M1 - AUDIO INTERCONNECTIONS and GROUNDING – DISPELLING THE MYTHS

Master Class
123RD Audio Engineering Society Convention
The Jacob K. Javits Convention Center, New York, NY
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1:30 pm to 3:00 pm

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ABSTRACT

AUDIO INTERCONNECTIONS – DISPELLING THE MYTHS

By Henry W. Ott

Cabling and interconnection is often the "Achilles Heel" of quality audio. Many myths and rules-of-thumb have been perpetuated both in-print and in-practice with respect to proper audio interconnection techniques. Some of these myths have a rationale basis to justify them, many others do not.

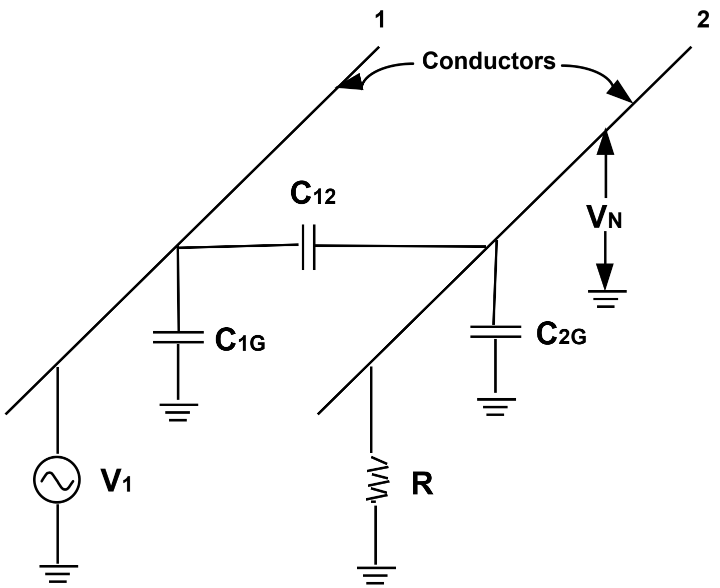
This presentation covers the fundamentals of electromagnetic field coupling, cable balancing, grounding and shielding in audio interconnections, based on the laws of physics, not conjecture, hype, or personal opinion.

Further complicating the audio interconnection situation today, is the fact that many audio devices also contain high frequency digital circuits.

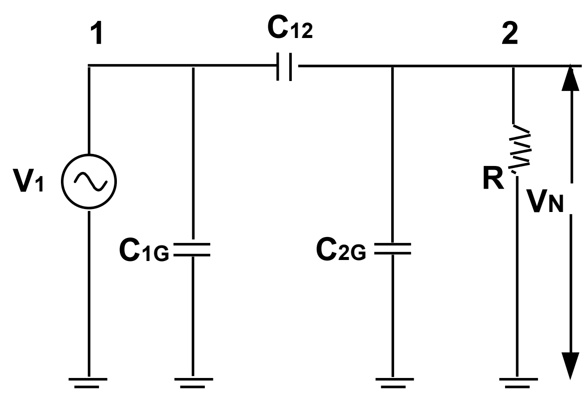
OVERVIEW

- We Will Analyze Electromagnetic Coupling To Cables
- We Will Use Circuit Theory, Not Field Theory
  - — Electric Field Coupling
  - — Magnetic Field Coupling
  - — Common Impedance Coupling
  - — Shielding
  - — Balancing
- We Will Assume That The Cables Are Electrically Short (Less Than One-Quarter of a Wavelength)
- This Will Give Us An Intuitive Understanding Of The Coupling Mechanisms And How To Minimize Noise Coupling

ELECTRIC FIELD COUPLING (CAPACITIVE COUPLING)



Physical Representation



Equivalent Circuit

Capacitive Coupling Between Two Conductors.

$$V_N = \frac{j\omega\left[C_{12}/(C_{12}+C_{2G})\right]}{j\omega + 1/R(C_{12}+C_{2G})}V_1$$

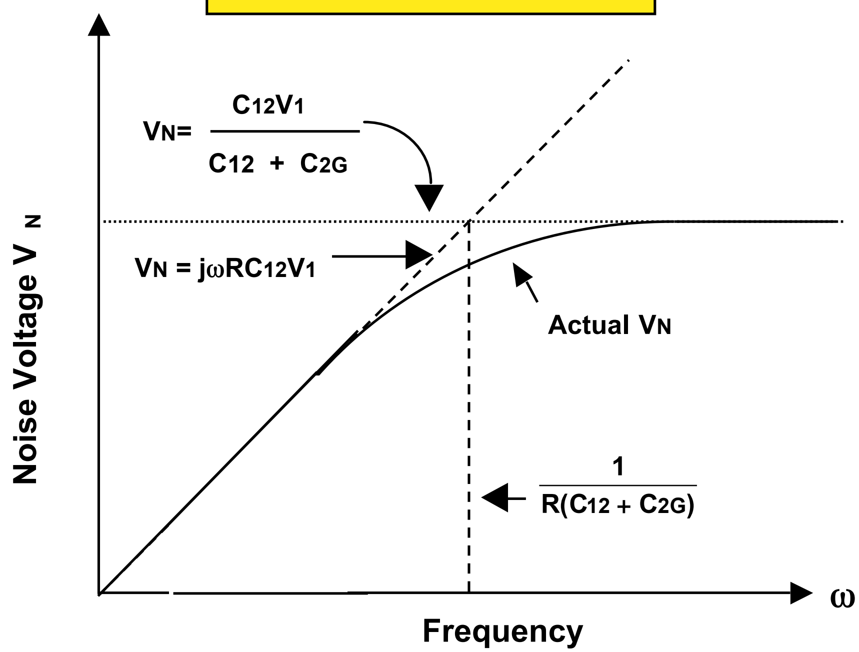
FREQUENCY RESPONSE OF CAPACITIVE COUPLED NOISE VOLTAGE

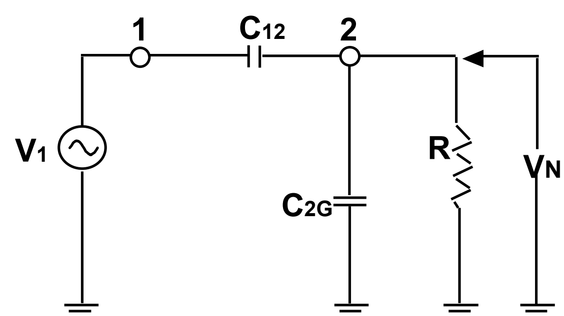
$$R \ll \frac{1}{j\omega(C_{12}+C_{2G})}$$

$$\boxed{V_N = j\omega R C_{12} V_1}$$

$$R \gg \frac{1}{j\omega(C_{12}+C_{2G})}$$

$$V_N = \frac{C_{12} V_1}{C_{12} + C_{2G}}$$

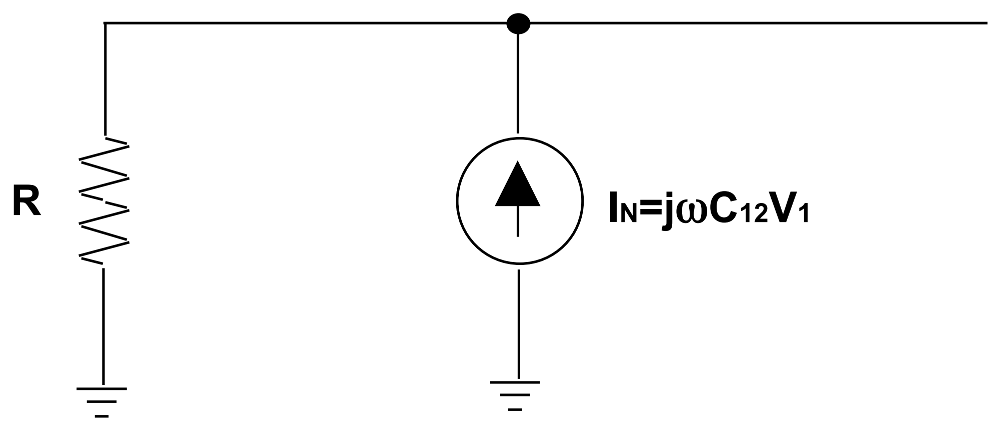




ELECTRIC FIELD (CAPACITIVE) COUPLING

$$V_N = j\omega R C_{12} V_1$$

RECEPTOR CIRCUIT



Equivalent Circuit

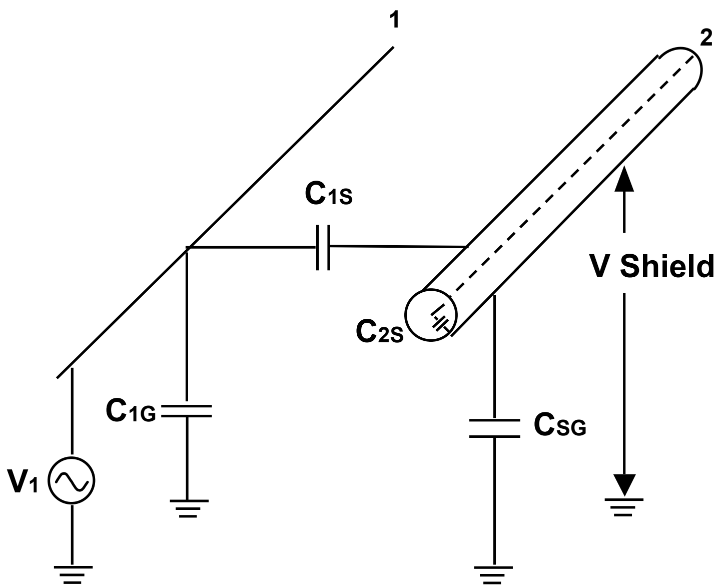
The Best Way to Decrease the Coupling is to:

