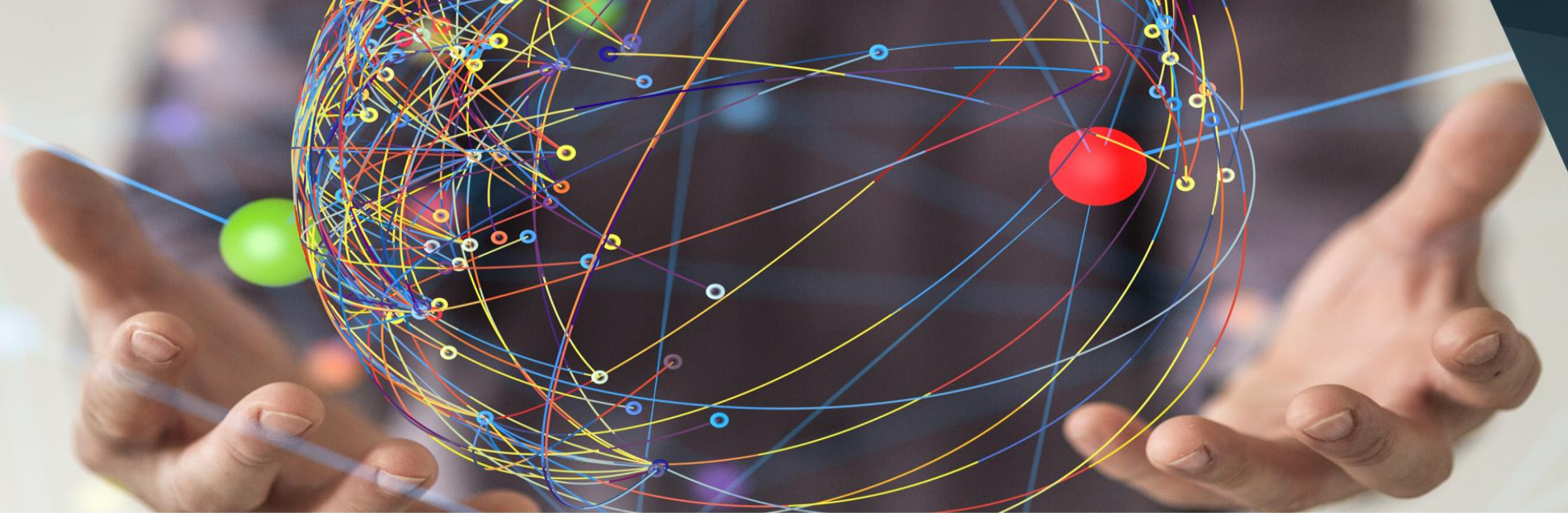


Science-based PCB Design

EM Physics Demystified

Daniel Beeker
Technical Director
NXP Semiconductor



The Billion Dollar Mistake

A simple diagram was all it took!

Daniel Beeker | Technical Director
NXP Semiconductor

NXP Semiconductor

We Are NXP

Committed to our people, our communities and our world.

From Austin to Toulouse, Shenzhen to Nijmegen, our people around the globe work to advance our world and make it a safer, smarter, more connected place. We're reaching those goals through our exceptional technological innovations, giving back to our local communities and instilling pride in our employees. Together, we're a united front, a force for good. Together, we are NXP.

Wij zijn NXP. 我們是恩智浦. Nous sommes NXP. 우리는 NXP입니다.
Wir sind NXP. 私たちはNXPです

Our People: The Heart of NXP

Our diverse and talented employees drive the innovation that sets our company apart and fuels our success in the market. NXP employees have a customer-focused passion to win, embrace new technologies and challenges, take pride in their work and seize opportunities for excellence, all while supporting each other.

Diversity, Equality and Inclusion

We embrace an inclusive culture with teams comprised of talented individuals from diverse backgrounds and cultures, each with unique experiences and ideas, regardless of race, gender, sexual orientation, nationality or social/economic background.

Disclaimer

- If you have taken this class before, there are not many changes.
- I teach other classes that contain similar material.
- If you are like me, you need to hear this more than one time for it to begin to make sense.
- I WILL continually mention the need for understanding how fields behave in order to be able to use them effectively.
- I would play my song over and over to brainwash you.

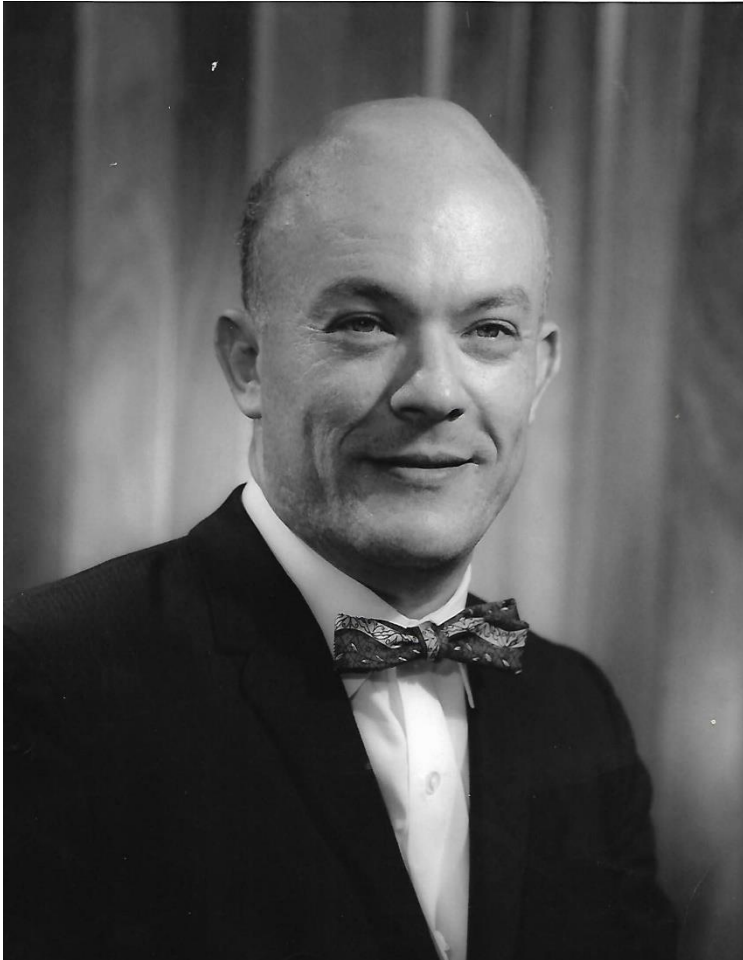
- This seminar emphasizes the need to concentrate on design of transmission lines, or the “spaces,” instead of the “wires.”
 - The industry focus has been on the movement of charges in the wires, which only occurs because the electric fields are moving.
 - The energy is carried by the fields, not the displacement current.
 - My apologies to the EM physicists for oversimplifying these concepts, but this approach will increase the chances of success for most designs.

The Billion Dollar Mistake

About Me: Daniel Beeker

- 40+ years experience at Motorola/Freescale/NXP designing and working with microprocessor and microcontroller development systems
- 30+ 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

In memory of
Ralph Morrison
January 4, 1925-August 2, 2019



Ralph Morrison

January 4, 1925 - August 2, 2019

Books Published:

Grounding and Shielding in Instrumentation Wiley 1967 – (6th edition 2016)

DC Amplifiers in instrumentation - Wiley 1970

Instrumentation Fundamentals and Applications – Wiley 1984

Grounding and Shielding in Facilities - Wiley 1990

Noise and Other Interfering Signals - Wiley 1991

Solving Interference Problems in Electronics - Wiley 1995

The Fields of Electronics - Wiley 2002

Electricity - A Self Study Guide Wiley - August 2003

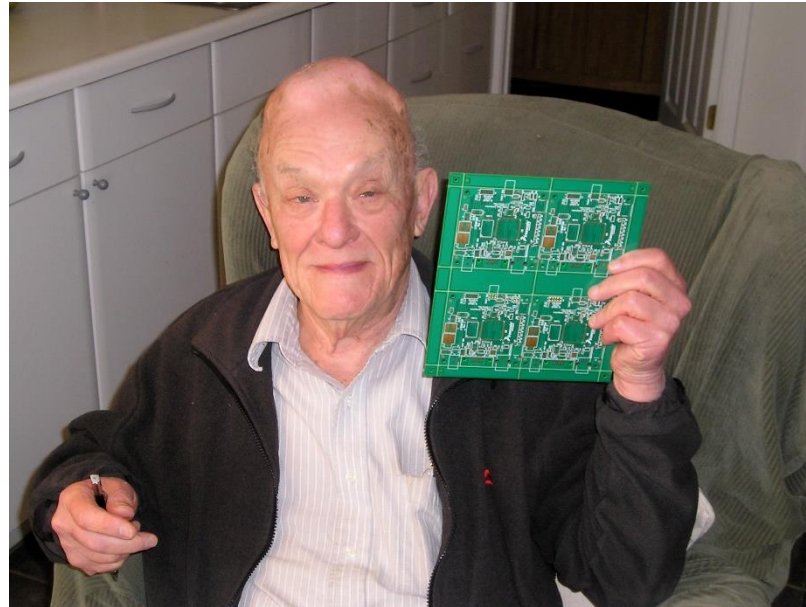
Electronics - A Self Study Guide Wiley - September 2003

