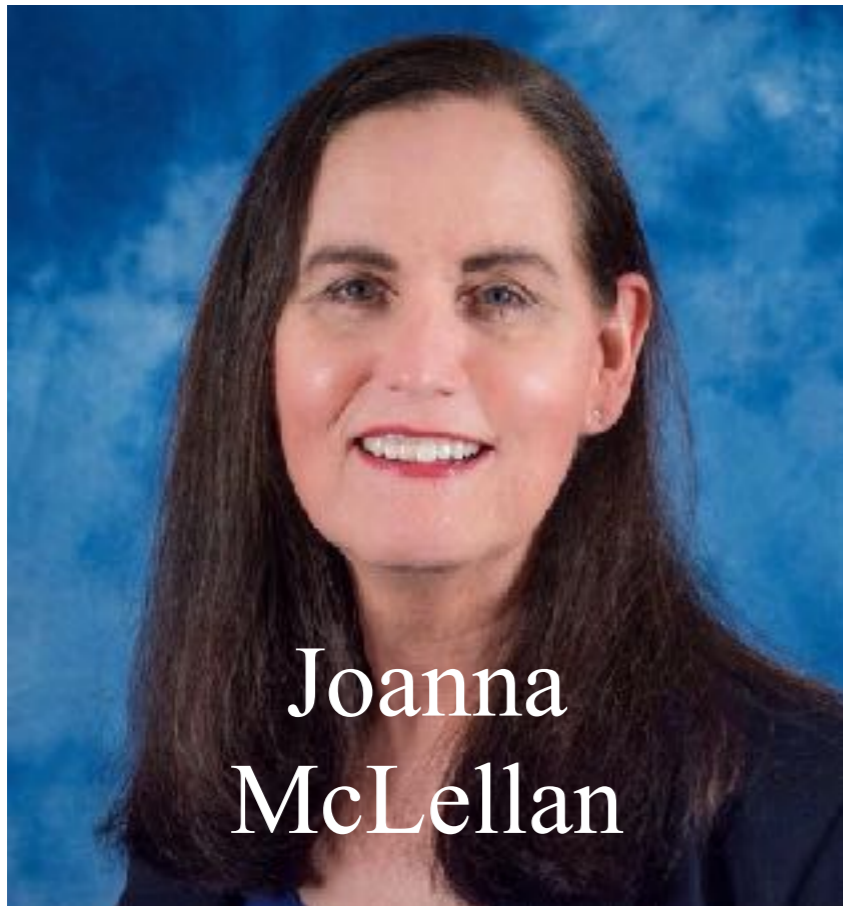


# Three phase power transfer, the automotive nightmare too expensive and too noisy.



We can predict performance by understanding the difference between DC and AC current flow in transmission lines.



+1 248-765-3599

[JoannaEMC@icloud.com](mailto:JoannaEMC@icloud.com)



# Thinking About Electricity

Most people think in terms of electrical voltage.

It is easy to understand and measure.

Some people also think in terms of current.

They know it flows in the circuits.

EMC engineers must think in terms of  
Electromagnetic energy fields.

How the fields move and,  
How energy leaks into and out of physical structures.

# Electromagnetic Fields

This presentation is about electromagnetic field energy escaping confinement.

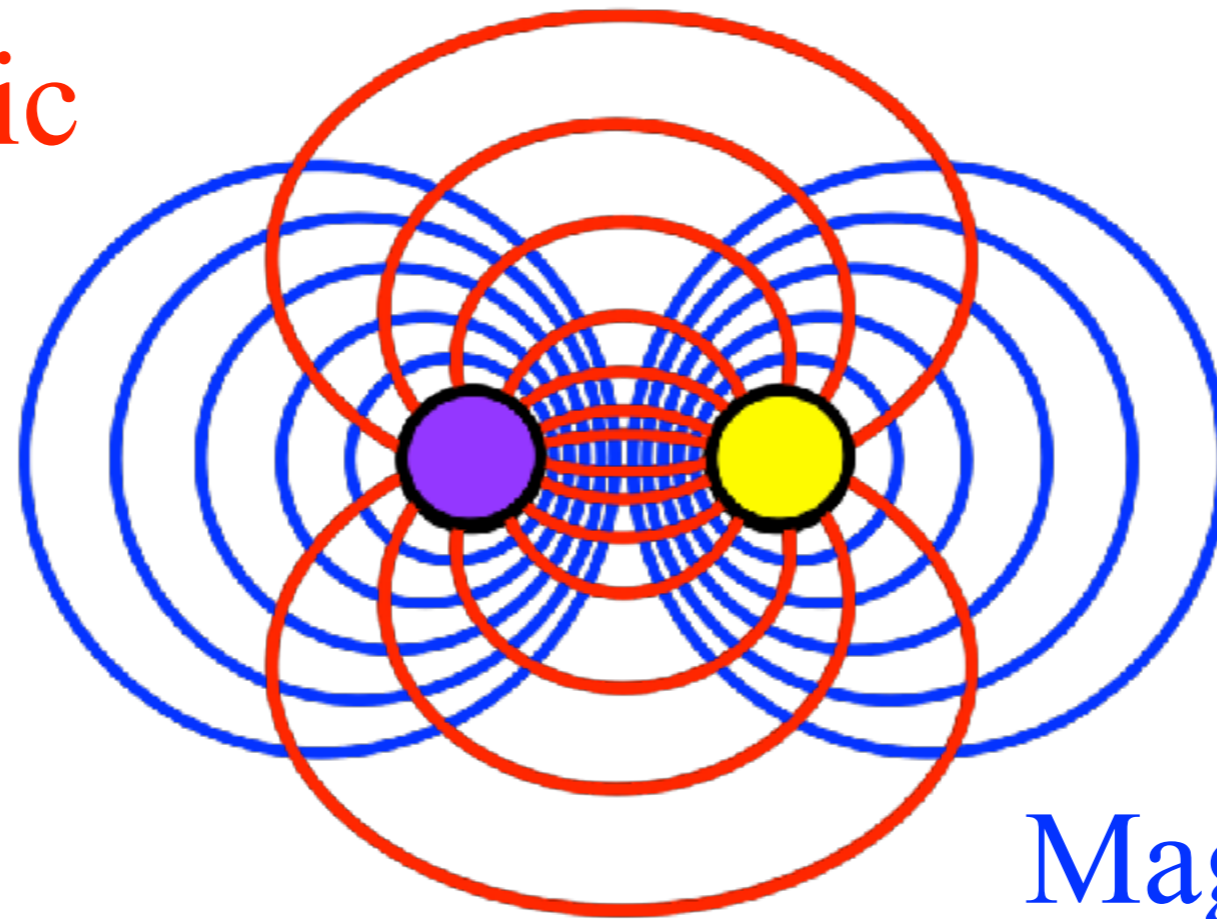
It is not about current or voltage.

Currents and voltages are used to help us locate the electromagnetic field energy.

EMC is about locating energy fields.

# Electromagnetic Fields

Electrostatic  
Field

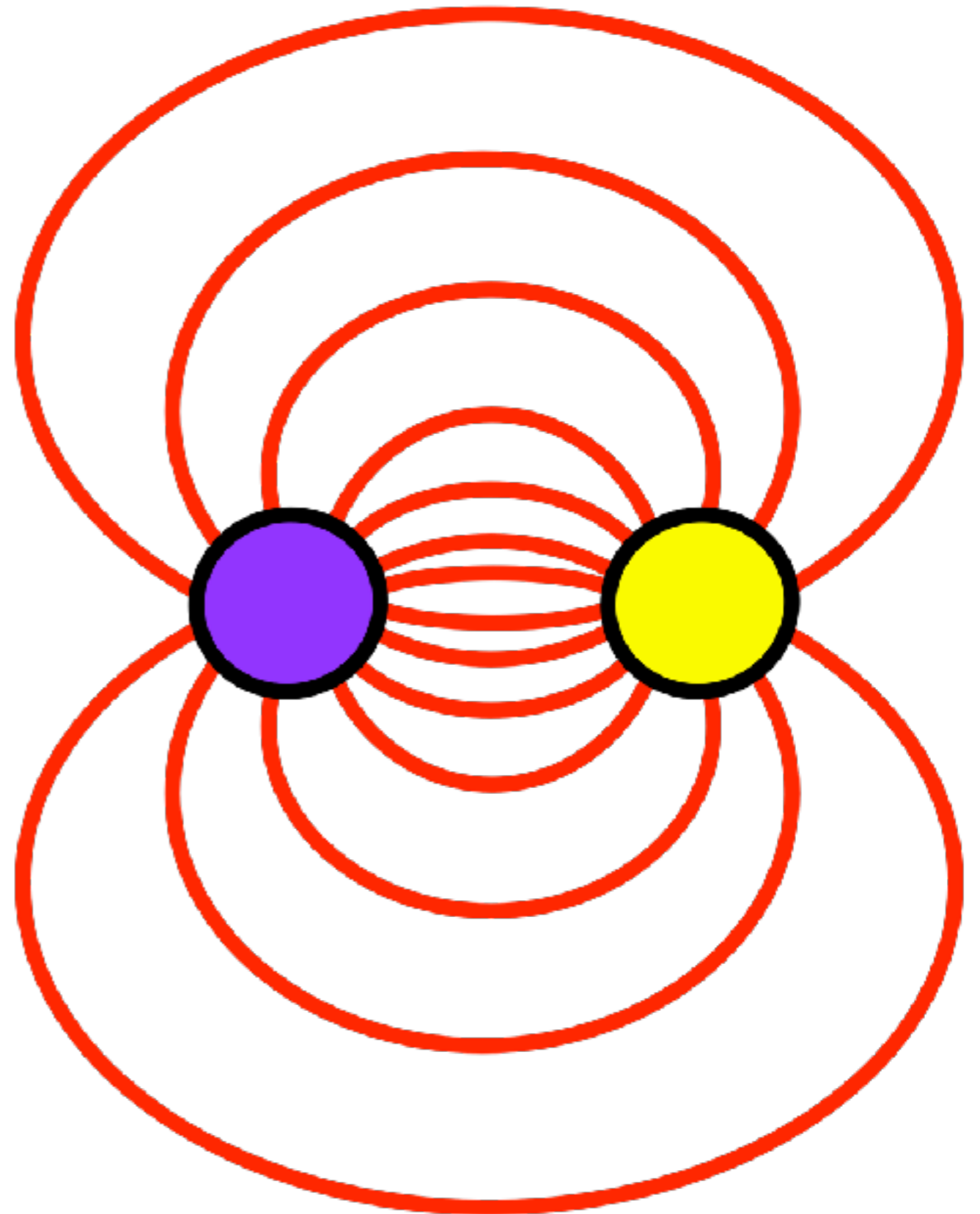


Magnetic Field

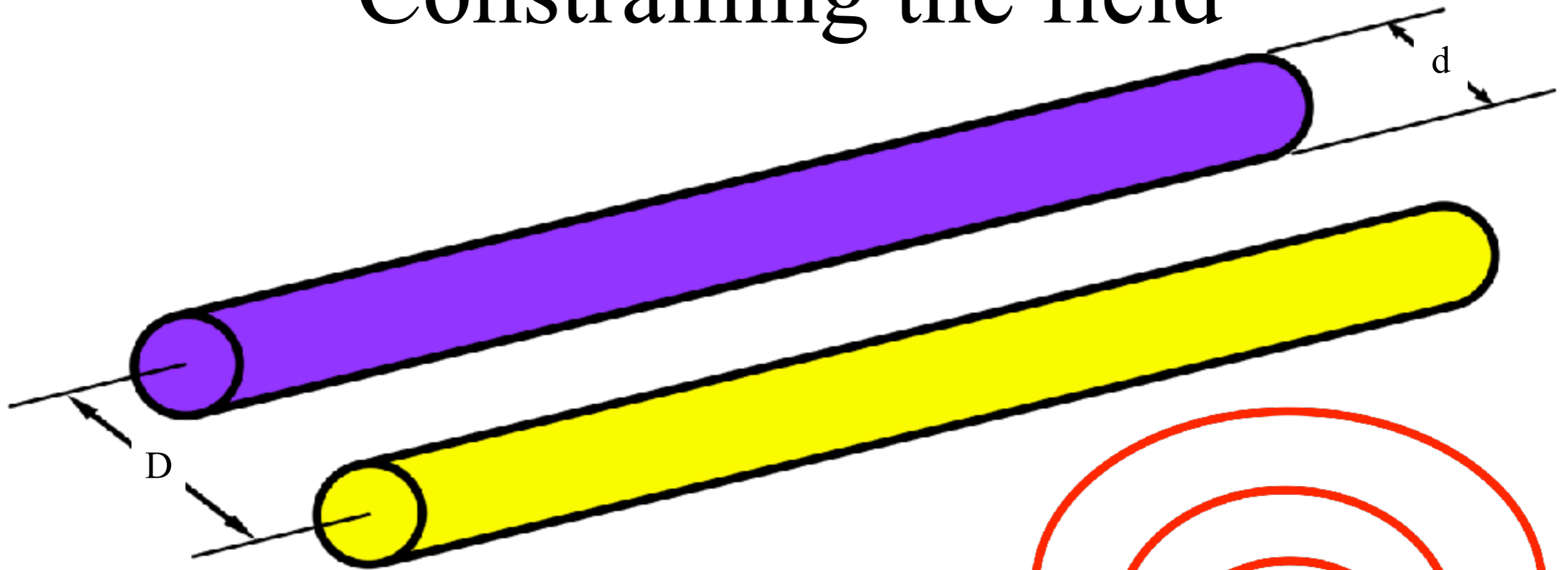
The current in these two conductors create an electromagnetic field around the conductors. The magnetic field is shown in **blue** and the electrostatic field is shown in **red**.

# Constraining the field

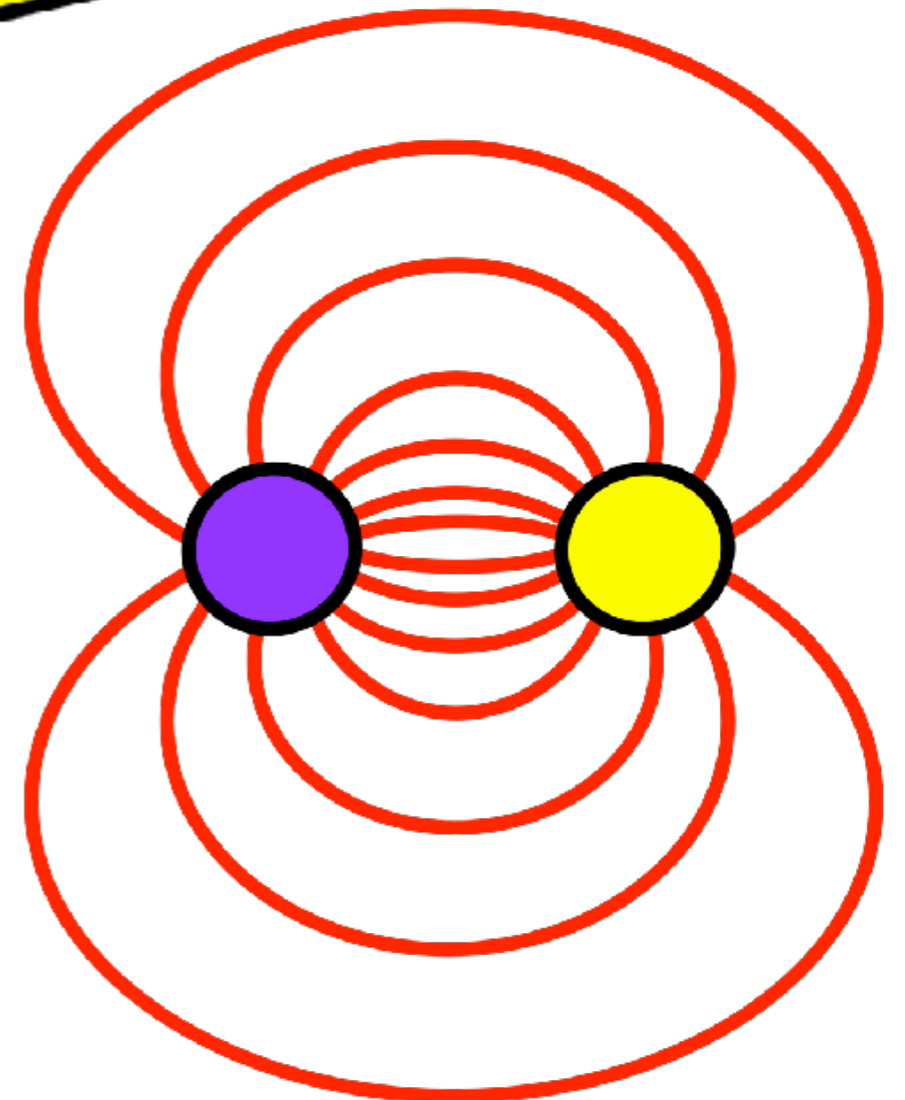
If you allow  
the RF energy  
to escape  
confinement,  
an EMC  
failure results.



