FTF FREESCALE TECHNOLOGY FORUM 2015

Electromagnetic Fields for Normal Folks: Show Me the Pictures and Hold the Equations, Please

FTF-DES-F1305

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External Use

Agenda

- Changes on the Wind
- Foundation of Electronics
- Electromagnetic Field Behavior
- What’s in the Waves
- Designing Good Transmission Lines
- Reference Information

Changes on the Wind

What Changes?

Smaller device geometries and higher current switching capabilities have thrust us all into the world of RF, HF, UHF and microwave *energy management*.

Rise times on even the lowest tech devices now exhibit gigahertz impact.

These changes directly impact product functionality and reliability.

What Changes?

IC technology was described as % shrink from Integer

Design Rules

- Circuit-based approach usually was close enough

IC technology now described in nanometers

- Circuit-based approach completely falls apart

EM field (physics) based approach essential

- EMC standards have changed
- Lower frequency compliance requirements
- Higher frequency compliance requirements
- Lower emission levels allowed
- Greater immunity required

The playing field and the equipment have changed!

This really is a brand new game!

What Can We Do?

- The skills required are only taught in a few universities
  - Missouri University of Science and Technology (formerly the University of Missouri-Rolla)
    http://www.mst.edu/
  - Clemson University
    http://www.cvel.clemson.edu/emc

- Our sagest mentors may not be able to help
- Nearly every rule of thumb is wrong
- To gain the skills needed, you have to actively seek them
- Industry conferences
  - PCB East and West
  - IEEE EMC Society events
- Seminars hosted by your favorite semiconductor supplier!

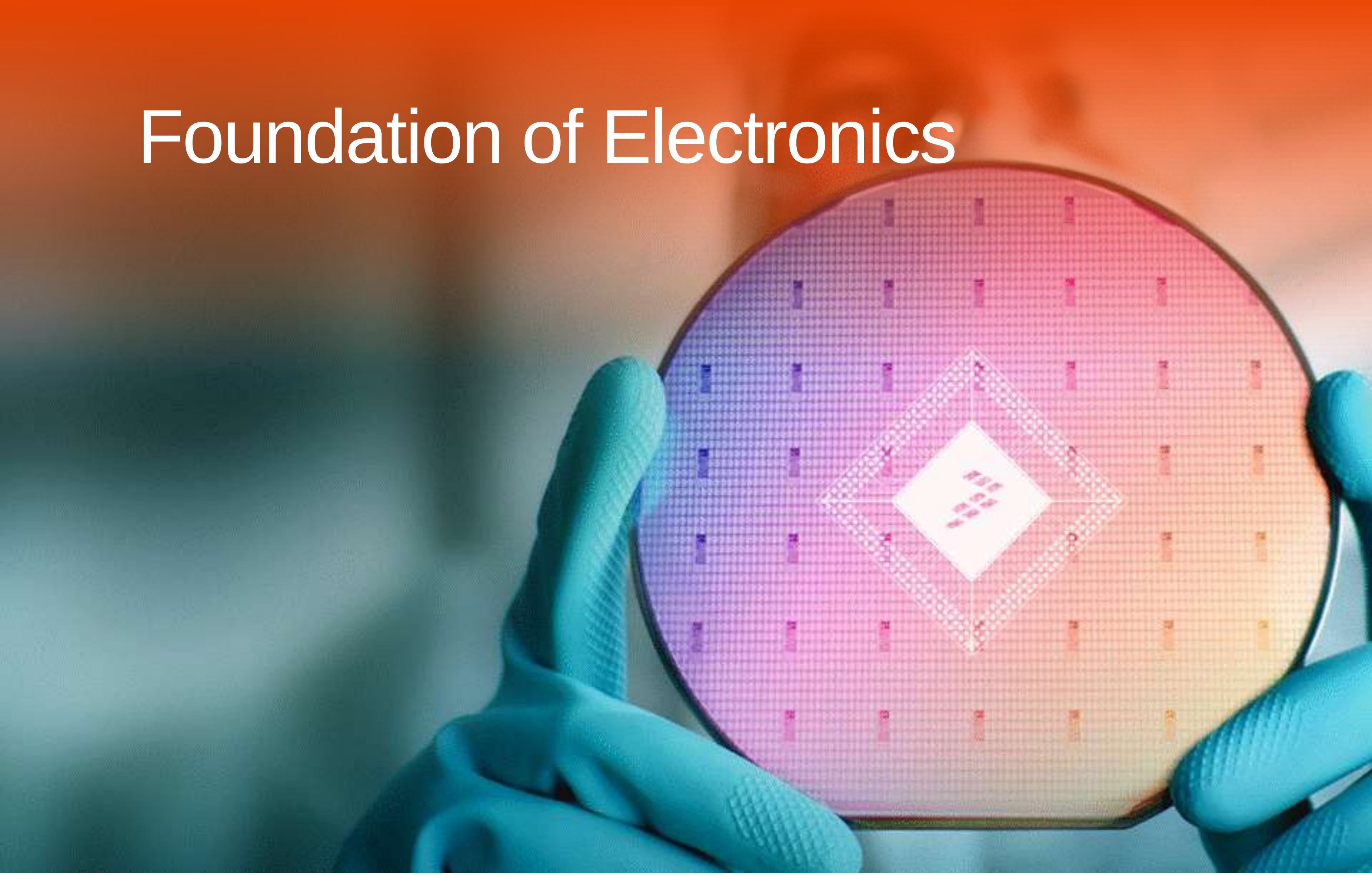
Freescale, of course!

What Can We Do?

About Me: Daniel Beeker

- 34+ years experience at Motorola/Freescale designing and working with microprocessor and microcontroller development systems
- 28+ years working with automotive customers in one of the most demanding embedded control environments
- Championing the cause for increased awareness of advanced design technologies
- Used to believe in *black magic*, but Ralph Morrison set me straight!
- Firmly entrenched in physics-based design philosophy

Foundation of Electronics



What is Electricity?

Is it *volts* and *amperes* …

or *electric* and *magnetic* fields?

What is Electricity?

- Fields are basic to all circuit operation
- Volts and amperes make things practical
  - We easily can measure volts and amperes
  - More difficult to measure “E” and “H” fields
- In high clock rate (and rise time) circuits, once the "quasi static” approximation does not hold true anymore, field control plays a critical role
- This must be a carefully considered part of any design

(Slide compliments of Ralph Morrison, Consultant)

Maxwell’s Equations

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_{\mathrm{B}}}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \varepsilon_0 \frac{d\Phi_{\mathrm{E}}}{dt} + \mu_0 i_{enc}$$

(Slide compliments of http://www.physics.udel.edu/~watson/phys208/ending2.html)

Maxwell's Equations

Maxwell *was* smart!

