PCB Design in the GHz Age

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Overview

• Introduction: Faster / Hotter / Smaller
• Problems: Implications for PCB Design
• Now What? Advice for ...
  – Academia
  – Industry
  – Individuals
• Conclusion
IC Design Trends Affecting PCB Design

**IC Design**

- Increasing
  - Wafer Size
    - $\Rightarrow 30\text{cm}$
  - MOSFET Gate
    - $L << 1\mu m$

**PCB Design**

- **Electrical**
  - System on a Chip Complexity
  - Signal Speed, Edge Rate
  - Supply Voltage
  - Noise Margin

- **Thermal**
  - Power Dissipation

- **Mechanical**
  - Pin Count
  - Package Complexity
  - Contact Spacing

McNEILL: PCB Design in the GHz Age
# Microprocessor Evolution

<table>
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<tr>
<th>Vendor</th>
<th>µP</th>
<th>Year</th>
<th>Pins</th>
<th>Package</th>
<th>V</th>
<th>I [A]</th>
<th>Bus [MHz]</th>
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<td>500</td>
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Sources:
Brey, The Intel Microprocessors, Prentice Hall
2001 ISSCC Digest of Technical Papers, IEEE
Implications for PCB Design

• Faster Edge Rates
  ⇒ Transmission Line, Signal Integrity Issues

• Higher Current Requirements
  ⇒ Thermal, dl/dt Issues

• Increased Package Complexity
  ⇒ Mechanical, Manufacturability Issues

• Life Getting More Difficult Challenging Interesting
Power Requirements

• Large $dI/dt \Rightarrow$ Low inductance supply current paths
• $V, I$ extrapolate to $V=0, I=\infty$ in year 2010 ...

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Faster Edge Rates

- Transmission Line Effects
- Rise time x Propagation velocity < Trace length

\[ t_r = 2 \text{ ns} \]

\[ t_r = 200 \text{ ps} \]

5 cm
Reflection Example

- Clock Distribution Network
Reflection Example: $t_r \approx 10\text{ns}$

\[
(1.0E-8[\text{sec}]) \cdot (0.7 \cdot (3.0E+10[\text{cm/sec}])) = 210\text{cm} > 30\text{cm}
\]

Transmission line effects negligible
Reflection Example: \( t_r \approx 200\text{ps} \)

\[
\left(2.0 \times 10^{-10} \text{[sec]}\right) \cdot \left(0.7 \cdot \left(3.0 \times 10^{2} \text{[cm/sec]}\right)\right) = 4.2\text{cm} < 30\text{cm}
\]

- Transmission line reflection problems:
  - Multiple clocking
  - Confusion for multilevel signaling (e.g. Rambus®)
Crosstalk / Jitter

- "Digital" Logic, 0 or 1
  Implication: only level (high/low) is important, but...
- Edge (0 to 1 transition) also matters: time information!
- Effect of crosstalk = "jitter"

[Diagram showing "Victim" and "Aggressor" signals with crosstalk and jitter annotations.]
Crosstalk / Jitter Experimental Configuration

- Models poor layout of long run on backplane
- Note that even “low frequency” interfering signal can cause problems ...

![Diagram showing 1GHz and 10MHz signals with 60 cm separation](image-url)
Crosstalk / Jitter Example: Baseline

Baseline jitter (adjacent line inactive) = 1.5ps rms
Crosstalk / Jitter Example

Jitter with crosstalk (adjacent line active) = 8.6ps rms
Now What?

• **Education** (antidote to fear, superstition)

  Advice for …
  
  • Academia
    – Reach out to student needs where they are
  • Industry
    – Create culture to support education
  • Individuals
    – Honest self-reflection
One Problem in Academia: Students

• In GHz age, everyone is an analog designer
  – Never mind Karnaugh maps
  – Digital designers need awareness of E&M fields
• Problem:
  – Students don't know what they need to know
  – Professors must "sell" unglamorous but necessary material
• WPI motto
  – Old: "Lehr und Kunst" (Theory and Practice)
  – New: "Someday you'll thank us"
Other Problem in Academia: Professors

