FTF 2016
TECHNOLOGY FORUM

POWER DISTRIBUTION MADE EASY

FTF-DES-N2001

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AGENDA

- Changes on the Wind
- Foundation of Electronics
- Electromagnetic Field Behavior
- Power Supply Basics
- What's in the Waves
- Managing the Spaces
- Component Placement and Routing
- PCB Layout Considerations
- Closing Remarks and 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 emissions 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! NXP, of course!

What Can We Do?

About Me: Daniel Beeker

- 35+ years experience at Motorola/Freescale/NXP designing and working with microprocessor and microcontroller development systems
- 29+ 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

Maxwell's Equations

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

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

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

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

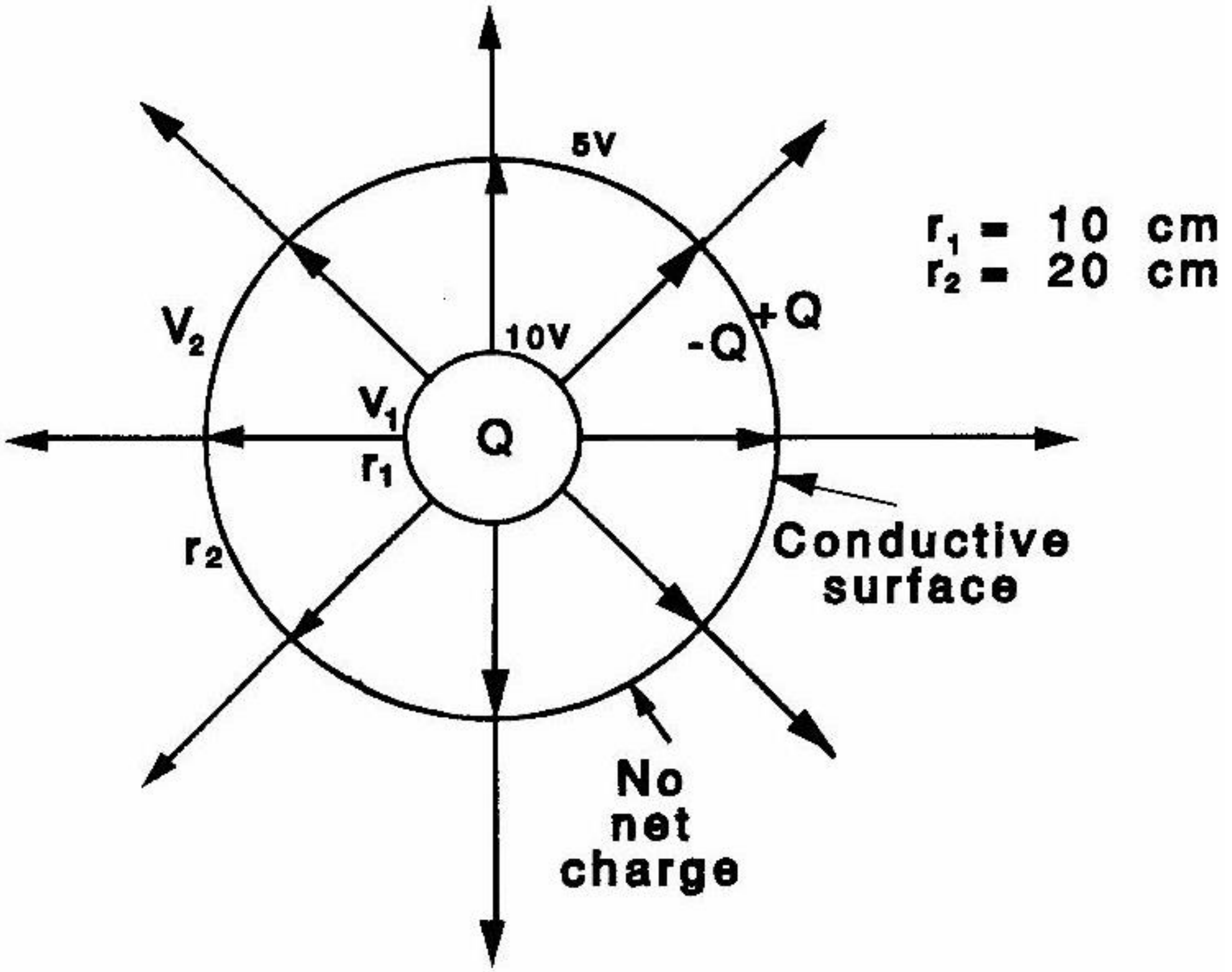
Maxwell's Equations

CV

Maxwell *was* smart!

ELECTROMAGNETIC FIELD BEHAVIOR

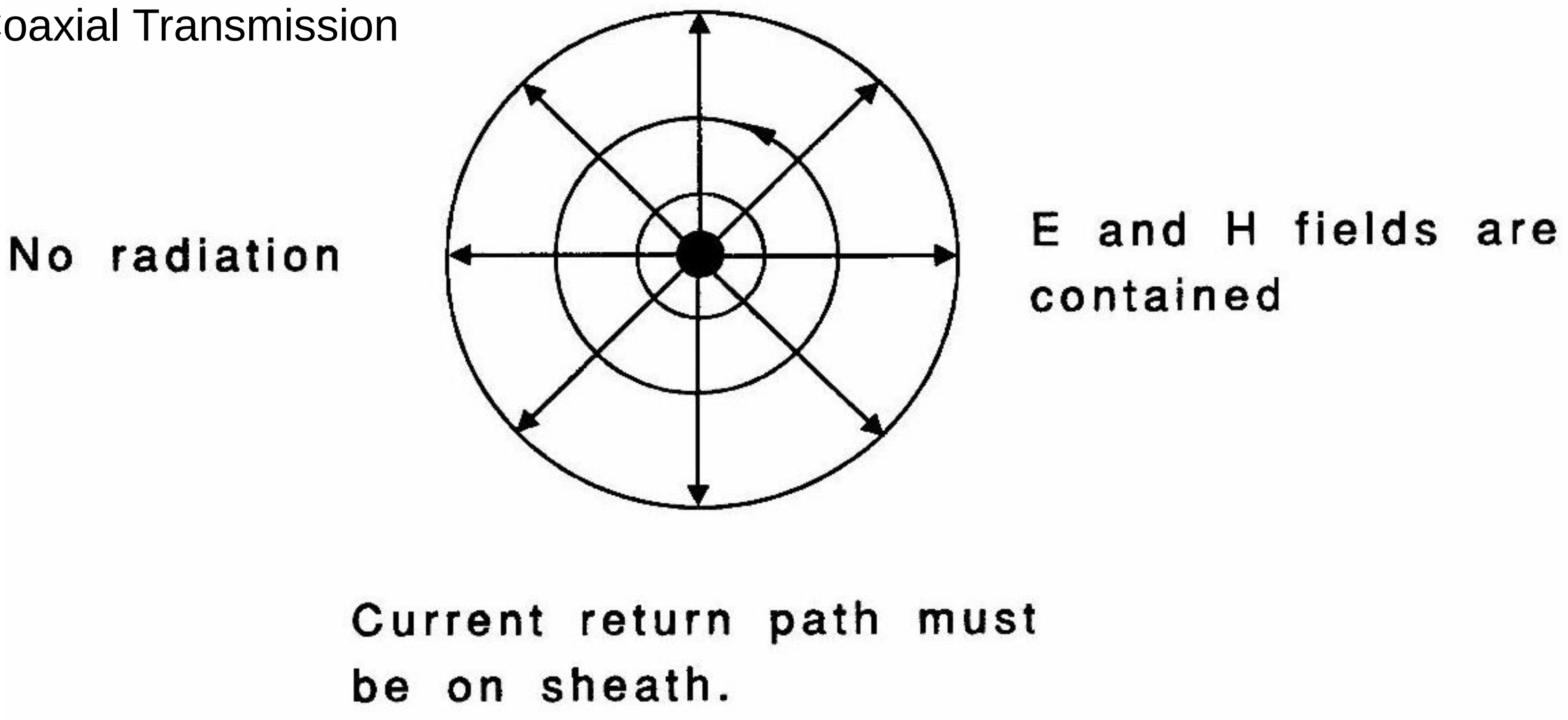
Contained Fields are Friendly!