Practical Electronics: A Self-Teaching Guide – Wiley 2008

The Fields of Electronics: Understanding Electronics Using Basic Physics – Wiley 2008

Digital Circuit Boards: Mach 1 GHz – Wiley 2012

Fast Circuit Boards: Energy Management – Wiley 2017



BS Physics 1949 California Institute of Technology
Pasadena, California

MS EE 1964 University of Southern California
Los Angeles, California

- Born in Los Angeles of immigrant parents in 1925, Ralph Morrison grew up in the great depression of the 30s. Ralph was uncertain whether to follow a career in music or science. He was keenly interested in electricity and radio as a teenager. Drafted at age 18, Ralph served in the infantry in WW2 in Patton's 3rd Army. He then used the GI Bill to get a BS in Physics from Caltech. After beginning his professional career at Applied Physics Corporation in Pasadena, Ralph received an MS in EE from USC at night school. Ralph designed instrumentation amplifiers for aerospace and formed a new company called Dynamics Instrumentation and functioned as VP of engineering. Ralph wrote numerous articles on shielding that were excellent sales tools. This led to writing his first book published by John Wiley in 1967. This book titled Grounding and Shielding has been rewritten every ten years and is now in its 6th Edition, selling over 2 million copies worldwide. He also wrote 12 other books on related topics.



A Passion for Music

Ralph was a serious and accomplished violinist.

A Passion for Music



Ralph and Elizabeth, a cellist, met while playing Beethoven.

In Case You Already Forgot...

“All About the Space” To the tune of Meghan Trainor’s “All about That Bass”. Copyright 2015 Daniel L. Beeker. <http://youtu.be/WglPHiZx4Gw>

Because you know it's all
about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space... space...
space... space

Yeah, it's pretty clear, you
don't believe it
But the wires just show, just
show, where all the fields
will fit
'Cause all the energy only
moves in the space
“Gotta put all the wires in all
the right places”

I know your teacher said, it's
the conductor
We know that's not the way,
don't listen to, the
instructor
If you got fields a movin', you
got current flow
'Cause it's the movin' fields
that really make
everything go

Yeah, your teachers they told
you "don't worry about
the field"
They said, “The math that
they use isn't something
you wish to wield”.
You know that circuits are
better, you just have to
make them connect

So, if that's what you're into,
then you know what to
expect
Because you know it's all
about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space... Hey!

I'm bringing physics back
Go 'head and tell them circuit
fossils that
No, I'm just saying, I know
you think they're right
But I'm here to tell you...
Physics tells us that it fields in
space that's really outta
sight

I know your teacher said, it's
the conductor that holds
the key
We know that's not the way,
you've gotta listen to me
If you got fields that are
movin', that makes all the
current flow
So, you gotta take all of this
in, and lose all that you
know

Because you know it's all
about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space, not wires
It's all about the space
'Bout the space...

EMC Certification

- Engineering teams around the world are facing increasingly difficult challenges to design electronic products and achieve good signal integrity and compliance.
- The status quo had become to expect the design to fail EMC testing, and not just once, but three, four, maybe even five times.
- Each time the design is sent to be retested, there is little confidence in success.

Negative Cycle

- This cycle is expensive in both the time it takes to redesign the product and the cost of expediting fabricating the new PCB and assembly
- Add this to the cost of retesting the product, and the numbers add up very quickly.
- This expense, and delay in product certification is not in the budget or the schedule.
- The expense not only directly affects the bottom line of the electronic supply company, but also affects the customers waiting for the product.

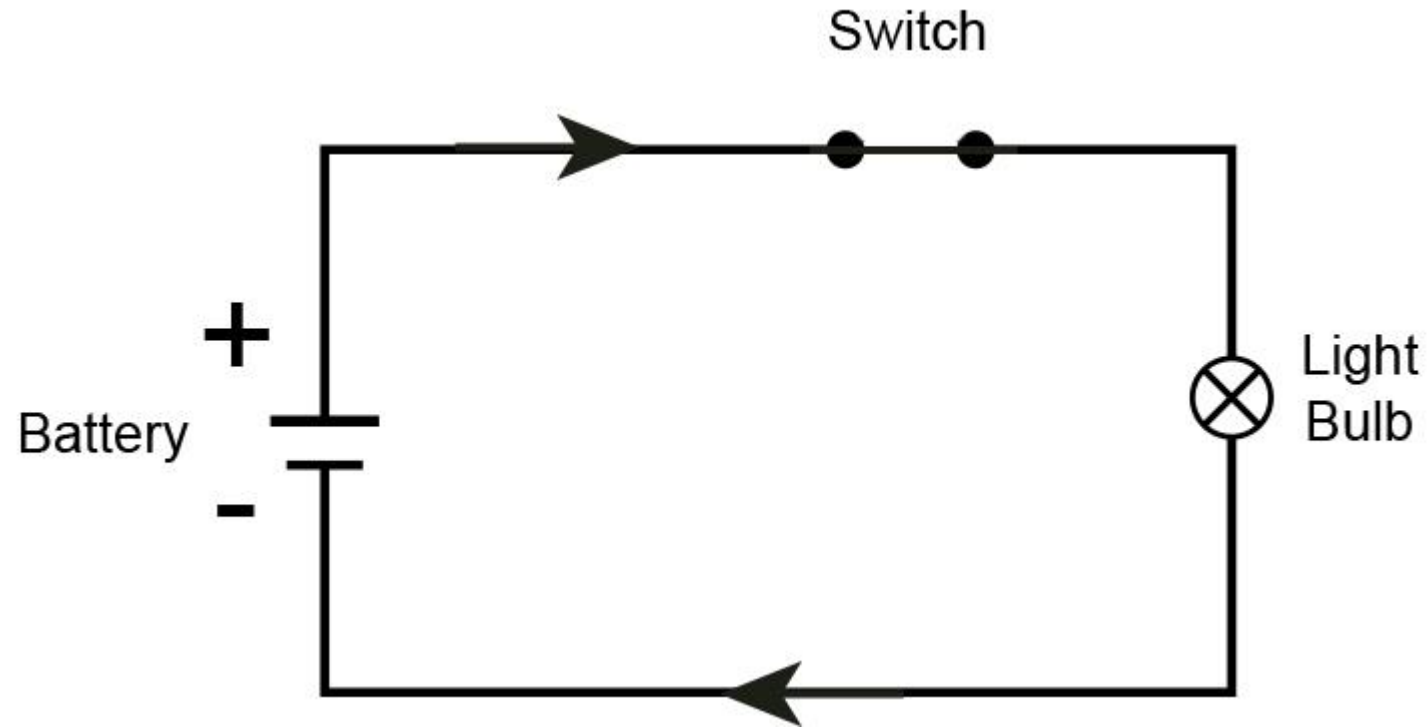
EVERYBODY LOSES!!

Impact on Future Products

- Instead of designing the next big thing, teams are trying to fix the current one.
- Billions of dollars are lost each year designing products that most likely will not work. What is wrong here?
- The billion-dollar mistake is rooted in the misunderstanding of the nature of electronic energy.
- One drawing is to blame.