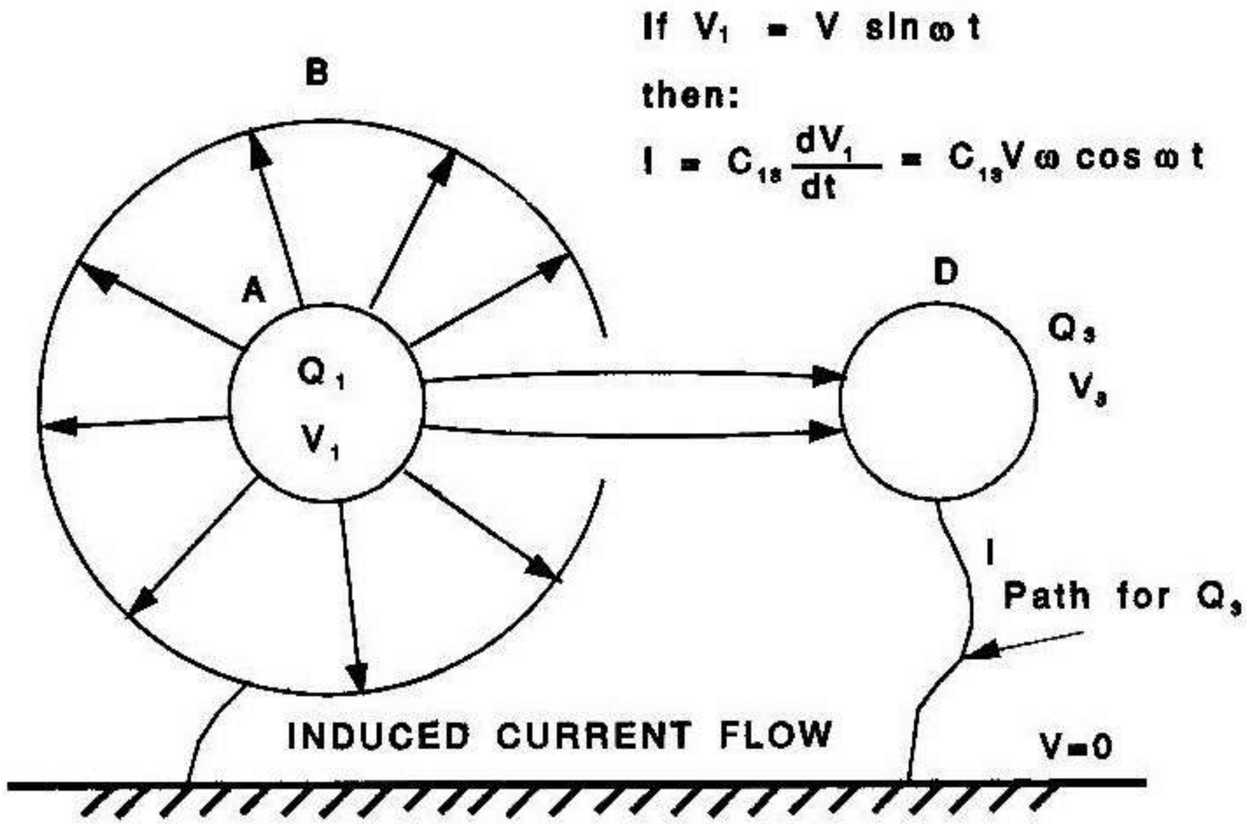
Electromagnetic Field Behavior

Myths We Depended On

- Fields are invisible
- Fields are well behaved
- Fields follow the trace
- Fields avoid open spaces
- Fields are someone else’s problem
- Fields are only important in RF and power supply designs
- Fields are only for farmers

A Loose Field is *Not* a Friendly Field

A shielded enclosure
with an opening

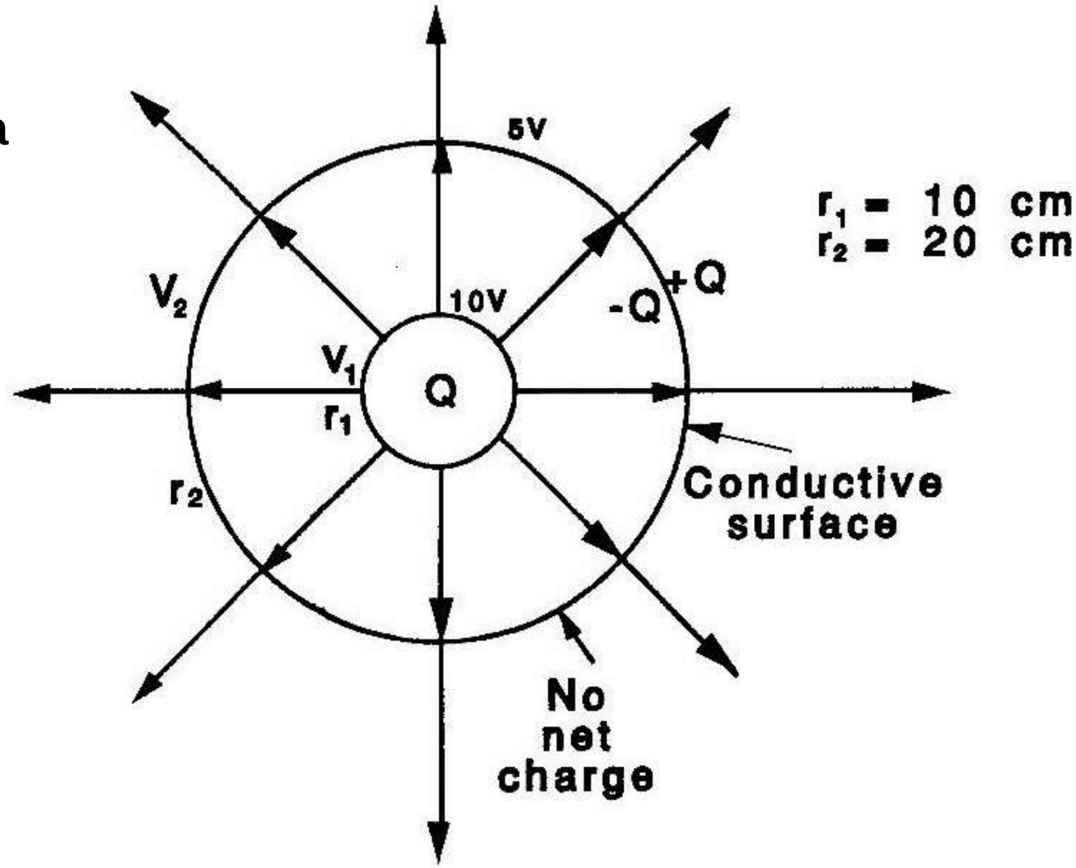


Field is not contained and looks for trouble

(Slide compliments of Ralph Morrison, Consultant)

Contained Fields are Friendly!

An equipotential surface around a charged sphere

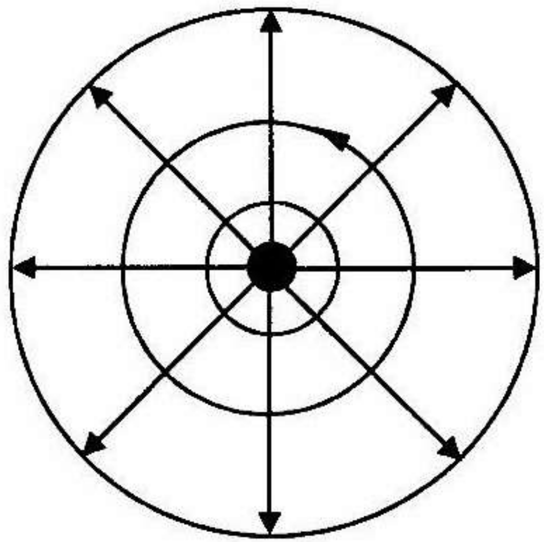


(Slide compliments of Ralph Morrison, Consultant)

Contained Fields are Friendly!

