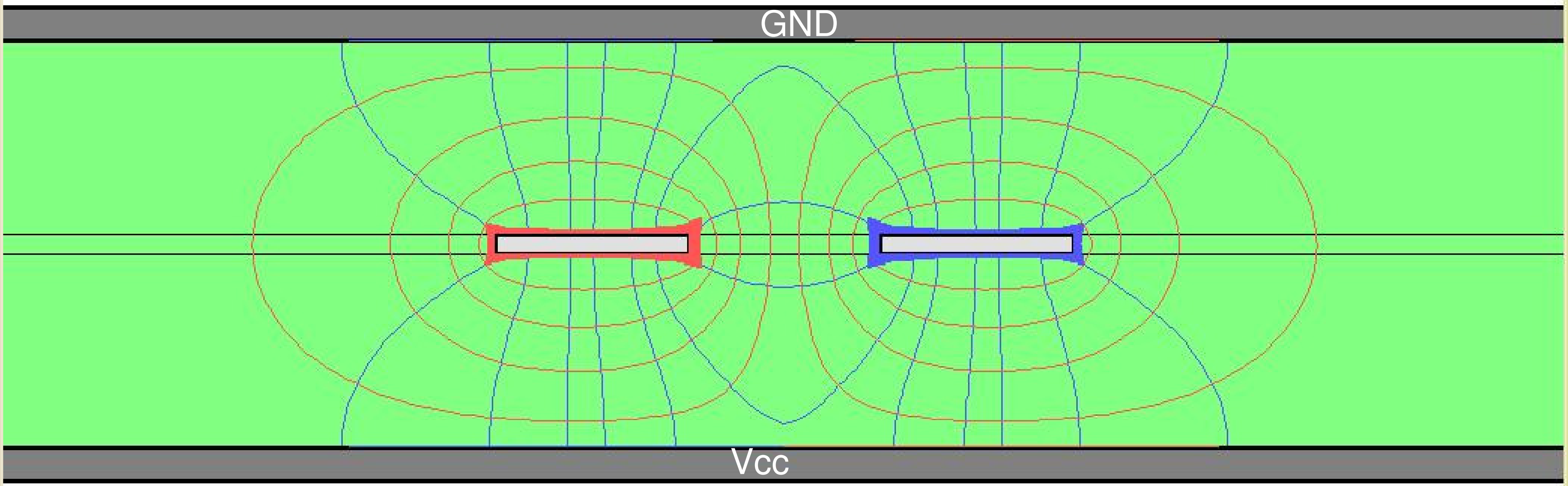


Electric/Magnetic Field Lines

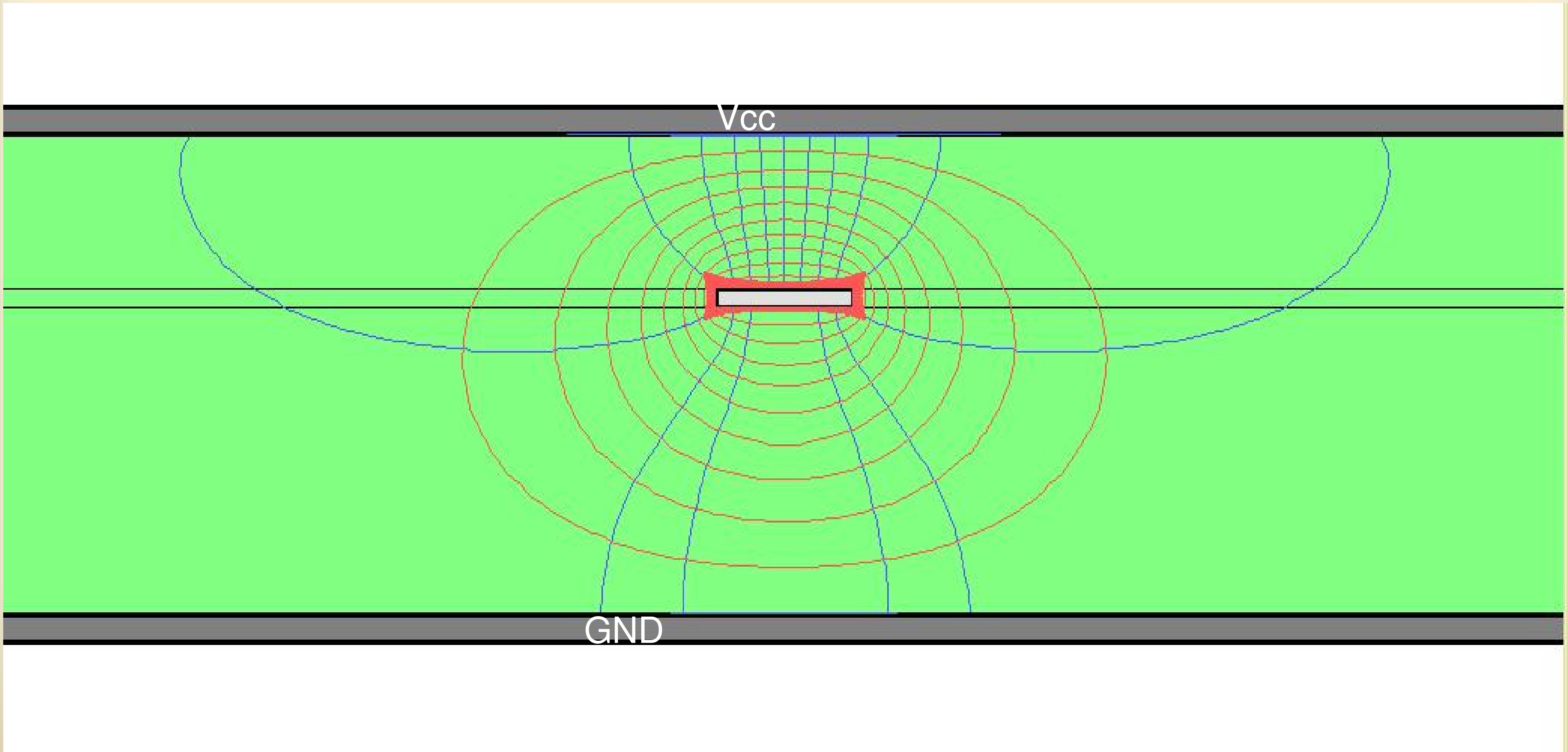
Symmetrical Stripline



Electric/Magnetic Field Lines
Symmetrical Stripline (Differential)

