## Lesson EPSI-05-01 Download pdf file here

# Course EPSI:
# Essential Principles of Signal Integrity

With Eric Bogatin,
Signal Integrity Evangelist, Teledyne LeCroy Front Range Signal Integrity Lab
Dean, Teledyne LeCroy Signal Integrity Academy
Adjunct Professor, University of Colorado, Boulder, ECEE

- EPSI-05-01: recorded live, Dec 1, 2013
  - Ground bounce and inductance
  - Download the pdf copy of the slides here



## Lesson EPSI-05-10 Recap of Signal Integrity Principles

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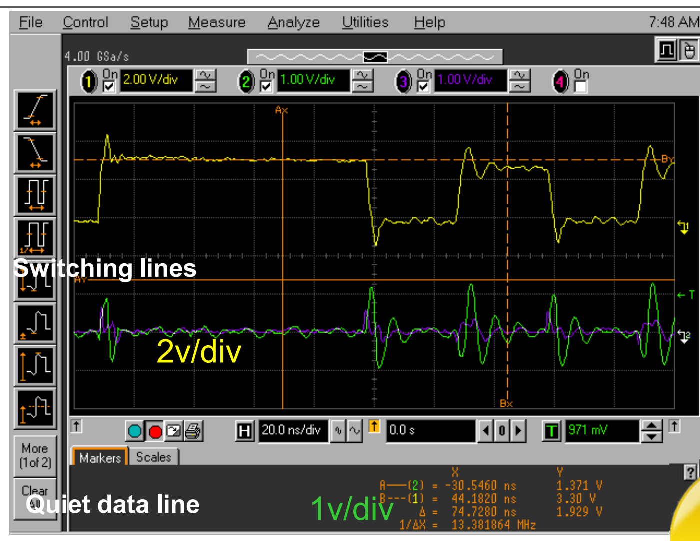
- EPSI-05-10: recorded live, Dec 1, 2013
  - Recap of the six families of signal integrity
  - The design methodology to eliminate signal integrity problems
  - The essential principles
  - The real root cause of ground bounce in packages

## Day 2

- Day 1
  - EPSI 1 Transmission Lines
  - EPSI 2 Differential Pairs and Lossy Lines
  - Lunch
  - EPSI 3 Reflections and Terminations
  - EPSI 4 Routing Topologies and Discontinuities
- Day 2
  - **EPSI 5 Eliminating Ground Bounce**
  - EPSI 6 Navigating Return Path Discontinuities
  - Lunch
  - EPSI 7 NEXT and FEXT Features
  - EPSI 8 PDN and EMI Design

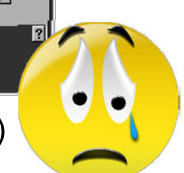


## The Problem: Ground Bounce




RPD:
Ground bounce happens anywhere
Switching noise happens near driver

Root cause: return path discontinuities (RPD)



## Lesson EPSI-05-20 Intro to ground bounce

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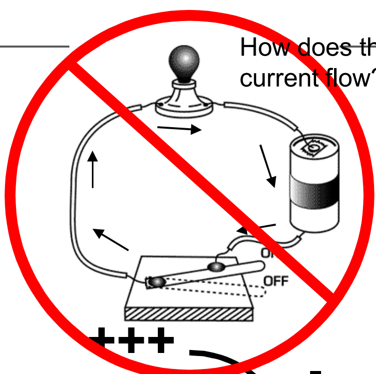
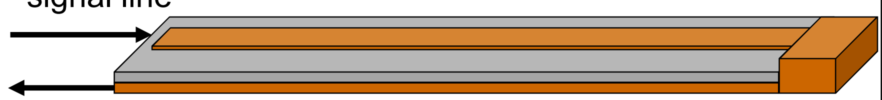
- EPSI-05-20: recorded live, Dec 1, 2013
  - How not to think about return current
  - When does return current come out the return path
  - Two important properties of return current
  - Where return current flows in a plane



## Return Current in T Lines

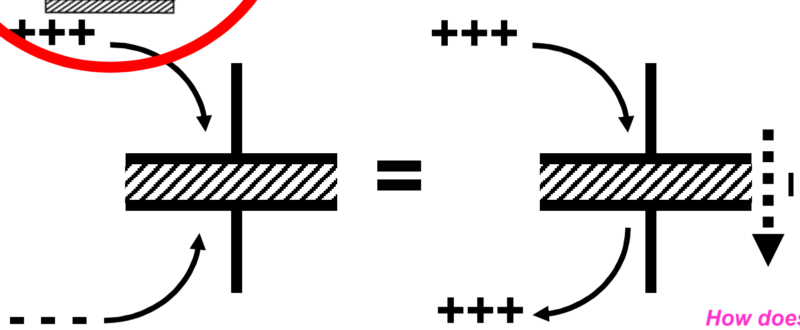



Current into signal line $I = \frac{V}{R} = \frac{1v}{50\Omega} = 20mA$



TD = 1 nsec

When does the return current return?