• Most professors are geniuses
  – The ones who understood everything the first time
  – "Pure beauty of Poisson's theorem"
  – The rest of us had no idea what was going on
• Present information, not motivation
  – Expect students to pay attention for material only
• Result: to get good grades, students memorize mathematical tools/techniques but miss meaning

For Example ...
Example

- Nondestructive test research
- Inject current into metallic sample
- Measure voltage distribution on surface
- My expected profile
Example

• Student's prediction
• Ripples "from the sine waves"
  – Tried to solve differential equation (Poisson's) with sine decomposition

**BUT:**
Sine waves aren’t really there!
Real Meaning of Poisson's Equation

- Poisson's equation
- 2-d (surface of sample)
- $\rho=0$ (no net charge)

$$\nabla^2 V = 0 \Rightarrow \frac{d^2 V}{dx^2} + \frac{d^2 V}{dy^2} = 0$$

- Discrete approximation of second derivative
  (Change in slope per $\Delta x$)

$$\frac{d^2 V}{dx^2} \approx \frac{\text{"UPPER" SLOPE}}{\Delta x} = \frac{V(x+\Delta x) - V(x)}{\Delta x} - \frac{\text{"LOWER" SLOPE}}{\Delta x} = \frac{V(x) - V(x-\Delta x)}{\Delta x}$$

$$\frac{d^2 V}{dx^2} \approx \frac{V(x+\Delta x) + V(x-\Delta x) - 2V(x)}{\Delta x^2}$$
Result

\[
\frac{V(x + \Delta, y) + V(x - \Delta, y) - 2V(x, y)}{\Delta^2} + \frac{V(x, y + \Delta) + V(x, y - \Delta) - 2V(x, y)}{\Delta^2} = 0
\]

\[
V(x, y) = \frac{V(x + \Delta, y) + V(x - \Delta, y) + V(x, y + \Delta) + V(x, y - \Delta)}{4}
\]

- V at any point is average of "nearest neighbor" voltages
- **Voltage varies smoothly**
  - Note: leads into finite element analysis!
Engineering Education Dilemma

• First: courses in mathematical tools
  – Prove truth, within a formal deductive system
  – Illusion of certainty

• Then: courses in engineering
  – Math is a description language for the world
  – Approximate description of reality

• Reality: World first, mathematical description second
Do you swear to tell the truth …

"The thought crossed my mind that in science the "truth" does not exist, since science does not prove but can only describe the ways of nature."

Science ≠ Truth

Do you swear to tell the truth …

"The thought crossed my mind that in science the "truth" does not exist, since science does not prove but can only describe the ways of nature.”

"I answered 'I do' anyway …”

Significance for Engineering

• FIRST: Qualitative insight into behavior
  “Voltage varies smoothly”
  – Need to guide design
  – Choose among options
• THEN: Quantitative statement of mathematical model
  Poisson’s Equation
  – Need to analyze
  – Compare performance to numerical specifications
• Must recognize limits of mathematical model
  NOT Math → Physical behavior
  Physical behavior first → Math
  – Many students get this turned around ...
Teaching E&M Fields

- Respond to need of engineering (not physics) students

- In GHz age, everyone needs to know E&M fields

- Problem: Surrounded by aura of mystery, magic, incomprehensibility

- Needs:
  1. Motivate students to take course in the first place
  2. Once in class, "demystify" fields
1. Motivating Students

• Old course description
  ‒ "Gauss' Law ... Ampere's Law ... Stokes' theorem ..."

• New course description
  ‒ Emphasis: signal integrity in digital systems
  ‒ Limit of lumped LC model: transmission line limiting propagation velocity, system speed, signal quality

  “Benefits not Features”
2. Demystifying Fields

• Electric field demonstration relatively easy
  – Rub a balloon on your sweater, stick it to a wall
  – See lightning, spark after shuffling across carpet
  – Opposite charges attract
  – E field tells you which way charges move (force acting on charge)

• Magnetic field
  – ???
  – Try a different way to look at things...