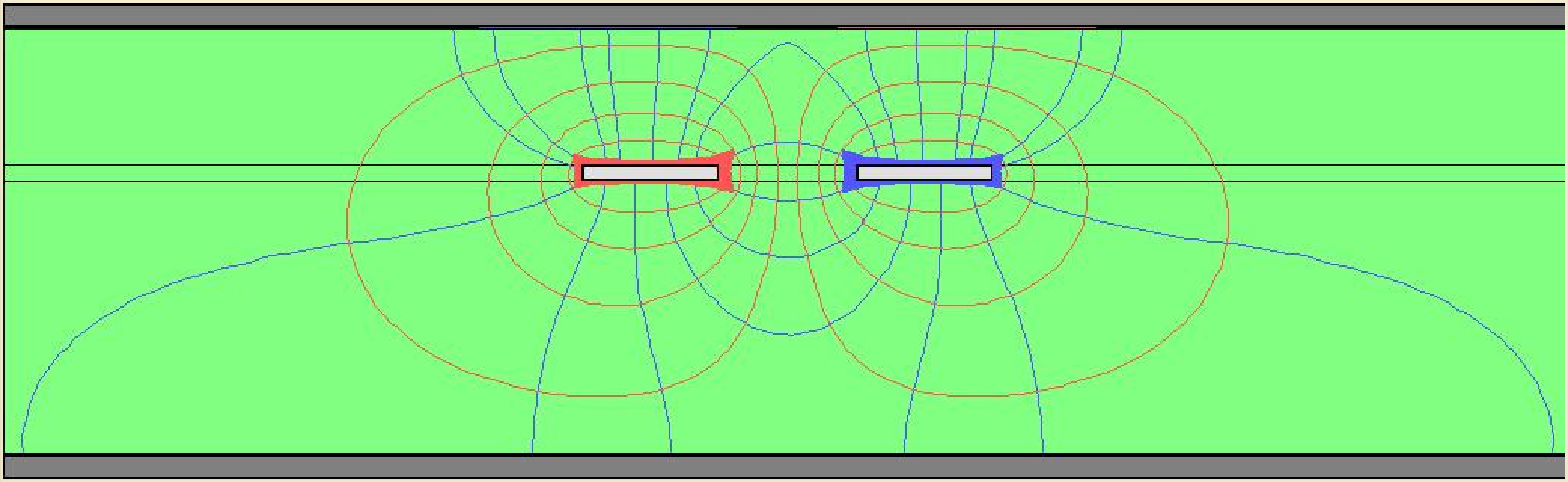


Electric/Magnetic Field Lines
Asymmetrical Stripline



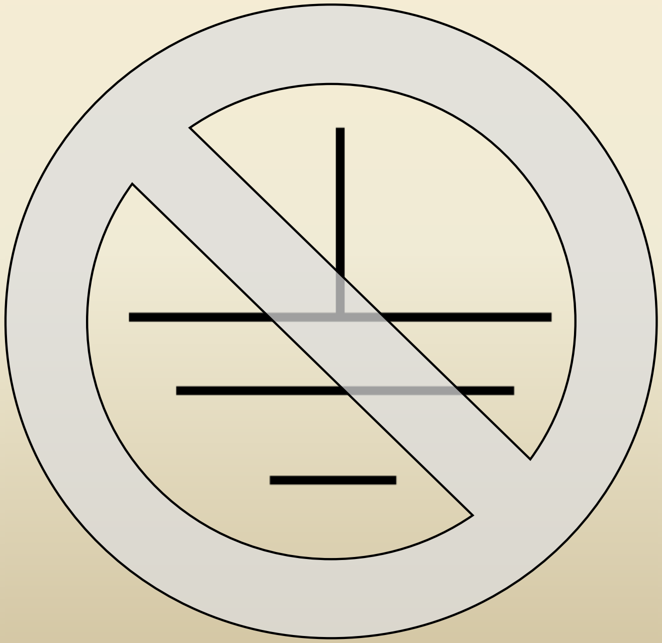
Electric/Magnetic Field Lines

Asymmetrical Stripline (Differential)



Return Current vs. "Ground"

- For high frequency signals, "Ground" is a concept that does not exist
- The important question is "where does the *return current* flow?"



Psudeo-Differential Net Summary

- Small amounts of skew can cause significant common mode current
- Small amount of rise/fall time deviation can cause significant amount of common mode current
- Discontinuities (vias, crossing split planes, etc) and convert significant amount of differential current into common mode current

Referencing Nets
(Where does the Return Current Flow??)

