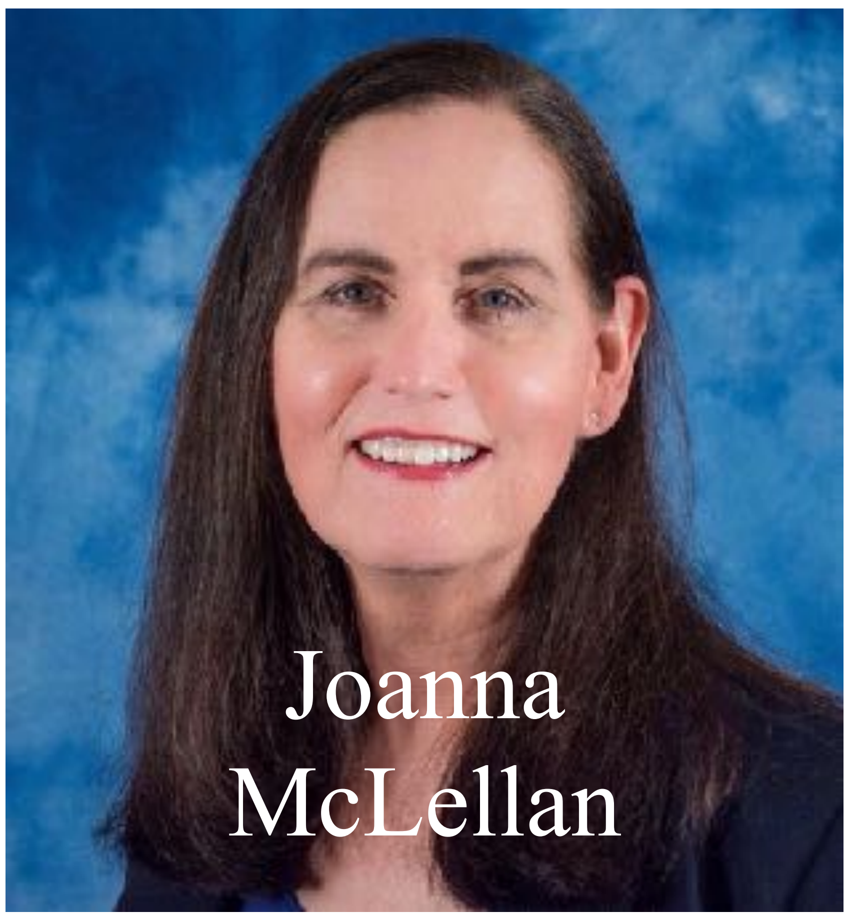
Three phase power transfer, the automotive nightmare too expensive and too noisy.



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

EMC PRODUCTIVITY™

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Florida Tech

GEORGIA TECH

IEEE EMC SOCIETY

iNARTE

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

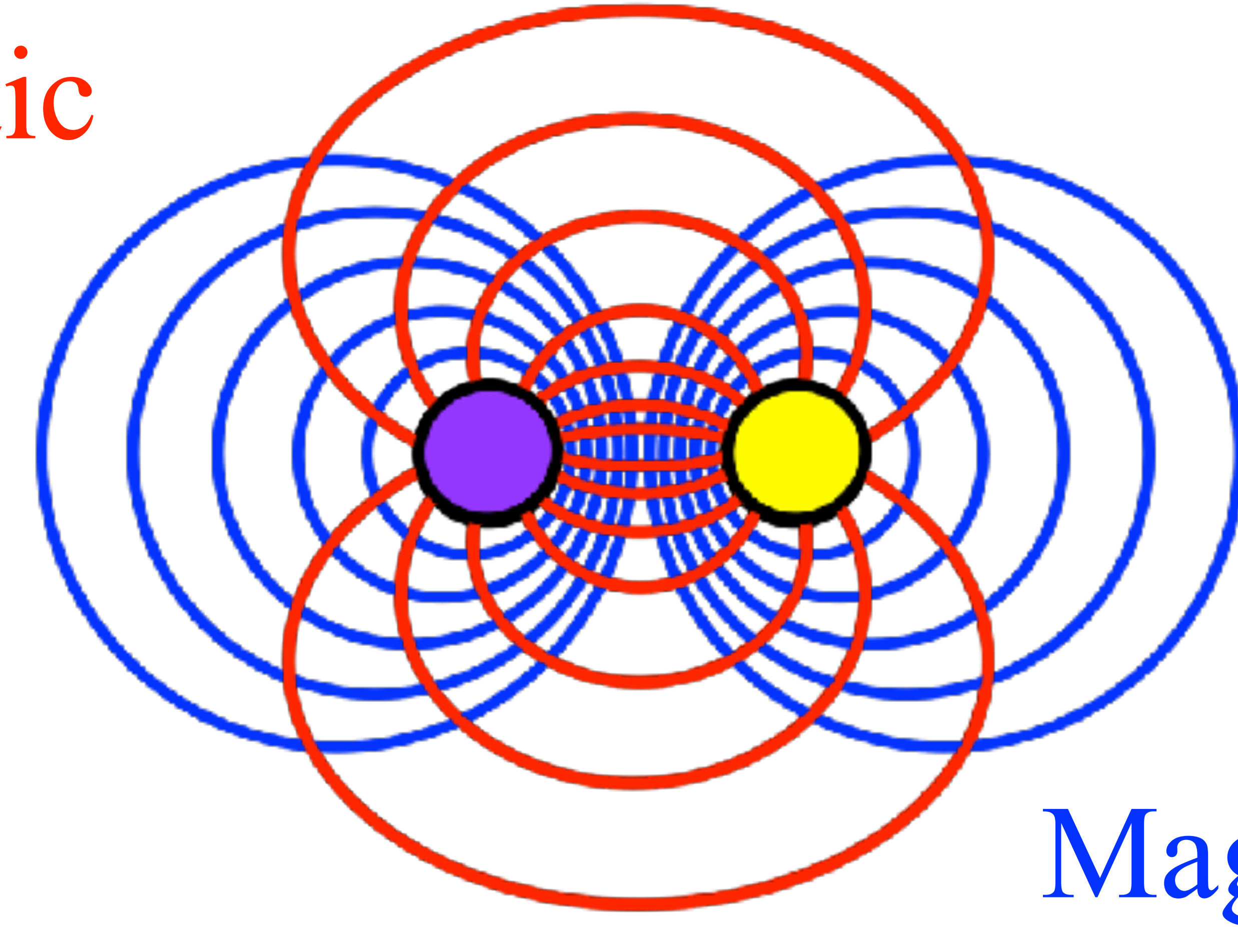
This presentation is about electromagnetic field energy escaping confinement.

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.

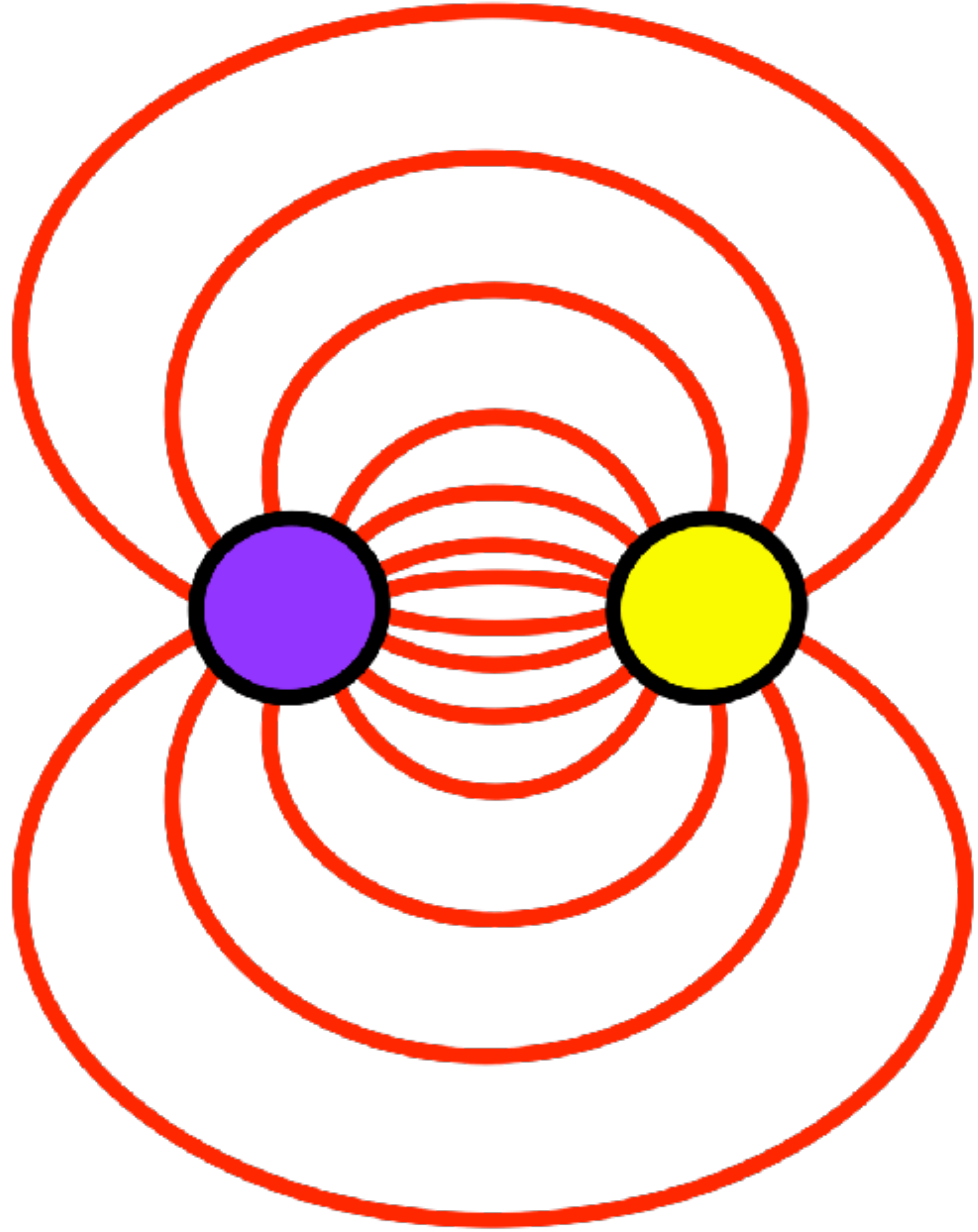
Electromagnetic Fields



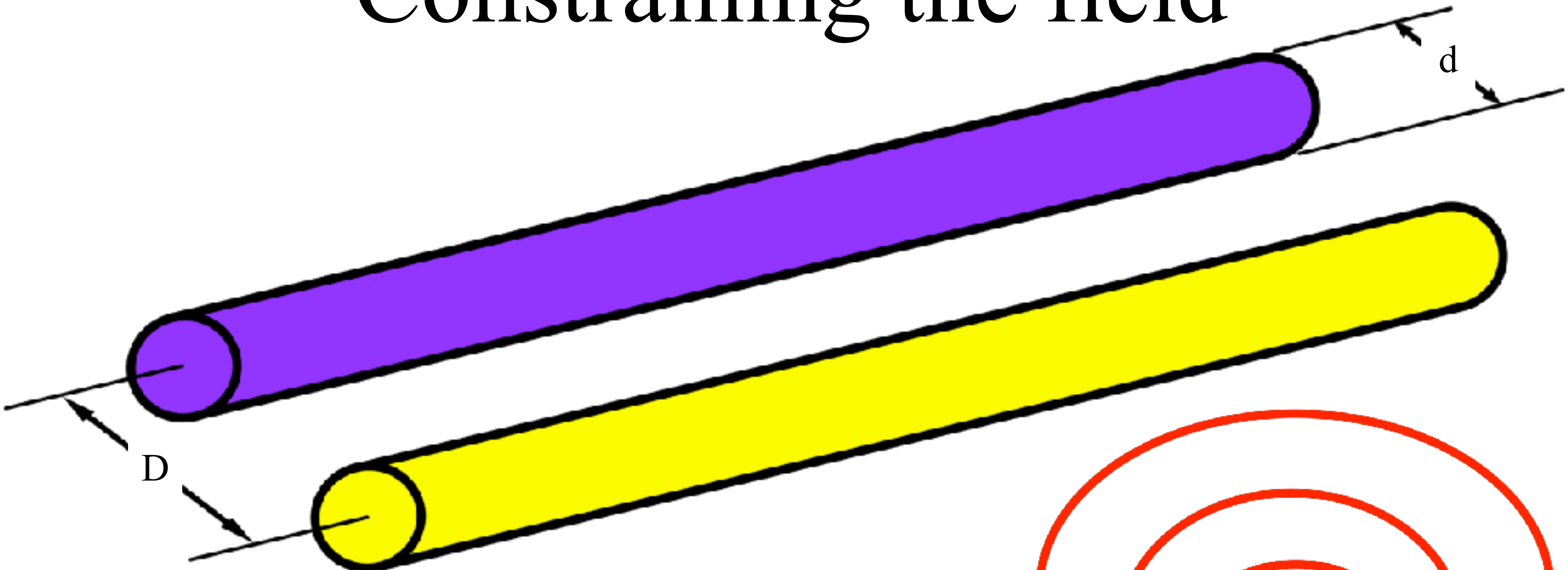
The current in these two conductors create an electromagnetic field around the conductors. The magnetic field is shown in blue and the electrostatic field is shown in red.

Constraining the field

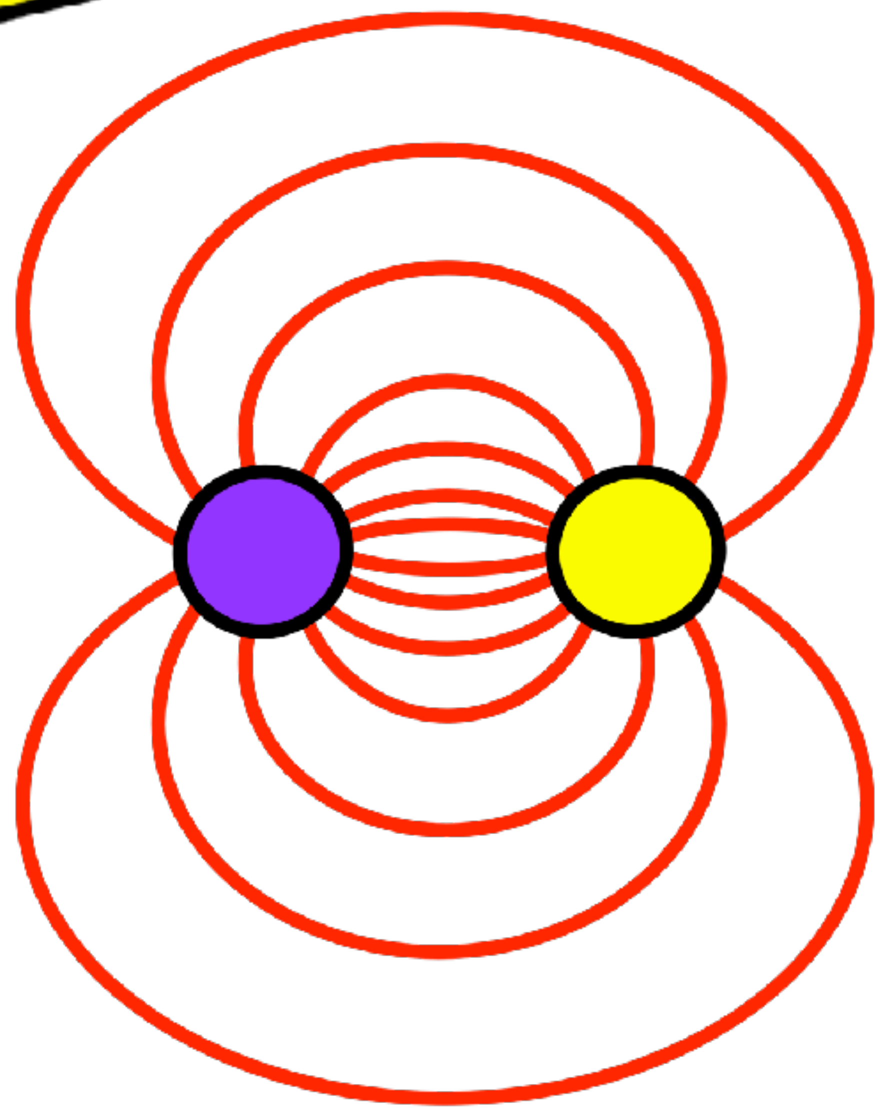
If you allow the RF energy to escape confinement, an EMC failure results.



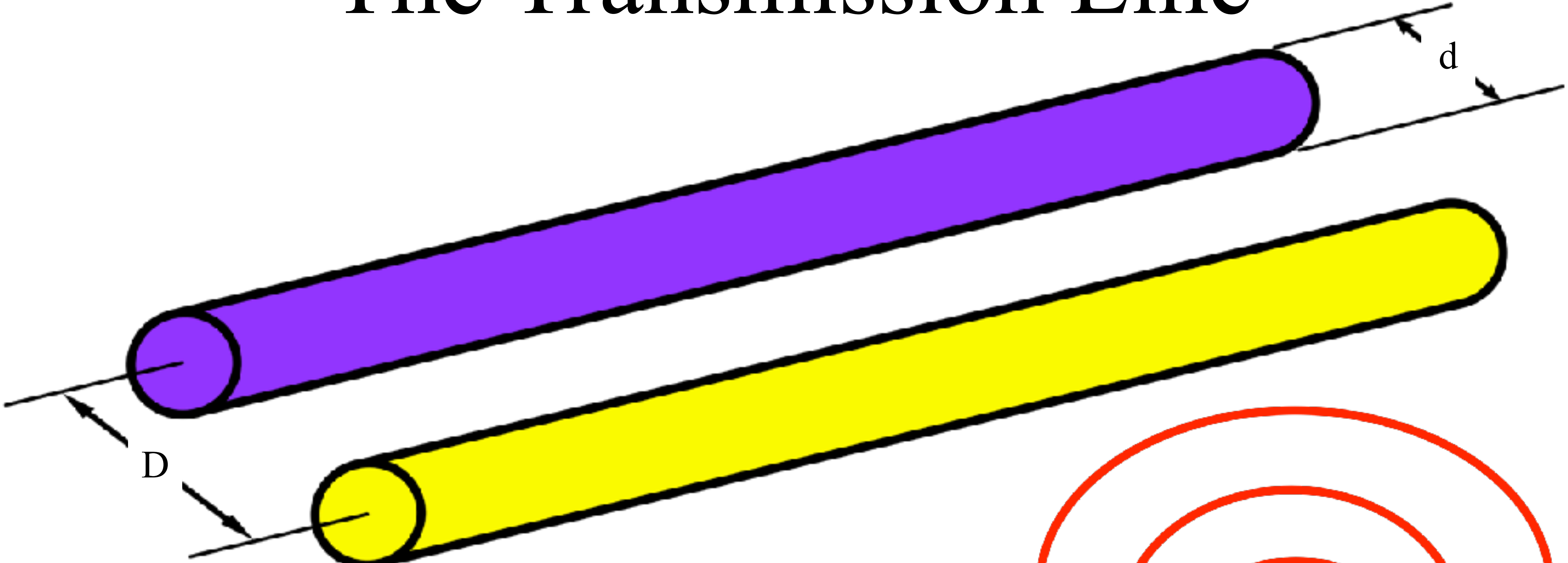
Constraining the field



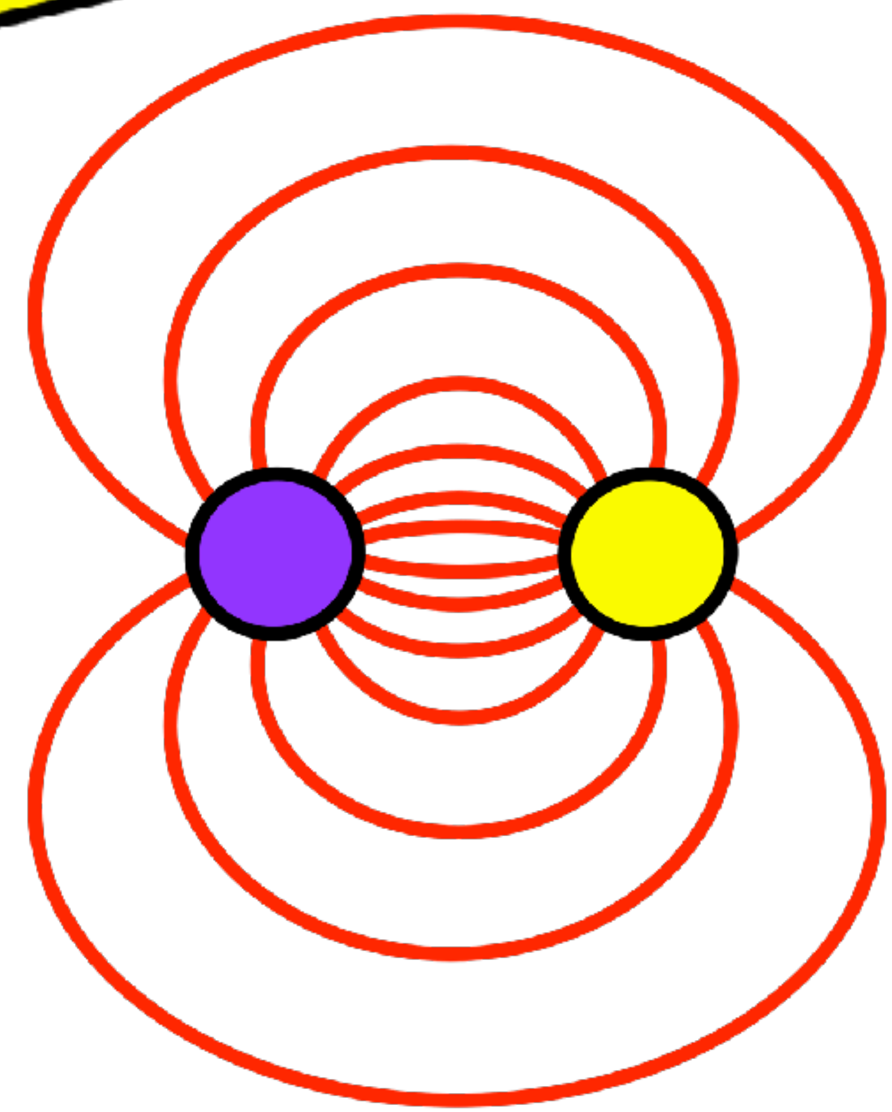
We constrain the fields with the shapes of the conductors and dielectrics.