Coaxial Transmission

No radiation



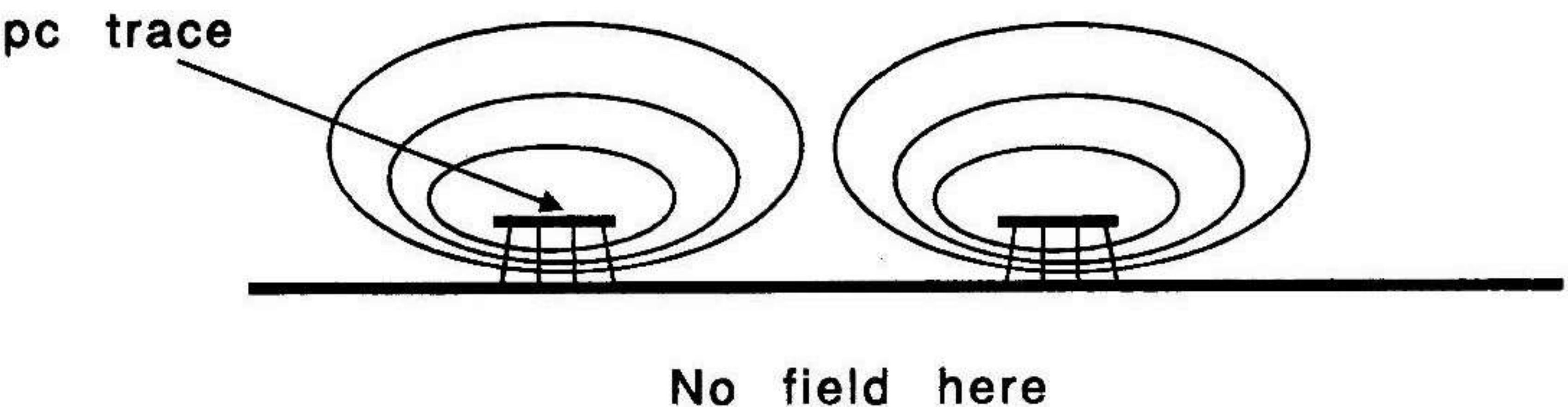
E and H fields are contained

Current return path must be on sheath.

(Slide compliments of Ralph Morrison, Consultant)

Contained Fields are Friendly!

Fields concentrate under the traces and there is little crosstalk.



Fields do not penetrate the plane.

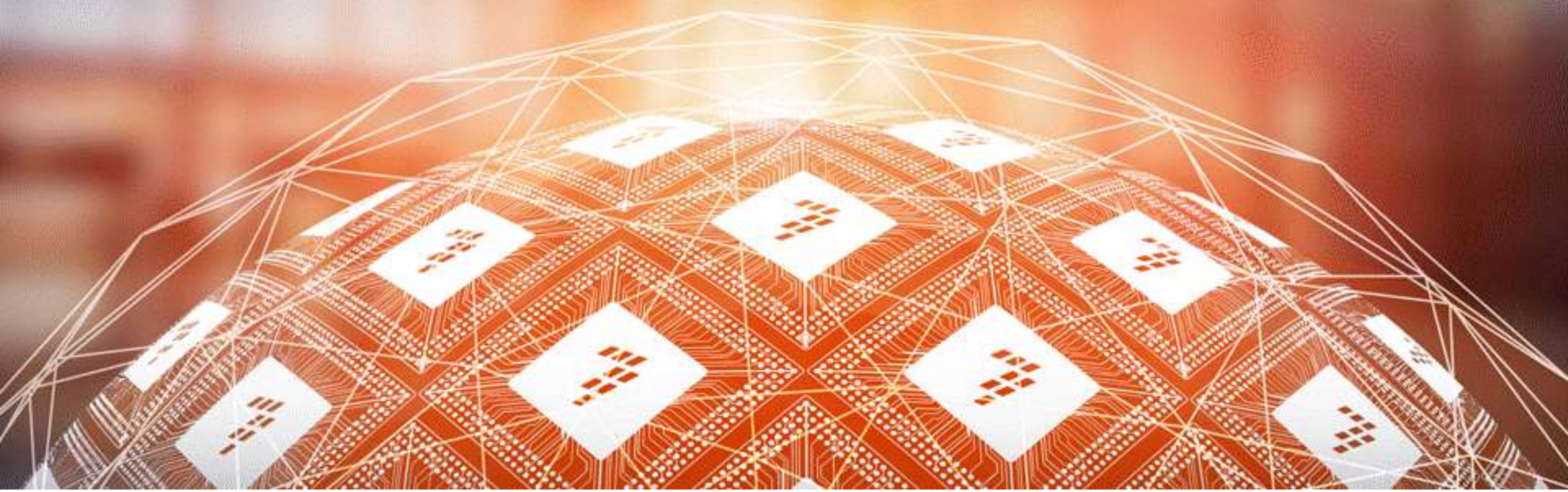
(Slide compliments of Ralph Morrison, Consultant)

Fields are Friendly!

A contained field is a friendly field:

- Happy field in a sphere
- Happy field in a good coaxial cable
- Happy field in a closely spaced transmission line pair
- Happy field between two closely spaced PCB planes

What’s in the Waves?



Fields are Friendly!

Fields need to be carefully managed:

- Every connection must be treated as part of a transmission line pair
- Field volumes (read *transmission line impedance*) must be carefully managed
- Each discontinuity (read *change in transmission line GEOMETRY*) results in reflections
- Each segment of this geometry must have enough field energy delivered to match the field density (read *voltage*) from the driver

- **This all takes TIME**

- Yes, this is now **a four-dimensional geometric design problem**

How Long Does It Take?

Wave velocity

- For traces on a circuit board $v = c / € ^{1/2}$
- Where c is the velocity of light and € is the relative dielectric constant
  - **v = 150 mm / ns or 6" / ns**

All energy is moved by wave action!

- A *drop in voltage* sends a wave to get more energy
- Waves reflect at discontinuities
- A source of voltage is a discontinuity
- Each reflected wave can carry a limited amount of energy

(Slide compliments of Ralph Morrison, Consultant)

Getting 1 Ampere to Flow

What does this mean in my circuit board?

