Audio Engineering Society
Conventions and Conferences

Tutorial T-2

An Overview of Audio System Grounding & Shielding

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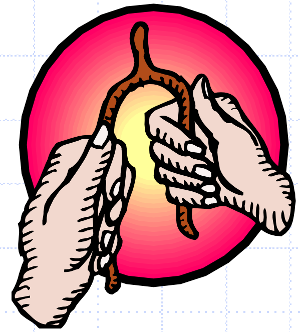
So Many Myths



- Look for **MYTH** alerts …
- Topic has "BLACK ART" reputation
- Basic rules of physics are routinely overlooked, ignored, or forgotten
- Manufacturers often clueless – don't know ground loops from

The Physics Police Rule!

The Electrical Environment

- Regulations protecting us from electrocution and fire also play a big role in noise problems
- NEC or "Code" requires 120-volt ac power distribution via a 3-wire system
- **Safety Grounding** electrically interconnects conductive objects to keep voltages between them safe, *even if equipment fails …*
- Neutral (white) and safety ground (green) are bonded together at service entrance only

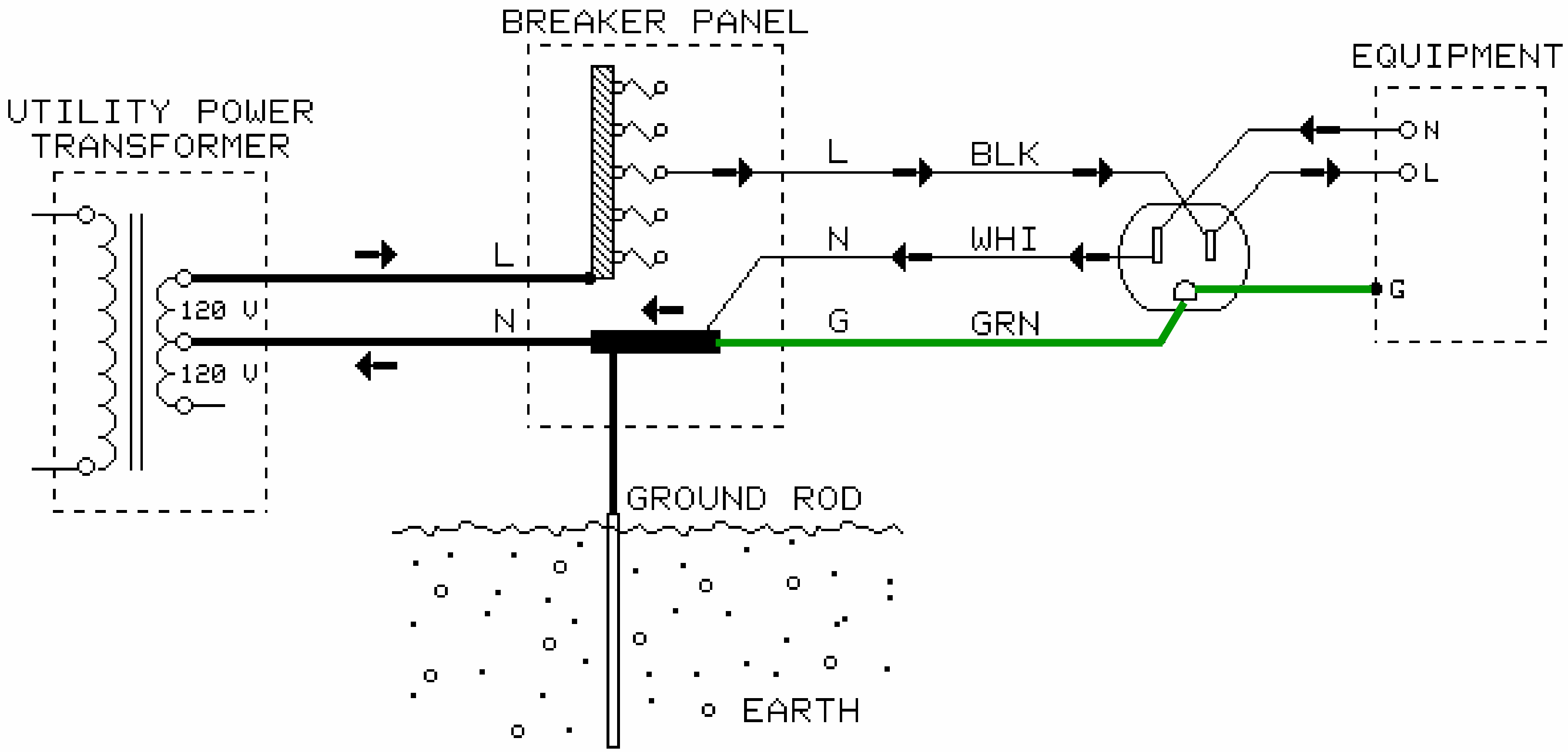
What is Grounding?

- **Electrical power**: an interconnection of exposed conductive objects to minimize voltage differences between them
- **Electronics**: a return path for current
- **Current *always* returns to its source** whether via an intentional or accidental path — *electrons don't read schematics!*

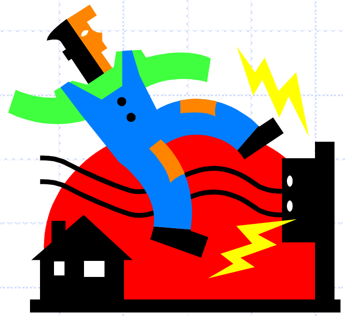
The 3-wire System

- One incoming service wires, often bare, is the *grounded* or "neutral" conductor
- NEC requires 120-volt ac power distribution via the 3-wire system
- Neutral (white) and "line" (black) are part of the normal *load* circuit
- Neutral and "grounding" (green) are bonded to ***each other*** and to earth ground at service entrance

Normal Load Current in Branch Circuit

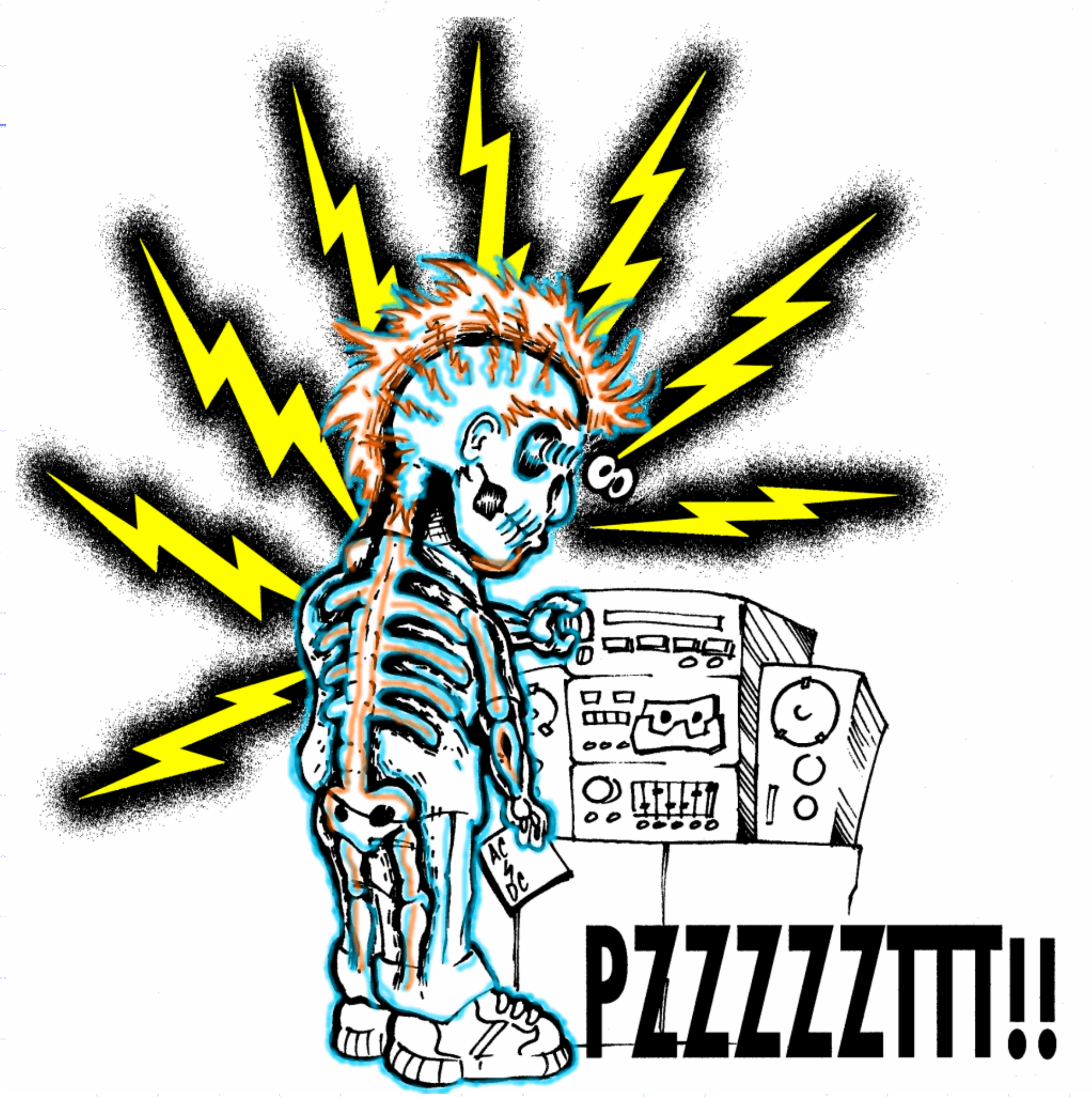


Deadly Equipment

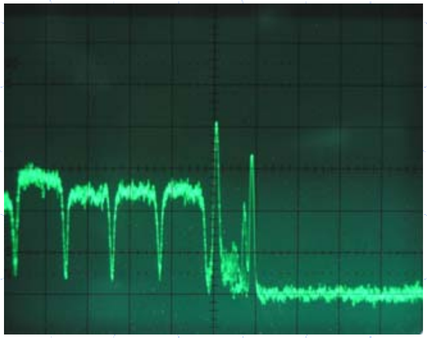


- Equipment can become a shock/electrocution hazard if its internal insulation fails
- Such a defect can make the entire device "live" at 120 volts and is called a **FAULT**
- Without a safety ground, these failures can shock or electrocute people or start fires!
- Signal cables conduct 120 volts – one FAULT can turn an entire system into a shock hazard

Don't Electrocute System Users!!



Shock and Electrocution

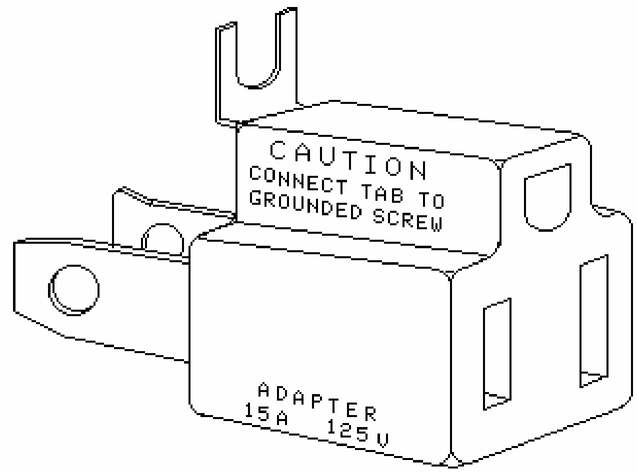


- CURRENT determines severity
  - Under 1 mA causes just an unpleasant "tingling"
  - About 10 mA causes involuntary muscle contraction and "death grip" or suffocation if through chest
  - Over 50 mA through chest can induce ventricular fibrillation – causing brain death minutes later
- Dry skin has high resistance – keeping current low when lightly touching a 120-volt wire
- Skin moisture, larger contact area, or increased pressure will substantially increase current
- Always respect the dangers of electricity!

DON'T BET YOUR LIFE!

NEVER, EVER defeat safety grounding to solve a noise problem!

This adapter is intended to **PROVIDE** safety grounding for a 2-prong receptacle
(via its cover mounting screw, metallic saddle, J-box, and conduit back to breaker box)



GFCI for Safety

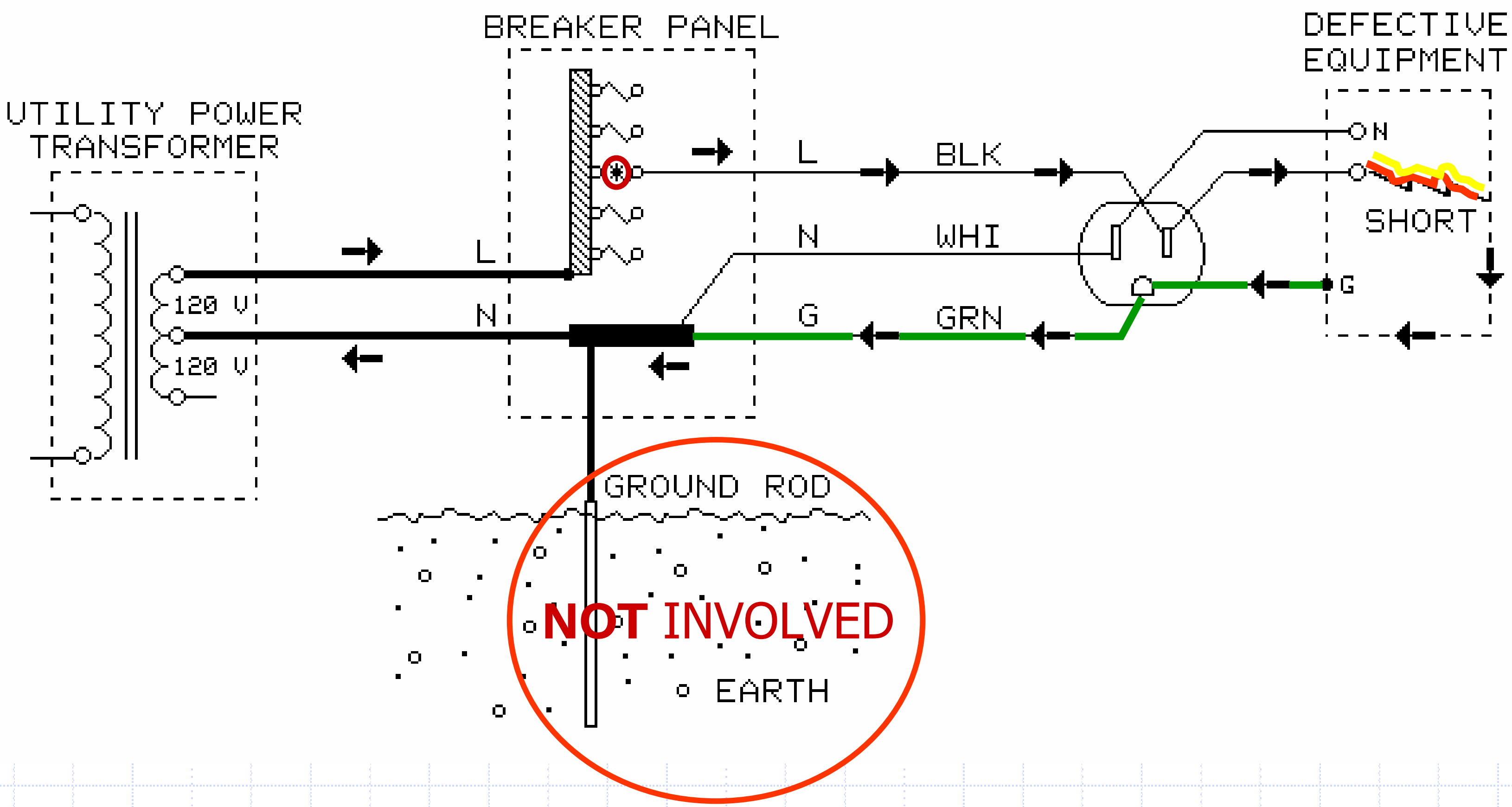
- Ground-fault circuit interrupter or GFCI does not require ground
- Senses difference between line and neutral current

- Difference is current ***not*** returning in neutral
- Presumed to be flowing through a person
- Trips at 4 to 7 mA
- GFCI shown has a retractable ground pin
- Nuisance trips may be a problem

MYTH: Safety Grounds Work Because of Earth Grounding

- Safety ground is bonded to **NEUTRAL** at main entry panel
- This low-impedance circuit allows high fault current, tripping breaker quickly
- Earth ground does **NOT** play a role!

Fault Current Trips Circuit Breaker



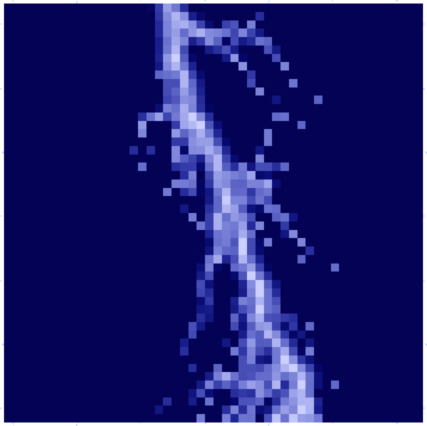
Consider Signal Cables

- Can distribute lethal voltage from “lifted” faulty device throughout entire system, or
- High fault current may flow through ***signal*** cable to reach grounded device, causing fire
- Defeating safety grounding is both dangerous and illegal — it also makes you legally liable!
  - Judge won’t care how your “fix” solved problem

Typical Statistics for USA

- Consumer audio/video equipment causes 10 ***electrocutions*** and 2,000 residential ***fires*** every year
- Fires result in 100 civilian ***injuries***, 20 ***deaths***, and over $30 million in property losses

Earth Ground is for LIGHTNING



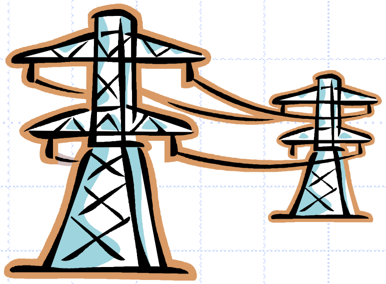
- Power lines become targets of …
- Before Code, power lines literally guided lightning into buildings!
- Outdoor power lines grounded at intervals
- Impedance of ground rod at service entrance is <25 Ω, sufficient to limit lightning damage
- Protection of phone and CATV lines, where they enter building, is also required by Code

Bond Added Ground Rods

- During actual strike, thousands of volts can develop between separate rods!
  - Consider computer modem bridging power and telephone lines
- Code requires that all other protective grounds be bonded to the utility power grounding electrode

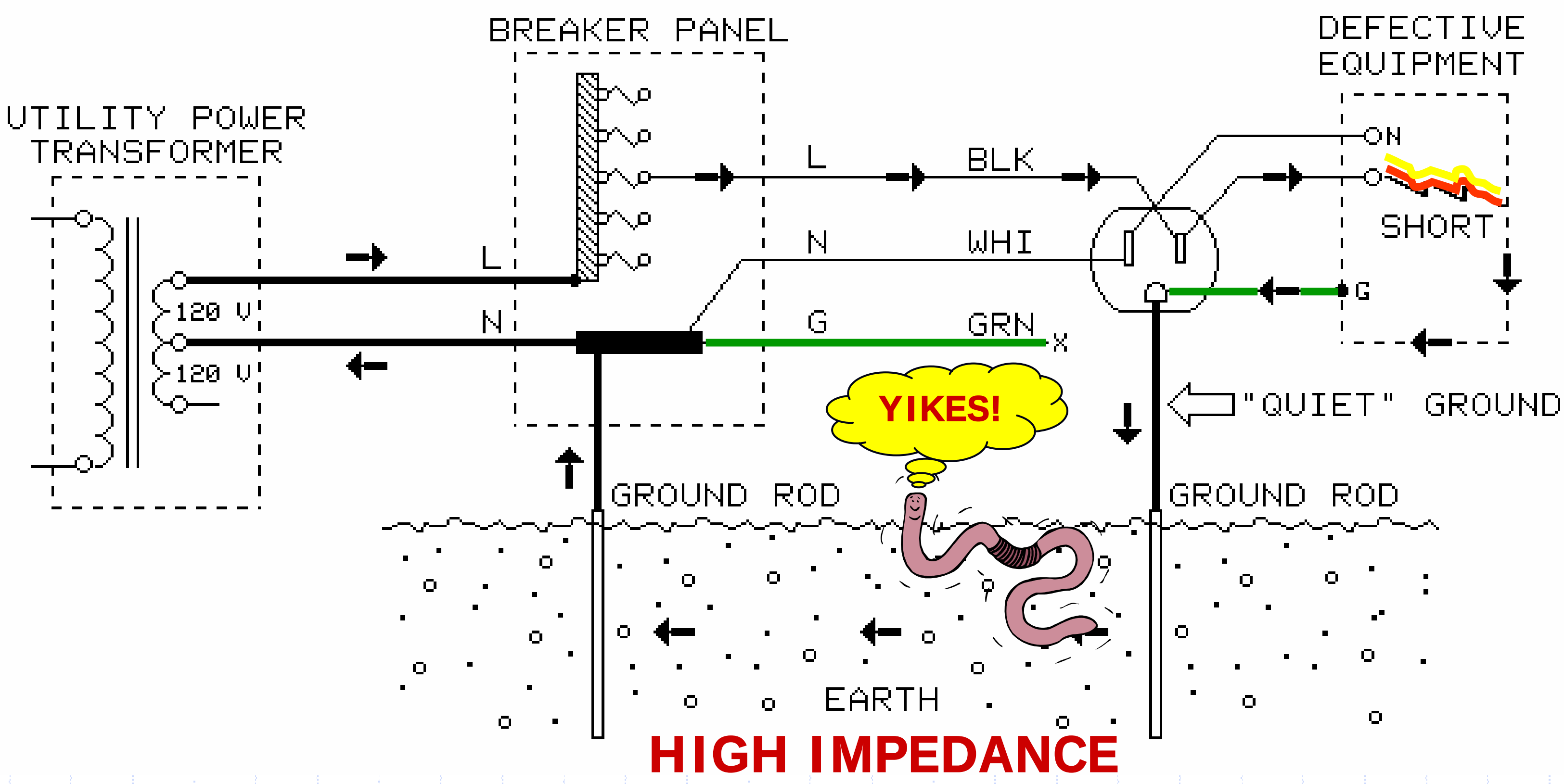
MYTH: Earth Ground = Zero Volts

- NOT with respect to each other or some mystical "absolute" reference point
- Other nearby ground connections create soil voltage gradients