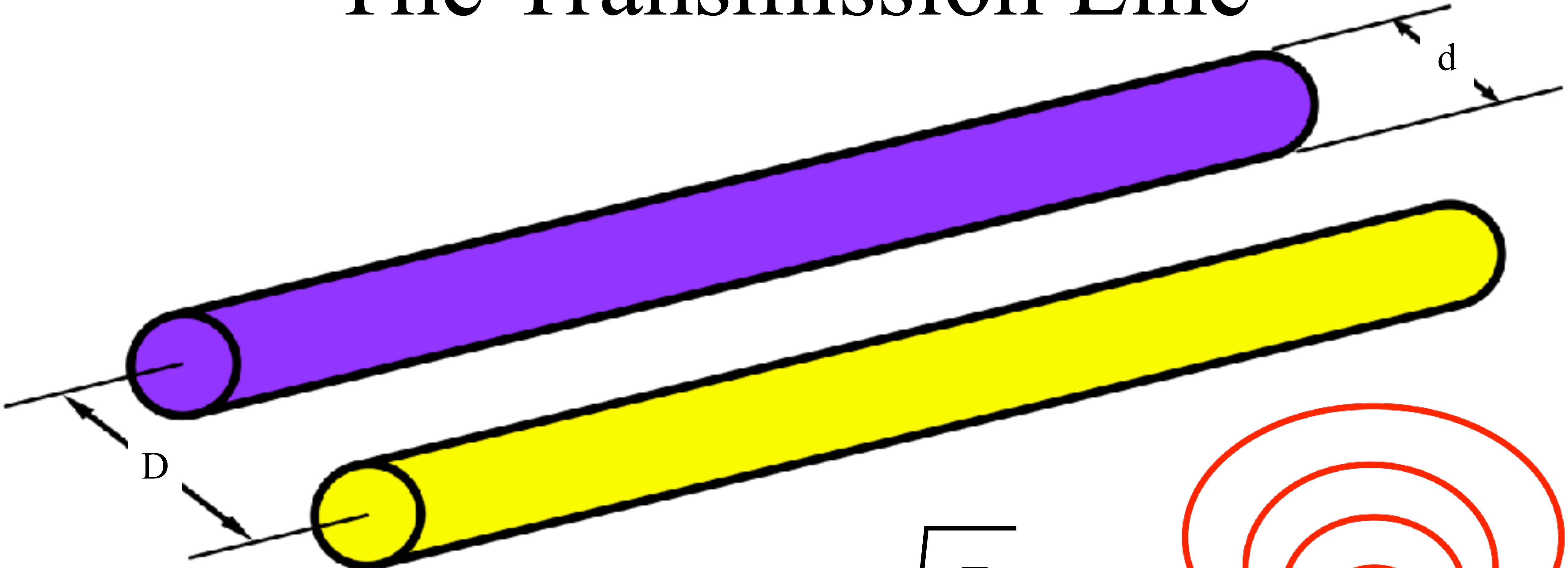
The Transmission Line



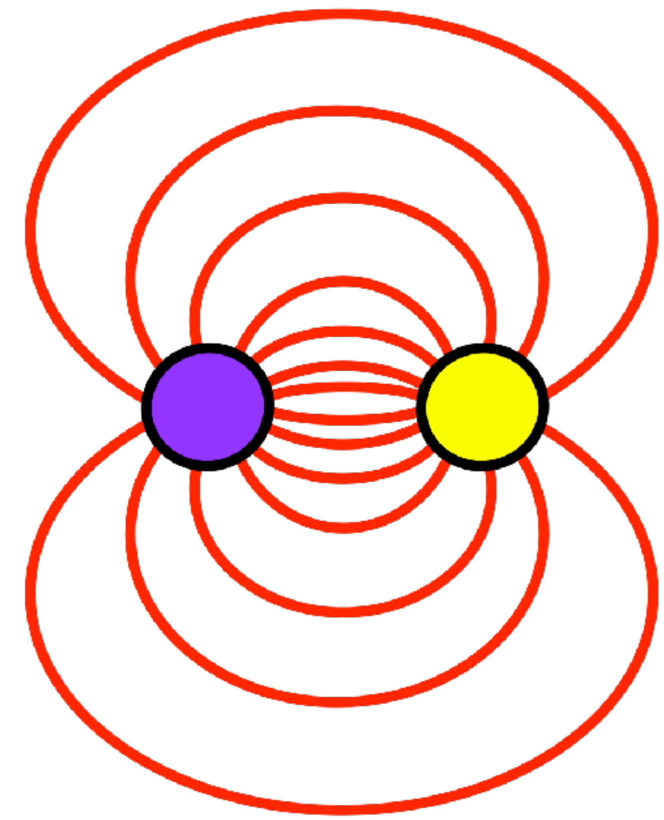
A transmission line is two or more conductors separated by a dielectric. It is the most basic building block of EMC.



The Transmission Line



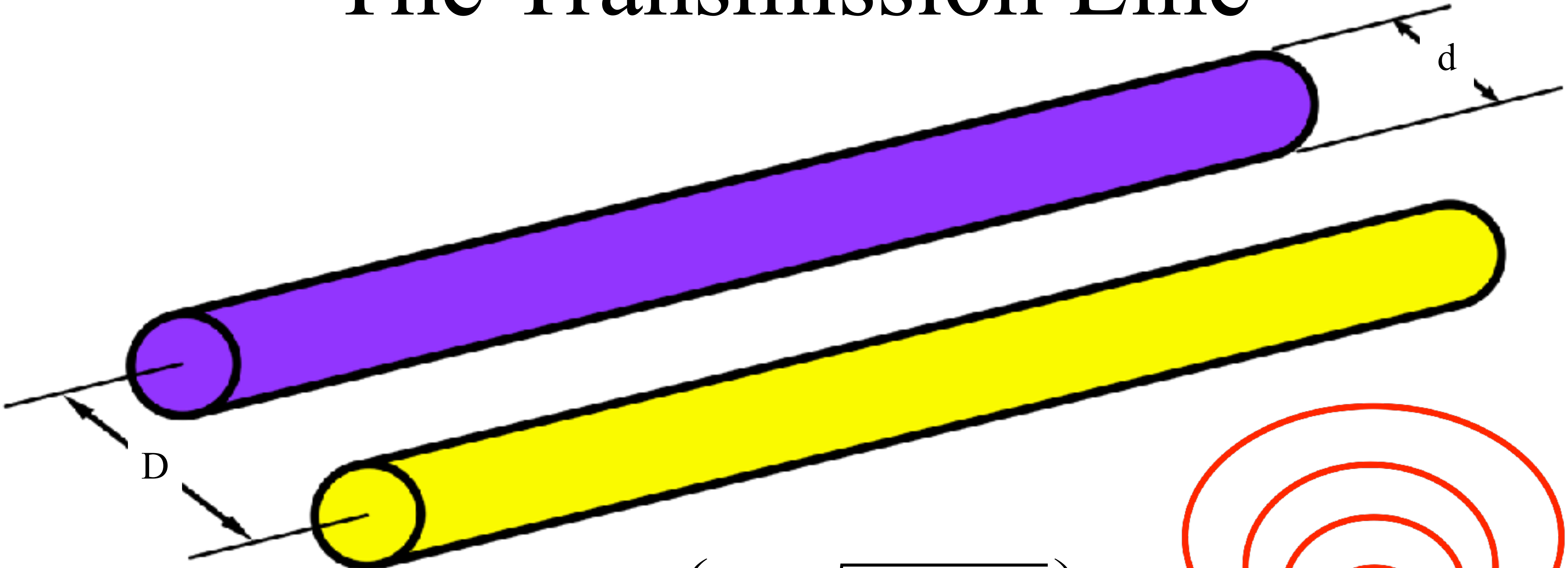
$$Z_0 \approx \sqrt{\frac{L}{C}}$$



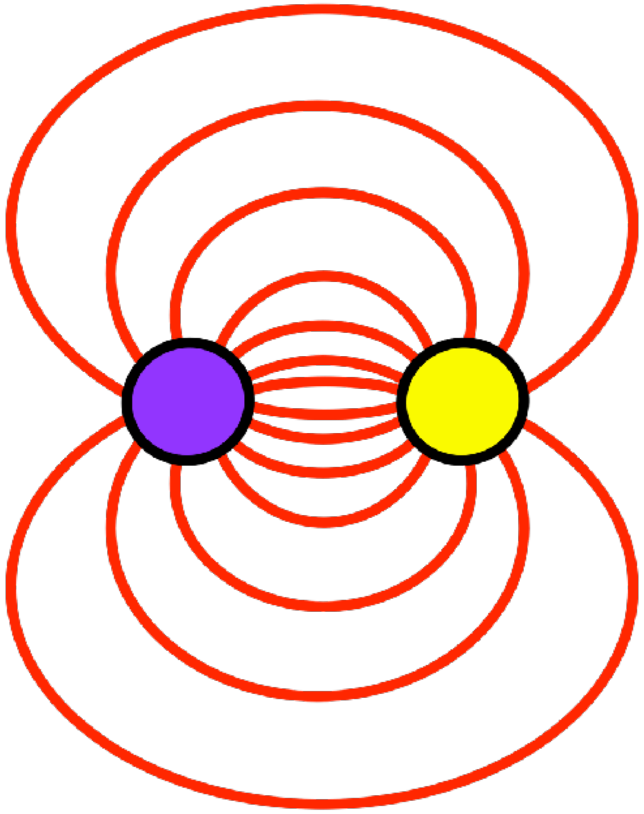
Smaller D increases C and lowers Z_0.
Larger d increases circumference, lowers L and increases C lowering Z_0.

Equation simplified form from Wikipedia with: https://en.wikipedia.org/wiki/Balanced_line

The Transmission Line



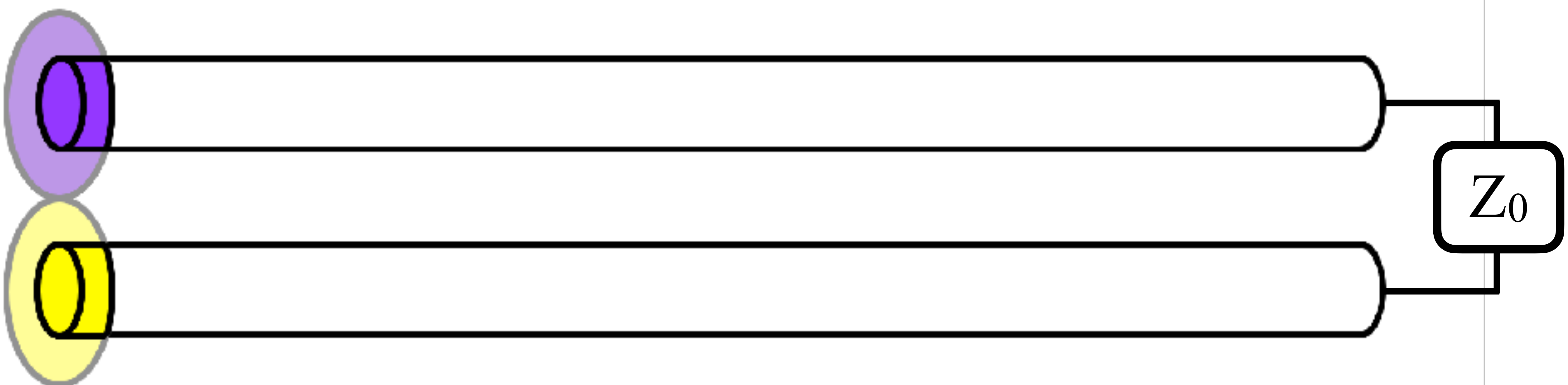
$$Z_0 = \frac{1}{\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}\, ln\left(\frac{D}{d}+\sqrt{\left(\frac{D}{d}\right)^2-1}\right)$$



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

Equation simplified form from Wikipedia with:https://en.wikipedia.org/wiki/Balanced_line

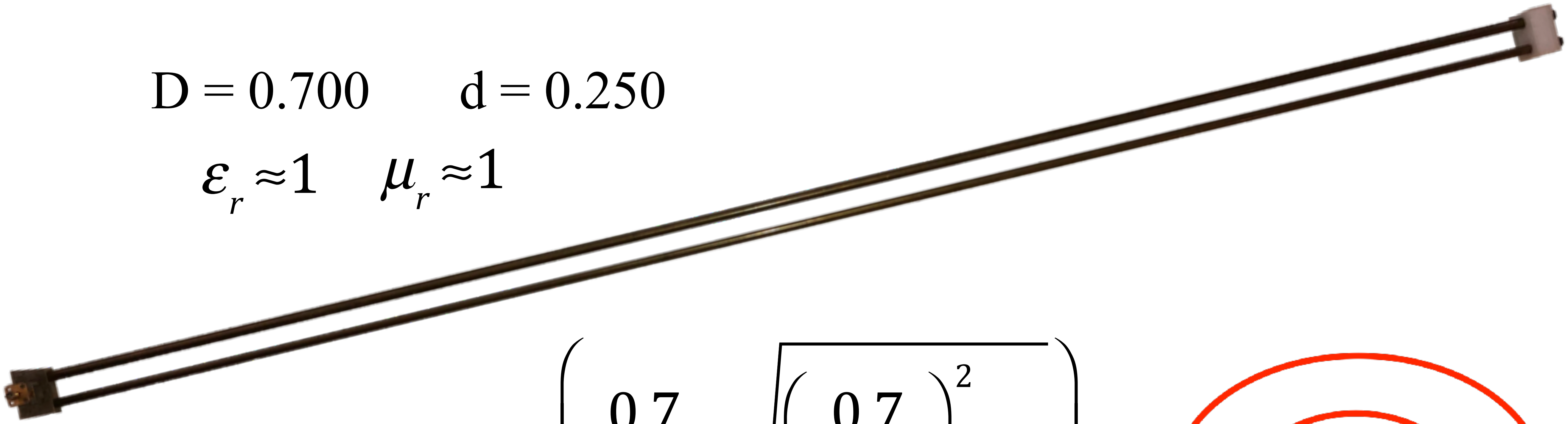
Energy Speeding Along a Transmission Line



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.™

PDF copies of this slide do not show the animation.

Two Wire 200 Ω Transmission Line

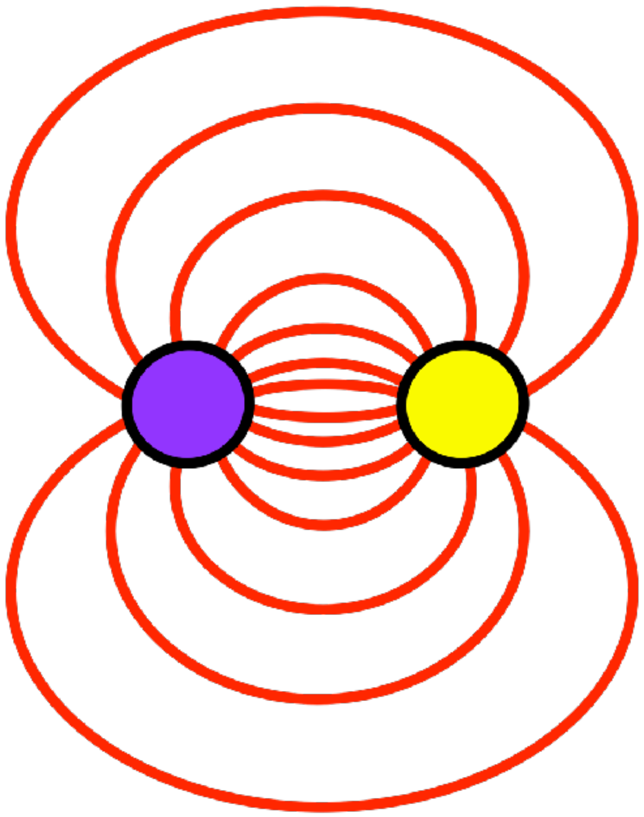


$D = 0.700 \qquad d = 0.250$

$\varepsilon_r \approx 1 \qquad \mu_r \approx 1$

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

$$\approx 202\,\Omega$$

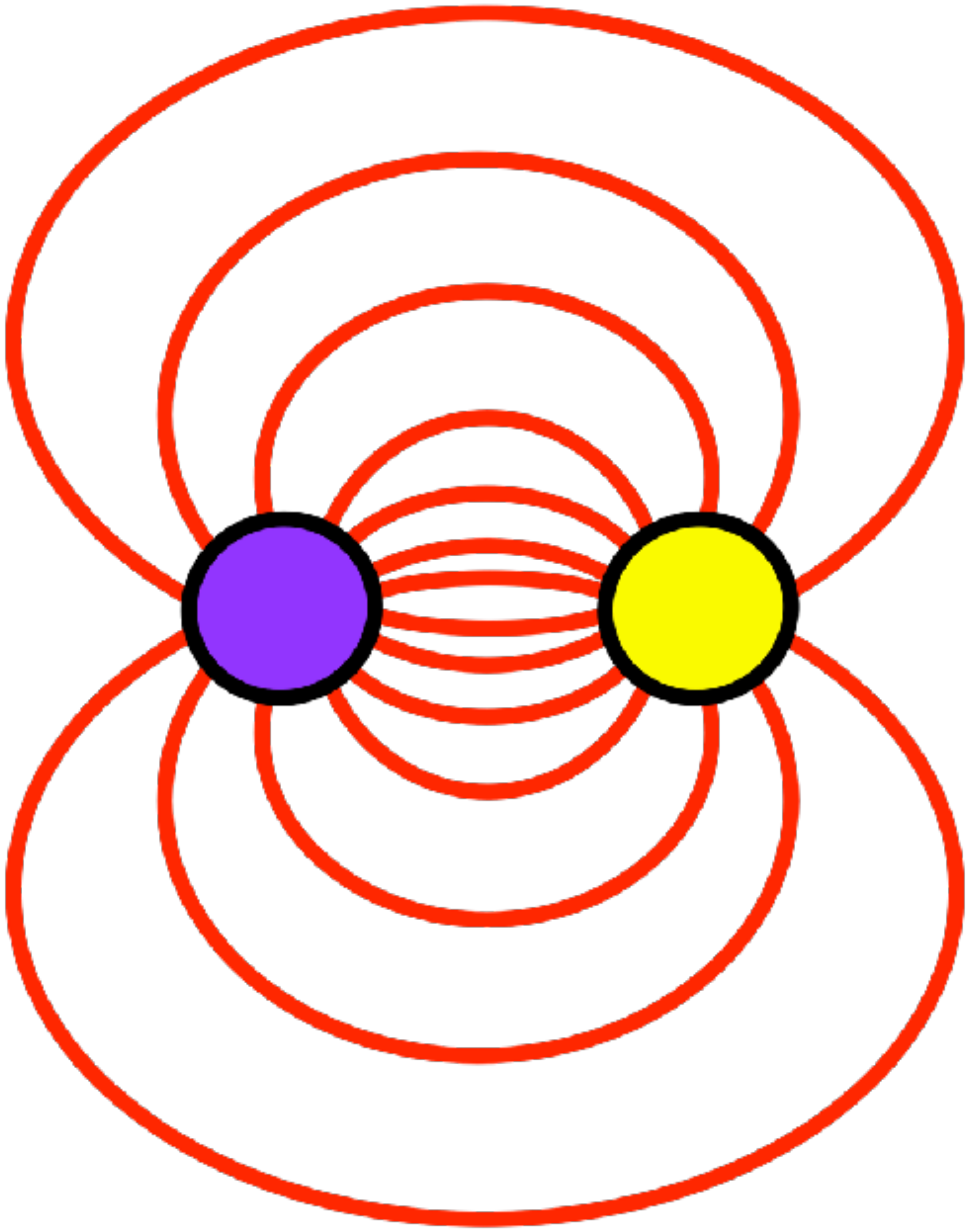


Do you think this 200 Ω transmission line will leak RF energy?