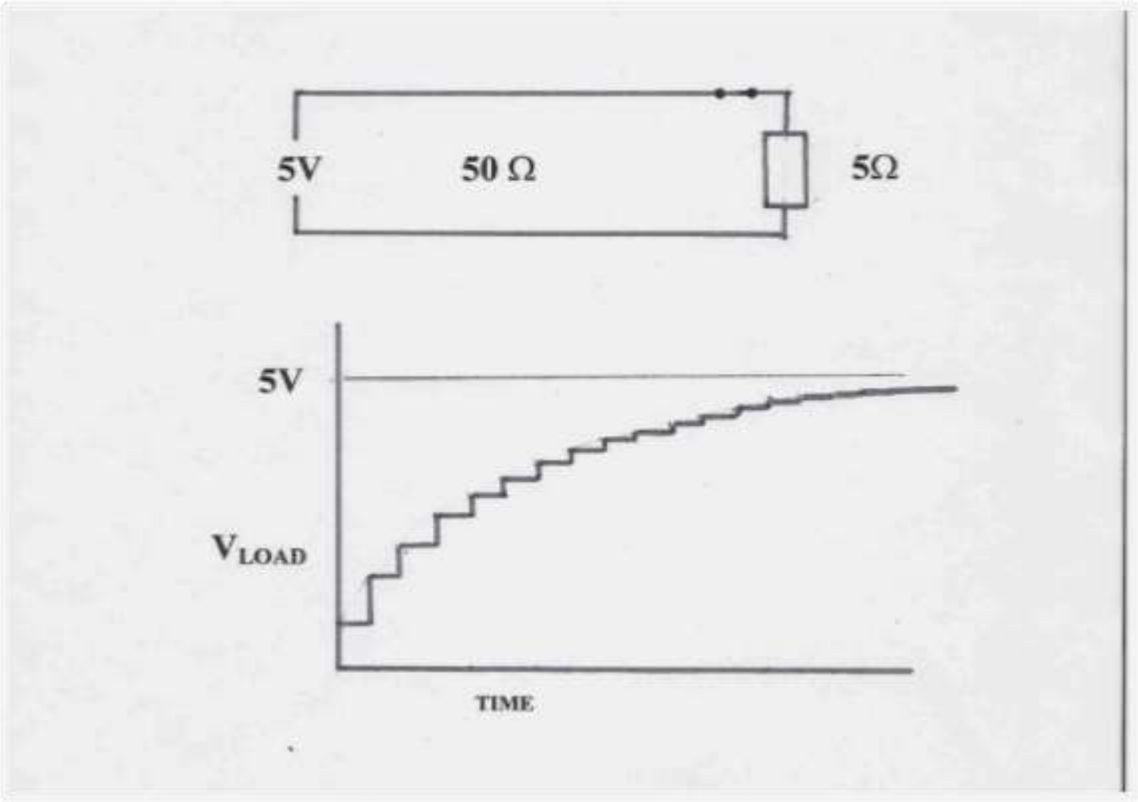
- Initial power level in a 50 Ohm line
  - 5 Ohm load and 5 V source
  - I = 0.1 amperes or ½ watt

Now, how do I get 1 ampere?

- Even if the line is only 1/16 inch long:
  - It takes 10 ps for a wave to go 1/16 inch in FR4
  - It takes 20 ps for a wave to make one round trip
  - It takes 30 round trips on that line to bring current level up to near one amp
  - That is 600 ps, assuming zero rise time

(Slide compliments of Ralph Morrison, Consultant)

Getting 1 Ampere to Flow



Note: This is not a curve, but a series of step functions. The amplitude of the step is determined by the impedance of the transmission line and the width of the step is determined by the length of the transmission line and a two way transition for the wave.

(Slide compliments of Ralph Morrison, Consultant)

Typical 1/16 Inch Connections

- Traces to capacitors
- Connections to IC dies
  - Lead frames and wire bonds
  - BGA interposers
- Traces to vias
- Vias to ground/power planes

Remember, 1/16 inch is about 10 pS

- Yes, you do care about *picoseconds* now!

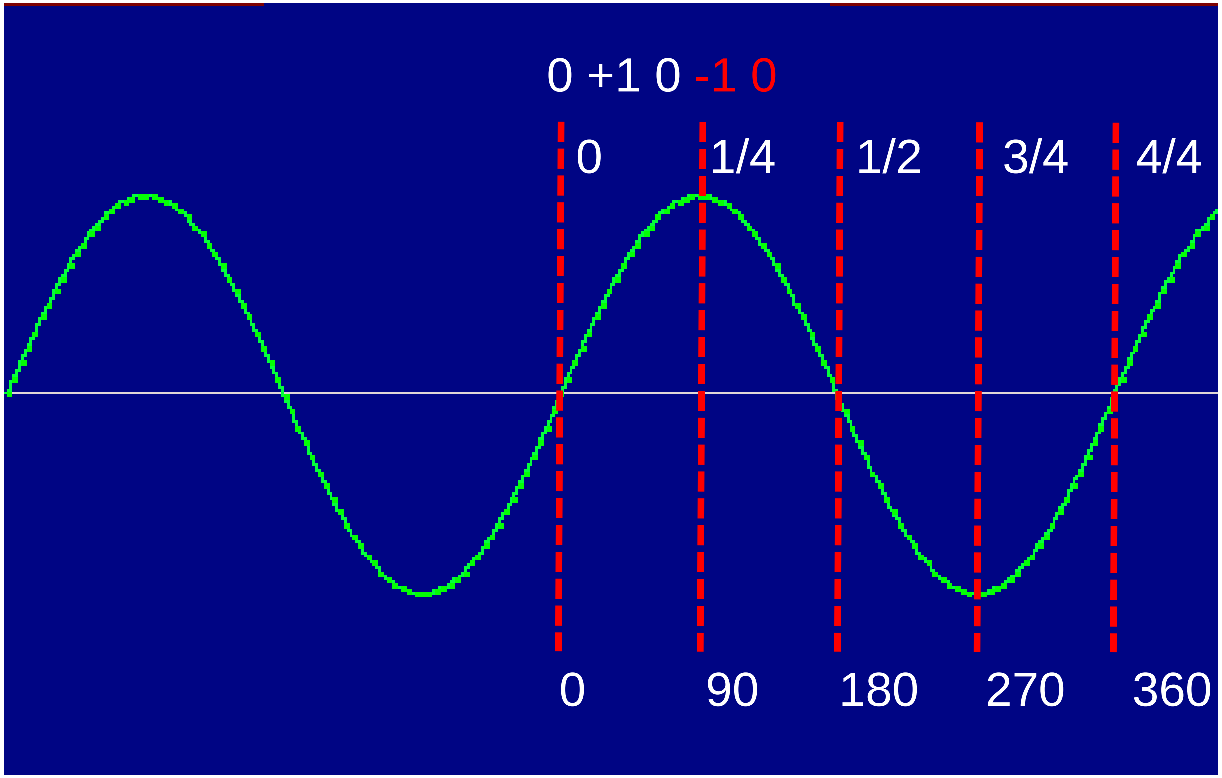
Antenna Size vs. Frequency

¼ wavelength is accepted as a good antenna size
In the Analog Domain, this is 90 degrees (0-1-0-1-0)