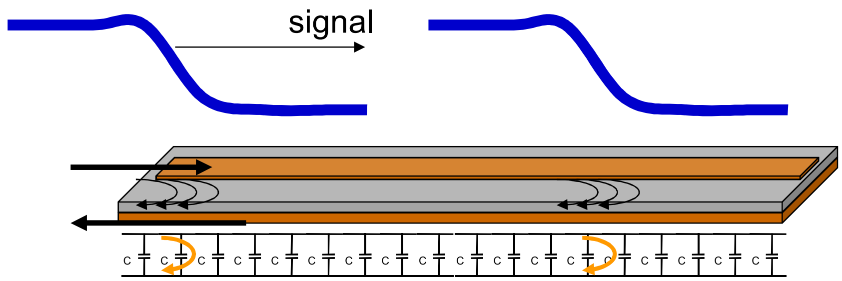



***Do actual + charges move through the insulating dielectric?***

"Displacement" current

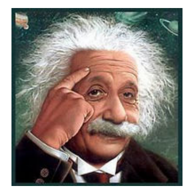
*How does current flow in transmission lines?*

## Essential Principle # 4: Current Propagates as a signal-return path loop wave front with a direction of propagation and a direction of circulation




***The current loop has two directions associated with it:***

1. ***A direction of propagation***
2. ***A direction of circulation***

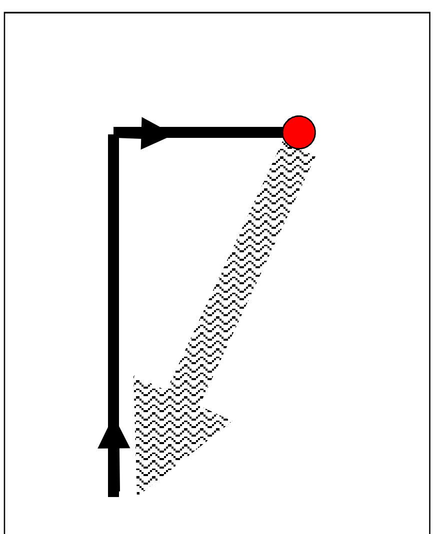


***They are independent!***



## Where Does the Return Current Travel in the Return Plane?

DC



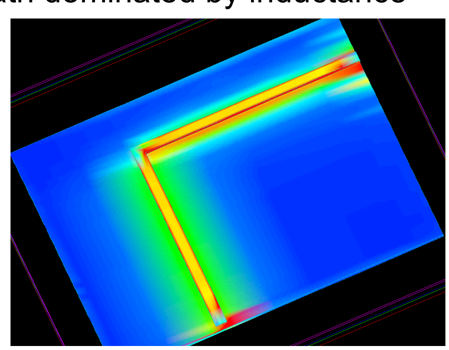
Current takes the path of lowest impedance

$$Z = R + i\omega L$$

Smaller the loop area, lower the inductance

@ > 1 MHz, $\omega L > R$, path dominated by inductance

f > ~ 1 MHz



## Lesson EPSI-05-30 Root cause of gnd bounce

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- EPSI-05-30: recorded live, Dec 1, 2013
  - Estimating the width of the return current
  - Inductance and a finite return path
  - Near and far end cross talk and finite return path
  - The two essential ingredients for ground bounce



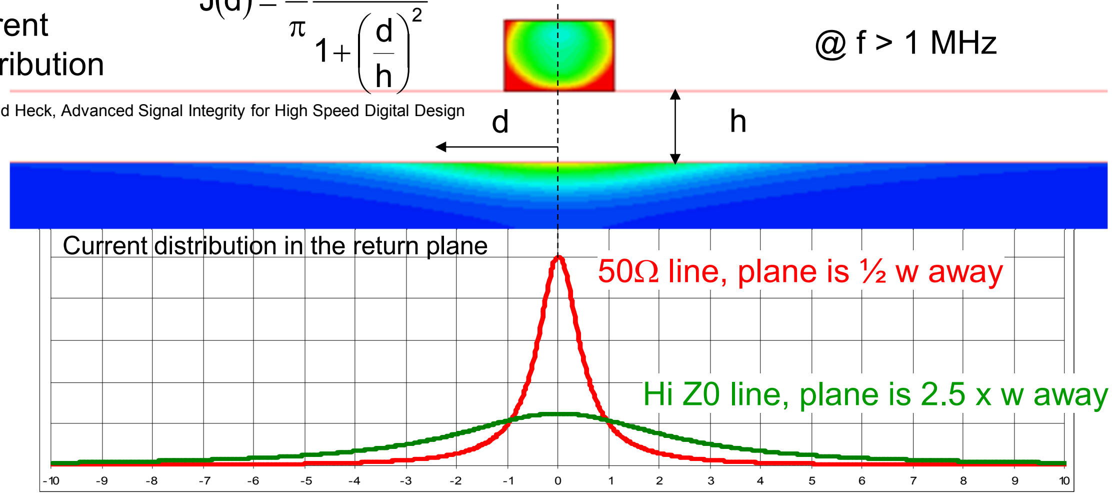
## Current Distribution in the Return Plane, Single-Ended Signal