Reduce C_{12}

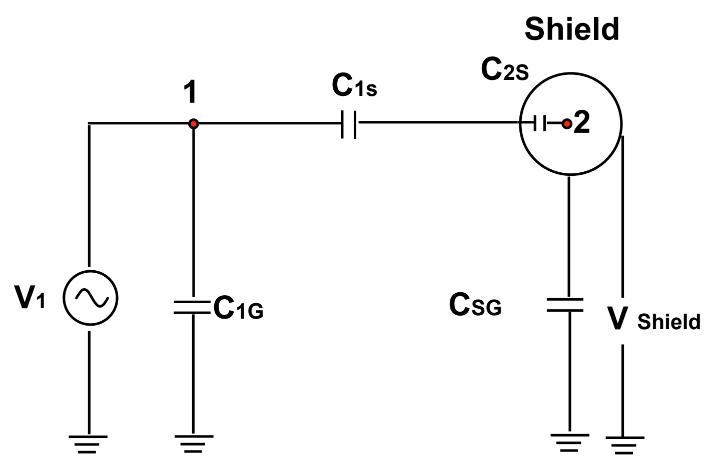
Separation, Orientation, Length &

Shielding

SHIELDED CABLE - IDEAL CASE



Physical
Representation



Equivalent
Circuit

Capacitive Coupling With Shield Placed Around Receiver Conductor.

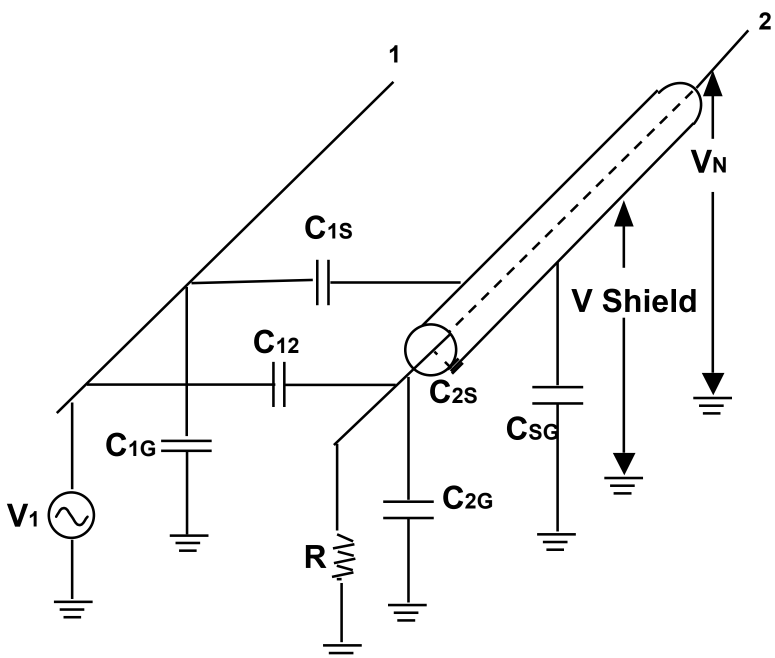
$$V_{shield} = \left(\frac{C_{1S}}{C_{1S} + C_{SG}}\right) V_1$$

$V_N = V_{Shield}$

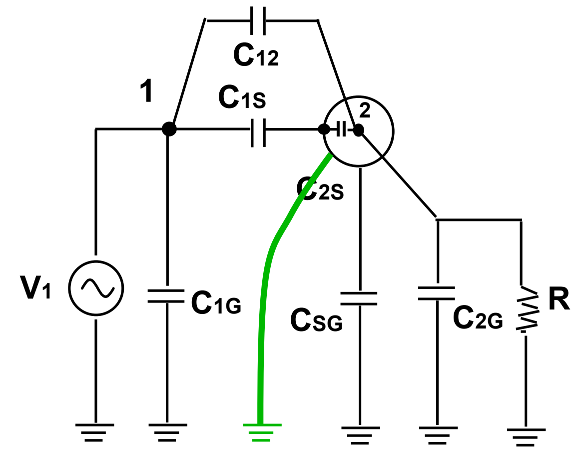
Note:

The Shield on a Shielded Cable is Unshielded!

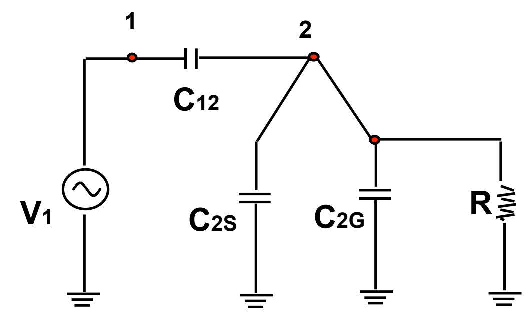
SHIELDED CABLE - PRACTICAL CASE



Physical Representation



Equivalent Circuit



Simplified Equivalent Circuit
For Grounded Shield

$$V_N = j\omega R C_{12} V_1$$

TERMINATIONS

Most Cabling Problems Are Due to Improper Terminations.

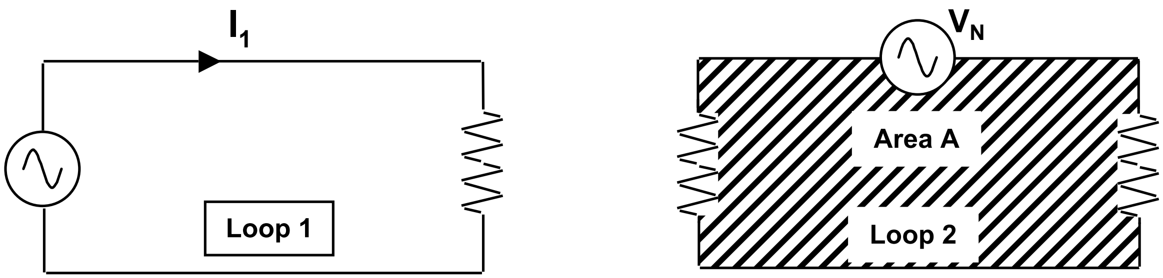
MAGNETIC FIELD COUPLING
(INDUCTIVE COUPLING)

The Voltage V_N Induced in a Loop of Area A in a Uniform Magnetic Field is (Faraday's Law):

$$\boxed{V_N = j\,\omega\, B\, A \cos\theta}$$

$$V_N = j\,\omega\,\Phi_{12}$$

$$\boxed{V_N = j\,\omega\, M_{12}\, I_1}$$



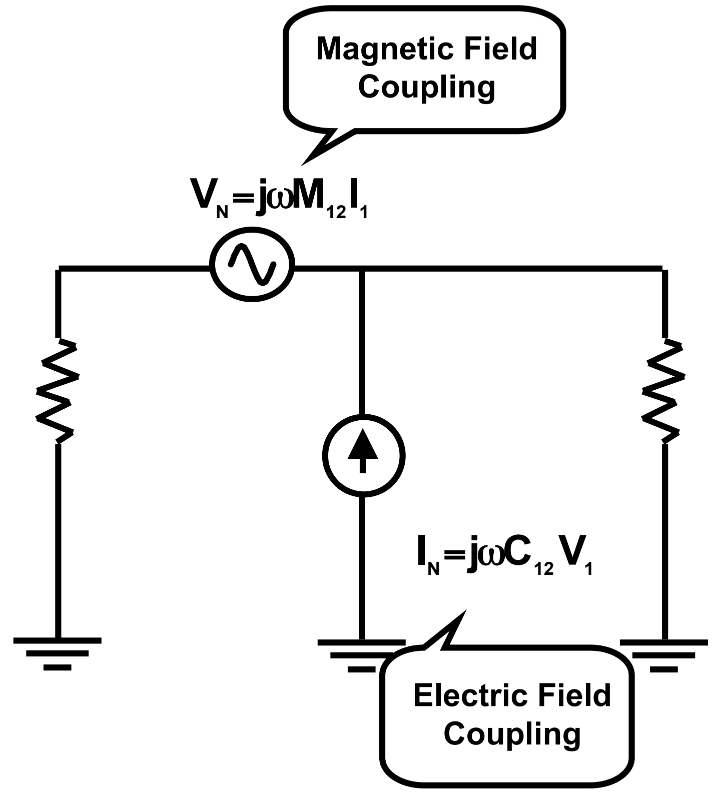
COMPARING ELECTRIC AND MAGNETIC FIELD COUPLING