(Acknowledgment: Paul Brokaw, Analog Devices)
Cause and Effect: Ohm's Law

- Which is cause, which is effect?
- V cause, I effect?
- I cause, V effect?
Chemistry vs. Electrical Engineering

\[ 2H_2 + O_2 \rightarrow 2H_2O \quad \quad V=IR \]

Cause                      Effect

- No arrow!
- V, I just "go together"
- View either as cause, effect
- Whatever is best for your purpose
You're the cause

V, I go together - Resistor doesn't care
What causes magnetic field?

• Usual answer: current
  – Usually introduced in terms of current in a wire creating an associated magnetic field
  – Physics (force-based) approach

• Think about it another way ...
  – Better way for circuit designers
  – What effect is field describing?

• Look at capacitance, inductance
Capacitance

- Represents energy stored in electric field
- Capacitor voltage can’t change instantaneously
- Time delay required to “build up” energy in field
- C tells you how much V results from applied A-sec

\[ I_C = C \frac{dV_C}{dt} \]

\[ V_C = \frac{1}{C} \int I_C dt \]
Inductance

- Represents energy stored in magnetic field
- Inductor current can’t change instantaneously
- Time delay required to “build up” energy in field
- L tells you how much I results from applied V·sec

\[ V_L = L \frac{dI_L}{dt} \]

\[ \Rightarrow I_L = \frac{1}{L} \int V_L dt \cdot \text{V·sec} \]
Different Approach to Magnetic Field

- Electric Field
  - Represented by capacitance
  - Voltage is result; cause is applied A-sec (charge)

- Magnetic Field
  - Represented by inductance
  - Current is result; cause is applied V-sec
Units of magnetic flux density

• Magnetic flux density $B$

\[
[tesla] = \left[ \frac{V \cdot \text{sec}}{m^2} \right]
\]

Meaning

• Apply 1V for 1sec to loop with area of 1m$^2$ (cause)
• Result is B field of 1 tesla (effect)
• What about current???
What about current?

• Observed that resulting current for a given V-sec/m² depends on material in which field lines exist
• Described with permeability $\mu$, magnetic field $H$:
  \[
  \vec{H} = \left( \frac{1}{\mu} \right) \vec{B}
  \]
• $H$ gives current through Ampere’s law
  \[
  I_{encl} = \oint \vec{H} \cdot d\ell
  \]
• Units: $H$ must have units [A/m]  
  \( \Rightarrow \) Permeability $\mu$ will have units [Hy/m] 
• Hint: $\mu$ will be involved in value of inductance!
Units of electric flux density

• Electric flux density $D$

$$\left[\frac{coul}{m^2}\right] = \left[\frac{A \cdot \text{sec}}{m^2}\right]$$

Meaning

• Apply 1A for 1sec to capacitor plates with area of 1m$^2$ (cause)
• Result is D flux of 1 A-sec/m$^2$ (effect)
• What about voltage?
What about voltage?

• Observed that resulting voltage for a given A·sec/m² depends on material in which field lines exist
• Described with permittivity $\varepsilon$, electric field $E$:

$$
\vec{E} = \left( \frac{1}{\varepsilon} \right) \vec{D}
$$

• $E$ gives voltage through path integral

$$
V_{ab} = \int_{a}^{b} \vec{E} \cdot d\vec{l}
$$

• Units: $E$ must have units [V/m]
  $\Rightarrow$ Permittivity $\varepsilon$ will have units [F/m]
• Hint: $\varepsilon$ will be involved in value of capacitance!
Parallel Plate Electromagnetics

• Area = 1m² a little large for our purposes ...
• Use geometry suited to PCB design: parallel plates
• Determine inductance, capacitance
• Assumption: Field density negligible outside volume enclosed by plates
**Magnetic Field / Inductance**

Procedure:

- $B$ from $V$-sec, area perpendicular to field lines
- $H$ from $\mu$, $B$
- Current $I$ from $H$, path integral
- Inductance from definition of $L$
Magnetic Field / Inductance

B from V-sec, geometry
\[ B = \frac{V_L \cdot t}{\ell \cdot h} \]

H from \( \mu \), B
\[ H = \left( \frac{1}{\mu} \right) B = \frac{V_L \cdot t}{\mu \cdot \ell \cdot h} \]

Path integral
\[ I = \oint \overrightarrow{H} \cdot d\ell = \frac{w \cdot V_L \cdot t}{\mu \cdot \ell \cdot h} \]