Approximate current distribution

$$J(d) = \frac{1}{\pi}\frac{J_0}{1+\left(\frac{d}{h}\right)^2}$$

@ f > 1 MHz

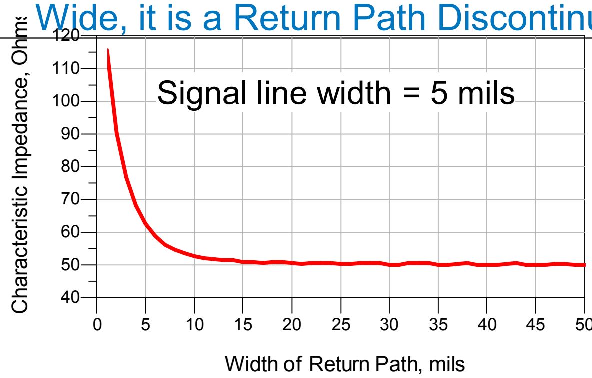
Hall and Heck, Advanced Signal Integrity for High Speed Digital Design

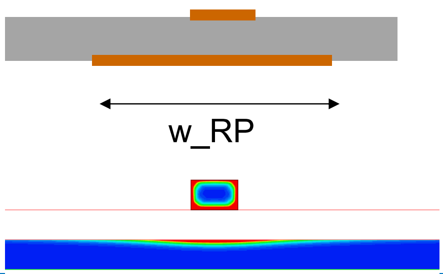



Distance, d, in units of w

*Return current spreads out ~ 3w (for 50 Ω line) under signal line: defines the RP.*

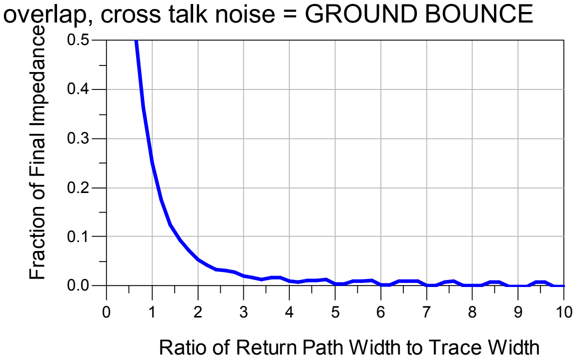
## If the Return Path is <u>ANYTHING</u> Other Than a Wide Conductor, > 3w Wide, it is a Return Path Discontinuity (RPD)



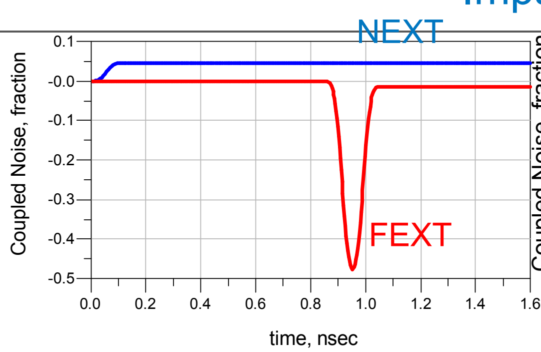

RPDs affect:

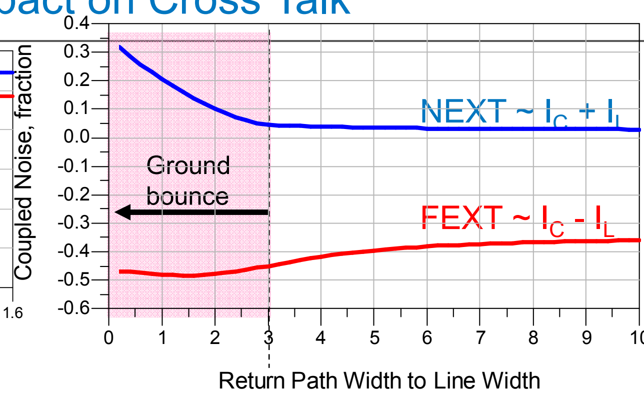
1. Single-ended Impedance of any line
2. Increased signal-return path loop inductance
3. Can contribute to higher mutual inductance to adjacent signal-return pairs
4. Special case: if the return currents of 2 signals overlap, cross talk noise = GROUND BOUNCE



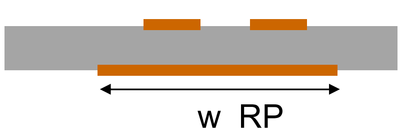



## Impact on Cross Talk




5 mil wide lines, 5 mil spacing




$I_C$ stays the same, but $I_L$ increases

- Ground bounce requires two special conditions
  1. <u>Screwed up return path</u> → higher total inductance in the return path
  2. Adjacent signals with <u>overlapping return currents</u> → dI/dt through higher L generates cross talk voltage