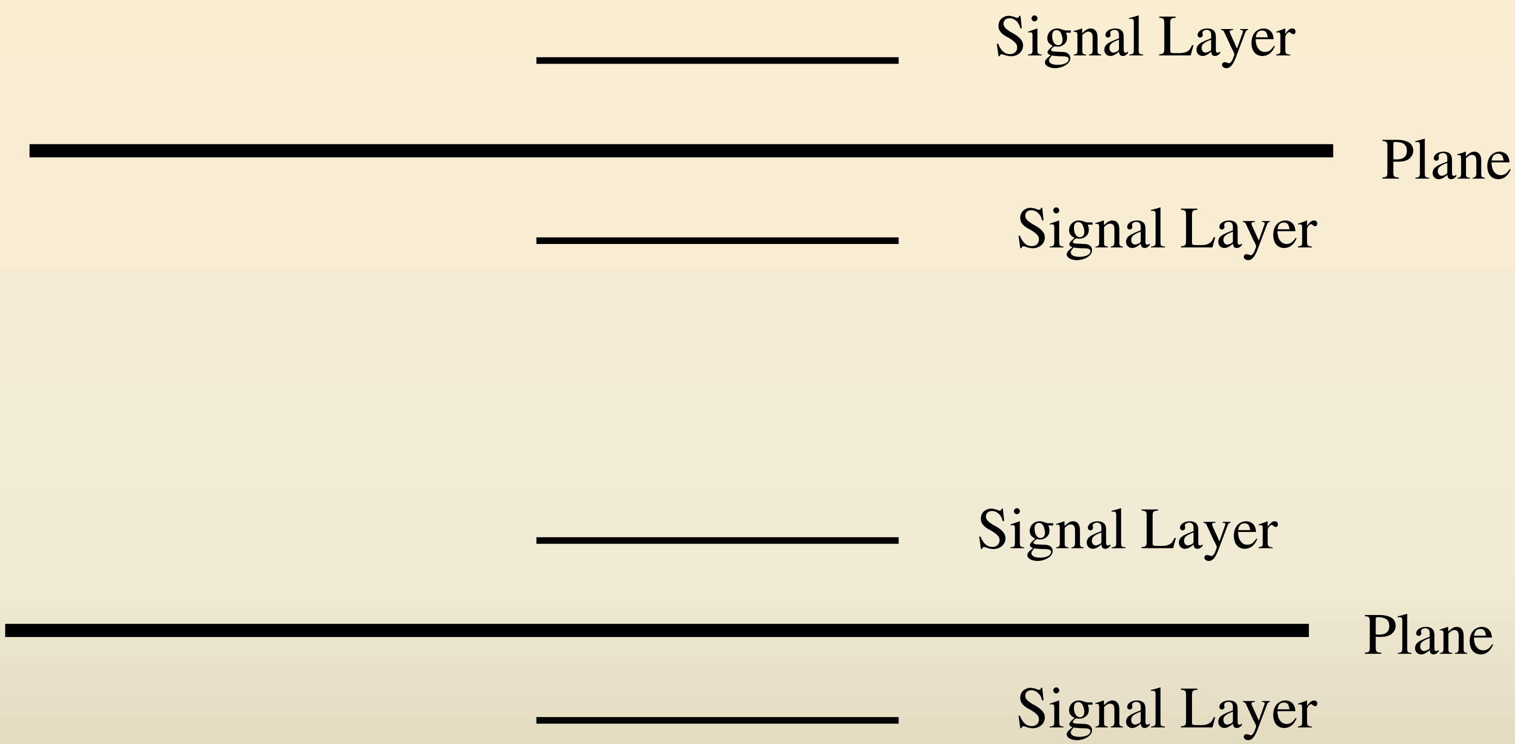
- Microstrip/Stripline across split in reference plane
- Microstrip/Stripline through via (change reference planes)
- Mother/Daughter card

Are Stitching Capacitors Effective ???

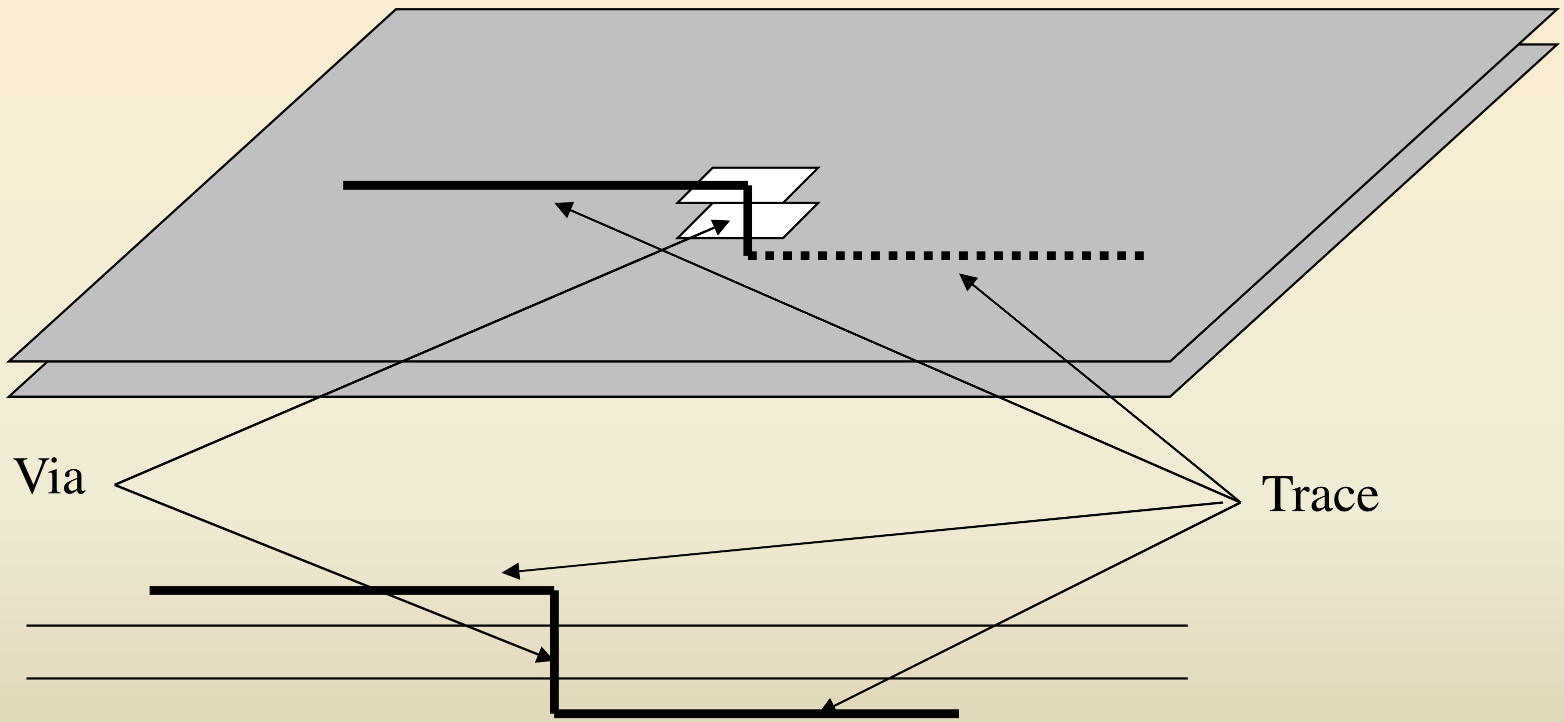
- YES, at low frequencies
- No, at high frequencies
- Need to limit the high frequency current spectrum
- Need to avoid split crossings with ALL critical signals