Frequency	¼ wave length
1 Hertz Rise time equivalent, who cares	246,000,000 feet (46,591 miles) Almost 6 times around the earth
10 Hertz Rise time equivalent, still who cares	24,600,000 feet (4,659 miles) Almost from Detroit to Honolulu
100 Hertz Rise time equivalent, .01 seconds	2,460,000 feet (466 miles) Almost from Detroit to New York
1 KHz Rise time equivalent, 1 millisecond	246,000 feet (46.6 miles) Almost from Novi to Flint
10 KHz Rise time equivalent, 100 microseconds	24,600 feet (4.659 miles) Almost from Freescale Novi to Walled Lake
100 KHz Rise time equivalent, 10 microseconds	2,460 feet (0.466 miles) Almost from the Freescale Novi to Meadowbrook Road
1 MHz Rise time equivalent, 1 microsecond	246 feet (0.0466 miles) Less than a football field
10 MHz Rise time equivalent, 100 nanoseconds rise time distance, 100 feet	24.6 feet Across the room
100 MHz (TTL Logic) Rise time equivalent, 10 nanoseconds rise time distance, 10 feet	2.46 feet Less than a yard
1 GHz (BiCMOS Logic) Rise time equivalent, 1 nanosecond rise time distance, 1 foot	0.246 feet (2.952 inches) Less than your finger
10 GHz (GaAs Logic) Rise time equivalent, 100 picoseconds rise time distance, 1.2 inches	0.0246 feet (0.2952 inches) Less than the diameter of a pencil
100 GHz (nanometer geometry HCMOS) Rise time equivalent, 10 picoseconds rise time distance, 0.12 inches	0.00246 feet (0.0295 inches) Half the thickness of a standard FR4 PCB

Analog Wave Perspective

- Seen as sine wave with positive and negative amplitude
- Rise time distance would be ¼ wavelength



Antenna Size vs. Frequency

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Frequency	¼ wave length
10 MHz **HMOS** Rise time equivalent, 100 nanoseconds rise time distance, 100 feet	**24.6 feet** Across the room
100 MHz (TTL Logic) **UDR HCMOS** Rise time equivalent, 10 nanoseconds rise time distance, 10 feet	**2.46 feet** Less than a yard
1 GHz (BiCMOS Logic) **IDR HCMOS** Rise time equivalent, 1 nanosecond rise time distance, 1 foot	**0.246 feet** (2.952 inches) Less than your finger
10 GHz (GaAs Logic) **65 nm HCMOS** Rise time equivalent, 100 picoseconds rise time distance, 1.2 inches	**0.0246 feet** (0.2952 inches) Less than the diameter of a pencil
100 GHz **32 nm HCMOS** Rise time equivalent, 10 picoseconds rise time distance, 0.12 inches	**0.00246 feet** (0.0295 inches) Half the thickness of a standard FR4 PCB

Antenna Size vs. Frequency

From the previous table, a few things become apparent:

- We got away with ignoring basic physics because IC switching speeds were slow and efficient antennas had to be *huge*.
- At a switching speed of 1 nanosecond, it only takes a PCB feature (trace or slot) of 3 inches to be an efficient antenna (1/4 wave length).
- Once you cross that magic boundary of 1 nanosecond, most PCB designs are capable of providing a wonderful source of antennas.
- At 10 picosecond speeds, every structure in the system can be an good antenna.

Since TTL days:

Four order magnitude change in switching speeds

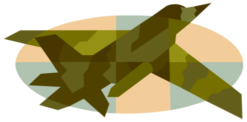
Almost no changes in PCB or system design philosophy

Four Order Magnitude Change

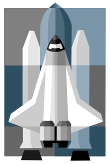
1st order: Vehicles go 6 miles an hour

2nd order: Vehicles go 60 miles an hour

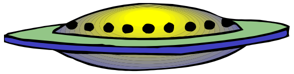
3rd order: Vehicles go 600 miles an hour



4th order: Vehicles go 6,000 miles an hour



5th order: Vehicles go 60,000 miles an hour



Only in our industry we try to make the buggy to go fast!

Designing Good Transmission Lines

Energy Management

Why does field energy follow conductors?

- Why does water ***flow*** in a stream?
  - Same reason
- Nature follows the path that stores the least energy
- It is easier for fields to follow traces than to go out across space

The Impedance of free space is 377 ohms

- Between conductor pairs it will be lower, so they follow the path of lowest <u>*impedance*</u>

(Slide compliments of Ralph Morrison, Consultant)

Energy Management

Transmission lines are convenient paths for energy flow:

- Every conductor pair is a transmission line
- Trace-to-trace or trace-to-conducting plane
- The fields, and thus the energy flow, will concentrate
  - between traces or between a trace and a conducting plane
- Draw the fields to locate the current

(Slide compliments of Ralph Morrison, Consultant)

Energy Management

A capacitor is:

A conductor geometry that concentrates the storage of electric field energy

An inductor is:

A conductor geometry that concentrates the storage of magnetic field energy

In a capacitor

Field energy is stored in the space between the plates

In an inductor

Field energy is stored in the space around wires and in gaps

(Slide compliments of Ralph Morrison, Consultant)

Transmission Line Properties

- They direct energy flow
- They can store field energy
- Their position in a circuit is critical
- They cross couple energy only at wave fronts
- They deliver energy at terminations
- They are bi-directional
- They can transport any number of waves at one time
- They can radiate

(Slide compliments of Ralph Morrison, Consultant)

Transmission Line Properties

We use transmission lines to transport energy and to carry logic signals:

- *A transmission line can carry any number of signals in either direction at the same time*
- Below 1 MHz, the geometry of these lines is not too critical
- With today's clock rates and rise times, the geometry of these lines is key to performance

In a good design:

- Fields associated with different signals do not share the same physical space
- If they do share the same space, there is crosstalk

(Slide compliments of Ralph Morrison, Consultant)

Energy and Logic Signals

- The transmission of a logic signal means that field energy is sent out on a transmission line
  - Logic drivers should be treated the same as any power source

- This is true even if the line is un-terminated
  - The driver does not know what is at the end of the transmission line
  - The driver only sees a short circuit until after a reflection occurs

- This energy must be transmitted to the receiver or lost in heat or radiation — it cannot be returned to the driver

Well-Defined Transmission Lines

- Signal traces *must* be one dielectric away from the return!
  - Adjacent to planar copper
  - Adjacent to ground trace
    - Any deviation from this *must* be an engineered compromise, *not* an accident of signal routing
  - Any deviation from this *will* increase radiated emissions, degrade signal integrity and decrease immunity

- Unless a transmission line is required to be controlled impedance (*read receiver is more than 1/6th wavelength away*), the goal should be the lowest possible (practical) impedance.