## Lesson EPSI-05-40 inductance and reducing ground bounce

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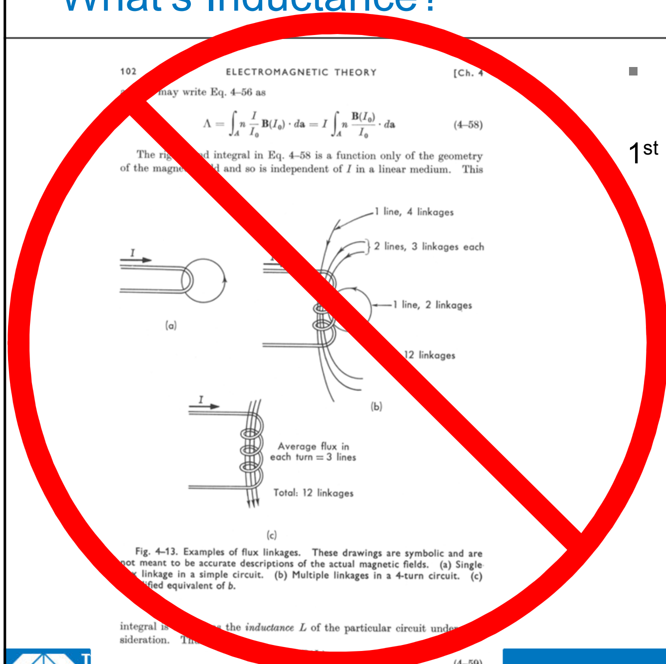
- EPSI-05-40: recorded live, Dec 1, 2013
  - How to reduce ground bounce based on its root cause
  - Everything you think you know about inductance is probably wrong
  - What really is inductance
  - The three most important design features to reduce loop inductance



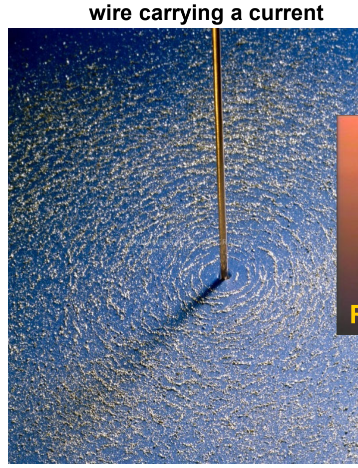
## What's Inductance?




- Deficiencies with text book definitions
  - Too mathematical to provide insight
  - Deals with coils, not traces on a board

1st step: rings of magnetic fields around currents

**wire carrying a current**



## Essential Principle #6: Inductance is fundamentally about how efficient a conductor is in generating rings of magnetic field lines.

***Definition of Inductance: Inductance is the number of rings of magnetic field lines around a conductor, per amp of current through it***

Units: Webers/amp = Henry
nH more common

Inductance is a measure of the efficiency of a conductor to create rings of magnetic field lines at the cost of current
- high inductance: lots of field lines per amp of current

3 ways of engineering lower inductance:

1. Wider conductors: more current spreads out, fewer field lines/amp
2. Shorter conductors: shorter the length, fewer field lines/amp
3. Bring return current closer to signal current: mutual field lines cancel out self field lines

*Important consequence: Planes have the LOWEST total inductance- anything else will have higher inductance*



## Lesson EPSI-05-50 the total inductance of the return path

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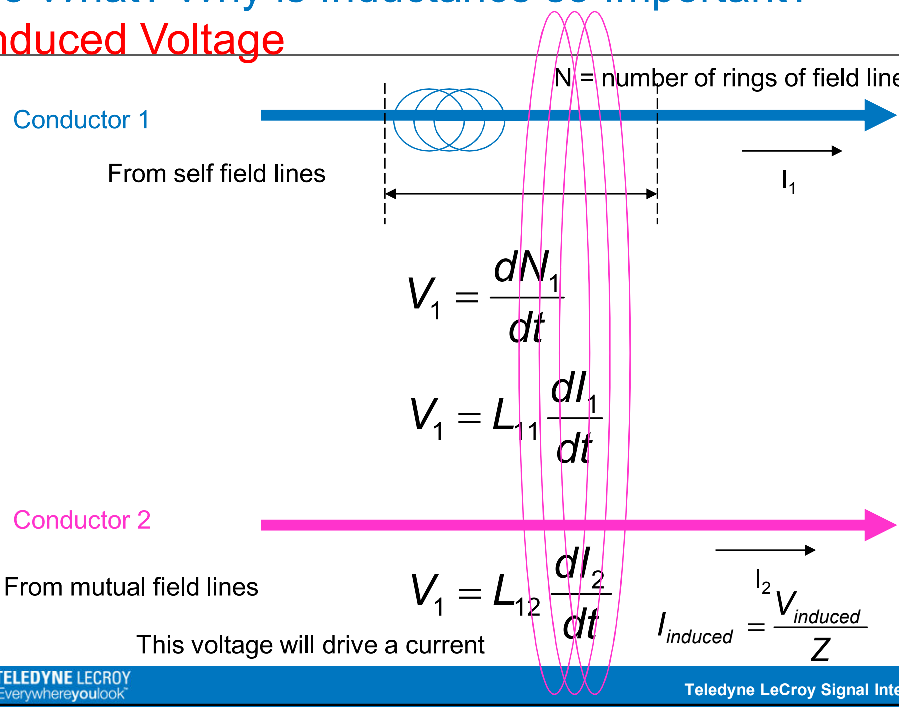
- EPSI-05-50: recorded live, Dec 1, 2013
  - Why inductance is so important: induced voltage and changing current
  - Inductively coupled cross talk
  - The total inductance of the return path: self and mutual inductance
  - Ground bounce and the inductance of the return path