Changing Reference Planes

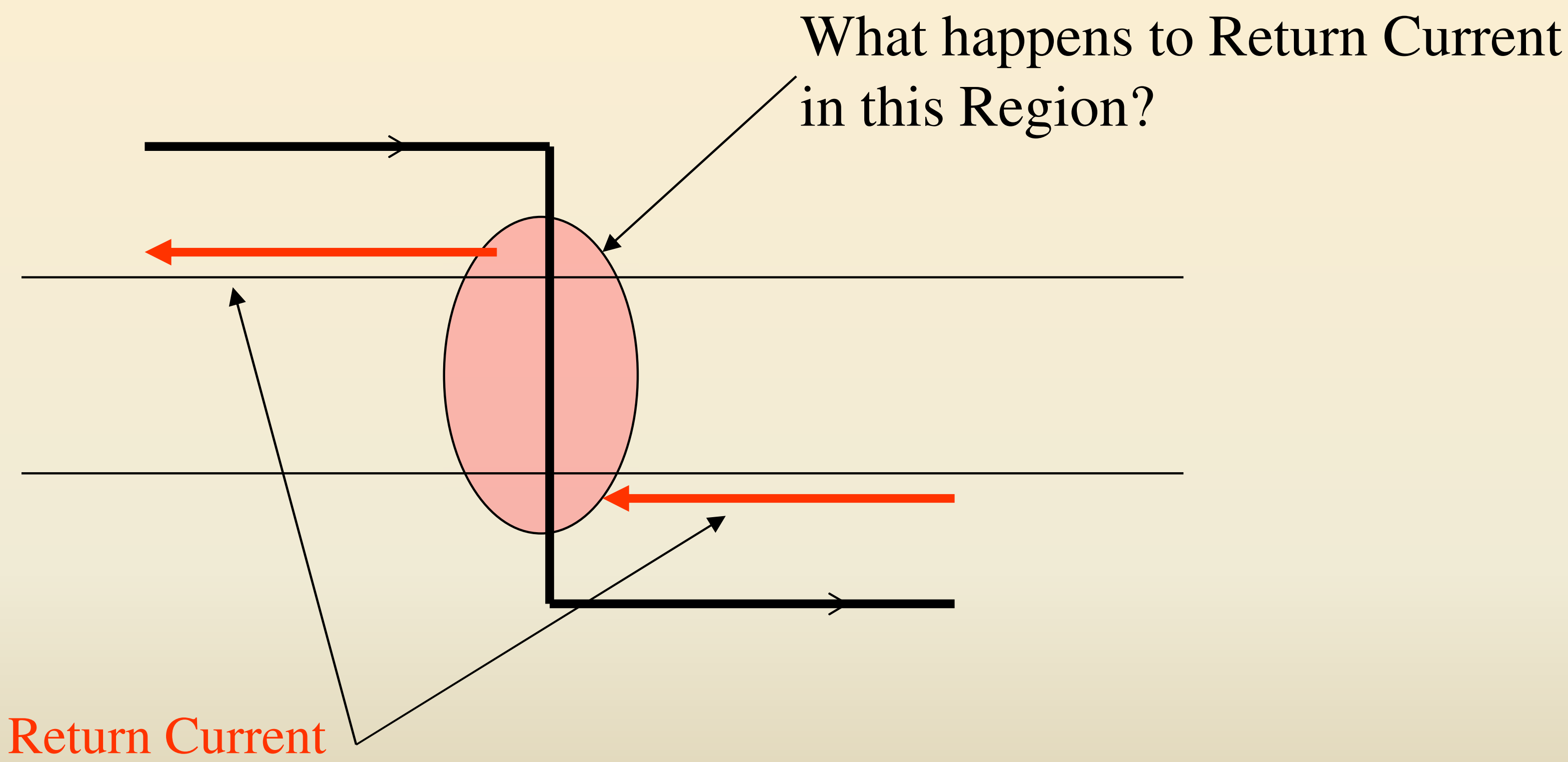
Six-Layer PCB Stackup Example



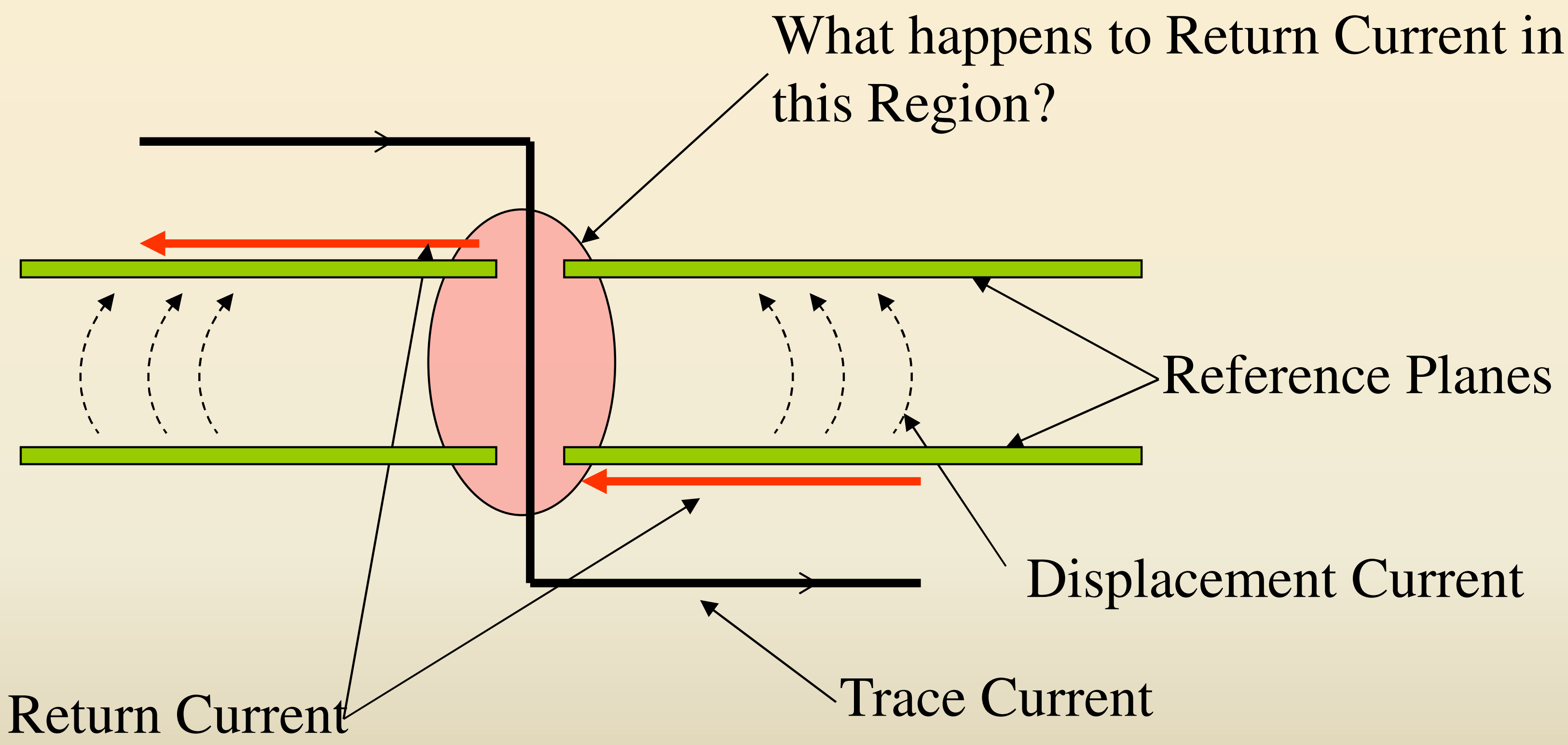
Microstrip/Stripline through via (change reference planes)