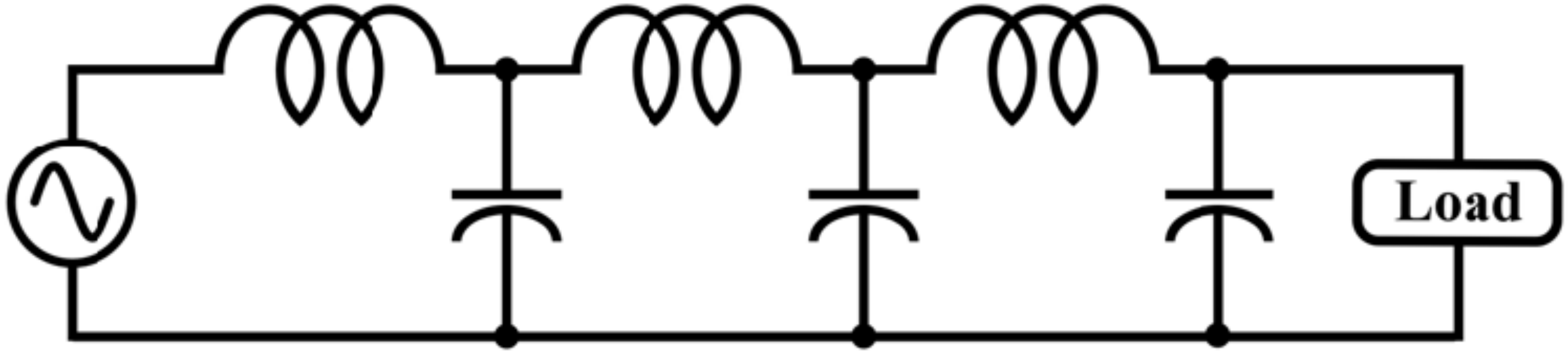
Absolutely!

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

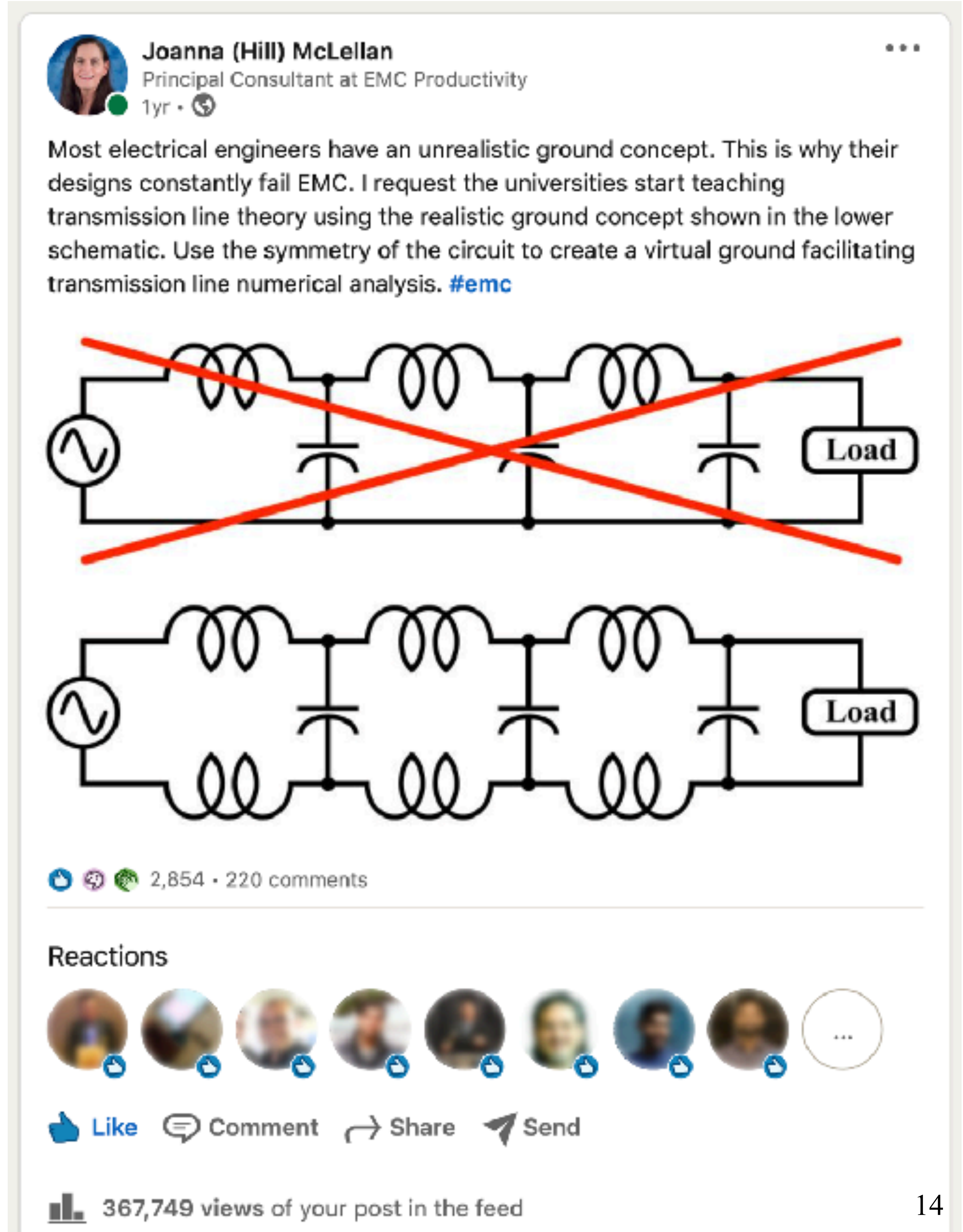


Classic Transmission Line theory is generally taught with an ideal ground. This unintentionally teaches that ground is ideal. Ground is NEVER ideal above 100 KHz.

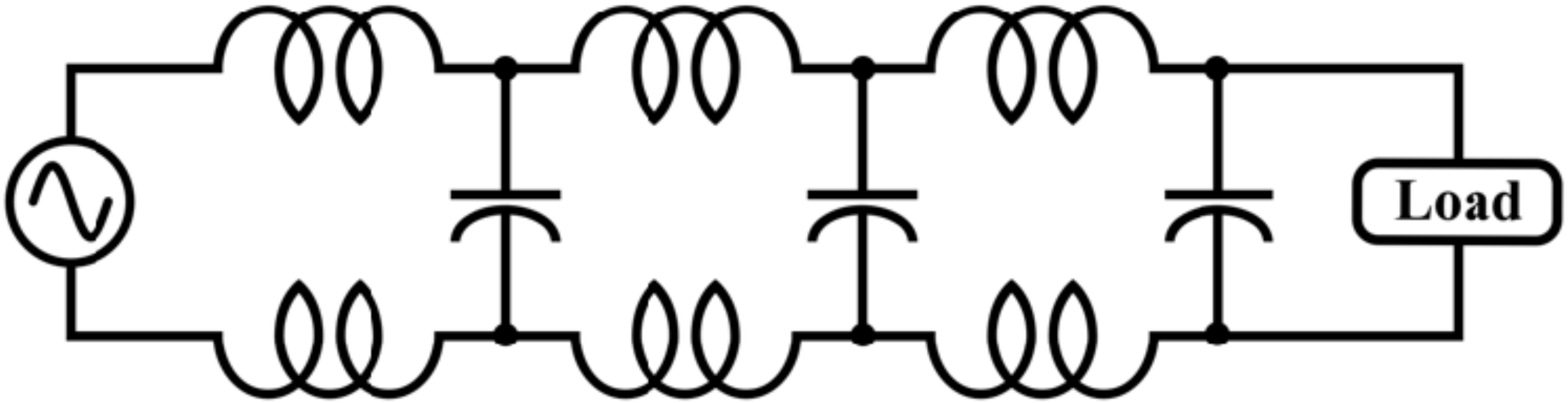
Teaching it this way unintentionally sabotages your ability to understand the physics of EMC.

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.

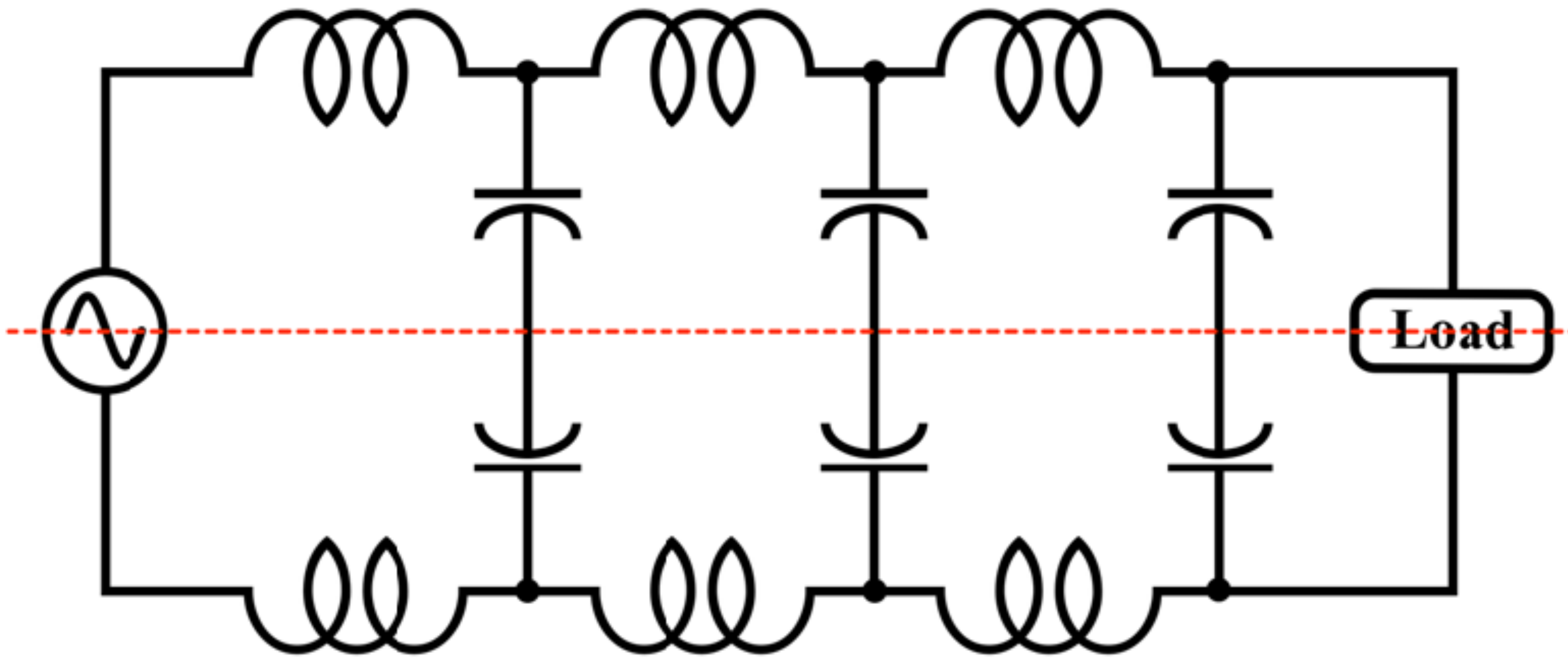


Classic Transmission Line Theory



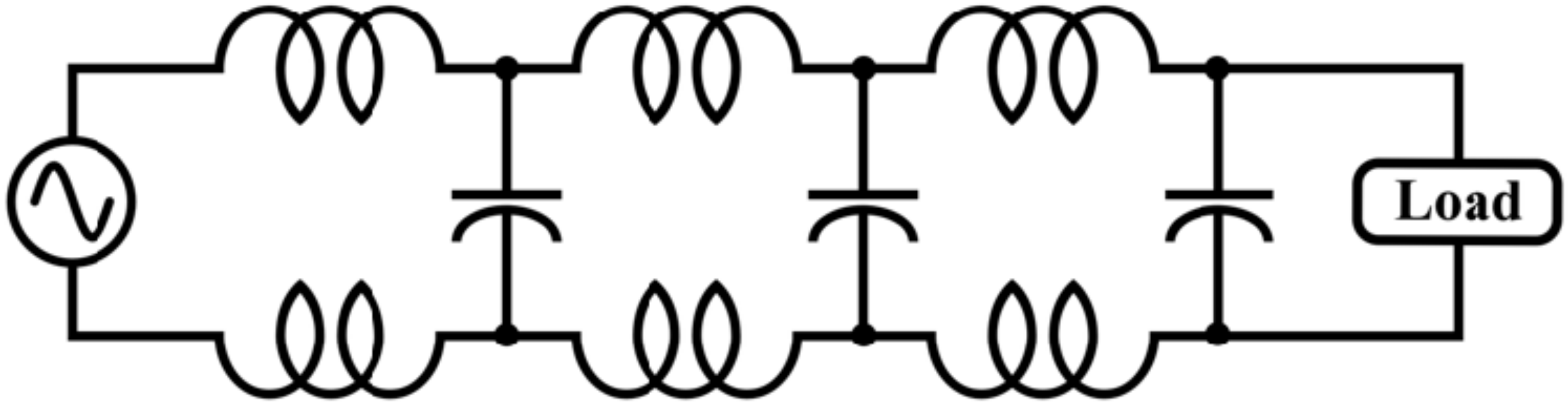
Real transmission lines have inductance in both the forward and return conductors.

Classic Transmission Line Theory



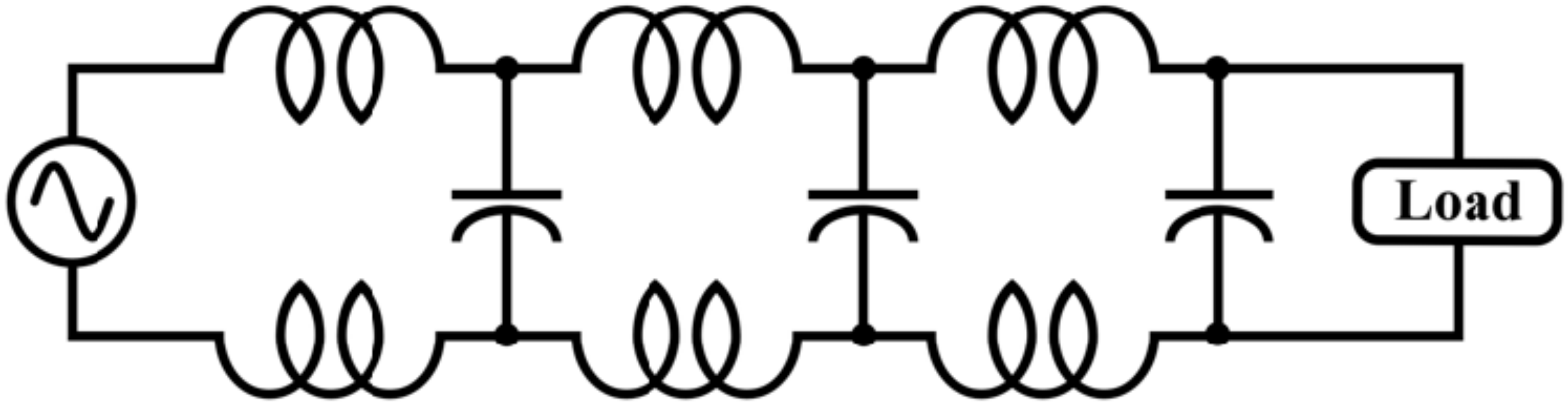
By using a virtual ground through the center of a balanced circuit we can still perform the classic numerical analysis.

To Consistently Pass EMC



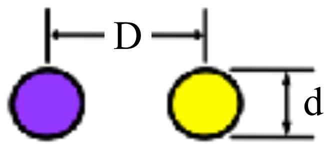
All currents with a frequency content above 100 KHz must be constrained within a suitably designed Transmission Line.

When is a Transmission Line not a Transmission Line?

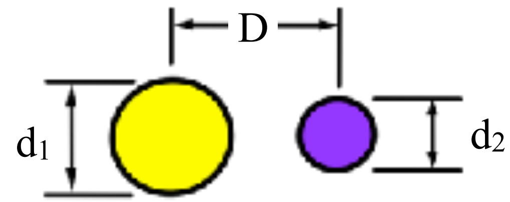


As the characteristic impedance of a transmission line approaches the characteristic impedance of free space, 377 ohms, we don't have a transmission line, we have an unintended antenna.

More Transmission Line Equations

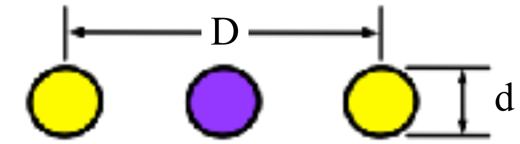


$$Z_0 = \frac{1}{\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}\, ln\left(\frac{D}{d} + \sqrt{\left(\frac{D}{d}\right)^2 - 1}\right)$$

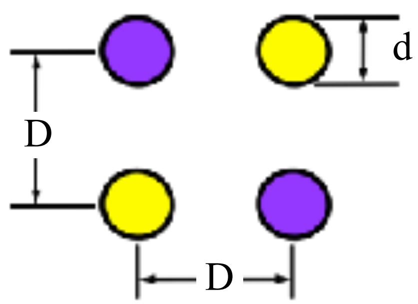


$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}\, ln\left(X + \sqrt{X^2 - 1}\right),$$

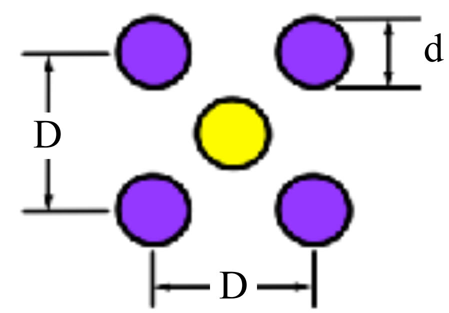
$$X = \frac{1}{2}\left(\frac{4D^2}{d_1 d_2} - \frac{d_1}{d_2} - \frac{d_2}{d_1}\right)$$



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



$$Z_0 \approx \frac{1}{2\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}\, ln\left(\sqrt{2}\frac{D}{d}\right), d \ll D$$



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

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

$for\ real\ x > 1$

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?

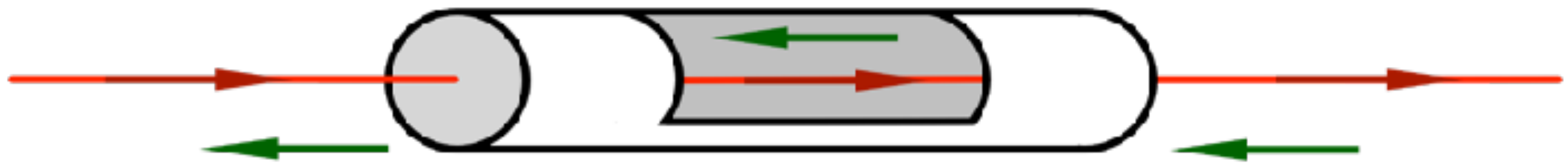
We start with a copper coaxial transmission line.

The Skin Depth of copper

$$\delta_{Copper\_60Hz} = \frac{1}{\sqrt{\pi 60Hz\, 4\pi 10^{-7}\, 5.95x10^{7}}} = 8.42mm = 0.331\, inches$$

$$\delta_{Copper\_100KHz} = \frac{1}{\sqrt{\pi 100KHz\, 4\pi 10^{-7}\, 5.95x10^{7}}} = 206\mu m = 0.00811\, inches$$

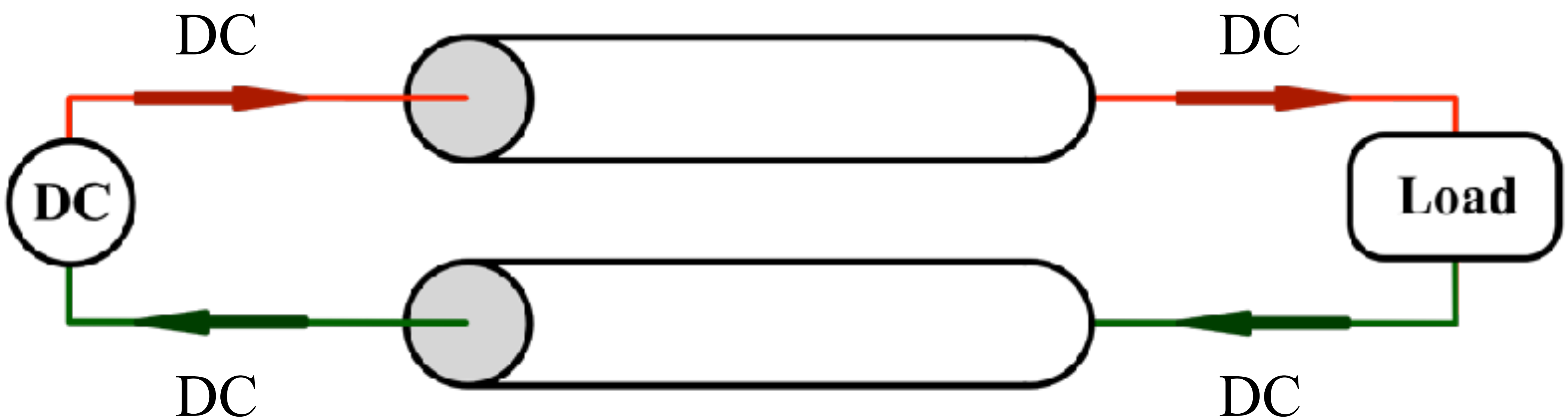
Where does the current go?