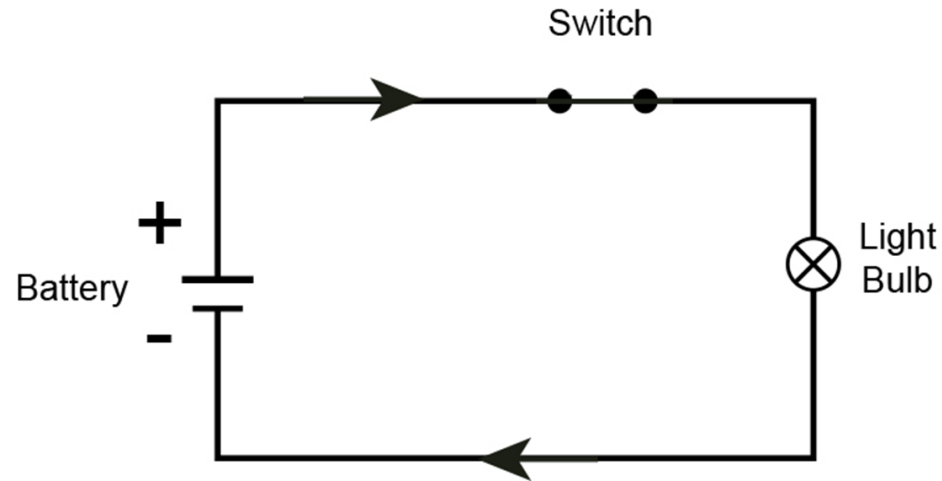
The Fatal Drawing

What is wrong with this picture?



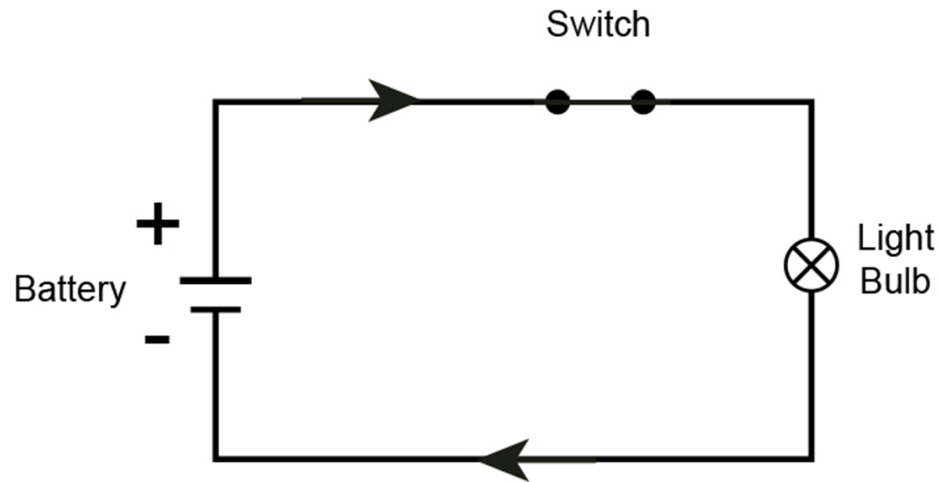
Picture courtesy of <https://mammothmemory.net/physics/electricity/which-way-does-electricity-flow/summary.html>

What is wrong with this picture?



- The perspective from this simple drawing has set the tone and philosophy for PCB design.
- The focus has been on current flowing in the conductor.
- The result has been a steady increase in failure to pass EMC requirements as the IC geometries grew smaller and switching frequencies increased.

What is wrong with this picture?



- The picture shows a battery connected by wires to a light bulb.
- The arrows are supposed to show current flow.
- From this, the wires started to be called “conductors,” since the energy flowed in the wires.
- The current flowed in a loop, so the idea that this was a circuit was born.

What is wrong with this picture?

- If this were true, then as soon as the switch was closed, the energy would be instantly seen at the load, and there would be no such things as signal integrity or EMC problems.
- *There would be no such thing as radio because the energy is the same in an electrical system or in the air.*
- There would not be any life on earth, as the light from the sun would not travel here without the wires.

What is wrong with this picture?

- WRONG! The wires are not conductors, they form boundaries, much like the banks of a stream (think “waveguides”).
- The energy does not flow through the wires, it travels through the space between the wires.
- This space, or dielectric, is the conductor.
- The energy is carried by the moving EM fields in the dielectric, not electron flow in the wires.
- Proper perspective for current flow is the amount of field moving past a point in the transmission line.

What is wrong with this picture?

- Ralph Morrison taught me how important language is.
- In this case, incorrect language set the stage for bad design practices.
- It became the norm to design the conductors, connecting the battery or power source to the load.
- As long as the speed of the switch was relatively slow, this appeared to be the correct perspective.

What is wrong with this picture?

- For earlier devices, this perspective was not so bad that it caused failures, leading to the creation of design rules that would lead to ever increasing difficulty in certification.
- This is quite like the tale of the frog in the pan of water. The frog does not notice that the water is heating until it is too late.
- The electronics industry has behaved much the same way.
- Now this incorrect perspective is costing the world billions of dollars every year.



Image courtesy of <https://www.pinterest.com/pin/8022105564247618/>

Ralph's Rules: Electromagnetic Field Energy

We all are involved with developing products which generate, control and consume **electromagnetic field energy**.

This is what we are taught:

- Circuit theory suggests that electrical energy is made up of electrons moving in the conductors.
- Switches add conductors, and the current instantly starts to move in the loop.
- The wires carry the energy, and the load instantly affects the flow of energy.

Wrong!

- Switches add new **spaces**, and the moving field carries the energy.
- It takes time for the field energy to move into that **space**.
 - The moving field energy has no idea of what it is at the end of the new **space**.
- Field energy moving through a **space** is the current flow.
 - The magic here is the displacement current flowing through the dielectric at the wave front, completing the circuit.

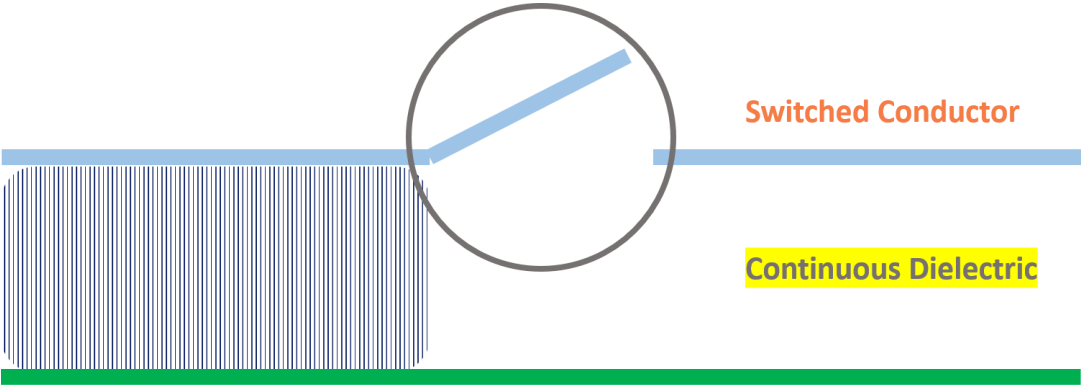
Heresy!!

- THAT is NOT what WE were taught.
- THAT is NOT the perspective we have used our entire careers.
- How dare you contradict my professors and my mentors?
- Didn't what we are doing work for years?
- Don't I just have to connect the pins and things will work?

...Wait a minute, then why do we have so much trouble with signal integrity and EMC??

Maybe there IS something we are missing...