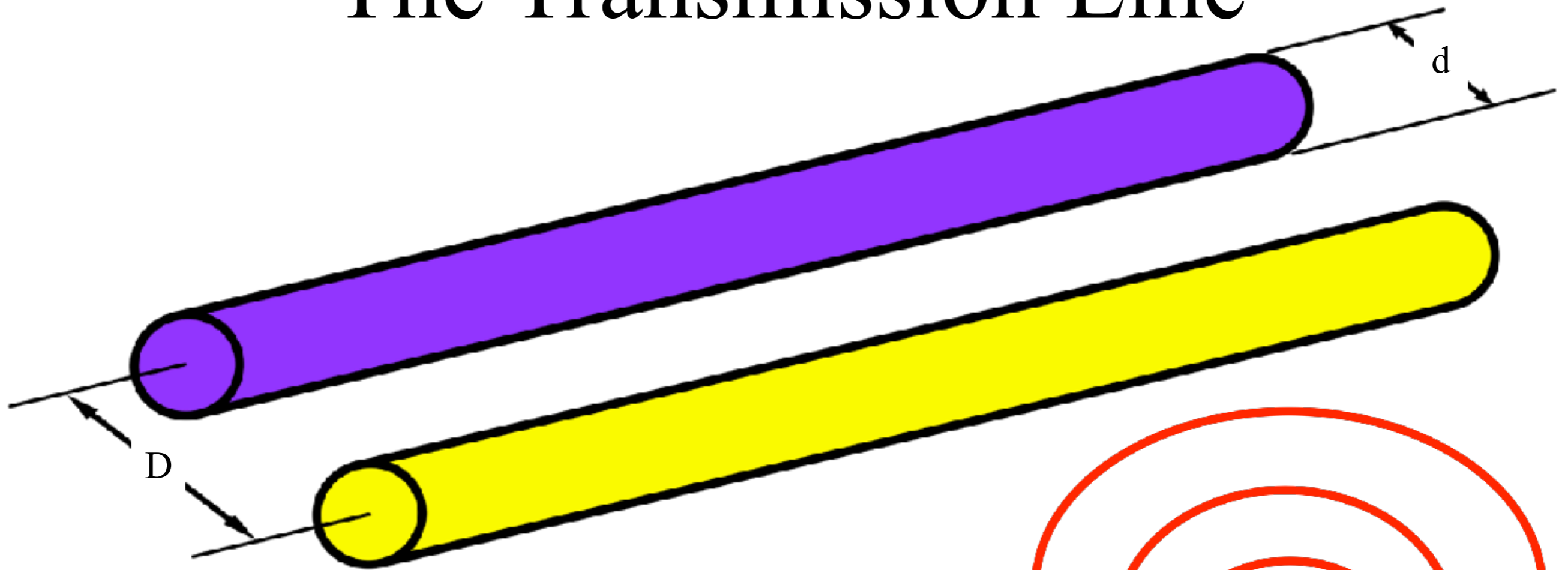
# Constraining the field



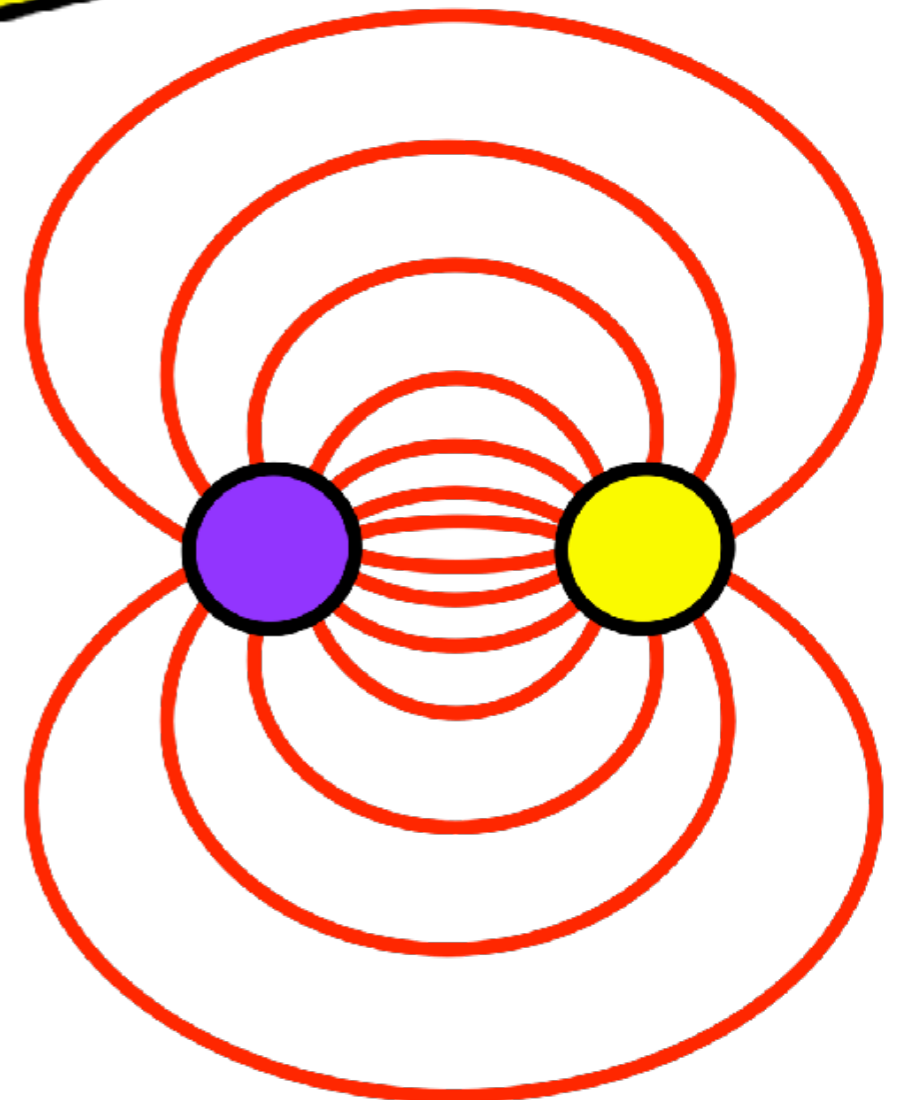
We constrain the fields with the shapes of the conductors and dielectrics.



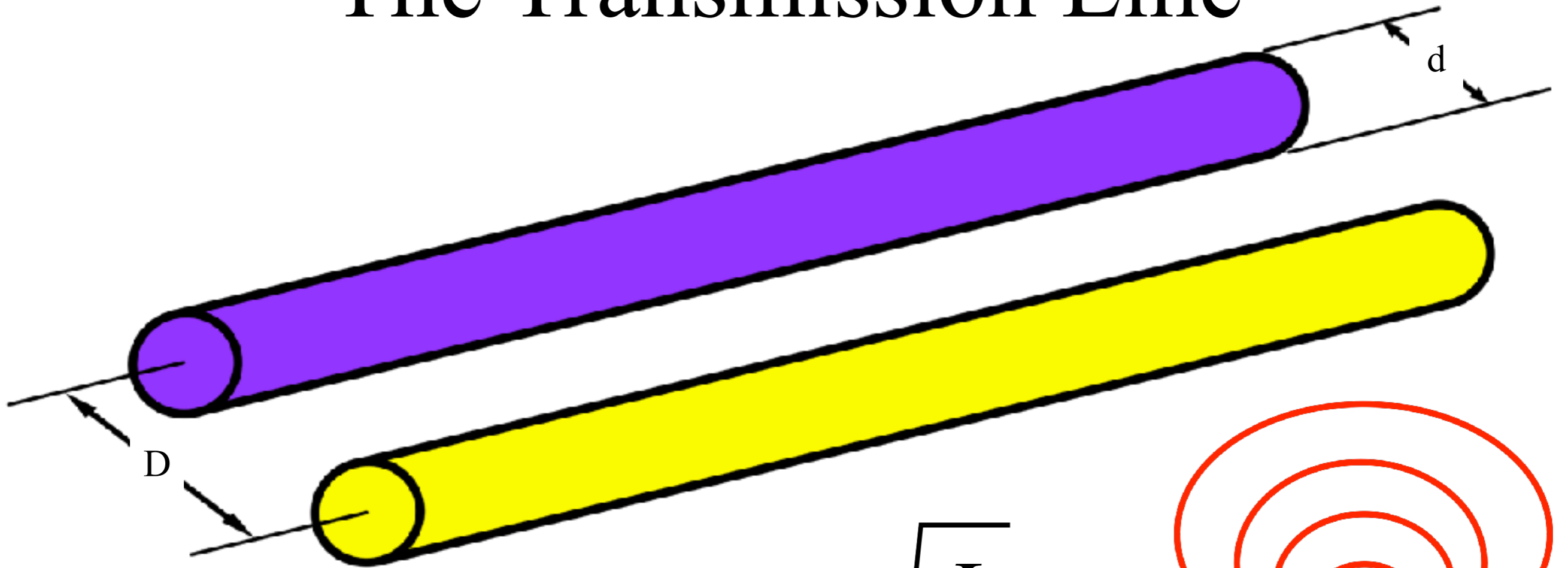
# The Transmission Line



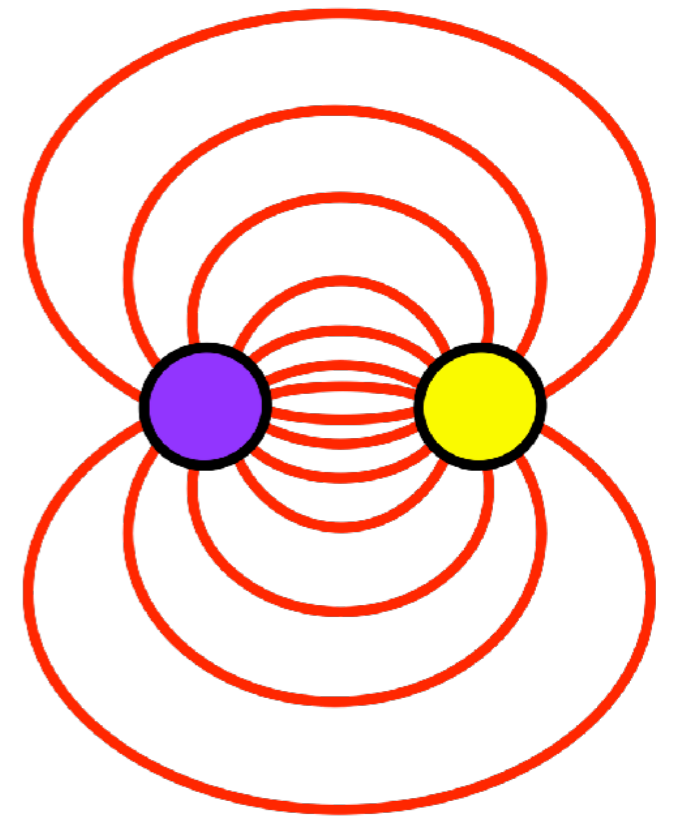
A transmission line is two or more conductors separated by a dielectric. It is the most basic building block of EMC.



# The Transmission Line



$$Z_0 \approx \sqrt{\frac{L}{C}}$$

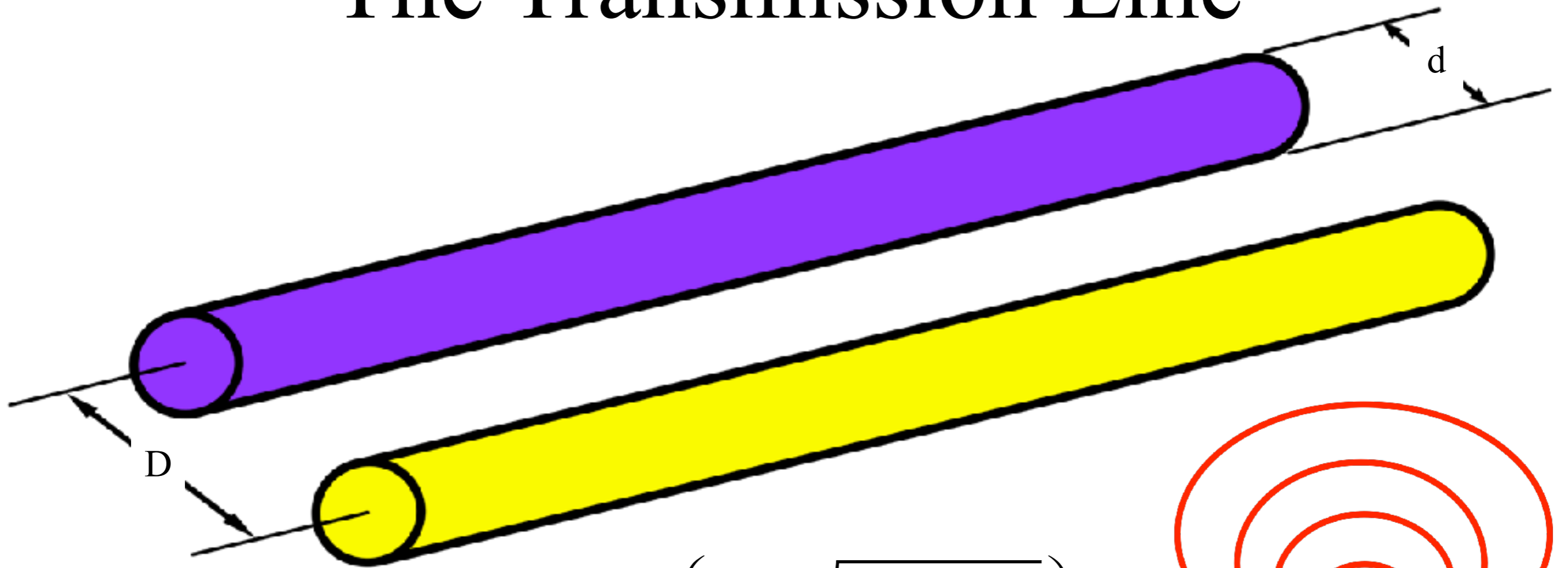


Smaller D increases C and lowers  $Z_0$ .

Larger d increases circumference, lowers L and increases C lowering  $Z_0$ .

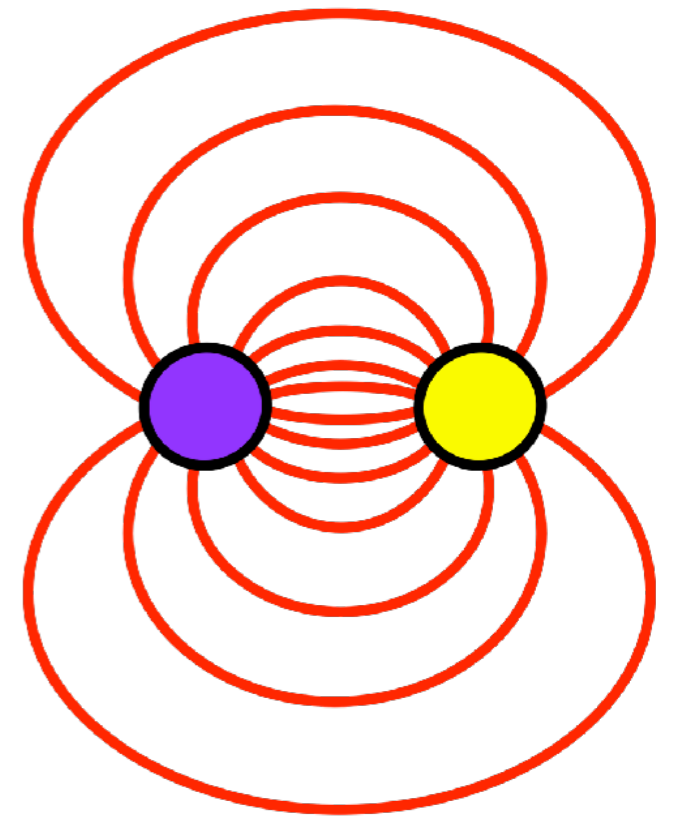


# The Transmission Line

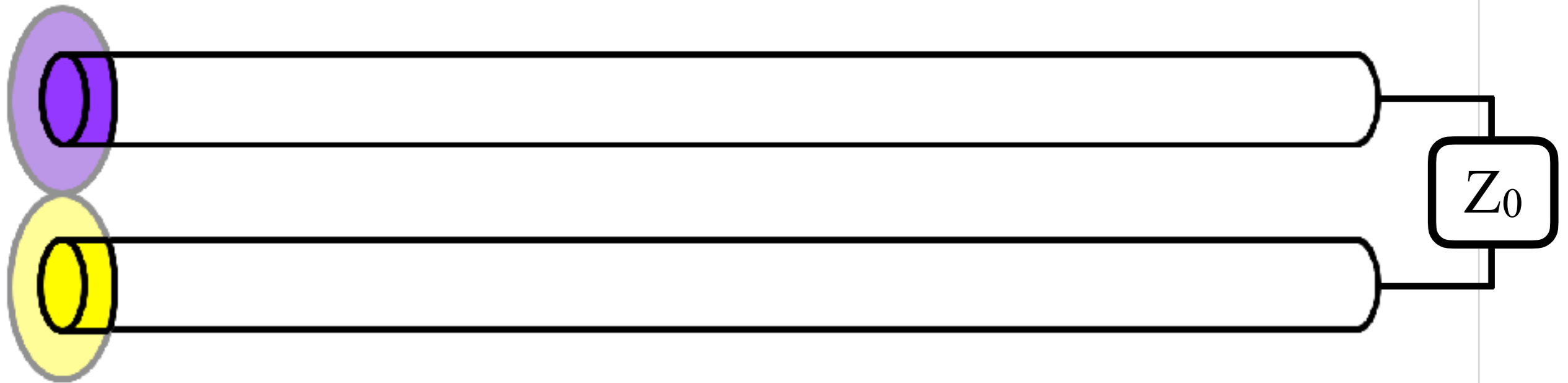


$$Z_0 = \frac{1}{\pi} \sqrt{\frac{\mu_r}{\epsilon_r}} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \left( \frac{D}{d} + \sqrt{\left(\frac{D}{d}\right)^2 - 1} \right)$$

The characteristic impedance of a transmission line formed by two parallel round conductors.



# Energy Speeding Along a Transmission Line



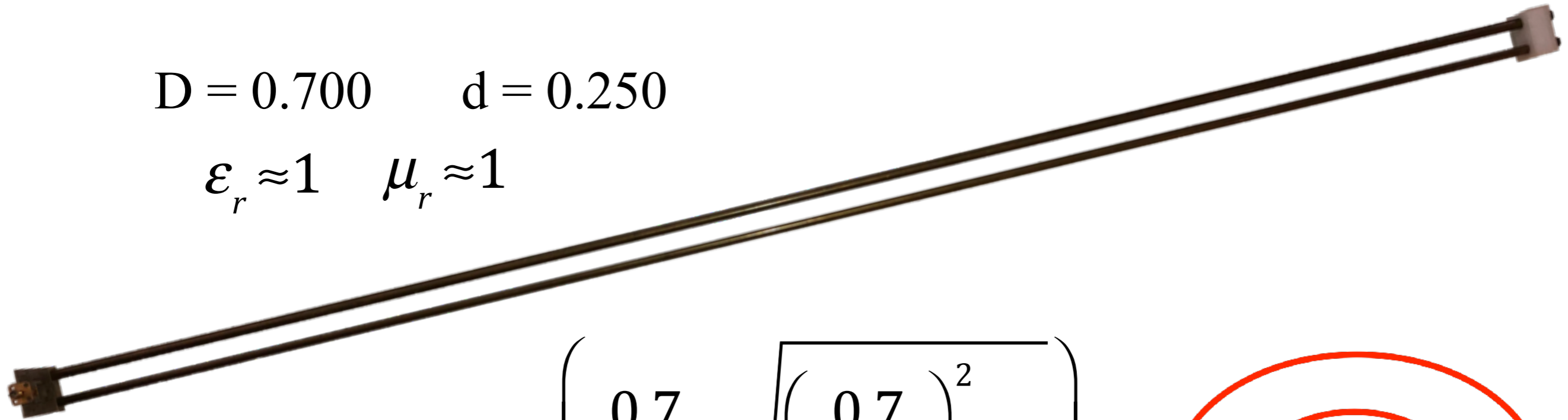
An electromagnetic field is created around both the forward and return conductors as soon as a voltage is applied. These electromagnetic energy fields then propagate towards the other end of the transmission line at the