Electric Field Coupling:

$$V_N = j\omega RC_{12}V_1$$

Magnetic Field Coupling:

$$V_N = j\,\omega\,M_{12}\,I_1$$

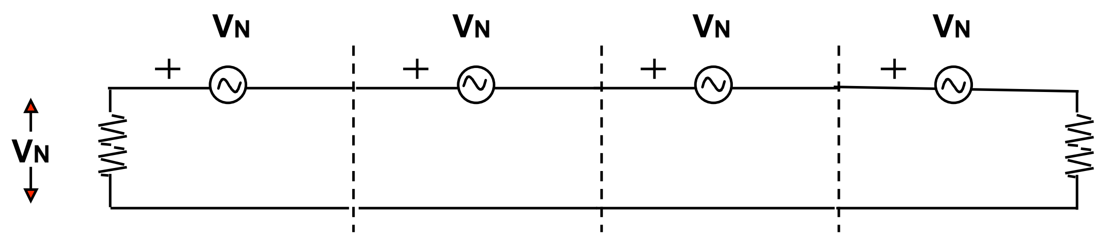


MAGNETIC FIELD (INDUCTIVE) COUPLING

$$V_N = j\omega \, B \, A \cos\theta = j\omega \, M_{12} \, I_1$$

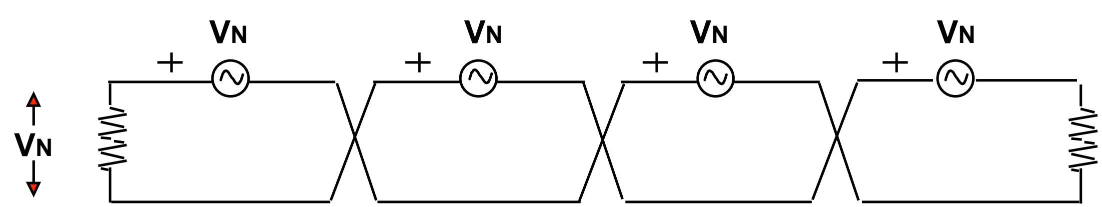
Decreasing The Area Is The Key To Controlling Magnetic Coupling

1) Place Conductors Close Together



Parallel Pair

2) Use Twisted Pair



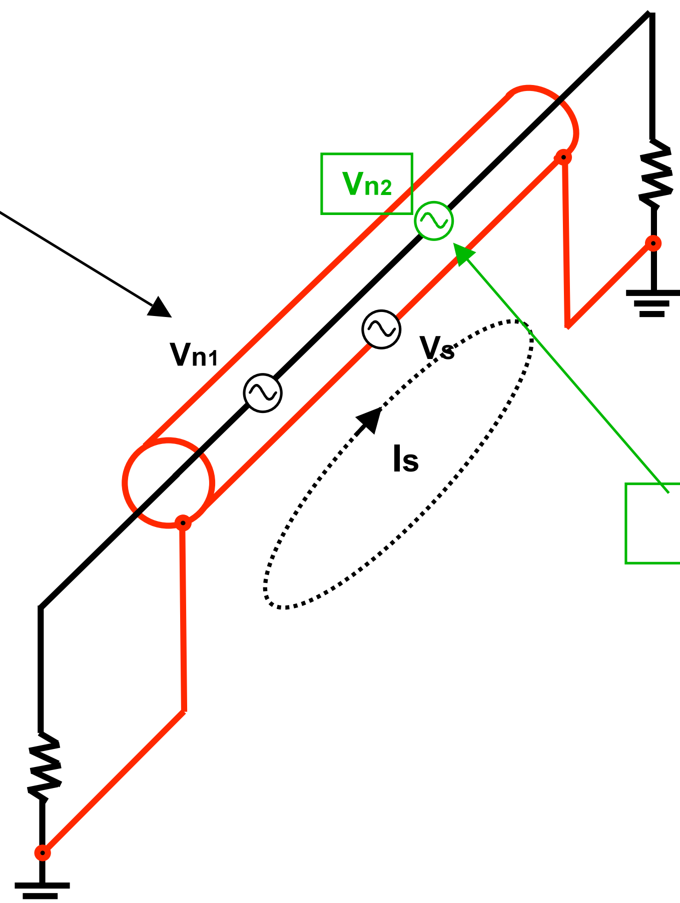
Twisted Pair

3) Use A Shielded Cable ??

CABLE SHIELDING FOR MAGNETIC FIELD SUPPRESSION

$V_{n1} = j\,\omega\,B\,A\cos\phi$

or $j\,\omega\,M_{12}\,I_1$



$V_{n2} = j\,\omega\,M_{s2}\,I_s$

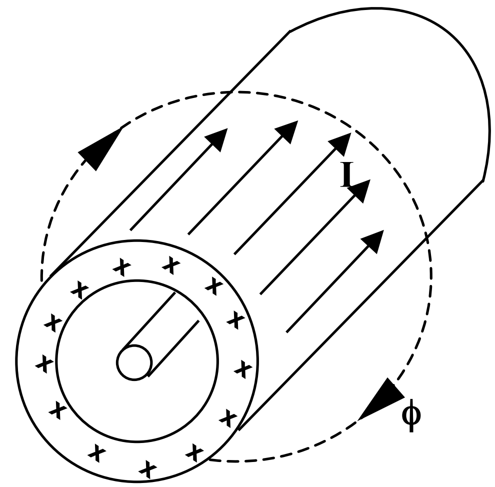
MAGNETIC COUPLING BETWEEN A SHIELD AND ITS CENTER CONDUCTOR

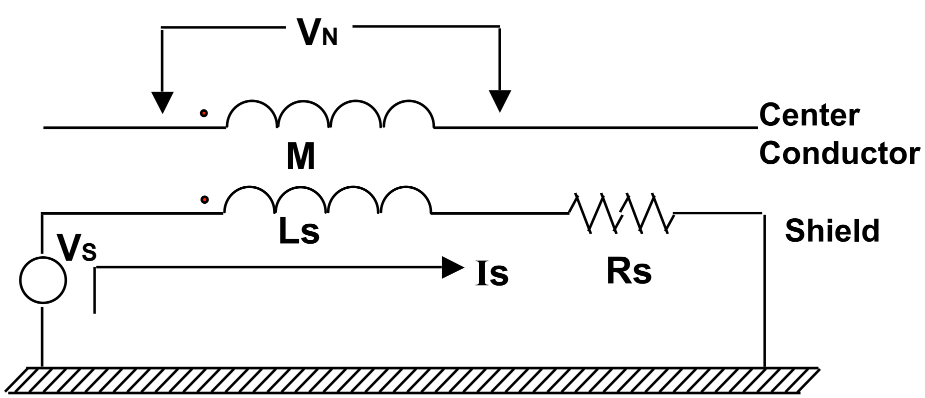
All The Magnetic Flux Due To The Shield Current Is Outside The Tube, None Is Inside. Therefore....

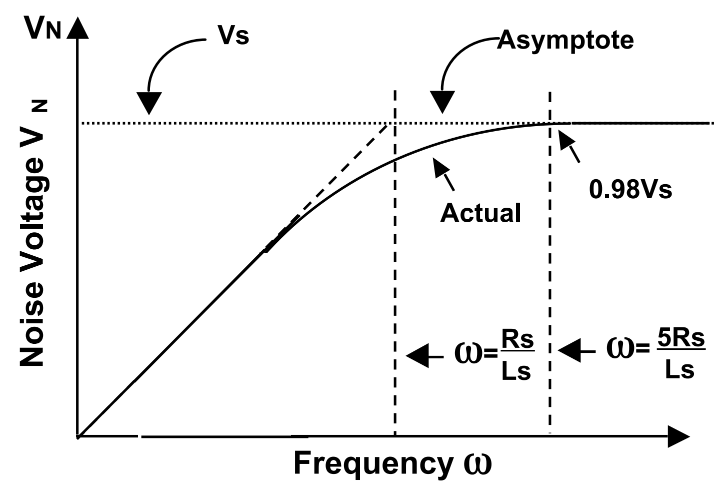
$$\boxed{M = L_S}$$

$$V_N = \frac{j\omega}{j\omega + R_S/L_S} V_S$$

$\omega_c = R_S/L_S$ = Shield Cutoff Freq.







