# *ECEN 5224 High Speed Digital Design*

### *applying Maxwell's Equations to tame Signal Integrity problems*

Prof Eric Bogatin

Signal Integrity Evangelist

Teledyne LeCroy

www.beTheSignal.com

Spring 2014

Jan 2014

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# *Jan 13, 2014: Lecture 1*

- **Who am I**
- **What this class is about**
- **My approach to Signal Integrity**
- **Grading and assignments**
- **Resources**
- **Hands on Labs**
- **Starting out: re-thinking signals**
- **Lab #1**

# Eric Bogatin
# (eric@beTheSignal.com)

- Education
  - ✓ SB, Physics, MIT; MS, PhD, Physics, Univ of AZ, Tucson
- Industry experience: R&D, prod development, mfg research
  - ✓ Large companies: Bell Labs, Sun Micro, Raychem
  - ✓ Small companies: Silicon Light, Xinix, IDI, Ansoft
- My Own company: Bogatin Enterprises
  - ✓ Teaching SI classes, world wide for 25 years
  - ✓ Writing columns, articles, white papers, books
  - ✓ Lecturing
  - ✓ Acquired by Teledyne LeCroy in 2011
- Now
  - ✓ Product development on scope applications
  - ✓ Teach at CU, Boulder
  - ✓ Lecture
  - ✓ Write textbooks, articles
  - ✓ Columnist, journalist for EE Times, EDN

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# All High-Speed Products Have One Thing in Common

TX ➤➤➤➤➤➤➤➤➤➤➤➤ RX
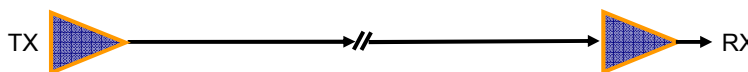
Transmit a signal from one TX to a RX, with acceptable quality

Driver   Package   Board   Backplane   Board   Package   Receiver
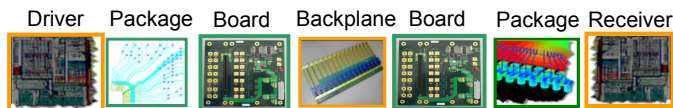


But interconnects are not transparent!     What can go wrong?
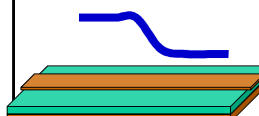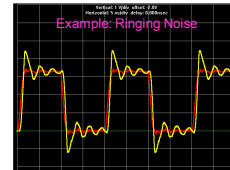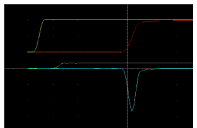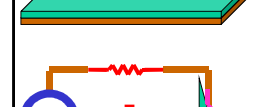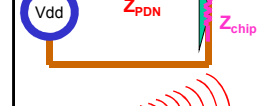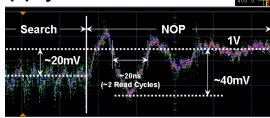
| | |
|---|---|
| Attenuation | Ringing |
| Non-monotonic edges | Dispersion |
| Skin depth | Loaded lines |
| Inductance | Ground bounce |
| Emissions | Cross talk |
| Terminations | NEXT |
| Via stubs | FEXT |
| Decoupling capacitors | Gaps in return path |
| Losses | Data clock skew |
| Surface roughness | Jitter |
| Dissipation factor | Changing reference planes |
| Skew | Stub lengths |
| Overshoot | Branch topology |

# Why Interconnects are Not Transparent:
## The Six Families of Signal Integrity Problems

1. Reflection noise

2. Cross talk

3. Ground (and power) bounce

4. Losses (@ Gbps)

5. Rail collapse, voltage droop, power supply noise

6. EMI

$Z_{PDN}$   $Z_{chip}$   Vdd

Example: Ringing Noise

Switching lines   2v/div   1v/div   Quiet data line

FR4 loss, after 12 inches

Search   NOP   1V   ~20mV   ~20ns (~2 Read Cycles)   ~40mV

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# An Efficient Design Methodology to Eliminate Problems Before the Design is Released

• An efficient methodology:

✓ Identify the SI problems    *understand the "essential principles"*

✓ Find the root cause

⬇ *Apply the "Youngman" principle*

✓ Establish practical design guidelines to minimize them

✓ If it's "free" always follow the "habits"

✓ Use analysis tools to evaluate cost-performance tradeoffs as early in the design process as possible

"If your arm hurts when you raise it, don't raise your arm."