**Pesky Slow Speed of Light.** <sup>TM</sup>

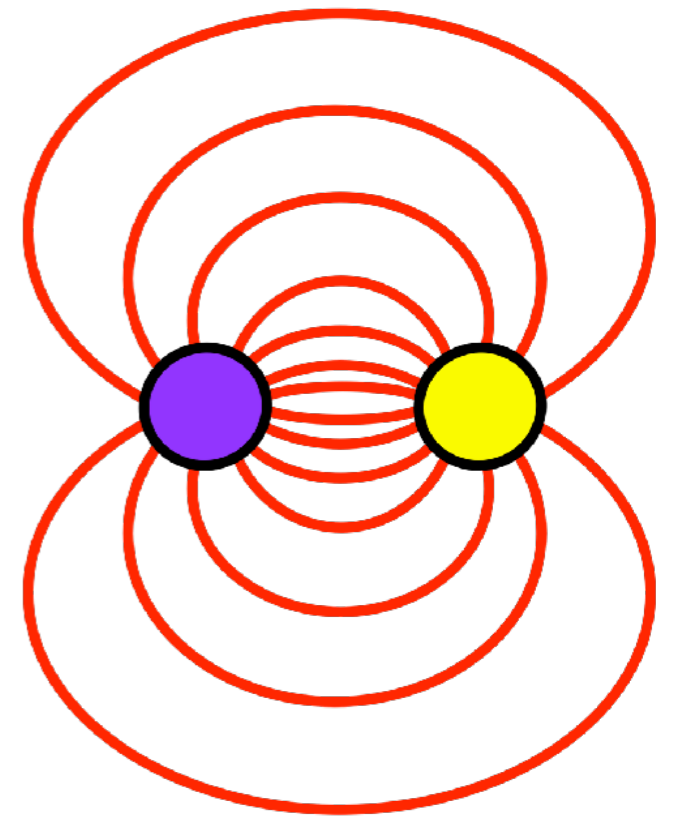
# Two Wire 200 $\Omega$ Transmission Line

$$D = 0.700 \quad d = 0.250$$

$$\epsilon_r \approx 1 \quad \mu_r \approx 1$$



$$Z_0 \approx 121 \ln \left( \frac{0.7}{0.25} + \sqrt{\left( \frac{0.7}{0.25} \right)^2 - 1} \right)$$
$$\approx 202 \Omega$$

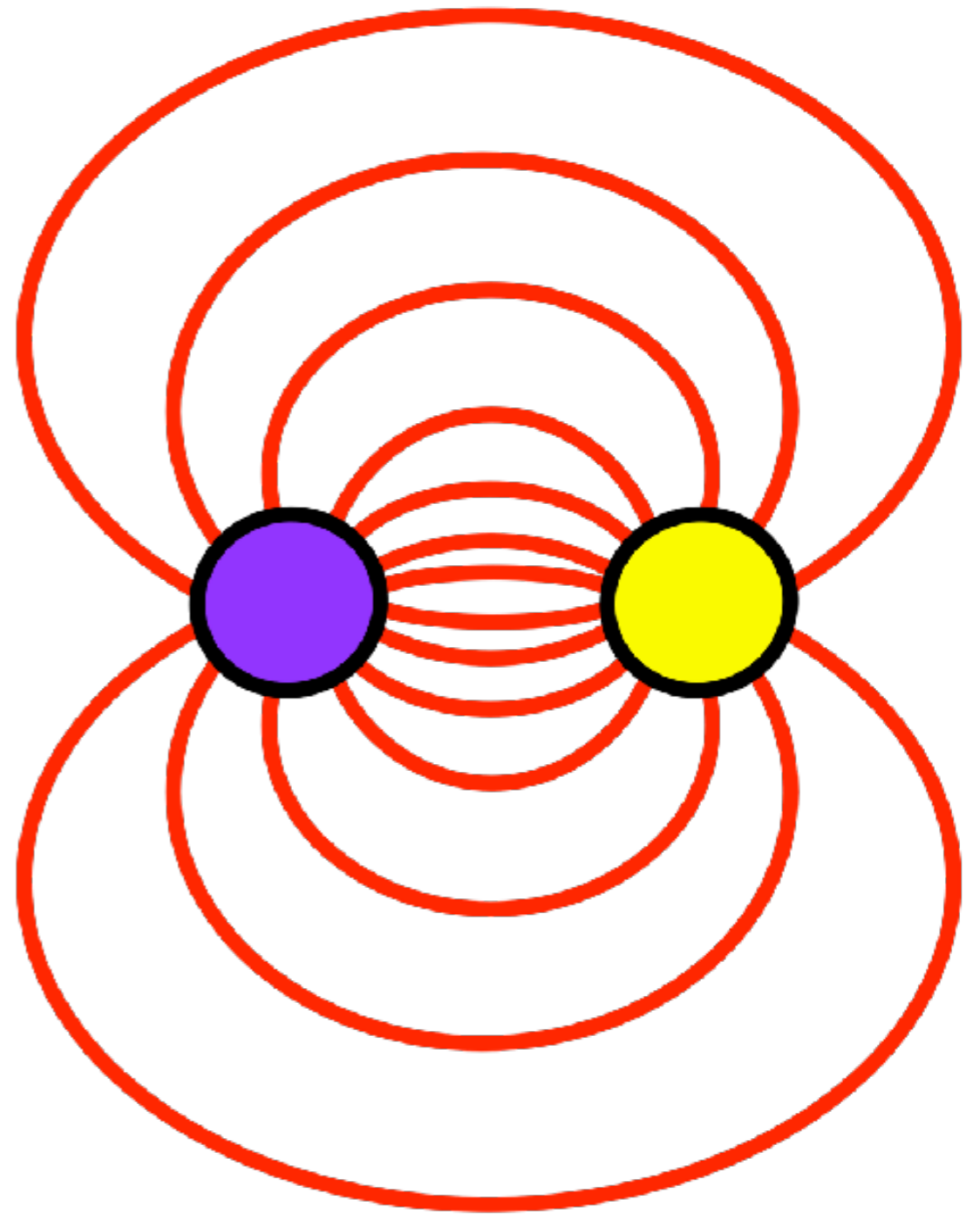


Do you think this 200  $\Omega$   
transmission line will  
leak RF energy?

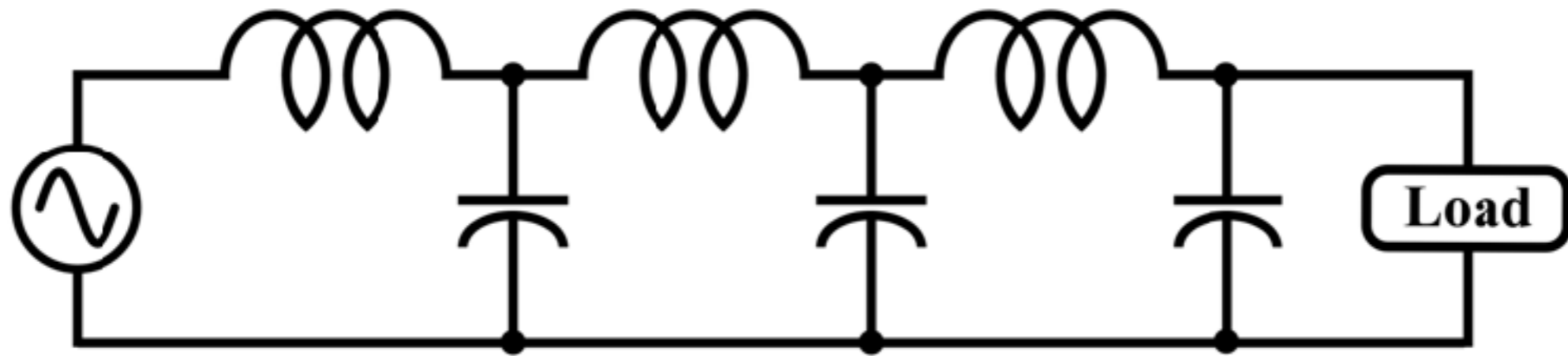
**Absolutely!**

# The Transmission Line

EMC problems are the result of poorly designed transmission lines that allow the RF energy to escape confinement.



# Classic Transmission Line Theory



Classic Transmission Line theory is generally taught with an ideal ground. This unintentionally teaches that ground is ideal. Ground is NEVER ideal above 100 KHz.

Teaching it this way unintentionally sabotages your ability to understand the physics of EMC.

# Classic Transmission Line Theory

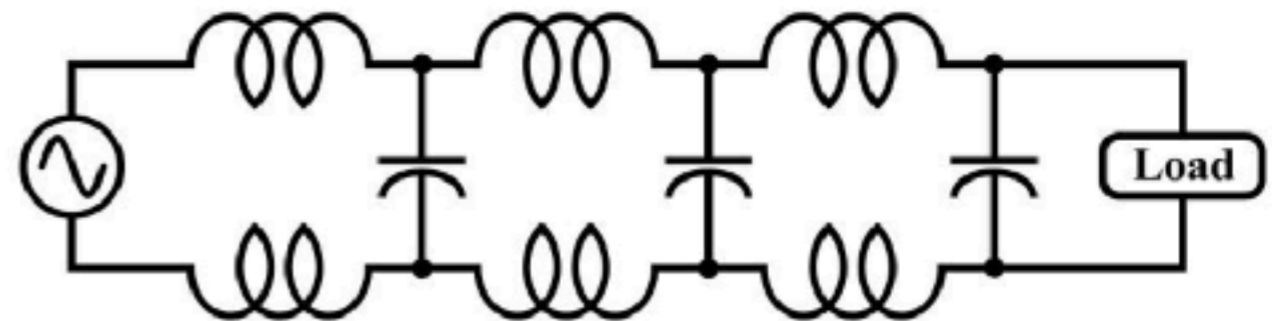
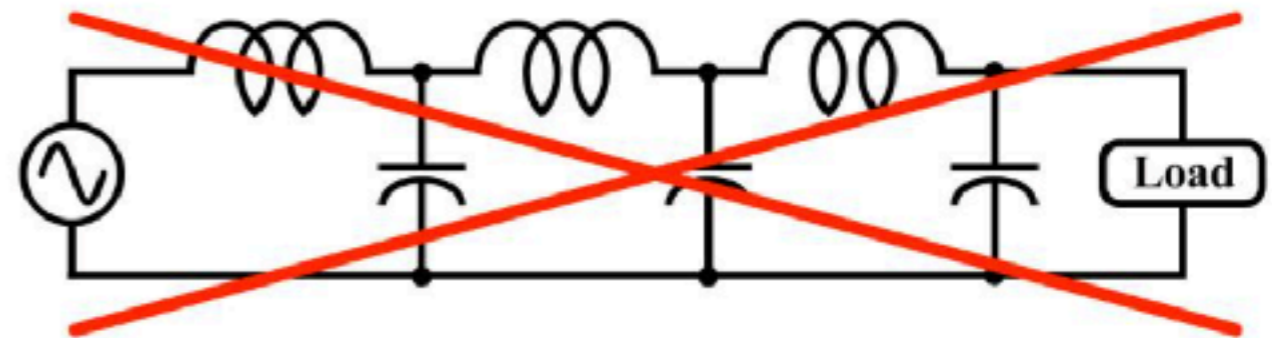
Most electrical engineers have an unrealistic ground concept.

This is why their designs constantly fail EMC. I request the universities start teaching transmission line theory using the realistic ground concept shown in the lower schematic. Use the symmetry of the circuit to create a virtual ground facilitating transmission line numerical analysis.



Joanna (Hill) McLellan  
Principal Consultant at EMC Productivity  
1yr · 🌐

Most electrical engineers have an unrealistic ground concept. This is why their designs constantly fail EMC. I request the universities start teaching transmission line theory using the realistic ground concept shown in the lower schematic. Use the symmetry of the circuit to create a virtual ground facilitating transmission line numerical analysis. #emc



👍 🌐 🌱 2,854 · 220 comments

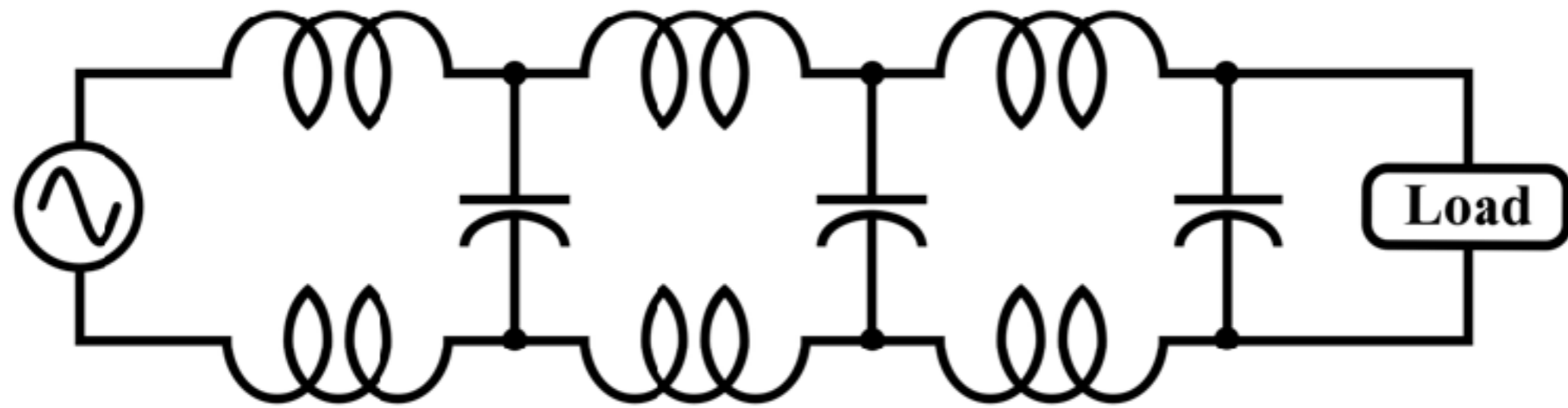
Reactions



👍 Like    💬 Comment    ➦ Share    ✉ Send

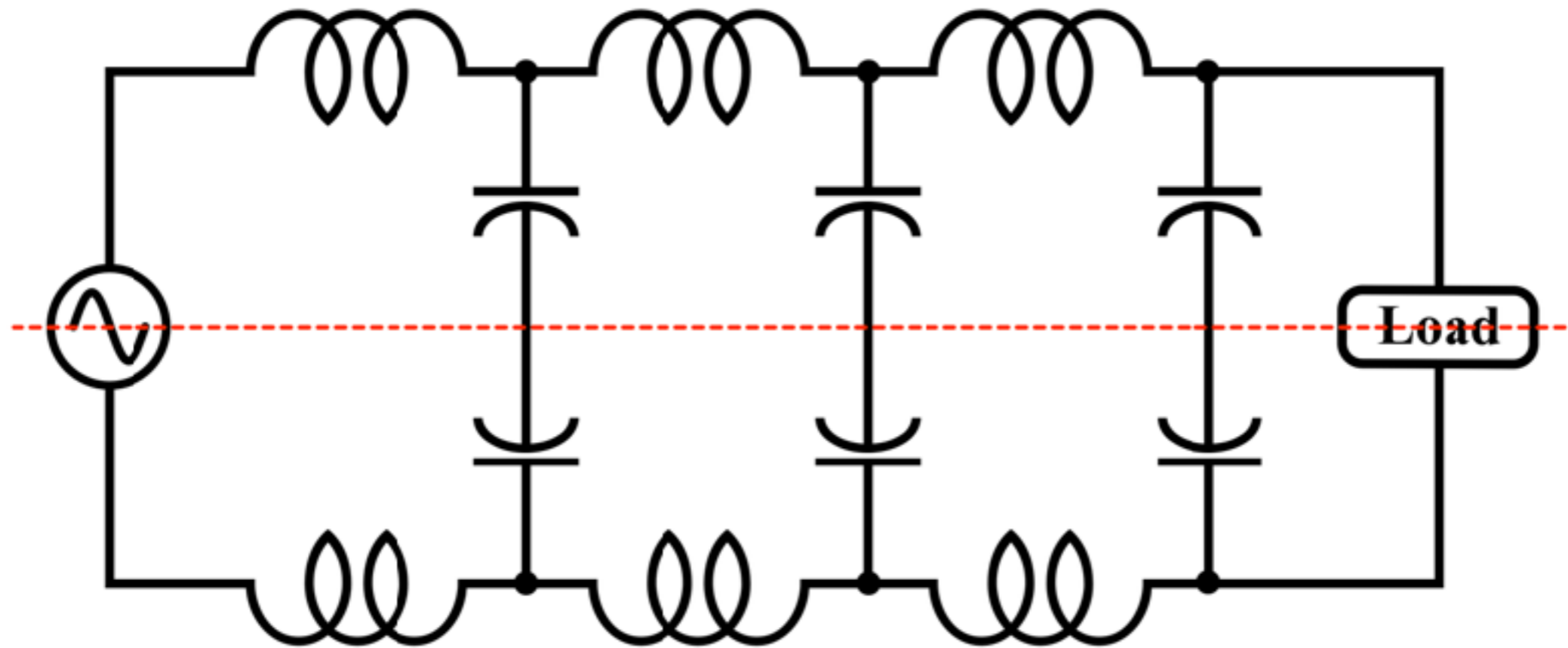
📊 367,749 views of your post in the feed

# Classic Transmission Line Theory



Real transmission lines have inductance in both the forward and return conductors.

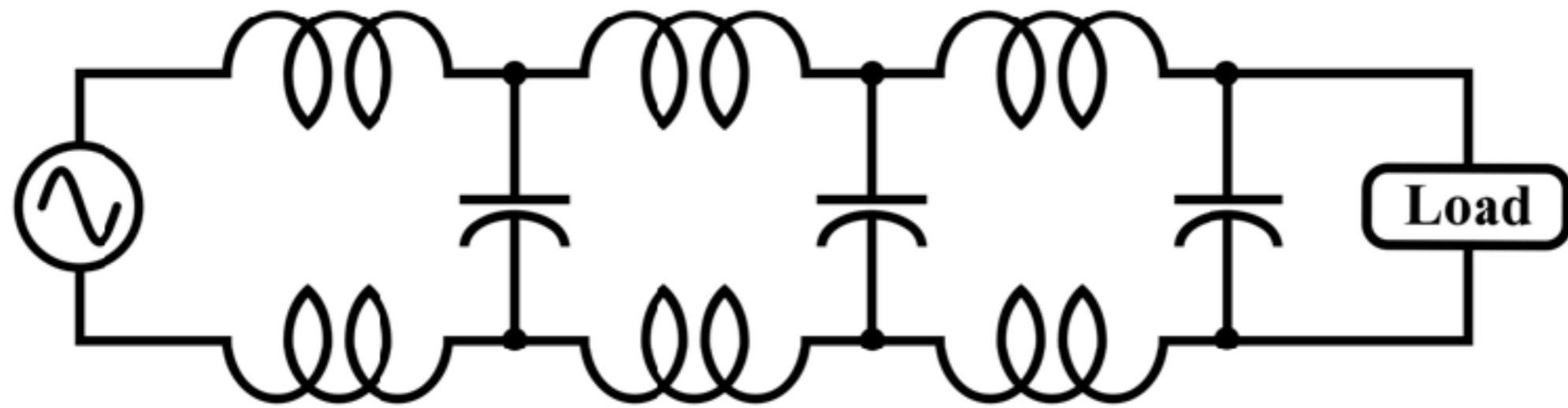
# Classic Transmission Line Theory



By using a virtual ground through the center of a balanced circuit we can still perform the classic numerical analysis.