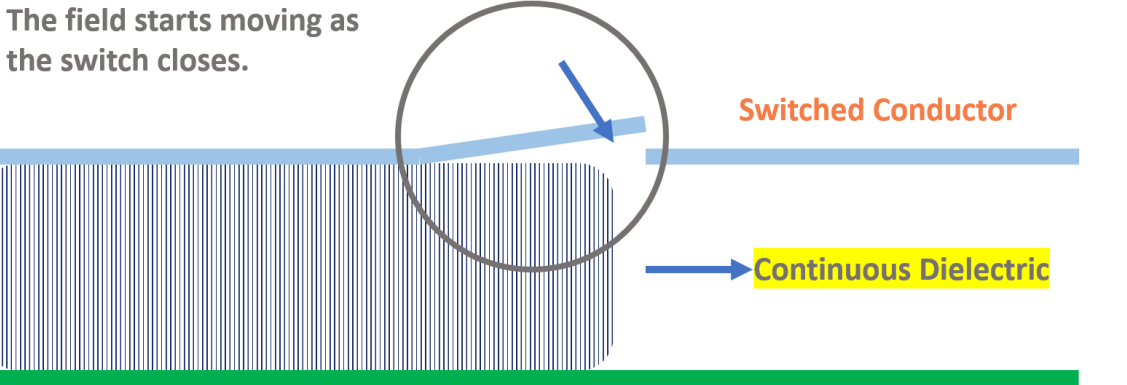
The Real Picture



Switched Conductor

Continuous Dielectric

Continuous Conductor

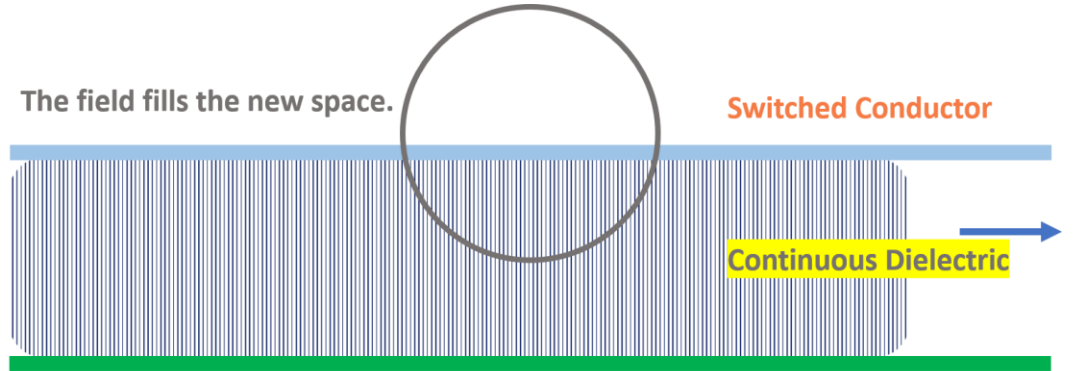


The field starts moving as the switch closes.

Switched Conductor

Continuous Dielectric

Continuous Conductor

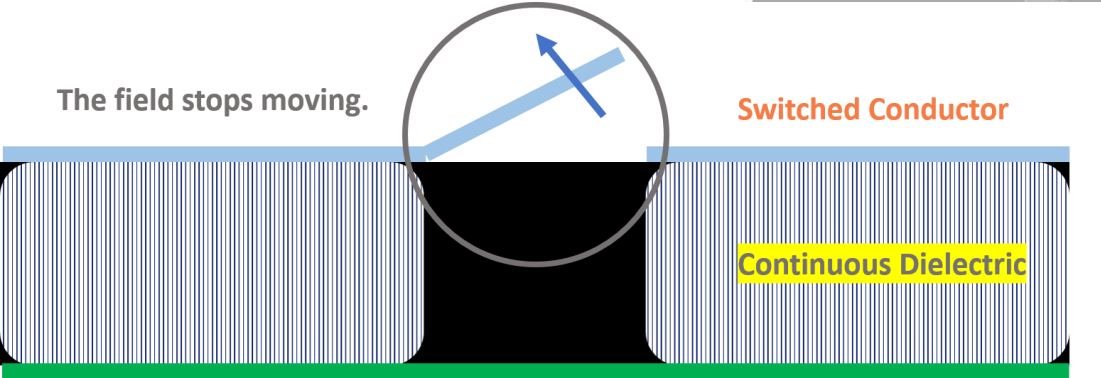


The field fills the new space.

Switched Conductor

Continuous Dielectric

Continuous Conductor



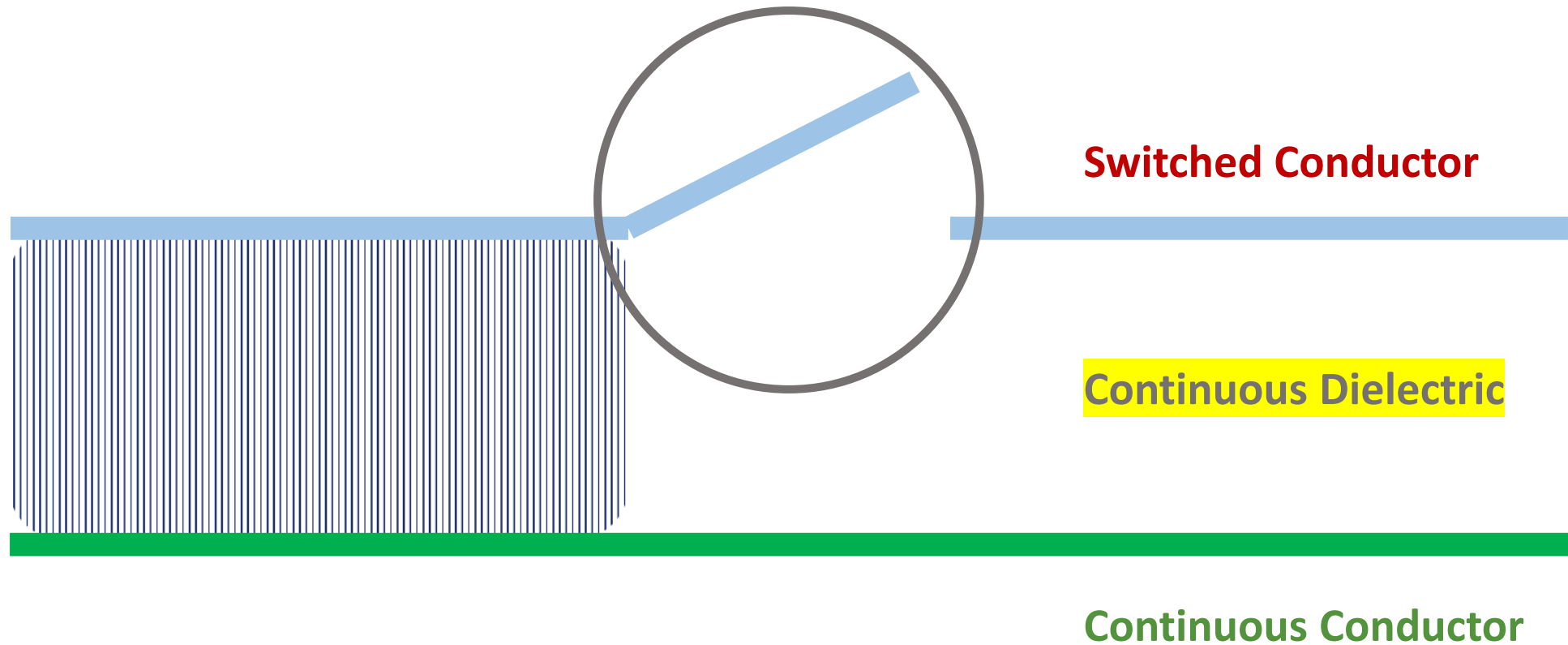
The field stops moving.