How can the Return Current Flow When Signal Line Goes Through Via??

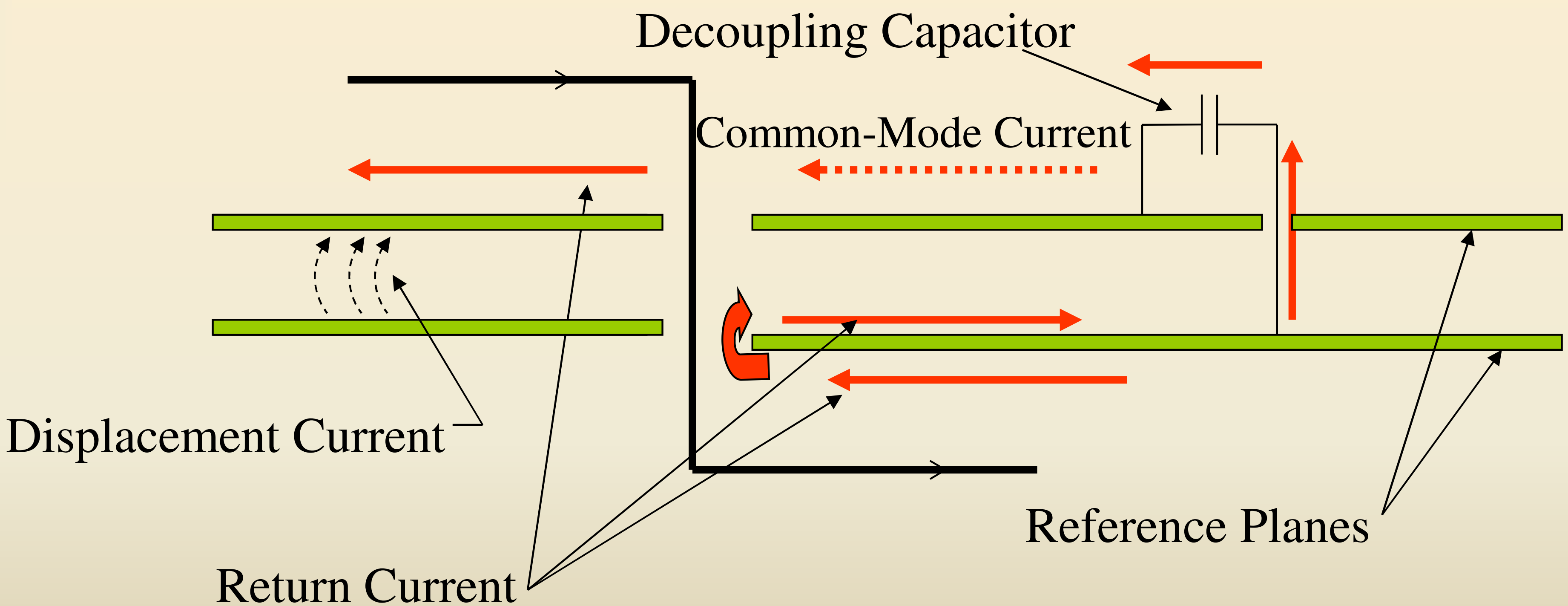


Return Current Across Reference Plane Change



Return Current Across Reference Plane Change

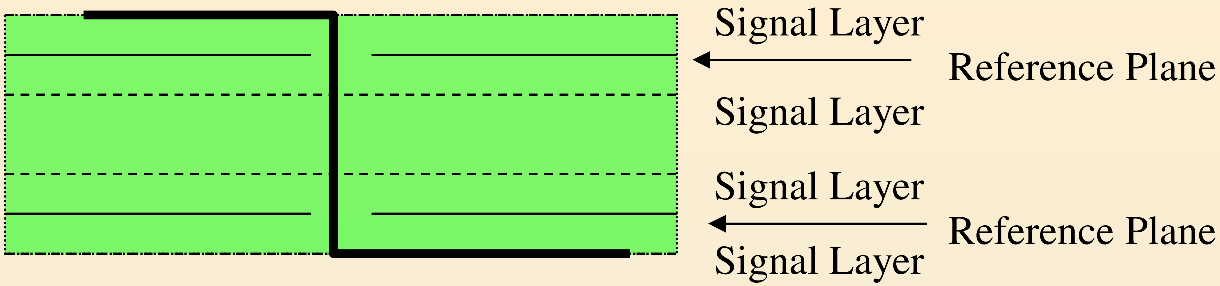
With Decoupling Capacitor (on Top)