"If problem A happens <u>because</u> your design has feature B,

then eliminate feature B from your design"

Identify the root cause of a problem and fix the root cause
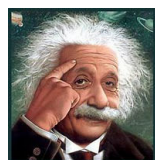
*"Are you sure about this Stan? It seems odd that a pointy head and a long beak is what makes them fly"*

# *Two World Views for Signals and Interconnects*

**Circuit elements
and sources:**

**George Simon
Ohm (1789-1854)**

**Electromagnetic Fields
and Boundary Conditions**
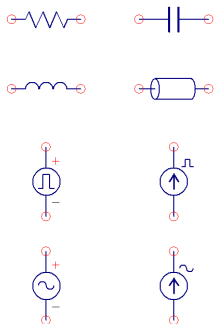
**James Clerk
Maxwell
(1831-1879)**



Electromagnetic Wave

λ

■ Magnetic field
■ Electric field
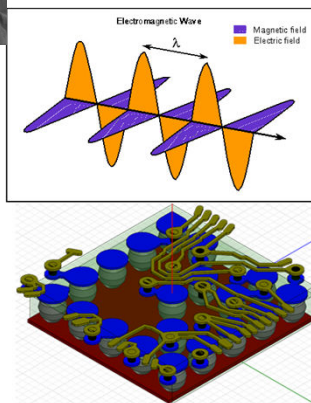
**Courtesy of Ansys**

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# *Two Different Approaches:  Similar Diff Eqs, Similar Behavior (in most cases)*

- A signal is a voltage or current
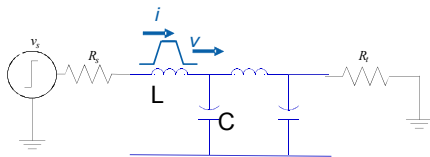
- A signal is a propagating electromagnetic wave



$v_x$   $R_s$   $i$   $v$   $L$   $C$   $R_t$
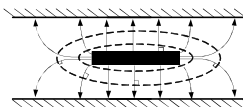
——— Electric field （E）

- - - Magnetic field （H）

<u>Lumped Circuit Elements</u>                          <u>Field quantity</u>

$$i(t) = C\frac{d\,v(t)}{d\,t}$$

$$\vec{a}_x\left(-\frac{\partial H_y}{\partial z} = \varepsilon\frac{\partial E_x}{\partial t}\right)$$

$$v(t) = -L\frac{di(t)}{dt}$$

$$\vec{a}_y\left(\frac{\partial E_x}{\partial z} = -\mu\frac{\partial H_y}{\partial t}\right)$$

*Similar differential equations, ....but with some differences*

*2 important "cheats" expand the use of lumped circuit elements*

### *The Real World Seems to be Based on Electromagnetic Fields and Boundary Conditions*

- Why not just ALWAYS just solve Maxwell's Equations to get to the answer?

  - ✓ Sometimes problems are really hard to solve using Maxwell's Equations

  - ✓ Sometimes it's difficult to gain physical insight from the equations

  - ✓ Sometimes there are no good analytical approximations and it requires complex numerical simulation- lots of time, expertise and $$ to get to an answer

  - ✓ "Sometimes an OK answer NOW! is more important than a good answer late."

  - ✓ Where it is OK, we will approximate the real world of fields and materials with circuit elements.

  - ✓ We have to watch out for when this is not ok.

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### *When Do We Need Maxwell's Equations?*
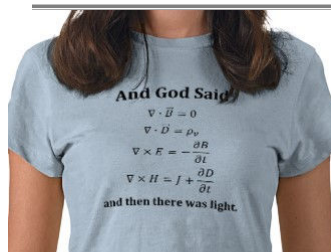


- When there is spatial variation in E, H field

- When there are propagating EM fields

- When modes are important

- Typically when Len > ~ $1/10^{th}$ $\lambda$

# *My Expectations for You After this Class*

- Have a solid engineering intuition about the behaviors of signals on interconnects
- Apply the principles of Maxwell's equations, without much of the equations
    - ✓ Understand the essential principles
- Skilled at "putting in the numbers"
    - ✓ "Engineering is Geek for Tradeoff Analysis" - Bruce Archambeault
    - ✓ Start with the simplest approach and build up complexity
    - ✓ Rules of thumb
    - ✓ Analytical approximations
    - ✓ Numerical simulation: circuit simulation, field solvers
- Able to analyze the results- answer the "so what?" question
    - ✓ Always apply rule #9
    - ✓ Apply analysis to real world problems
    - ✓ Turn information into action (answer the ..so what? Question)
- Experience leveraging commercially available measurement and simulation tools once we know what to expect
- Get in the habit of Questioning authority: become your own expert

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# *Bogatin's 10 Rules*
## *(PCD&F Magazine, Aug 10 , 2010*
## *or www.beTheSignal.com, BTS218))*