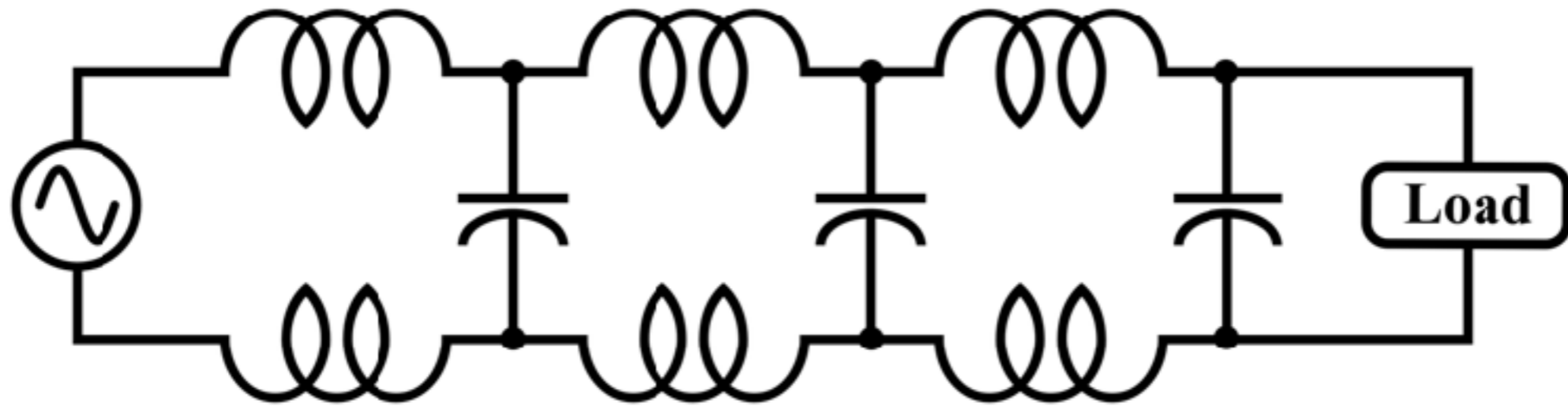


# To Consistently Pass EMC



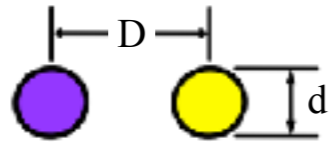
All currents with a frequency content above 100 KHz must be constrained within a suitably designed Transmission Line.

# When is a Transmission Line not a Transmission Line?

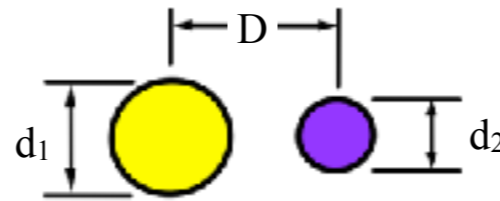


As the characteristic impedance of a transmission line approaches the characteristic impedance of free space, 377 ohms, we don't have a transmission line, we have an unintended antenna.

# More Transmission Line Equations

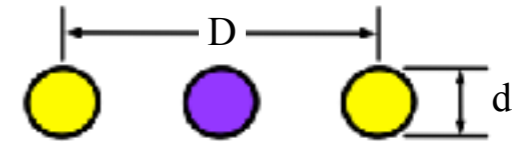


$$Z_0 = \frac{1}{\pi} \sqrt{\frac{\mu_r}{\epsilon_r}} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \left( \frac{D}{d} + \sqrt{\left(\frac{D}{d}\right)^2 - 1} \right)$$

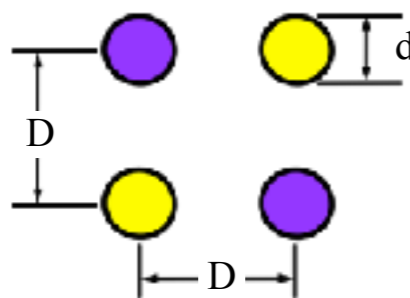


$$Z_0 = \frac{1}{2\pi} \sqrt{\frac{\mu_r}{\epsilon_r}} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \left( X + \sqrt{X^2 - 1} \right),$$

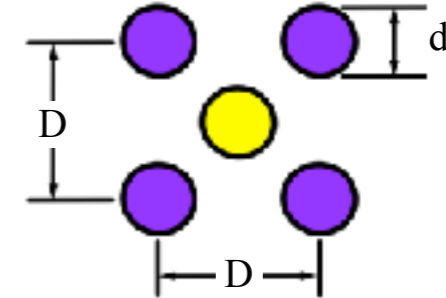
$$X = \frac{1}{2} \left( \frac{4D^2}{d_1 d_2} - \frac{d_1}{d_2} - \frac{d_2}{d_1} \right)$$



$$Z_0 \approx 476.4 \ln \left( 1.59 \frac{D}{d} \right), d \ll D$$



$$Z_0 \approx \frac{1}{2\pi} \sqrt{\frac{\mu_r}{\epsilon_r}} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \left( \sqrt{2} \frac{D}{d} \right), d \ll D$$



$$Z_0 \approx 74.95 \ln \left( \frac{D}{0.993d} \right), d \ll D$$

$$\cosh^{-1}(x) = \ln \left( x + \sqrt{x^2 + 1} \right)$$

for real  $x > 1$

<https://mathworld.wolfram.com/InverseHyperbolicCosine.html>

Adapted from the Fifth edition of the Howard W. Sams Co., ITT Reference Data book For Radio Engineers page 22-22 and Antenna Handbook by Y.T. Lo & S.W. Lee Table 4 section 28-11.

# Where does the current go?



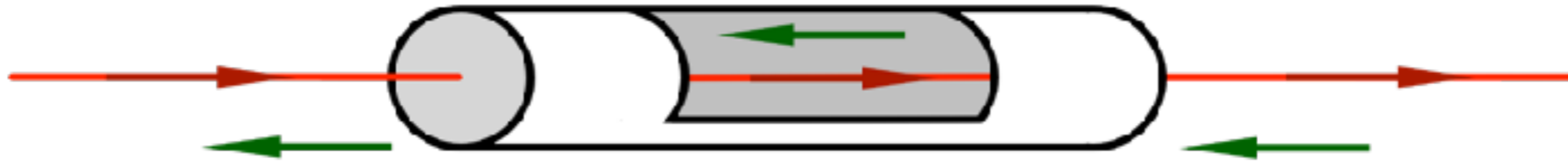
We start with a copper coaxial transmission line.

## The Skin Depth of copper

$$\delta_{\text{Copper}_{60\text{Hz}}} = \frac{1}{\sqrt{\pi 60\text{Hz} 4\pi 10^{-7} 5.95 \times 10^7}} = 8.42\text{mm} = 0.331\text{ inches}$$

$$\delta_{\text{Copper}_{100\text{KHz}}} = \frac{1}{\sqrt{\pi 100\text{KHz} 4\pi 10^{-7} 5.95 \times 10^7}} = 206\mu\text{m} = 0.00811\text{ inches}$$

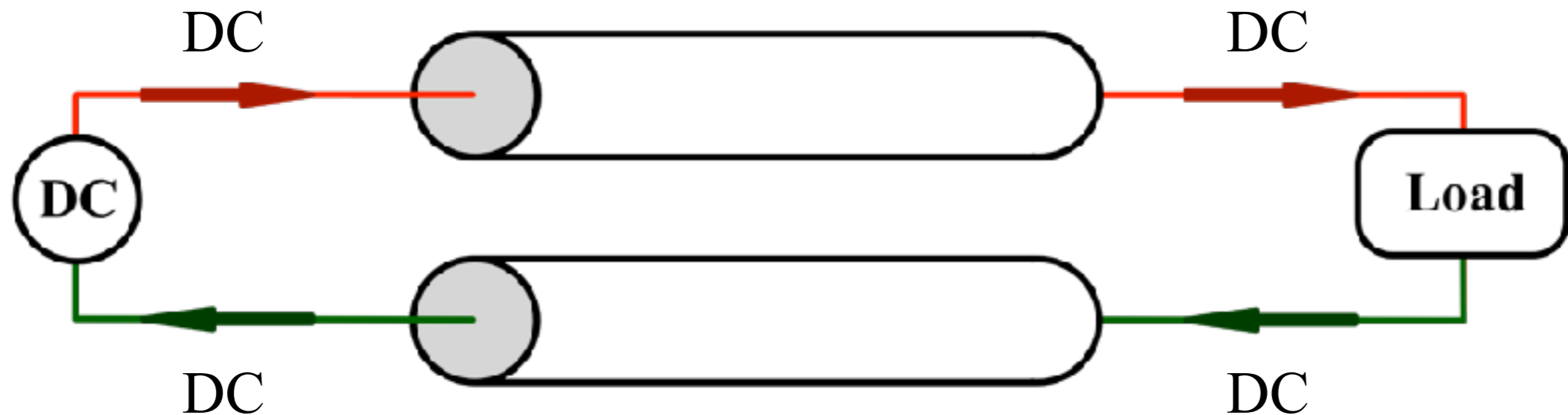
# Where does the current go?



We see the currents inside and outside the coax.  
As with all transmission lines there are equal  
and opposite currents on both sides.

More importantly the currents below 100 KHz  
(DC) and the currents above 100 KHz (AC)  
travel in the same conductors.

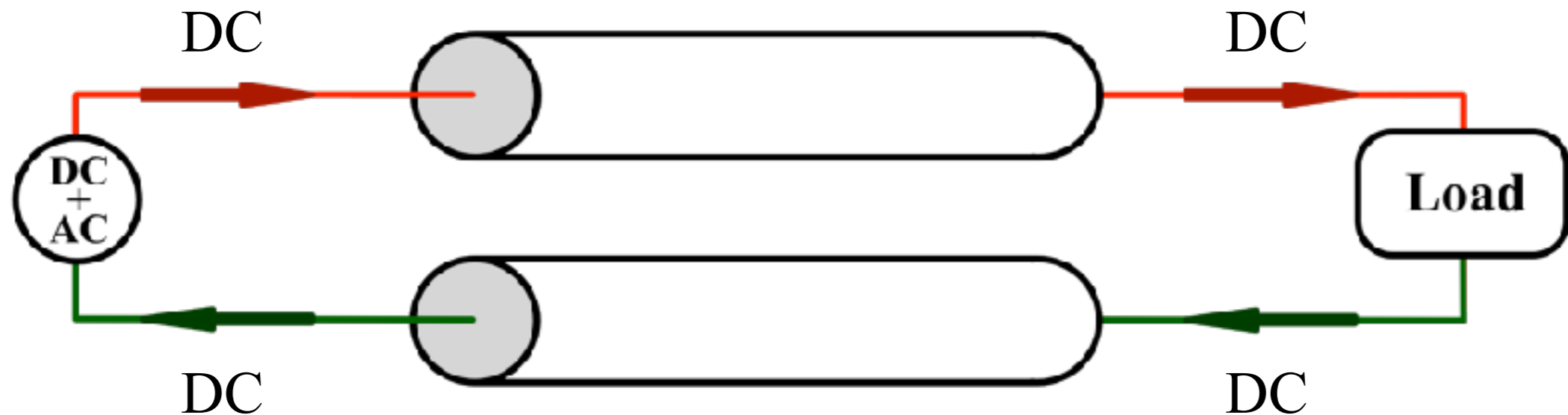
# Where does the current go?



Consider two coax cables with a DC forward and return current in two different coax cables.

The currents below 100 KHz (DC) travel through the two center conductors.

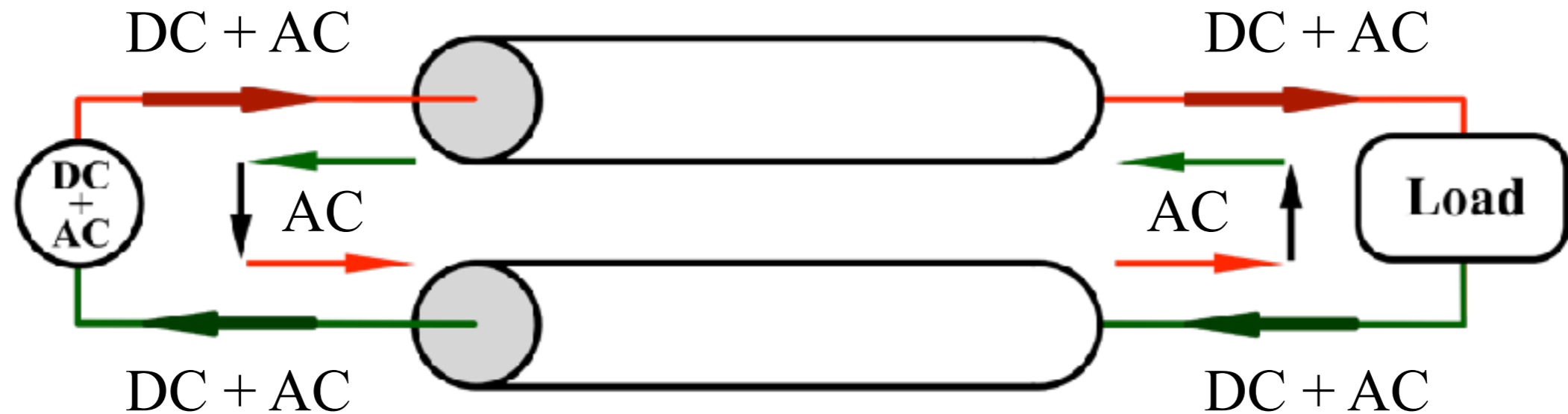
# Where does the current go?



Now consider if we put DC and AC current into one coax cable with the return currents in a different coax cable.

The DC current continues to travel the same path.

# Where does the current go?

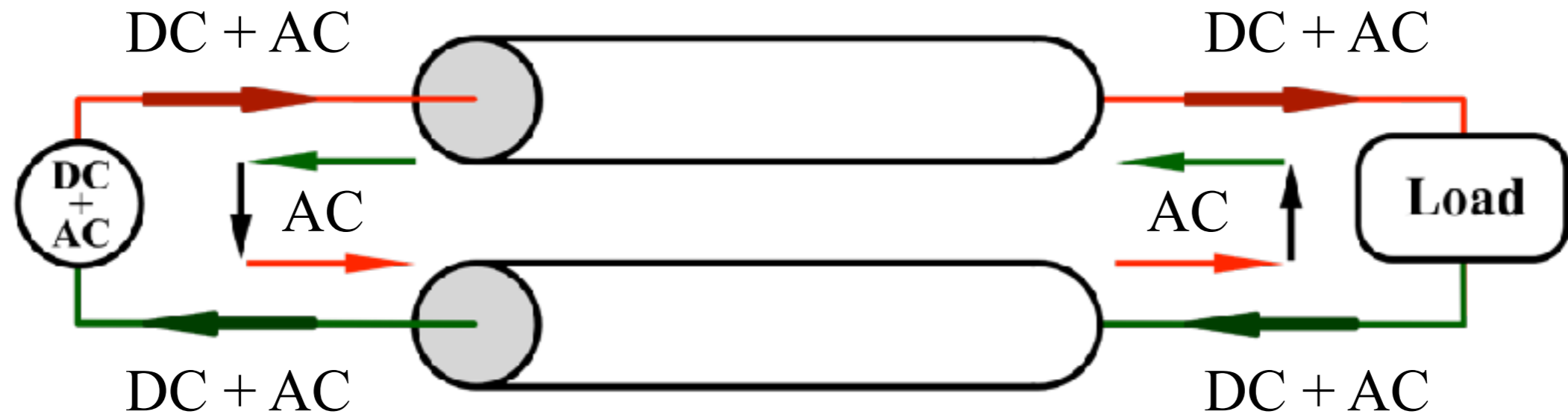


Now consider if we put DC and AC current into one coax cable with the return currents in a different coax cable.

The AC currents take a very different path. The transmission line is acting like a transformer.



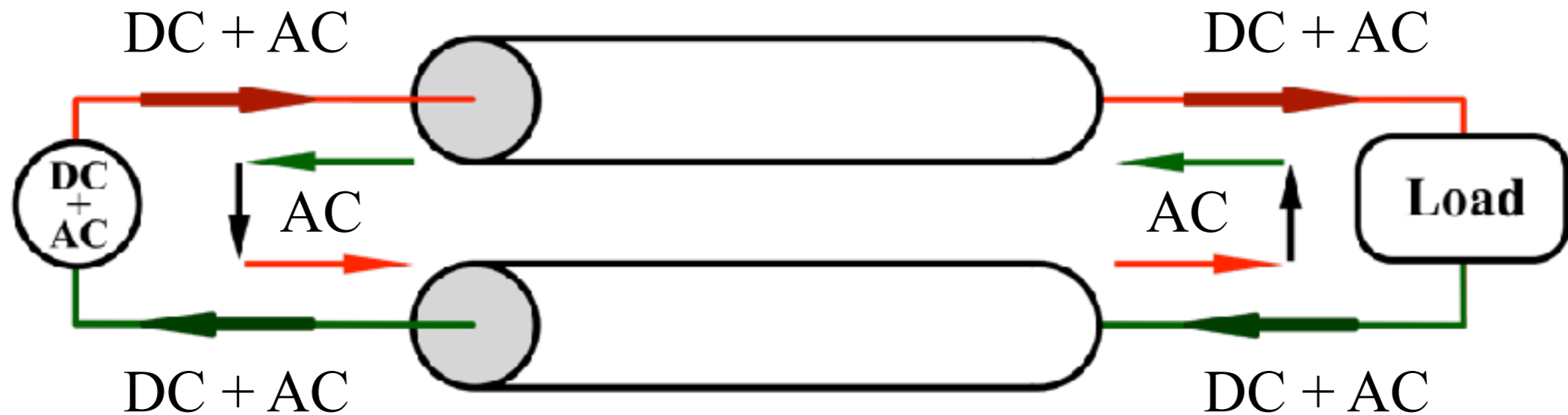
# Where does the current go?



The AC current travels through the center conductors and an equal and opposite AC current is created on the inside of the outer conductors.

This AC current combines at both ends of the coax cable.