## So What? Why is Inductance so Important?

## Induced Voltage




Self field lines

$$N_1 = L_{11} I_1$$

$$V_1 = \frac{dN_1}{dt}$$

$$V_1 = L_{11}\frac{dI_1}{dt}$$

Mutual field lines

$$N_1 = L_{12} I_2$$

From mutual field lines

$$V_1 = L_{12}\frac{dI_2}{dt}$$

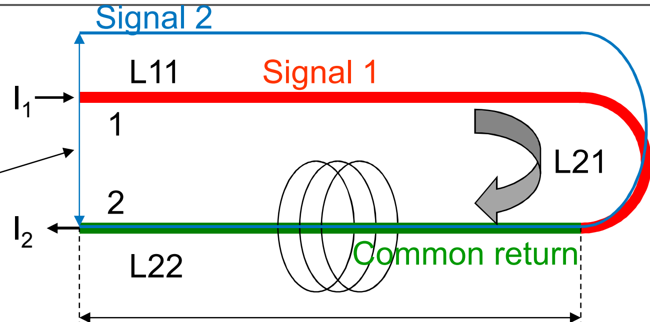
This voltage will drive a current

$$I_{induced} = \frac{V_{induced}}{Z}$$



## A Simple Model for Ground Bounce Voltage

Voltage across signal 2 has ground bounce voltage in series with it - crosstalk




$I_1 = I_2$

$$N_{total} = L_{22} I_2 - L_{21} I_1$$

$$V_{gndBounce} = \frac{dN_{total}}{dt}$$

$$V_{gndBounce} = (L_{22} - L_{21})\frac{dI_1}{dt} = L_{total}\frac{dI_1}{dt}$$

Ground bounce noise related to total inductance of RP

Three geometry design features will reduce total inductance of RP:

1. ***Shorter return path length (CSP)***
2. ***Wider return path conductor- spread current out (multilayer BGA)***
3. ***More mutual field lines from signal path: bring them closer (lower impedance)***

## Lesson EPSI-05-60 estimating gnd bounce

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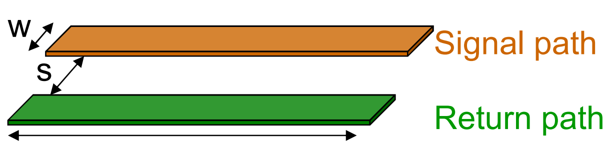
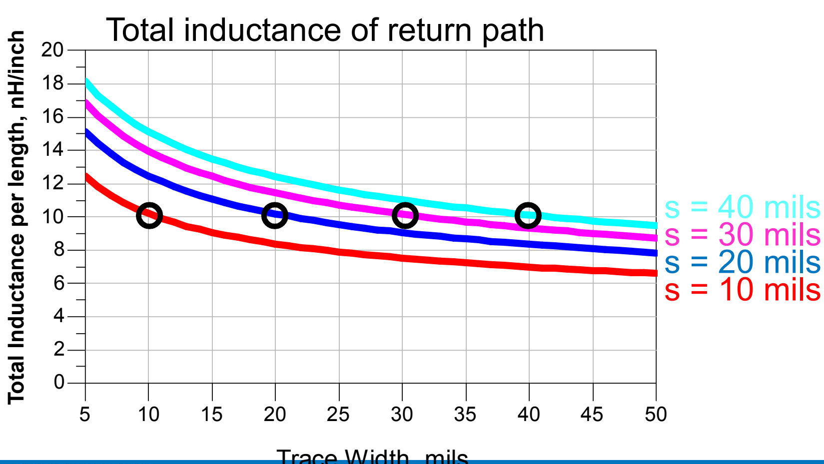
- EPSI-05-60: recorded live, Dec 1, 2013
  - Total inductance of the return path
  - A simple rule of thumb for the total inductance of the return path
  - Estimating ground bounce
  - Ground bounce in packages and connectors