- "Those looking for a better earth or better ground to solve a noise problem are looking for pie in the sky." Ralph Morrison

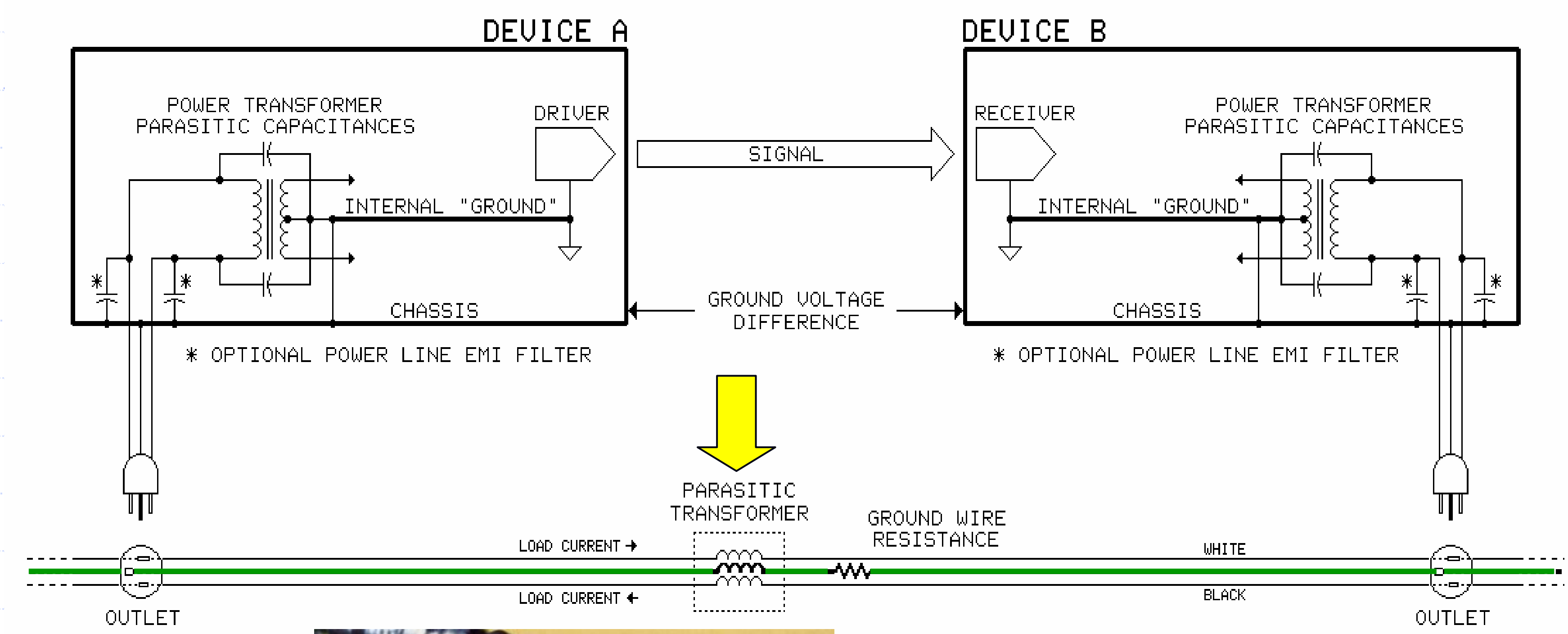
Ground Rod is Useless for Fault Currents

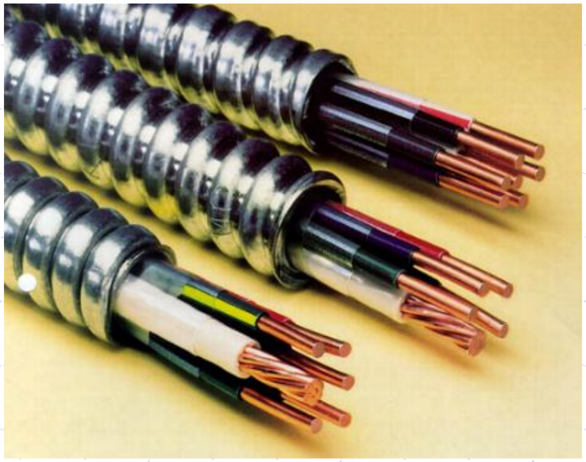


MYTH: Most Noise is Caused by "Improper" AC Power Wiring

- Small voltages between outlet safety grounds is **NORMAL** in proper wiring
  - Parasitic transformer effects in wiring
  - Lowest between nearby outlets on the same branch circuit
  - Highest (up to a few volts) between distant outlets on different branch circuits
- INTERFACE problems cause the NOISE!

The Parasitic Transformer





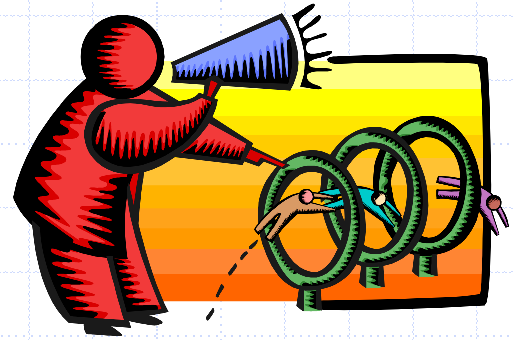
Load current magnetically induces voltage in ground wiring between outlets

Copper Institute

The Parasitic Transformer

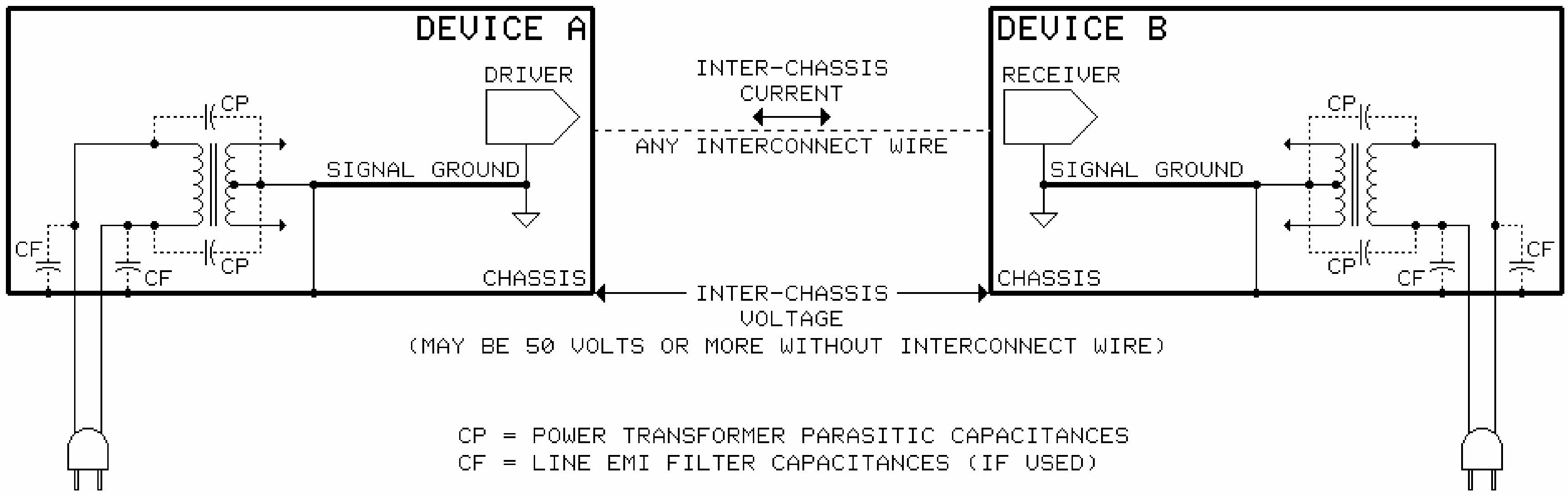
- Load current in line and neutral produce equal but opposing magnetic fields
- Imperfect cancellation *magnetically induces* voltage in safety ground conductor
  - Highest voltages with loose wires in steel conduit
  - Lower voltages with uniform geometry of Romex®
- 1 volt difference between outlets not unusual
- Proportional to load current

About 2-prong Plugs



- UL approval requires extraordinary protection
  - Must remain safe in spite of component failure, overload, and rough handling
- Chassis voltage can approach 120 volts but current is limited by parasitic capacitances
  - 0.75 mA maximum for consumer electronics
- This "**LEAKAGE**" current will flow in signal cables connected to other equipment

Equipment with 2-prong Plugs



LEAKAGE current flows in signal cables between devices with 2-prong ac plugs

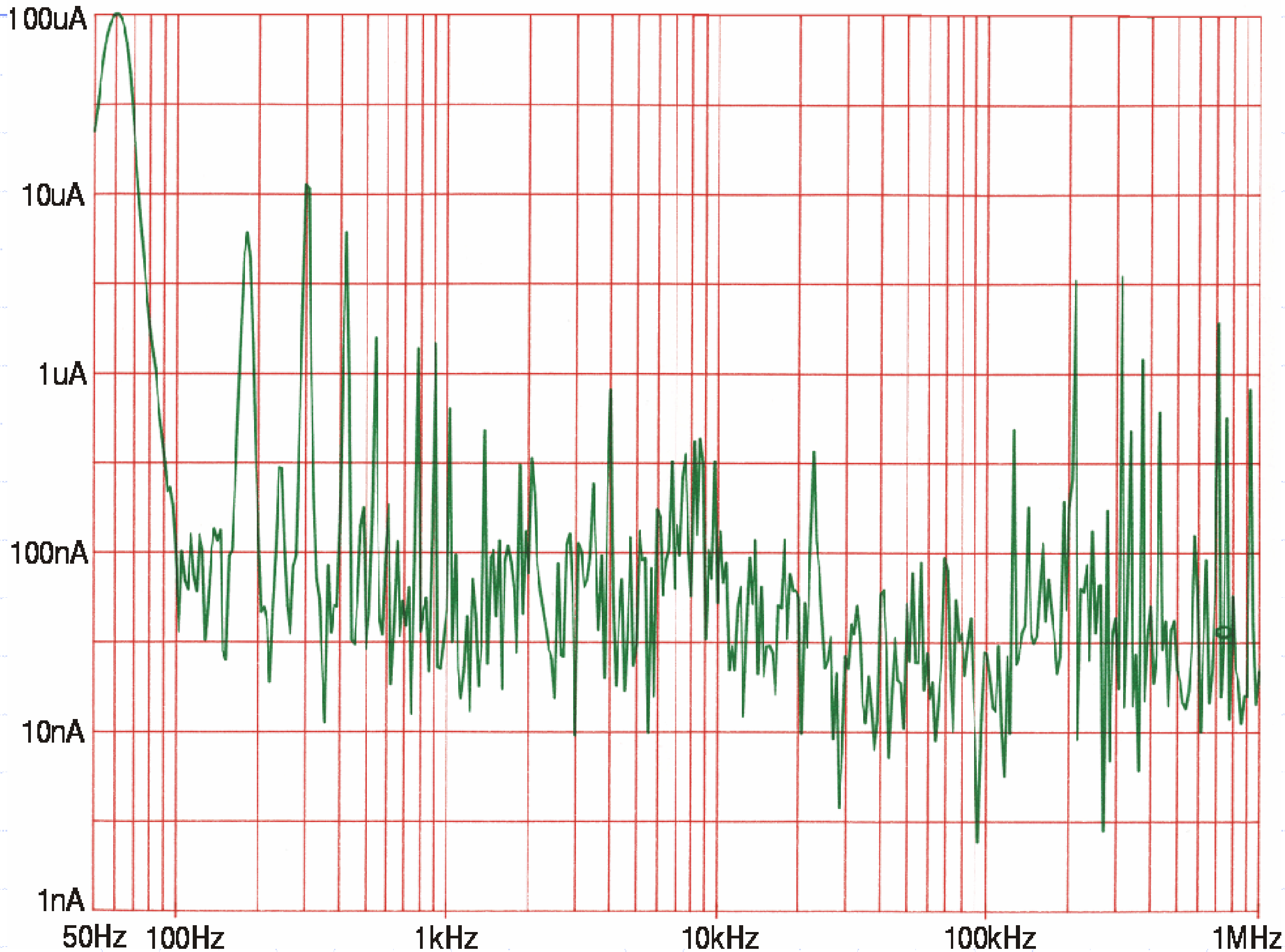
The Facts Of Life

- Ground voltage differences will ALWAYS exist between outlets
- Leakage currents will ALWAYS flow in signal cables
- **COUPLING** allows them to enter the signal path and is the REAL problem!

It’s Not Just 60 Hz

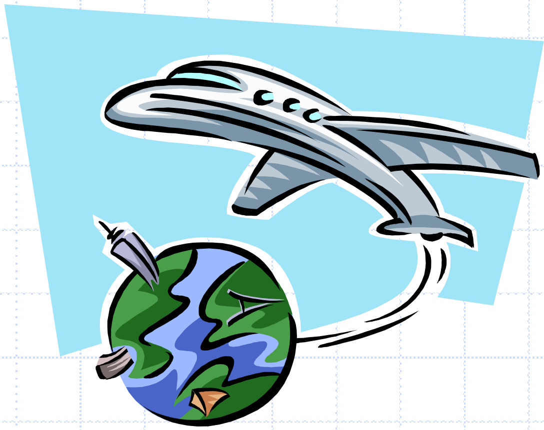
- Many, if not most, loads draw current non-uniformly during each cycle
- Waveform distortion = 2% to 6% THD
- Higher frequencies generated by abrupt current changes (as in light dimmers)
- Power wiring “rings” and reflects energy throughout building

Typical Leakage Current Spectrum



MYTH: These Voltages and Currents can be Eliminated

- "SHORT 'EM OUT" with massive copper bus bars
- Experiment to find a "better" or "quieter" ground
- Route noise to an **earth** ground where it disappears
- Make the electrician fix "his" problem
- Install equipment to "purify" the "dirty" ac power
- Does an earth ground really stop noise? Think about all the electronics in a 747 ...

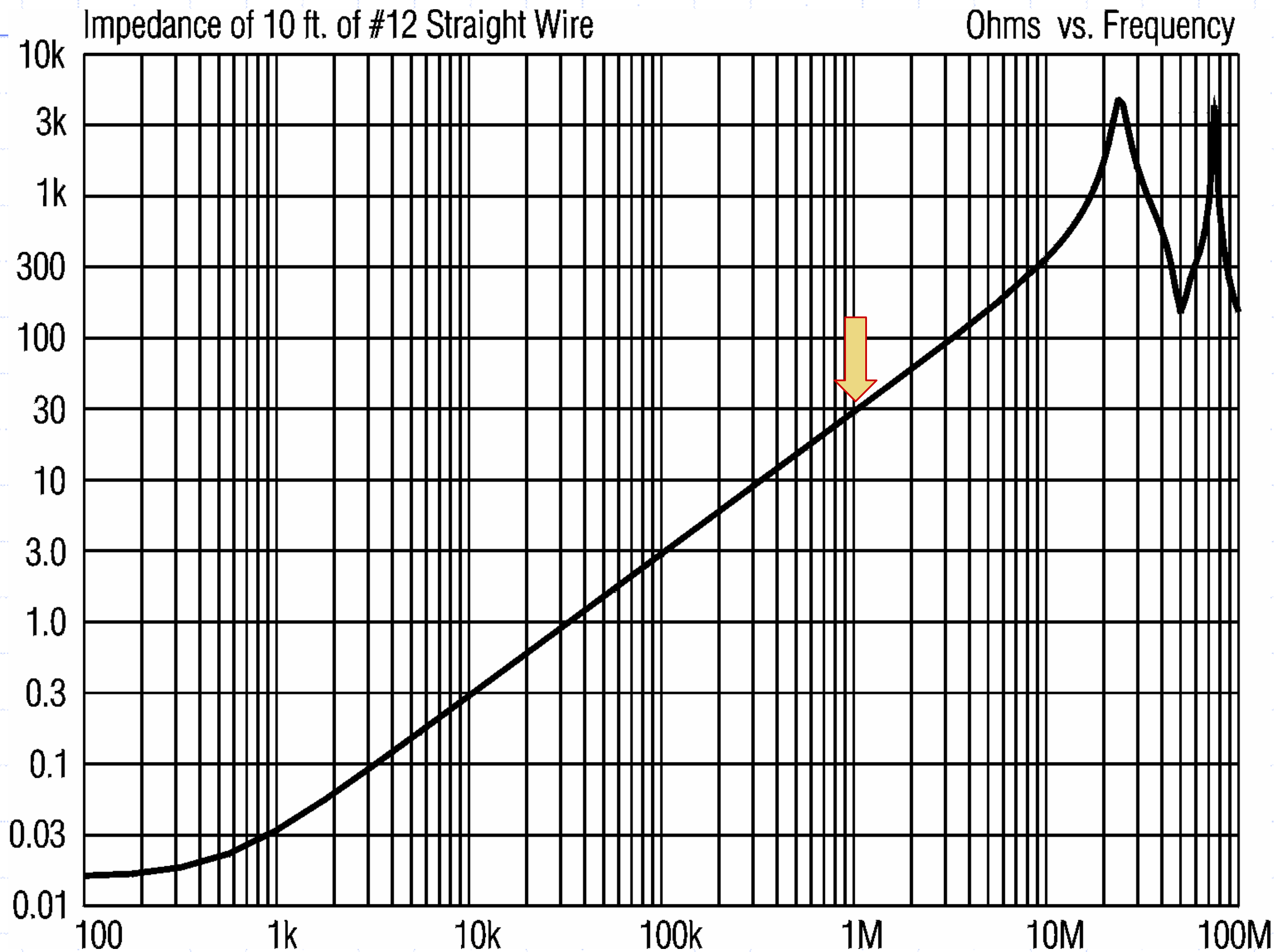


MYTH: Wire "Shorts Out" Voltage

- DC **resistance** is directly proportional to length and applies only at low frequencies
  - 0.015 Ω for 10 feet of #12 AWG example
- **Inductance** is directly proportional to length and nearly independent of its diameter
  - 4.8 μH for example (straight)
  - Increases substantially at bends

Wire Impedance vs Frequency

For comparison, ½-inch copper rod = 25 Ω at 1 MHz



Think "Outside the Box"

- **SIGNALS** accumulate **NOISE** as they flow through a system
- Removing noise without altering/degrading the signal is essentially impossible
- Entire signal path must prevent noise coupling
- Signal **INTERFACES** are the danger zone, rather than the equipment itself
- *"A cable is a source of potential trouble connecting two other sources of potential trouble."*

What's an Interface?

- Signal transport sub-system consisting of a line **DRIVER** (output), the **LINE** or cable, and a line **RECEIVER** (input)
- **TWO** conductors are always required to complete a signal (or any) current path

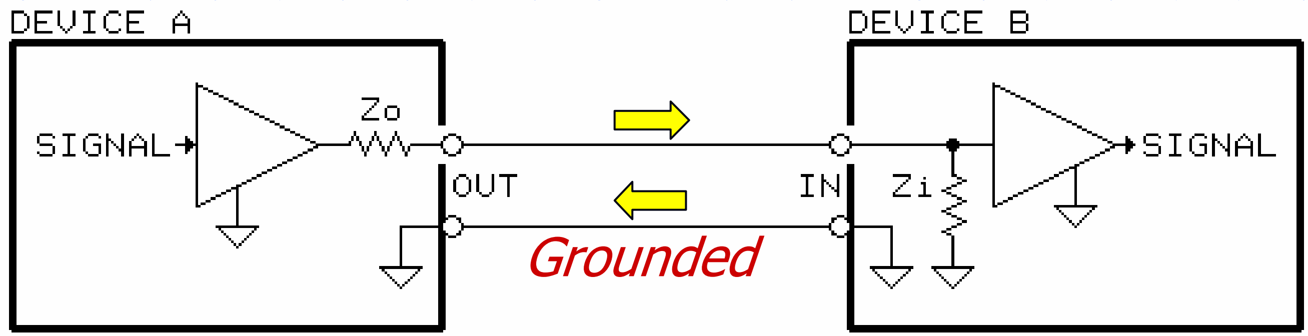
What's Impedance?