An equipotential surface around a charged sphere

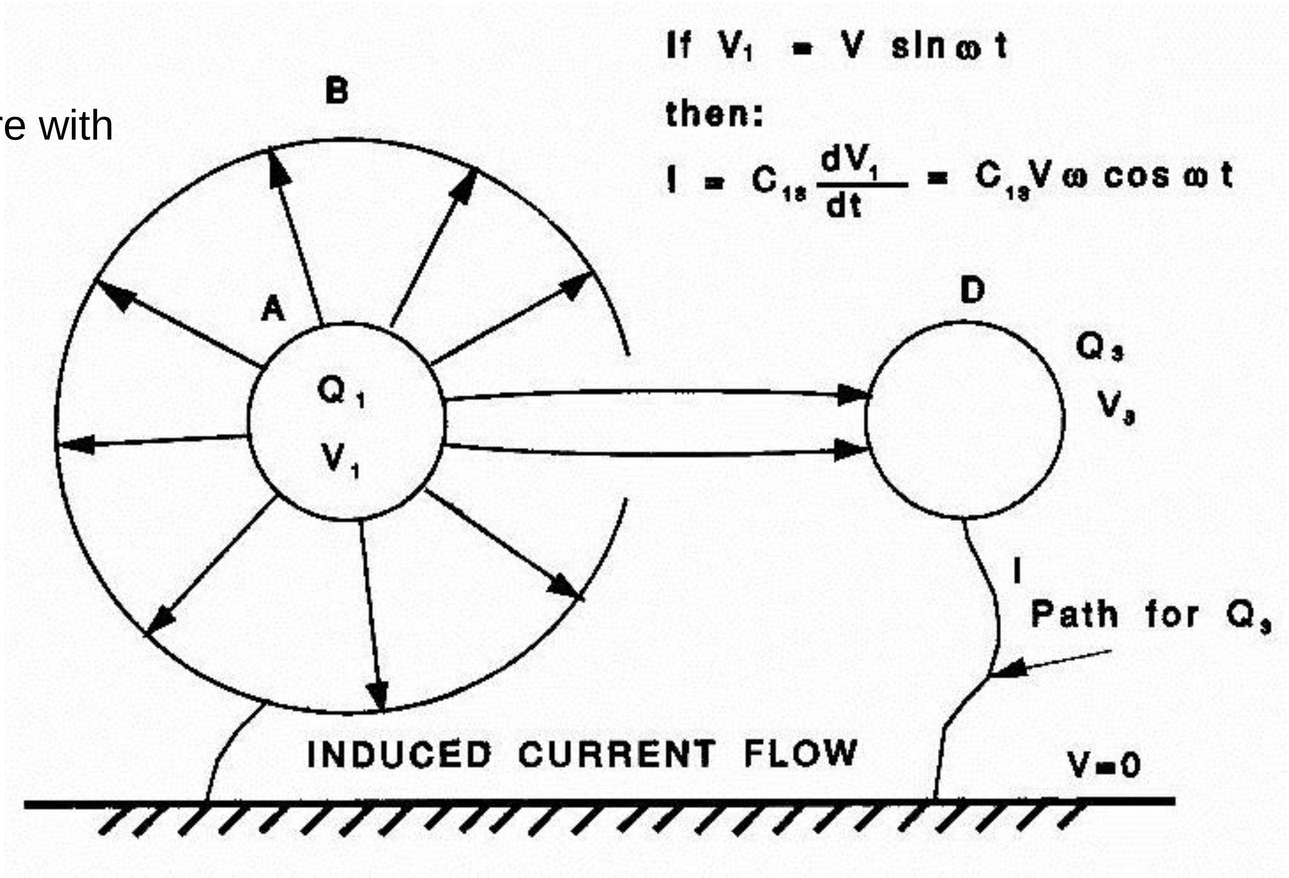
Contained Fields are Friendly!

Coaxial Transmission



A Loose Field is Not a Friendly Field

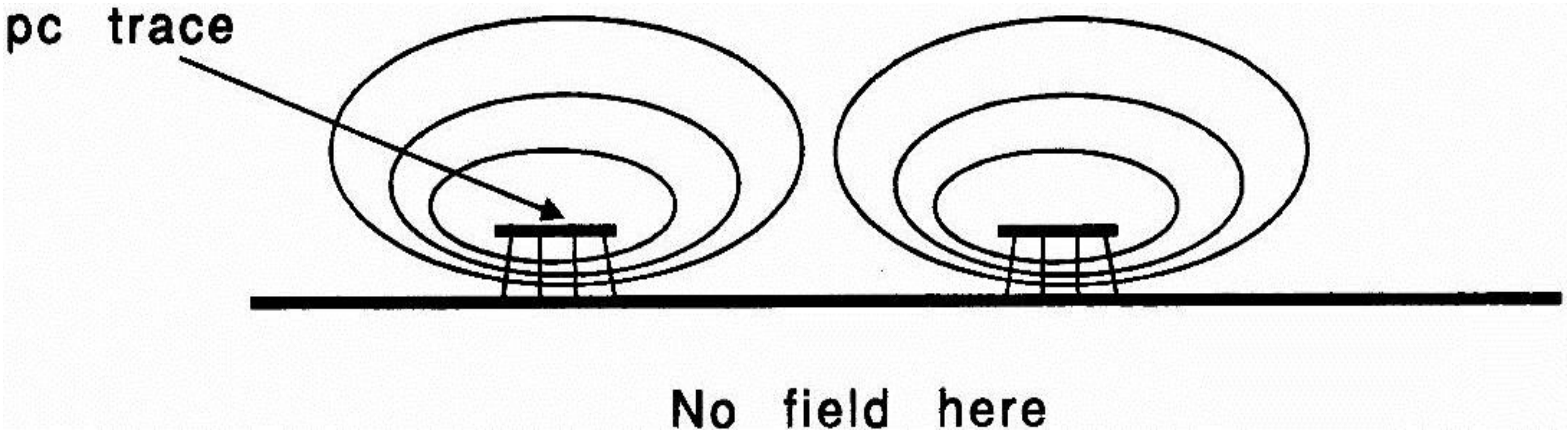
A shielded enclosure with an opening



Field is not contained and looks for trouble

Contained Fields are Friendly!

Fields concentrate under the traces and there is little crosstalk



Fields do not penetrate the plane

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

POWER SUPPLY BASICS

Energy Management

A capacitor is:

A conductor geometry that concentrates the storage of electric field energy

In a capacitor:

Field energy is stored in the space between the plates

An inductor is:

A conductor geometry that concentrates the storage of magnetic field energy

In an inductor:

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

Power Supply 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

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

Getting 1 Ampere to Flow

What does this mean in my circuit board?

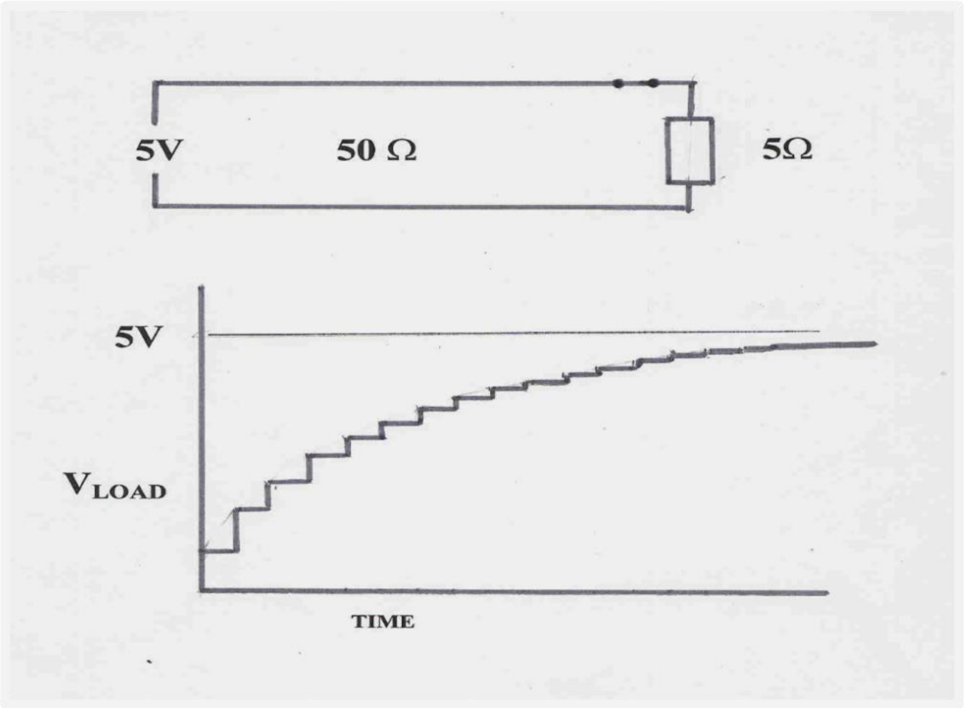
- Initial power level in a 50 Ohm line
  - 5 Ohm load and 5 V source
  - I = 0.1 amperes or ½ watt

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

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.