This is a very serious problem and a big change from normal board design philosophy

Wave Reflection

Reflection Coefficient

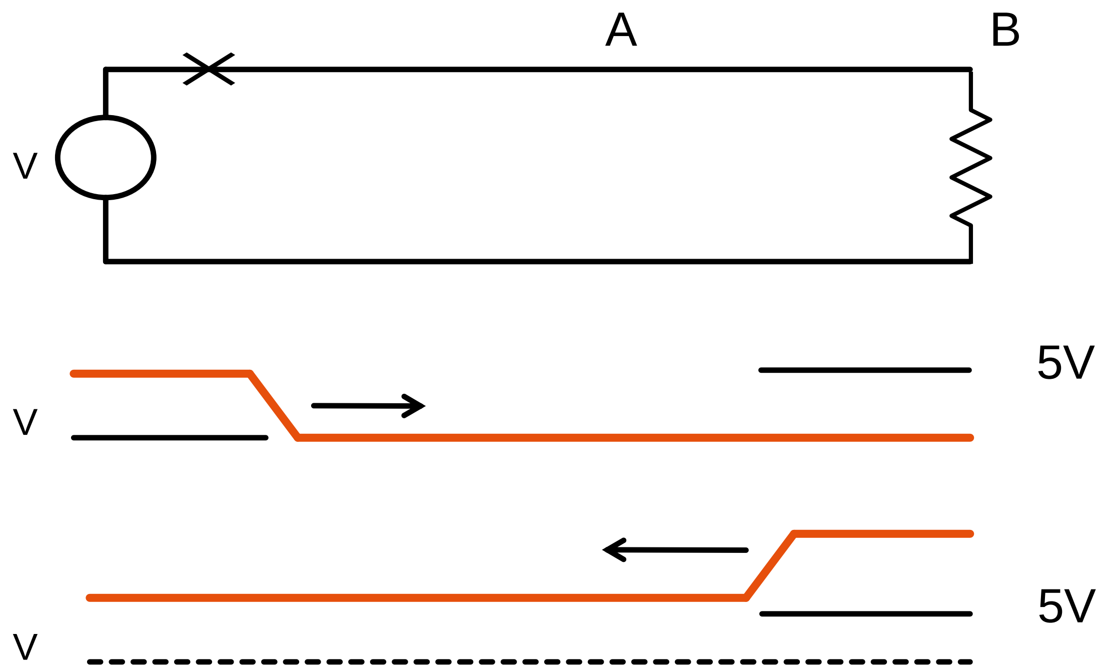
Reflection: $$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

- When $Z_2 = Z_1$ then $\rho = 0$ or *no reflection*
- When $Z_2 > Z_1$ then $\rho > 0$ or *a plus reflection*
- When $Z_2 < Z_1$ then $\rho < 0$ or *a negative reflection*

(Slide compliments of Ralph Morrison, Consultant)

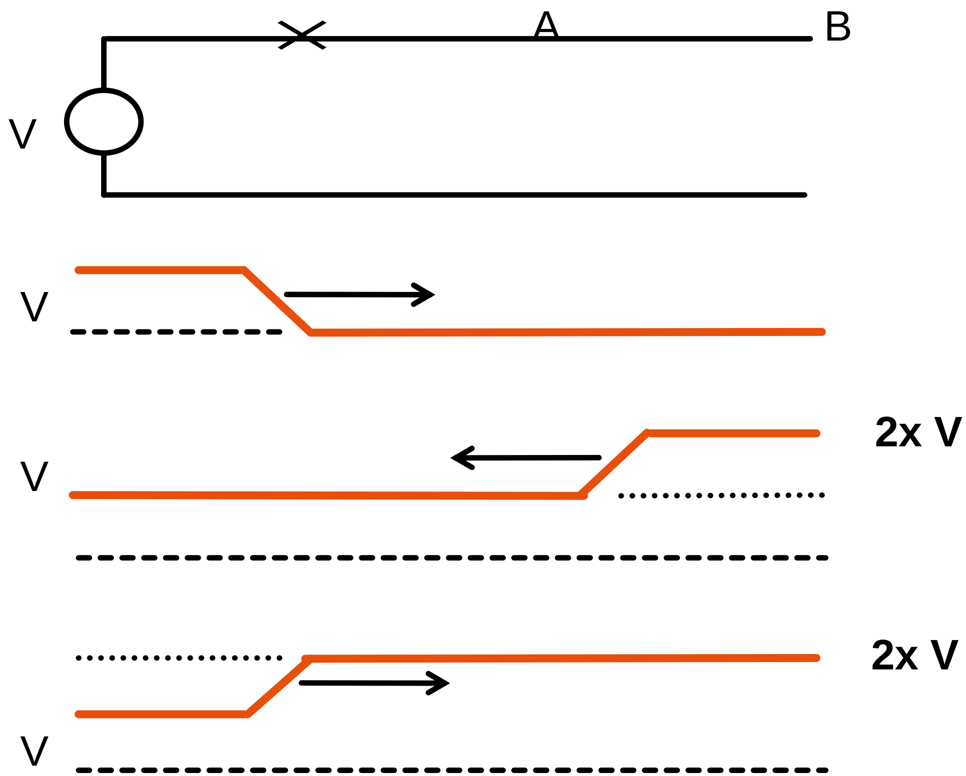
Wave on a Transmission Line

Low impedance source to high impedance load
Wave reflects and voltage doubles



(Slide compliments of Ralph Morrison, Consultant)

Second Reflection at Source



From a low impedance to a high impedance, the wave voltage is doubled and reflected.
From a high impedance to a low impedance, the wave voltage is inverted and reflected.

This is called “ringing” and continues until all of the energy is either transferred to the receiver, converted to heat in the dielectric, or radiates.

(Slide compliments of Ralph Morrison, Consultant)

Well-Defined Transmission Lines

- Good news is that any discontinuity that is less than 1/6th wavelength is virtually invisible to the signal
  - Routing schemes need to be driven by the transistor geometry

- Any failure to insure that both signal and ground copper are contiguous (and adjacent) results in large discontinuities that will cause signal integrity and EMC issues
  - Vertical transitions can not be not excluded
    - This is the most common mistake made in otherwise good designs

Rise Time Distance

- Now, what does this really mean?

- Rise time distance is how far the wave travels by the time it reaches full amplitude.
- Determined by the switching speed of the output driver
- In digital circuits, this is really ½ wavelength, or 180 degrees!

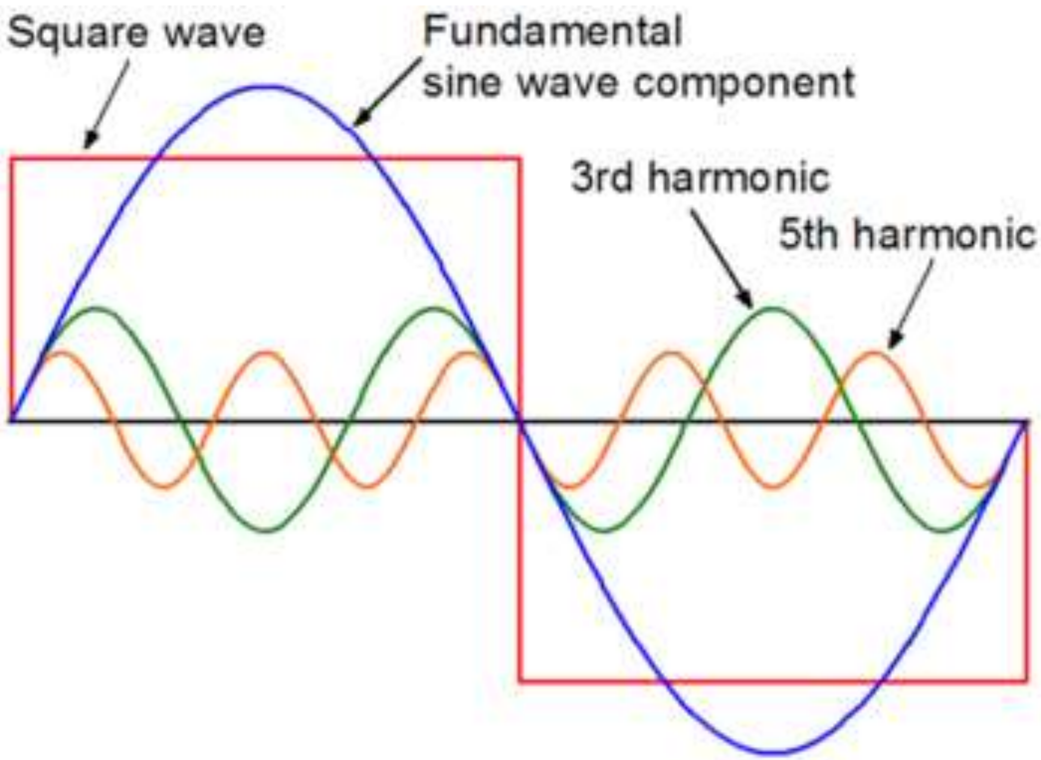
- Let's look at this from a *switching speed* vs. lumped distance perspective.
- Remember, lumped distances are basically the size of a discontinuity which remains invisible to the energy flow.