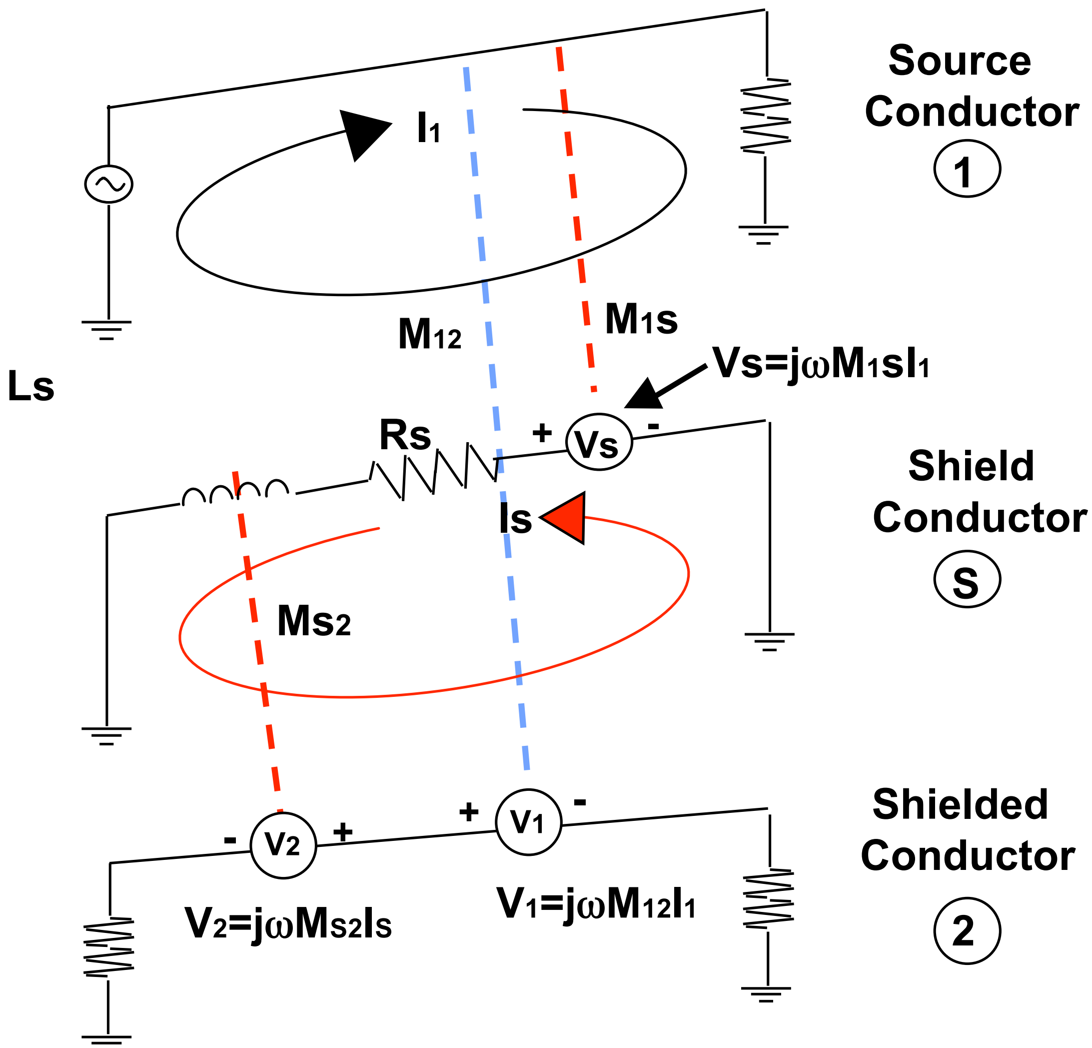
MEASURED VALUES OF SHIELD CUTOFF FREQUENCY

CABLE	IMPEDANCE (Ω)	CUTOFF FREQUENCY (kHz)	FIVE TIMES CUTOFF FREQUENCY (kHz)	REMARKS
COAXIAL CABLE				
RG-6A	75	0.6	3.0	DOUBLE SHIELD
RG-213	50	0.7	3.5	
RG-214	50	0.7	3.5	DOUBLE SHIELD
RG-62A	93	1.5	7.5	
RG-59C	75	1.6	8.0	
RG-58C	50	2.0	10.0	
SHIELDED TWISTED PAIR				
754E	125	0.8	4.0	DOUBLE SHIELD
24 Ga.	--	2.2	11.0	
22 Ga.*	--	7.0	35.0	ALUMINUM FOIL SHIELD
SHIELDED SINGLE				
24Ga.	--	4.0	20.0	

* One Pair Out Of An 11 Pair Cable (Belden 8775)

From: Noise Reduction Techniques In Electronic Systems, By H.W. Ott, © 1976, 1988 AT&T Bell Laboratories.

SHIELDED CABLE - MAGNETIC FIELD COUPLING



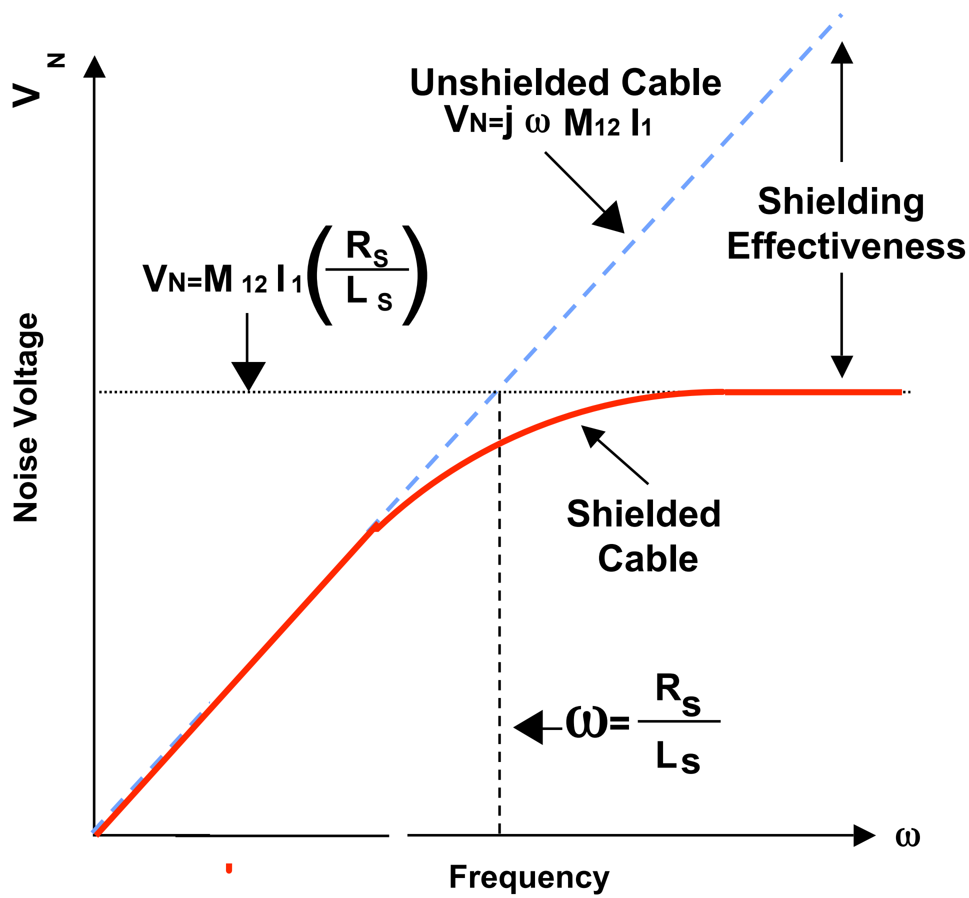
For A Coaxial Shield:

$M_{s2} = L_s$
$M_{1s} = M_{12}$

Total Voltage Induced Into Conductor 2 Is:

$V_N = V_2 - V_C$

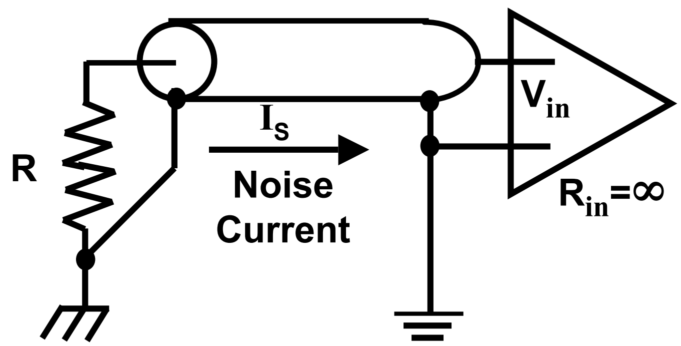
MAGNETIC COUPLING, OPEN-WIRE TO SHIELDED CABLE



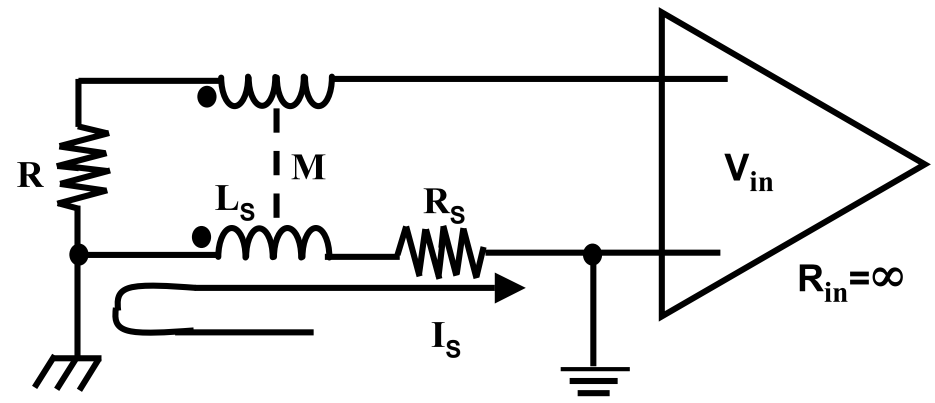
Noise Coupling To Shielded Cable

$$V_N = j\omega M_{12} I_1 \left[\frac{Rs / Ls}{j\omega + Rs / Ls}\right]$$

EFFECT OF SHIELD CURRENT ON INPUT NOISE VOLTAGE



Physical Representation



Equivalent Circuit

$$V_{in} = -j\,\omega\, M\, I_s + j\,\omega\, L_s\, I_s + R_s\, I_s$$

Since $M = L_s$,

$$\boxed{V_{in} = R_s\, I_s}$$

COMMON IMPEDANCE COUPLING

- The Effect Described on the Previous Slide is Called Common Impedance Coupling
- In the Audio World it is Often Referred to as Shield Current Induced Noise (SCIN)*
- It Results From the Shield Having to Carry Two Currents:
  - The Signal Current
  - The Induced Noise Current
- Common Impedance Coupling Can be Eliminated or Reduced by Using a Cable That Has Three Conductors
  - Triaxial Cable (Two Shields Insulated From Each Other)
  - Twinaxial Cable (Two Balanced Signal Conductors Within a Single Shield)