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!

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

- See the previous diagram!

WHAT'S IN THE WAVES?

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 wire bonds
- Between layers of Substrate (BGA) or lead frame (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.

Energy Delivery From A Storage Device

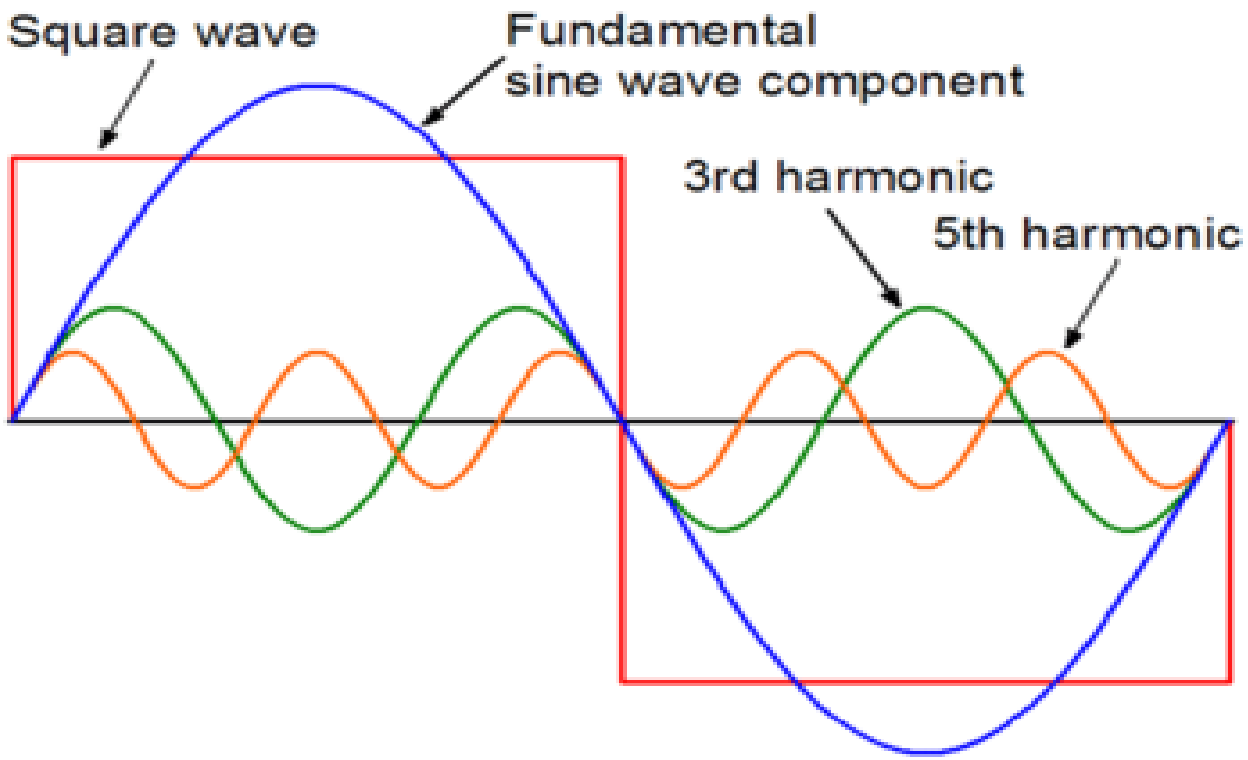
For energy to be delivered from a storage device:

- The wave requesting the energy (seen as a dip in the power supply caused by the switching event) has to travel to the source and back to the switch.

It's a two-way trip!

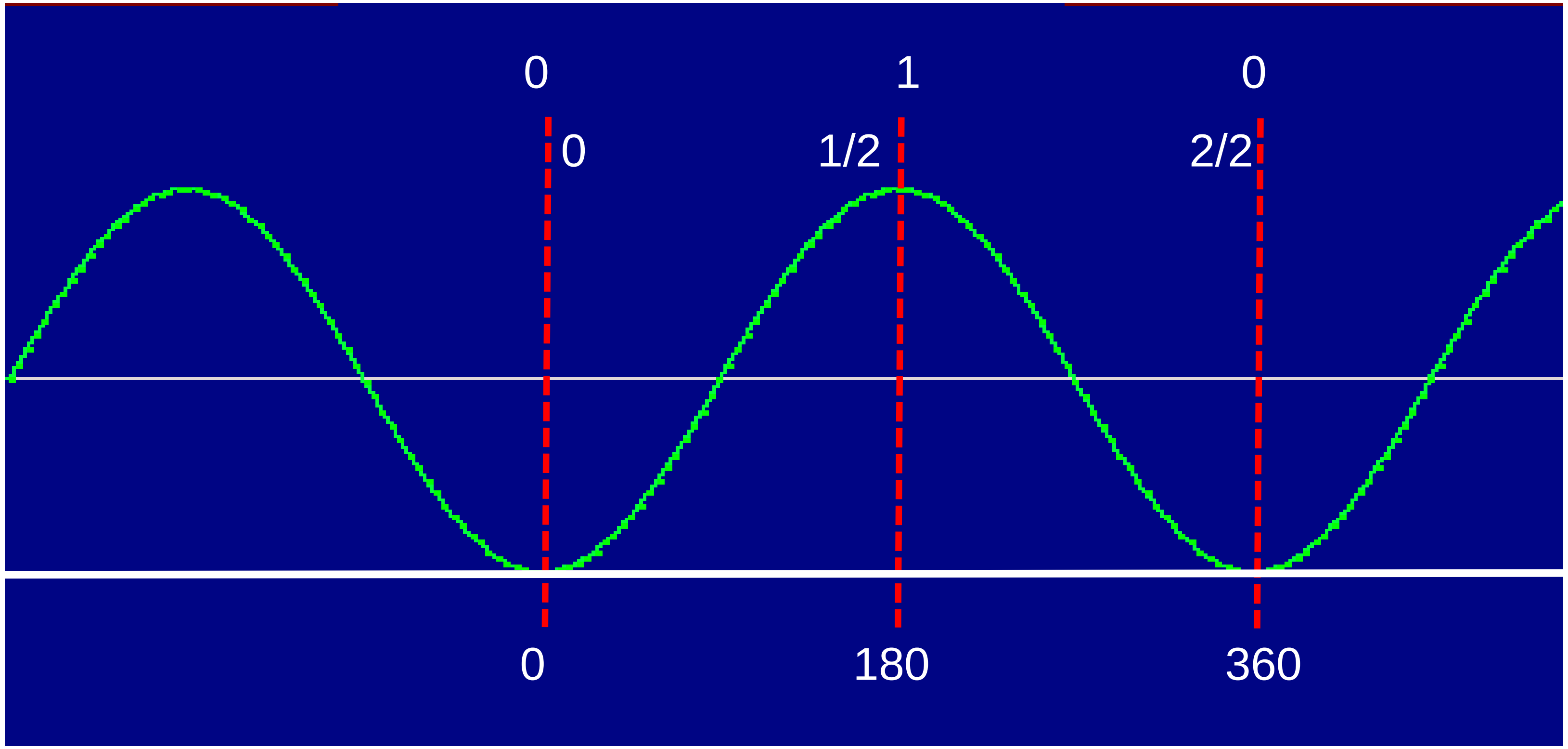
Digital Wave Perspective

- 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. 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

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.