# Where does the current go?



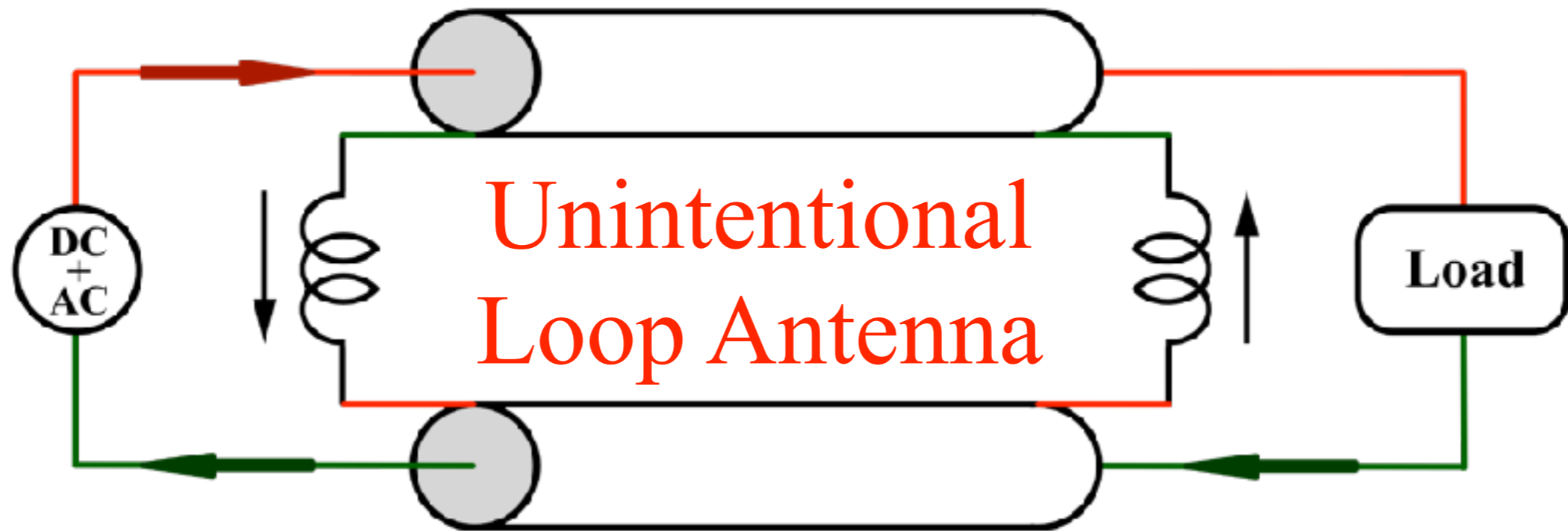
Unfortunately the outer conductor connections are imperfect as they have resistance and physical length, hence inductance.

# Where does the current go?



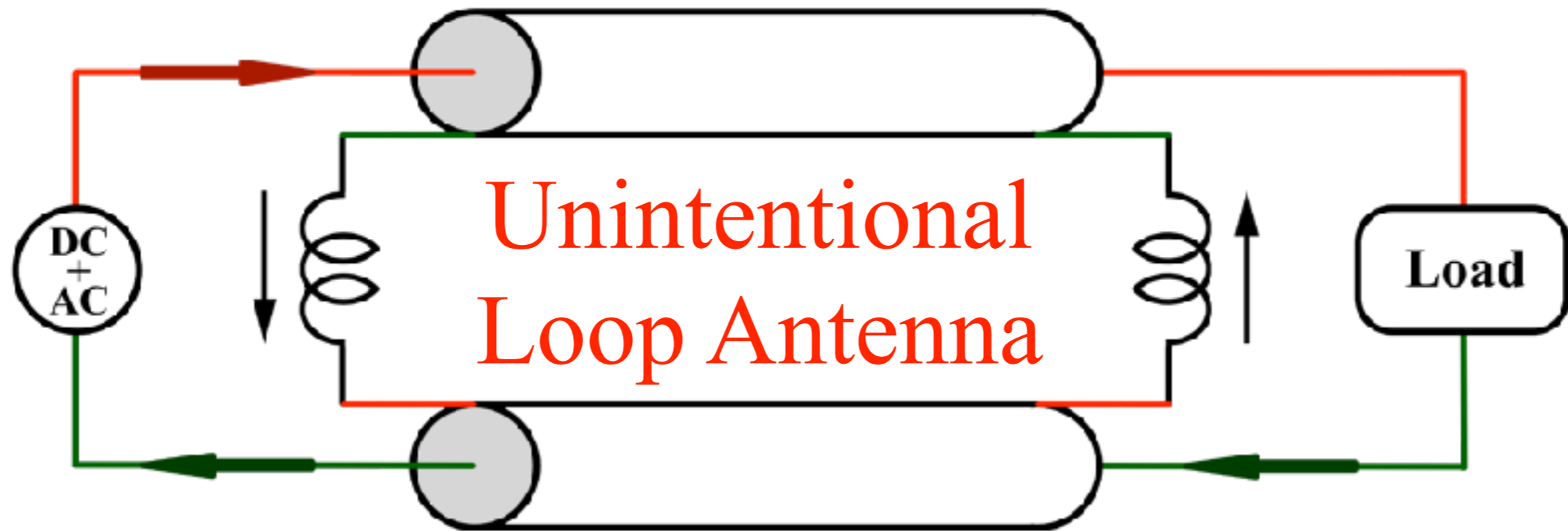
All the current above 100 KHz will travel through the impedances resulting in two voltage drops that will feed the transmission line formed by the outside of the two coaxial shields.

# Where does the current go?



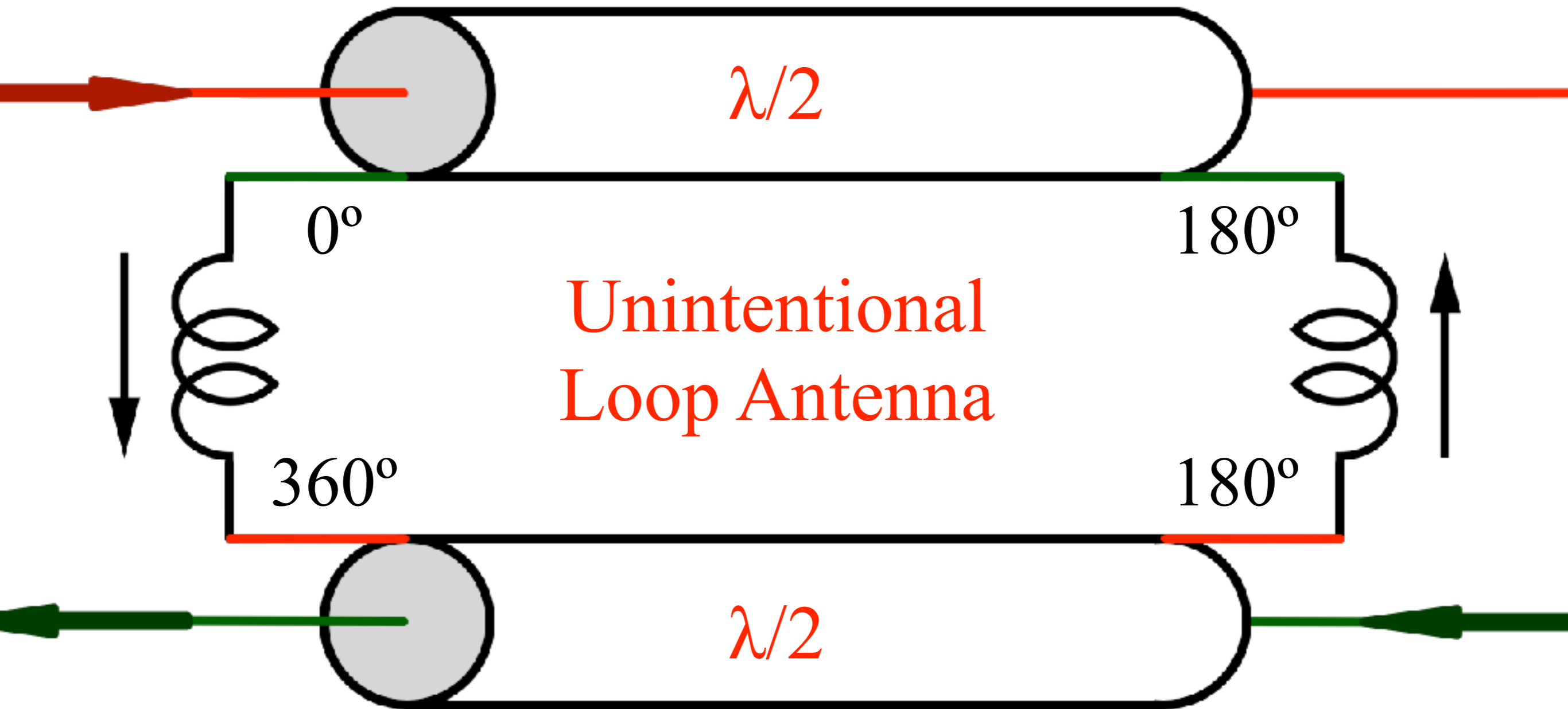
If the characteristic impedance of the coaxial shield transmission line is near or above 377 ohms, you don't have a transmission line, you have an unintended loop antenna.

# Where does the current go?

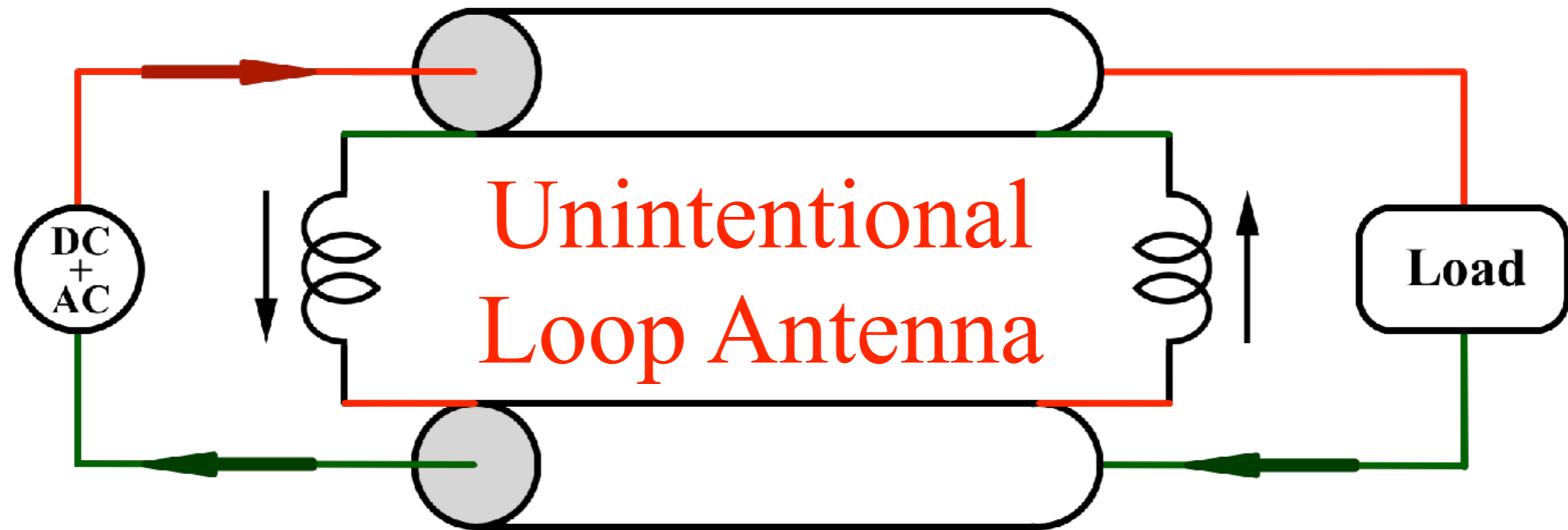


The current loop is from one impedance across the outside of an outer conductor to the second impedance and back across the second outer conductor.

# Where does the current go?

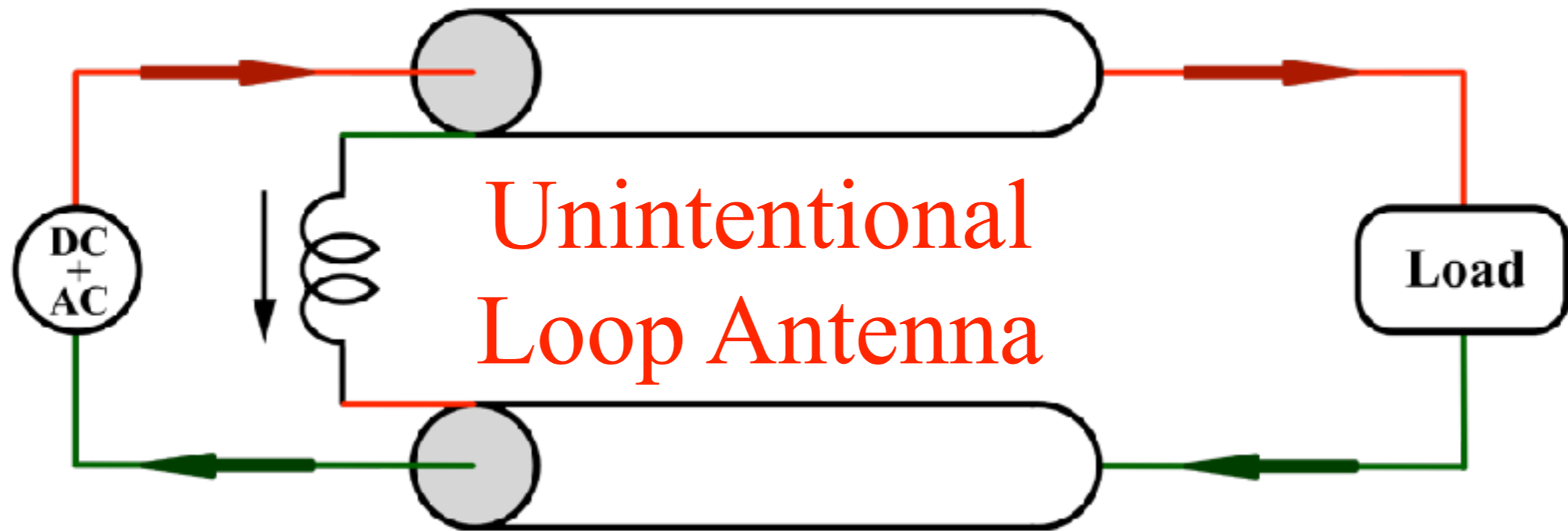


# Where does the current go?



The resulting EMC issue will be centered at a coax length of approximately half a wavelength and again at one wavelength, etc.

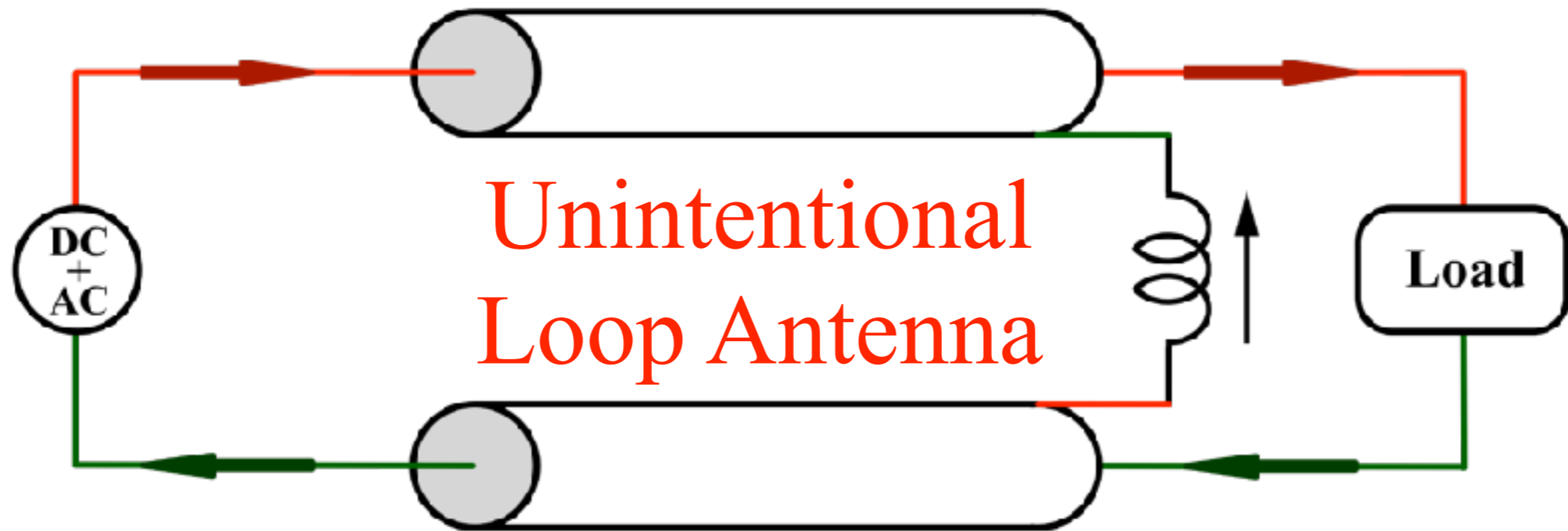
# Where does the current go?



If the coax outer conductors are not connected on the load side it forms an unintentional folded dipole antenna.



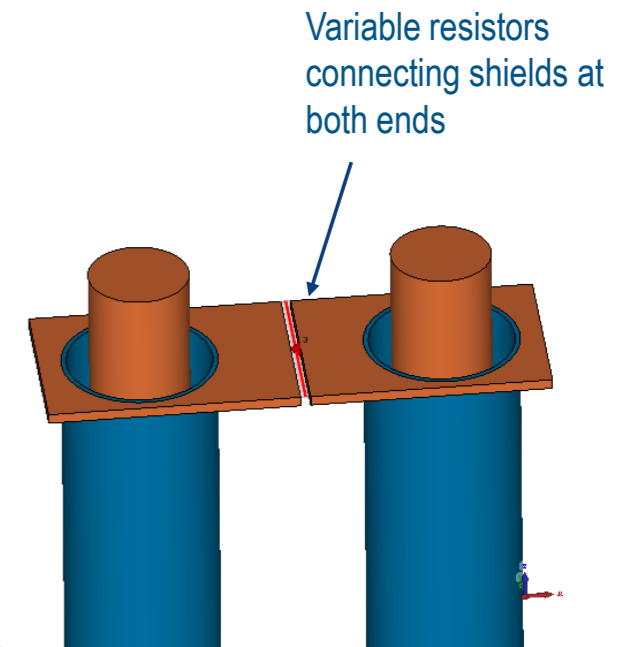
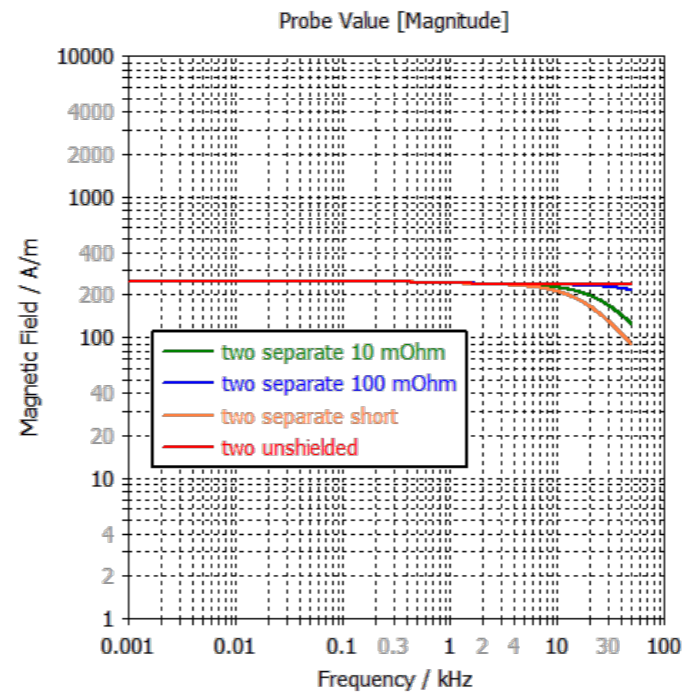
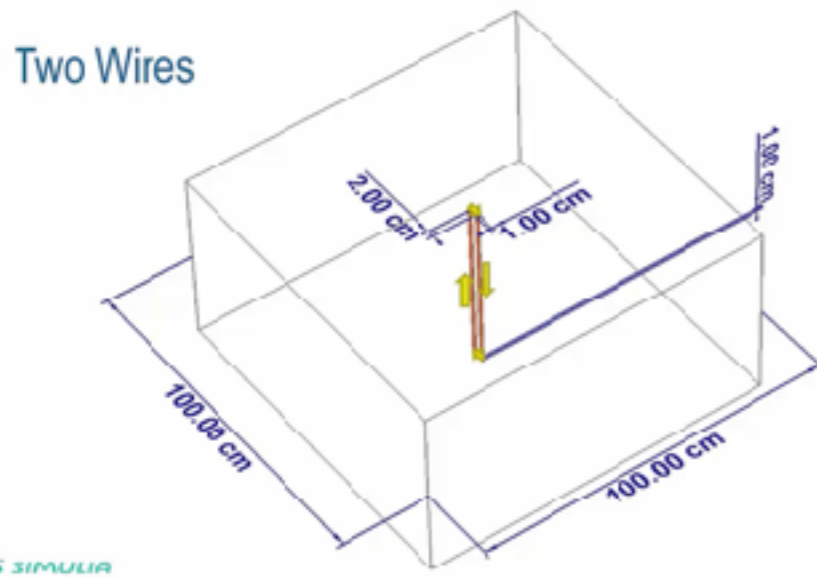
# Where does the current go?