1. Answer "it depends" questions by "putting in the numbers"
2. Separate myth from reality by "putting in the numbers"
3. Watch out for the whack-a-mole effect
4. Most important step in solving a problem: find the root cause
5. Apply the Youngman Principle to optimize designs
6. Sometimes an OK answer now! is better than a good answer late
7. Evaluate "bang for the buck" with virtual prototypes
8. Watch out for mink holes
9. ***Never perform a measurement or simulation without first anticipating what you expect to see***
10. There are two kinds of designers: those who have signal integrity problems and those who will

### Rule #9: Never do a measurement or simulation without first anticipating what you expect to see.

If you are wrong, there is a reason- either the set up is wrong or your intuition is wrong. Either way, by exploring the difference, you will learn something

If you are right, you get a nice warm feeling that you understand what is going on.

### Corollary to rule #9:

There are so many ways of screwing up a measurement or simulation, you can never do too many consistency checks

## *Schedule*

1.  Jan 13:    Welcome and intro
2.  Jan 20  holiday (chpt 1, 2, 3)
3.  Jan 27:    Transmission lines and signals (chpt 7)
4.  Feb 3:     Reflections and circuit simulations (chpt 8)
5.  Feb 10:    Discontinuities (chpt 5, 6)
6.  Feb 17:    Differential pairs (chpt 11)
7.  Feb 24:    S-parameters and the TDR (chpt 2, 12)
8.  Mar 3:     Attenuation and loss (chpt 9)
9.  Mar 10:    High speed serial links (chpt 9, 11, 12) (mid term take home)
10. Mar 17:    High speed scope measurements and jitter analysis
11. Mar 24: spring break
12. Mar 31    Cross talk (chpt 10)
13. April 7:    Ground bounce (chpt 6)
14. April 14:    PDN (chpt 4, 6, 13)
15. April 21:    Special topics
16. April 28    Class presentations (invited guests)
17. May 5:     final

Textbook for the class

**Signal and Power Integrity**
**SIMPLIFIED**
Second Edition

Eric Bogatin

Prentice Hall Modern Semiconductor Design Series
Prentice Hall Signal Integrity Library
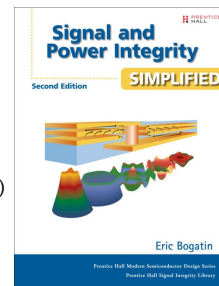
# *Special Saturday Sessions with Tim*

- 1:30pm on Saturdays in ECCR 108 engineering class rooms off from the café in ECOT lobby

- Lecture review

- Some more advanced content

- Some lab reviews

- Additional Q&A

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# *Grading*
## *> 90% A, 80-89% B, 70-79% C*
## *(undergraduates, get an extra +5 points handicap)*

- Weekly quizzes (25 points)
  - ✓ 13 lectures
  - ✓ Top 10 scores count
- Homework (labs) (25 points)
  - ✓ Top 10 scores count
- Midterm and final (25 points)
  - ✓ Midterm is take home (10 points)
  - ✓ Final is in class (15 points)
- Projects (25 points) (teams of up to 3 are ok)
  - ✓ Send me an email (5 points) (individuals only!)
  - ✓ How good are approximations or rules of thumb (10 points)
  - ✓ Establish a design guideline with a field solver or circuit simulator (10 points)
- Extra credit
  - ✓ Be the first to find the error in my textbook (+1 point)
  - ✓ 5 min presentation: SI in the news, on the web, "they are wrong" (+1 point)
  - ✓ Class presentation on last day (+3 points)

## *Projects (10 points each)*
## *can work in teams of up to 3*

1. Send me an email (eric@beTheSignal.com) (5 points) (due before the next class)
   - ✓ What EE classes have you taken? Most favorite and why
   - ✓ What are your education goals?
   - ✓ What are your plans for after school?
   - ✓ Why you are taking this class?
   - ✓ (A free 5 points)

2. How good are Rules of Thumb or approximations? (due on 3/10/2014)
   - ✓ Pick an example
   - ✓ Compare it to a numerical simulation tool
   - ✓ Establish when it applies, when it doesn't, roughly what accuracy
   - ✓ See my Rules of Thumb column for EDN
   - ✓ Write a report: 1200 words, 5 figures (like a feature article)

3. Establish a design guideline with a field solver or circuit simulator (due on 4/21/2014)
   - ✓ Pick a structure like a transmission line, a via, a signal over a gap
   - ✓ Identify the sort of SI problems to expect
   - ✓ Parameterize it and model it with a simulation tool
   - ✓ Determine a set of parameters for good signal integrity, and when problems will arise
   - ✓ Generate examples of good designs, bad designs
   - ✓ Write a report: 1200 words, 5 figures (like a feature article)