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

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

Power Supply Connections

- Must be Well-Defined Transmission Lines
- Power traces MUST be one dielectric away from the return!
  - Adjacent to planar copper
  - Adjacent to ground trace
  - Any deviation from this WILL increase noise floor and radiated emissions, degrade signal integrity and decrease immunity

Field Storage Devices

- Energy storage component geometry and placement requirements are determined by the switching speed of the device
- The faster the switch, the more critical this becomes
- Do not expect behaviors from energy storage devices that are not possible

Field Storage Devices

- The frequency at which Capacitors can respond to energy requirements is determined by their physical geometry and the connecting copper, not by their value

  - Smaller capacitor packages respond faster because their connections are closer together

  - Devices which are closer to the switch respond faster because it takes less time to request and deliver energy

Field Storage Devices

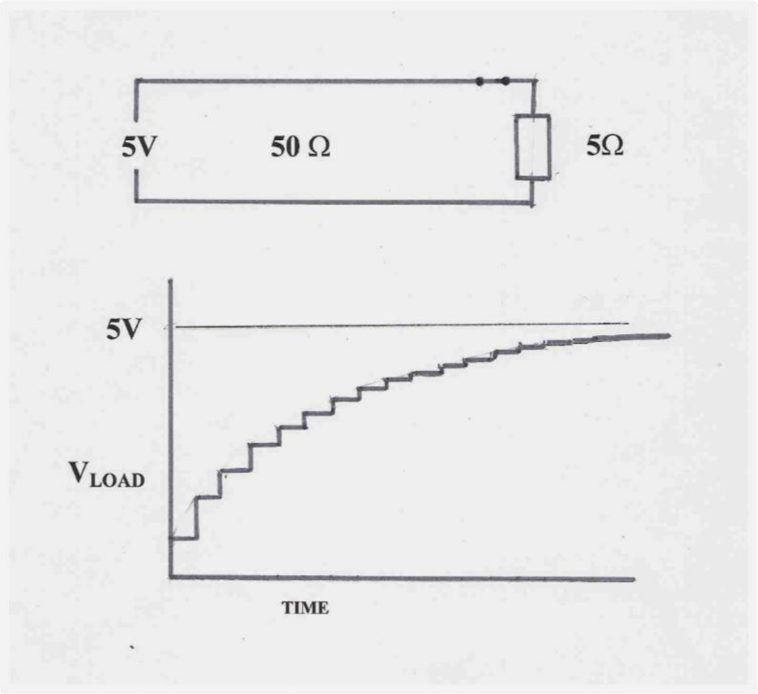
- Total energy delivered to each wave is determined by the impedance of the capacitor structure (ESR) and the interconnecting structures

- The time it takes is determined by the distance from the switch and the length of the plate structure

Remember This Slide?

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.
- Note to self: this is exactly how a capacitor behaves!



MANAGING THE SPACES

Now for the Eureka Moment!

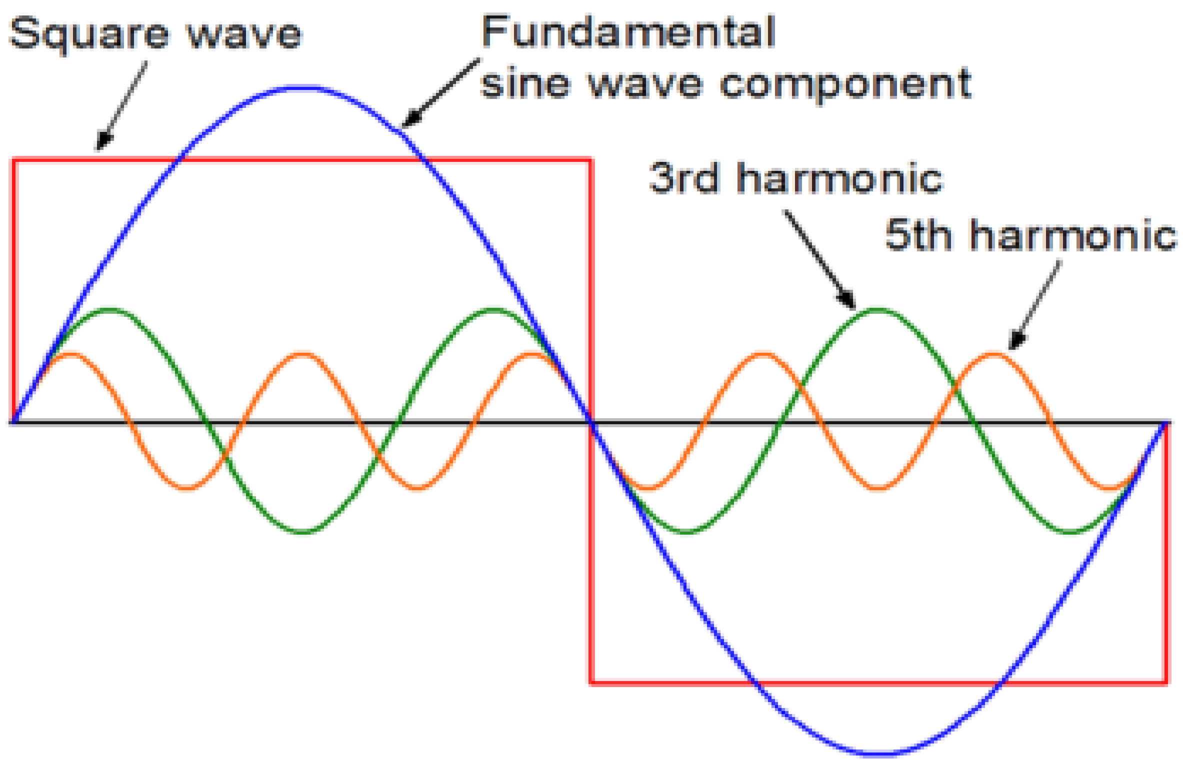
- Energy delivery from power supplies is a one way path!

- Each node in the power supply should be considered a discrete domain, with field energy traveling downstream from the power source to the switching device.

- The farther away from the switch, the longer it takes for the request for energy to be answered.

Now for the Eureka Moment!

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



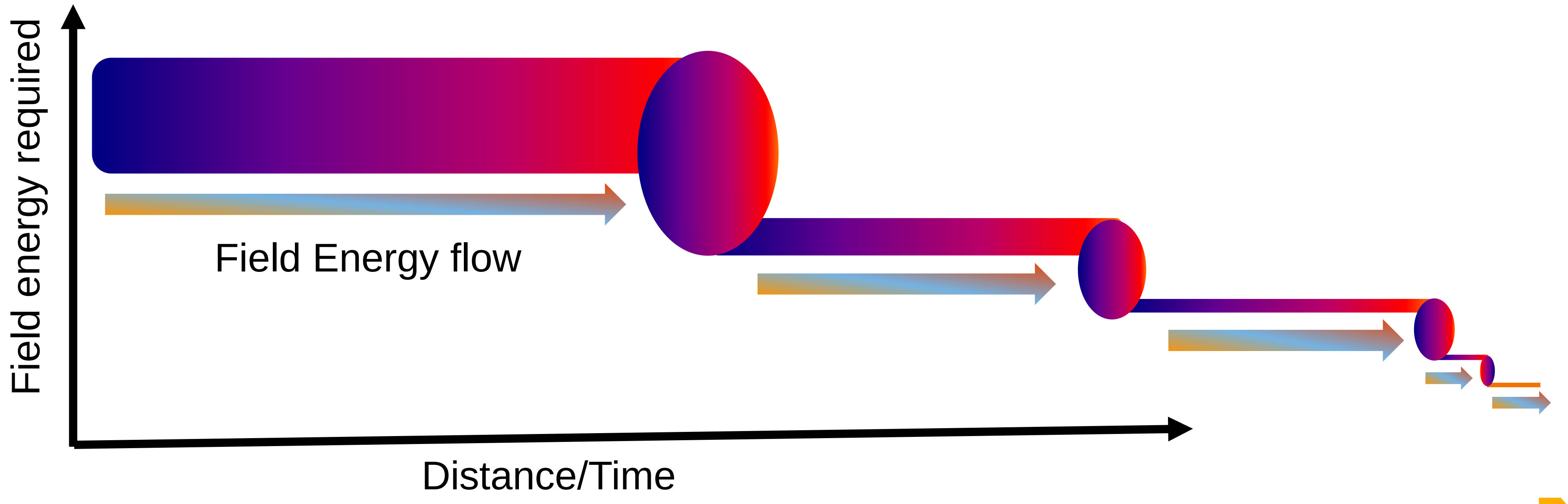
Now for the Eureka Moment!