- The apparent resistance to current flow in an AC circuit – *the functional equivalent of resistance in a DC circuit*
- Symbolized **Z** and measured in ohms

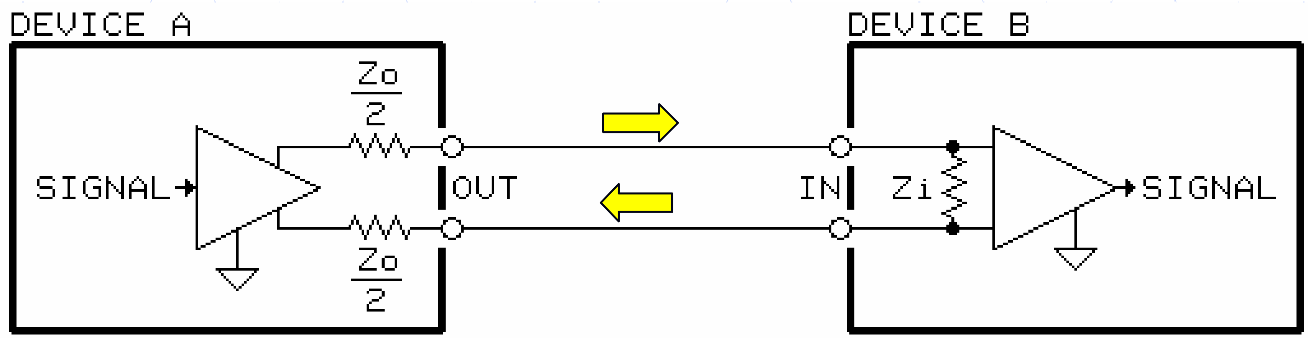
Balanced and Unbalanced

- Status depends **ONLY** on the **IMPEDANCES** (to ground) of the two signal conductors
- In <u>un</u>balanced interface, one line has **zero** impedance (grounded) and other has some higher impedance
- In balanced interface, both have nominally **equal** impedances
  - Requires that driver, line, and receiver <u>each</u> maintain equal impedances

Unbalanced vs Balanced Interfaces



Unbalanced



Balanced

Driver & Receiver Impedances

- Every **driver** has an internal impedance called **output impedance**, shown as Zo
  - Real outputs can't have zero output impedance, but lower is better
  - Not to be confused with **load** impedance!!
- Every **receiver** has an internal impedance called **input impedance**, shown as Zi
  - Real inputs can't have infinite input impedance, but higher is better

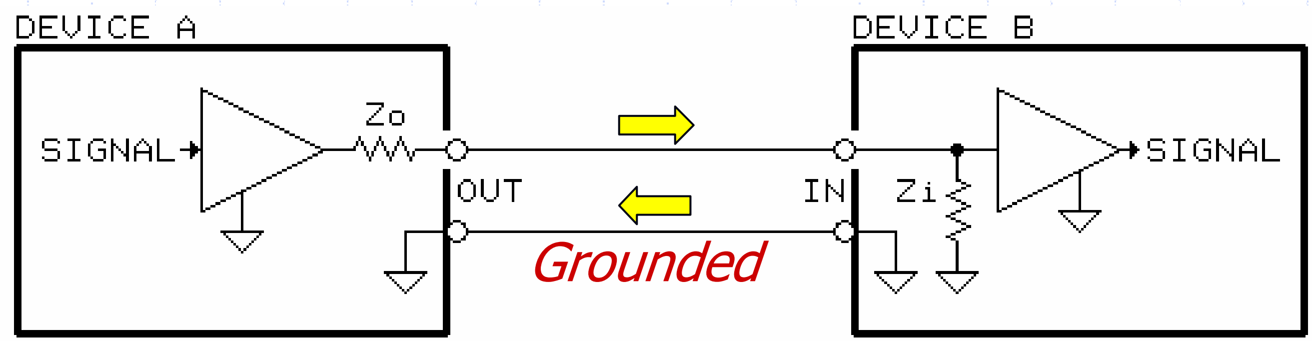
MYTH: Impedance Implies Level

- Signal level, impedance, and balance are completely <u>independent</u> of each other:
  - Pro Mic out = lo-Z, lo-level, balanced
  - Pro Line out = lo-Z, hi-level, balanced
  - Consumer/MI Line out = lo-Z, hi-level, unbalanced
  - Consumer Mic out = lo-Z, lo-level, unbalanced
  - Phono out = hi-Z, lo-level, unbalanced
  - Guitar out = hi-Z, hi-level, unbalanced

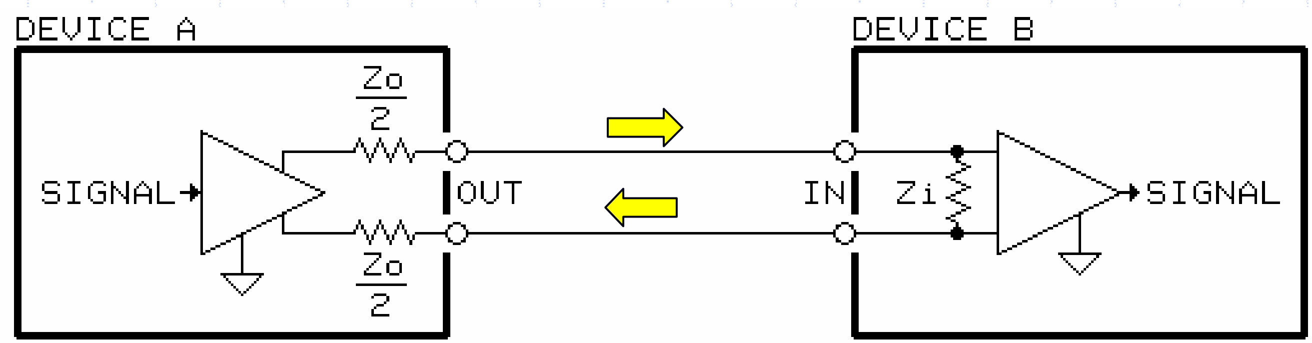
A Signal Voltage Divider

- Driver and receiver impedances Zo and Zi form **series circuit** called a voltage divider
- Voltage drops are proportional to impedance
- For maximum signal **voltage** at receiver, Zi must be much greater than Zo
- Typical audio interfaces transfer 90% to 99.9% of the available signal voltage

The Signal Voltage Divider



Unbalanced



Balanced

MYTH: Audio Inputs and Outputs Should Be "Impedance Matched"

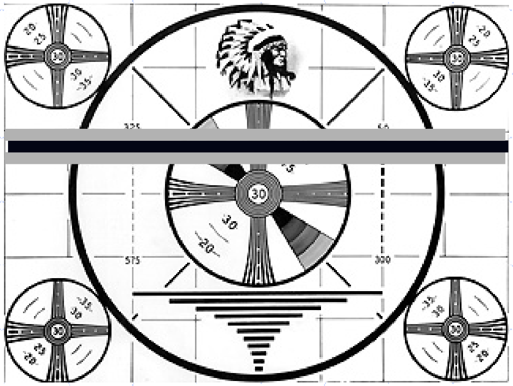
- Wastes half the signal voltage <u>and</u> places an unnecessarily heavy load on the driver!
- Transfers maximum **power** in vintage passive 600 Ω systems but <u>not</u> applicable to modern audio systems driven by signal **voltage**
- Higher frequency cables are terminated with the "characteristic impedance" of the cable to avoid "transmission line" effects
  - Characteristic impedance is that of an **infinite length** of cable and varies with construction

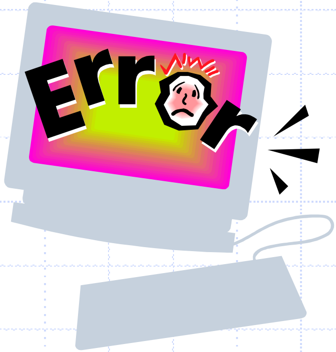
Termination for Video and RF

- "Transmission line" effects start to become significant when the physical length of a cable becomes ~10% of an electrical *wavelength*
- Applies to video cables over a few feet long and CATV cables over a few inches long
- To avoid video "ghosts," source and load impedances at physical ends must match the *characteristic impedance* of the cable
- For ***audio*** cables, termination is a concern only when cables are over 4,000 feet long!

UNBALANCED Interfaces

- **EXTREMELY susceptible to noise coupling!**
- Ironic that, after 50 years, they <u>remain</u> the norm in consumer and audiophile audio, even as dynamic range requirements have steadily increased
- **Video** interfaces (analog)
  - Coupling causes visible “hum bars”
- **RS-232** interfaces
  - Coupling causes “mysterious” problems



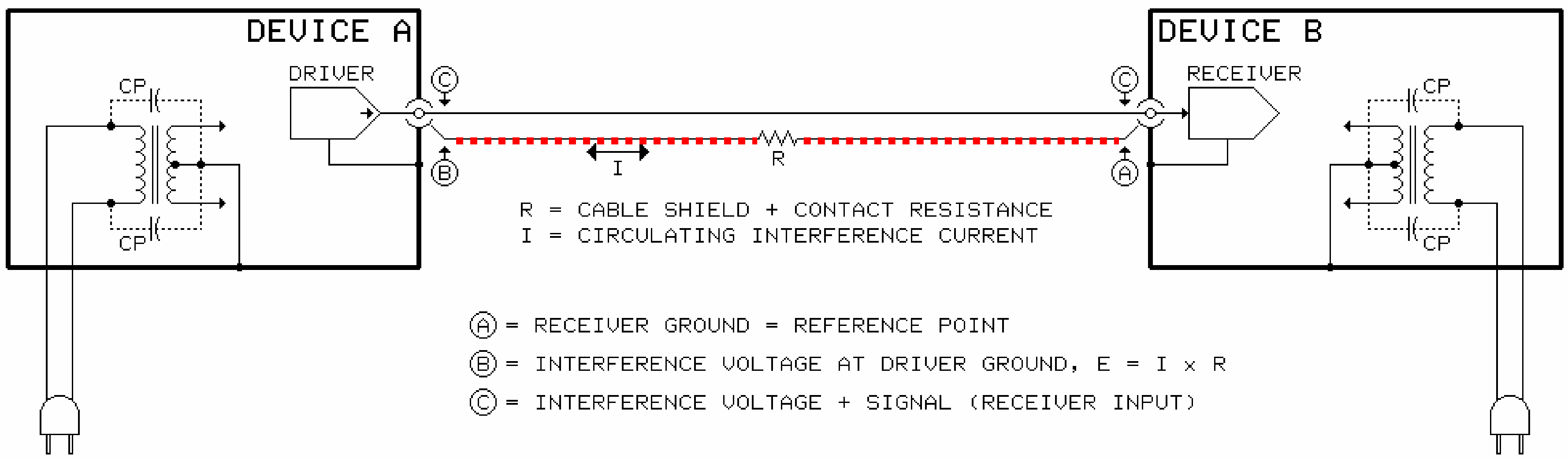


The Big Problem

- Leakage currents flow in signal cables
  - Virtually all in grounded conductor, typically the "shield," whose impedance is not zero
- Noise voltage generated over its length due to its resistance – Ohm's Law
- Noise **directly adds to signal** seen at receiver (voltages <u>add</u> in series circuit)

Common-Impedance Coupling

It's **NOT** about SHIELDING!



MYTH: Poor Shielding Causes Noise

- Common-impedance coupling causes 99% of noise problems in unbalanced interfaces
- Trivial noise contributor in modern systems
- Audiophile cables from famous maker, costing $80 to $500 per 1-meter pair, have no shield at all — wires are simply woven together!
- Shielding <u>can</u> be issue with old vacuum-tube equipment because of high Zo in drivers

A Real-World Example

- Assume 25-foot, foil-shield cable with #26 AWG drain wire, R = 1 Ω
- Assume leakage current between 2-prong (ungrounded) devices is 316 μA
- Noise voltage = 316 μV
- Consumer reference = 316 mV
- S/N ratio = 316 mV/316 μV = only 60 dB
- Belden #8241F cable, shield R = 0.065 Ω, would improve S/N by some 24 dB!

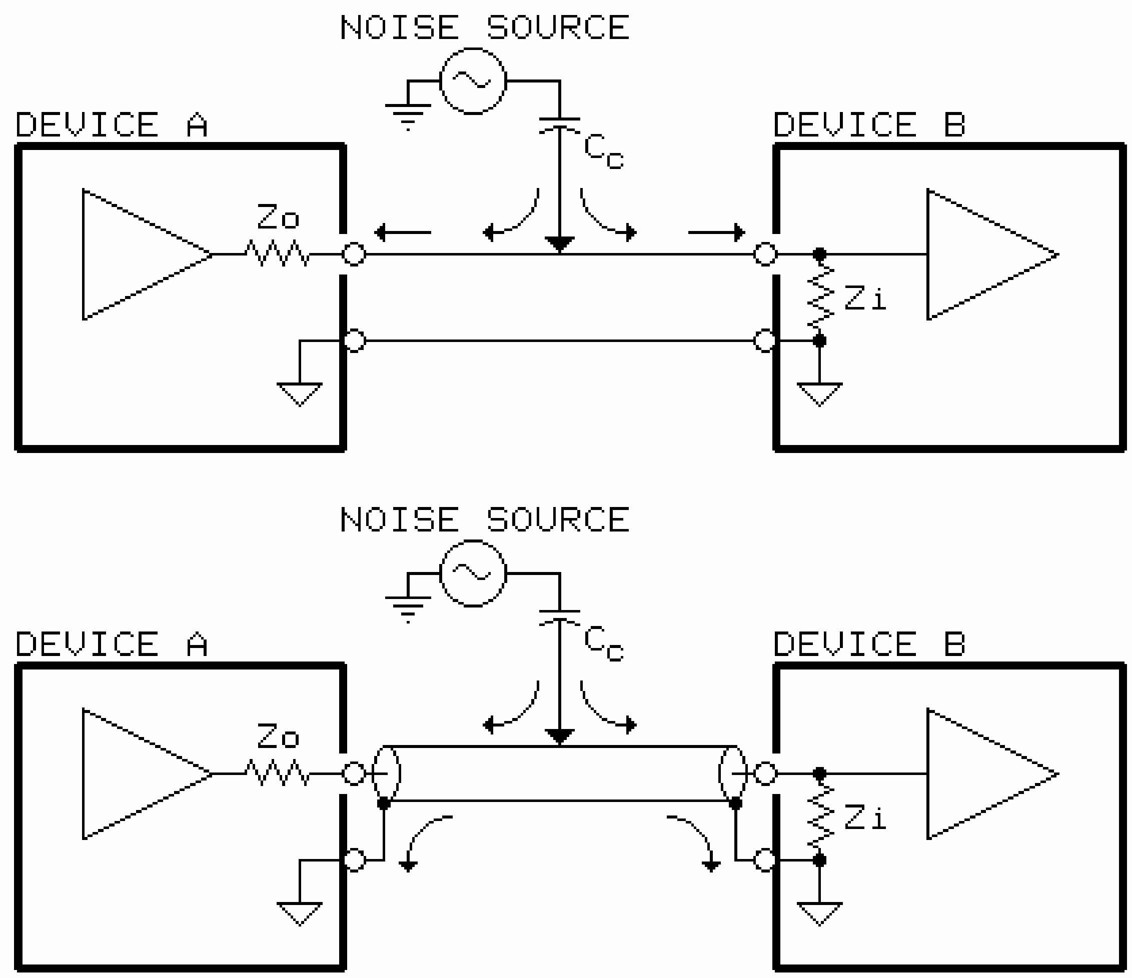
From Bad to Worse …

- When devices are grounded, often via other system cables, noise can become EXTREME!
  - When ground voltage difference of only 30 mV between outlets is impressed across length of cable, resulting S/N becomes only 20 dB
  - Huge problem in home theater systems having multiple ground connections – sub-woofers and projectors with 3-prong plugs, CATV, and satellite TV connections

Cable Shielding

- Shields prevent ONLY *electric* field coupling
- Electric fields produced by high ac voltages
- Capacitance Cc in space to offending source
- AC voltage causes current flow in Cc
- Without shield, current flows into signal line, creating a noise voltage
- Grounded shield diverts currents to ground

Electric Field Coupling



Shield "Coverage"

- Foil is usually 100% (optically opaque)
- Braided from 85% to 95% because of tiny openings — usually entirely adequate
- Problem only for very high-impedance line drivers – typical of some vacuum-tube gear
- Trivial issue in the vast majority of systems
  - Well-known maker offers several lines of cables, priced from $80 to $500 per 1-meter pair, which have *no overall shield* — wires are simply woven

Immunity to Magnetic Fields

- Regardless of cable construction, unbalanced interfaces **can't** fully nullify the effects
- Effective *magnetic* shielding, especially at power frequencies, is very difficult to achieve
- Only magnetic materials like steel conduit provide any significant shielding — ordinary cable shielding has <u>no</u> effect
  - More about this later (balanced interfaces)

Physics from Another Universe?

- Audio, especially "high-end," abounds with pseudo-science and mysticism
- Double-blind tests prove that audible differences among cables, *if they actually exist*, are entirely predictable
- Marketing hype* often invokes transmission line theory and implies that nano-second pulse rise-times are important
  - Audio cables only *begin* to exhibit such effects when they become about **4,000 feet** long!

** Hype: enthusiasm without knowledge*

MYTH: Exotic Cables Stop Noise

- Expensive cables, even if double or triple shielded, made of 100% unobtainium, and hand woven by virgins will have <u>no</u> significant effect on hum or buzz ……
- Only the resistance of the grounded conductor can make a difference!