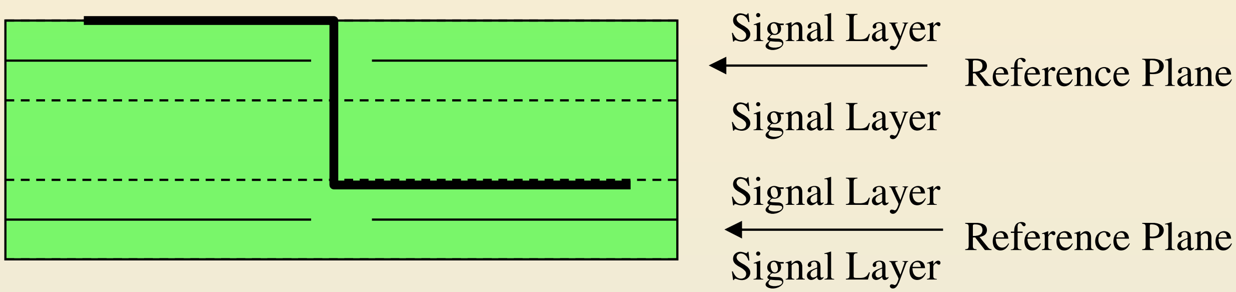
Possible Routing Options

Six-Layer Board

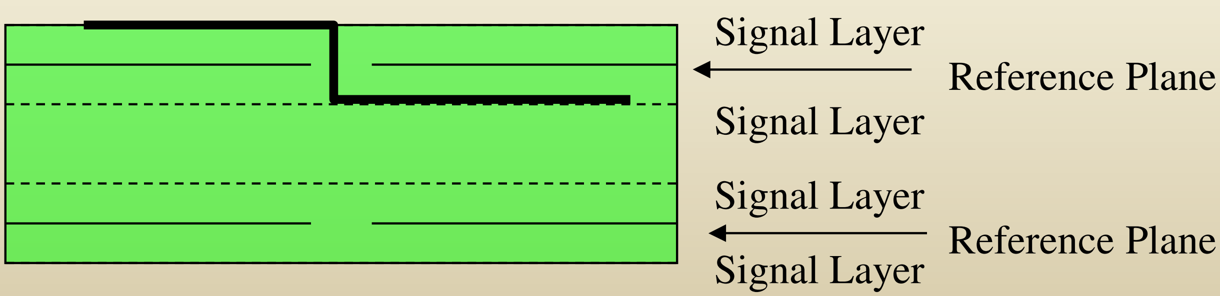
Bad



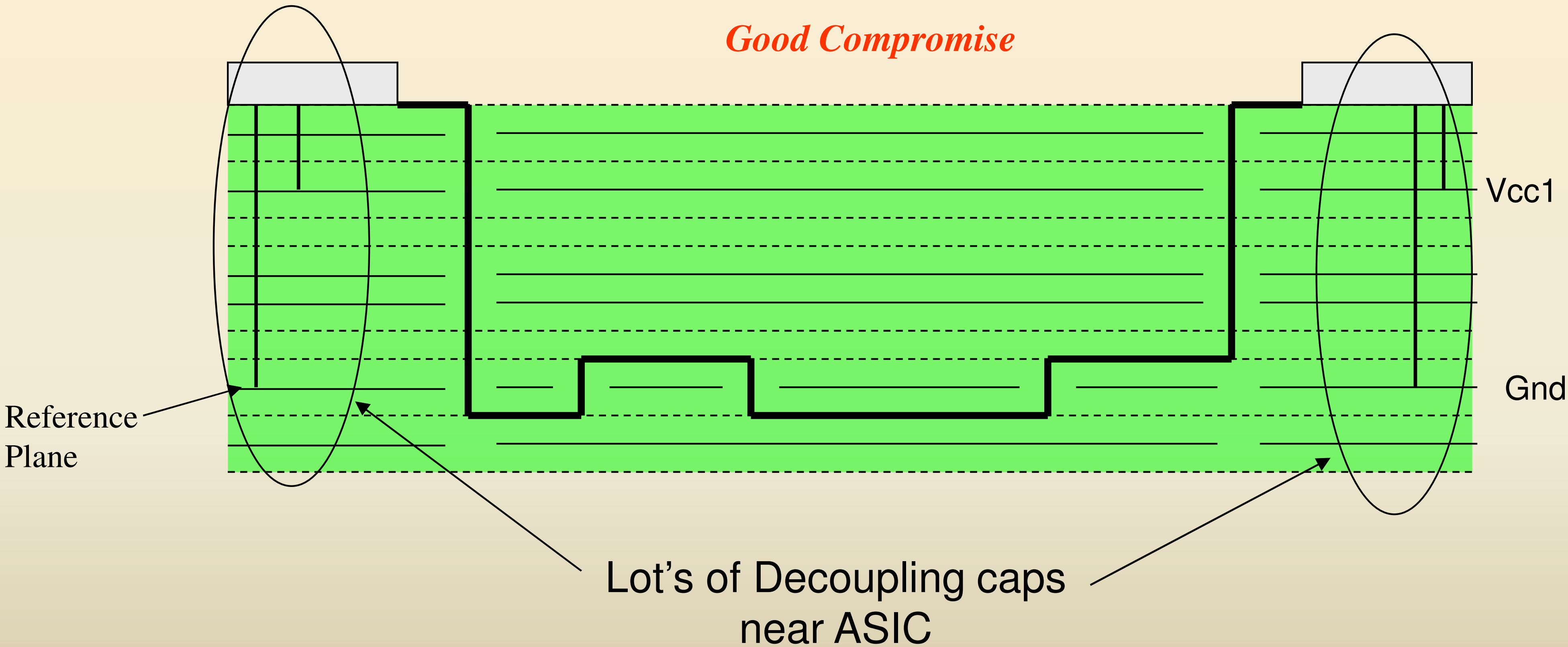
Bad