- DO NOT ask for fast energy from a large package capacitor far away, and you will not be disappointed.

- Design the supply system to deliver different parts of the energy spectrum from matching structures.

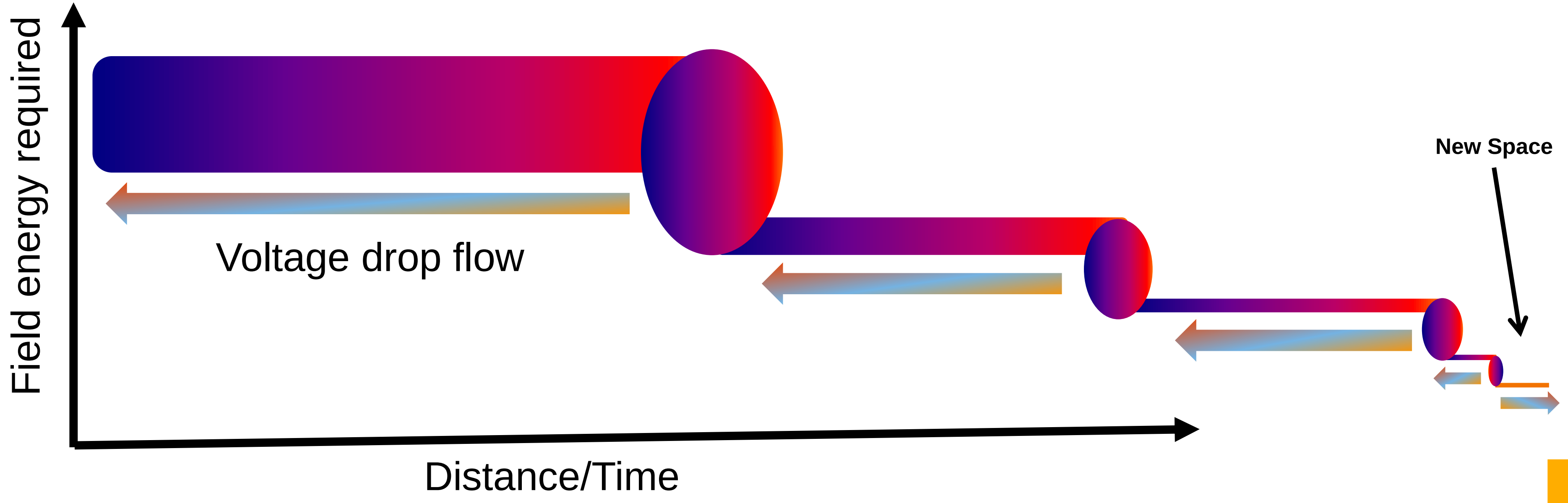
Now for the Eureka Moment!

- Imagine that you have water pipes of different sizes.
- The big pipes carry lots of water, but don’t respond quickly to changes in the output.
- The little pipes don’t carry much water, but respond quickly to changes in the output.
- The capacitors are like buckets for the water, they have to fill up before the water moves further down the pipe.
- The overall behavior is more like the loads are sucking the water, not that the source is pushing the water.
- Field energy is moving to the switch at the end to fill another space that is now connected when the switch is turned on.



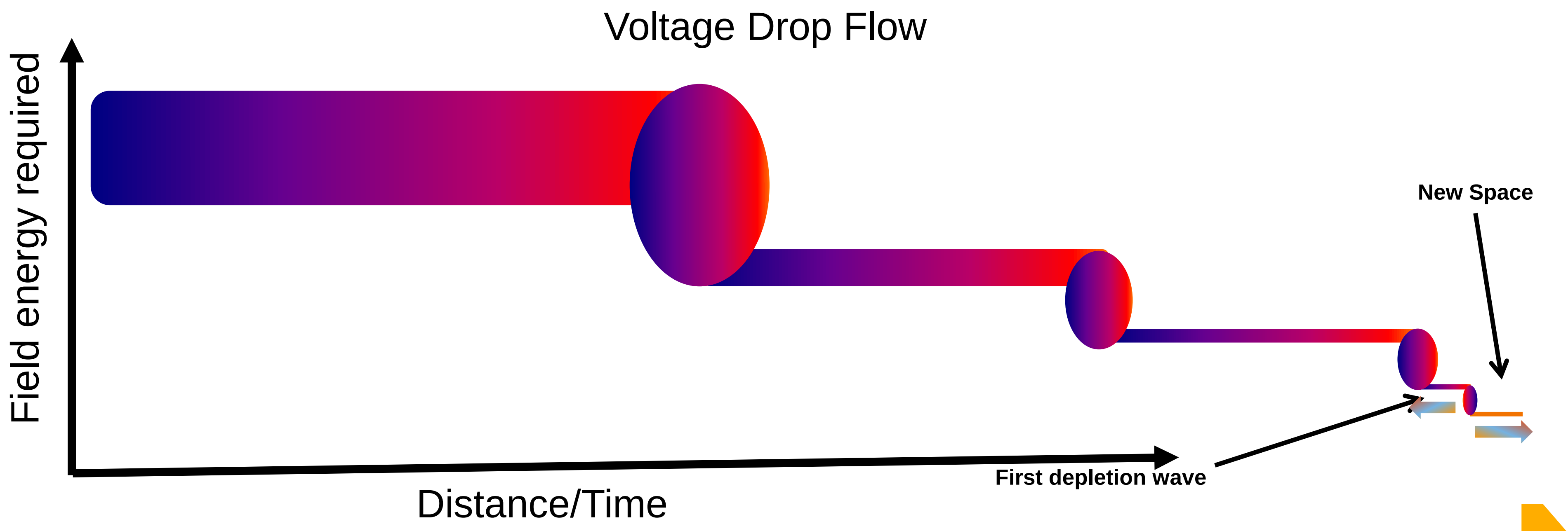
Now for the Eureka Moment!

- Yes! When you turn on a switch, you are adding a new space which has a different field density than the input to the switch.
- It takes time for the new space to fill with EM field energy, and it moves from the switch outward, inducing current flow in the conductors as it moves through the new space.
- Displacement current through the dielectric is what completes the circuit as the energy moves to fill the new space.
- The field density near the switch drops, as the energy moves into the new space.
- This causes a wave which travels upstream until it finds a discontinuity (change in transmission line geometry, or “impedance”) and reflects back with more field energy to replace that which moved into the new space.
- This process continues until either the switch is opened, or the new space has the same field density as the power supply.



Now for the Eureka Moment!

- Each reflection causes a drop in field density at the discontinuity, which in turn causes a new wave to move upstream to get more energy.
- The reflections from energy storage devices which are closer return faster. Reflections from discontinuities that are farther away take longer.
- This process continues until either the switch is opened, or the new space has the same field density as the power supply.



Now for the Eureka Moment!