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.

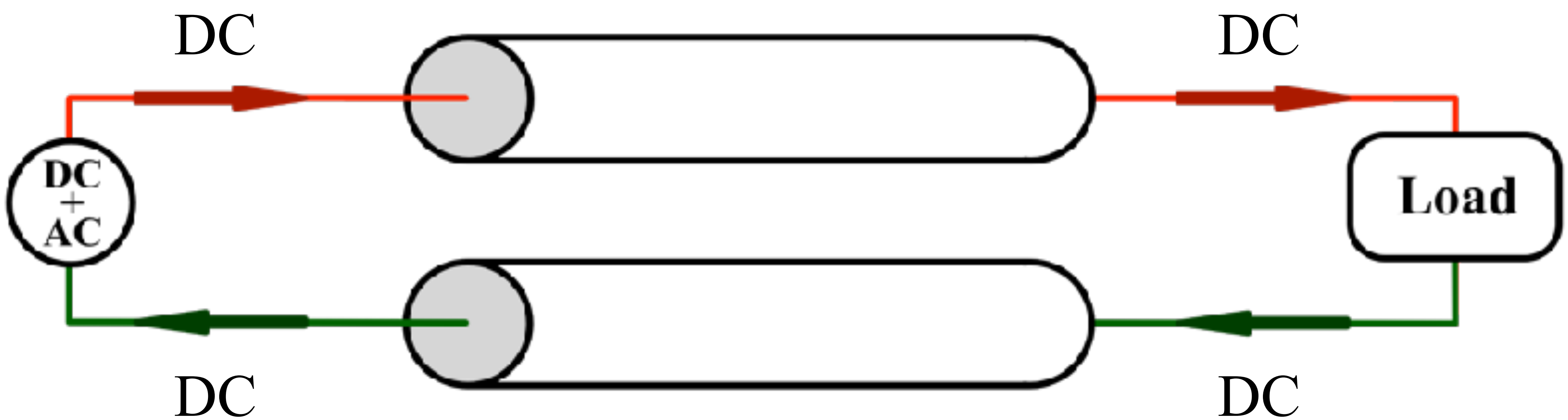
Where does the current go?



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.

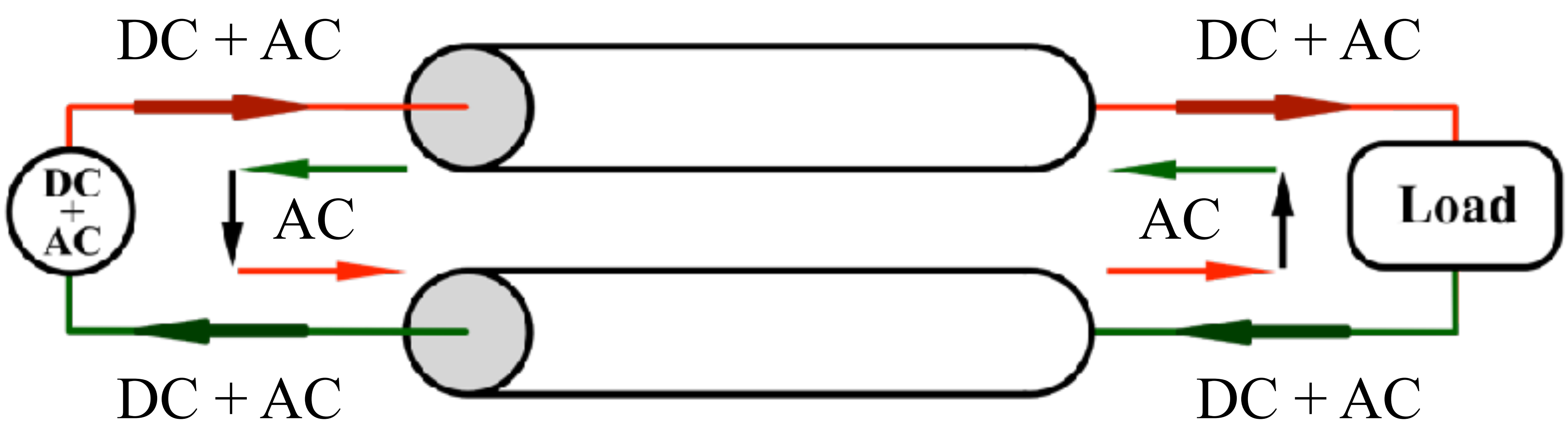
Where does the current go?



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.

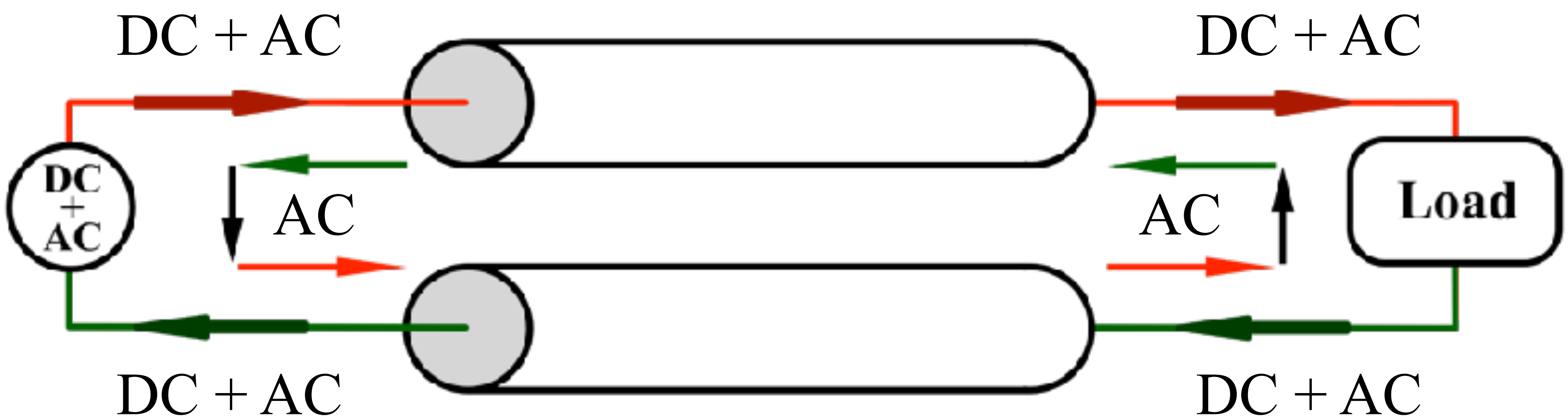
Where does the current go?



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.

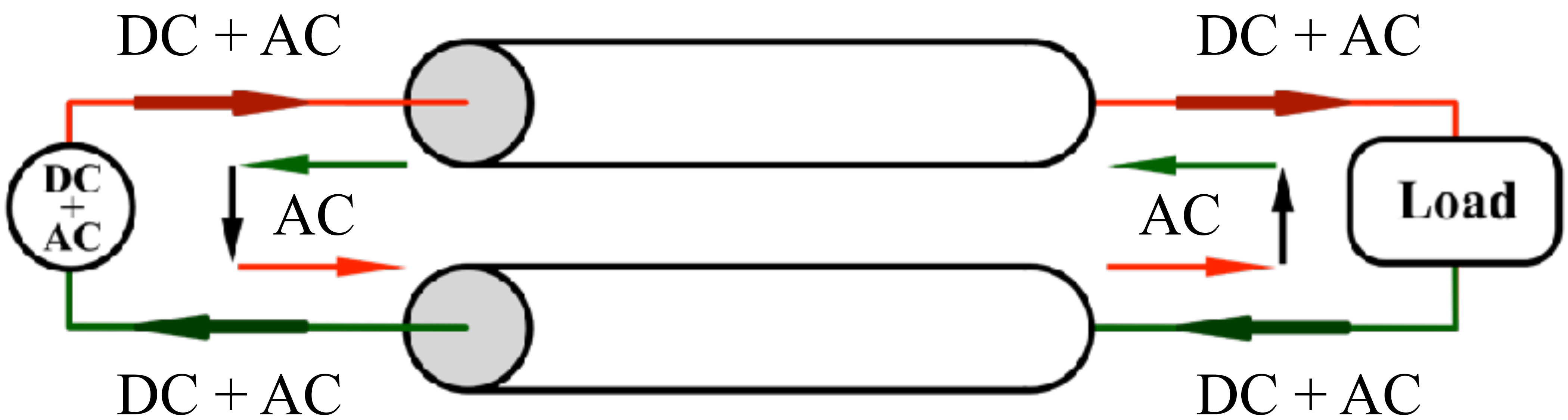
Where does the current go?



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

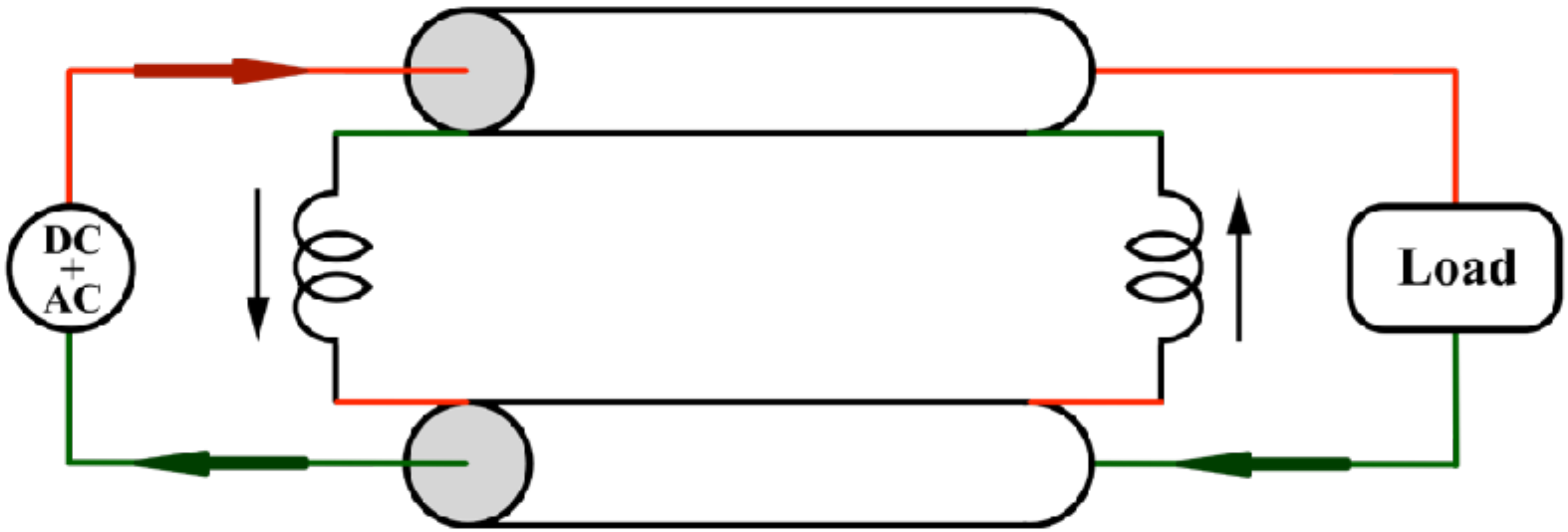
This AC current combines at both ends of the coax cable.

Where does the current go?



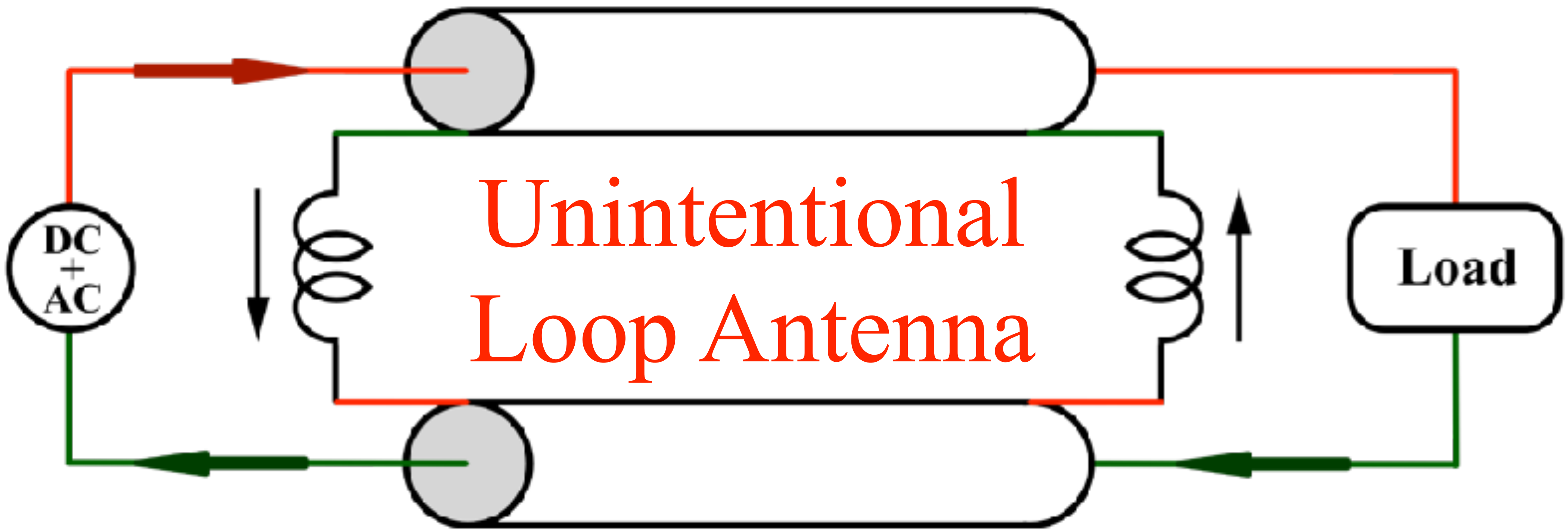
Unfortunately the outer conductor connections are imperfect as they have resistance and physical length, hence inductance.

Where does the current go?



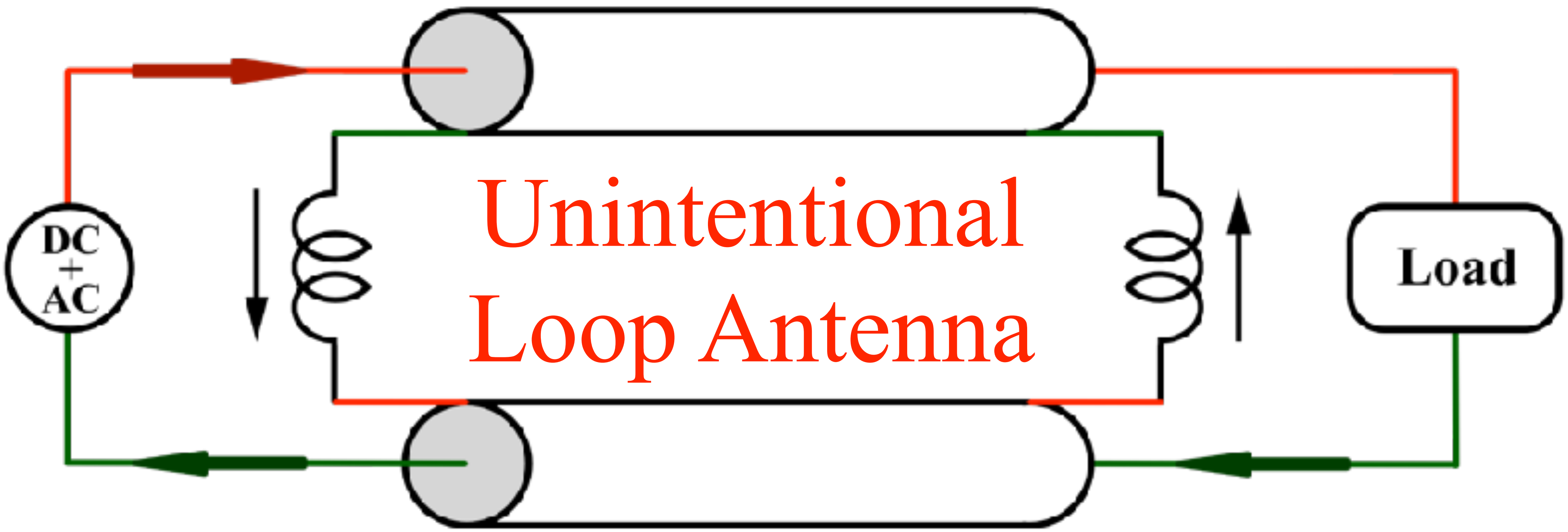
All the current above 100 KHz will travel through the impedances resulting in two voltage drops that will feed the transmission line formed by the outside of the two coaxial shields.

Where does the current go?



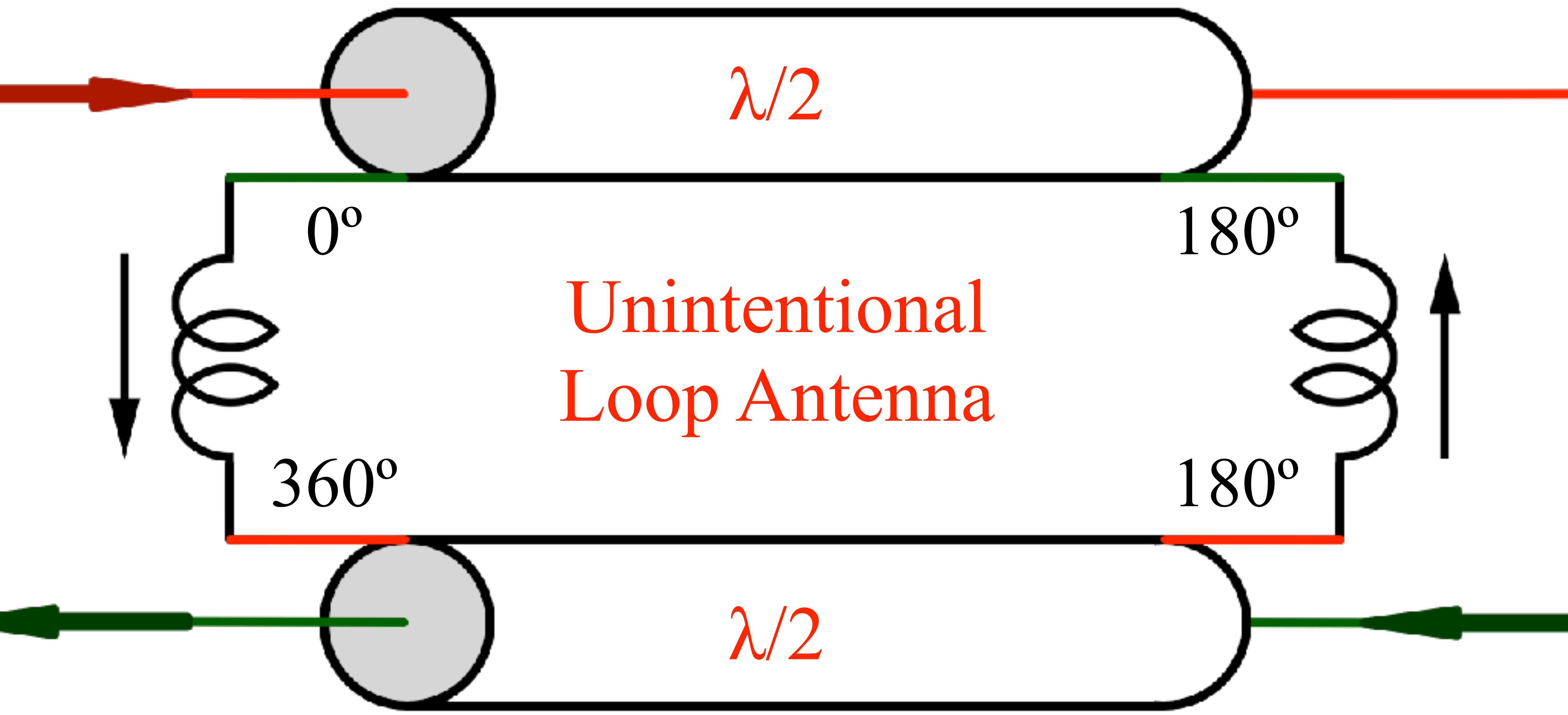
If the characteristic impedance of the coaxial shield transmission line is near or above 377 ohms, you don't have a transmission line, you have an unintended loop antenna.

Where does the current go?