## Calculating Total Inductance of the Return Path is Hard!




**"if all you have is a hammer, everything looks like a nail"**

For w = s
$L_{total}$ ~ 10 nH/inch x Len

## Estimating Ground Bounce Noise

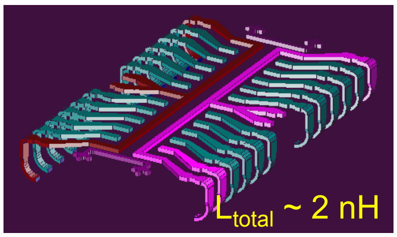
$$V_{gnd} = L_{total} n \frac{dI}{dt}$$

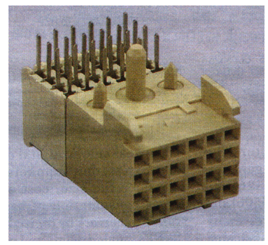
$$\frac{dI}{dt} = \frac{V_{sig}}{Z_0 RT}$$

$$\frac{V_{gnd}}{V_{sig}} = \frac{L_{total} n}{Z_0 RT} = 2\% \text{ x } \frac{L_{total}[nH] \text{ x } n}{RT[n\sec]}$$

$L_{total}$[nH] = total inductance of return path
n = number of simultaneous signals switching
RT[nsec] = 10-90 rise time of signal current

$L_{total}$ ~ 10 nH/inch x Len



$L_{total}$ ~ 5 nH

Example: n = 3, RT = 0.5 nsec
gb noise ~ 2% x 2 x 3 / 0.5 = 24%

Example: n = 2, RT = 1 nsec
gb noise ~ 2% x 5 x 2 / 1 = 20%

***Do you wonder why ground bounce is so common in packages and connectors?***



## Lesson EPSI-05-70 measuring ground bounce

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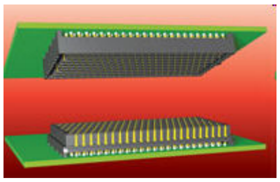
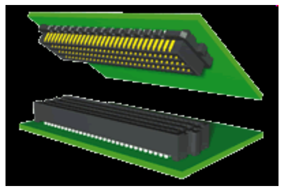
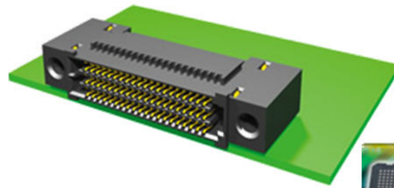
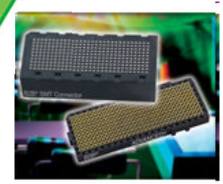
- EPSI-05-70: recorded live, Dec 1, 2013
  - Example of ground bounce in a package
  - Return path in the package
  - Ground bounce signature in a circuit
  - Reflections and the impact on ground bounce

## Open Pin Field Connectors:

How many signals can share the same return pin?


$$\frac{V_{gnd}}{V_{sig}} = 2\% \text{ x } \frac{L_{total}[nH] \text{ x } n}{RT[n\,sec]}$$

$$n = noise\% \frac{Z_0 RT[n\,sec]}{L_{total}[nH]}$$

If noise% = 15%, $Z_0$ = 50 Ohms

Len = 0.1 inch, $L_{total}$ ~ 1 nH, RT = 1 nsec

$$n = 0.15 \text{ x } \frac{50 \text{ x } 1}{1} = 7.5 \sim 7$$

Len = 0.25 inch, $L_{total}$ ~ 2.5 nH, RT = 0.5 nsec

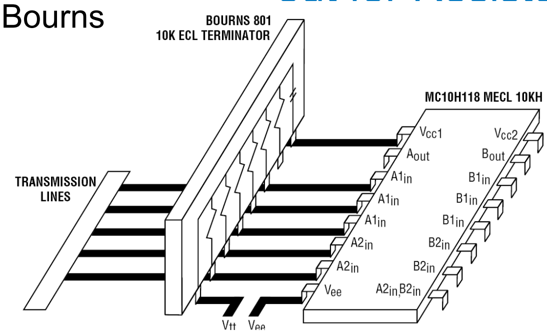
$$n = 0.15 \text{ x } \frac{50 \text{ x } 0.5}{2.5} = 1.5 \sim 1$$



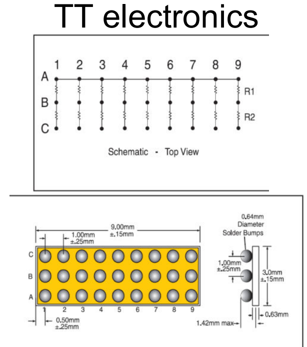
## Return Bounce in Resistor Networks: watch out for Resistor SIPS