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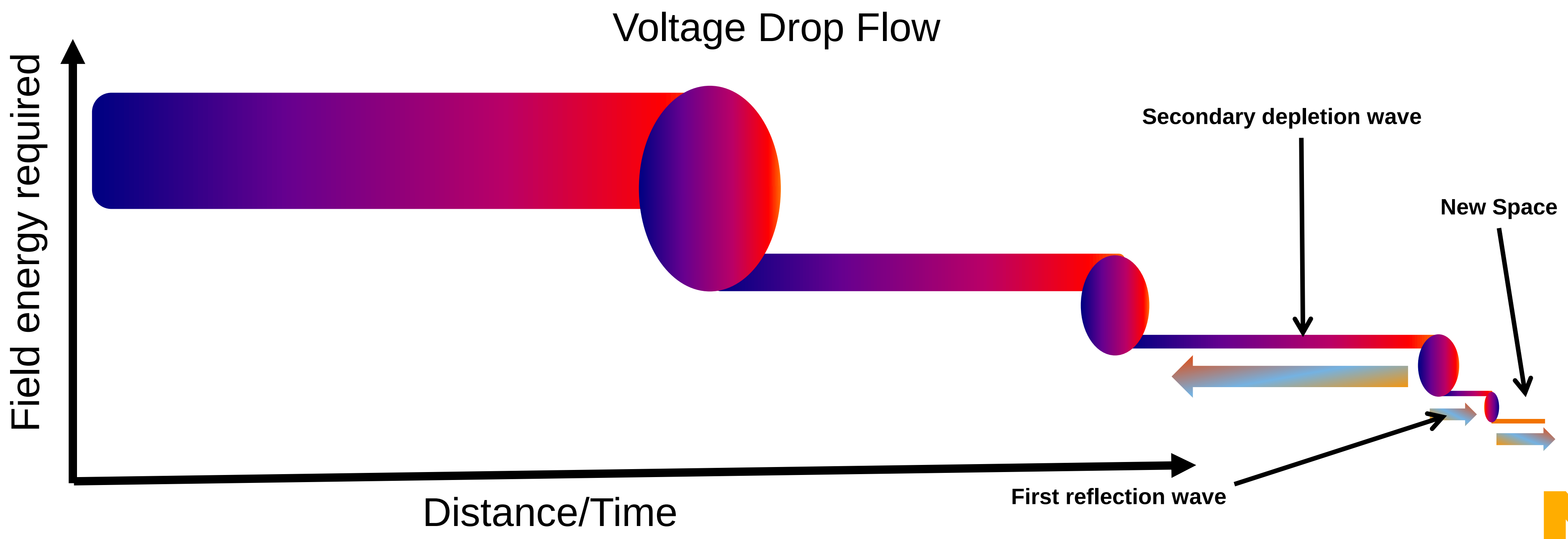
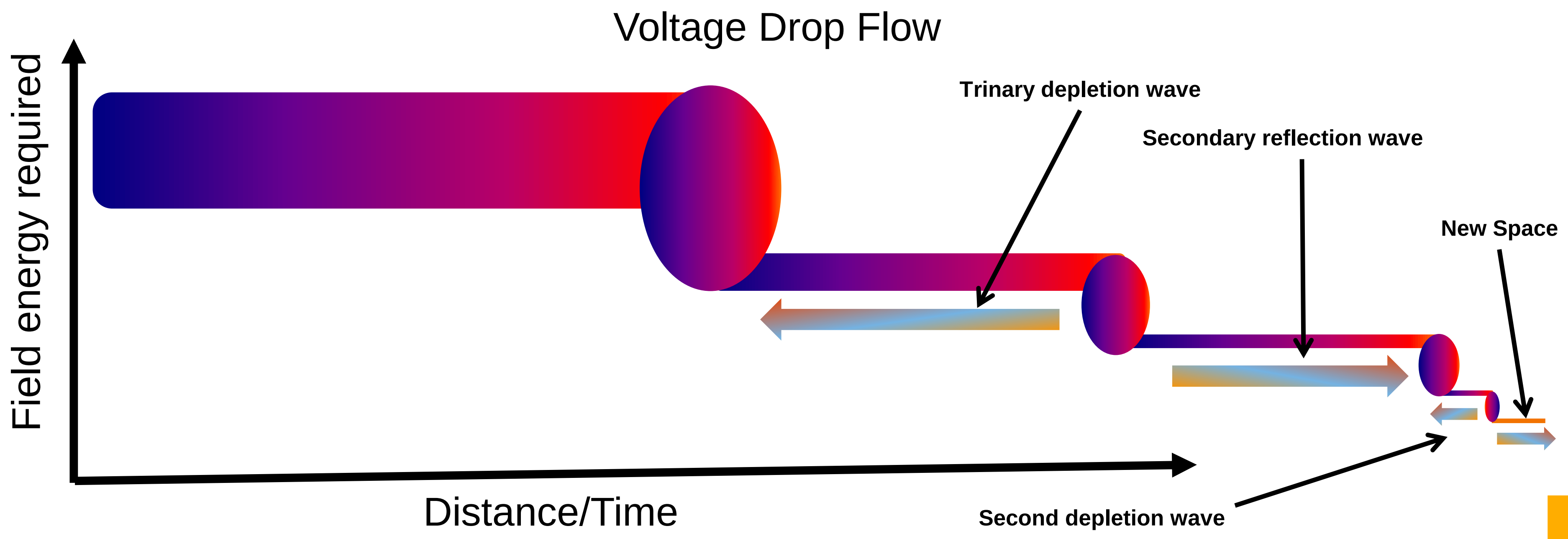


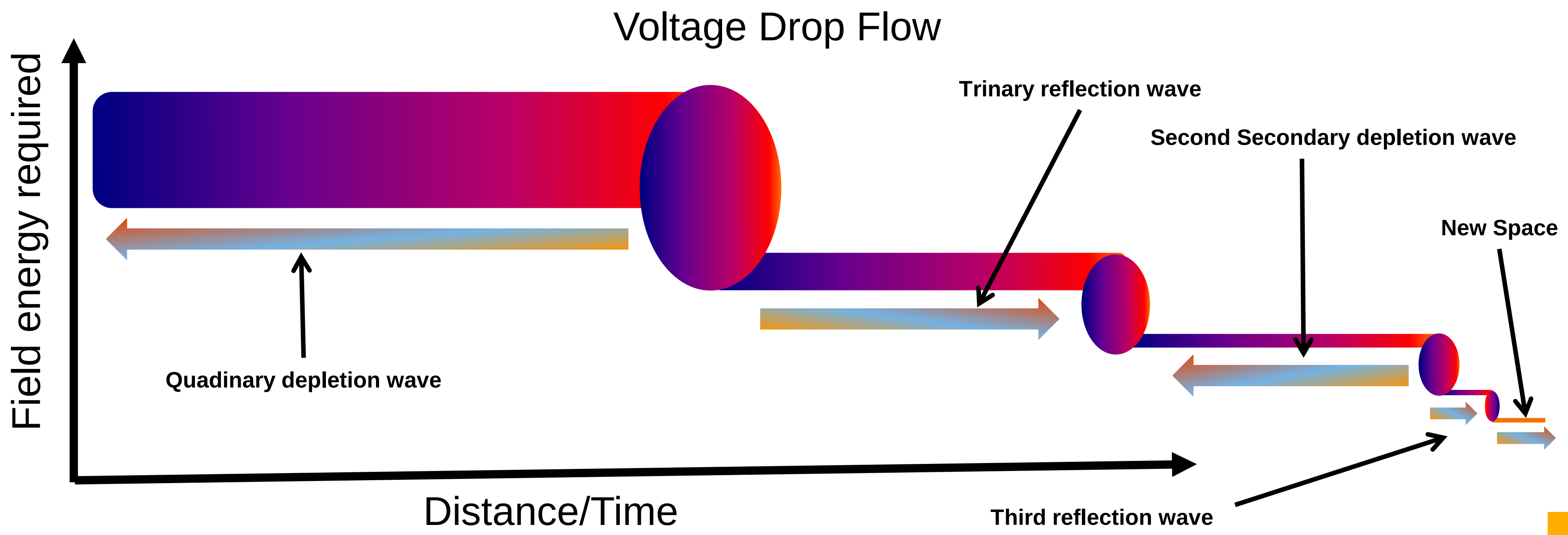
Now for the Eureka Moment!

- The charge storage devices upstream do not see any field depletion waves until many, many cycles occur at the switch point, because they are farther away!!
- Most system noise (radiated emission) is the result of too little energy stored close enough to the switch to keep the higher frequency depletion waves from finding a conductor that is long enough to be an antenna
- This is determined by the switching speed of the driver