Good



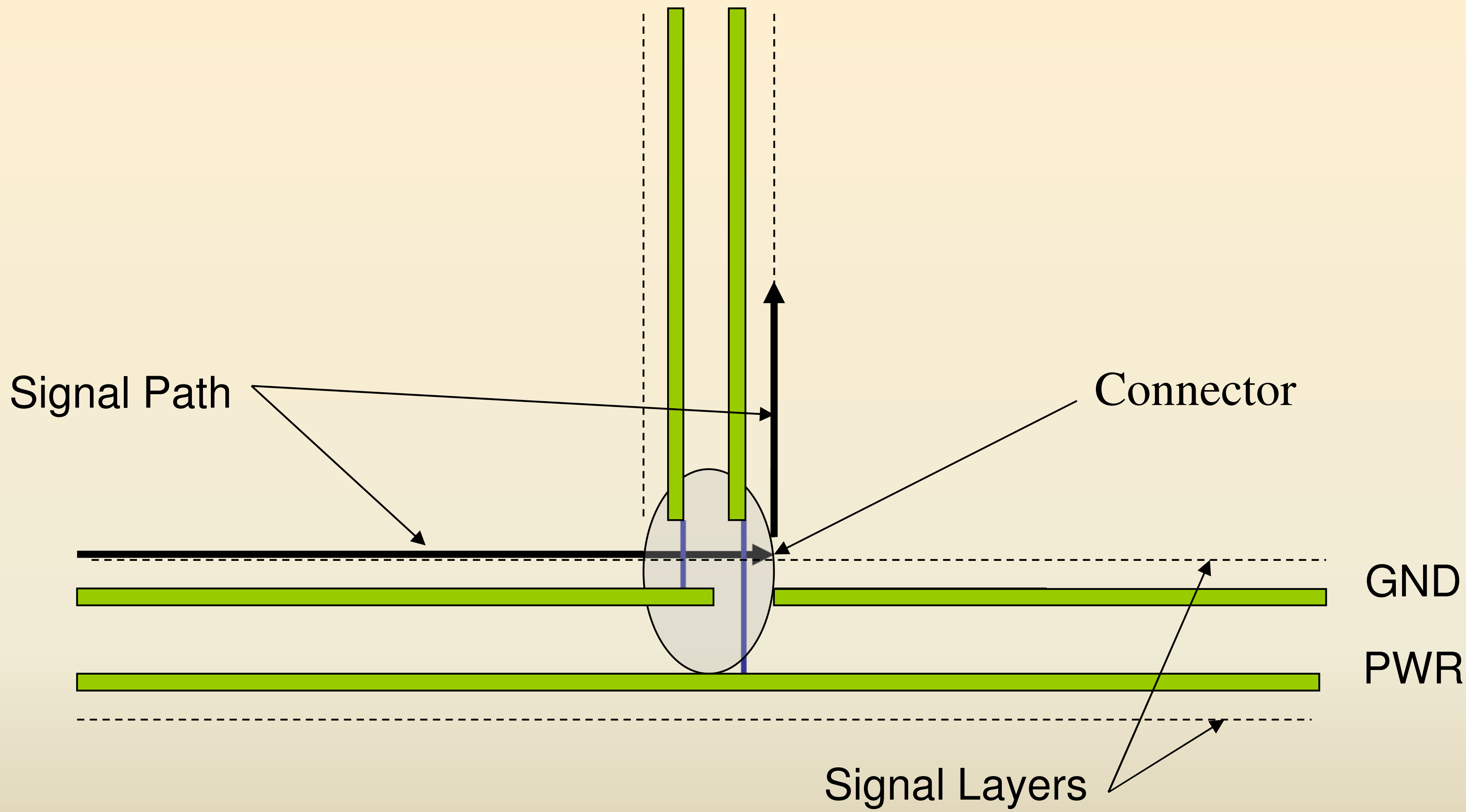
Compromise Routing Option for Many Layer Boards



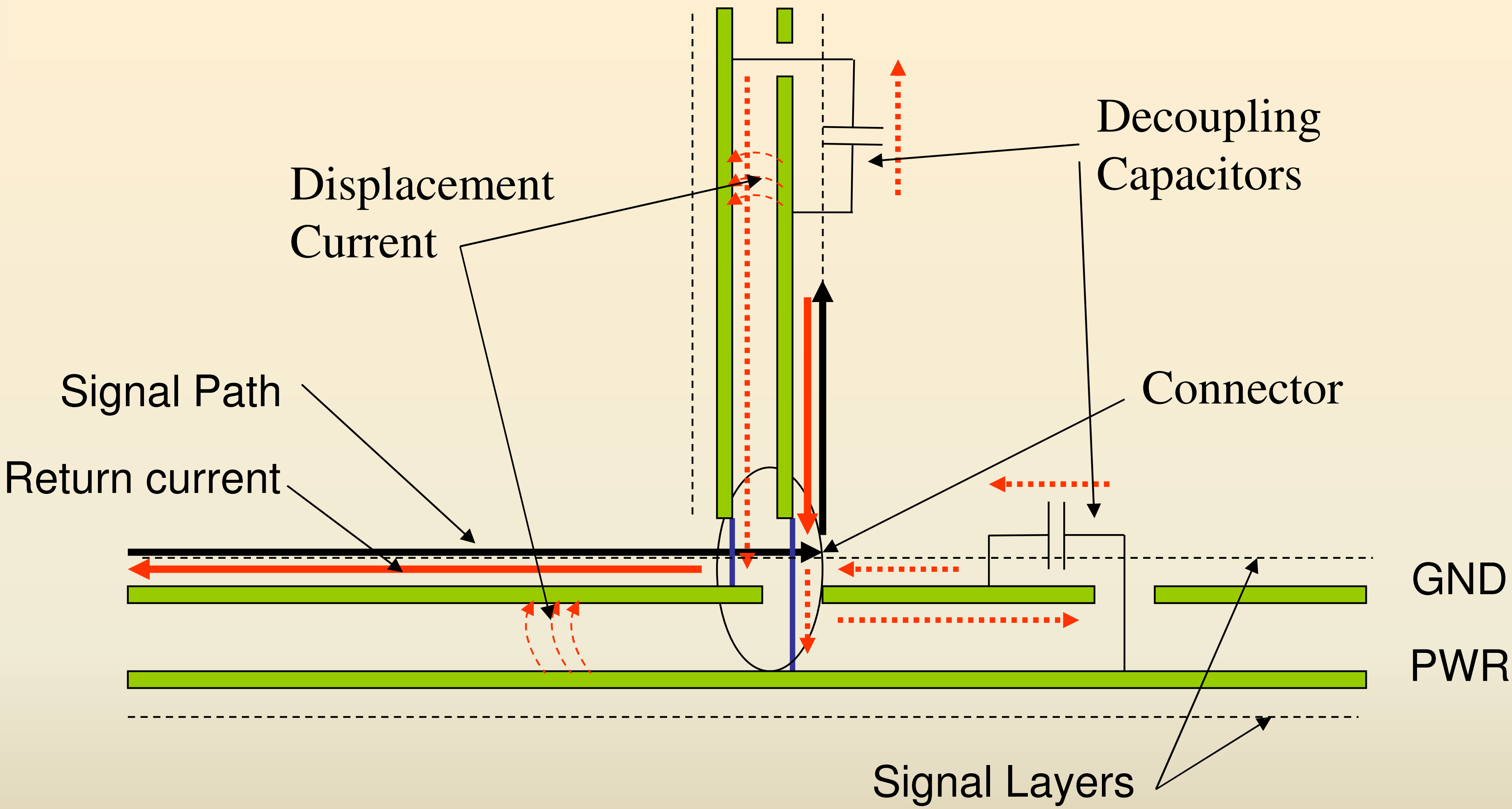
Mother/Daughter Board Connector Crossing