Return Bounce in Resistor Networks: watch out for Resistor SIPS

Bourns

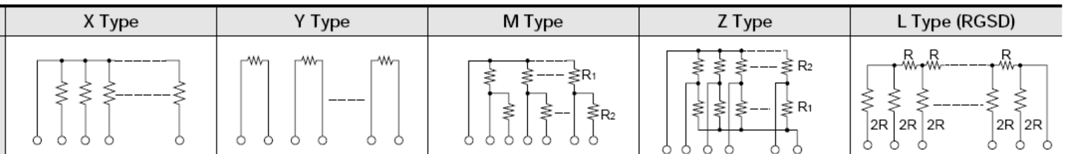



TT electronics



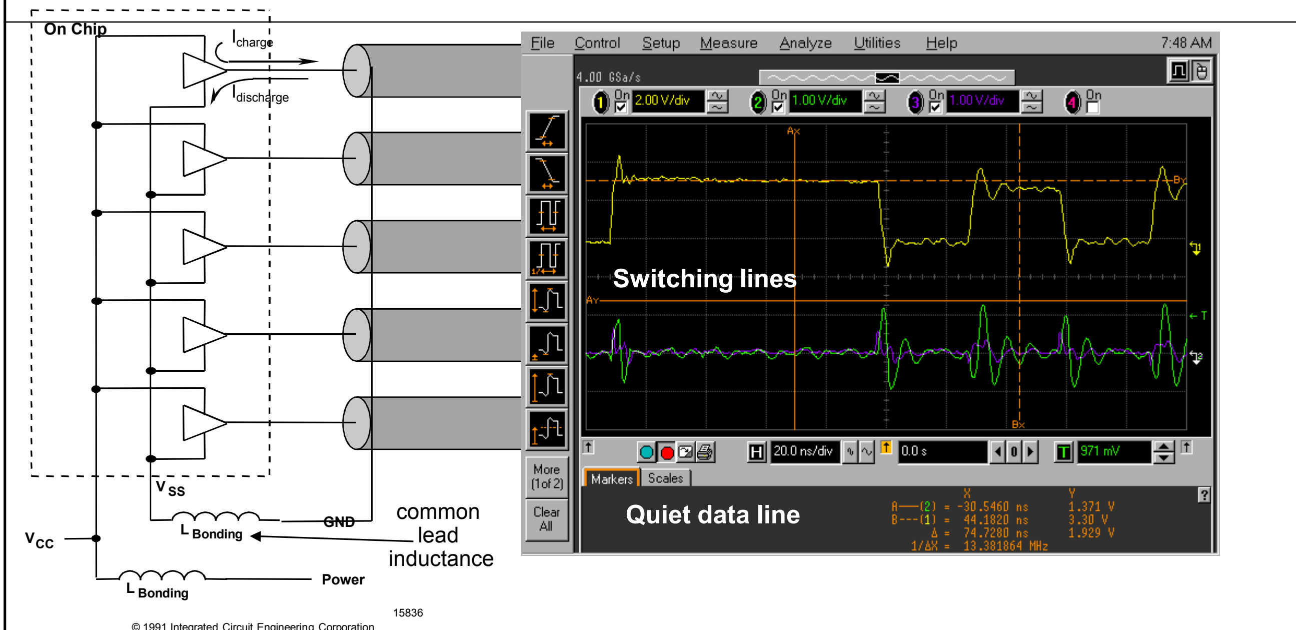

Standard Circuits

| Type Code | X Type | Y Type | M Type | Z Type | L Type (RGSD) |
|---|---|---|---|---|---|
| Circuit | | | | | |




muRata

## How Ground Bounce Causes Bit Errors






## Lesson EPSI-05-80 simulating gnd bounce

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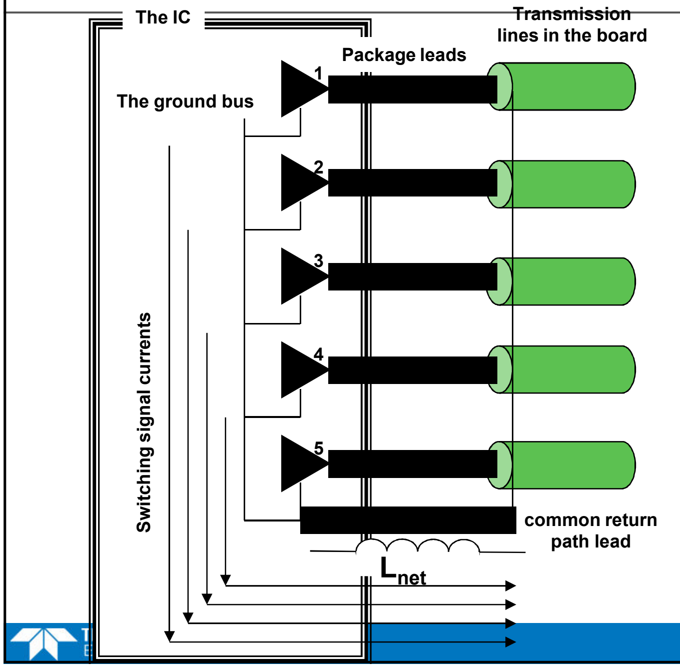
- EPSI-05-80: recorded live, Dec 1, 2013
  - Translating real features into a simple simulation
  - Impact of source termination on transient current
  - Comparing the simulated ground bounce voltage and measured
  - Using the simulation to explore design features to reduce ground bounce

## Differential Driving Will Reduce Ground Bounce




If 1 and 2 switch in the same direction, what is the current through the common return path lead?