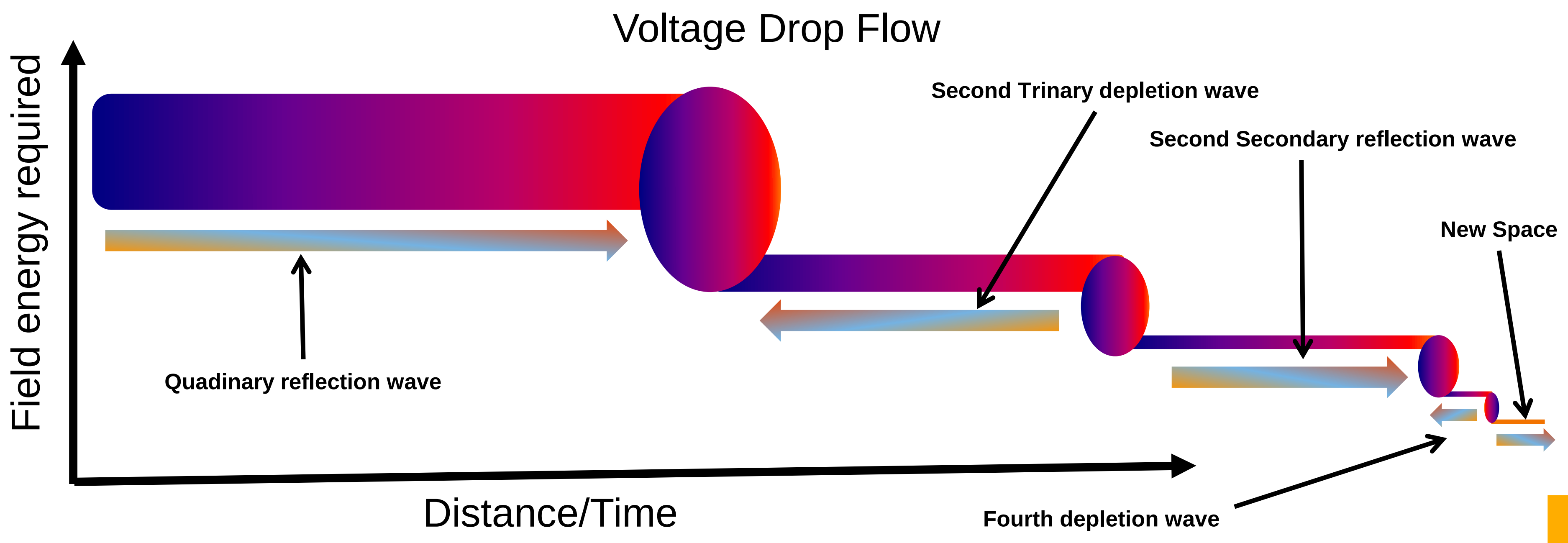
Now for the Eureka Moment!

- The goal of a good power supply design is to prevent this, and insure that the depletion/reflection cycles upstream have a slower and slower slope to the wave front
- The geometry of the transmission line and the energy storage device determine the cycle time and the amount of energy each wave contains
- In most designs, the connections to the capacitor packages pose the largest discontinuities, because the connections are farther apart than the power supply transmission line conductors



Now for the Eureka Moment!

- Proper power supply design results in depletion/reflection cycles with increasing cycle times and decreasing wave front slopes
- This is driven by the distance between field storage devices and their package sizes
- Proper power supply design results in a virtual steady state flow of field energy from the input power supply to the devices which consume the field energy
- It is all about managing the movement of field energy through the spaces



Now for the Eureka Moment!

- The goal is to create a network that basically allows for steady state delivery of energy, with each successive element only responsible for providing energy for the next downstream user.
  - Remember this list?

Energy source hierarchy

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

Now for the Eureka Moment!

- Each can supply energy determined by the space it contains and the space between the elements

- On-chip capacitance
  - Closest, supports the highest frequencies
- Space between the wire bonds
  - Farther away, but still help to feed the on-chip capacitors
- Between layers of Substrate (BGA) or lead frame (QFP)
  - Farther still, feeds the wire bond spaces
- Power/ground plane pairs, if present
  - Power islands are best, used to collect the power pins and connect to the next element, feed the package
- Local bypass capacitors
  - Small geometry (usually 0402), placed as close as possible, feed the power islands or package
- Field energy stored across the PCB structure
  - Larger packages placed in the realm of the ICs, feed the local bypass devices
- Bulk storage capacitors
  - Near the voltage regulator, feed the regional capacitors
- Finally the power supply
  - Collects energy from the outside world and fills the bulk capacitors

Now for the Eureka Moment!

- In designs where there is not enough energy storage close to the switch, or the connections between the elements of the power distribution system are not one dielectric away from each other, the result will be switch coherent radiated emissions.
- The frequency of this noise is determined by the switching speed of the switch itself. The pulse recurrence time of the noise is driven by the distance between the discontinuities and the period of the switch toggle.
- Clock coherent switching noise results from inadequate energy delivery to the IC core
- Bus coherent switching noise results from inadequate energy delivery to the address/data bus drivers

Now for the Eureka Moment!

- This will not work unless they are all transmission lines!!
- Must be Well-Defined Transmission Lines
- Power traces MUST be one dielectric away from the return!
  - Adjacent to planar ground copper
  - Adjacent to ground trace
  - Any deviation from this WILL increase noise floor and radiated emissions, degrade signal integrity and decrease immunity
- Important facts to remember
  - When a switch is closed, it becomes a power supply (the same behavior and rules apply)
  - When a switch is closed, all of the other switches using the same source of energy that are closed will see the depletion waves, including the spaces they are connected to

Now for the Eureka Moment!

- From all of this, we can see that most EMC issues result from starving the switches
- Correcting most EMC issues requires providing adequate energy from close enough sources to prevent the depletion waves from finding an antenna

- You prevent EMC issues by insuring the switches are properly fed, not by restricting the flow of energy

- One more point:
  - In a good power supply design, there is no need for ferrites, inductors, or filters, reducing system cost

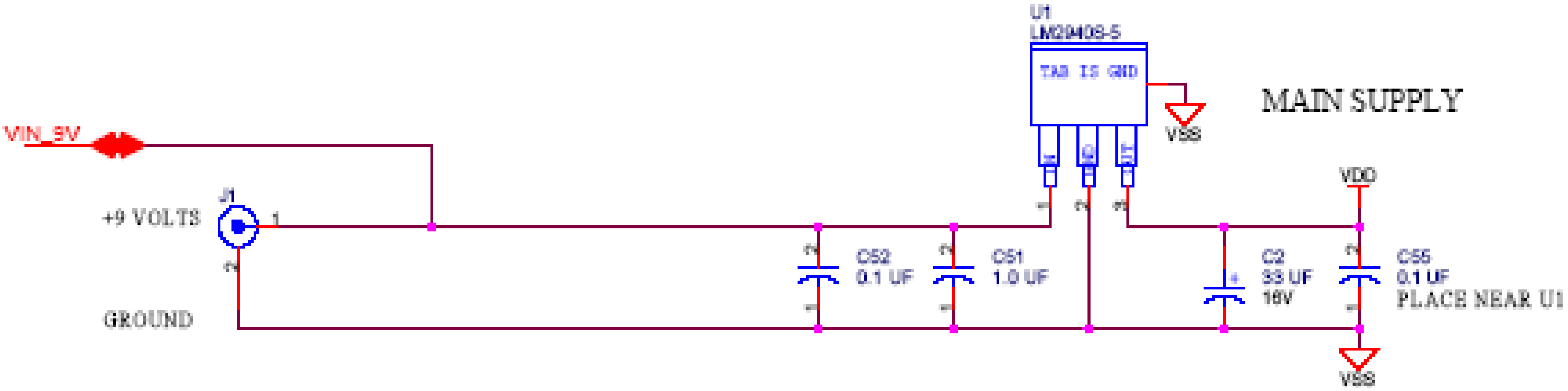
COMPONENT PLACEMENT AND ROUTING

Where Do We Start?

- Board outline / usually pre-determined
  - Defined by previous product
  - Customer requirements
- Placement
- Pre-defined components / usually connectors
- Filter components / high priority, must be as close to the pins as allowed by manufacturing
- Power control / as close to connector involved as possible
- Voltage regulators
- Power switching devices
- See number 2 above

Power Supply Design Made Easy!