Real Unbalanced Cable Issues

- Resistance of grounded conductor
  - 99% of problems are common-impedance coupling
- Capacitance
  - Affects signal bandwidth for long lengths
- Shielding
  - Affects only LF electric fields and RF
- Magnetic field immunity
  - Provided by coaxial or twisted construction

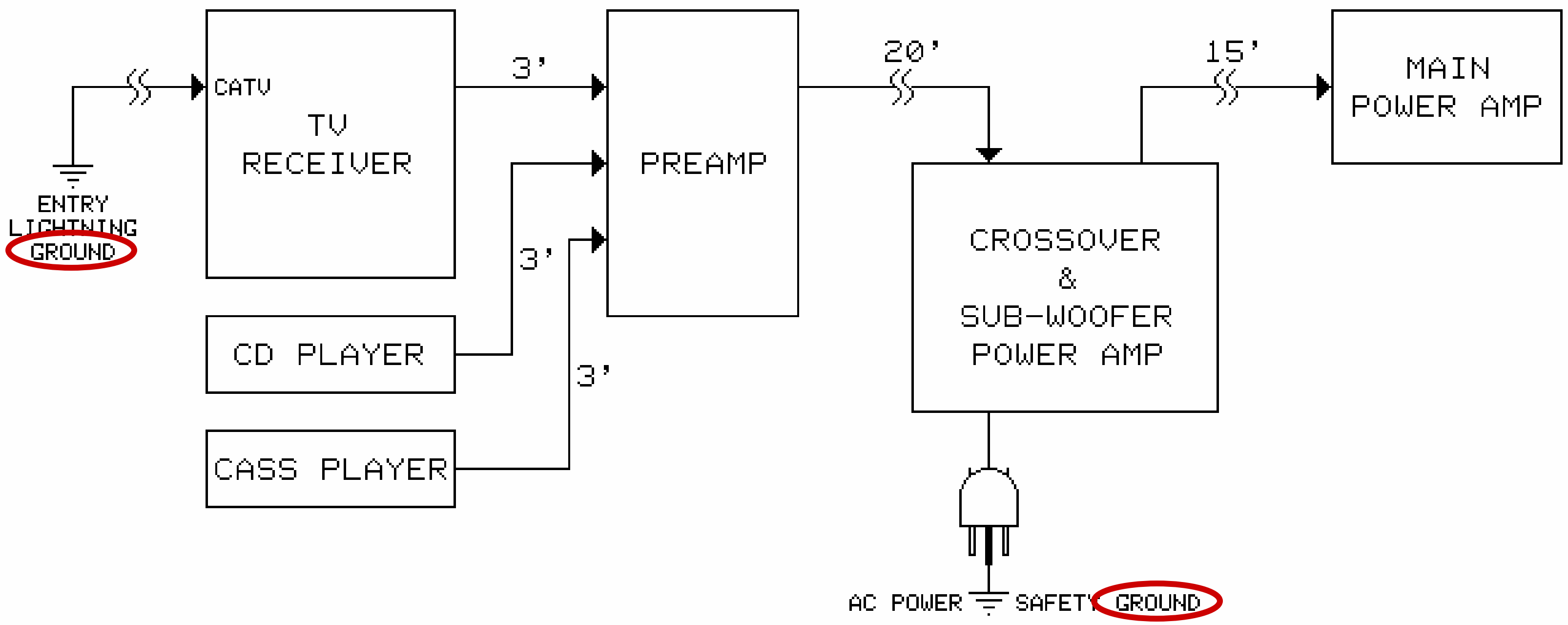
Troubleshooting

- Troubleshooting without ***method*** can be very frustrating and time-consuming
- Don't start by changing things!
- Ask questions – "Did it *ever* work right?"
- Equipment controls provide valuable clues
- Keep written notes, memory is less reliable
- Problems that go away by themselves also tend to come back by themselves

Draw a "One-Liner"

- Show <u>all</u> signal cables, including digital and RF, and indicate their approximate length
- Mark any balanced inputs or outputs Generally, show stereo pairs as a single line
- Note equipment grounded by its 3-prong power plug
- Note any other ground connections such as cable TV or DSS dishes

A Sample One-Liner



Work Backwards

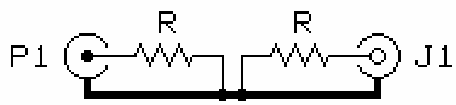
- Unless clues suggest otherwise, always begin at audio power amplifier inputs or video monitor inputs and test interfaces sequentially back toward signal sources
- **Remove any ground "lift" devices before you begin troubleshooting!**

Testing Audio Interfaces

- “Dummies” can locate noise coupling point
- Also reveal the nature of the problem:
  - Common-impedance coupling - unbalanced cables
  - Shield-current-induced coupling - balanced cables
  - Magnetic or electric field coupling in cables
  - “Pin 1 problems” in defective equipment

Building Audio "Dummies"

Unbalanced Interfaces



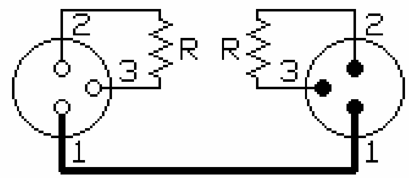
For Audio RCA

P1 = Switchcraft 3502 Plug
J1 = Switchcraft 3503 Jack
R = 1 kΩ, 5%, 1/4 W Resistor

For Audio 2C Phone

Use Switchcraft 336A and 345A
Adapters with RCA version

Balanced Interfaces



For Balanced Audio XLR

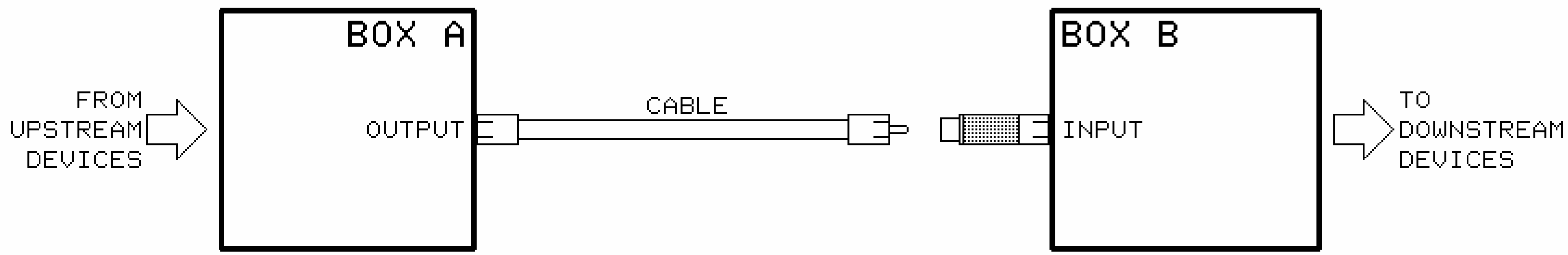
P1/J1 = Switchcraft S3FM Adapter
with QG3F and QG3M Inserts
R = 604 Ω, 1%, 1/4 W Resistor

For Balanced Audio 3C Phone

Use Switchcraft 383A and 387A
Adapters with XLR version

They do NOT pass signal
Don't leave one in a system!

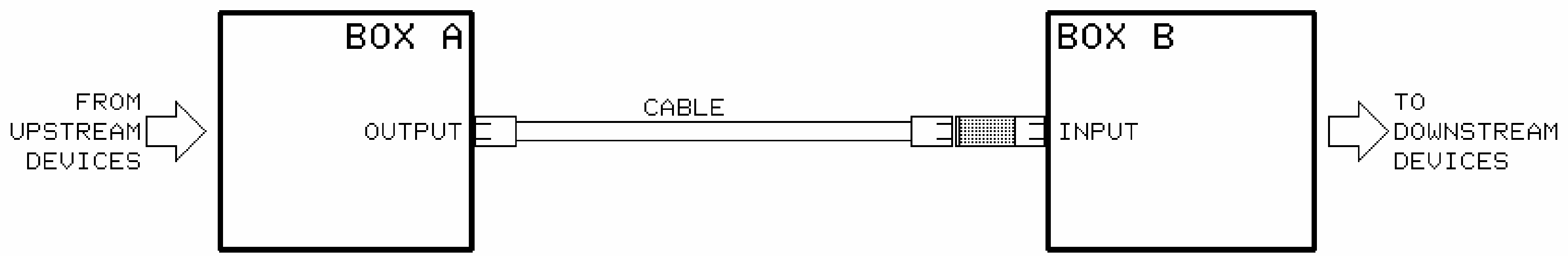
STEP 1



Unplug the cable from the input of Box B and plug in only the dummy

- **Noise** — problem in Box B or downstream
- **Quiet** — go to next step.

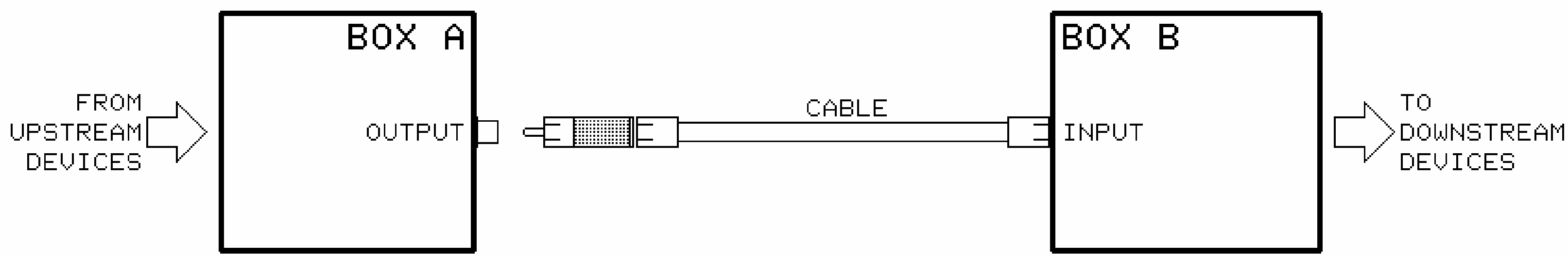
STEP 2



Leave the dummy at the input of Box B, plug the cable into the dummy

- **Noise** — Box B has a "pin 1 problem"
  Confirm with hummer test
- **Quiet** — go to next step

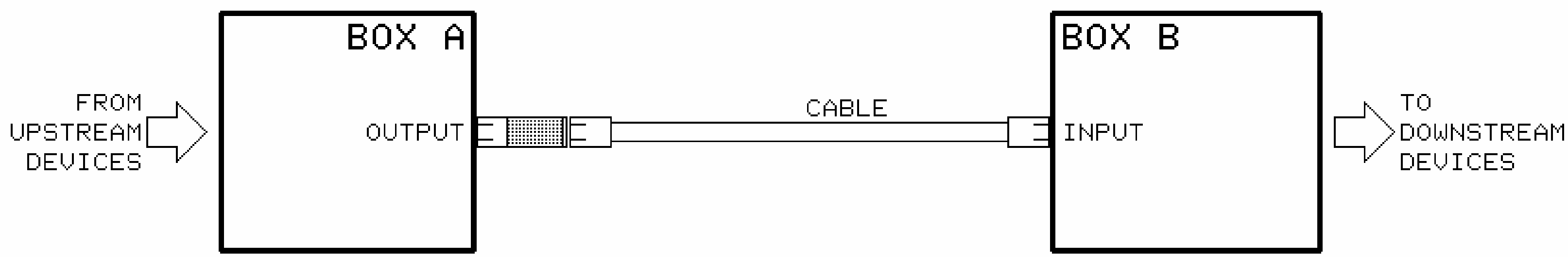
STEP 3



Remove dummy and plug cable into Box B input. Unplug cable from Box A output and plug into dummy. *Don't let dummy touch anything conductive.*

- **Noise** — magnetic or electric field induced noise. Re-route cable to avoid field.
- **Quiet** — go to next step.

STEP 4



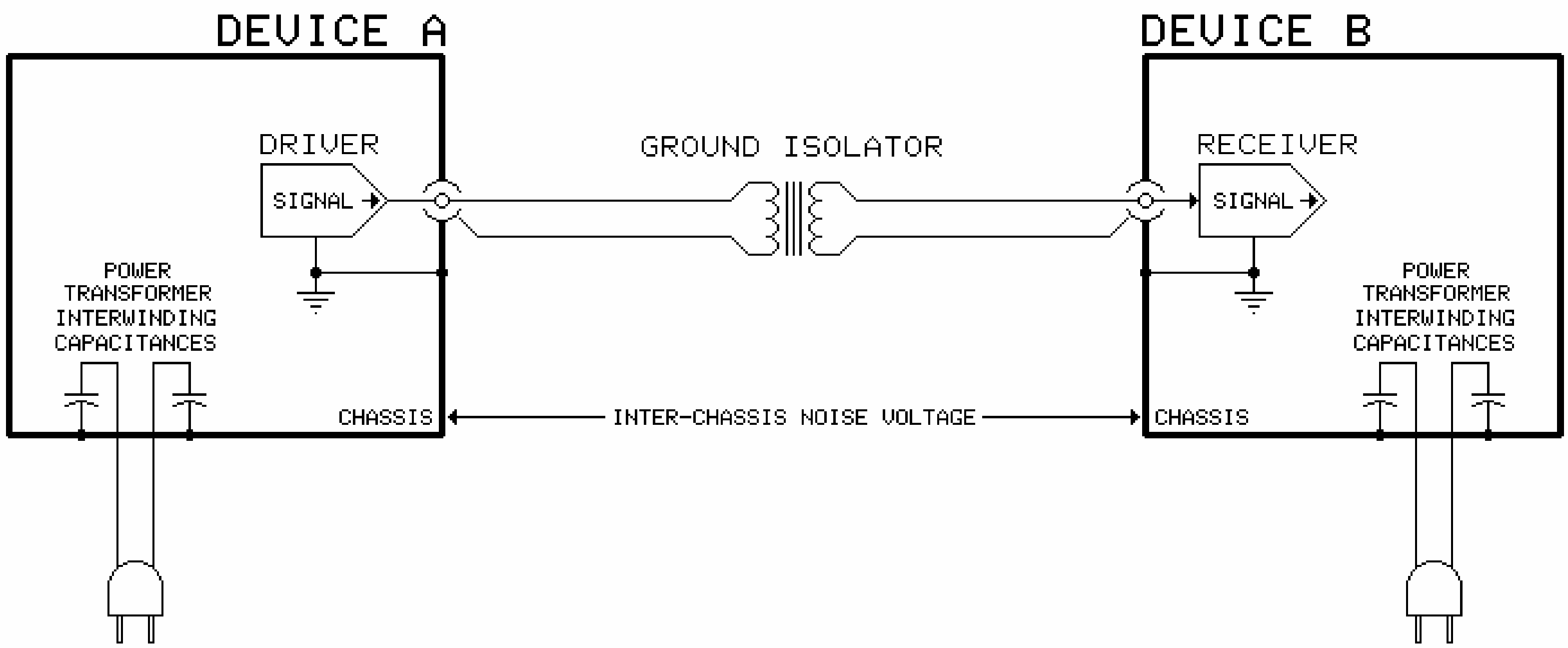
Leaving the dummy on the cable, plug the dummy into the output of Box A.

- **Noise** (unbalanced) — common-impedance coupling. Install an isolator.
- **Noise** (balanced) — SCIN. Replace cable or reduce current in shield.
- **Quiet** — noise coming from output of Box A. Perform test sequence on upstream interface.

Isolators for Unbalanced Audio

- Ground isolators attack the FUNDAMENTAL problem with unbalanced interfaces
  - Technically, a differential responding device having high common-mode rejection
  - **NOT A FILTER** that can be placed *anywhere* in signal path to recognize and remove noise!
  - Stops noise current flow that causes common-impedance coupling in cable’s grounded conductor
- Must be installed at interface where coupling actually occurs!

Audio Transformer Isolator

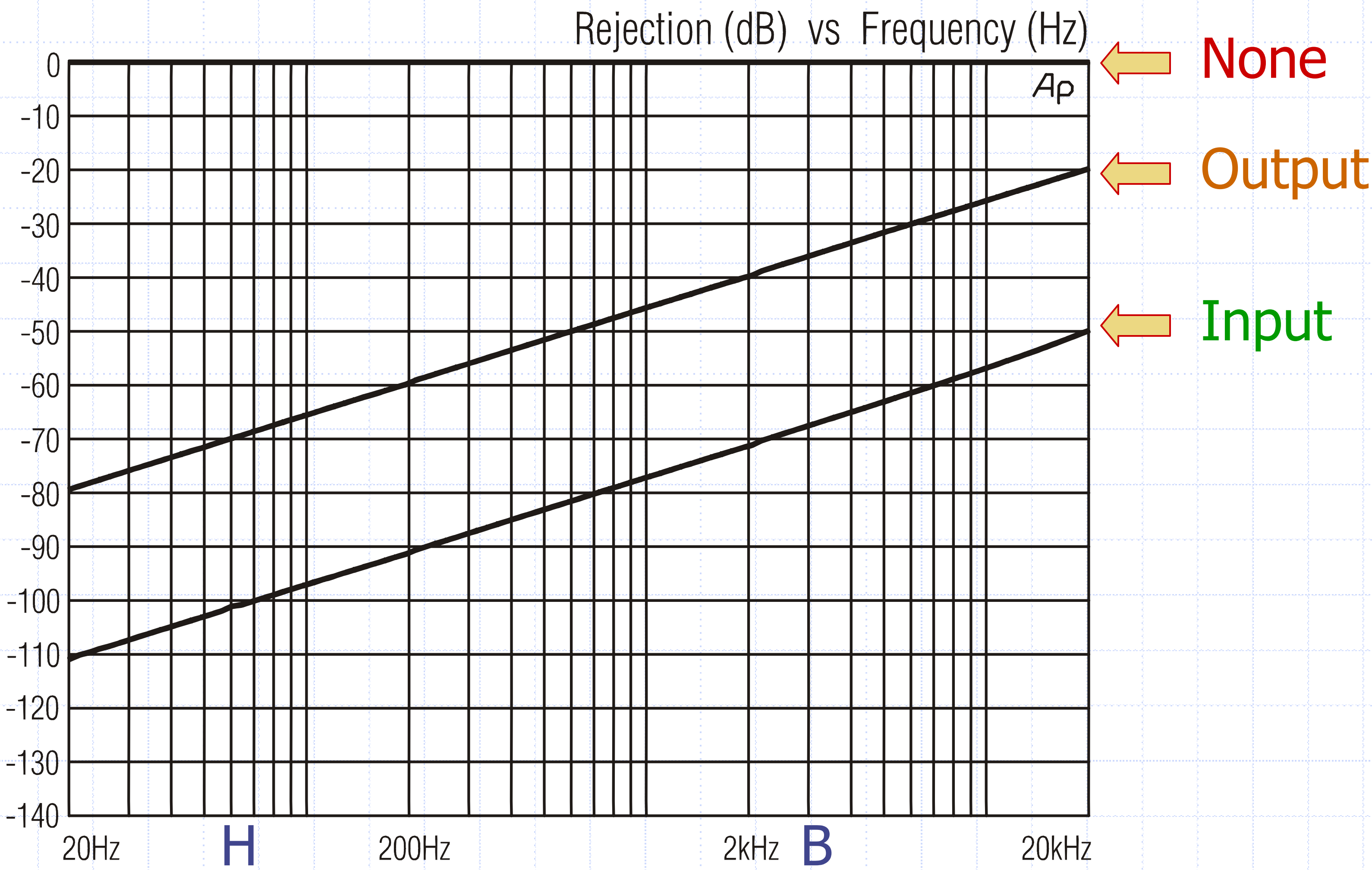


Signal transferred *with NO electrical connection* between driver and receiver

All Transformers NOT the Same!

- Theoretical transformer would *completely* stop current in grounded conductor – and noise
- Practical reduction of current depends critically on construction of the transformer
- Two basic types:
  - **Output** interleaves primary and secondary windings
    - High capacitance allows current flow between windings, and through cable shield, limiting noise reduction
  - **Input** inserts a grounded shield between windings
    - **Faraday shield** (it's <u>not</u> a magnetic shield) effectively *eliminates* capacitance, vastly improving noise reduction

Relative Performance



Commercial "Black Boxes"

Ebtech

- Nearly all contain *output* transformers
  - *Devices above typical of many on market*
- Can be *installed anywhere* along cable

High Rejection “Black Box”

Jensen Transformers

- Faraday-shielded *INPUT* transformers
- < 3 ft output cable to preserve bandwidth

Balance an Unbalanced Line?

- Two devices on same line NOT required
  - Unbalanced to balanced at driver end
  - Balanced to unbalanced at receiver end
- Generally better noise reduction with only *input* transformer at receive end!

Signal Quality Issues

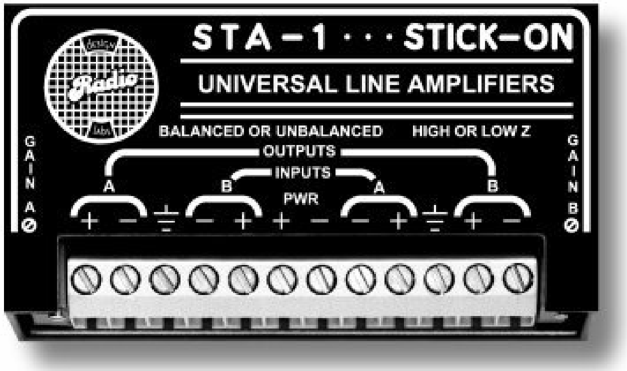
- Check isolator performance carefully
- Specs often vague or non-existent
- Some contain $2 "telecom" transformers
  - Loss of deep bass
  - Bass distortion
  - Poor transient response
- Specs of quality products are complete, unambiguous, and verifiable

Transformer Benefits

- Input-transformer-based isolators
  - Make inputs truly universal – accept signals from either *balanced or unbalanced* outputs while maintaining >80 dB noise rejection
  - Inherently suppress RF and ultrasonic interference, reducing "spectral contamination"
- ALL transformer-based isolators
  - Passive – require no power
  - Robust, reliable, and virtually immune to transient over-voltages

Active Electronic Isolators

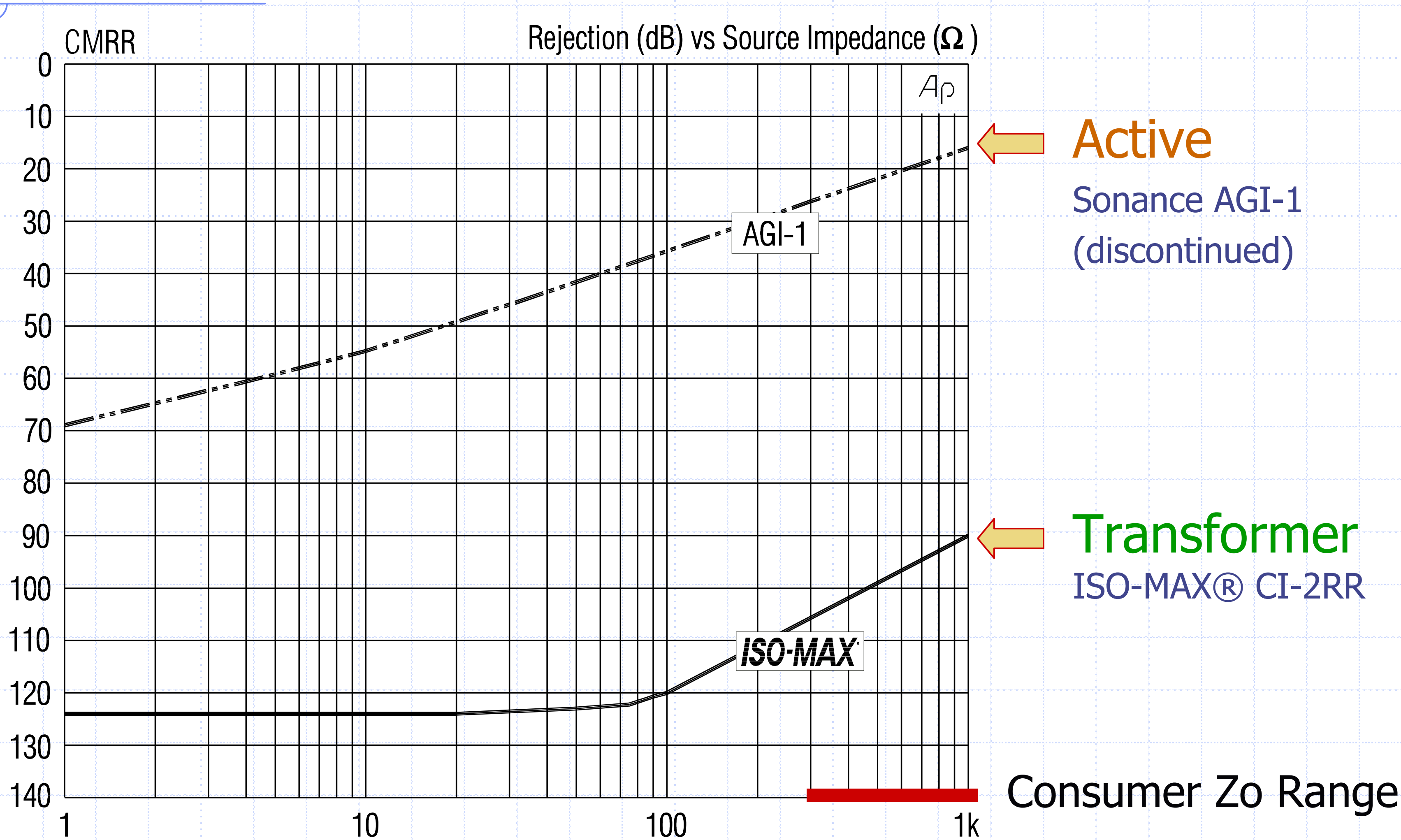
- Many powered interface devices claim to alleviate ground loop problems