- Critical Signals must be referenced to same plane on both sides of the connector

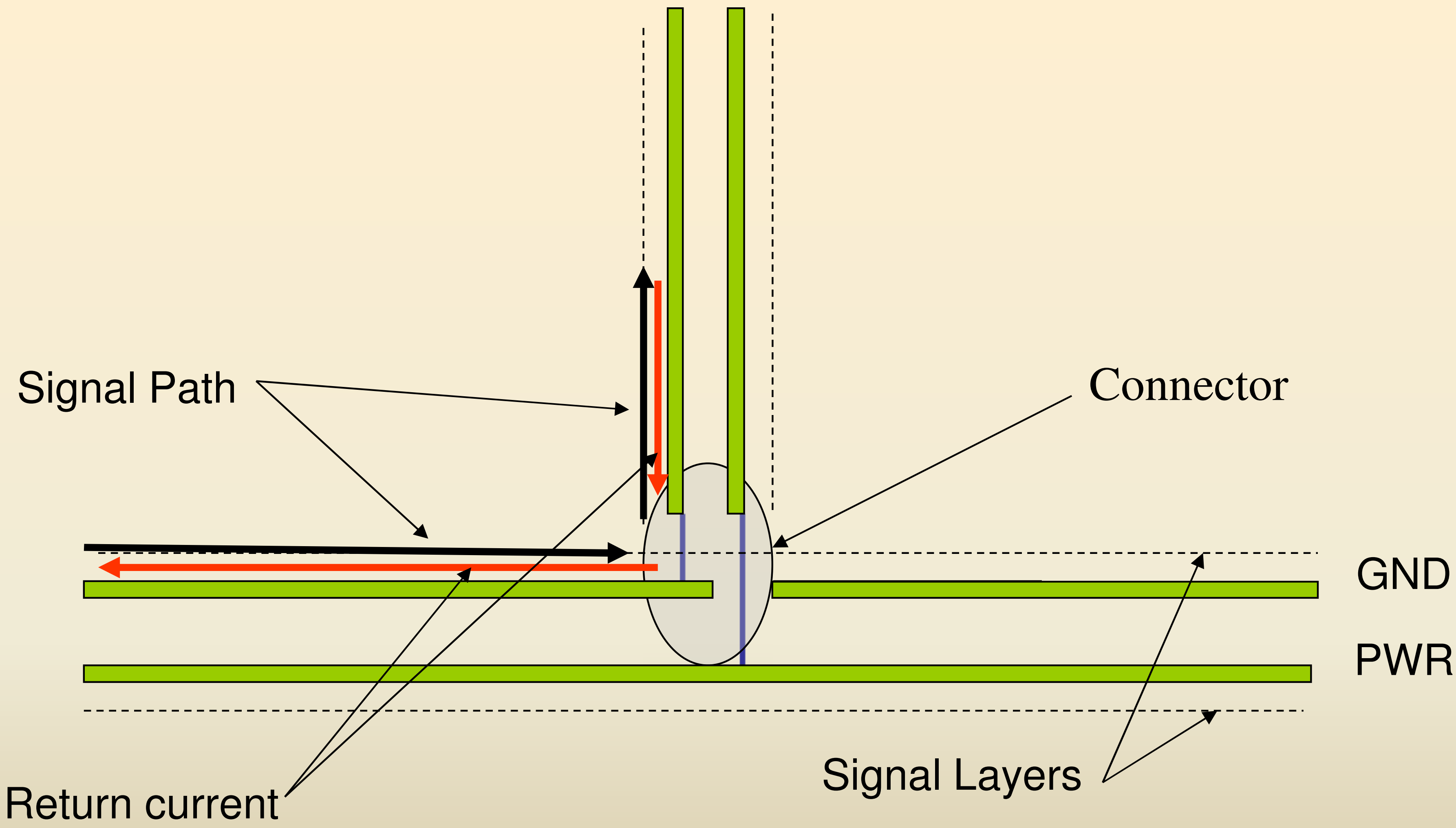
Mother/Daughter Board Connector Crossing



Return Current from Improper Referencing Across Connector



Return Current from Proper Referencing Across Connector



How Many “Ground” Pins Across Connector ???

- Nothing ***MAGICAL*** about “ground”
- Return current flow!
- Choose the number of power and “ground” pins based on the number of signal lines referenced to power or “ground” planes
- Insure signals are referenced against same planes on either side of connector

Summary

- Electromagnetics is not hard
  - Must get past the messy math
- Understanding what the basic equations mean is important
- ***CURRENT*** is important
- "Ground" is a place for potatoes and carrots!
- Where does the return current flow?
  - #1 cause of EMC related problems