- To prevent problems on uncontrolled impedance transmission lines, the load must be less than 1/6 of the wavelength (67% amplitude reflection)
- The voltage developed is less than ½ of the output voltage, so the reflection is less than the output voltage
- One reflection and the transmission line is stable

- How far is that for a given switching speed?

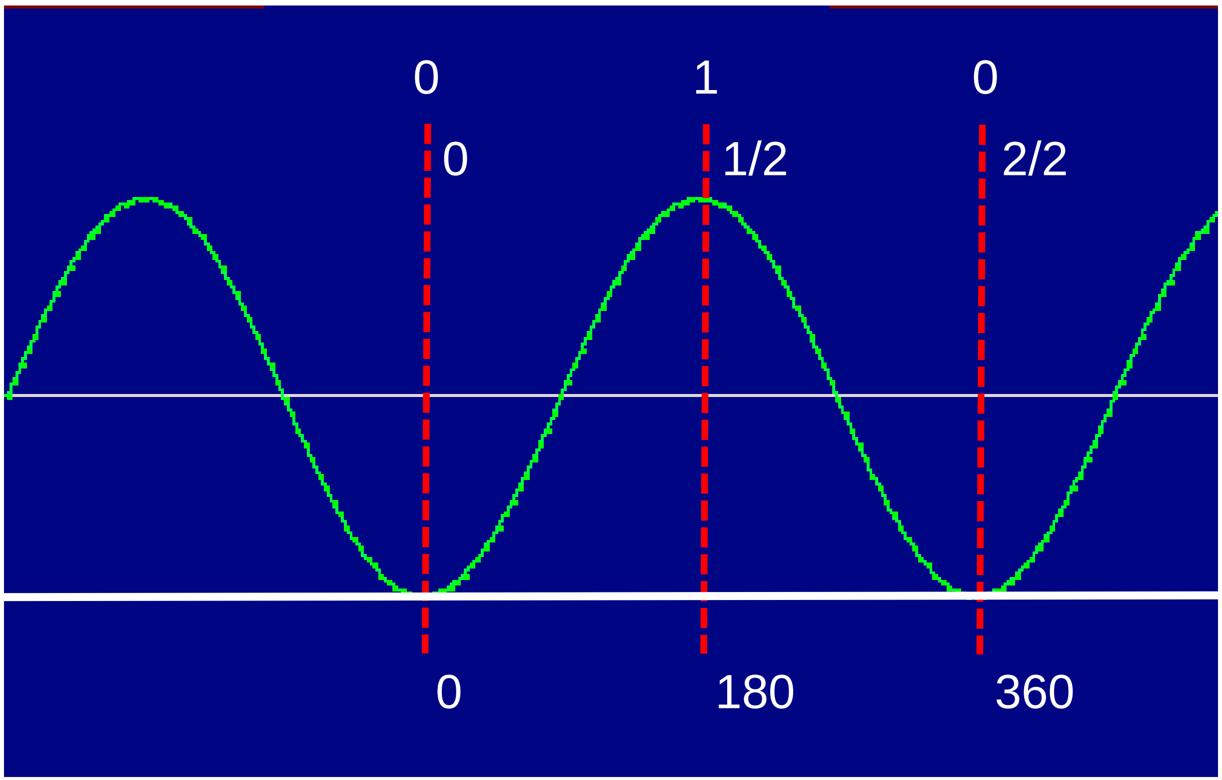
Digital Wave Perspective

- Square wave is made up of an infinite number of frequencies
- Design for the highest frequency the driver is capable of supporting



Digital Wave Perspective

- Seen as sine wave with positive amplitude, the reference is at the lowest point
- Rise time distance would be ½ wavelength



Switching Frequency vs. Lumped Distance (Inner Layer)

- Rise time distance is ½ wavelength in digital domain, or 180 degrees

Frequency	1/6 wave length
5 MHz **HMOS** Rise time equivalent, 100 nanoseconds Rise time distance, 100 feet	**16.4 feet** In the room
50 MHz (TTL Logic) **UDR HCMOS** Rise time equivalent, 10 nanoseconds Rise time distance, 10 feet	**1.64 feet** Anywhere on the board
500 MHz (BiCMOS Logic) **IDR HCMOS** Rise time equivalent, 1 nanosecond Rise time distance, 1 foot	**0.164 feet** (1.968 inches) Pretty close
5 GHz (GaAs Logic) **65 nm HCMOS** Rise time equivalent, 100 picoseconds Rise time distance, 1.2 inches	**0.0164 feet** (0.1968 inches) In the package
50 GHz **32 nm HCMOS** Rise time equivalent, 10 picoseconds Rise time distance, 0.12 inches	**0.00164 feet** (0.01968 in. or 500 µm) On the die

Logic Families / Rise Time / Max Length

DEVICE TYPE	RISETIME	Max Line Length Inner (inch/mm)	Max Line Length Outer (inch/mm)
Standard TTL	5.0 ns	7.27 / 185	9.23 / 235
Schottky TTL	3.0 ns	4.36 / 111	5.54 / 141
10K ECL	2.5 ns	3.63 / 92	4.62 / 117
ASTTL	1.9 ns	2.76 / 70	3.51 / 89
FTTL	1.2 ns	1.75 / 44	2.22 / 56
BICMOS	0.7 ns	1.02 / 26	1.29 / 33
10KH ECL	0.7 ns	1.02 / 26	1.29 / 33
100K ECL	0.5 ns	.730 / 18	.923 / 23
GaAs	0.3 ns	.440 / 11	.554 / 14

(Calculated assuming a nominal Er = 4.1)

(Slide compliments of Rick Hartley, Consultant)

Transmission Line Properties

In a good design:

- Energy is available whenever there is a demand
- The voltage source must be reasonably constant
- Energy must be replaced after it is used or there will be logic (signal integrity) problems
- This is called energy management

Local sources of energy:

- Decoupling capacitors
- There is also energy available from ground/power plane capacitance

New problem:

- It takes *time* to move this energy from storage to a load

(Slide compliments of Ralph Morrison, Consultant)

Energy Management

All energy is moved by wave action!