Switched Conductor

Continuous Dielectric

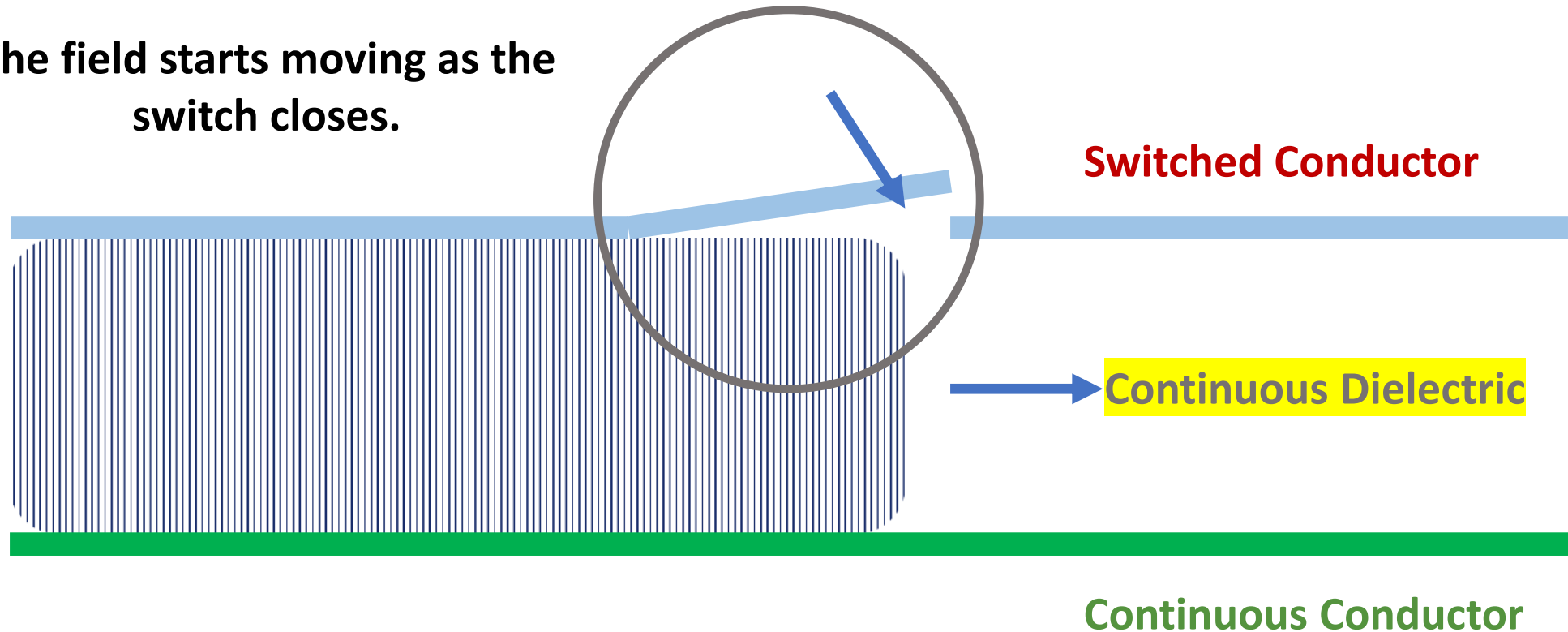
Continuous Conductor

Ralph's Rules: Fields Stays Put



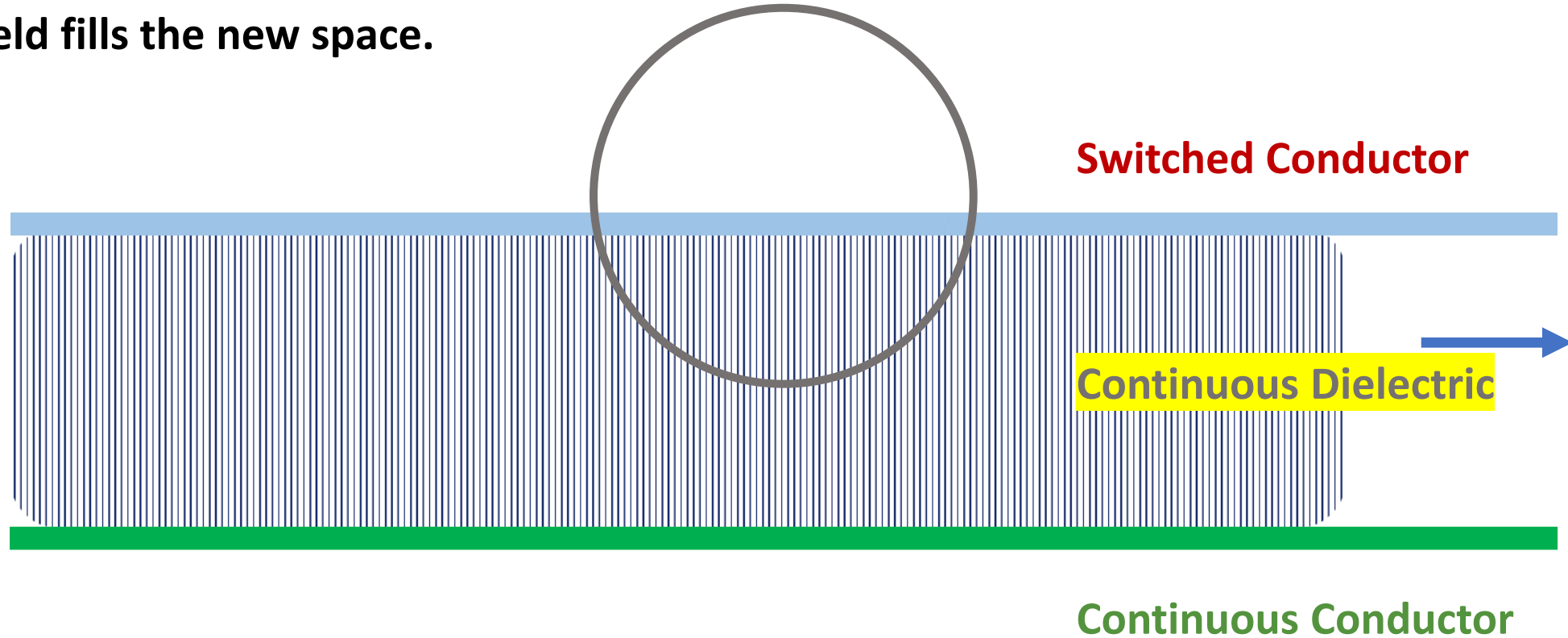
Ralph's Rules: Fields Look for Empty Space

The field starts moving as the switch closes.



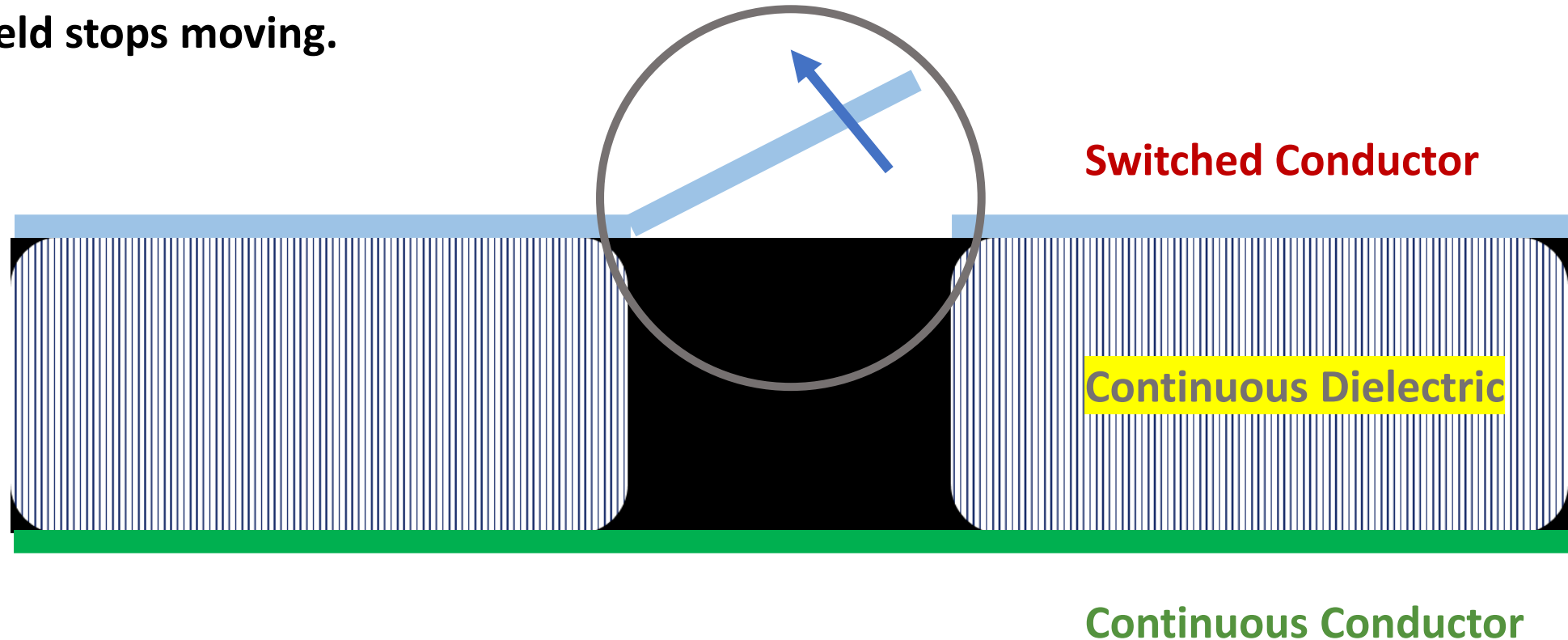
Ralph's Rules: Fields Go Where They are Told

The field fills the new space.