CMRR of their diff-amps is inherently sensitive to the slightest source impedance imbalance

- Entire output impedance, typically 200 Ω to 1 kΩ, of *unbalanced* source becomes *imbalance*
- Resulting noise rejection is quite low

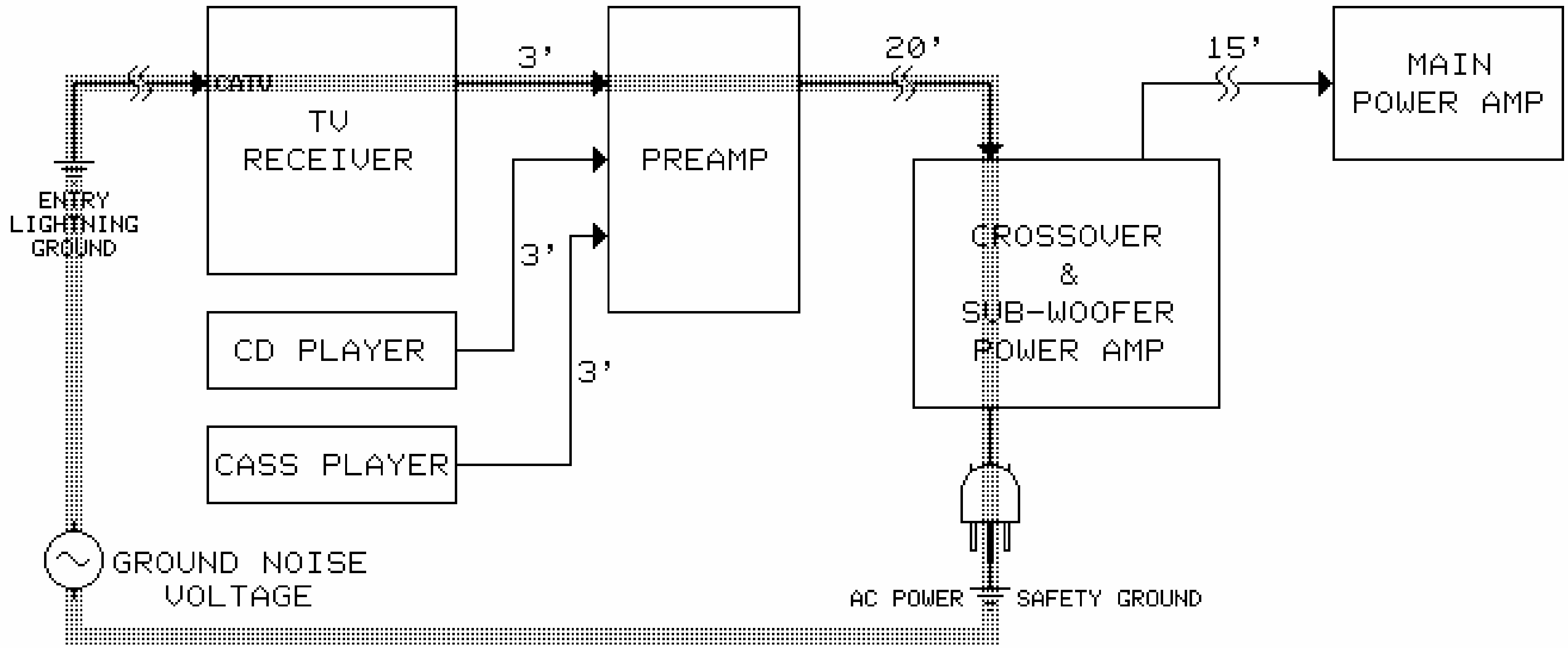
Active vs Transformer Isolators



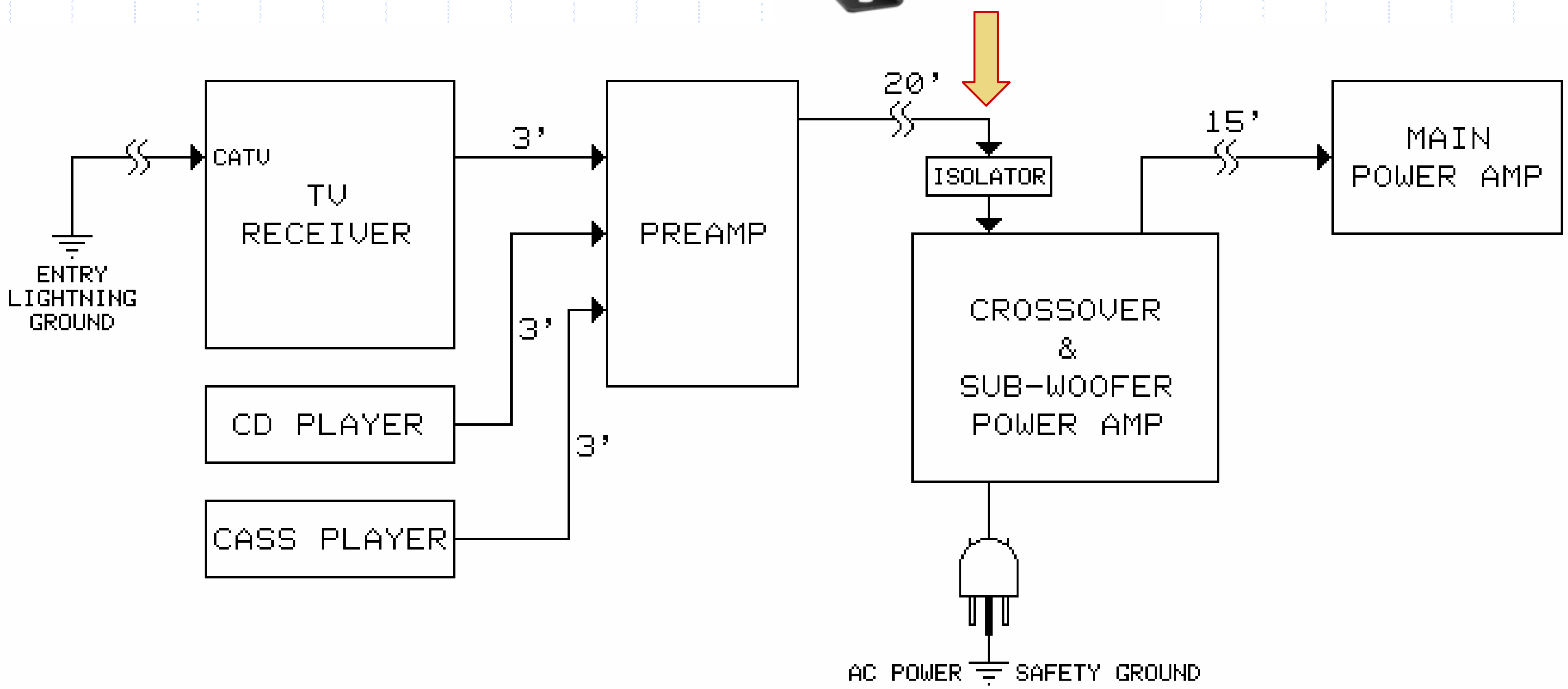
Break the Loop Where?

- Ground loop may include many cables
- Coupling usually proportional to length
- Never defeat safety grounding!
- Install a ground isolator in signal path
- Choice may be cost driven
- In example, either at *receive* end of long audio cable or a CATV isolator

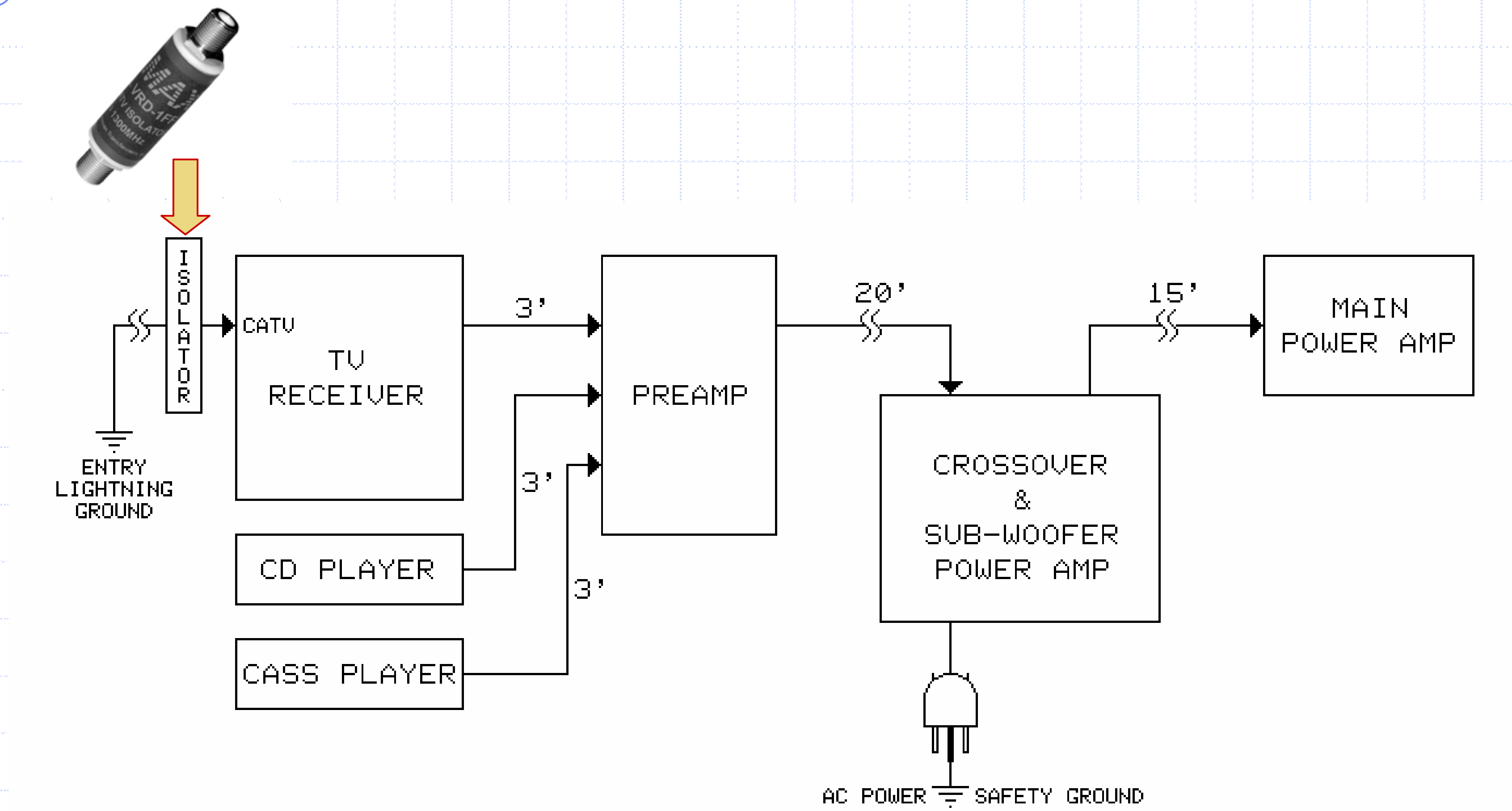
Two Grounds = Loop



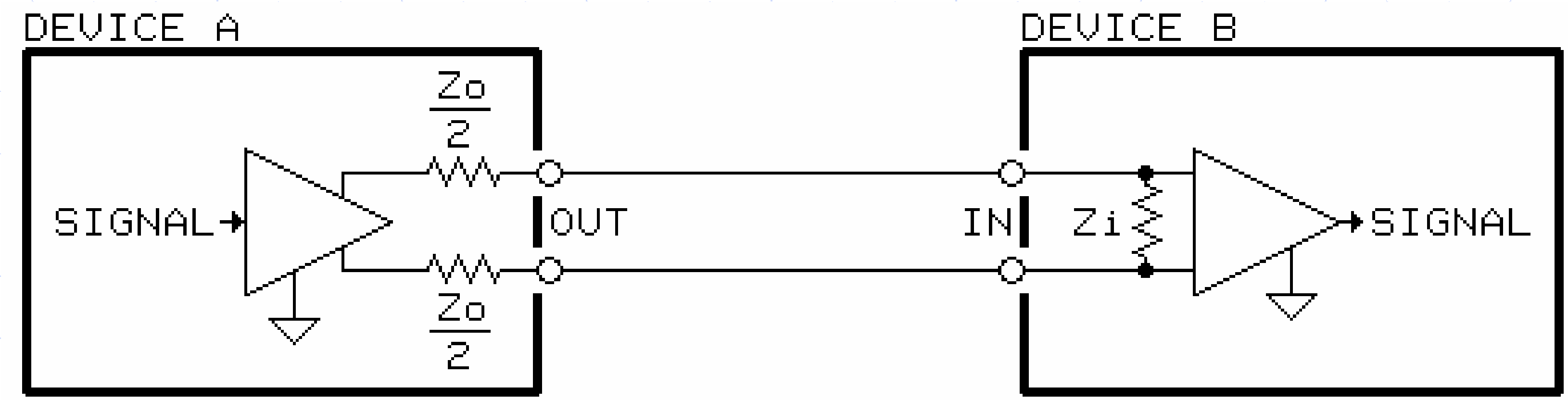
Audio Isolator Breaks Loop



CATV Isolator Breaks Loop



BALANCED Interfaces



- **THE ULTIMATE** in noise prevention!
- The only technique used in telephone systems

MYTH: Balance = Signal Symmetry

Example from “white paper” at well-known manufacturer’s website:

- “Each conductor is always equal in voltage but opposite in polarity to the other. The circuit that receives this signal in the mixer is called a differential amplifier and this opposing polarity of the conductors is essential for its operation.”

  Not only WRONG but it misses <u>the</u> truly essential feature of a balanced interface

The Real Definition

"A balanced circuit is a two-conductor circuit in which both conductors and all circuits connected to them have the same impedance with respect to ground and to all other conductors. The purpose of balancing is to make the noise pickup equal in both conductors, in which case it will be a common-mode signal which can be made to cancel out in the load."

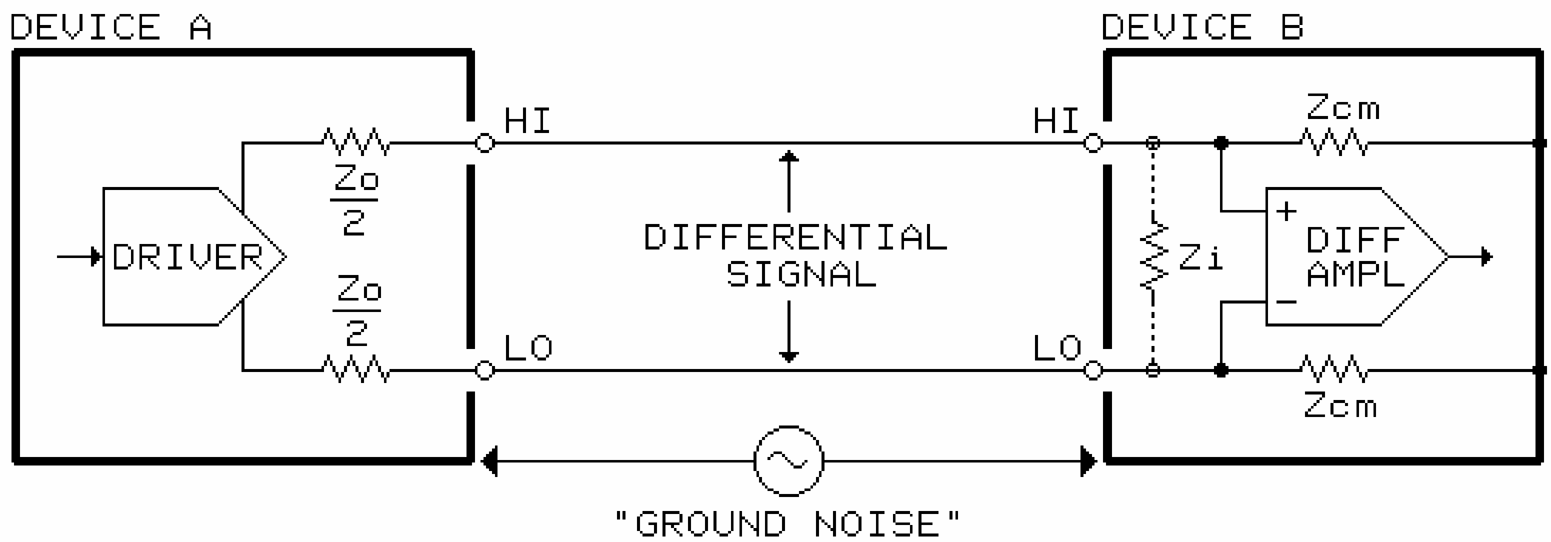
- Henry Ott

Furthermore …

"Only the common-mode impedance balance of the driver, line, and receiver play a role in noise or interference rejection. This noise or interference rejection property is independent of the presence of a desired differential signal. Therefore, it can make no difference whether the desired signal exists entirely on one line, as a greater voltage on one line than the other, or as equal voltages on both of them. Symmetry of the desired signal has advantages, but they concern headroom and crosstalk, not noise or interference rejection."

from "Informative Annex" of IEC Standard 60268-3

The Basic Concept



Any interference that creates identical voltages at the receiver inputs is rejected

The History of Balanced Lines

- Bell Telephone pioneered use
- Early systems passive – no amplifiers
- Miles of existing telegraph lines used
- Wire size & spacing set 600 Ω standard
- Transformers & filters made for 600 Ω
- Equipment migrated to radio & recording
  - The "600 Ω legend" just won't go away!

Where Did We Go Wrong?

- TRANSFORMERS were essential elements of EVERY balanced interface 50 years ago …
- High noise rejection was taken for granted but very few engineers understood why it worked
- Differential amplifiers, cheap and simple, began replacing audio transformers by 1970
- Equipment specs promised high CMRR, but noise problems in real-world systems became more widespread than ever before …
  - Reputation of balanced interfaces began to tarnish and "pin 1" problems also started to appear!

Common Mode? Normal Mode?