If the coax outer conductors are not connected on the source side it also forms an unintentional folded dipole antenna.

# Andreas Barchanski Simulation

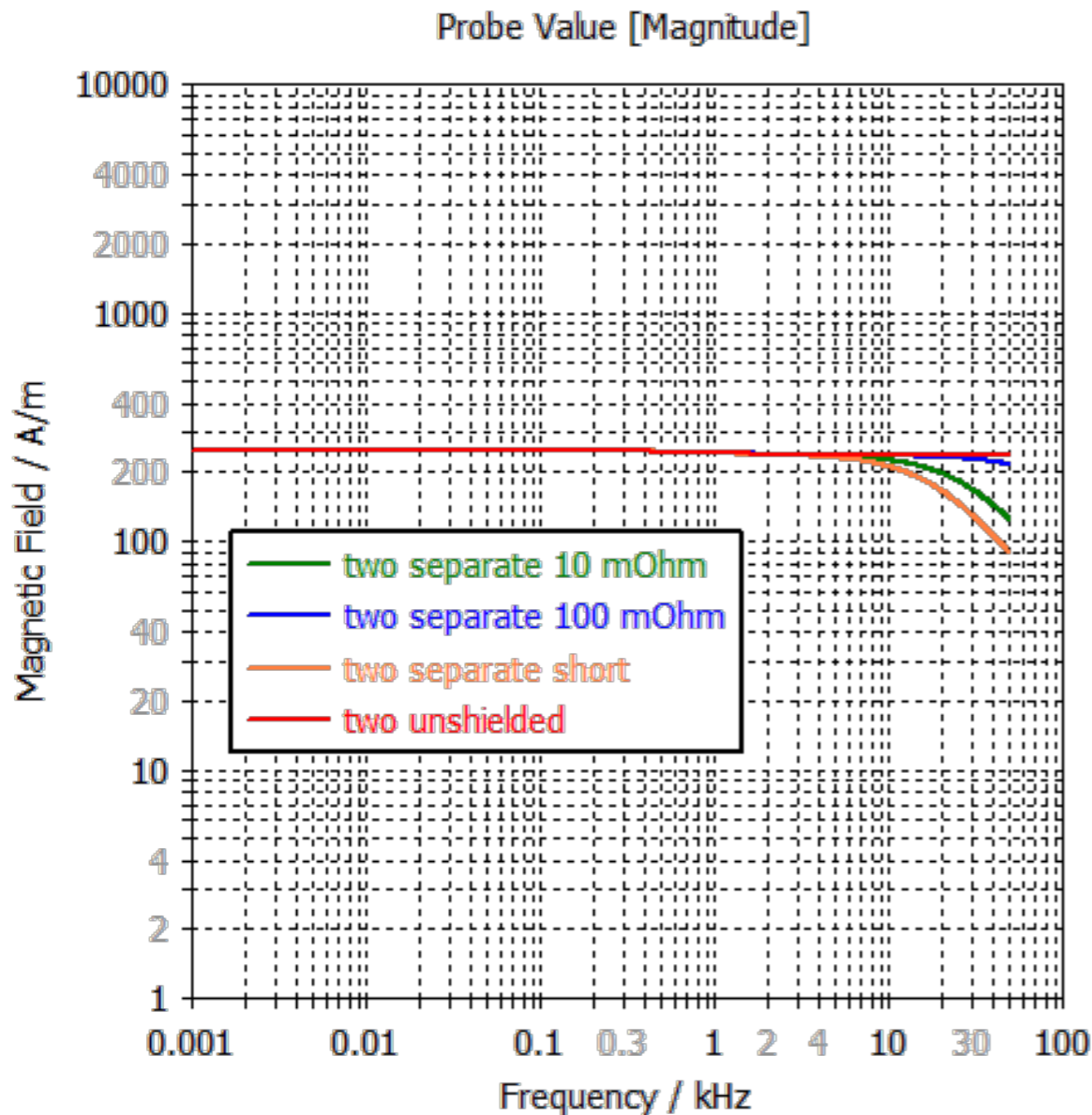
## Two Wires Separate Shield – H Field



Andreas Barchanski of Dassault Systemes has done an excellent video showing his simulations on magnetic field strength near various wire shapes. The simulations are from 1 Hz to 50 KHz.

[https://www.youtube.com/watch?v=pIDC6NBUCXw&feature=emb\\_logo](https://www.youtube.com/watch?v=pIDC6NBUCXw&feature=emb_logo)

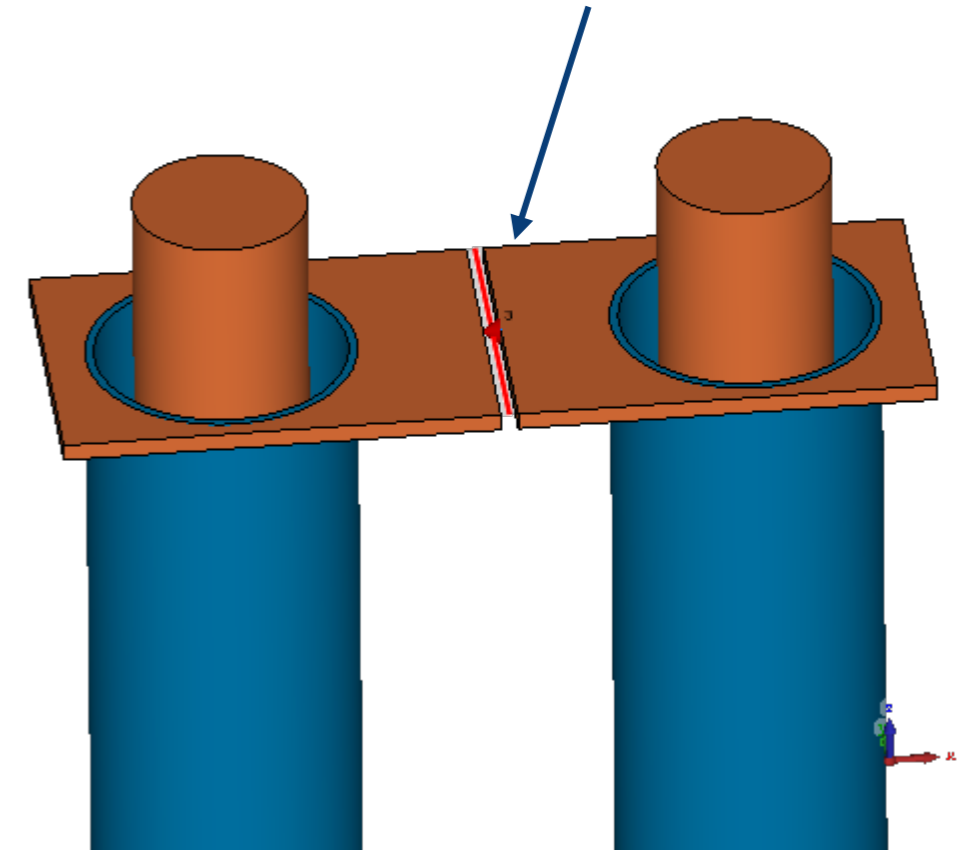
# Two Wires Separate Shield – H Field



No shielding effectiveness

Variable resistors connecting shields at both ends

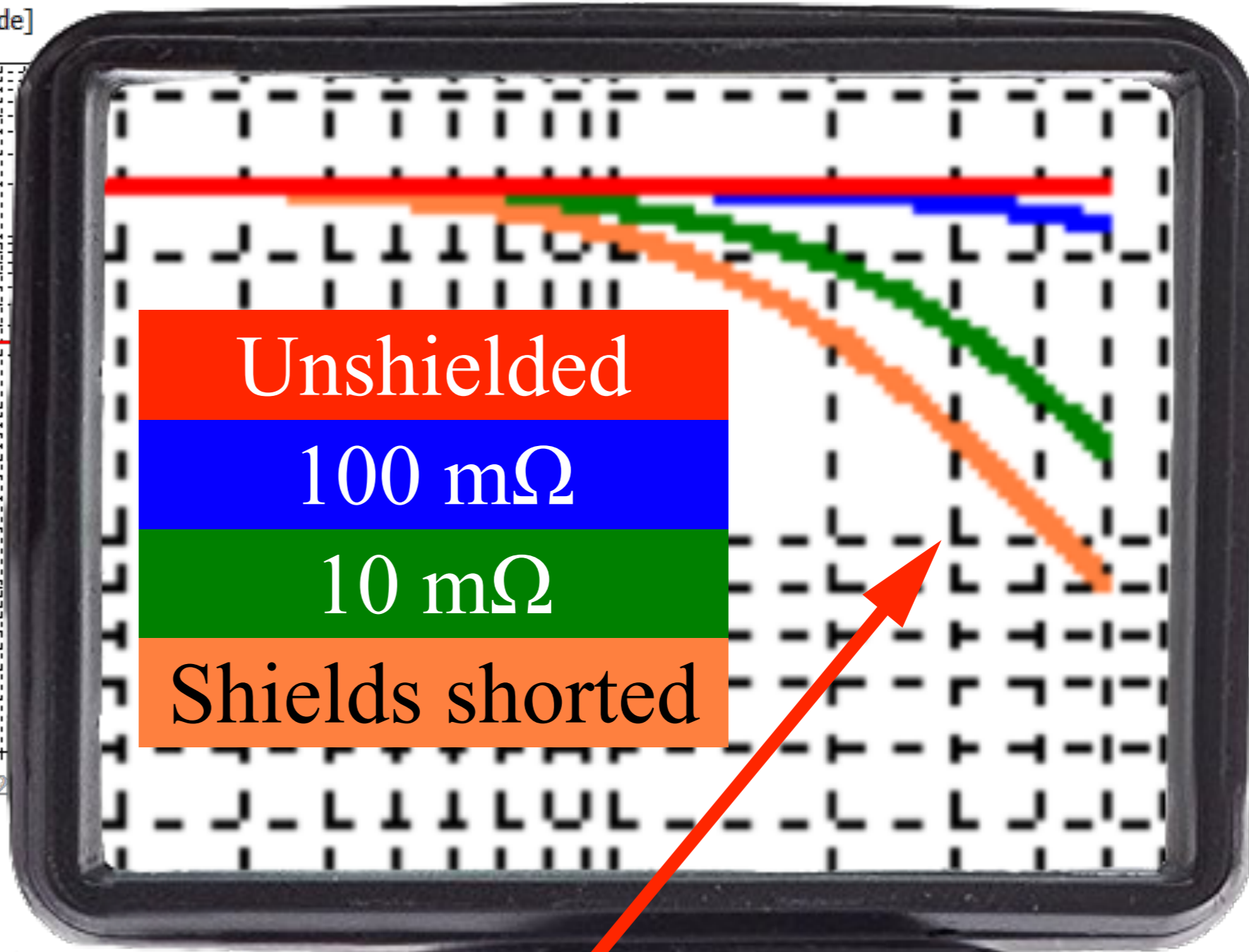
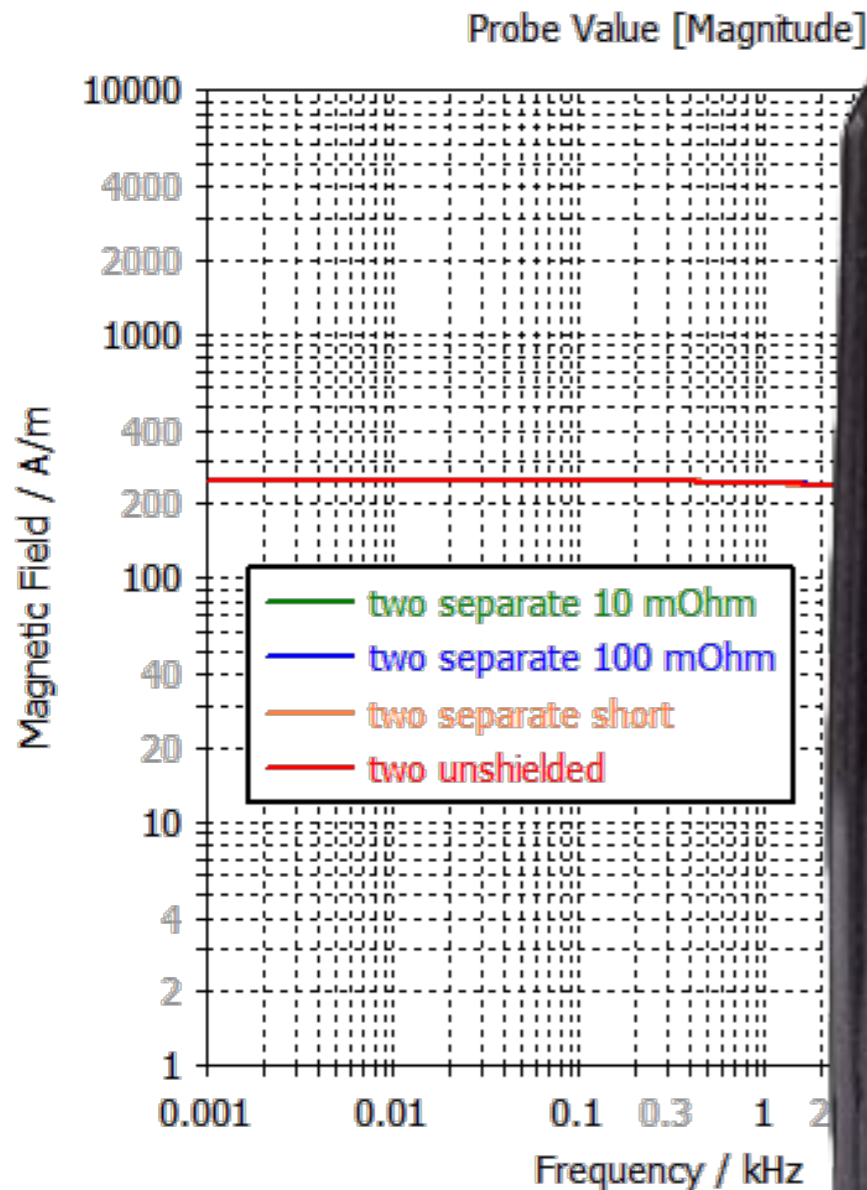
Better shielding effectiveness



In the graph a lower number shows better shielding effectiveness.

Mr. Barchanski's slides used with permission.

# Two Wires Separate Shield – H Field

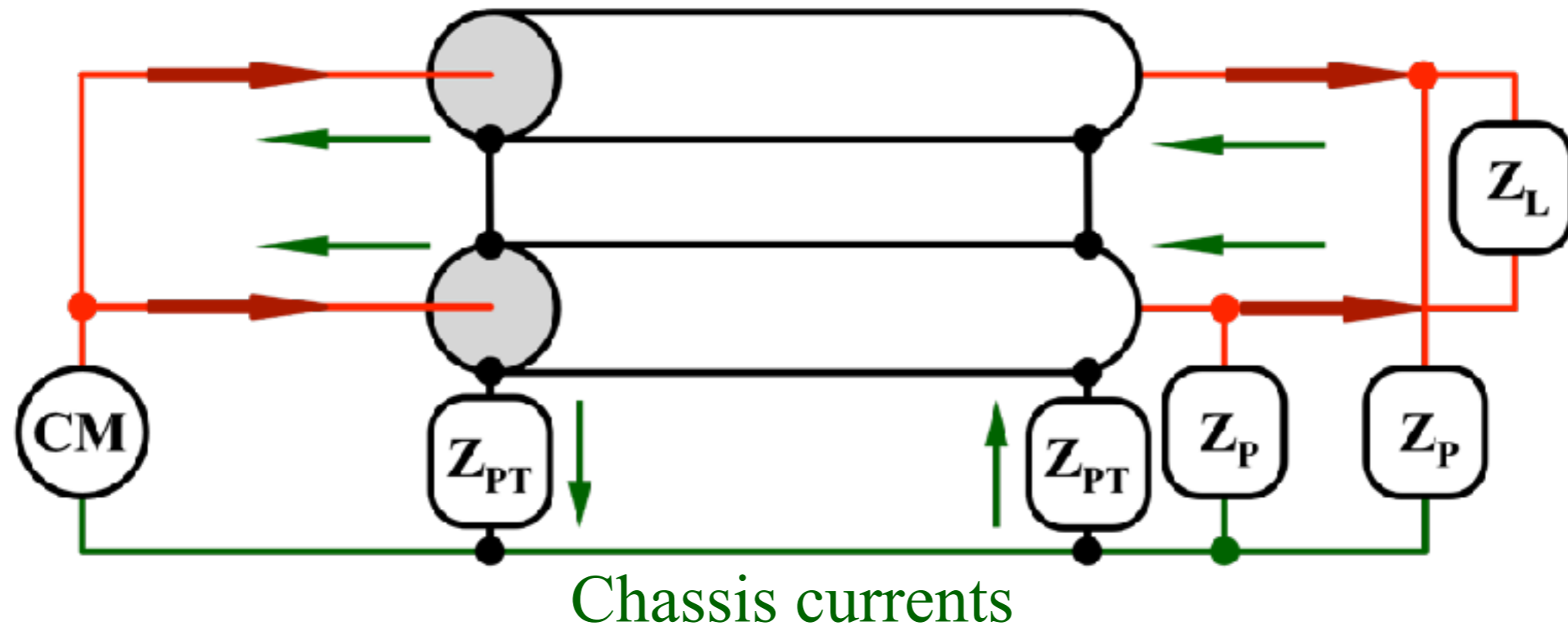


Resistance between the shields reduces shielding effectiveness.