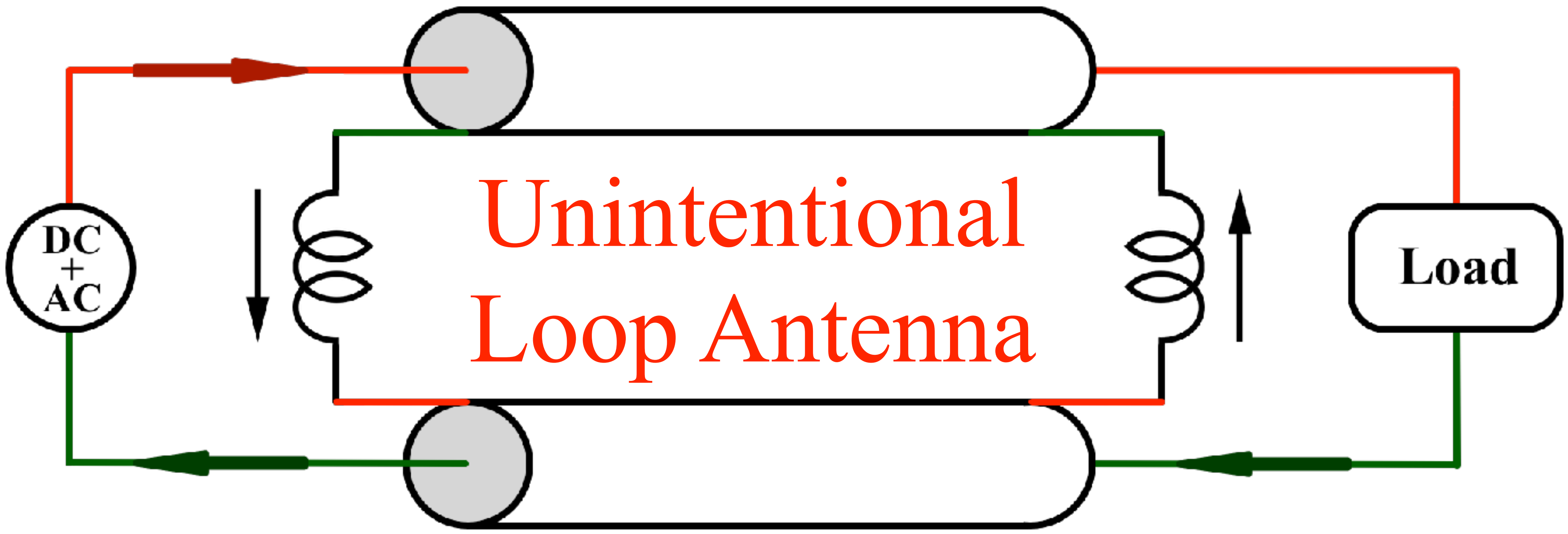


The current loop is from one impedance across the outside of an outer conductor to the second impedance and back across the second outer conductor.

Where does the current go?

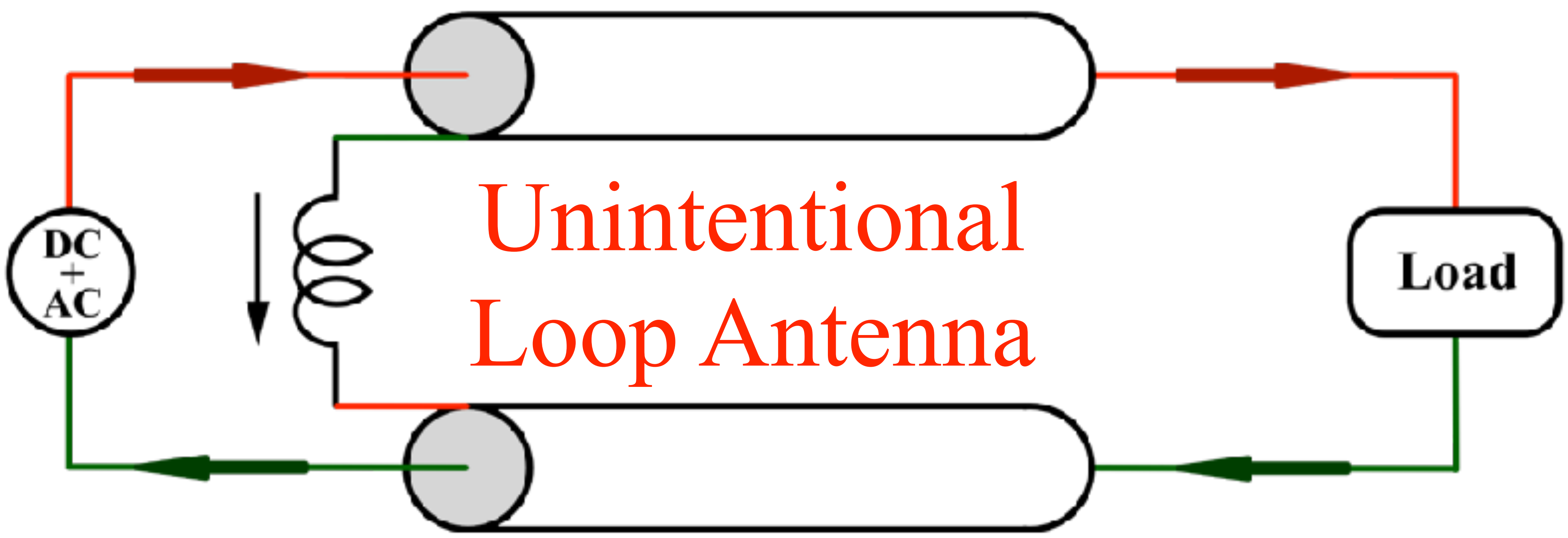


Where does the current go?



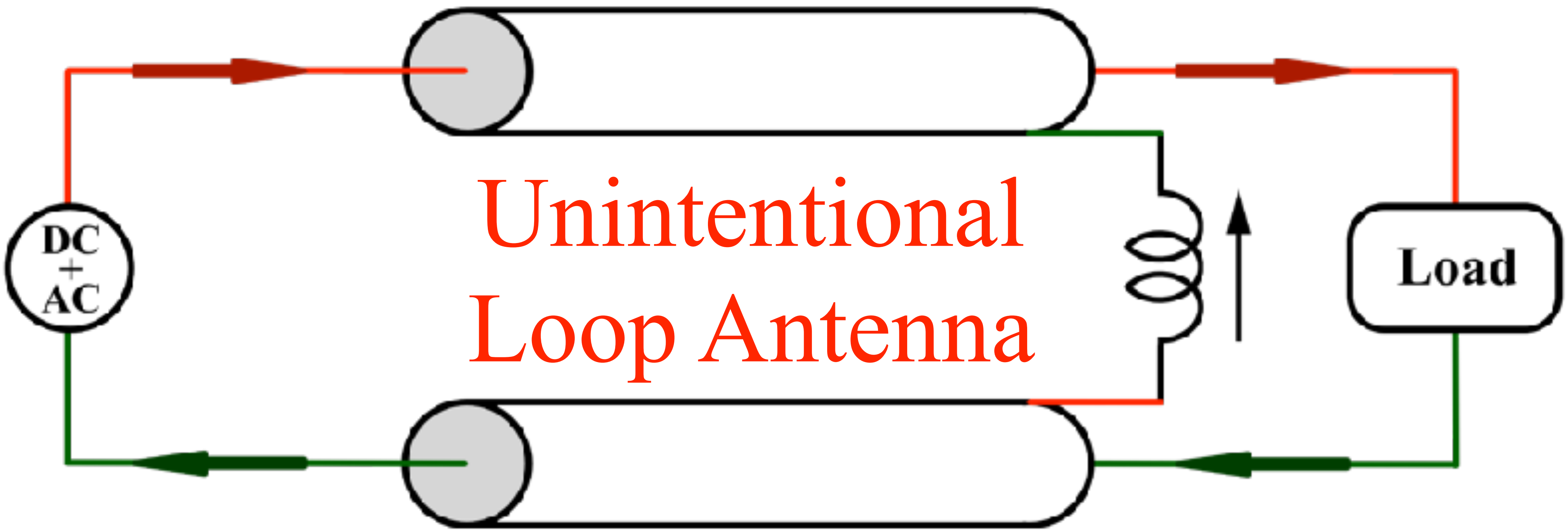
The resulting EMC issue will be centered at a coax length of approximately half a wavelength and again at one wavelength, etc.

Where does the current go?



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

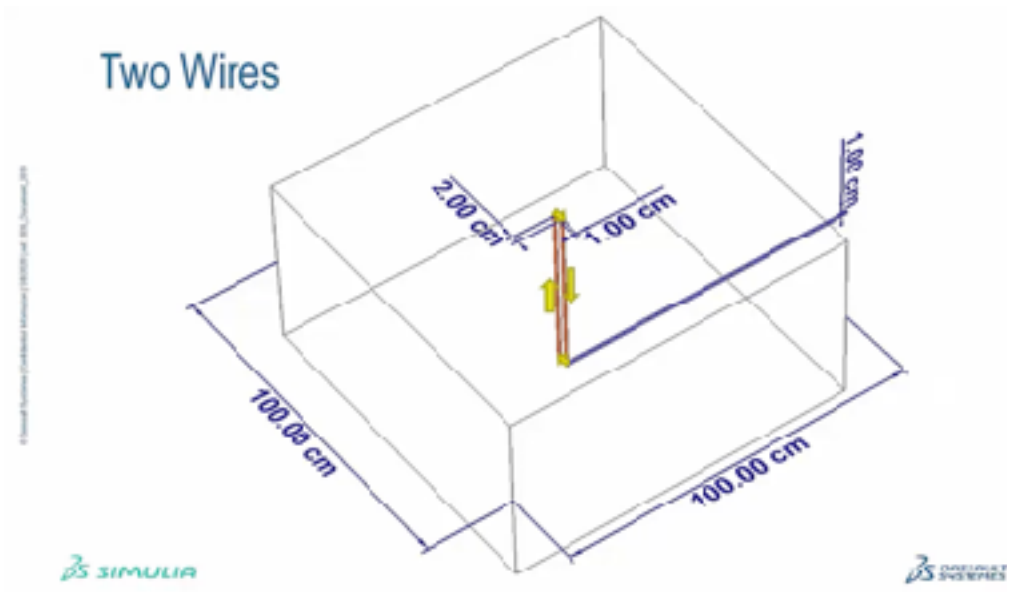
Where does the current go?

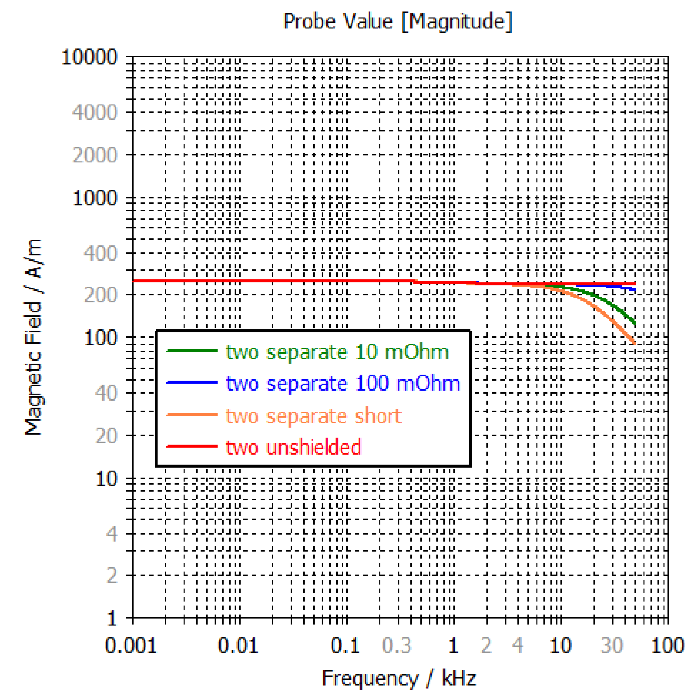


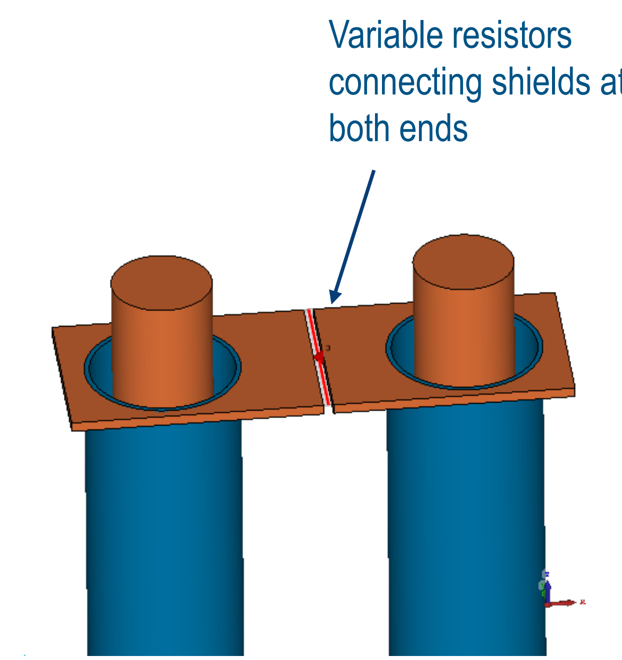
If the coax outer conductors are not connected on the source side it also forms an unintentional folded dipole antenna.

Andreas Barchanski Simulation

Two Wires Separate Shield – H Field





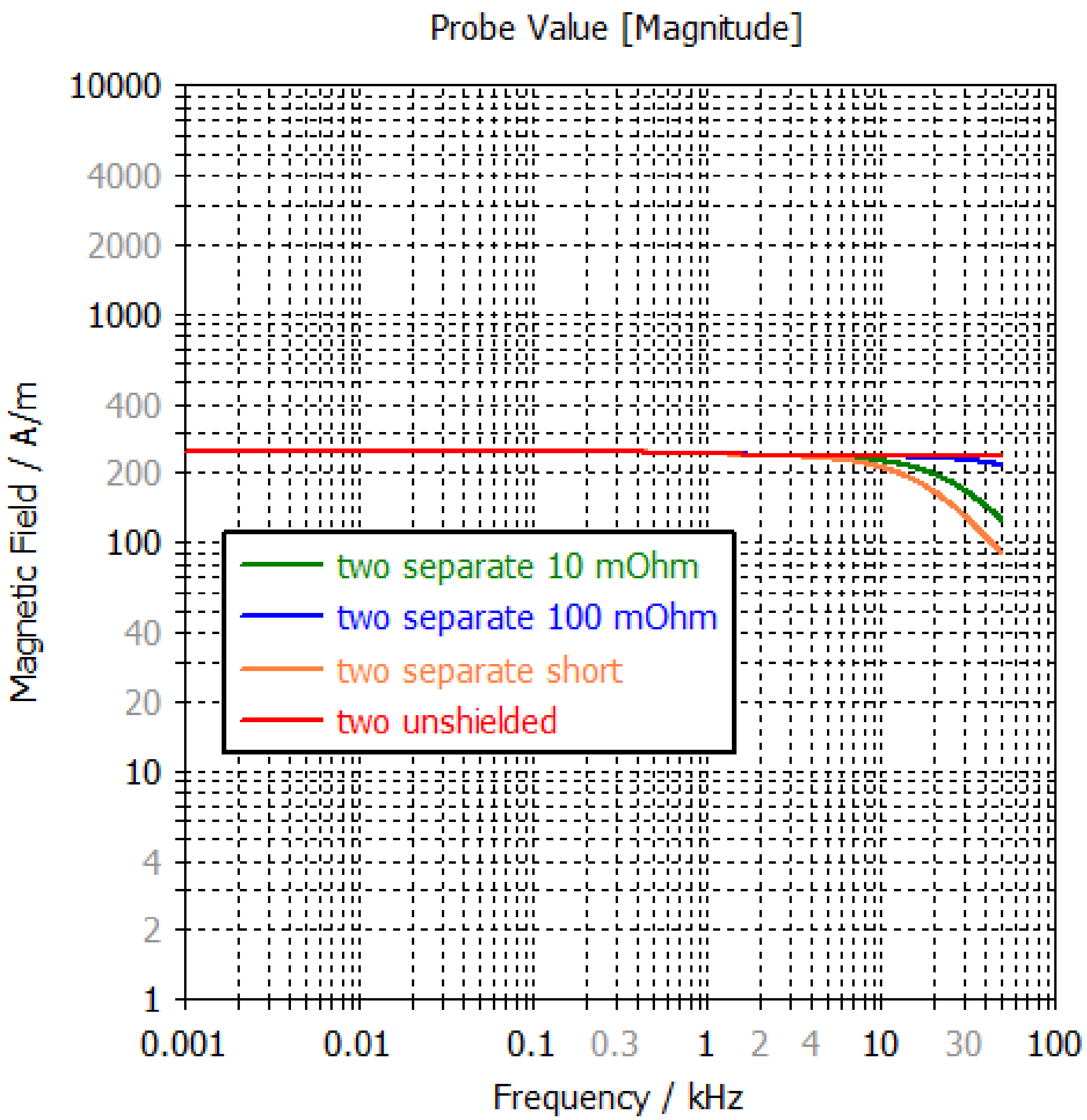


Andreas Barchanski of Dassault Systemes has done an excellent video showing his simulations on magnetic field strength near various wire shapes. The simulations are from 1 Hz to 50 KHz.

https://www.youtube.com/watch?v=pIDC6NBUCXw&feature=emb_logo

Mr. Barchanski's slides used with permission.

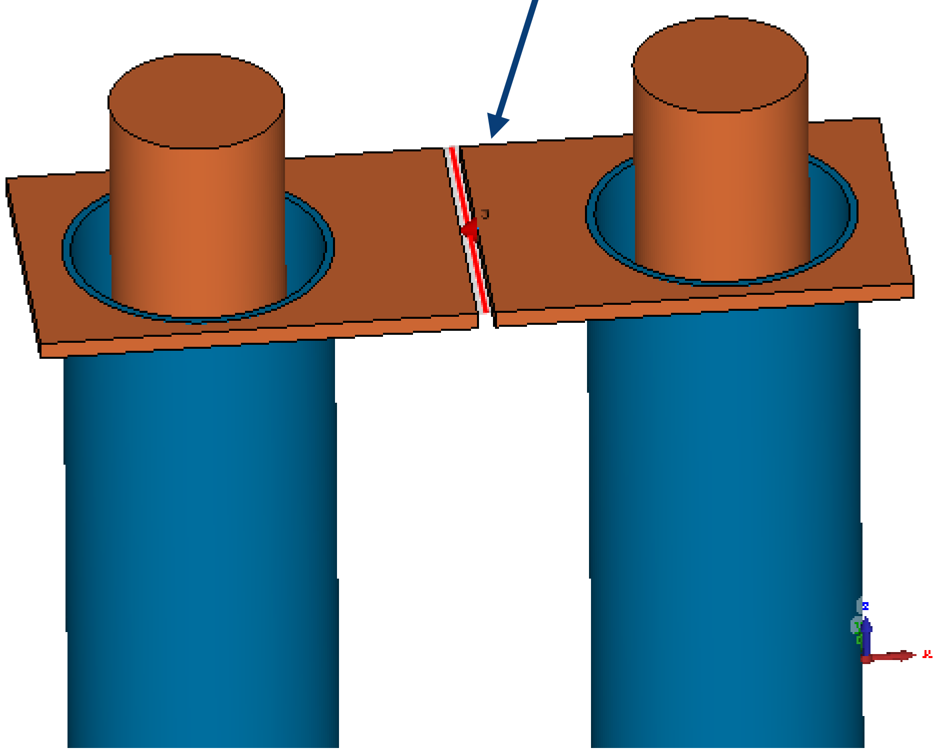
Two Wires Separate Shield – H Field



No shielding effectiveness

Better shielding effectiveness

Variable resistors connecting shields at both ends



SIMULIA

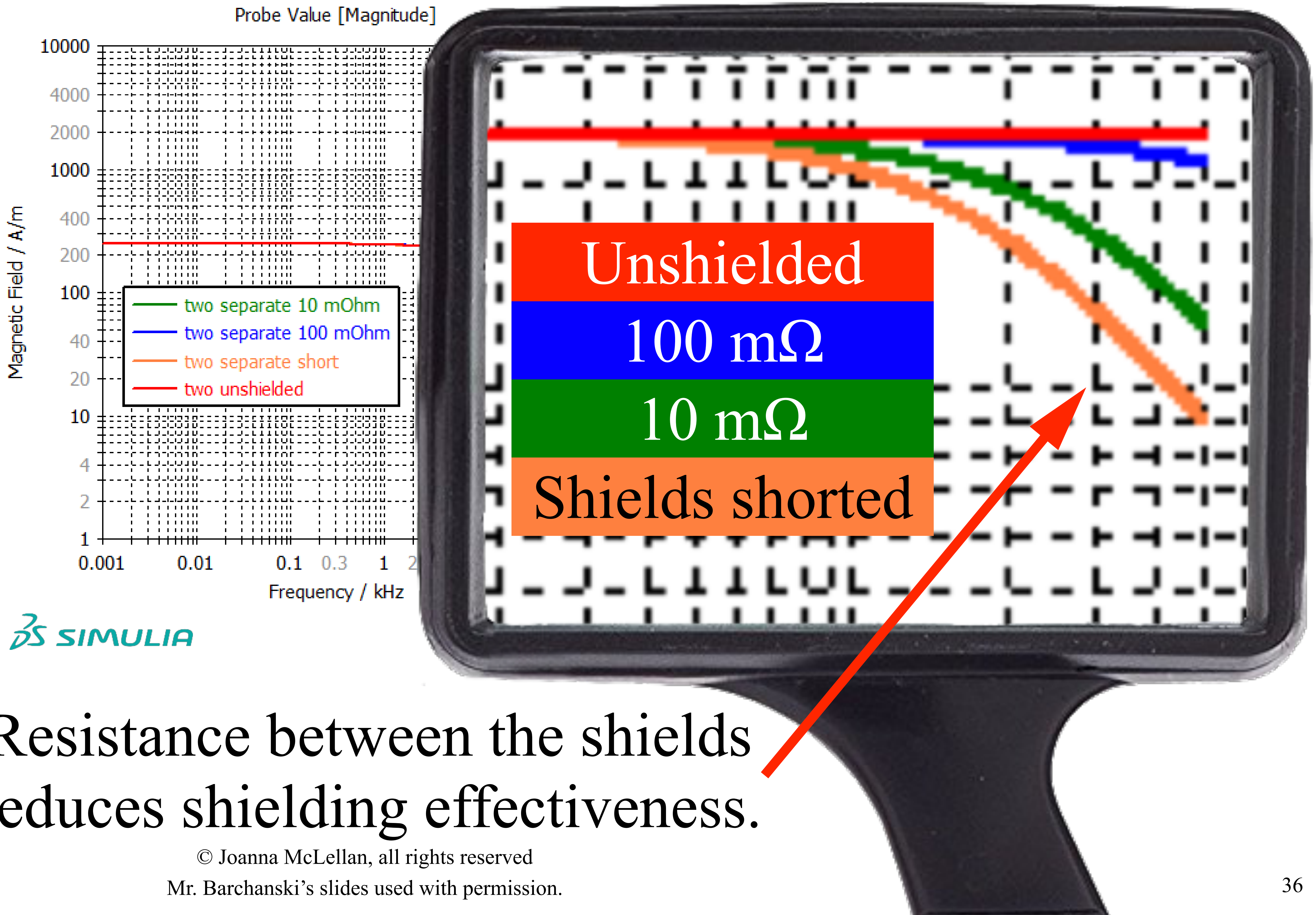
DASSAULT SYSTEMES

In the graph a lower number shows better shielding effectiveness.