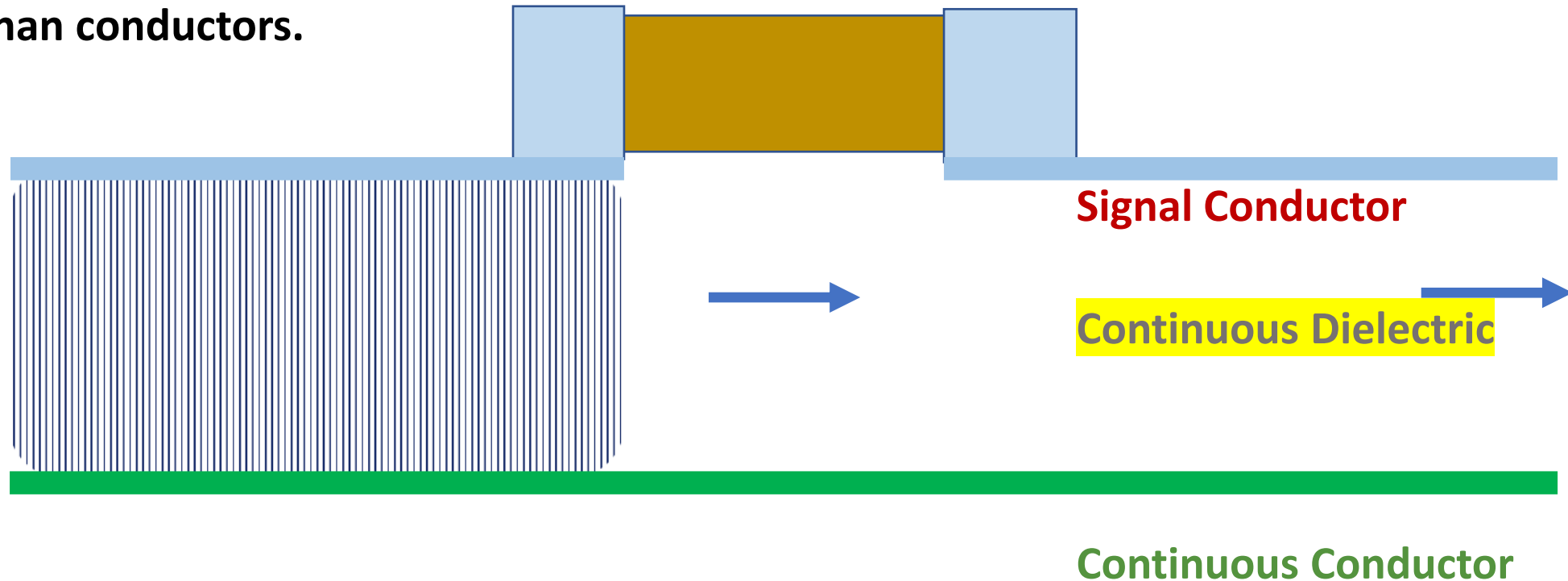
Ralph's Rules: Fields Stays Put

The field stops moving.



Ralph's Rules: Resistors

Resistors are made of materials that more readily interact with EM field than conductors.

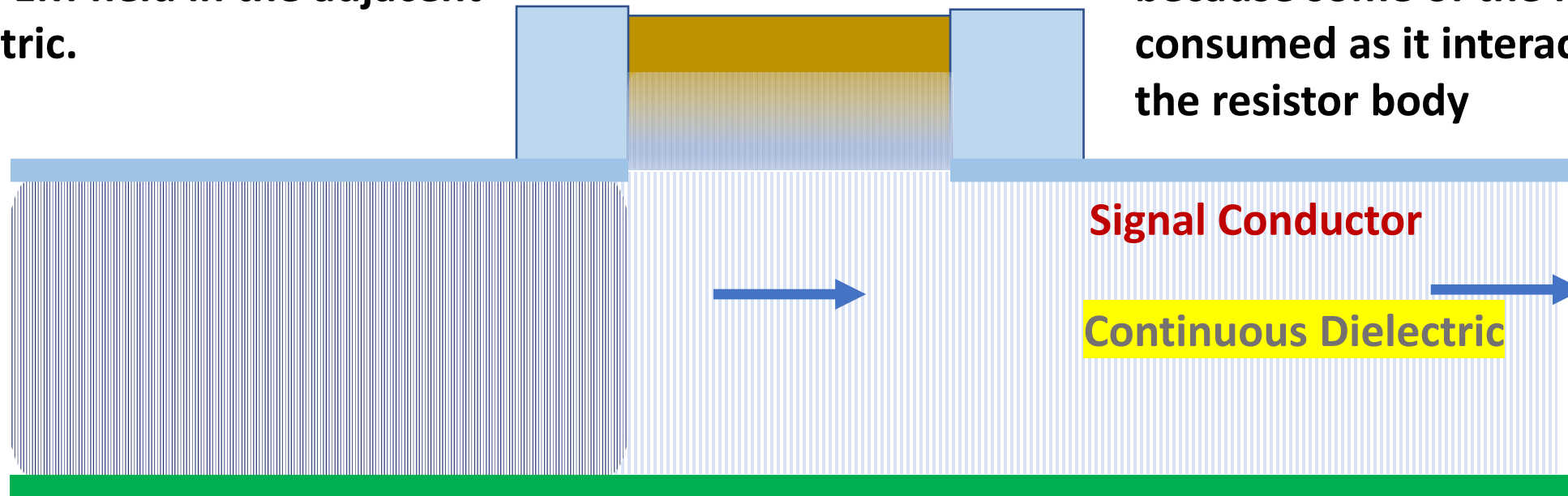


Ralph's Rules: Resistors

Fields Interact with the boundary materials

The Resistor body must be exposed to the EM field in the adjacent dielectric.

The Voltage is "dropped" because some of the field is consumed as it interacts with the resistor body

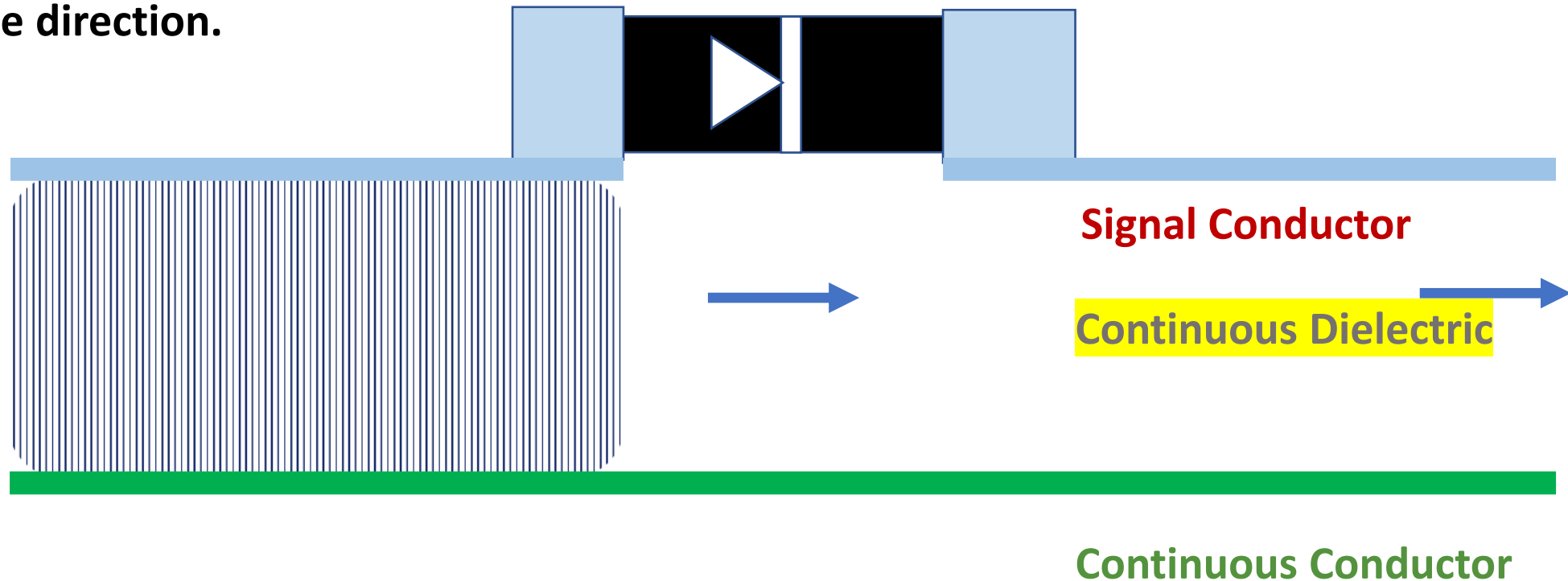


The field interacts with the molecules in the Resistor and some of the field is converted to heat, reducing the field density, or voltage.

Continuous Conductor

Ralph's Rules: Diodes

Diodes are made of material
restricts the movement of charge
in one direction.