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Mr. Barchanski's slides used with permission.

# The Common Mode Path



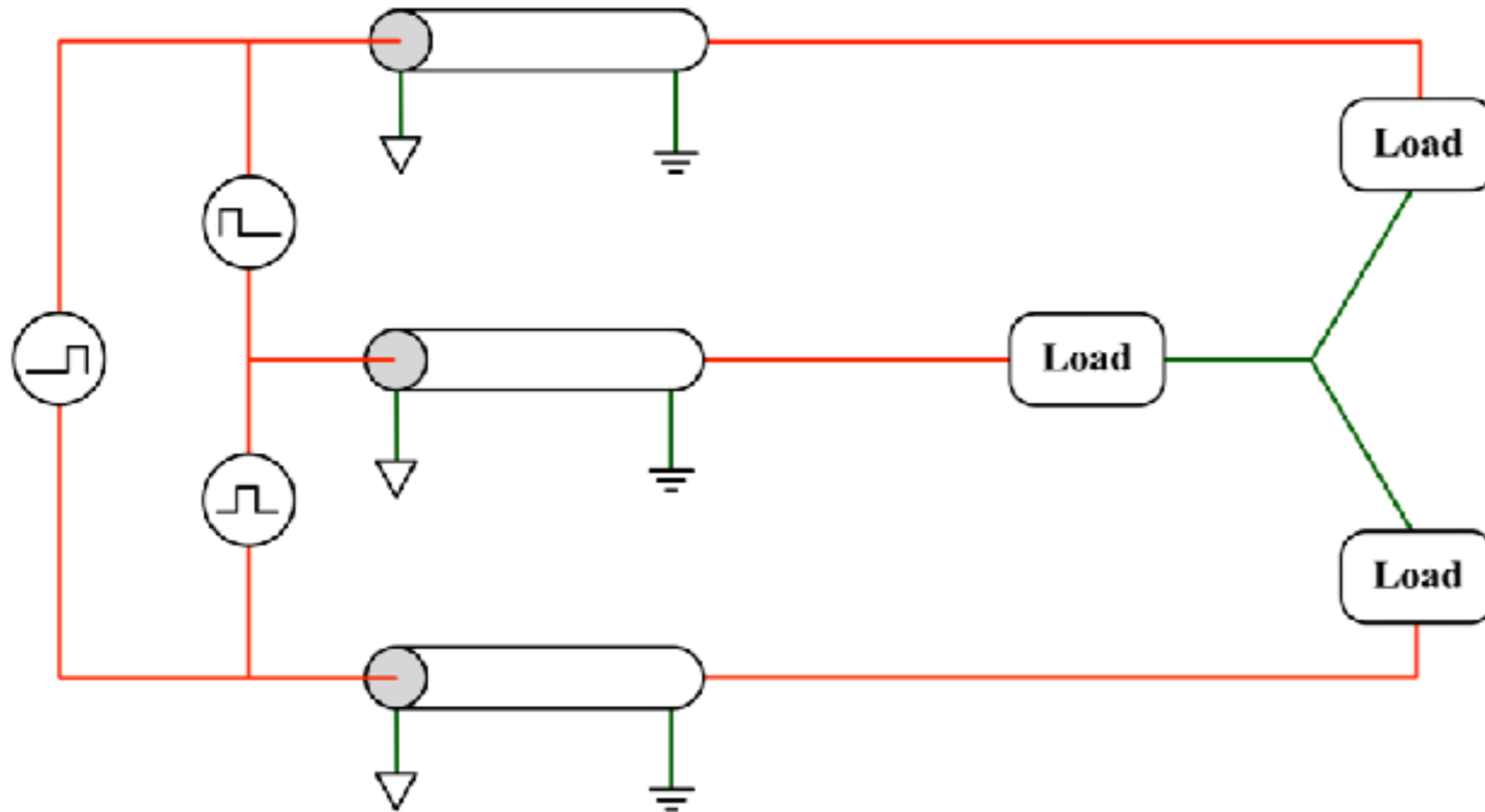
Typically the common mode path is well controlled as long as the impedances from the coax to the source and load are small.

Many high current PWM devices  
use three phase power transfer.

Image from CHARGED  
Electric Vehicle Magazine,

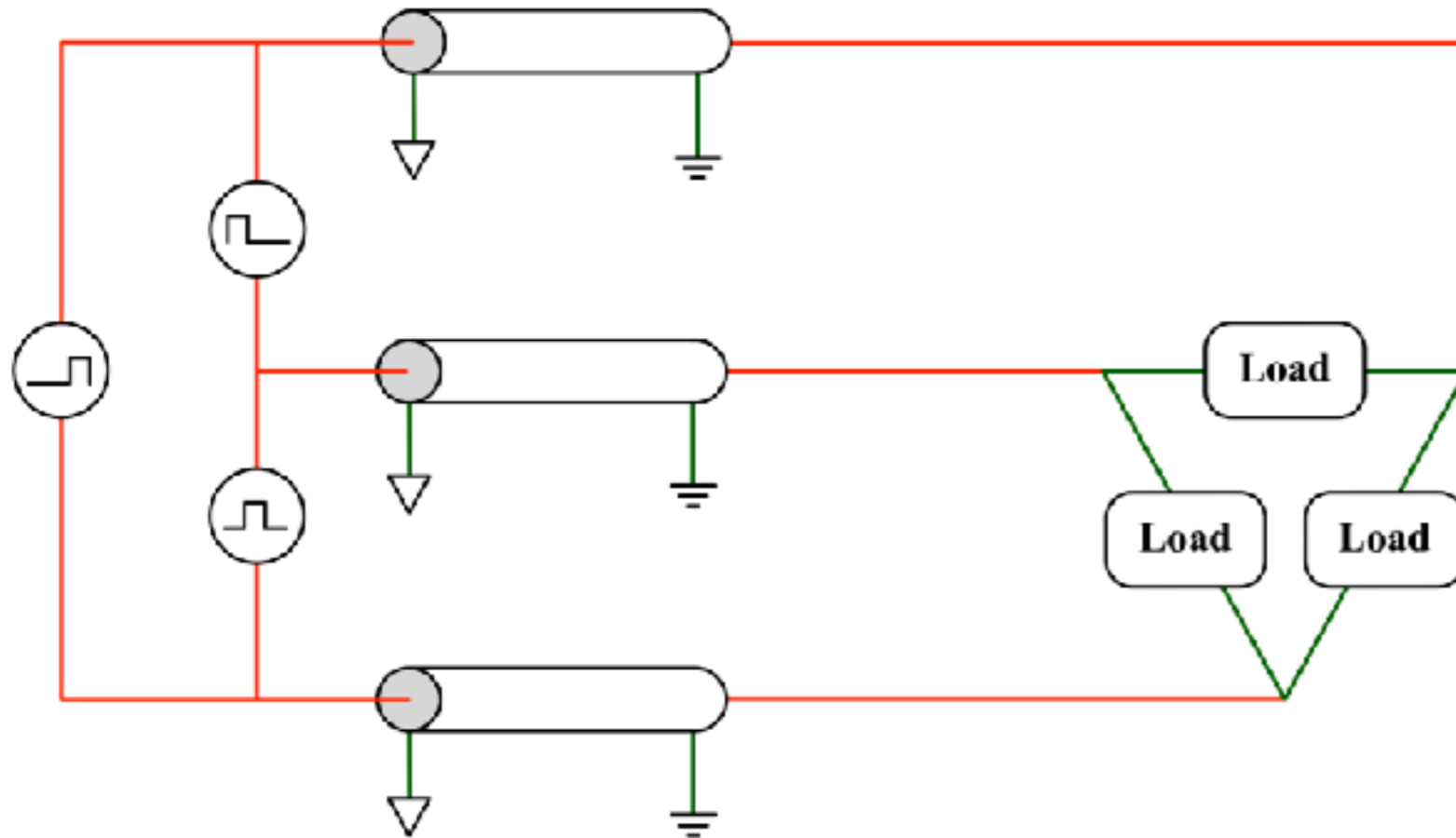
December 17, 2018.

# Where does the current go?



With a three phase Wye configuration there are three unintentional antennas formed by the circulating currents between the coaxial outer conductors.

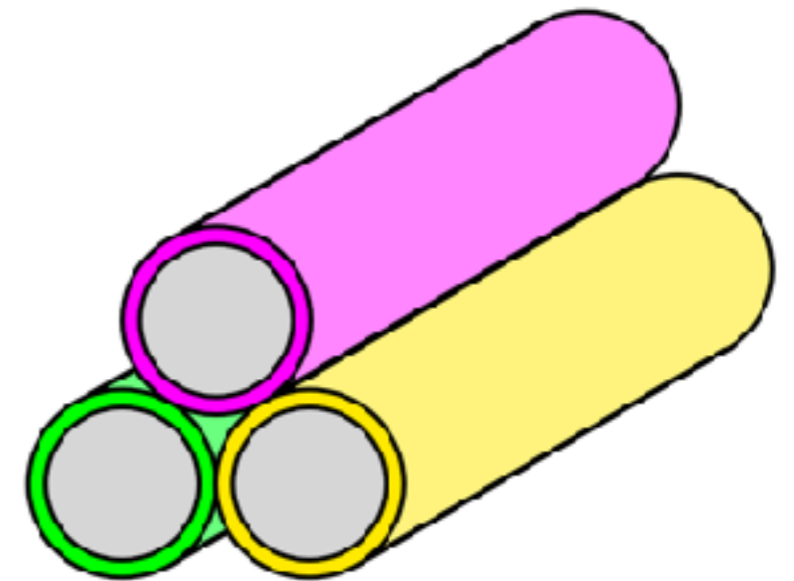
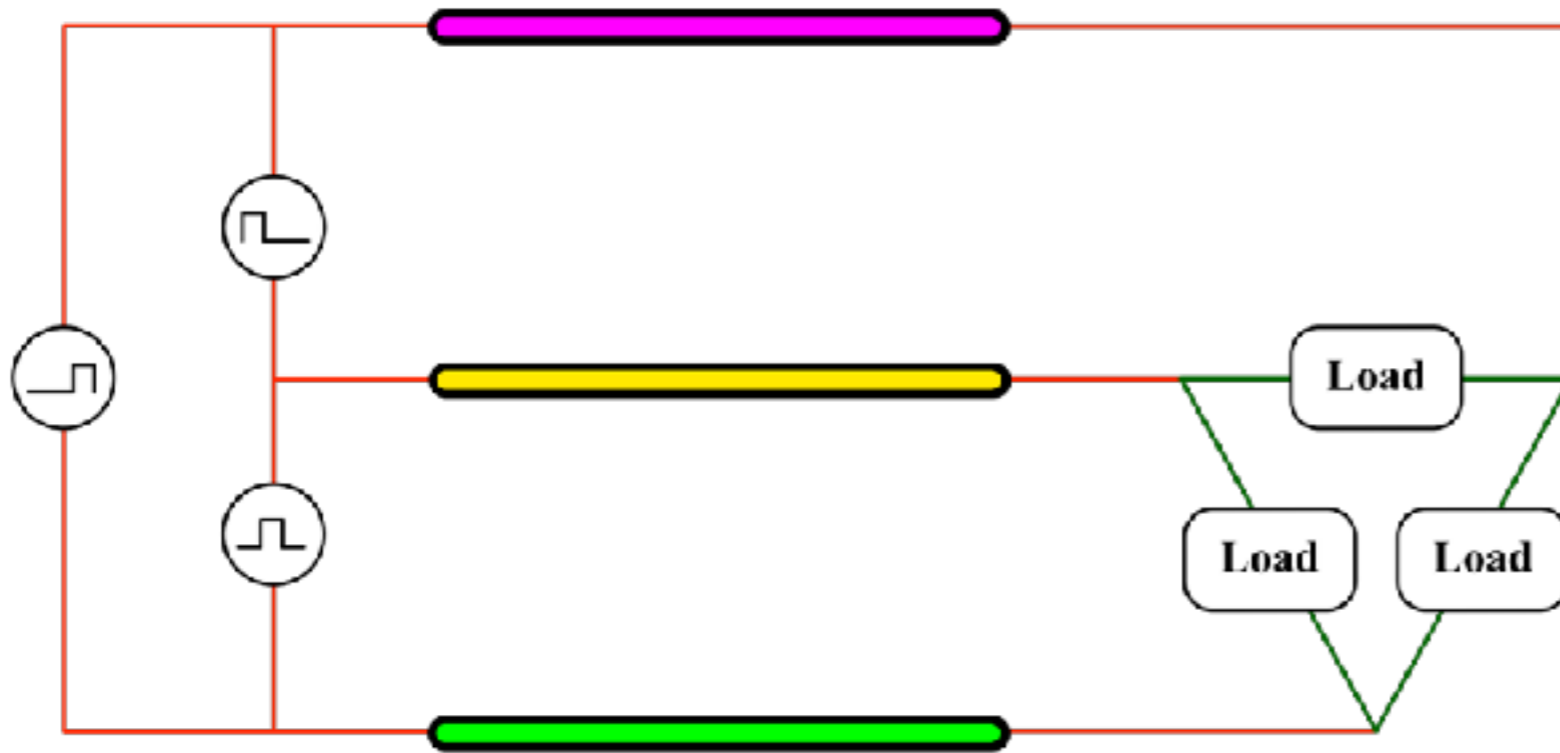
# Where does the current go?



With a three phase Delta configuration there are also three unintentional antennas formed between the coaxial outer conductors.

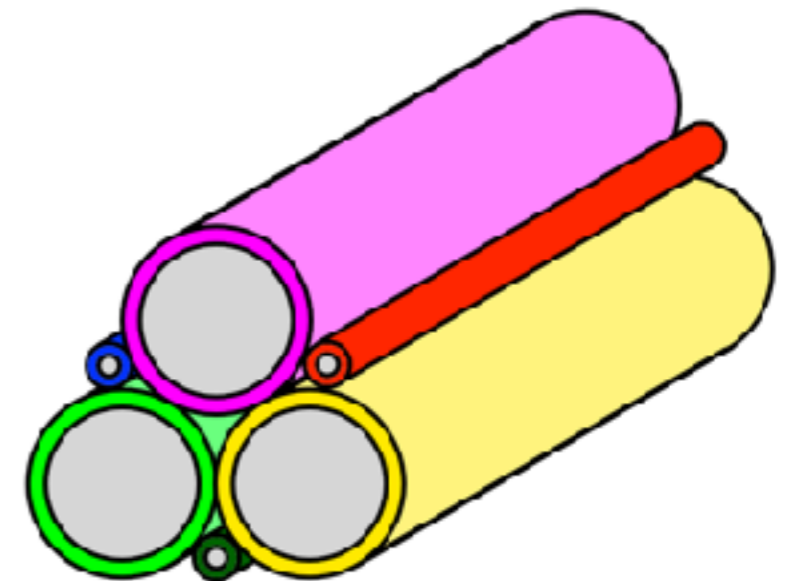
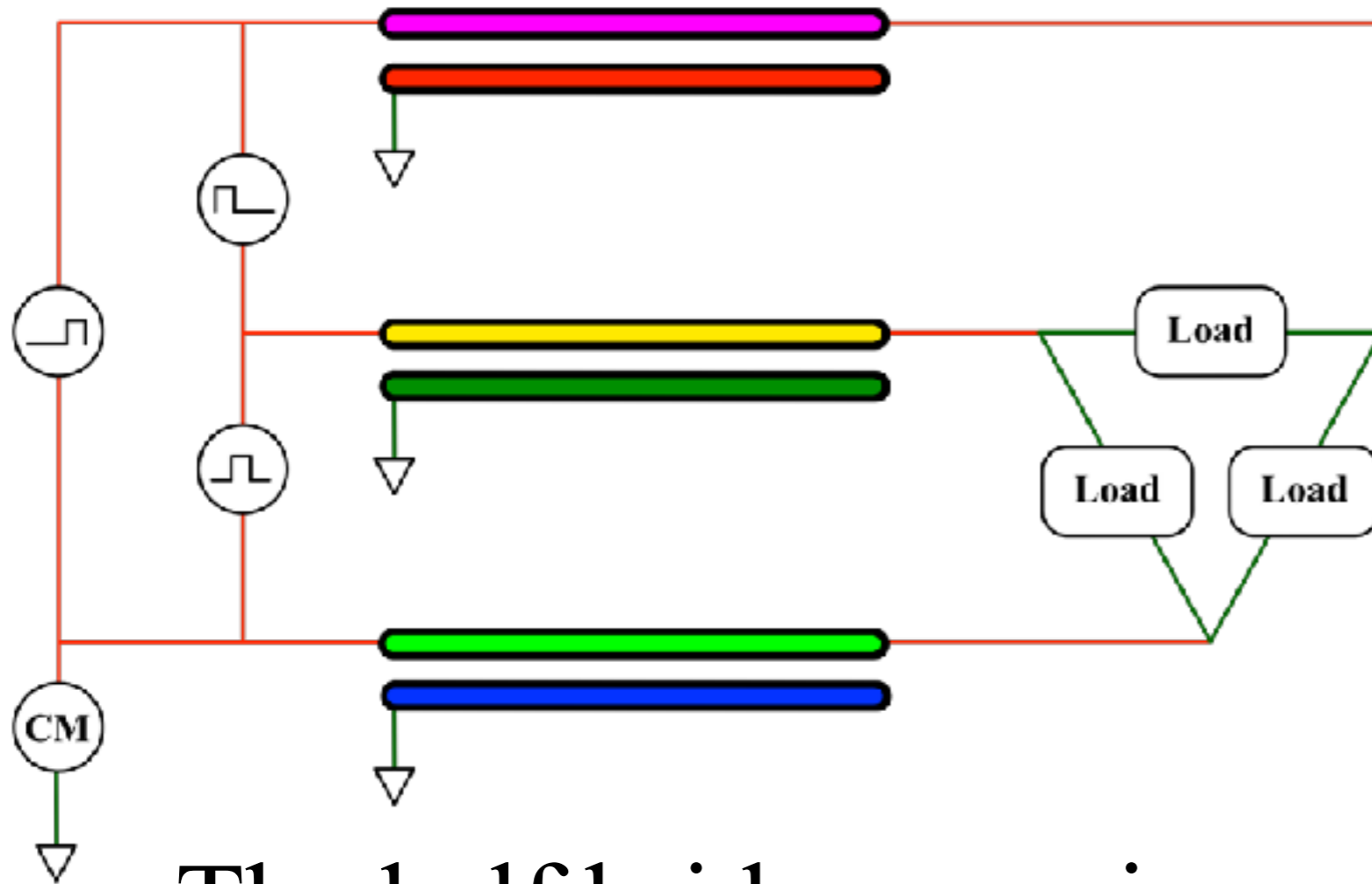