- Voltages, to ground, that are equal at <u>both</u> inputs are called **common-mode**
  - Voltage between driver & receiver grounds
  - Voltage induced in cable by magnetic fields
  - Voltage induced in cable by electric fields
- Voltages <u>between</u> the inputs are called "differential" or **normal-mode** (signal)

Common-mode Rejection

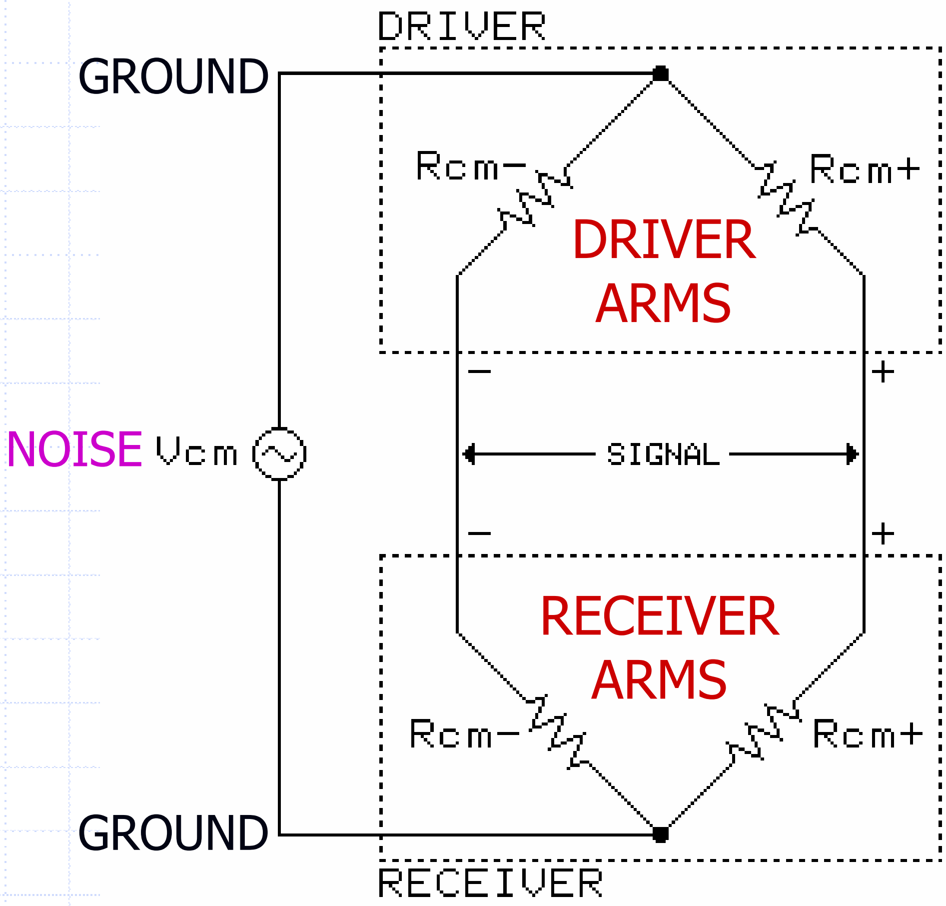
- IDEAL receiver responds only to normal-mode, with no response to common-mode … it would have infinite Common-Mode Rejection
- Rejection is limited in real-world receivers
- Ratio, in dB, of differential to common-mode gain is Common-Mode Rejection Ratio, **CMRR**
- Noise rejection of the entire interface (what really matters) is highly dependent on how the line and driver affect the receiver!

The Wheatstone Bridge

- Driver and receiver common-mode impedances form a classic Wheatstone bridge
- Bridge imbalances cause **conversion** of common-mode noise into normal-mode signal
- Balance depends critically on matching ratios of common-mode impedances of the lines
  - Most sensitive to component tolerances when driver and receiver arms have same impedances
  - Least sensitive when driver and receiver arms have widely differing impedances

Receiver arm impedances should be very high!

A Question of Balance

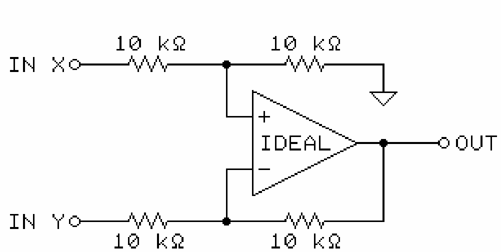


Blinded by Bad Science

- CMRR traditionally measured with a **perfect** source … Good marketing but bad science!
- Impedance imbalance at outputs of <u>real</u> audio gear can be ±30 Ω or more
- IEC recognized inadequacy of their existing CMRR test in 1998 and invited comments
- Whitlock suggested a new procedure that was adopted in August, 2000 as IEC 60268-3
  - Inserts 10 Ω imbalances, first in one leg and then in the other, of the test signal generator

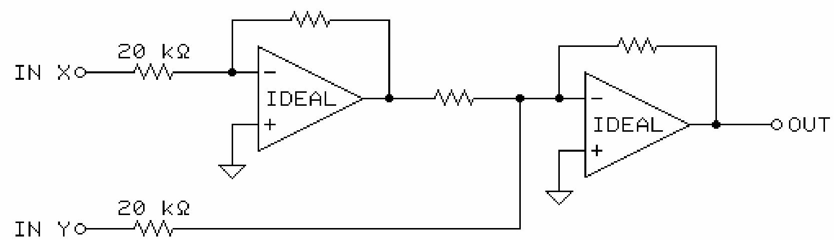
Conventional Active Input Stages

All have 20 kΩ common-mode input impedances!

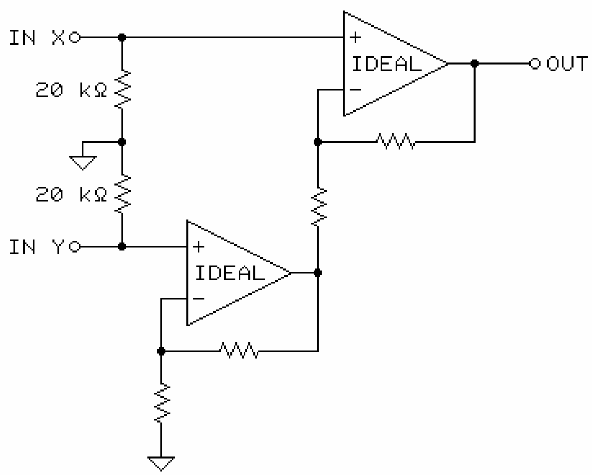


"SIMPLE" SINGLE OP-AMP

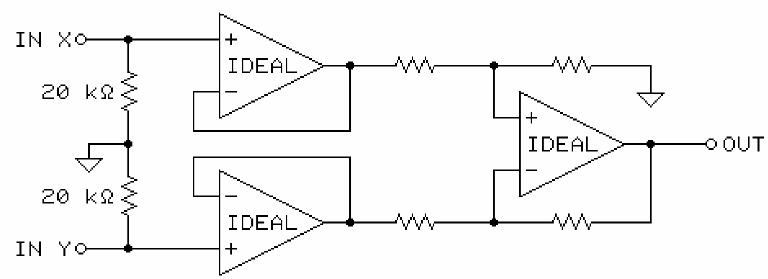
OVER 90% OF ALL BALANCED INPUTS



CURRENT MODE DUAL OP-AMP



VOLTAGE MODE DUAL OP-AMP

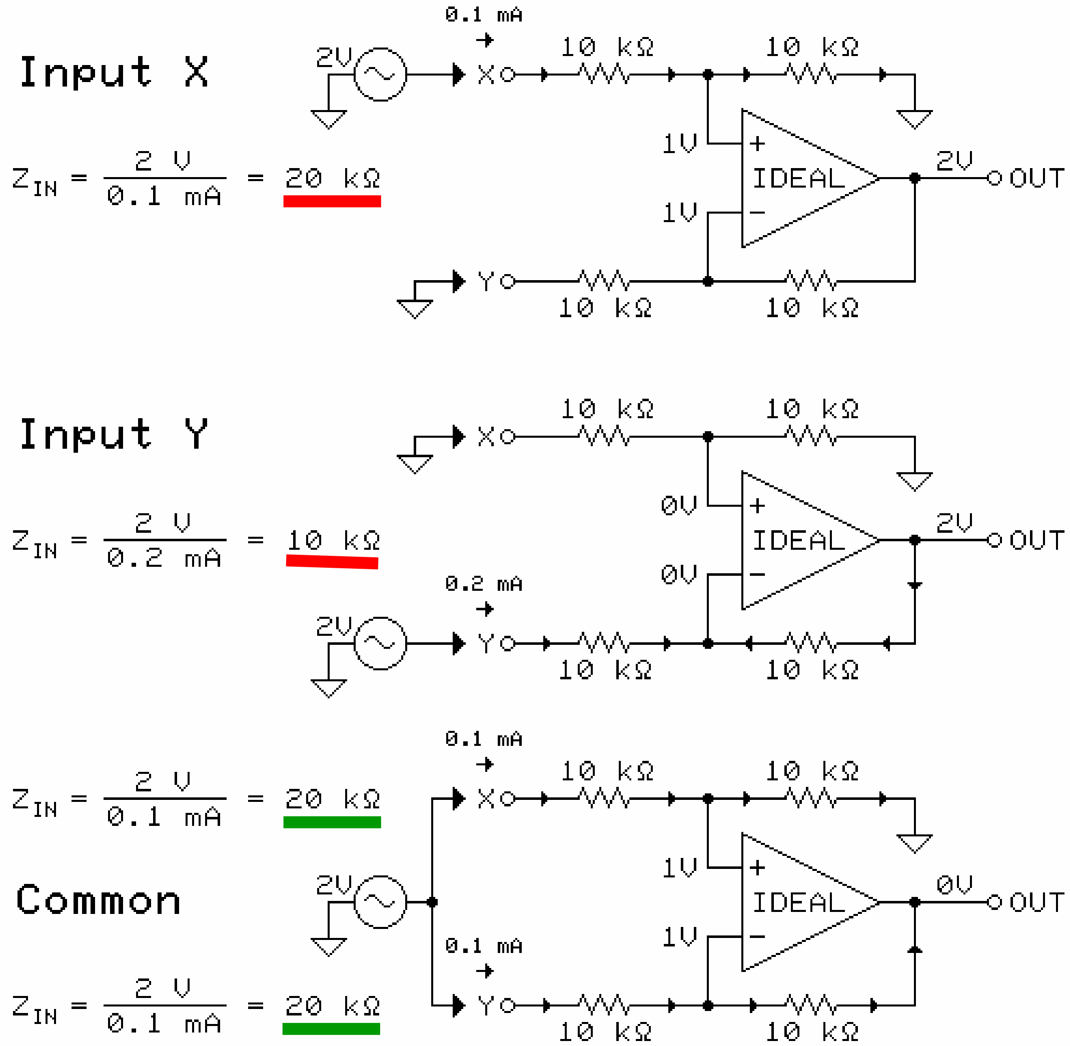


"INSTRUMENTATION" or TRIPLE OP-AMP

MYTH: The Diff-Amp Needs Fixing

Driven separately, input impedances are not equal … This is NOT a problem!

COMMON-MODE input impedances are equal … OK!

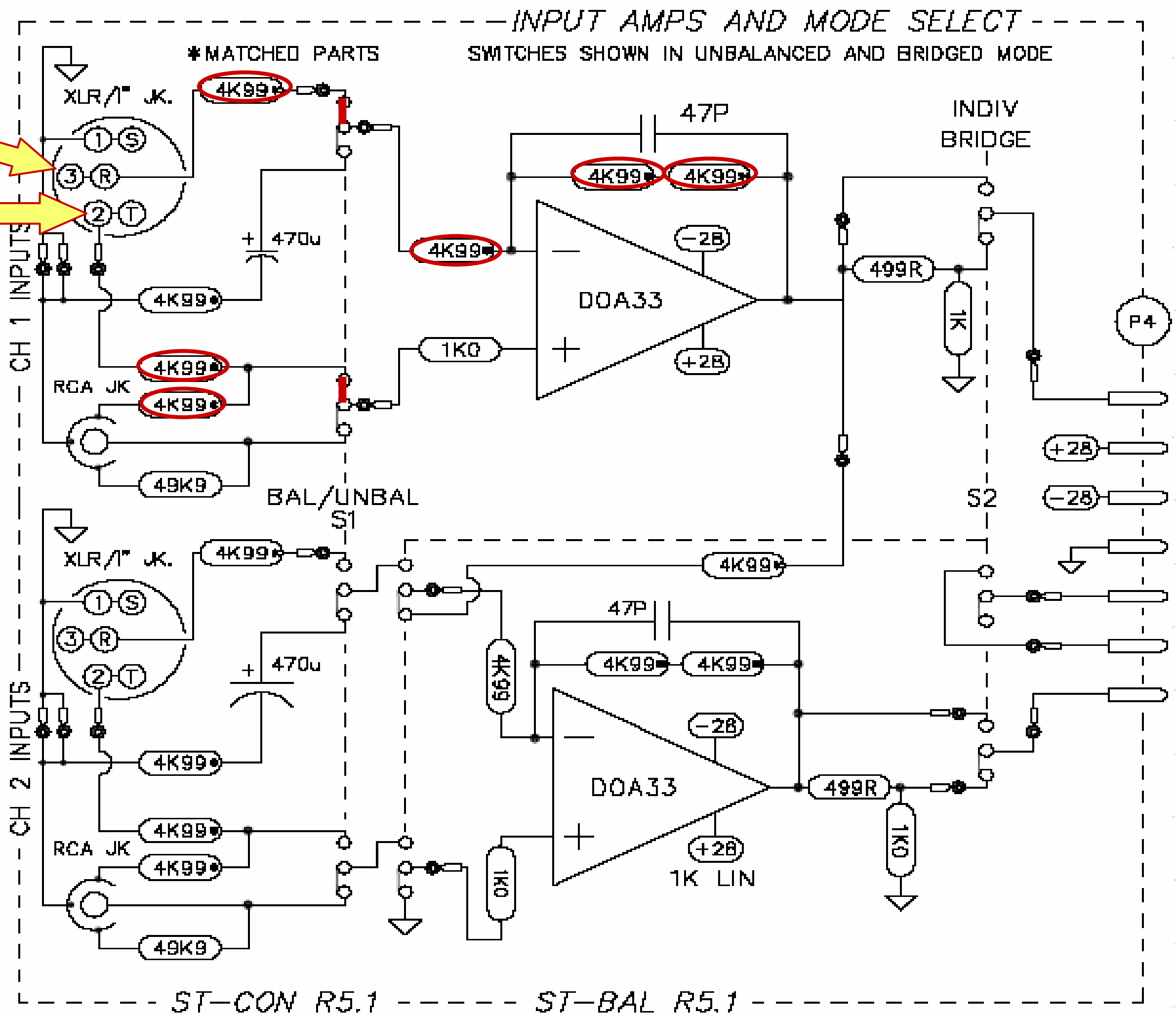


A Commercial “Fix” Example

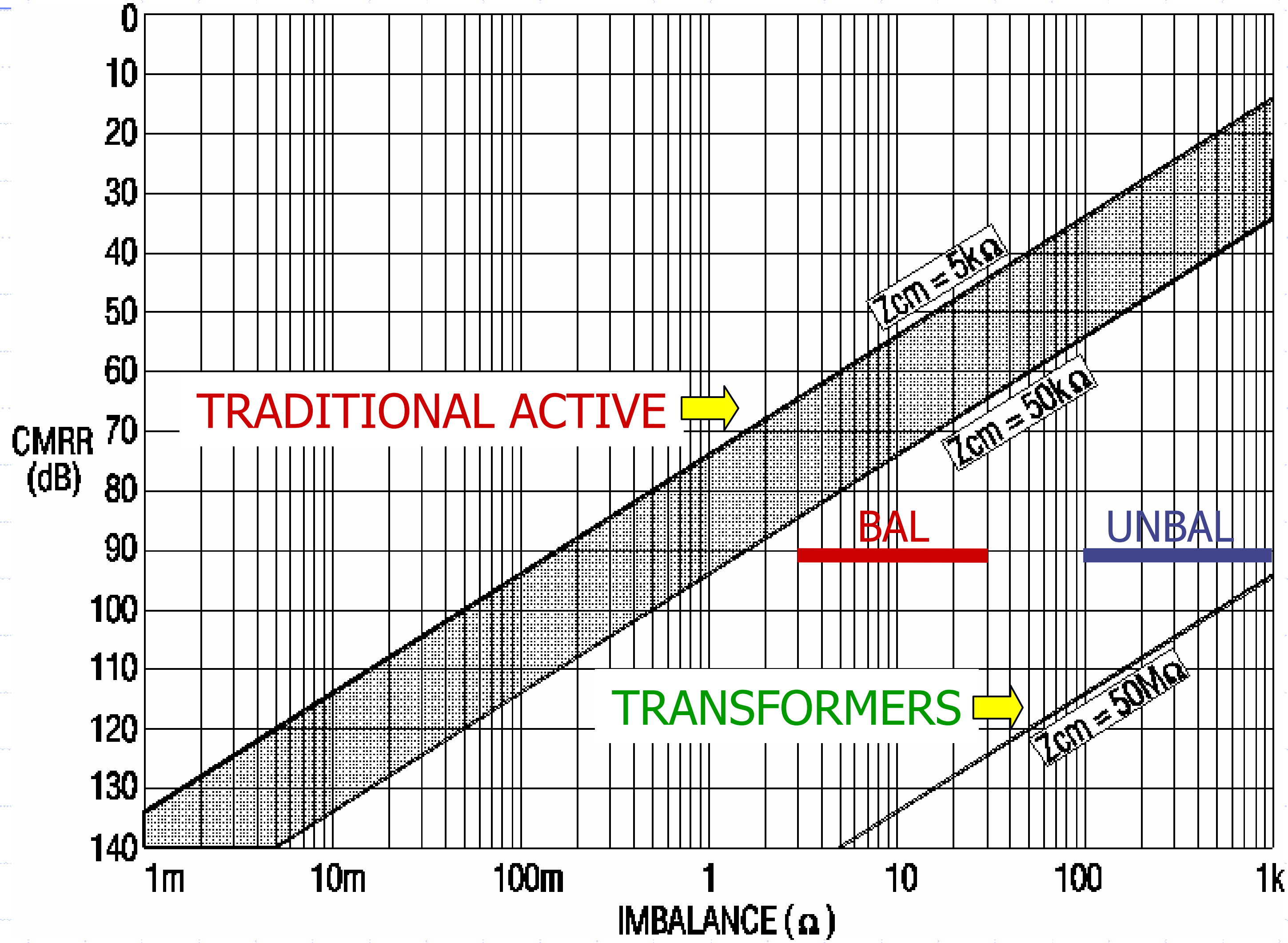
$Z_{CM} = 20\ \text{k}\Omega$

$Z_{CM} = 10\ \text{k}\Omega$

This input will have poor CMRR when driven from any real-world *(non-zero common-mode impedances)* signal source!



CMRR vs Real-World Imbalances



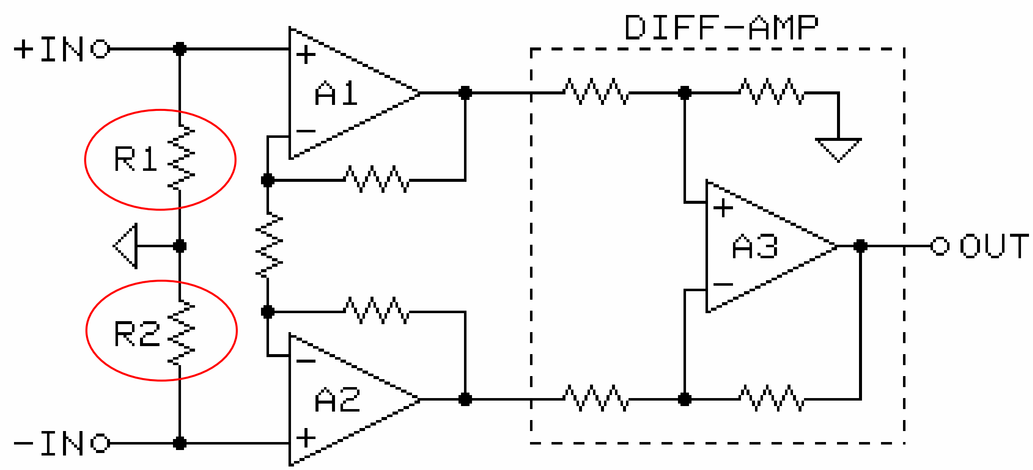
Why Transformers are Better

- Typical "active" input stage common-mode impedances are 5 kΩ to 50 kΩ at 60 Hz
  - Widely used SSM-2141 IC loses 25 dB of CMRR with a source imbalance of only 1 Ω
- Typical transformer input common-mode impedances are about 50 MΩ @ 60 Hz
  - Makes them 1,000 times more tolerant of source imbalances – full CMRR with any real-world source

Imitate a Transformer?