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# *Homework: Hands On Labs*

- Free tools:
  - ✓ QUCS
  - ✓ Teledyne LeCroy Si Studio (free version)
  - ✓ Teledyne LeCroy Reflection simulator
  - ✓ Sonnet Lite
  - ✓ Quick Field student version
  - ✓ Simbeor level 1
- Polar SI 9000 (license until end of Feb, can be extended)
- Mentor HyperLynx (CU license)
- Teledyne LeCroy Si Studio (licensed version, from me)
- Matlab
- Ansys HFSS
- Agilent ADS
- Agilent PLTS

*Special note: if you are enrolled in ECEN 4224/ 5224 and you are using a software tool licensed through this class, you CAN NOT use this tool for commercial use. These can only be used for class assignments.*

# *Resources*

**Signal and Power Integrity**

**SIMPLIFIED**

Second Edition

Eric Bogatin

Prentice Hall Modern Semiconductor Design Series
Prentice Hall Signal Integrity Library

**Published by Prentice Hall, 2009**
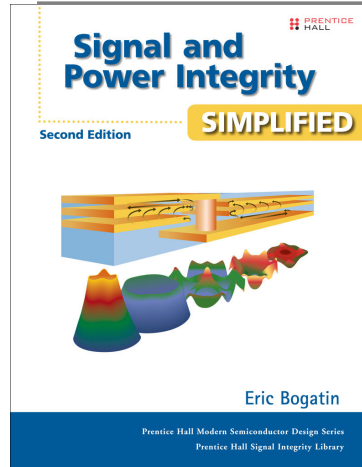
- www.beTheSignal.com
- Check the web site for:
  - ✓ More details
  - ✓ Assignments
  - ✓ Resource materials
- My EDN, EE Times columns

**@beTheSignal**

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# *Special Notes*

1. I will usually be in the room at 5:15 pm before class if you want to chat
   1. Use the Doctor Is In feature on beTheSignal.com for technical questions
   2. Use Tim's review sessions for technical questions
2. Typical class schedule:
   1. Sign up on the white board before class if you want 5 min to present after the quiz
   2. We will start on time at 6 pm
   3. There will be a pop quiz. If you miss it, you miss it.
   4. We will collect homework
   5. Up to 3, 5-min presentations on what's new, resources on the web, "they were wrong"
   6. 2, 45 min lectures with break
   7. Review of the new labs and homework assignments
3. Lecture notes and labs will be posted on beTheSignal.com
4. See me:
   1. If you don't have your own PC laptop to run the software,
   2. If you want suggestions for projects,
   3. If you have an interest in working on SI related projects outside of class,
   4. If you are looking for a job in this field when you graduate

# *Pop Quiz*
# *( a free 2.5 points)*

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## *Homework Assignment #1, due Jan 27, 2014*

- QUCS
- Polar Instruments SI9000


1. Install the tools
2. Get familiar with them
3. Download a few QUCS circuits
4. Run the exercises
5. Write the report

### *Remember rule #9*

# *Lab Report*

- No more than 1 page

- Pick one or two of the exercises

- Answer the following questions

  - ✓ What did you do?

  - ✓ Did you learn anything new? Did anything surprise you?

  - ✓ So what? Do you see any way what you learned could be applied to guide a design, influence a decision or even suggest another thing to try as a consistency test?

- My hidden agenda

  - ✓ I often find, the process of writing up what you did in an experiment helps you think through what you learned, what would have been a good test to try to check for consistency and fit the puzzle pieces together.

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# *QUCS Lab Exercises 1*

## *Remember rule #9*

- Signals and bandwidth

  - ✓ What is the BW of a signal with 1 nsec rise time?

  - ✓ What is the BW of a signal with a 0.8 nsec rise time?

  - ✓ What is the accuracy of the BW?

  - ✓ What happens to the BW of a signal if the clock frequency increases?

- Impedance analyzer in the frequency domain

  - ✓ Verify you can extract the RLC values from a simple RLC circuit

  - ✓ How well does the analytical solution for the SRF match the simulation?

  - ✓ Compare the input impedance of a transmission line open at the far end and shorted at the far end with an L or C model, with an LC model. Why don't they match?

  - ✓ Add a resistor at the end of the transmission line. What does the input impedance look like as you change R?

University of Colorado **Boulder**    ECEN 5224 High Speed Digital Design Prof Eric Bogatin www.beTheSignal.com