* Brown & Whitlock, 2003

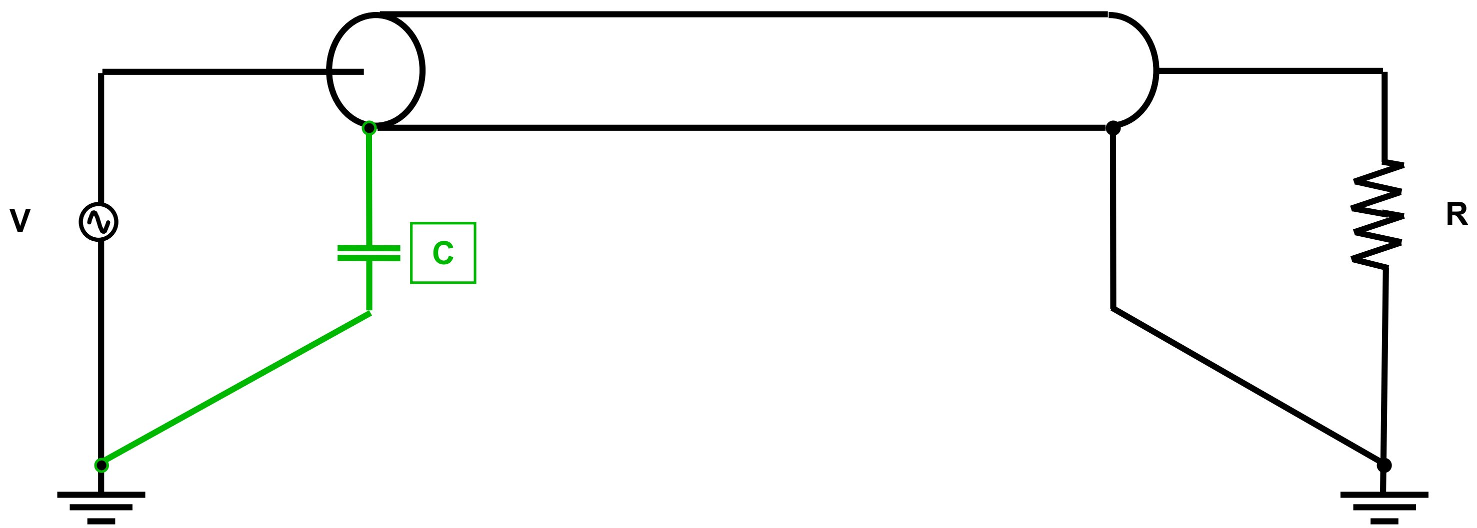
WHAT CAUSES SHIELD CURRENTS

- Differences in Ground Potential
- Magnetic Field Induction
- Radio Frequency Pickup

WHAT CAN WE DO TO REDUCE SCIN

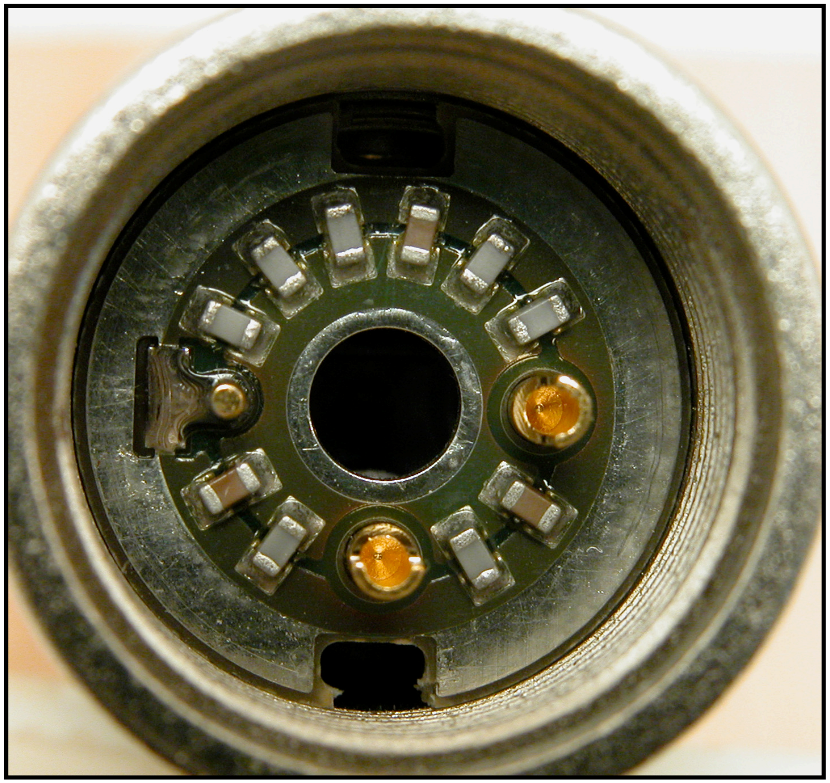
- In All Cases
  - Use a Shield With Low Resistance (Cu Braid Not Al Foil)
  - Use Balanced Interconnections
- In The Case of Low Frequency Shield Currents (< 500 kHz)
  - Reduce Ground Potential Difference By Adding a Heavy Gauge Parallel Earth Conductor (PEC)
  - Ground Only One End of the Shield (This However May Cause High Frequency Emissions & Susceptibility)
  - Use Hybrid Shield Grounding
- In The Case of High Frequency Shield Currents (> 500 kHz)
  - Add Ferrite Core (C-M Choke) to The Cable
  - At Frequencies Above About 10 MHz an Unbalanced Coaxial Cable, Because of Skin Effect, Contains Three Isolated Conductors:
    - » The Center Conductor
    - » The Inner Surface of the Shield Conductor
    - » The Outer Surface of the Shield Conductor
    - » Therefore, Common Impedance Coupling Does Not Occur

EXAMPLE OF A HYBRID GROUND

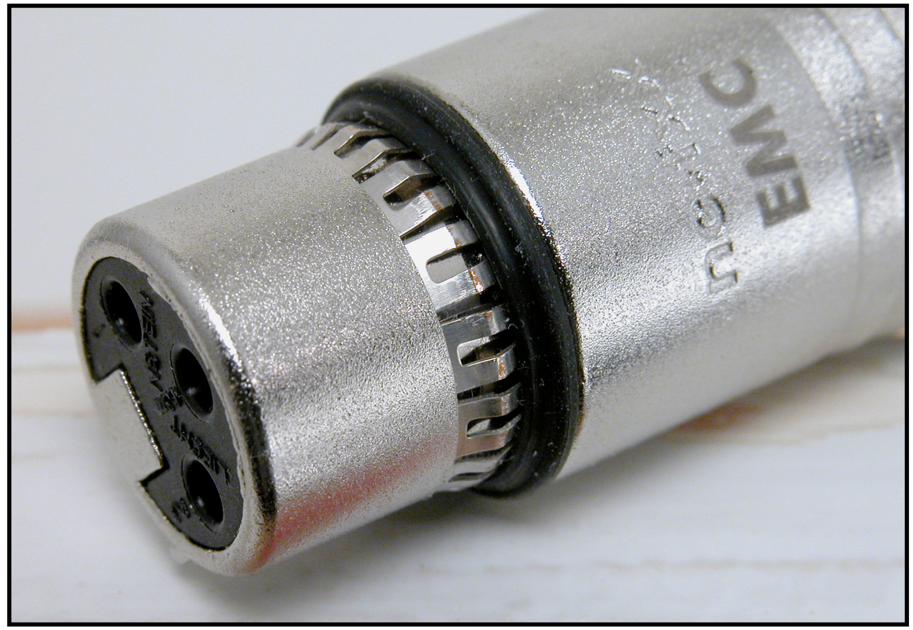


Cable Shield is Hybrid Grounded

XLR CONNECTOR



Hybrid Cable Shield Termination

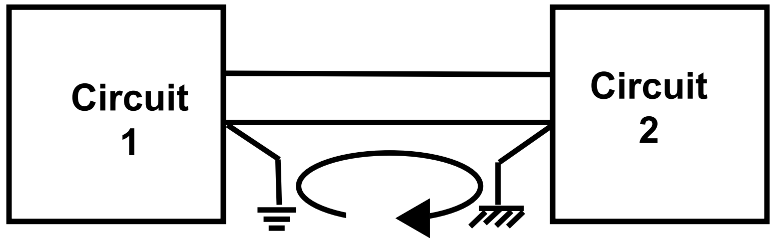


Spring Fingers For 360º Backshell Contact

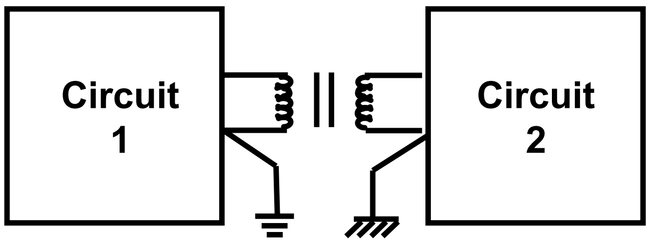
REQUIREMENTS FOR A PROPER SHIELD TERMINATION