Transformer advantage = high common-mode impedances

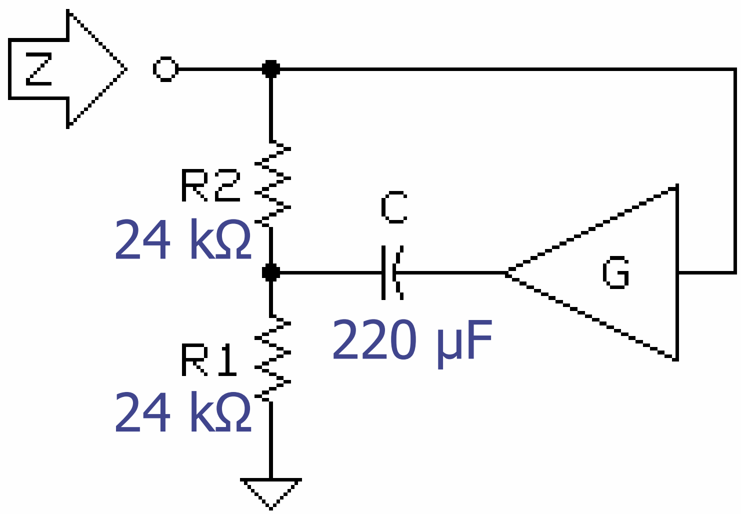
R1 and R2 supply bias current to A1 and A2 but lower input impedances



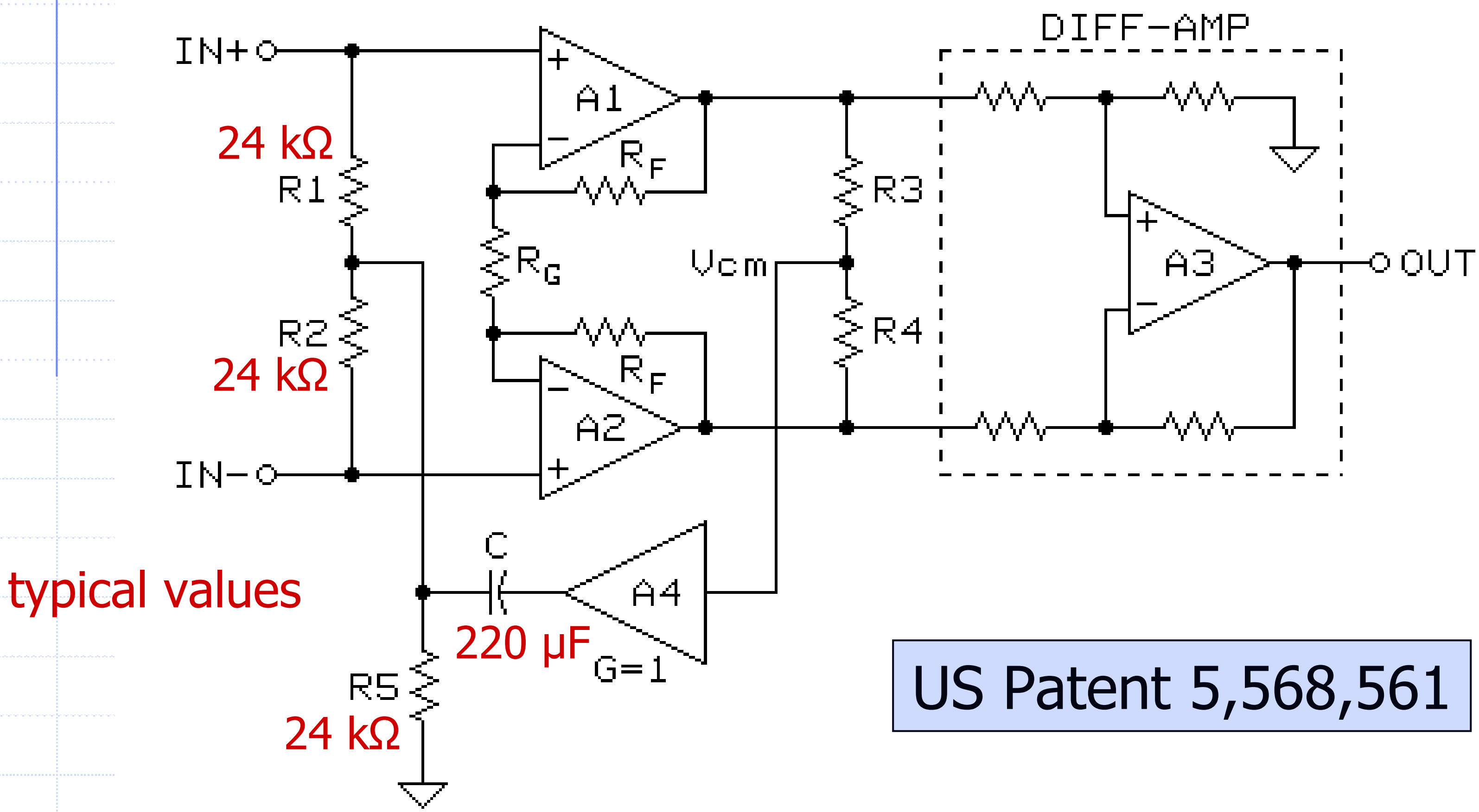
Up, Up and Away!

- "Bootstrapping" is a well-known method for increasing ac impedance of resistors

48 kΩ @ dc
10 MΩ @ 60 Hz



Bootstrapping the Common-Mode



US Patent 5,568,561

InGenius® Implementation

- R1, R2, and R5 necessary to supply amplifier bias currents (sources may have no dc path)
- CM voltage extracted by R3 and R4
- A4 buffers CM voltage and “bootstraps” R1 and R2 via external C, typically 220 µF
- Common-mode input impedances increased to 10 MΩ at 60 Hz and 3.2 MΩ at 20 kHz!
- R_F and R_G covered by patent for high-gain applications like microphone preamps

InGenius® IC Design Features

- Fabricated using 40-volt complementary bipolar Dielectric Isolation (DI) process
  - High performance NPN *and* PNP transistors like discretes
  - High isolation between transistors and no substrate connection
  - Low stray capacitances for high bandwidth and slew rates
- Folded cascode op-amp designs with PNP front ends
  - Better noise performance
  - High gain and simple stability compensation
  - Greater input voltage range
- Output driver uses novel, patented output stage

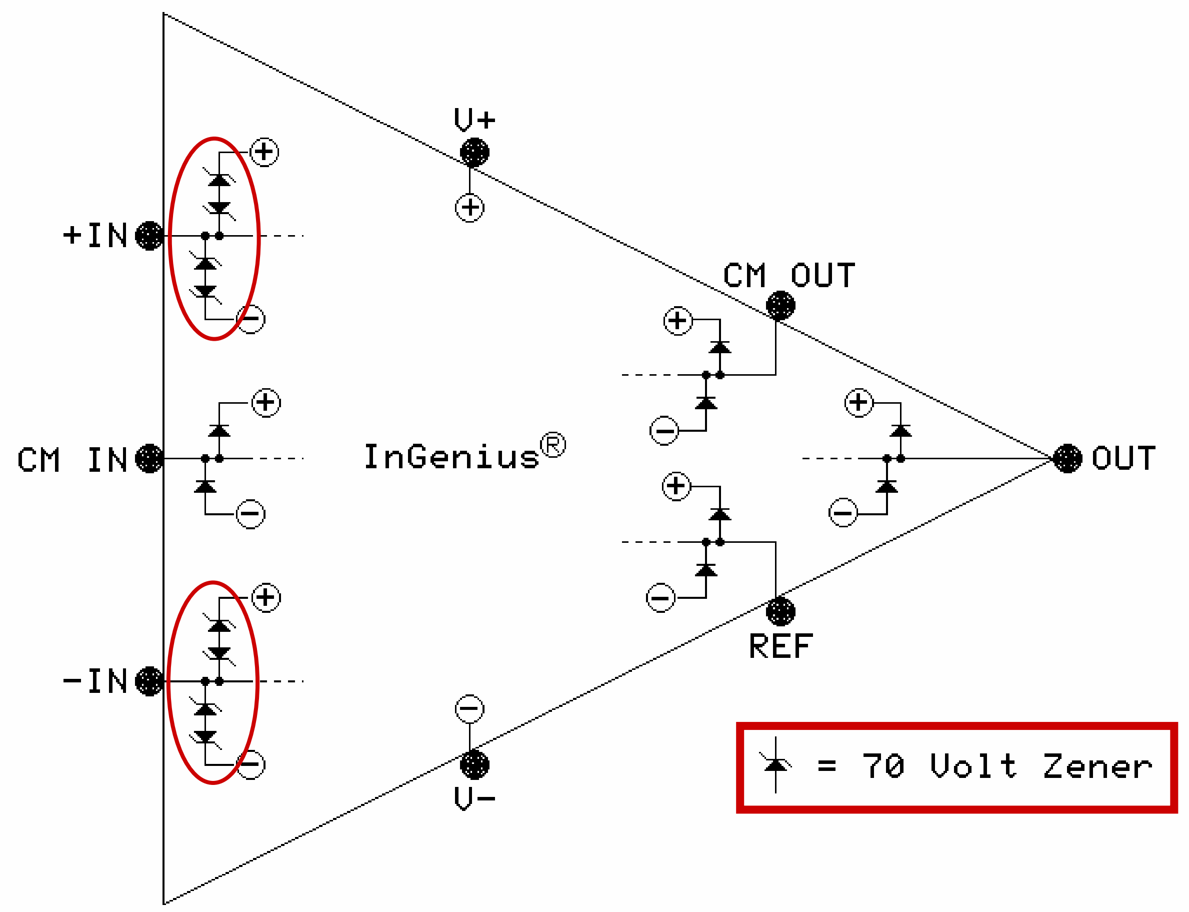
InGenius® IC Features

- Thin-film Si-Cr (silicon-chromium) resistors utilized
  - Better stability over time and temperature than Ni-Cr (nickel-chromium) or Ta-Ni (tantalum nitride) types
  - Sheet resistance minimizes total die area
  - Accuracy and matching achieved by laser trimming
- Resistor matching is critical to CMRR and gain accuracy
  - Match typically within 0.005% … results in about 90 dB CMRR
  - Coarse and fine laser trimming optimizes speed and cost
  - This matching both difficult and expensive in discrete designs
  - Accelerated life tests predict >70 dB over life of part

InGenius® IC Fabrication

- Thin-film resistors vulnerable to electrostatic discharge (ESD) damage
  - Input pins must accept input voltages greater than supply rails, posing an ESD protection challenge
  - New “lateral” protection diode, with typical breakdown of 70 volts, was designed to utilize existing diffusion and implant sequences
- All other pins are protected by conventional clamp diodes to supply rails

InGenius® ESD Protection

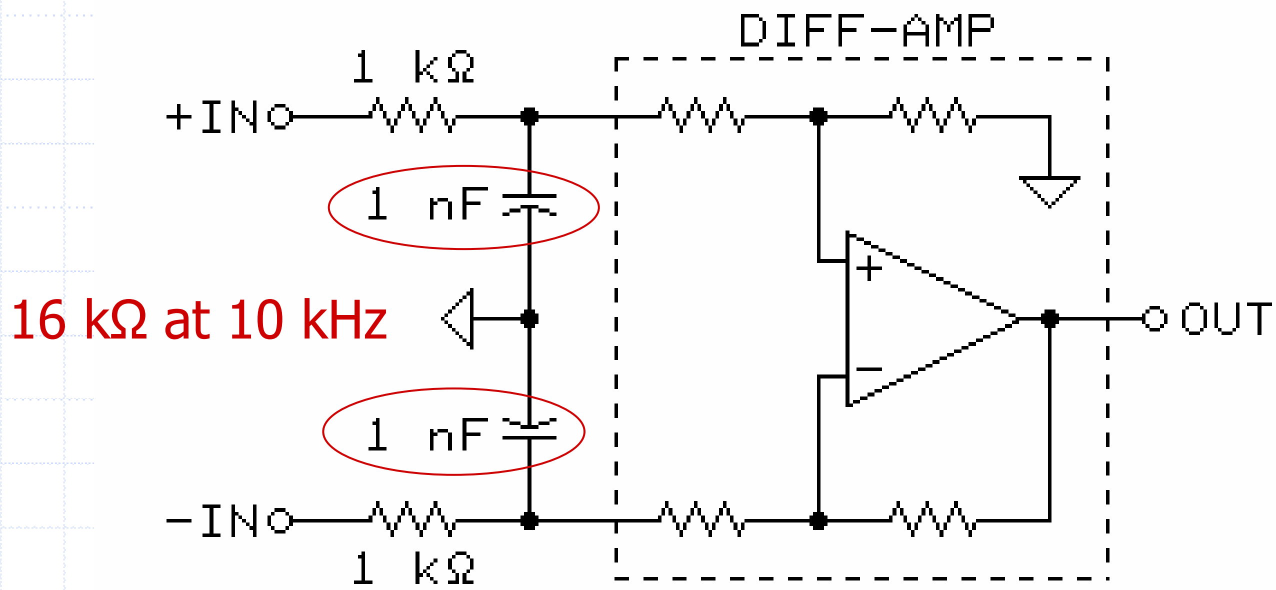


InGenius® IC Performance

- High CMRR maintained with real-world sources
  - 90 dB @ 60 Hz, 85 dB @ 20 kHz with zero imbalance source
  - 90 dB @ 60 Hz, 85 dB @ 20 kHz with IEC ±10 Ω imbalances
  - 70 dB @ 60 Hz, 65 dB @ 20 kHz with 600 Ω unbalanced source!
- THD 0.0005% typical at 1 kHz and +10 dBu input
- Slew rate 12 V/µs typical with 2 kΩ + 300 pF load
- Small signal bandwidth 27 MHz typical
- Gain error ±0.05 dB maximum
- Maximum output +21.5 dBu typical with ±15 V rails
- Output short-circuit current ±25 mA typical
- 0 dB, -3 dB, -6 dB gain versions = THAT 1200, 1203, 1206

Traditional RFI Suppression

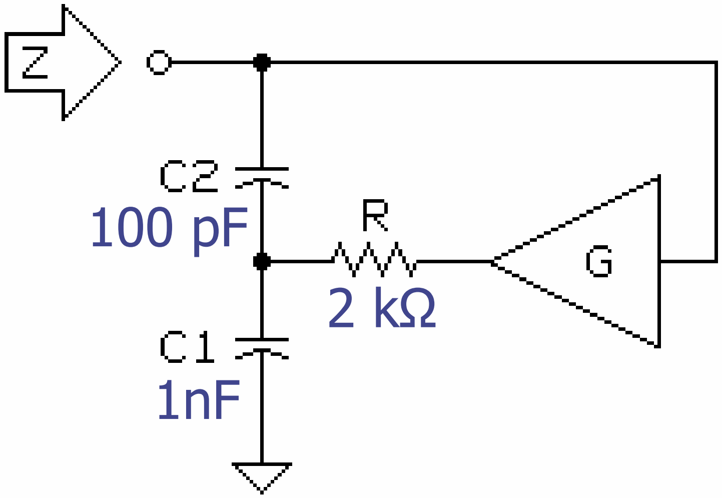
Lowers common-mode Zs significantly at higher audio frequencies, which makes CMRR degrade more with source imbalances



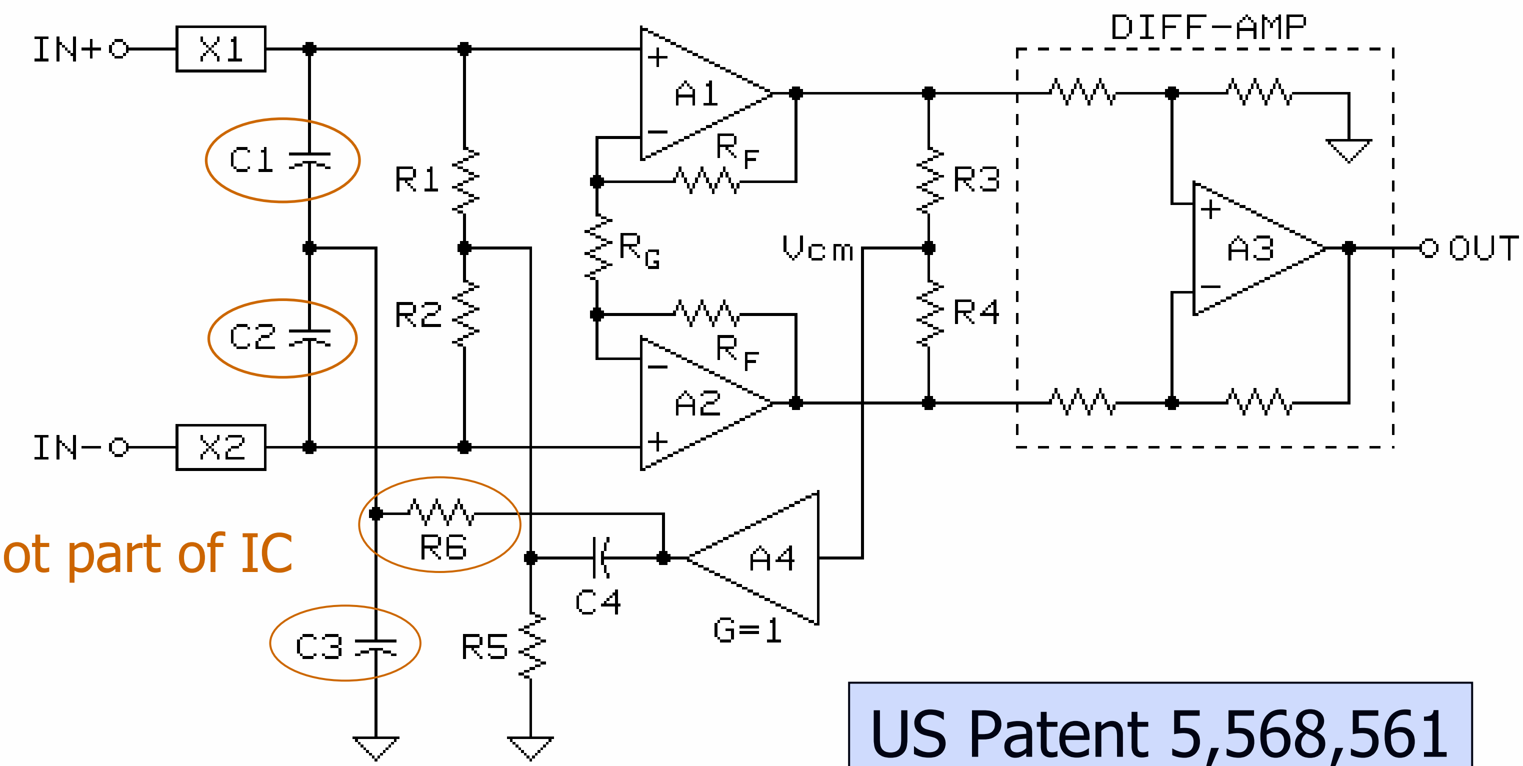
Raising Impedance of Capacitor

- "Bootstrap" lowers effective capacitance of RF filter capacitors at audio frequencies

Effectively 15 pF @ 10 kHz
and 91 pF @ 100 kHz



Bootstrap of RFI Filter Capacitors



Not part of IC

US Patent 5,568,561

THAT Corporation
Making Good Sound Better®

InGenius® Summary

- Conventional active receivers are far cheaper, smaller, and lighter than a quality transformer, but …
- Transformers consistently outperform them for reasons that need to be widely understood and appreciated
- The main transformer advantage stems from its inherently very high common-mode impedances
- The InGenius® IC exhibits the very high CM impedances previously associated only with transformers
  - Excellent noise rejection even with UNBALANCED sources!
- Its bootstrap feature lends itself to novel and very effective RF interference suppression
- Its high-quality internal op-amps give it GREAT SOUND

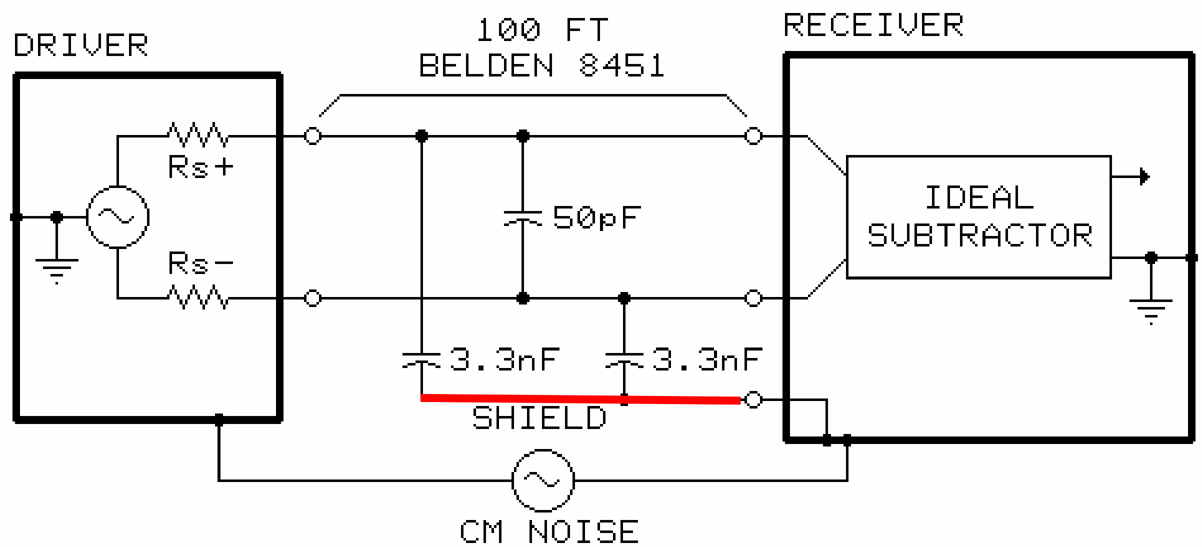
Balanced Cable Issues

- Capacitance imbalance
- Shielding for electric fields and RF
- Immunity to magnetic fields
- Shield current induced noise (SCIN)

Shielding

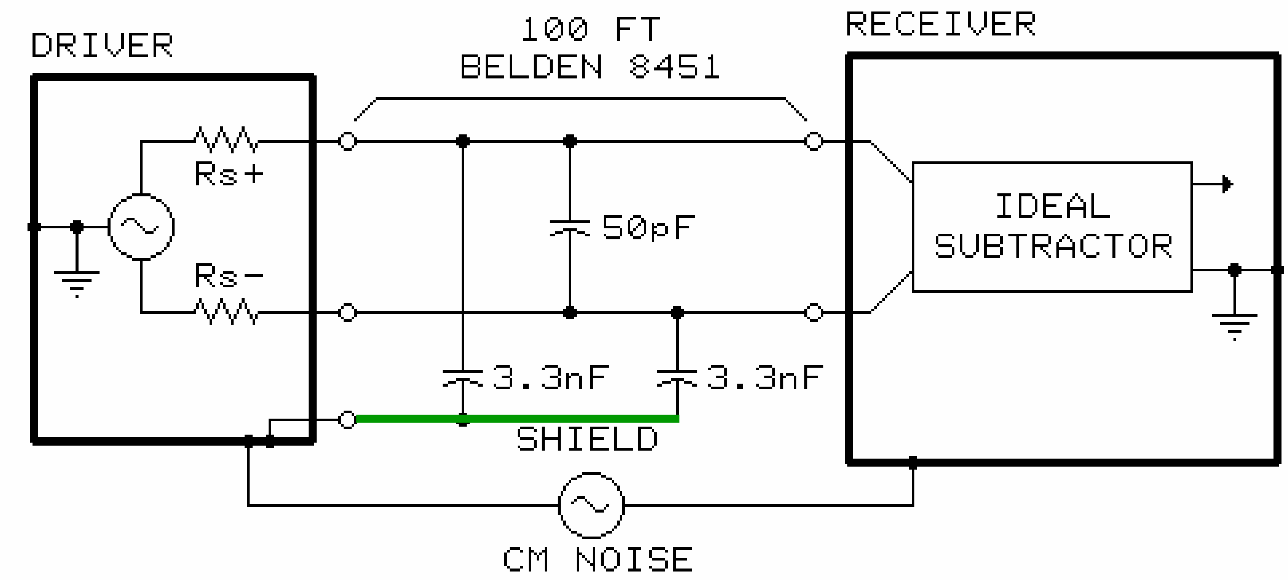
- Electric field couples to both signal conductors – coupling may be unequal
  - **Twisting** improves match by averaging physical distances to external field source
- Grounded shield avoids problem by diverting field current to ground
- Braided shield of 85% to 95% coverage is usually adequate

Ground Only at Receiver = Bad



- Forms pair of low-pass filters for common-mode noise
- Driver Zo imbalances and 4% to 6% typical cable C imbalances create mismatched filters
- Mismatched filters cause conversion of common-mode noise to differential, degrading CMRR

Ground Only at Driver = Good



Grounding only at driver completely ELIMINATES FILTERS!