# Where does the current go?



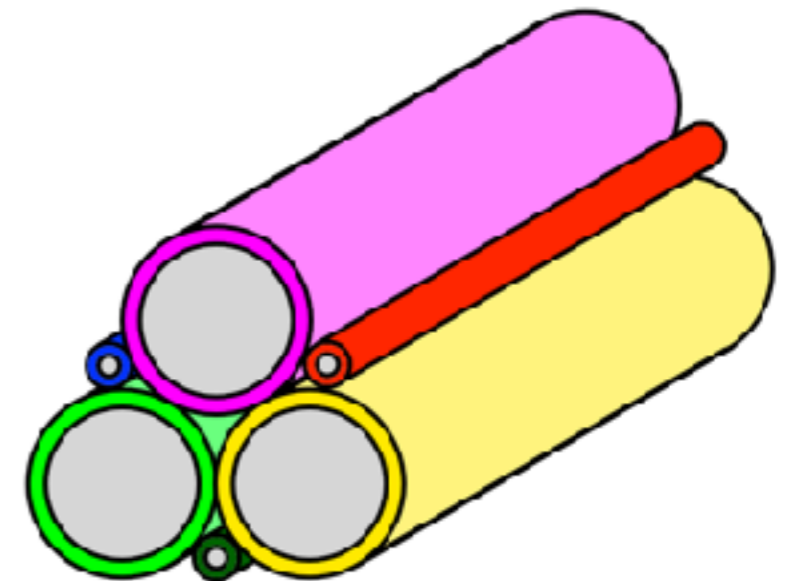
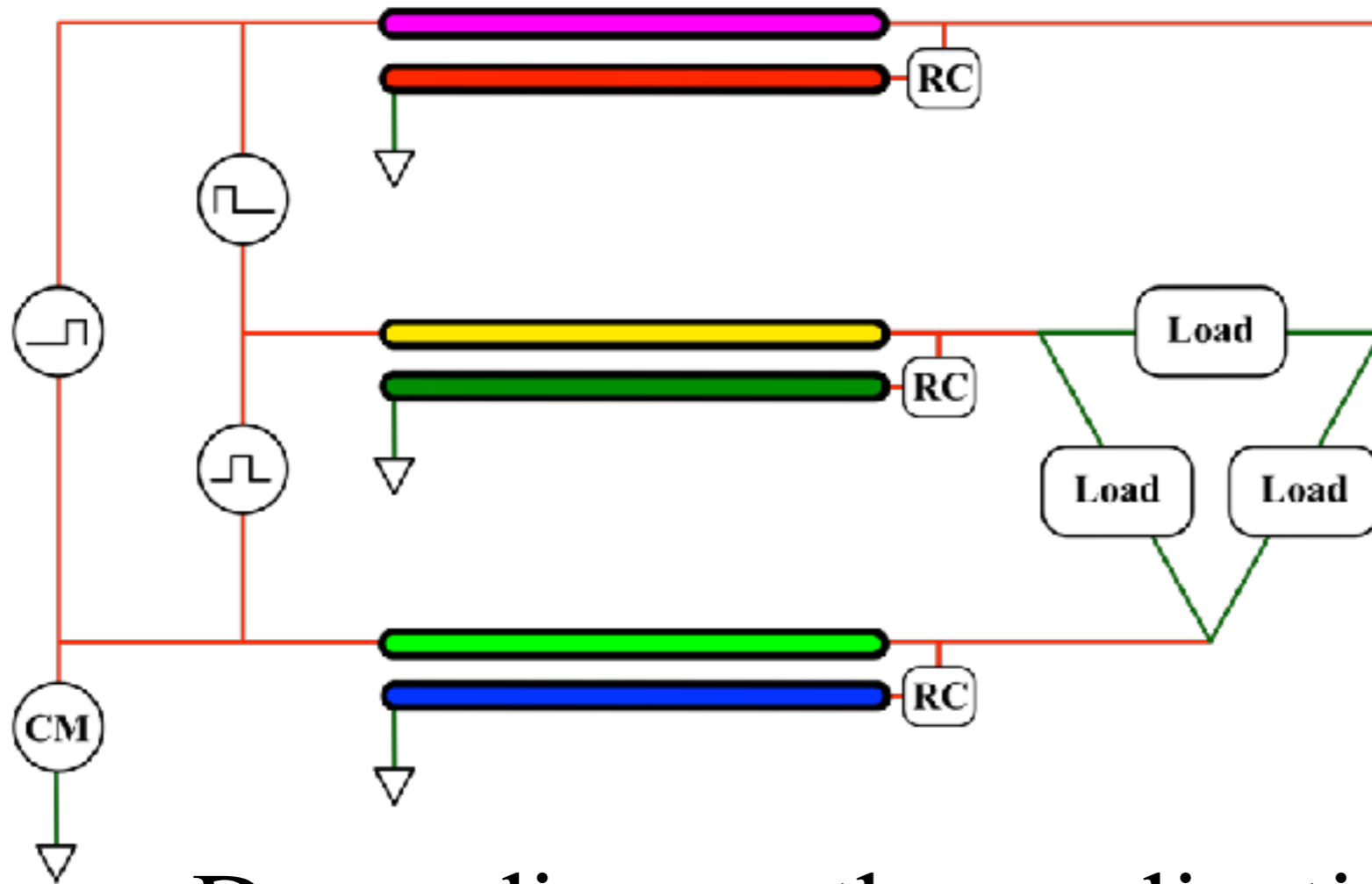
To allow the magnetic fields of all three current pairs to cancel they must be in a single transmission line, a triplet.

# Where does the current go?



The half bridges are imperfect and create three common mode forward currents. Here again these forward currents can be constrained in transmission lines.

# Where does the current go?



Depending on the application the common mode transmission lines may need to be terminated. Some applications will also need the  $Q$  of the motor windings controlled.

How do you solve EMC issues  
when your team fails.

~~Hire an EMC consultant.~~

If the engineers don't understand what they  
are doing, they don't do it.

Engineers that don't understand the physics  
don't implement the solution.

As a result an expert with the solution is often  
ignored and the problem is not resolved.

How do you solve EMC issues  
when your team fails.

~~Hire an EMC consultant.~~

~~Have a dedicated EMC team.~~

Engineers that don't understand the physics  
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As a result the dedicated team with the solution  
is often ignored and the problem is not resolved.

How do you solve EMC issues  
when your team fails.

~~Hire an EMC consultant.~~

~~Have a dedicated EMC team.~~

To fix the EMC problem train the  
engineering team, all of them;  
Mechanical, System, Electrical  
Engineers, Layout and Technicians.

# So what is the solution?

The  
first  
80%

To fix the EMC problem train the engineering team, all of them; Mechanical, System, Electrical Engineers, Layout and Technicians.

The  
last  
20%

Hire an EMC consultant,  
Train a company expert or,  
Train an EMC team or,  
Train specific engineers.

# Team EMC Productivity

Most issues are resolved in 30 hours or less;  
16 hours of training over 4 days,  
4 hour workshop and  
10 hours of office hours / support.

Train the entire team all at once to build Teamwork.

Mechanical, System, Test, and Electrical Engineers,  
Supervision, PCB Layout and Technicians.


Train the Physics of EMC conceptually  
without Vector Calculus.






# Increase Team Productivity

## Introduction to Electromagnetic Compatibility for Increased Team Productivity




Joanna McLellan  
+1 248-765-3599  
[JoannaEMC@icloud.com](mailto:JoannaEMC@icloud.com)



This class transforms EMC from a subject dominated by a few experts into a team sport where the engineering disciplines solve problems together.



Video and audio recording is prohibited.  
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## Welcome to the Brave New EMC World above 100 KHz



In this session we continue to explore the physicality of Electromagnetic Compatibility. This is the second session in the series of four.

Presented by JoannaEMC  
+1 248-765-3599 [JoannaEMC@icloud.com](mailto:JoannaEMC@icloud.com)

My apologies to Aldous Huxley author of Brave New World, 1931.  
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## Dorothy we are not in Kansas any more, we are in Impedance land. Oh my!






In this section we are going to explore Impedance Land, the third sessions in the EMC series.

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## Raid for EMC bugs, stop those nasty EMC bugs cold in their tracks

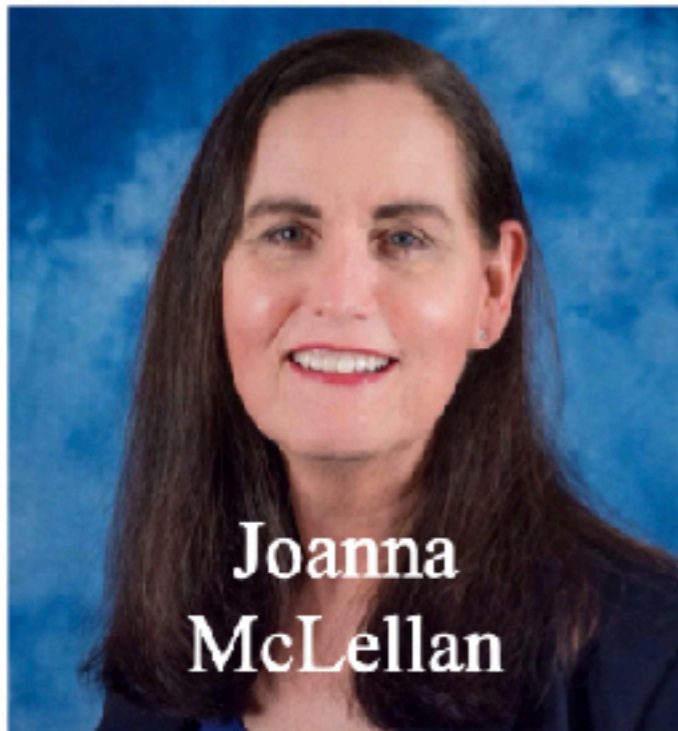


In this fourth session we are going to learn about antennas and how to get the EMC bugs out by designing bad antennas.

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# Increase Team Productivity

## Introduction to Electromagnetic Compatibility for Increased Team Productivity



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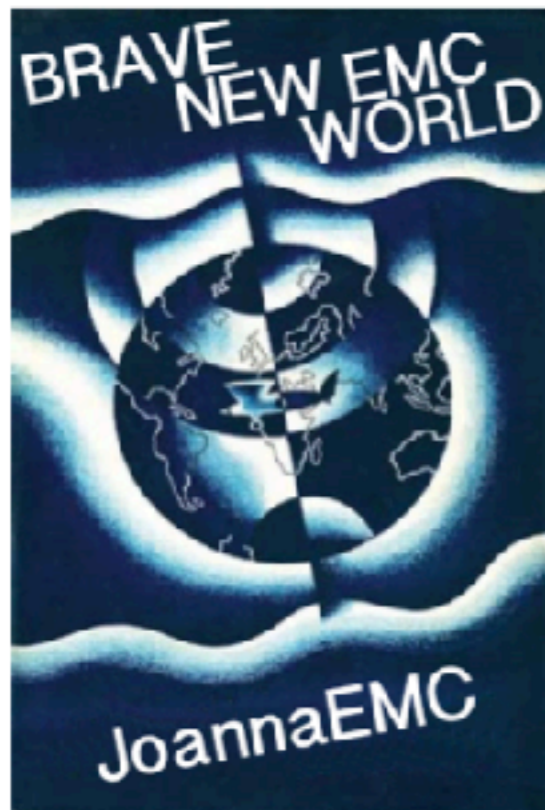
This class transforms EMC from a subject dominated by a few experts into a team sport where the engineering disciplines solve problems together.



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# Increase Team Productivity

## Welcome to the Brave New EMC World above 100 KHz



My apologies to Aldous Leonard Huxley  
author of Brave New World, 1931.

In this session we continue to explore the physicality of Electromagnetic Compatibility. This is the second session in the series of four.



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2

# Increase Team Productivity

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# Goals, Objectives and Outcomes

Our goal is to transforming the typical first pass EMC test failure rate of 80% into an 80% success rate.

Our objective is to provide the incremental information required to design in compliance.

The learning outcomes include; understanding that ground does not exist above 100 KHz, RF energy travels in the spaces between conductors, and the implications of the Pesky Slow Speed of Light.<sup>TM</sup>

# Who Needs What Training?

Executive Management, stabilize execution.

Engineering Management, what to expect.

Mechanical engineers, recognize shape is critical.

Electrical engineer, recognize and how to correct.

Test engineers, recognize and how to correct.

PCB Layout, recognize and how to correct PCBs.

System engineers, recognize issues.

Manufacturing engineers, recognize issues

# Fixing EMC Issues Without The Training

1. Add a Ferrite.

Fixes the issue only to create a new one.

2. Add a Capacitor.

Fixes the issue only to create multiple new ones.

3. Add a Resistor.

Not typically considered.

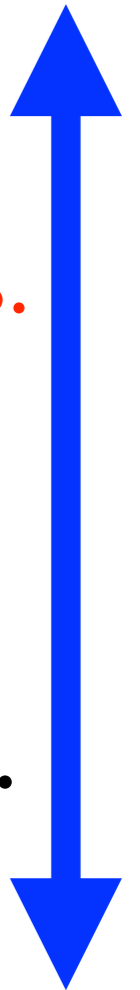
4. Form a Low Impedance Transmission line.

Not typically considered.

5. Find and Break the Antenna.

Not typically considered.


Higher  
Cost



Lower  
Cost



# Fixing EMC Issues With The Training

1. Find and Break the Antenna.  
**First look for the unintentional antennas.**
  2. Form Low Impedance Transmission lines.  
**Route the return current back to the source.**
  3. Add a Resistor.  
**Lower the Resonant Circuit Q factors.**
  4. Add a Capacitor.  
**Don't Play Capacitor Whack-a-Mole.**
  5. Add a Ferrite.  
**When all else fails, consider using a Ferrite.**
- Lower Cost
- 
- Higher Cost

# To Consistently Pass EMC

All signals with frequency content above 100 KHz must be contained in a transmission line containing both the forward and reverse currents.

And the characteristic impedance and construction of that transmission line must be designed to constrain the electromagnetic fields given the current.

# Golden rules of Electromagnetic Compatibility

1. Think wavelength, not frequency.
2. The longer you wait the more you pay.
3. There is no such thing as ground above 100 KHz.
4. All conductors have length, phase change and inductance.
5. Two conductors separated by a dielectric is a capacitor.
6. Never use any more bandwidth than you need.
7. Add resistors rather than capacitors.
8. Keep node impedance below  $10\text{K}\Omega$ .
9. Fractional wavelength is one thing,  
dimensions near or above a wavelength is another.
10. Welcome to the brave new world above 100 KHz.



Thank you for allowing me to  
share this information with  
you.

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Image from TEDGlobal 2009, Bertrand Piccard

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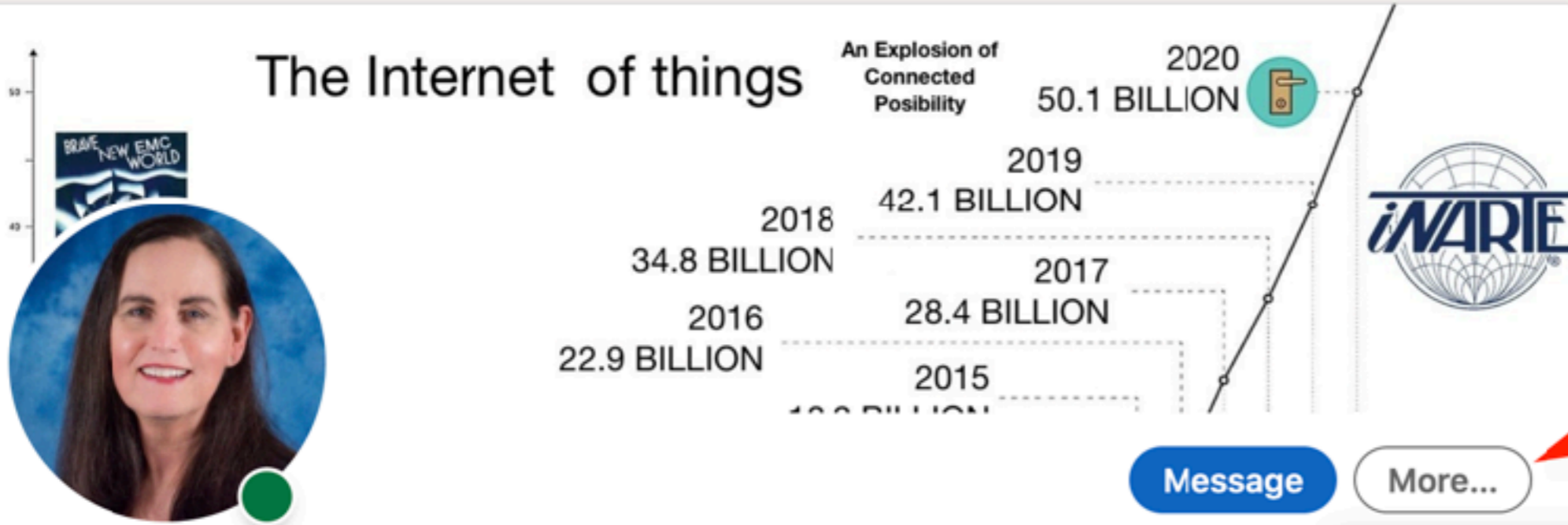
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# LinkedIn Kudos & Recommendations




**Joanna (Hill) McLellan** · 1st   
Principal Consultant at EMC Productivity  
Holly, Michigan, United States · [500+ connections](#) · [Contact info](#)

 EMC Productivity  
 Georgia Institute of Technology

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Joanna (Hill) McLellan  
Principal Consultant  
Holly, Michigan, United States  
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## Write Joanna a recommendation

The recommendation will appear on Joanna (Hill) McLellan's profile.

How do you know Joanna?

Relationship

- ✓ Select relationship
- You managed Joanna directly
- You reported directly to Joanna
- You were senior to Joanna
- Joanna was senior to you
- You worked with Joanna in the same group
- You worked with Joanna but in different groups
- You worked with Joanna but at different companies
- Joanna was a client of yours
- You were a client of Joanna's
- You taught Joanna
- You mentored Joanna
- You and Joanna studied together



# LinkedIn Kudos & Recommendations



Joanna (Hill) McLellan  
Principal Consultant  
Holly, Michigan, United States  
[Contact info](#)

The Internet of things

An Explosion of  
Connected  
Possibilities

2020  
50.1 BILLION

## Write Joanna a recommendation



The recommendation will appear on Joanna (Hill) McLellan's profile.

How do you know Joanna?

Relationship

You and Joanna studied together

Position at the time

- ✓ Select Joanna's position at the time
- Principal Consultant at EMC Productivity
- EMC Specialist at Hella
- Technical Specialist at Kostal North America
- Lead Electrical Engineer for Vision at TK Holdings (formerly Takata)
- Senior Engineer at Harman Becker International
- Senior Engineer at Siemens VDO Automotive
- Senior Engineer at Lear Corporation (formerly UTA)
- Project Engineer, at Burroughs
- Engineer, Test Tooling at Texas Instruments
- Student at Georgia Institute of Technology (MSEE)
- Student at Florida Institute of Technology (BSEE)