- Shield Must be Connected to the Proper Potential
- A Low Impedance Connection
- A 360º Contact to the Shield

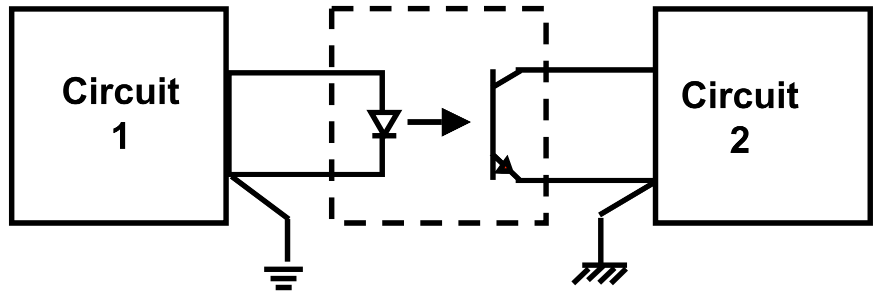
METHODS OF BREAKING GROUND LOOPS



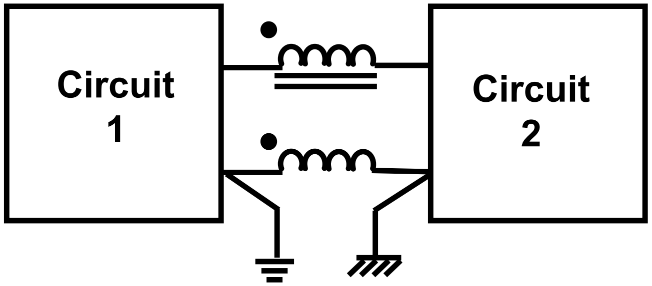
Ground Loop



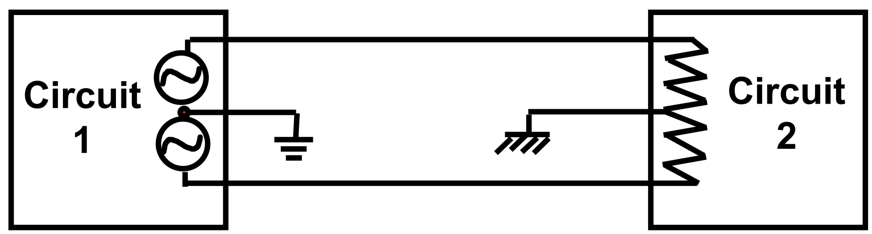
Transformer



Optical Coupling



Common-Mode Choke



Balanced Circuit

HOC
ELECTROMAGNETIC
COMPATIBILITY

WHERE NOT TO BREAK A GROUND LOOP

- Why Does Some Equipment Have a Grounded Three Wire Plug?
- For Safety!
- Do Not Break a Ground Loop by Lifting a Ground From Equipment With a Three Wire Plug
- Doing So is Unsafe!
- Rather Break the Ground Loop in the Signal Interconnection as Was Shown on the Previous Slide
- An Excellent Reference for Troubleshooting Ground Loop Problems in Unbalanced Audio Systems is the *Jensen System Troubleshooting Guide*, by Bill Whitlock (www.jensentransformers.com/apps_wp.html)

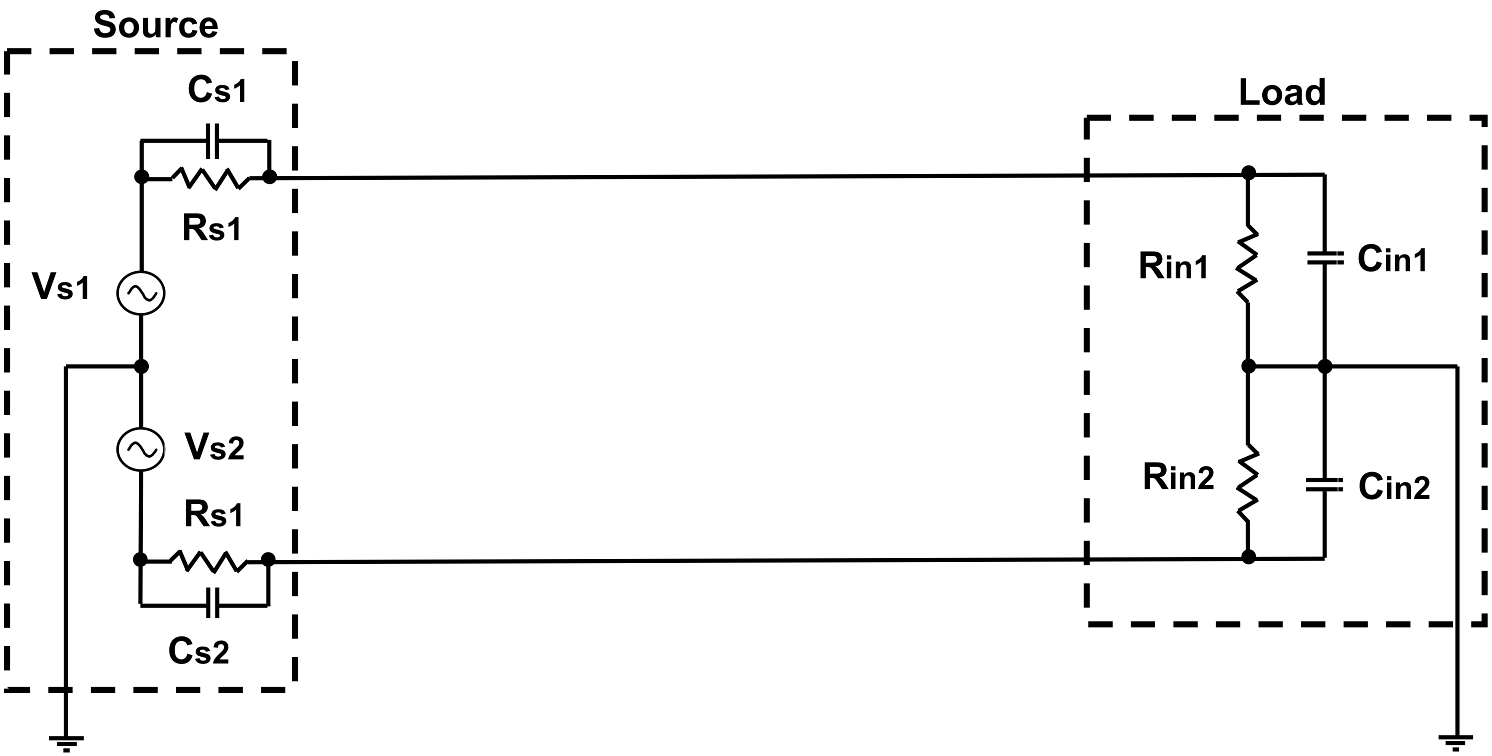
BALANCING

- Balancing Is Often an Overlooked Noise Reduction Technique.
- The Purpose of Balancing is to Make the Noise Pickup in Both Conductors Equal, In Which Case it Can be Made to Cancel Out in the Load.
- Balancing Can Be Used in Addition to Other Techniques for Additional Noise Suppression; or It Can Be Used As the Primary Means of Noise Suppression.
- Balancing Is Normally Used in Interconnection or Cabling Systems to Reduce Noise Pick-up or to Minimize Radiation.

BALANCING

Balance is defined in terms of the impedance of the two signal conductors with respect to a reference, which is usually ground. If these impedances are equal and non-zero, the system is balanced. If the impedances are unequal the system is unbalanced. A signal conductor with a grounded return conductor is, therefore, an unbalanced (sometimes referred to as a single ended) system.