Inductance
\[ I = \left( \frac{1}{L} \right) \int V_L \, dt \Rightarrow L = \mu \frac{\ell \cdot h}{w} \]
Electric Field / Capacitance

Procedure:

• D from A-sec, area perpendicular to field lines
• E from $\varepsilon$, D
• Voltage V from E, path integral
• Capacitance from definition of C
Electric Field / Capacitance

D from A-sec, geometry
\[ D = \frac{I_C \cdot t}{\ell \cdot w} \]

E from \( \varepsilon \), D
\[ H = \left( \frac{1}{\varepsilon} \right) D = \frac{I_C \cdot t}{\varepsilon \cdot \ell \cdot w} \]

Path integral
\[ V = \int \vec{E} \cdot d\ell = \frac{h \cdot I_C \cdot t}{\varepsilon \cdot \ell \cdot w} \]

Capacitance
\[ V = \left( \frac{1}{C} \right) \int I_C dt \Rightarrow C = \varepsilon \frac{\ell \cdot w}{h} \]
Parallel Plate Summary

• PCB trace: Energy in both electric, magnetic fields

\[ C = \varepsilon \frac{\ell \cdot w}{h} \]
\[ L = \mu \frac{\ell \cdot h}{w} \]
Transmission Line Impedance

- Lumped L, C model (limit as segment length → 0)

\[
Z = j\omega L + \left(\frac{1}{j\omega C}\right)Z \\
Z \Rightarrow Z = \sqrt{\frac{L}{C}} = \sqrt{\left(\frac{\mu}{\varepsilon}\frac{\ell h}{w}\right)\left(\frac{h}{\varepsilon \ell w}\right)} = \frac{h}{w} \sqrt{\frac{\mu}{\varepsilon}}
\]
Qualitative interpretation

Low impedance
- Wide, close to return path (supply distribution)
- High current (energy in magnetic field)

High impedance
- Narrow, far from return (low power signal)
- Low current (energy in electric field)

$$Z = \frac{h}{w} \sqrt{\frac{\mu}{\varepsilon}}$$

GEOMETRY \quad MATERIAL
“Parallel Plate” E&M summary

• Example of approach for academia:
  – Same concepts, different application
  – Responsive to needs of community

• Qualitative insight, guidance

• Quantitative predictions
Improving Education: Industry

Create culture that supports education:

• Industry-academia relationship
  – Let us know what you need!

• Industry-individual relationship
  – Culture must allow "I don't know"
  – Key: Enables start of education process
  – What is culture’s response to "I don't know"
    • Good: opportunity for education
    • Bad: admission of weakness
Improving Education: Individuals

Expect to Understand!!!

• Ask Questions!!!
  – Ask yourself, what does that equation mean?
  – If you don't know, ask the professor

• If you don't understand, it's because (choose one):
  a) you're stupid
  b) it hasn't been explained to you correctly
Professor problem

• Shocking secret:
  Most professors have little or no training in education
• Most professors understood material the first time
  – Only know (need) one explanation
• Advice for students:
  – Keep pushing
  – Connect explanation to basics
  – Question assumptions
Fear Factor

• Exponential growth in material to be learned
  – Now teaching material to juniors that didn't exist 20 years ago
• No shame in admitting "I don't know"
• Don't panic
  – Answer is out there somewhere
• Don't reinvent wheel
  – People have been looking at high speed problems for a long time
Connect from analogous situations

- Repeaters for transatlantic cable (20th century):
  \[ f_{\text{max}} \approx 200\text{kHz} \]
  \[ \approx 60\text{km} \]

- Repeaters for on-chip clock distribution (21st century):
  \[ f_{\text{max}} \approx 2\text{GHz} \]
  \[ \approx 1\text{mm} \]

Ismail, Friedman, Neves, “Repeater Insertion in Tree Structured Inductive Interconnect, IEEE TCAS, May, 2001
Conclusion

We've all got work to do:

• Academia:
  – More learner centered, meet needs of students

• Industry:
  – Create, maintain culture that supports education

• Individual:
  – Expect to understand, question assumptions