Mr. Barchanski's slides used with permission.

Magnetic probe at 10 cm   Wire diameter of 1 cm   Shield thickness of 0.5 mm

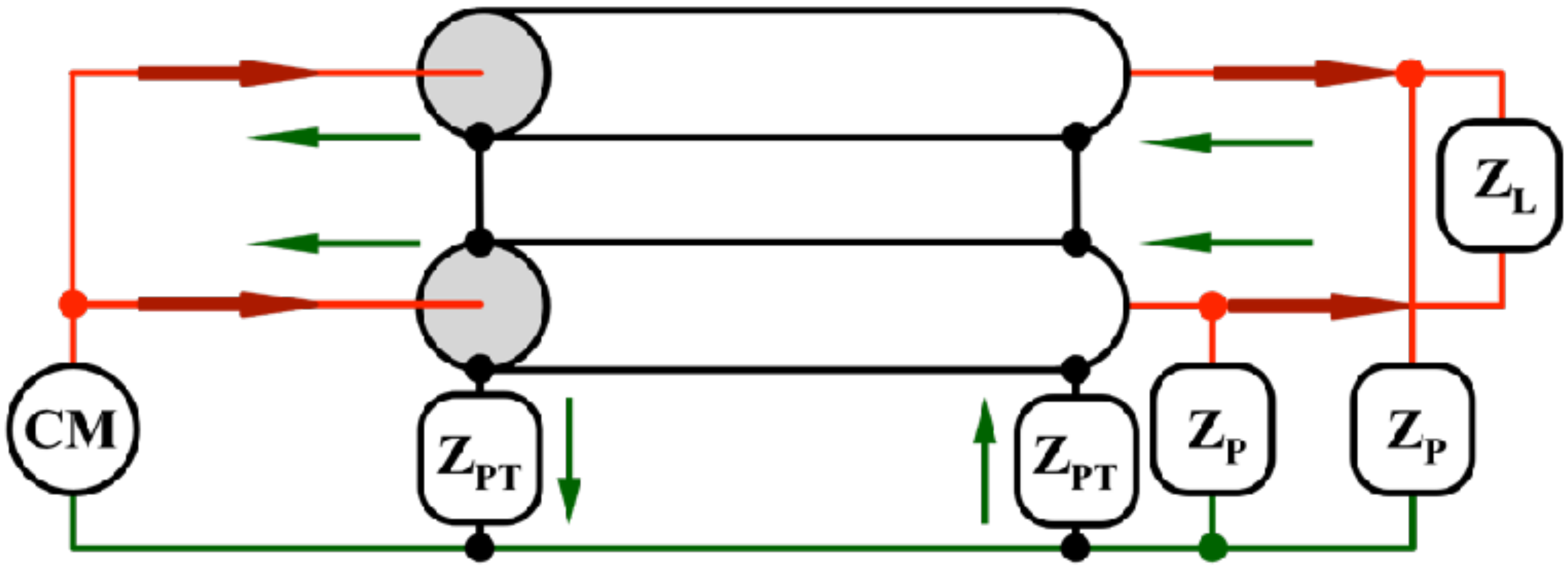
Two Wires Separate Shield – H Field



SIMULIA

Resistance between the shields reduces shielding effectiveness.

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.

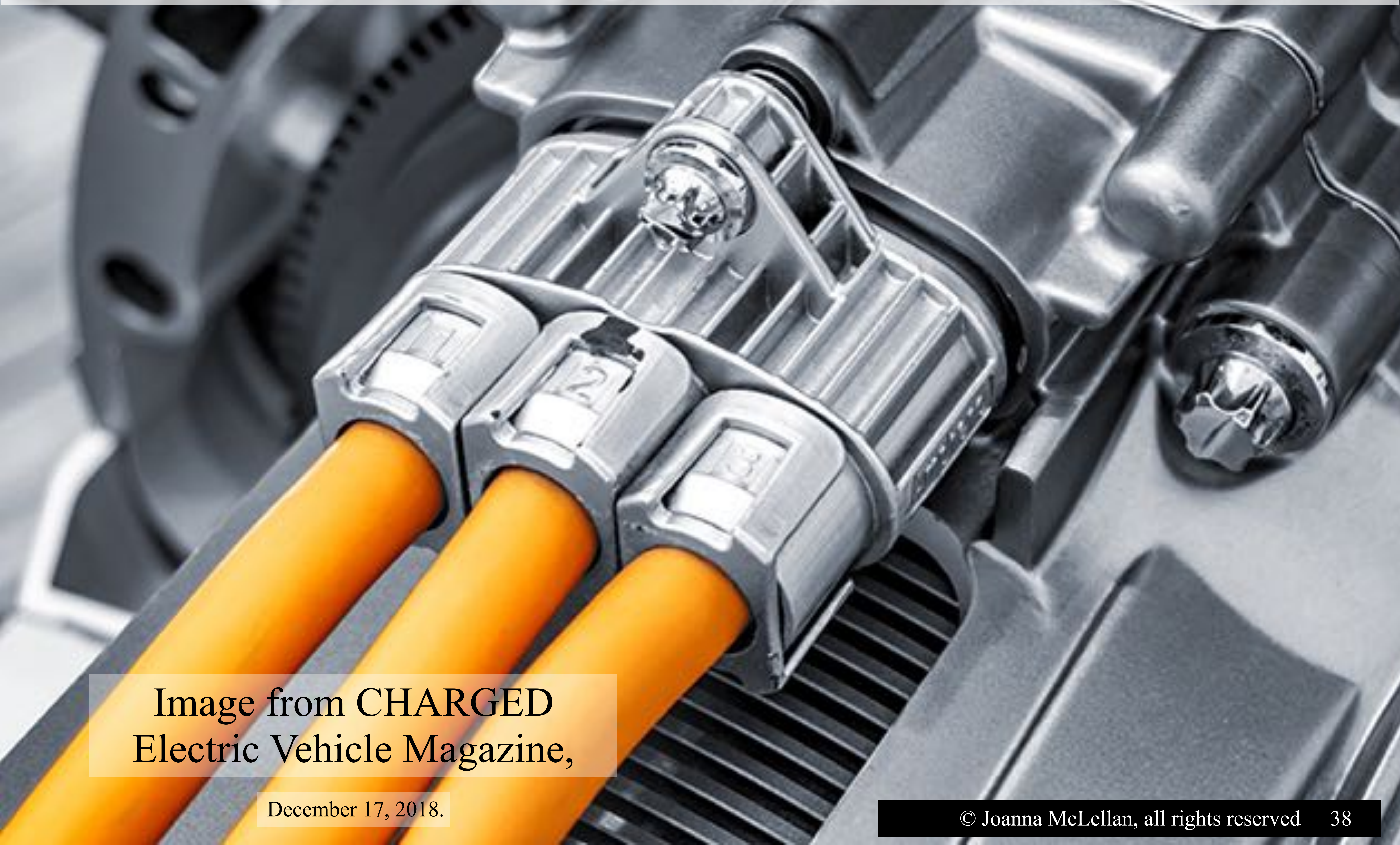
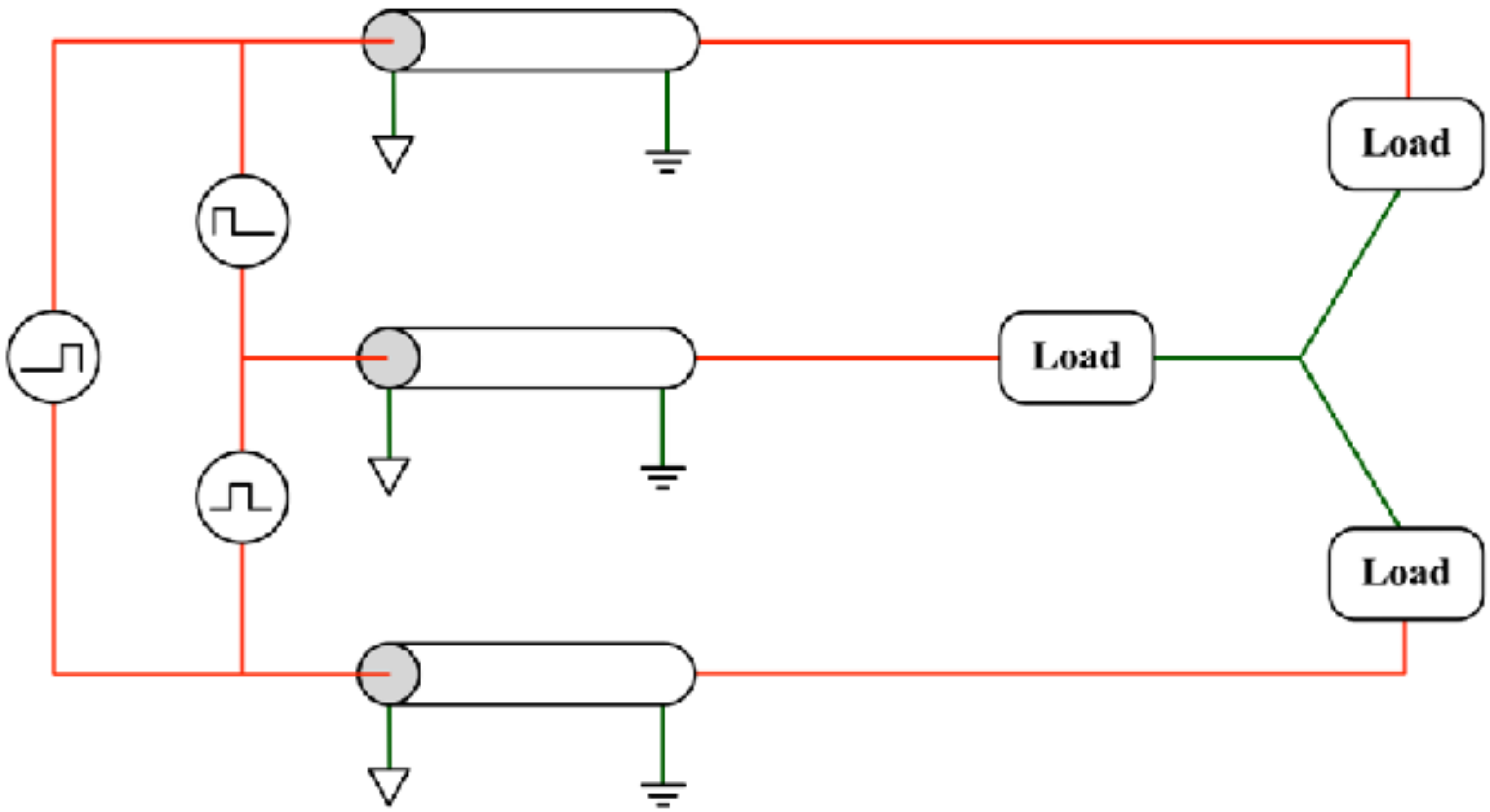


Image from CHARGED Electric Vehicle Magazine,

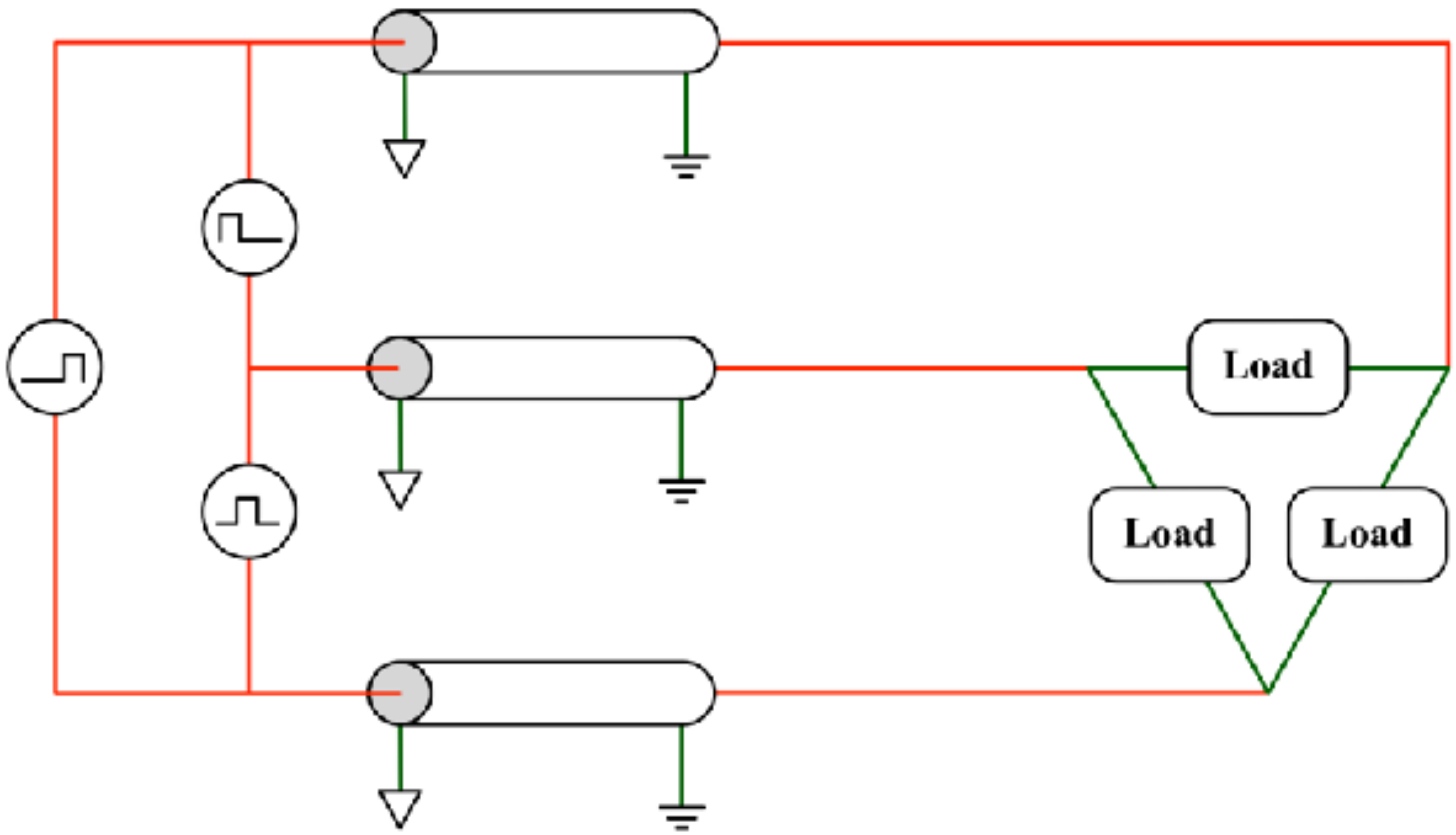
December 17, 2018.

Where does the current go?



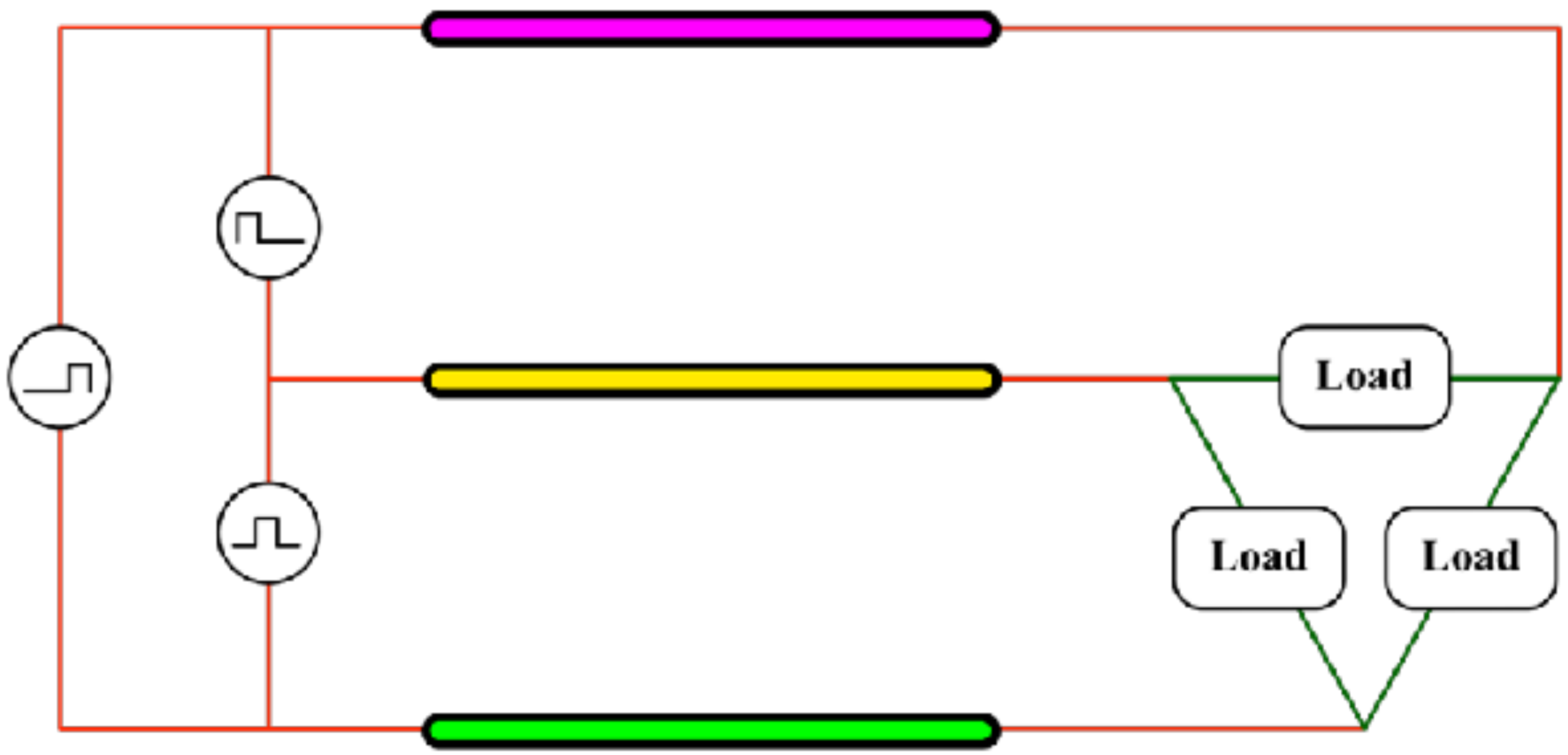
With a three phase Wye configuration there are three unintentional antennas formed by the circulating currents between the coaxial outer conductors.