A BALANCED CIRCUIT



For Balance: Rs1=Rs2
Cs1=Cs2

For Balance: Rin1=Rin2
Cin1=Cin2

Note: Vs1 Does Not Have to Equal Vs2
Vs1 or Vs2 May Even be Zero

THE TELEPHONE CONNECTION

An excellent example of the effectiveness of using a balanced system to reduce noise is the telephone system, where signal levels are typically tens to hundredths of millivolts. Telephone cables often run for many miles parallel to high voltage (4,000 to 14,000 volts) AC power lines and you do not hear any 60 Hertz hum in the telephone. This is because the telephone system is balanced. On the rare occasions where you do hear hum in the telephone, it is because something has caused an unbalance to occur in the lines and it will go away once the balance is restored.

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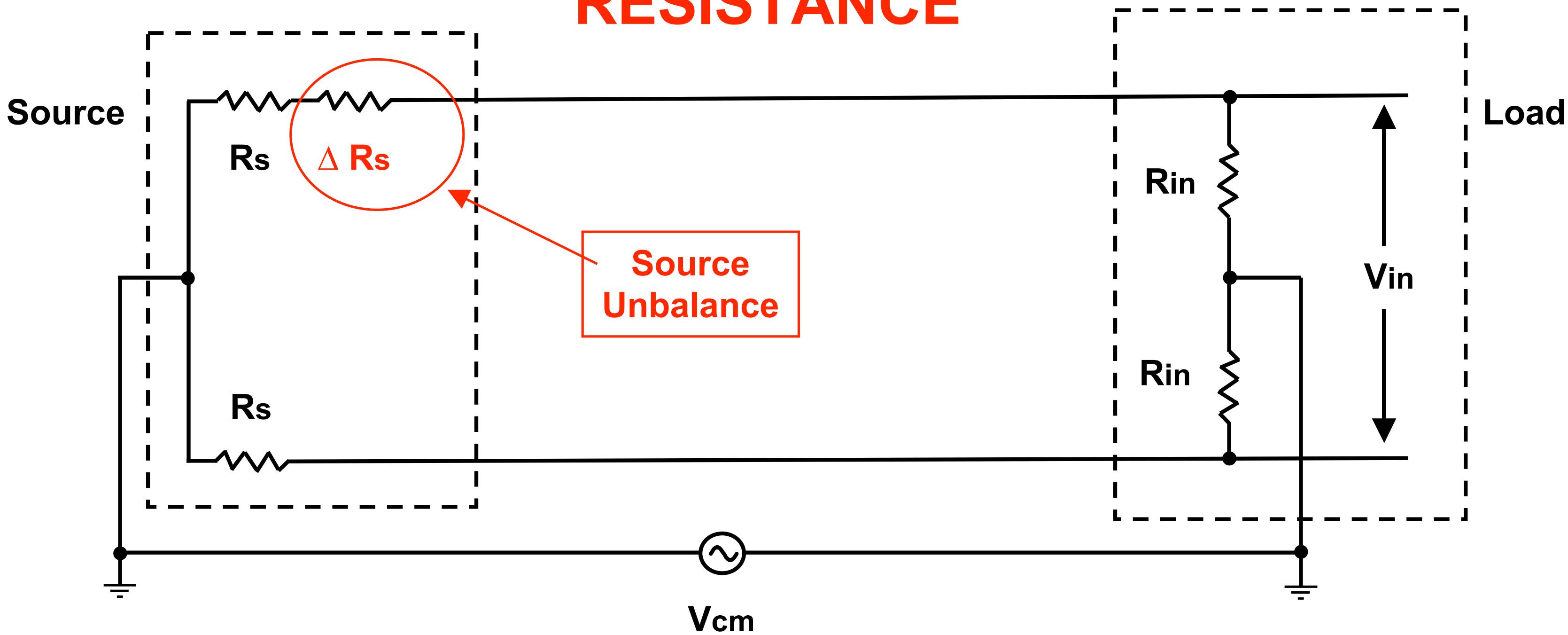
CMRR DUE TO AN UNBALANCED SOURCE RESISTANCE



$$\text{CMRR} = \frac{(R_{in} + R_s + \Delta R)\,(R_{in} + R_s)}{R_{in}\,\Delta R}$$

If $R_{in} \gg R_s + \Delta R$ Then $\boxed{\text{CMRR} = \dfrac{R_{in}}{\Delta R}}$

Example:

$R_{in} = 10\ \text{k}\Omega$

$\Delta R = 10\ \Omega$

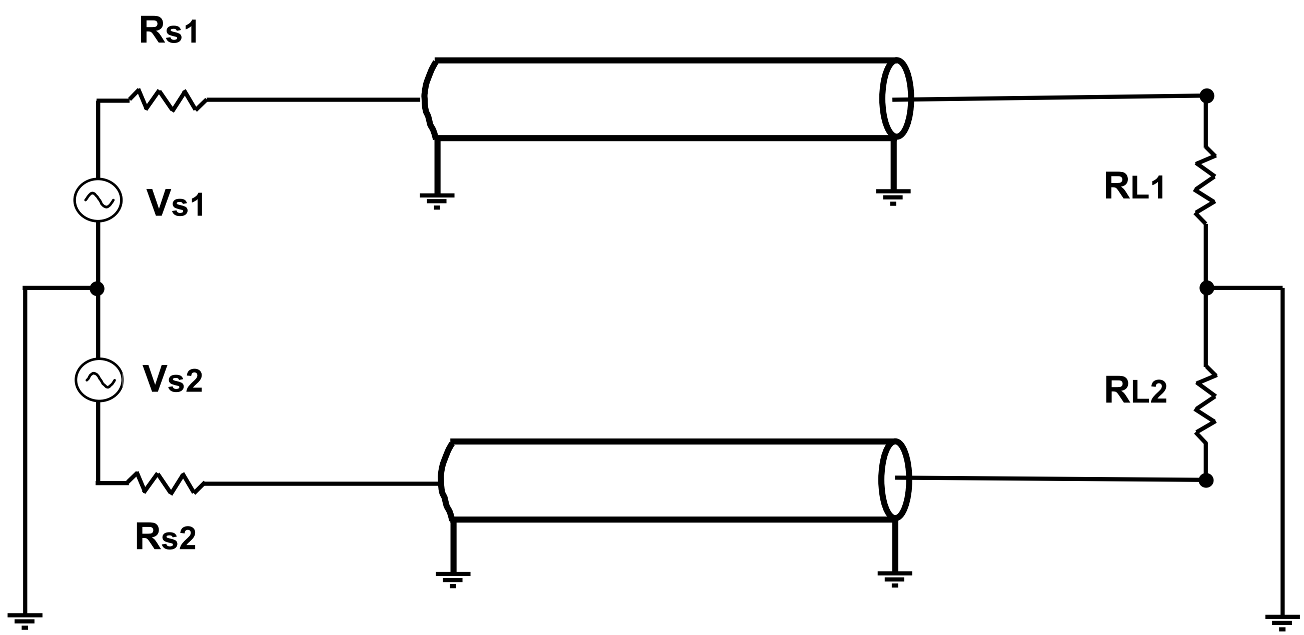
CMRR = 1,000 or 60 dB

HOC
ELECTROMAGNETIC COMPATIBILITY

TWISTED PAIR WIRING

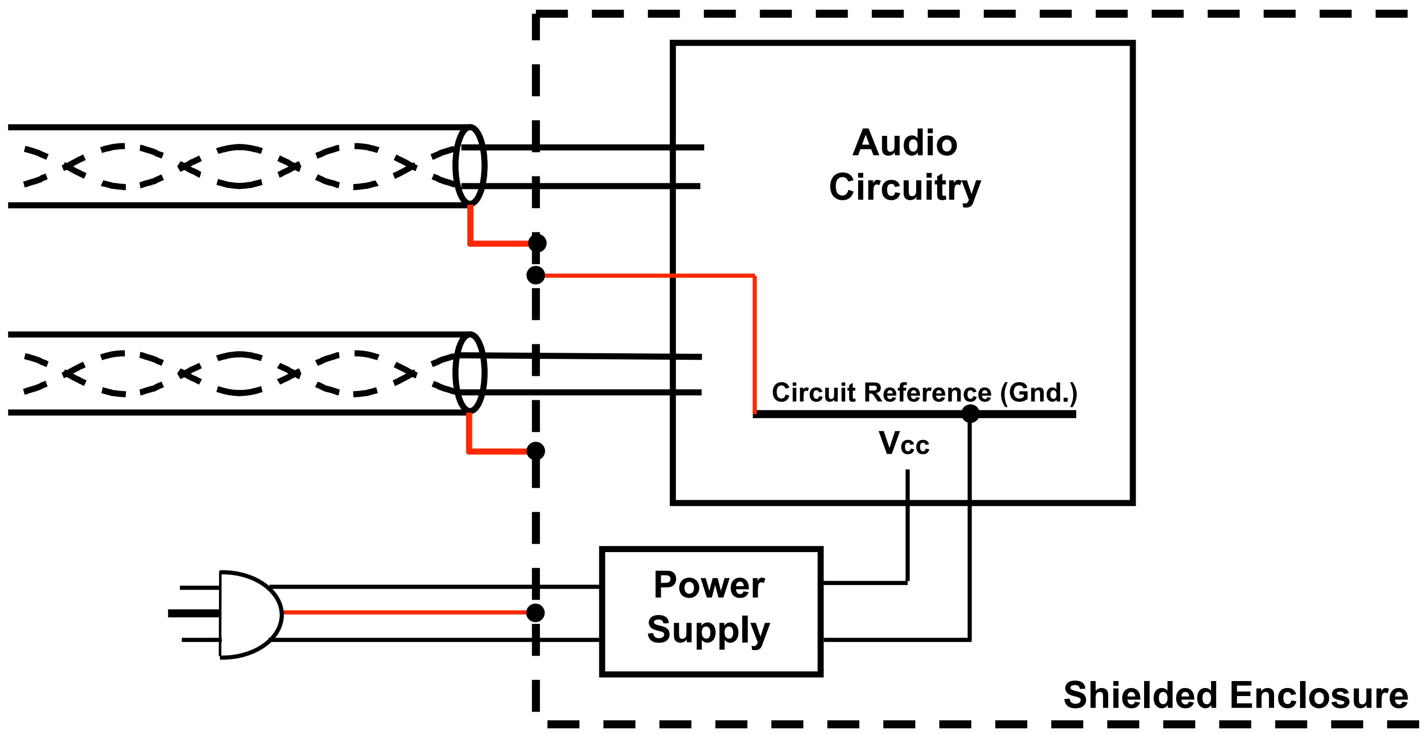
- Twisted Pair Wiring, Even When Unshielded, is Very Effective in Reducing Magnetic Field Coupling
- Two Necessary Conditions
  - Signal Must Flow Equally & in Opposite Directions in the Two Conductors
  - The Pitch of the Twist Must be Less Than 1/20 Wavelength (One Twist per Inch Will be Effective Up to 500 MHz)
- The Above is True Whether the Terminations are Balanced or Not
- If the Terminations are Balanced, Twisted Pair Wiring Will Also be Effective in Reducing Electric Field Coupling
- Do Not Confuse Twisted Pair Wiring With Balancing, They Are Two Different Things, Although Often Used Together