When a switching element closes, this results in a drop in the voltage on the power supply. The *resulting* field energy request wave travels until this request is filled or it radiates.

The only way to reduce noise in a system is to reduce this distance and provide adequate sources of electromagnetic field energy.

Energy source hierarchy

- On-chip capacitance
- Space between the wirebonds
- Between layers of Substrate (BGA) or leadframe (QFP)
- Power planes if present
- Local bypass capacitors
- Field energy stored across the PCB structure
- Bulk storage capacitors
- Finally the power supply

We have to keep the field happy and contained as far up the food chain as we can, to reduce system noise.

(Slide compliments of Ralph Morrison, Consultant)

Energy Delivery From A Storage Device

- **For energy to be delivered from a storage device:**
  - The wave requesting the energy (seen as a drop in the power supply voltage caused by the switching event) has to travel to the source and back to the switch

- **It's a two-way trip!**

Switching Frequency vs. Power Source

Frequency	1/20 wave length
5 MHz **HMOS** Rise time equivalent, 100 nanoseconds Rise time distance, 100 feet	**4.92 feet** Somewhere in the room
50 MHz (TTL Logic) **UDR HCMOS** Rise time equivalent, 10 nanoseconds Rise time distance, 10 feet	**.492 feet** Somewhere on the board, should be routed as co-planar pairs
500 MHz (BiCMOS Logic) **IDR HCMOS** Rise time equivalent, 1 nanosecond Rise time distance, 1 foot	**0.0492 feet** (0.59 inches) Width of your finger, time to look at small geometry capacitors and power islands
5 GHz (GaAs Logic) **65 nm HCMOS** Rise time equivalent, 100 picoseconds Rise time distance, 1.2 inches	**0.00492 feet** (0.059 in. or 1498.6 µm) In the package
50 GHz **32 nm HCMOS** Rise time equivalent, 10 picoseconds Rise time distance, 0.12 inches	**0.000492 feet** (0.0059 in. or 149.86 µm) On the die

Transmission Lines

Capacitors are short transmission lines:

- Wave action is required to move energy in and out of a capacitor
- *Don’t forget the connections to the capacitor!*
- Self inductance does not properly tell the story of why it takes time to supply energy
- Circuit theory does not consider time delays

(Slide compliments of Ralph Morrison, Consultant)

Switching Frequency vs. Power Source

- If the energy source is **not** inside the 1/20 wavelength distance, there will be radiated energy caused by the switching event
- The job of the PCB designer is to minimize the amount of energy by managing the power delivery system for each type of switching event
- As the geometry of the ICs we use continues to shrink, so does the area of effective power delivery
- Well-defined power delivery transmission lines and small geometry, low impedance field storage devices are essential
- Even if they are outside of the "**zone**," they can minimize the amount of radiated energy

Closing Remarks and Reference Materials PCB Design is Not a Black Art!

Fundamentals to Remember

- Electromagnetic fields travel in the space between the conductors, not in the conductors
- The switching speed of the transistors determines the frequency of operation, not the clock rate
- Signal and power connections need to be one dielectric from ground for their entire length (including layer transitions)
  - Adjacent plane
  - Co-planar trace
- **There is no such thing as a noisy ground, just poor transmission line design**
- To quote Dr. Todd Hubing, “Thou shalt not split ground.”
- Any compromises to these rules will increase system noise and must be done as carefully considered engineering decisions

Special Thanks to My Mentors

- Rick Hartley (PCB designer extraordinaire) started me down this trail in 2004 at PCB West
- Ralph Morrison (author, inventor, and musician) has patiently and steadily moved me from the fuzzy realm of “circuit theory” and “black magic” into the solid world of physics
- Dr. Todd Hubing (researcher and professor) whose research at UMR and Clemson has provided solid evidence that Maxwell and Ralph have got it right
- Finally, my team at Freescale. We really have come a long way!

High Speed Design Reading List

- *Right the First Time: A Practical Handbook on High Speed PCB and System Design* Volumes I & II, Lee W. Ritchey. Speeding Edge, ISBN 0-9741936-0-7
- *High Speed Digital System Design: A Handbook of Interconnect Theory and Practice*, Hall, Hall and McCall. Wiley Interscience 2000, ISBN 0-36090-2
- *High Speed Digital Design: A Handbook of Black Magic*, Howard W. Johnson & Martin Graham. Prentice Hall, ISBN 0-13-395724-1
- *High Speed Signal Propagation: Advanced Black Magic*, Howard W. Johnson & Martin Graham. Prentice Hall, ISBN 0-13-084408-X
- *Signal Integrity Simplified*, Eric Bogatin. Prentice Hall, ISBN 0-13-066946-6
- *Signal Integrity Issues and Printed Circuit Design*, Doug Brooks. Prentice Hall, ISBN 0-13-141884-X

(Slide compliments of Rick Hartley, Consultant)

EMI Reading List

- PCB Design for Real-World EMI Control, Bruce R. Archambeault. Kluwer Academic Publishers Group, ISBN 1-4020-7130-2
- Digital Design for Interference Specifications: A Practical Handbook for EMI Suppression, David L. Terrell & R. Kenneth Keenan. Newnes Publishing, ISBN 0-7506-7282-X
- Noise Reduction Techniques in Electronic Systems, 2nd Edition, Henry Ott. John Wiley and Sons, ISBN 0-471-85068-3
- Introduction to Electromagnetic Compatibility, Clayton R. Paul. John Wiley and Sons, ISBN 0-471-54927-4
- EMC for Product Engineers, Tim Williams. Newnes Publishing. ISBN 0-7506-2466-3
- Grounding & Shielding Techniques, 5th Edition, Ralph Morrison. John Wiley & Sons, ISBN 0-471-24518-6

(Slide compliments of Rick Hartley, Consultant)

Additional References

- Ralph Morrison's New Book: Digital Circuit Boards: Mach 1 GHz. Available from Wiley and Amazon
- The Best PCB design conference website: http://pcbwest.com/
- Doug Smith's website: http://www.emcesd.com/ (He is the best at finding what is wrong! Lots of useful app notes.)
- IEEE EMC Society website: http://www.emcs.org/
- Clemson's Automotive Electronics website: http://www.cvel.clemson.edu/auto
- Clemson's EMC website: http://www.cvel.clemson.edu/emc
- Missouri University of Science and Technology website: http://www.mst.edu/about/
- IPC — Association Connecting Electronics Industries website: http://www.ipc.org/default.aspx

Closing Remarks

“Buildings have walls and halls.
People travel in the halls not the walls.

Circuits have traces and spaces.
Energy and signals travel in the spaces not the traces.”

- Ralph Morrison

Summary and Q&A

- Electromagnetic fields travel in the space between the conductors
- Movement of EM fields induces current flow in the conductors, not visa versa
- It is important to consider the time it takes for the EM fields to move through the dielectric from the transmitter to the receiver
- Switching speed of the output devices determines the requirements of the power supply
- Switching speed of the output devices determines the requirements of the transmission line design
- Well-defined transmission lines result in significantly improved EMC performance

- **The *black magic* is tamed!**

- Q&A

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