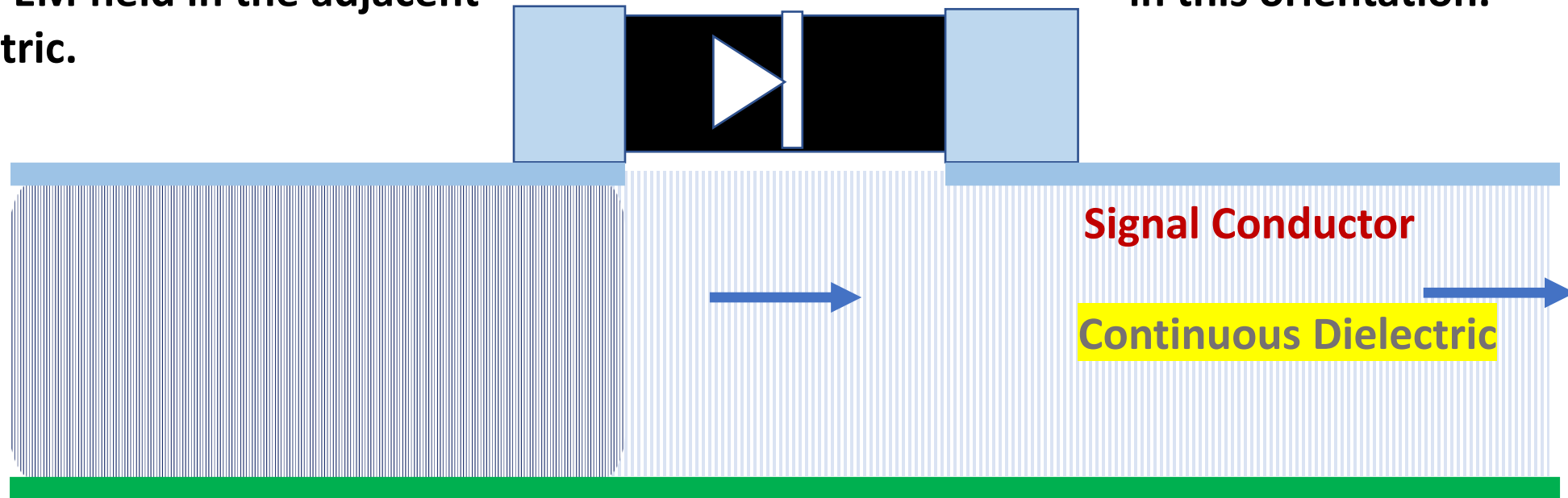


Ralph's Rules: Diodes

Fields Interact with the boundary materials

The Diode body must be exposed to the EM field in the adjacent dielectric.

Movement of charge is enabled in this orientation.



The field interacts with the molecules in the Diode and some of the field is converted to heat, reducing the field density, or voltage.

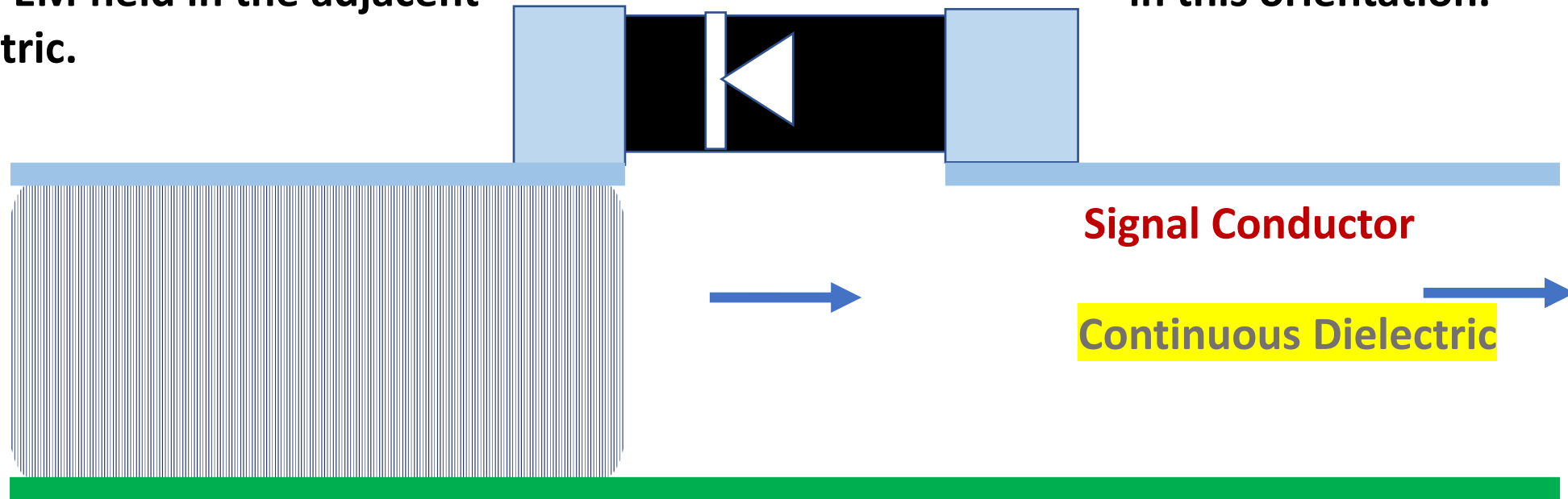
Continuous Conductor

Ralph's Rules: Diodes

Fields Interact with the boundary materials

The Diode body must be exposed to the EM field in the adjacent dielectric.

Movement of charge is disabled in this orientation.



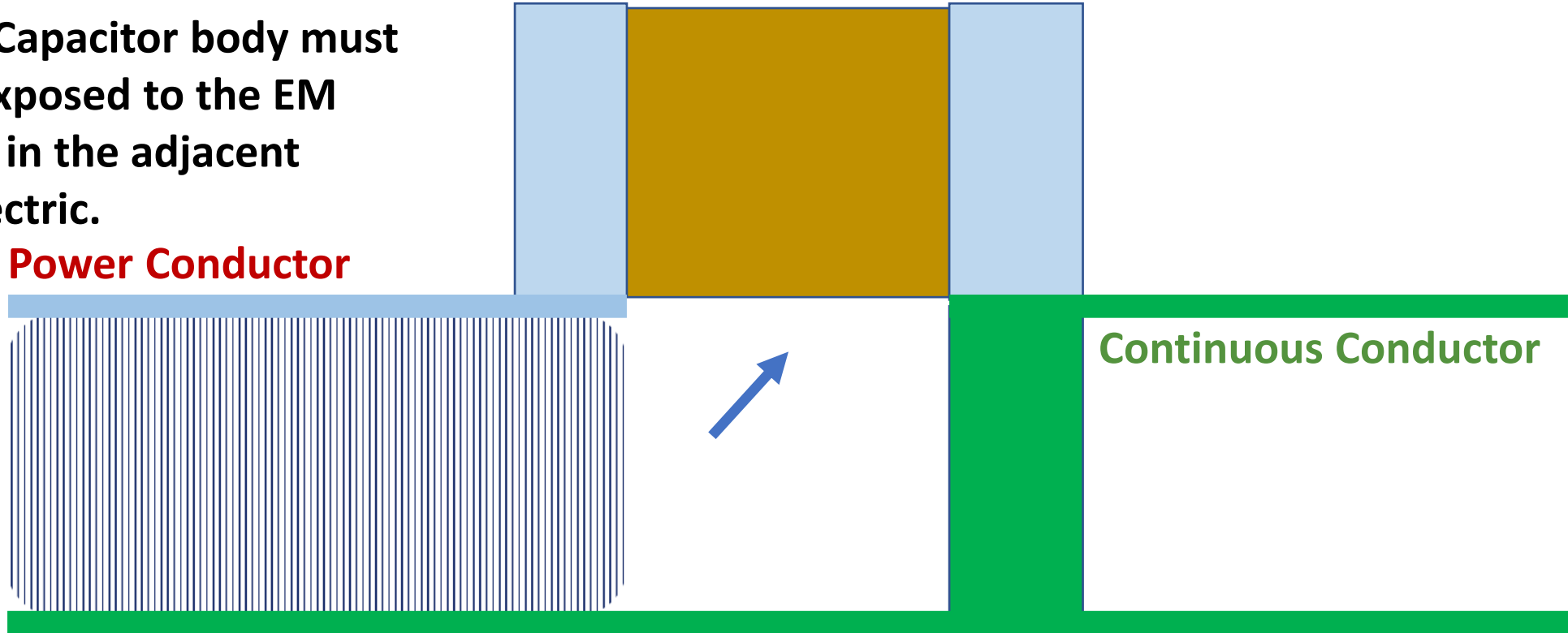
The prevention of charge movement stops the EM field from moving forward in the transmission line.

Continuous Conductor

Ralph's Rules: Capacitors

The Capacitor body must be exposed to the EM field in the adjacent dielectric.