USE OF UNBALANCED CABELS IN A BALANCED CIRCUIT



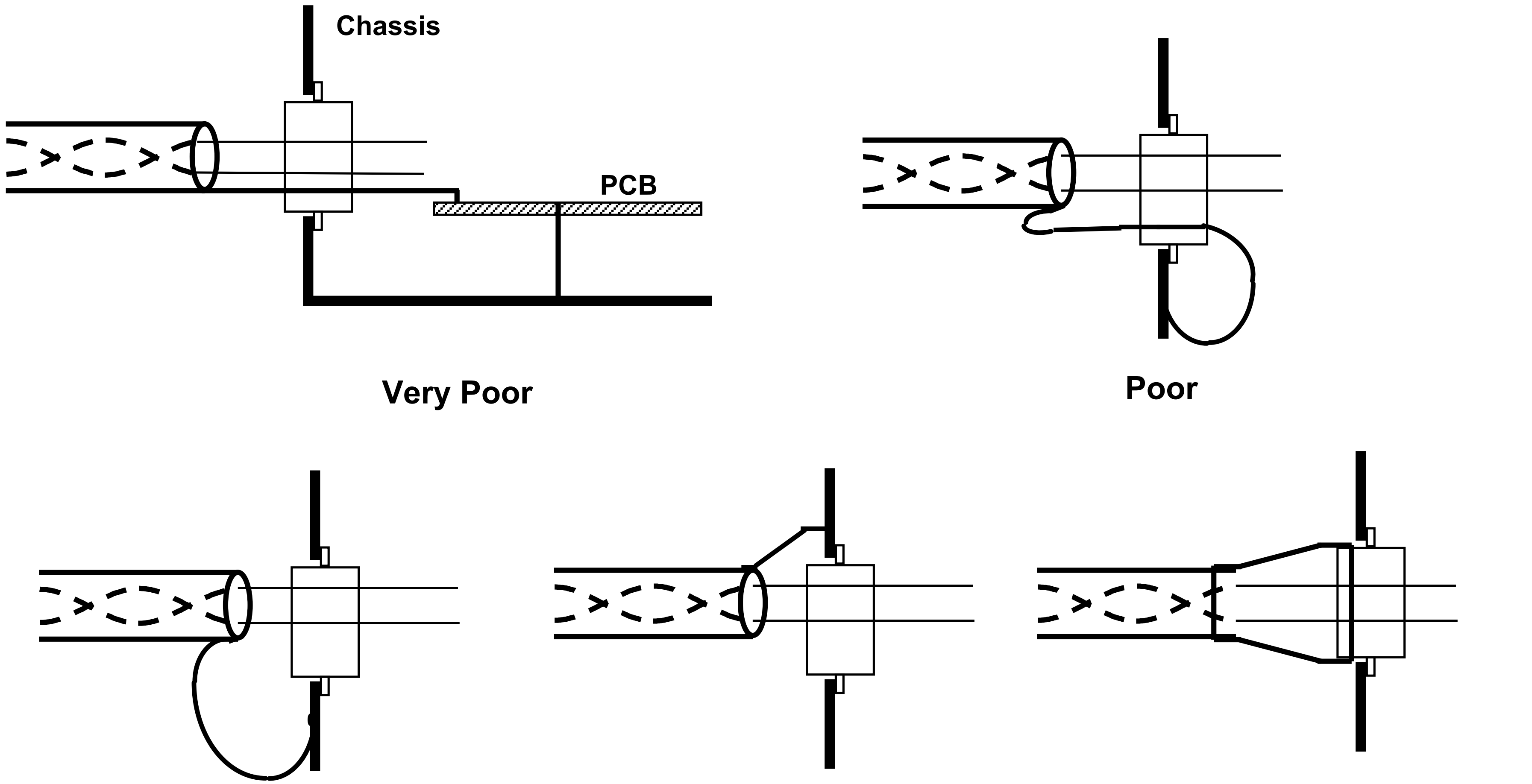
Twisted Pairs or Shielded Twisted Pairs Are Usually Used in Balanced Circuits, Since a Twisted Pair is Inherently a Balanced Configuration.
A Coaxial Cable is Inherently an Unbalances Structure But Can Still Be Used In a Balanced System if Properly Configured as Shown Above.

CABLE SHIELD TERMINATIONS TO A SHIELDED ENCLOSURE



Think of Cable Shields as an Extension of the Shielded Enclosure, and Therefore, They Should be Connected DIRECTLY to The Enclosure With a 360º Termination.

CABLE SHIELD TERMINATION METHODS



Very Poor

Poor

Better (Long Pigtail)

Good (Short Pigtail)

Best (360º Shield Connection)

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COMPATIBILITY

IMBALANCE IN A BALANCED SYSTEM

- In An Ideal Balanced System, No Noise Will Couple Into the Circuit.
- In the Real World, However, Small Unbalance Will Limit the Noise Suppression Possible. These Include:
  - Load Imbalance
  - Source Imbalance
  - Cable Imbalance
- Cable Imbalance
  - Resistive Unbalance (Usually Negligible)
  - Capacitive Unbalance (Typically 3 to 5%)
  - Inductive Unbalance
    - » Improper Shield Termination (Non 360º Contact)
    - » Common in Foil Shielded Cables Due to the Drain Wire Current
    - » Virtually Nonexistent in Braid Shielded Cables @ High Frequencies (> 100 kHz), if Properly Terminated

SLIDES FOR PRESENTATION AVAILABLE AT:

www.hottconsultants.com/pdf_files/aes-2007.pdf

BIBLIOGRAPHY

- Ott, H. W., *Noise Reduction Techniques in Electronic Systems*, Second Edition, John Wiley & Sons, 1988.
- AES48-2005, *Grounding and EMC Practices - Shields of Connectors in Audio Equipment Containing Active Circuitry*, Audio Engineering Society, 2005.
- Muncy, N. A., "Noise Susceptibility in Analog and Digital Signal Processing Systems, *Journal of the Audio Engineering Society*, June 1995.
- Whitlock, Bill, "The Mixed Marriage," *Live Sound International*, July 2007.
- RaneNote 110, *Sound System Interconnection*, Rane Corporation, 1995.
- RaneNote 151, *Grounding and Shielding Audio Devices*, Rane Corporation, 1995, 2002.
- Ott, H. W., "Ground - A Path for Current Flow," *1979 IEEE International Symposium on EMC*, San Diego, CA, October 9-11, 1979.

BIBLIOGRAPHY (CONT.)

- Ott, H. W., *Balanced vs. Unbalanced Audio System Interconnections,* www.hottconsultants.com/tips.html, 2005.
- Brown J. and Whitlock, B., *Common-Mode to Differential-Mode Conversion in Shielded Twisted-Pair Cables (Shield Current Induced Noise)*, Audio Engineering Society 114 Convention, 2003.
- Whitlock, B., *Understanding, Finding, & Elimination Ground Loops in Audio & Video Systems*, www.jensen transformers.com/an/generic%20seminar.pdf, 2005.
- Whitlock, B., Jensen System Troubleshooting Guide, www.jensentransformers.com/apps_wp.html, 1999.
- Whitlock, B., "Balanced Lines in Audio Systems: Fact, Fiction, and Transformers," *Journal of the Audio Engineering Society*, June 1995.