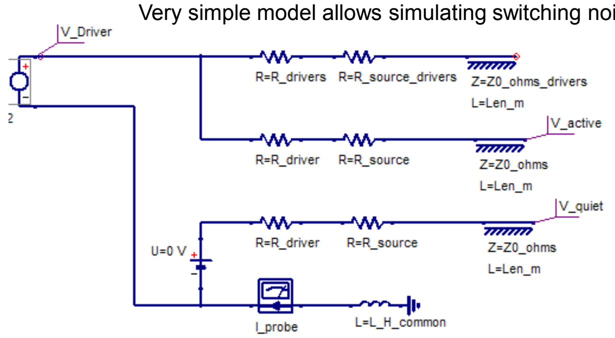
If 1 and 2 switch in the opposite direction, what is the current through the common return path lead?

*Differential signaling can significantly reduce ground bounce if the return currents overlap*

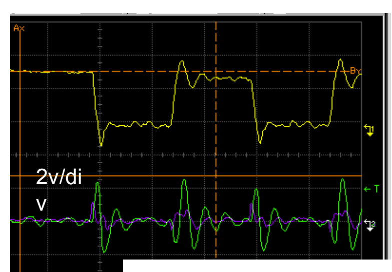


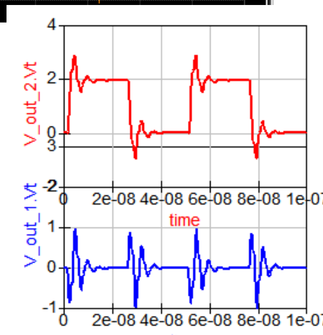
## Simplest Ground Bounce Circuit Using SPICE or QUCS

Very simple model allows simulating switching noise



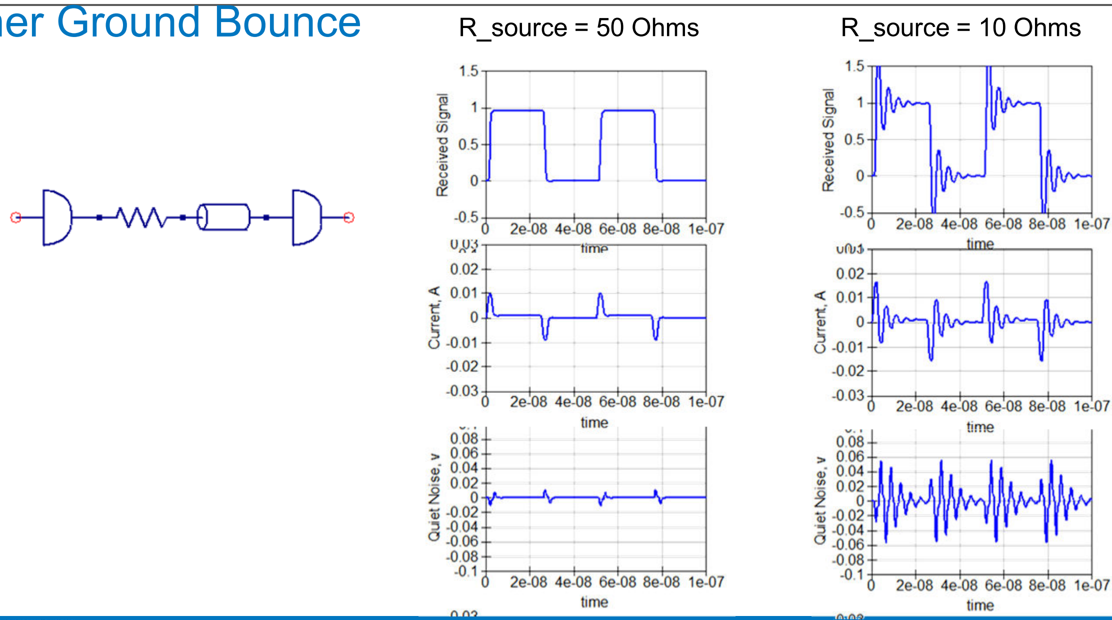

Data line




RT = 1 nsec
L_comm = 4 nH
n = 4 switching
TD = 1.1 nsec
R_source = 20 Ohms

## Poor Termination Means Higher dI/dt in Return Current and Higher Ground Bounce






## Design Guidelines to Reduce Ground Bounce When Due to Constricted RPD

$$V_{gnd} = L_{total} n \frac{dI_{return\ current}}{dt}$$

- $L_{total}$: Reduce total inductance of return conductors
  - Short return conductors
  - Wide return conductors
  - Signals close to returns
  - For power/gnd paths: use planes, with thin dielectric
- n: Reduce number of switching signals sharing same return path
  - Don't share return paths- each signal has its own return path
- dI, I: Reduce the return currents that overlap
  - Stagger I/O switching
  - Use source series termination series resistor (higher R, tradeoff noise/rise time)
  - Use differential signals
- dt: increase the rise time of the signal
  - Always use as long a rise time as possible consistent with timing budget
  - Slew rate control


Done!