Power Conductor



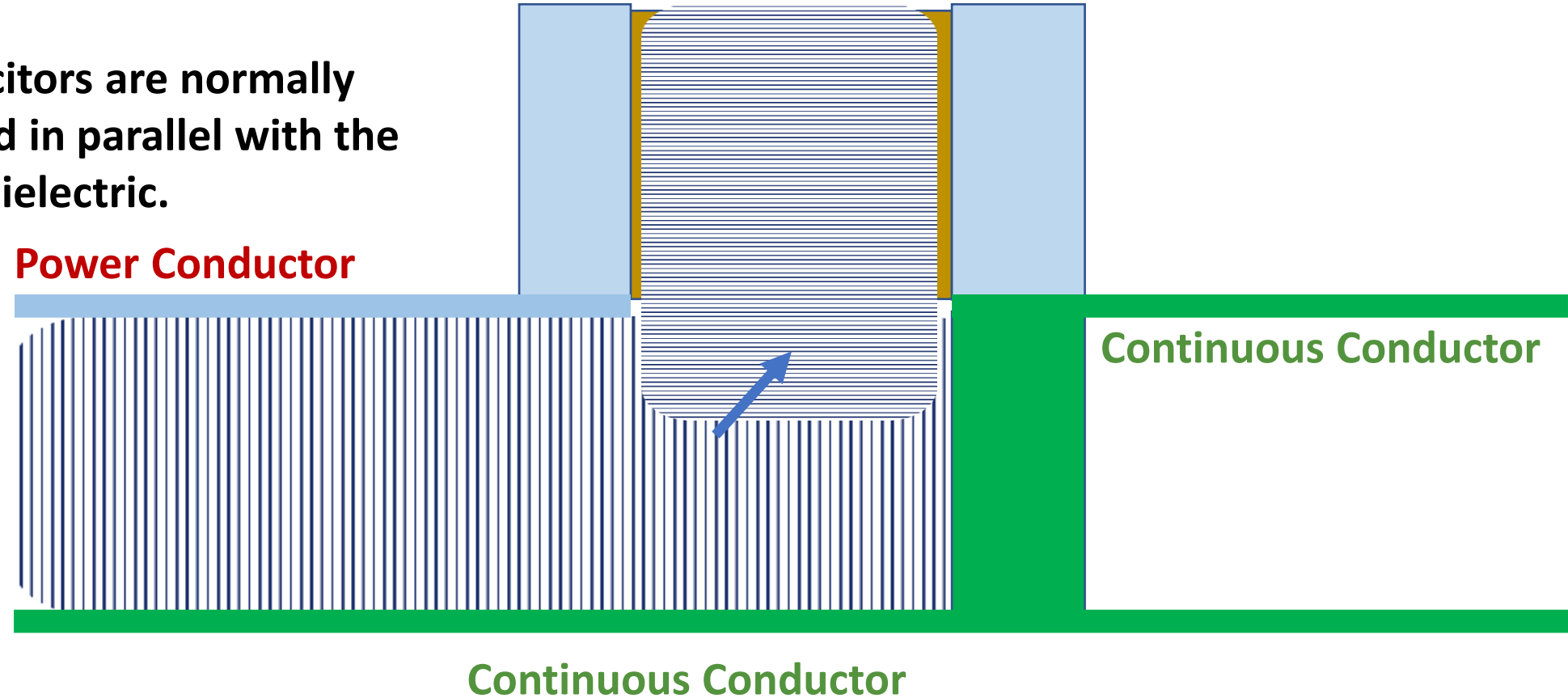
Continuous Conductor

Capacitors are made of material that can contain very high densities of EM field

Continuous Conductor

Ralph's Rules: Capacitors Fields Fill connected spaces

Capacitors are normally placed in parallel with the PCB dielectric.



Capacitors present a lower impedance due to their materials and conductor spacing and store larger amounts of EM field than the PCB dielectric.

Components on a PCB

- Diodes, Inductors, Integrated Circuits, Mechanical Switches, Resistors, and Transistors, Resistors replace sections of PCB trace.
 - If there was no ground there before, then it can't be there now.
 - The PCB dielectric between the outer layer and the inner ground plane must be exposed to the body of these components the same as a trace.
- Capacitors are structures that add parallel dielectrics to the PCB dielectric.
 - These structures form a low impedance transmission line that provides high density storage of EM field.
 - They are open-ended transmission lines.
 - The dielectric between the leads must be exposed to the PCB dielectric.

Moving Fields Cause Trouble

- Moving field interacts with the molecules of the boundary materials.
 - The amount of interaction depends on the molecular structure/density.
 - The more compact, such as with metallic conductors, the less they interact with the EM fields.
 - Less compact materials, such as those used in resistors, interact more, and consume more energy.
- Semiconductors have the property to vary the amount of charge movement, but still interact with the moving field, again consuming energy and heating up.
- Everything the field interacts with will change some of the EM energy to kinetic energy, even the dielectric.
 - Voltage drop is the result of this interaction

Changing Fields Cause Trouble

- Some energy is lost in crosstalk as the EM field “leaks” from our leaky water pipes.
 - This happens at the wavefront, the result of a changing E field.
- The changing E field creates a changing H field in the adjacent conductors.
 - Traces are affected at a higher magnitude than planes because the field is more condensed.
- The changing H field creates a changing E field in the adjacent dielectric
- This changing E field creates a changing H field in the next conductor it sees.
- This finally causes a change in the E field in the next space, resulting in “noise” we call crosstalk.

Ralph's Rules: The New (Old) Reality

The Rules of Triplets

You only need 3 components to use to contain EM energy

- Conductor
- Spaces (dielectric)
- Conductor



You only get 3 components to use to build electronic systems

- Conductors
- Spaces (dielectric)
- Switches



You can only do 3 things with Electromagnetic Field Energy

- Store it
- Move it
- Convert it to kinetic energy

This is not rocket science!

What is the result?

- This misconception has led to design practices that almost guarantee failure.
- The cost to the industry is staggering.
- When a typical project fails EMC testing, it must be redesigned, remanufactured, and retested, under pressure to get it done quickly.
- These redesign cycles usually involve minimal changes, and the results are often disappointing.
- The cost can range from tens of thousands, to hundreds of thousands of dollars and weeks to months of delay.
- There is typically no budget for either the funds or the time, and the impact to the business is huge.

What is the result?

- Imagine this on a global scale; thousands of design teams spending time and money redesigning their products instead of working on new projects.
- All because of a simple mistake in language.
- **To call this a Billion Dollar mistake is an understatement.**

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.

It's all about the space!

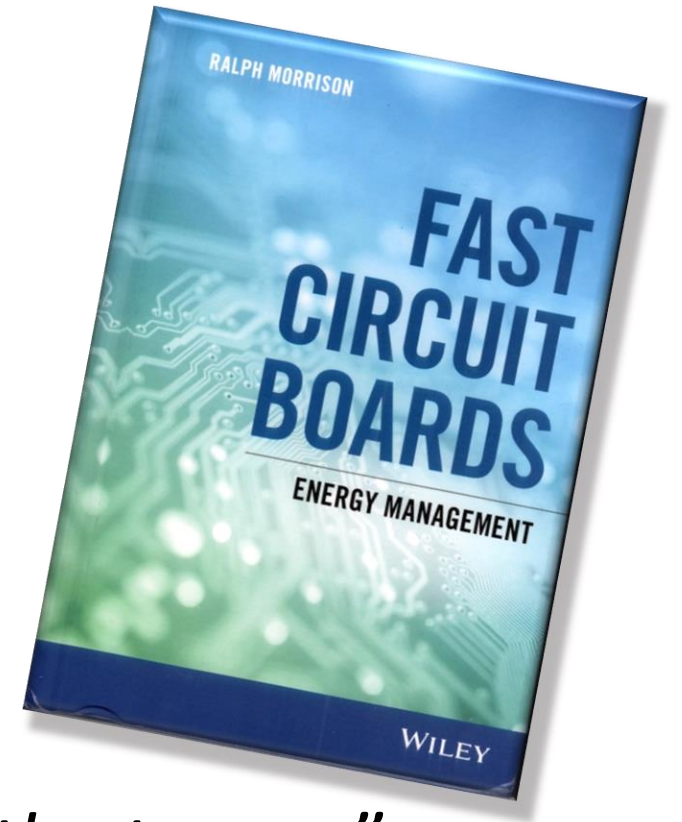
“Buildings have walls and halls.

People travel in the halls not the walls.

Circuits have traces and spaces.

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

Go to www.ralphmorrison.com for additional information.





SECURE CONNECTIONS
FOR A SMARTER WORLD

www.nxp.com