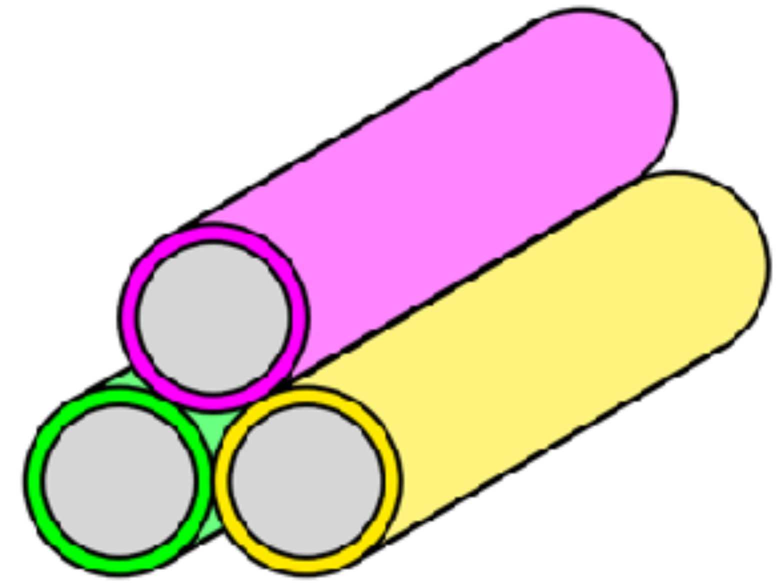
Where does the current go?



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

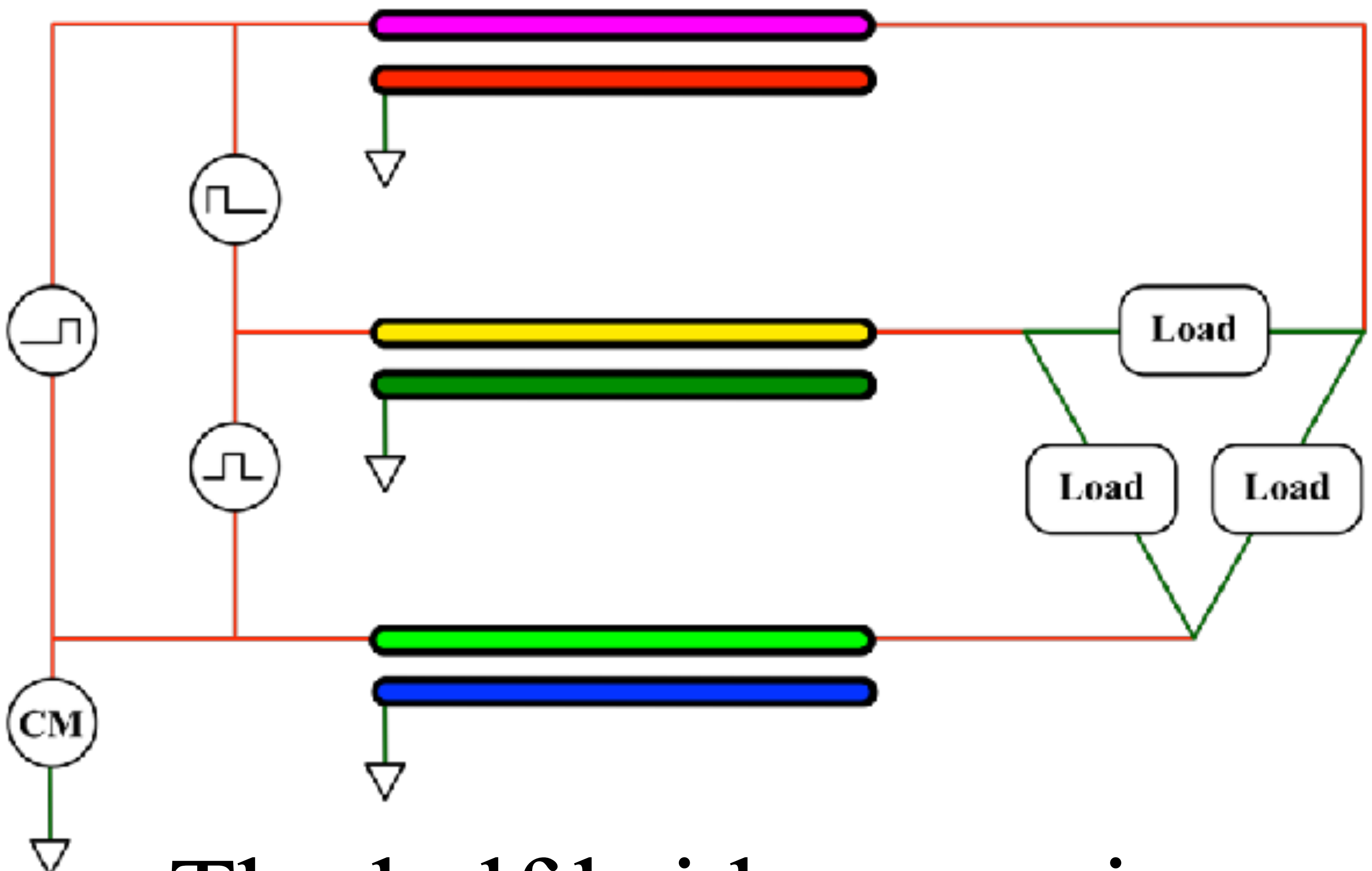
Where does the current go?

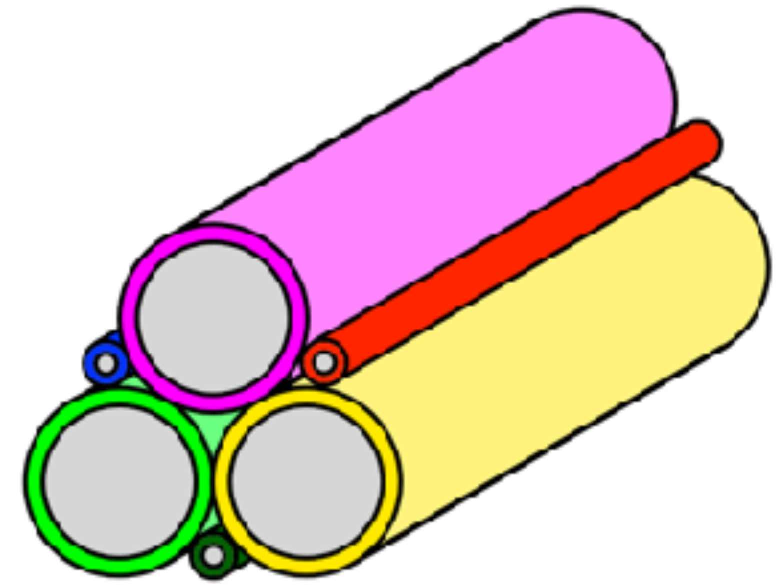




To allow the magnetic fields of all three current pairs to cancel they must be in a single transmission line, a triplet.

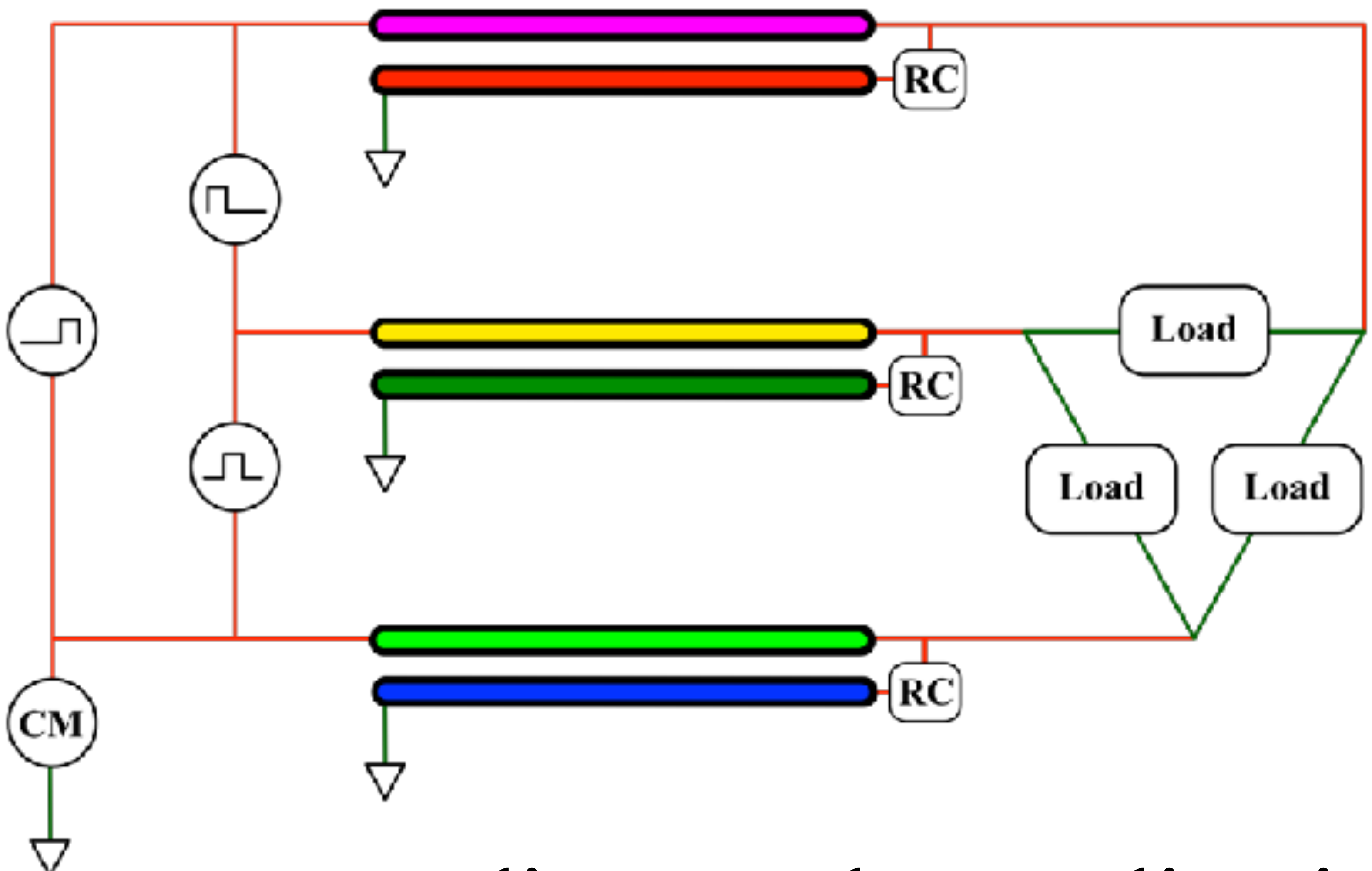
Where does the current go?

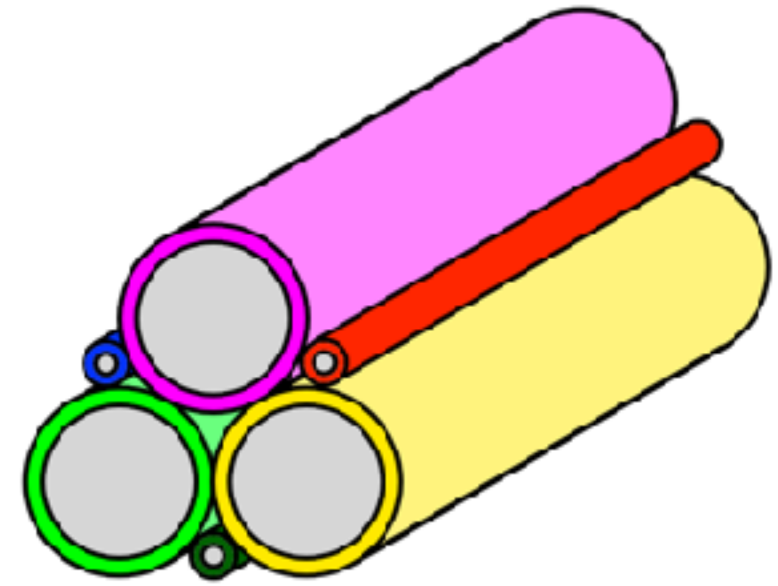




The half bridges are imperfect and create three common mode forward currents. Here again these forward currents can be constrained in transmission lines.

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 don’t implement the solution.

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.~~

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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

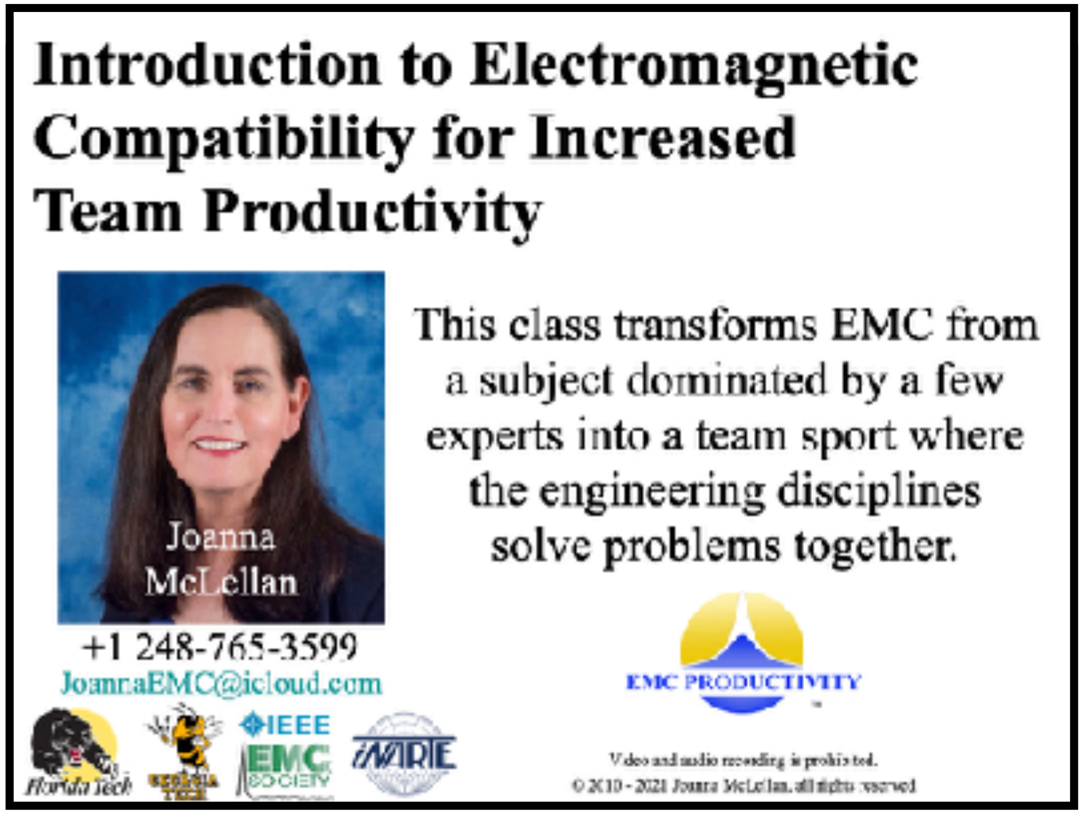
Most issues are resolved in 30 hours or less;
16 hours of training over 4 days,
4 hour workshop and
10 hours of office hours / support.

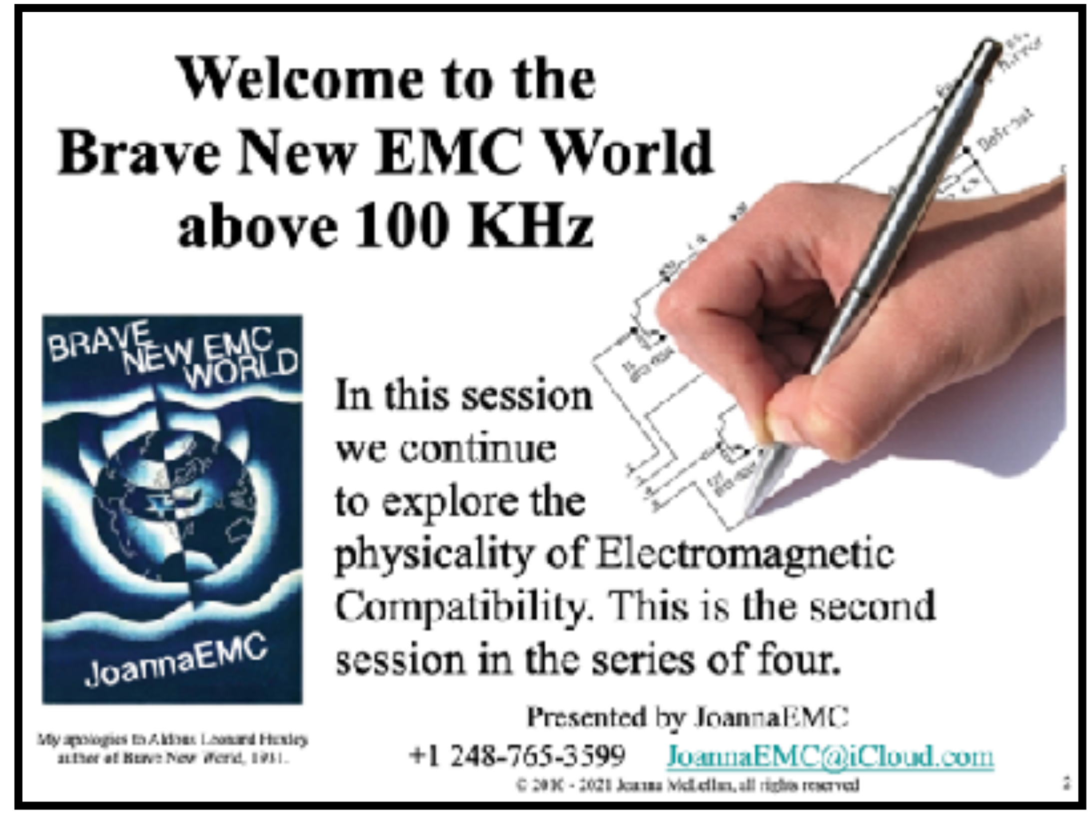
Train the entire team all at once to build Teamwork.

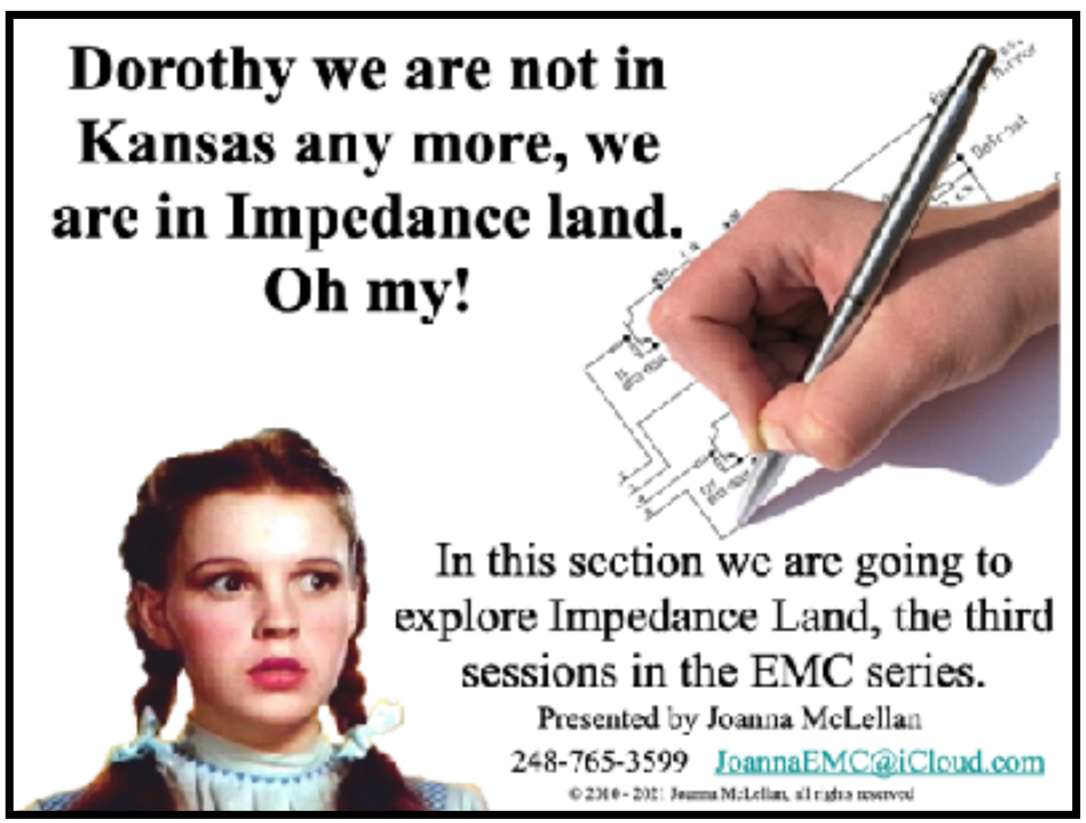
Mechanical, System, Test, and Electrical Engineers,
Supervision, PCB Layout and Technicians.