- Schematic must be evaluated during layout
  - Schematic is often lacking in order definition
  - Capacitors must be placed in the daisy chain in the correct order



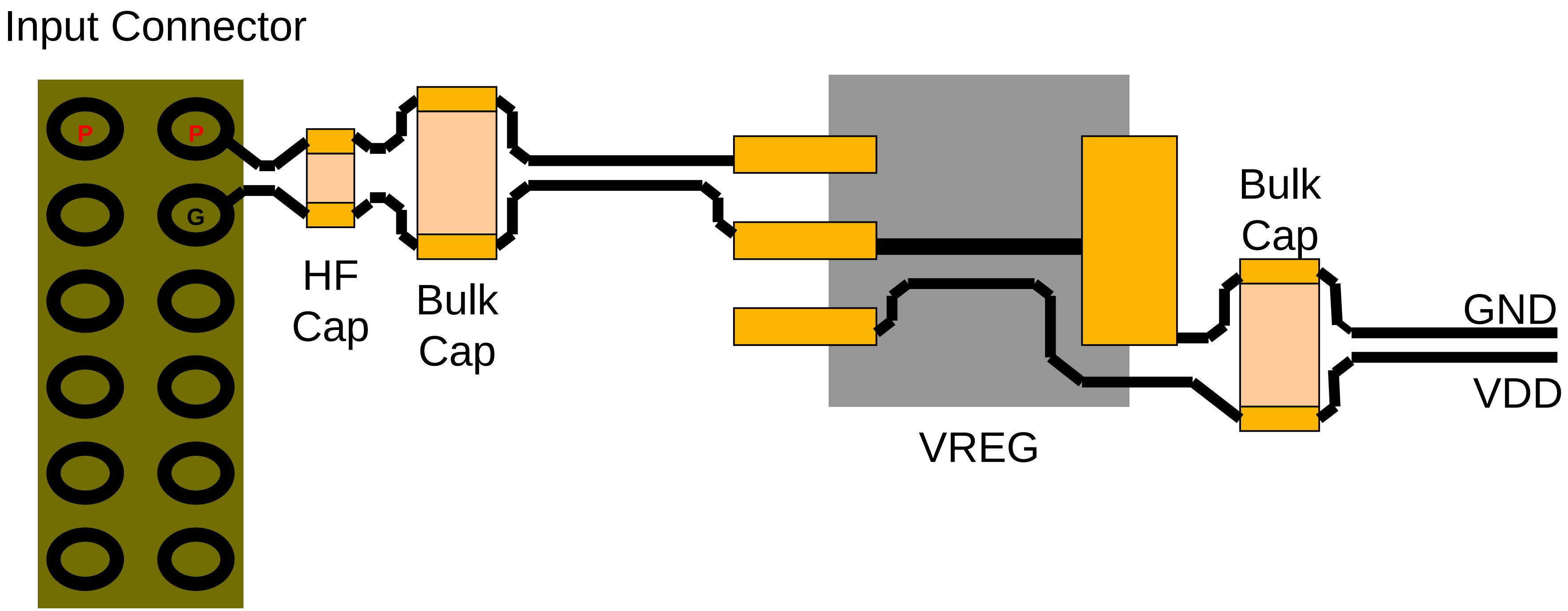
PCB signal Transmission ~~Line~~ Routing

- The first and most important job is to route the power distribution network – it is the source of all of the electromagnetic energy you will be managing on the PCB.

- On low layer count boards, with no dedicated ground plane, the power lines must be routed in pairs
  - Power and ground
  - Side by side
    - Trace width determined by current requirements
    - Spaced as close as manufacturing will allow them
  - Daisy chain from source to destination, connecting to each component, then finally to target devices

- Minimize the volume of the power transmission network

PCB signal Transmission ~~Line~~ Routing



Minimize loop area, or field volume

Energy flows from left to right, never the reverse!

PCB signal Transmission ~~Line~~ Routing

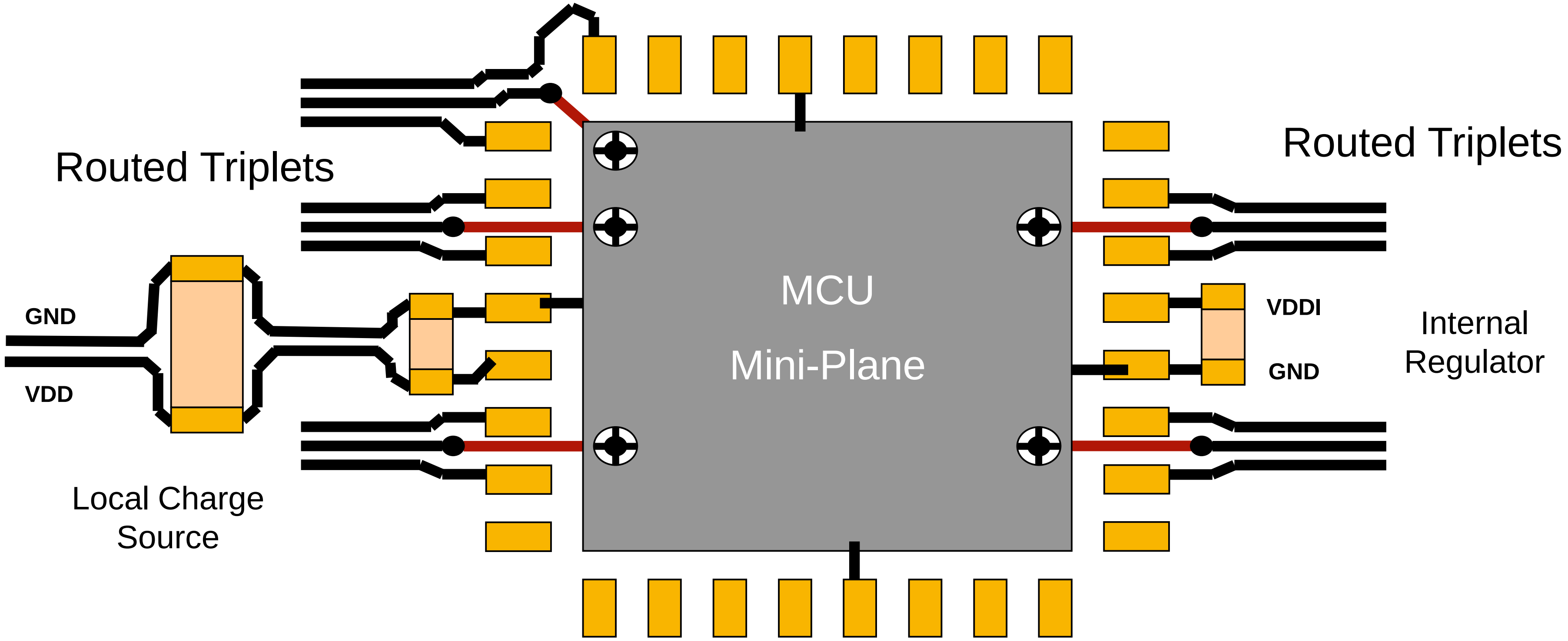
- Route power and ground traces as close as manufacturing allows
- Internal and customer separation requirements
- PCB fabrication limits for chosen supplier
  - Yes, you do need to know what the supplier can manufacture
  - Can have big impact on PCB cost
- Small changes in routing can have a large impact on performance
- Component placement is critical
  - Staying within lumped distance
    - Reduces component count
    - Reduces system cost
    - Improves EMC performance
    - Minimize the volume of the power transmission network

Power Supply Design Made Easy!

- PCB power transmission line routing
  - Power distribution component placement is critical
    - Supporting fast switches requires close placement
    - You MUST know how fast each device is switching
      - This determines the requirements of the power supply design
  - Input storage devices at the connector must be large enough to support the energy needs of the devices connected to them
    - Wiring harnesses are too long allowing energy to be delivered quickly
    - Design each element of the power network to put a steady state demand on the field sources immediately upstream
    - As you get nearer to each switch group, provide progressively smaller structures that are physically closer

Power Supply Design Made Easy!

PCB signal transmission line routing



PCB LAYOUT CONSIDERATIONS SOME NEW “RULES OF THUMB"

PC Board Considerations

Flooding unused spaces on the PCB with Ground:

- Properly implemented, will improve EMC performance
- Reduce cost by increasing PCB manufacturing yield
  - Less etch required, so less chemical is used
  - Balanced copper improves plating and
- Balanced copper improves final assembly yield
  - Reduced board warping

Remember to stitch the ground islands and planes together

  - Trying to make a pseudo-Faraday cage!

PC Board Considerations

- **Use minimum trace widths and spacing for signal transmission lines**
  - Refer to PCB fabricator's capabilities without a cost adder
  - Same thing goes for drill sizes and pad rings
- May be defined by either customer or internal requirements
- Wider traces for power supply transmission line pairs
- Provides maximum trace density

- **Make room for all of those ground traces!**

CLOSING REMARKS AND REFERENCE MATERIALS

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
- Switching speed determines the power supply requirements, not just the DC current specification
- 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 NXP. 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

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

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

It’s All About the Space!

“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
- Well-defined transmission lines are critical for power supply design
- Switching speed of the output devices determines the requirements of the power supply
- Using the correct physical size of capacitors in the correct place are key to reducing power supply noise
- Don't expect anything from the power supply components that they cannot deliver
  - Distance from the switch tells you how long it takes to request the energy
  - Size of the package determines the amount of energy you get in each wave
- The black magic is tamed!

- Q&A

THANK YOU

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