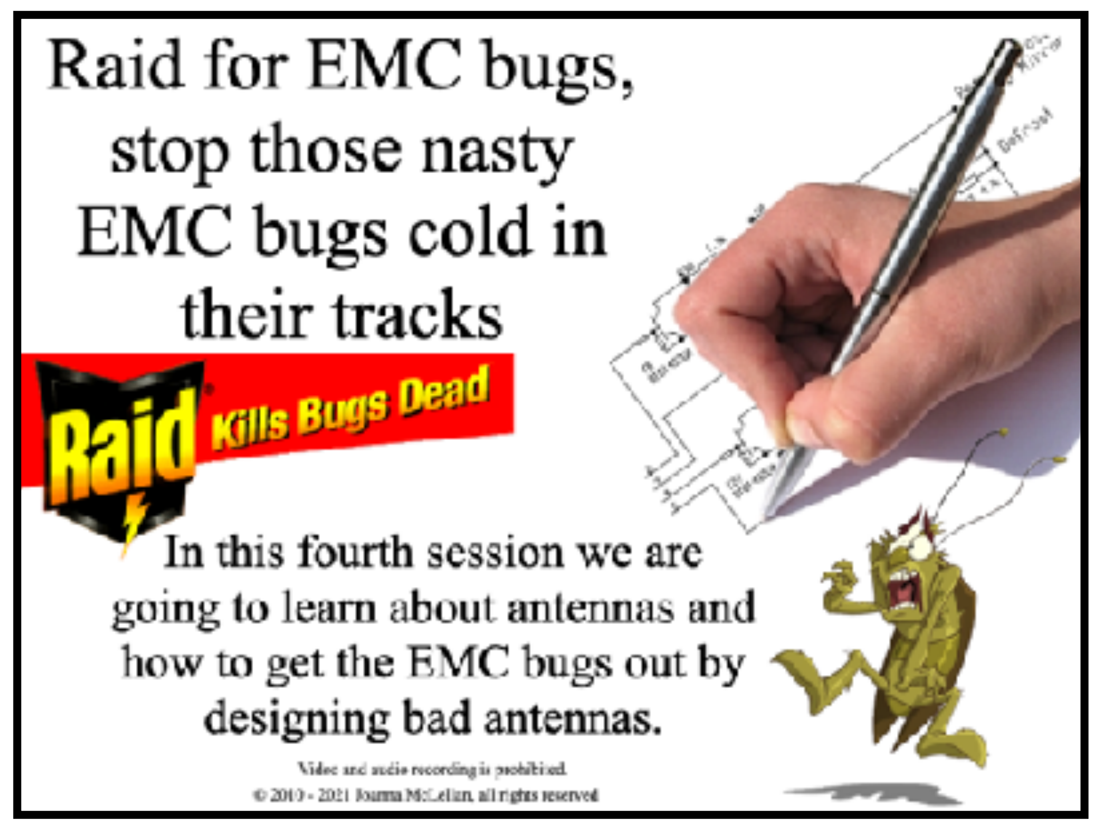
Train the Physics of EMC conceptually
without Vector Calculus.

Increase Team Productivity



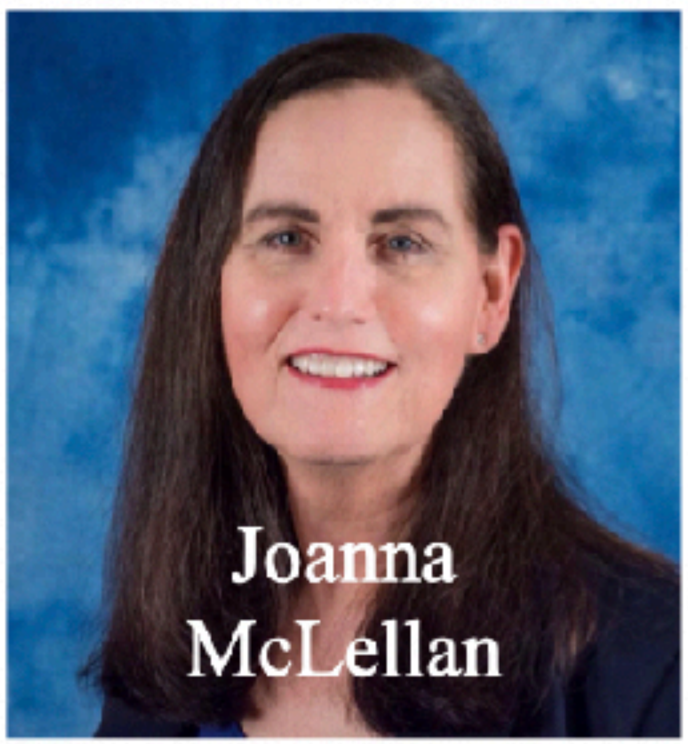






Increase Team Productivity

Introduction to Electromagnetic Compatibility for Increased Team Productivity



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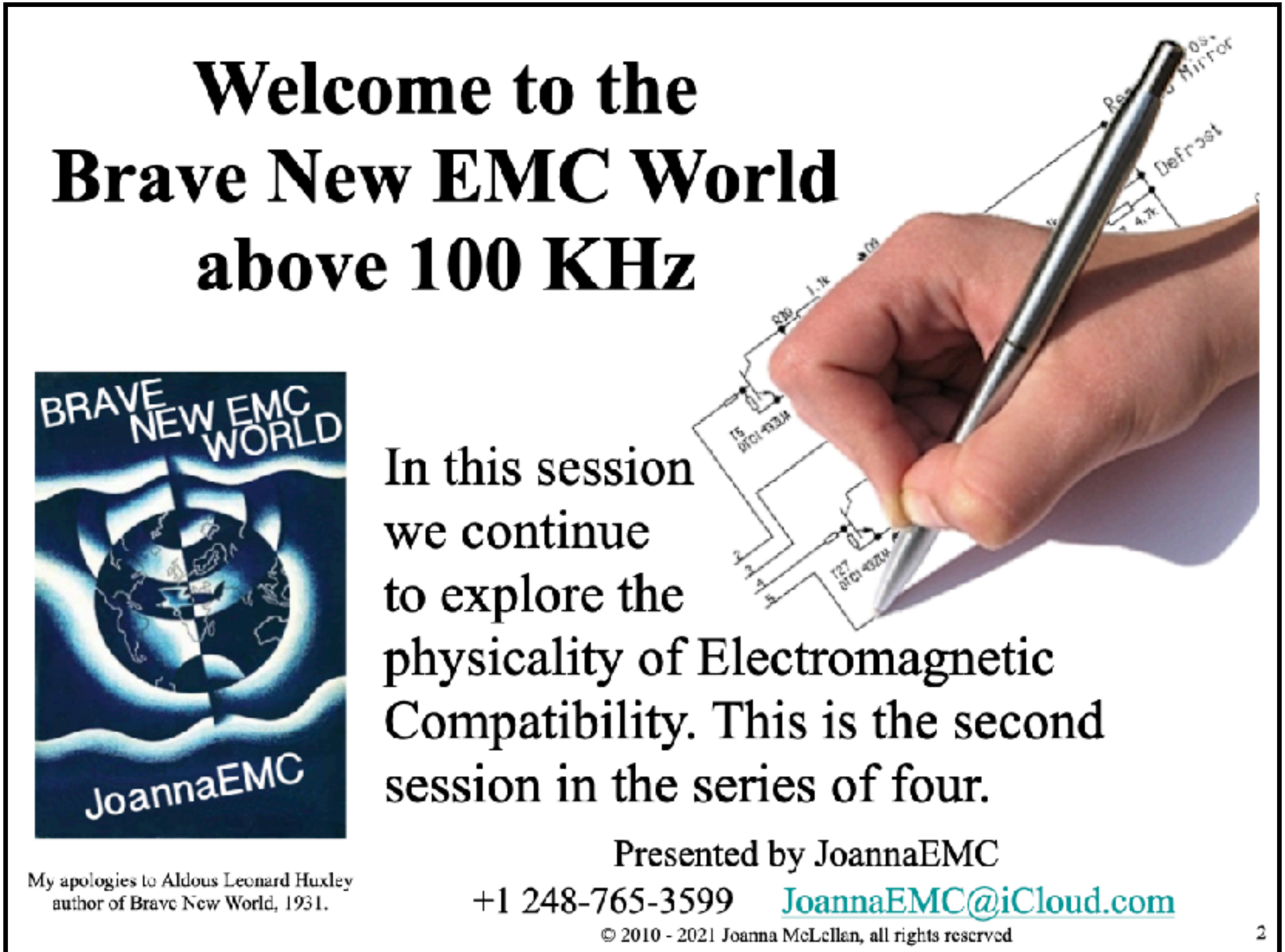
This class transforms EMC from a subject dominated by a few experts into a team sport where the engineering disciplines solve problems together.

EMC PRODUCTIVITY™

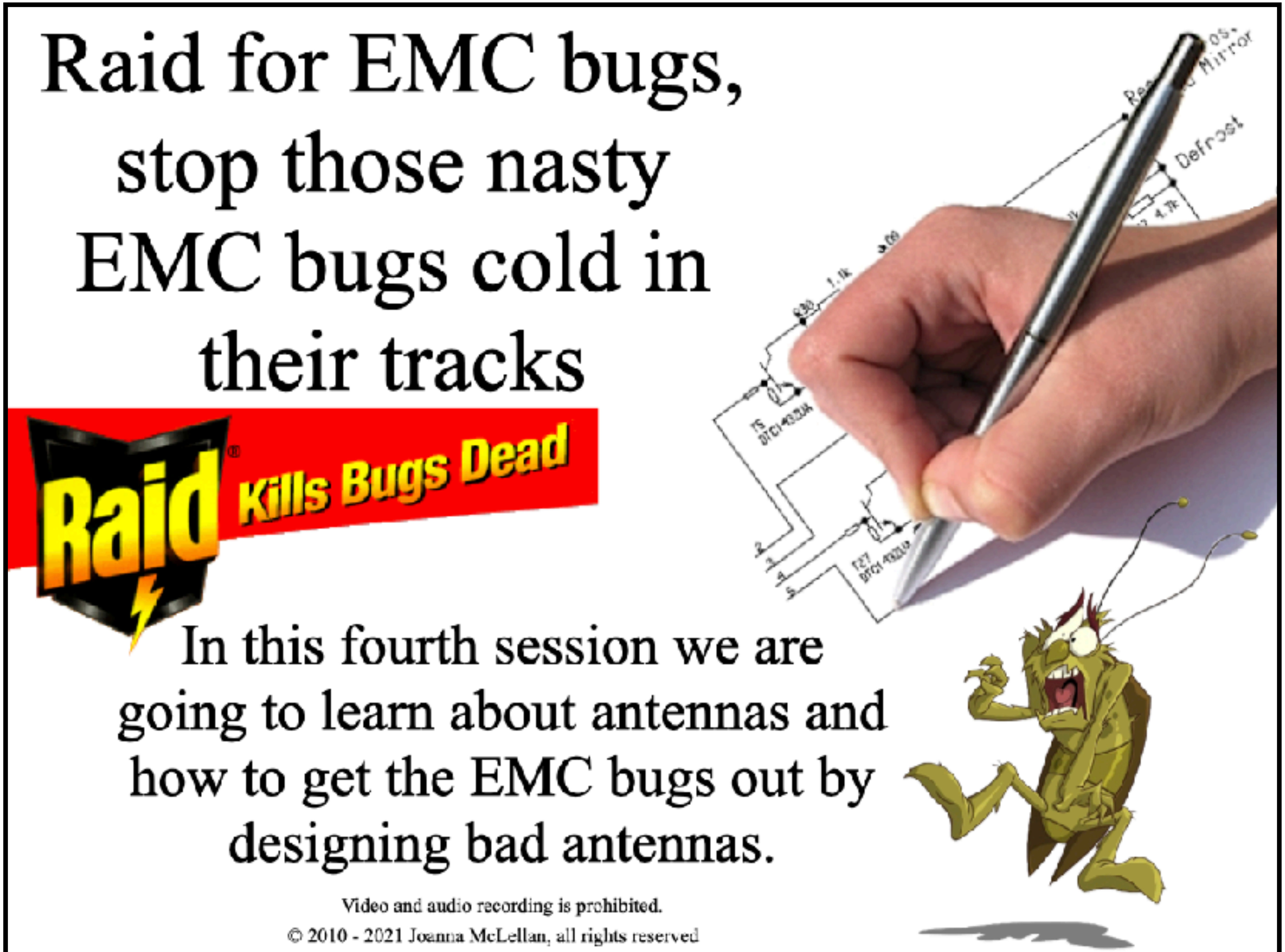
Florida Tech
GEORGIA TECH
IEEE EMC SOCIETY
iNARTE

Increase Team Productivity



Increase Team Productivity

Increase Team Productivity



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.™

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

Higher Cost

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.

Lower Cost

Fixing EMC Issues With The Training

Lower Cost

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.

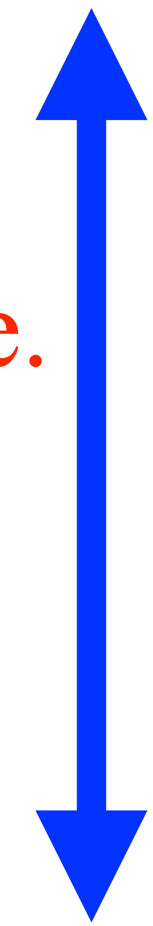
   Lower the Resonant Circuit Q factors.

4. Add a Capacitor.

   Don’t Play Capacitor Whack-a-Mole.

5. Add a Ferrite.

   When all else fails, consider using a Ferrite.



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 10KΩ.
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.

Presented by Joanna McLellan

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Image from TEDGlobal 2009, Bertrand Piccard

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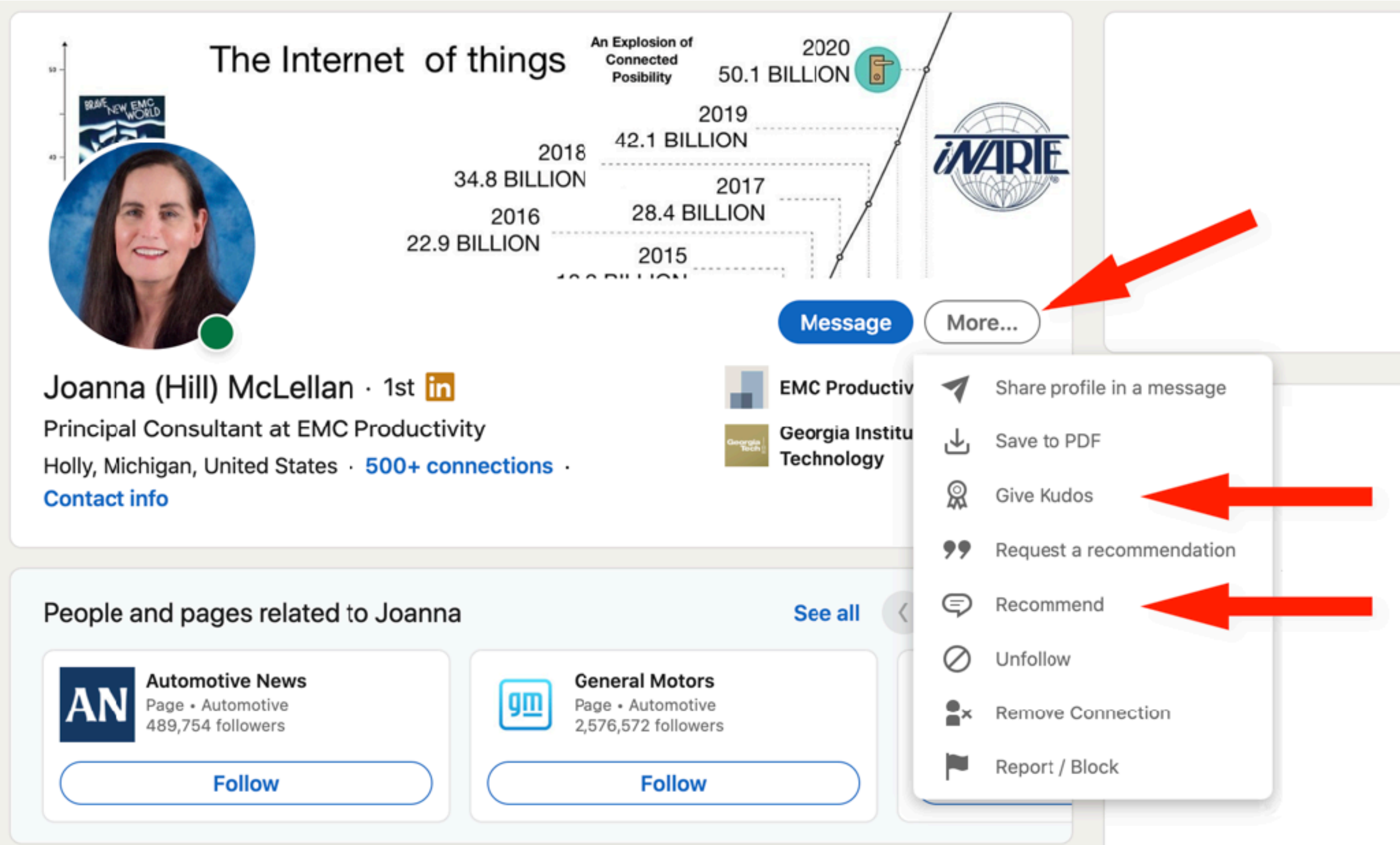
LinkedIn Kudos & Recommendations



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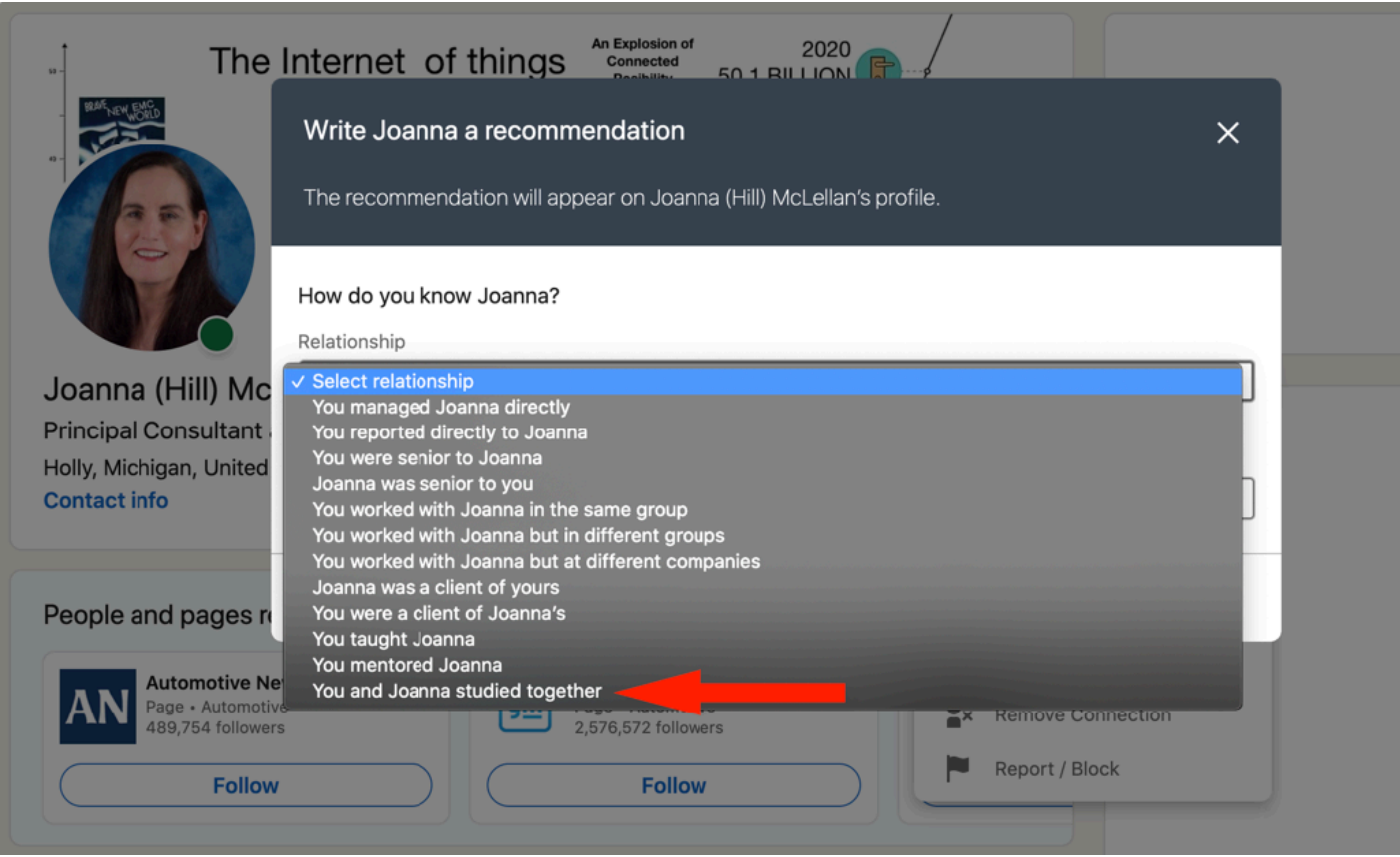

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