All filter elements move together (with driver ground)

Connections and Crosstalk

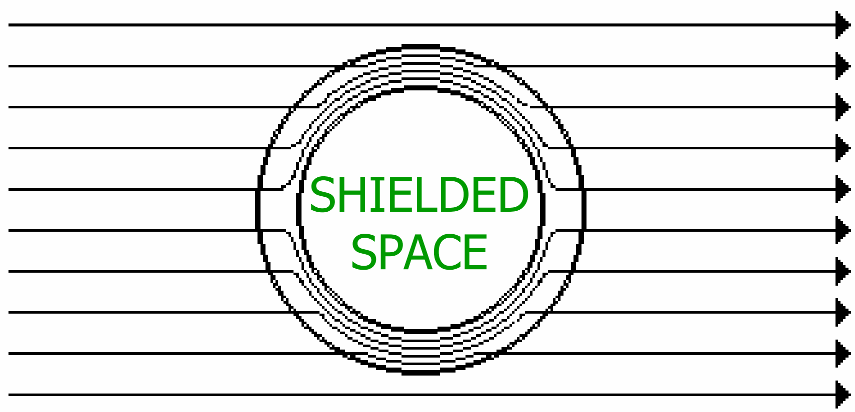
- Signal asymmetry and capacitance mismatch cause signal current flow in the shield
  - Grounding only at receiver forces current to return to the driver via an undefined path – can result in crosstalk, distortion, or oscillation
  - Grounding only at driver allows current to return directly to the driver – NO PROBLEMS
- The **driver** end of a balanced cable should **always** be grounded, whether or not the receiver end is grounded

Common-Mode Voltage Limits

- ±10 volts (peak) for typical active circuits
  - Total loss of CMR if exceeded = very nasty distortion
- ±250 volts for typical transformer
  - No audible effect if exceeded (only insulation failure)
- Voltage between driver & receiver ground
  - Less than few volts if both devices grounded
  - Can approach 120 volts if either device ungrounded
  - Shield ground at <u>both</u> ends minimizes
  - Other grounding required in some cases

Immunity to Magnetic Fields

- Voltages are induced in conductors exposed to ac magnetic fields – voltages may not be equal
  - **Twisting** averages physical distances to external field source
- Effective magnetic shielding at 60 Hz is very difficult
- Only ferrous metals (steel conduit) are low-frequency magnetic shields — ordinary cable shielding is <u>not</u>

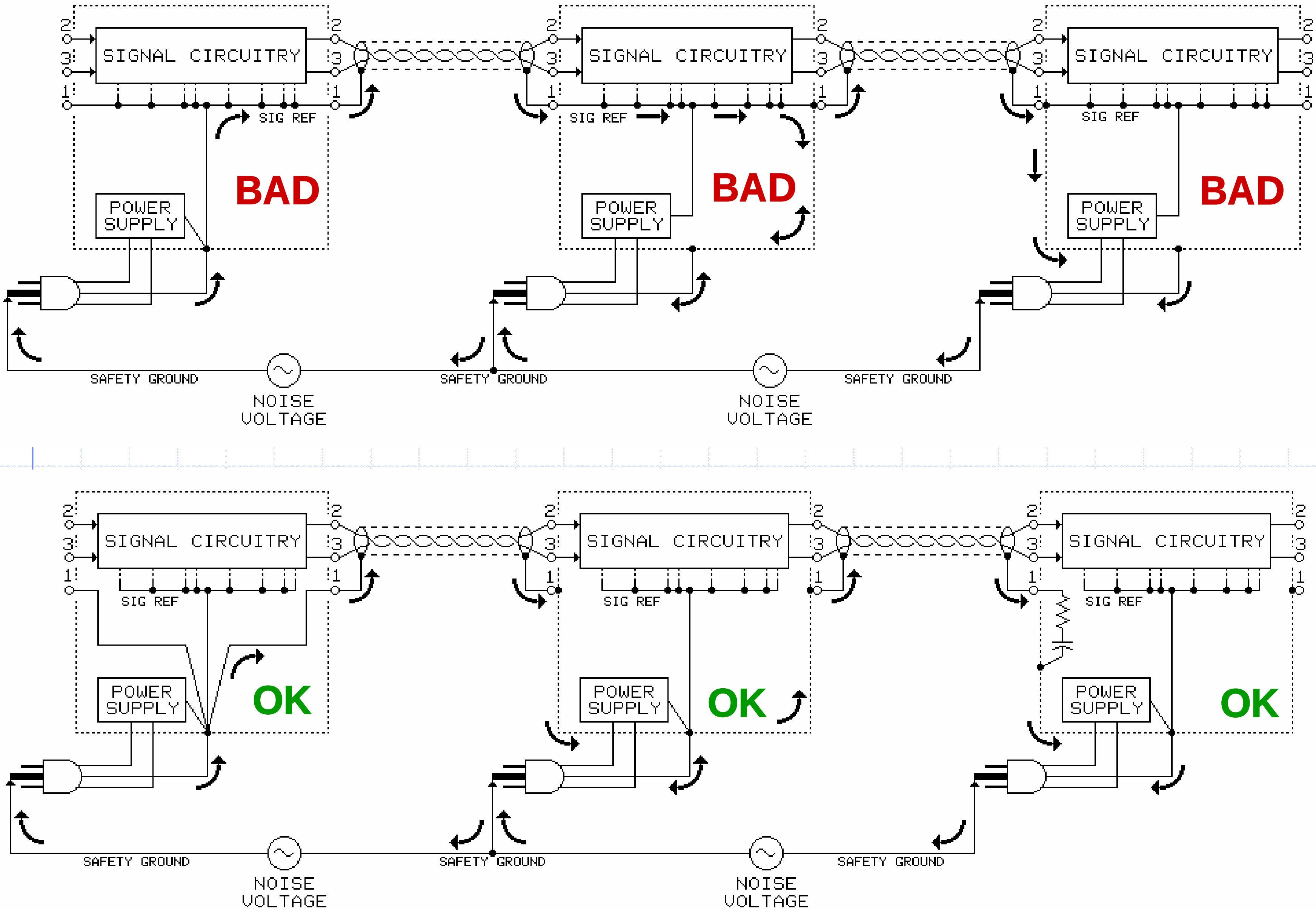


Shield Current Induced Noise

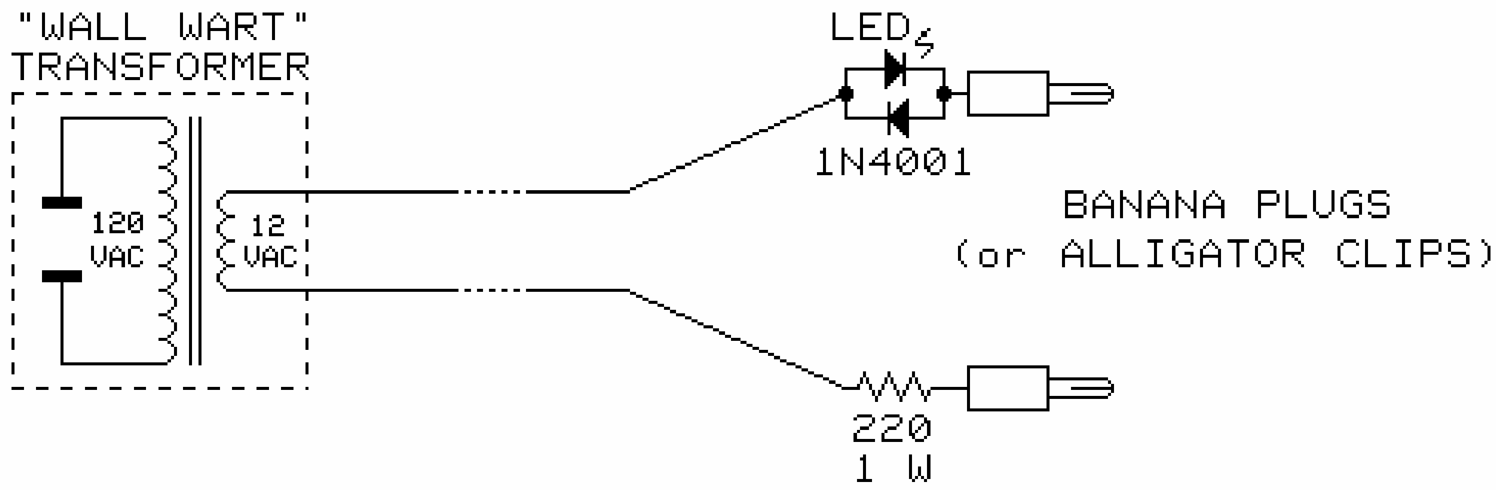
- Any current flow in shield creates magnetic field extremely close to the twisted pair
- Slightest imperfections in cable construction result in unequal induced voltages
  - Dubbed SCIN in 1994 paper by Neil Muncy
  - **Best** cables use braided or dual counter-wrapped spiral shields and **no drain wire**
  - **Worst** cables use a **drain wire**, regardless of other construction details *[Brown-Whitlock paper]*

A "Designed-In" Noise Problem

- Common-impedance coupling <u>inside</u> devices turns shield connection into an audio input!
- Dubbed the "Pin 1 Problem" (XLR pin 1 is shield) by Neil Muncy in 1994 AES paper
- Inadvertently designed into a surprising number of products
- Shield current, mainly power-line noise, flows in wiring or PCB traces shared by amplifier signal circuitry


SIGNAL CIRCUITRY
SIG REF
POWER SUPPLY
BAD
SAFETY GROUND
NOISE VOLTAGE
OK
2
3
1

“Pin 1 Problem” Testing



“HUMMER" forces about 50 mA of 60 Hz ac through suspect shield connections

* LED indicates current is flowing

Using the "Hummer"

1. Monitor one output and disconnect any other I/O cables and chassis connections
2. For reference, listen to the output *without* the hummer connected
3. Connect one hummer lead to chassis and other to shield of each I/O connector
4. Good designs will have no output hum or change in the noise floor
5. Other paths include safety ground to I/O shields and input shields to output shields

Isolators for Balanced Audio

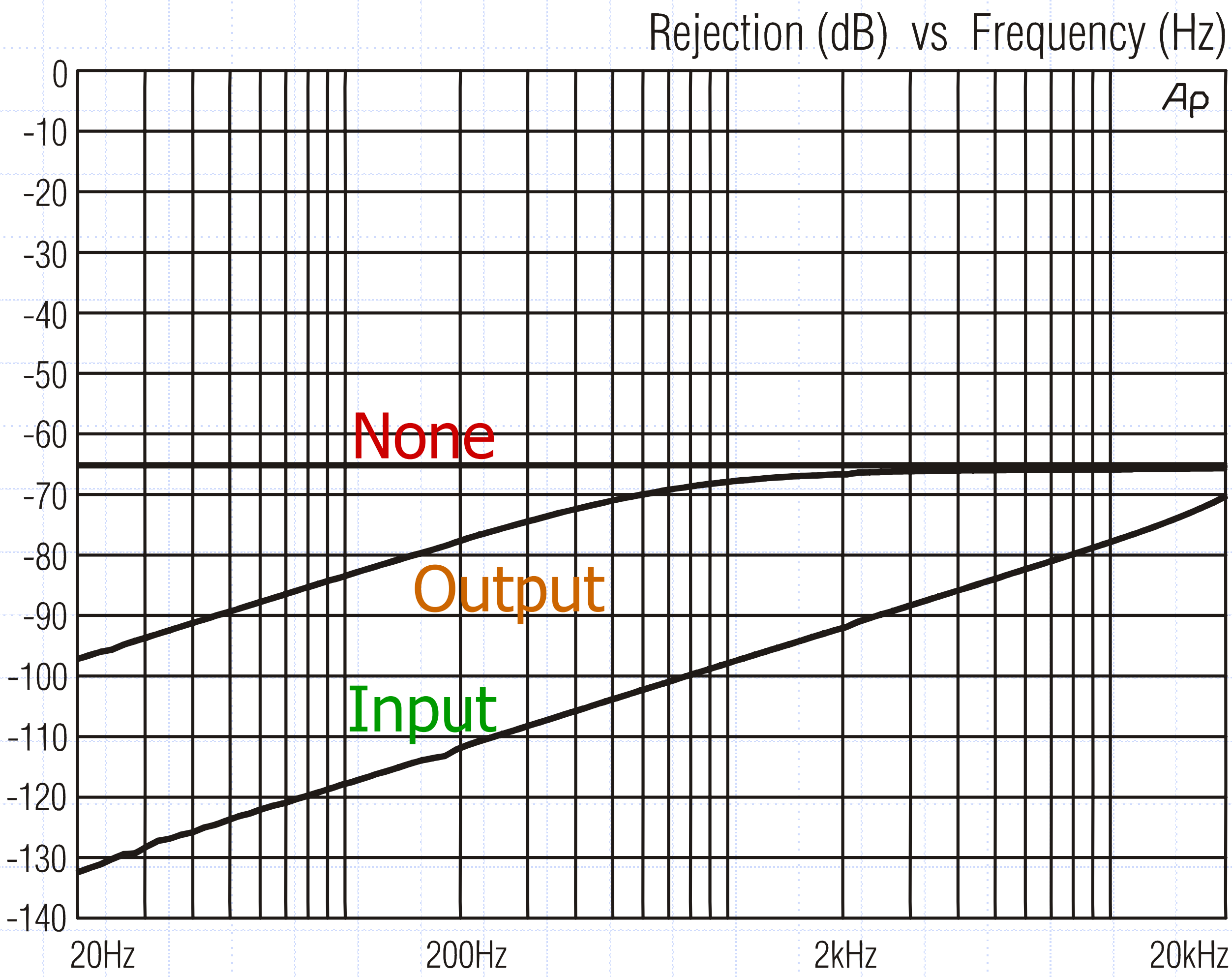
- Top problems in "pro" equipment:
  - "Pin 1" problems
  - Poor real-world CMRR

ISO-MAX® PI-2XX

switches on bottom

- This isolator solves both
  - DIP switches reconfigure shield connections
  - Faraday-shielded **input** transformers add CMRR

Transformers Improve CMRR



IEC CMRR test
of advertised
"90 dB CMRR"
balanced input

Transformer Performance

- Beware "weasel-words" & "market-speak"
  - Missing specs or unspecified test conditions
  - Level handling & distortion rated at 50 Hz
- Jensen data complete and user-verifiable
  - Sonic transparency is the design goal
  - Level handling & distortion rated at 20 Hz
    - High level, low frequency distortion most telling
  - Phase distortion (deviation from linear phase) specified on every spec sheet

A Balanced Checklist

- Keep balanced line pairs tightly twisted
  - Immunity to magnetic fields
  - Especially important in low-level mic circuits
    - Terminal blocks and XLRs vulnerable to magnetic fields
    - “Star-Quad” mic cable reduces magnetic pickup 40 dB
  - Immunity to electric fields for unshielded pairs
- Grounding of cable shields is important
  - **Always** ground at the driver
  - **OK** to ground at both ends
  - **Never** ground **only** at the receiver

Unbalanced to Balanced Audio

- AKA “Consumer to Pro”
- Reference signal levels are different
  - Consumer ref = -10 dBV = 0.316 V rms
  - Professional ref = +4 dBu = 1.228 V rms
  - Requires voltage gain of ~4x = 12 dB
- Use a 1:4 step-up transformer?

It Seems Like a Good Idea …

Rane Corp.

Uses 1:4 step-up transformer

- ► 1:4 turns ratio transformer reflects impedances at 1:16 ratio
- ► Consumer output drives 625 Ω to 2.5 kΩ load (not recommended)
- ► Headroom, distortion, and frequency response are degraded
- ► Actual gain becomes 3 to 8 dB

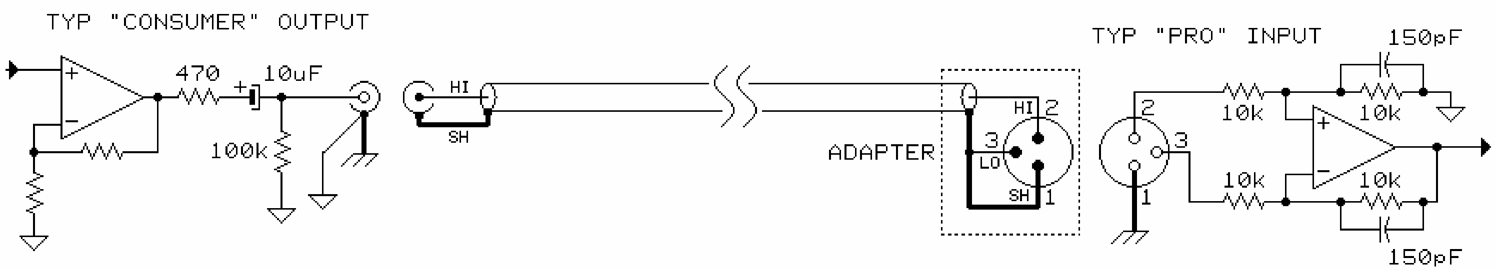
NOT a good solution …

12 dB of gain "reach" is normally available at the balanced input

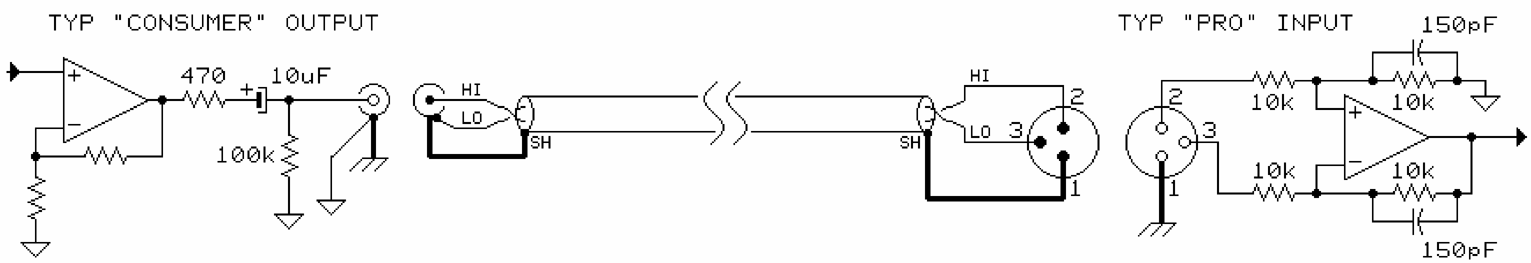
Simple but Smart

- Noise rejection is usually issue, <u>not</u> gain
- Use of 2-conductor cable invites noise due to common-impedance coupling
- Use of 3-conductor cable stops ground noise current flow in signal conductors!
  - If input uses transformer or InGenius® IC, rejection can be up to 100 dB

2 Conductors or 3?

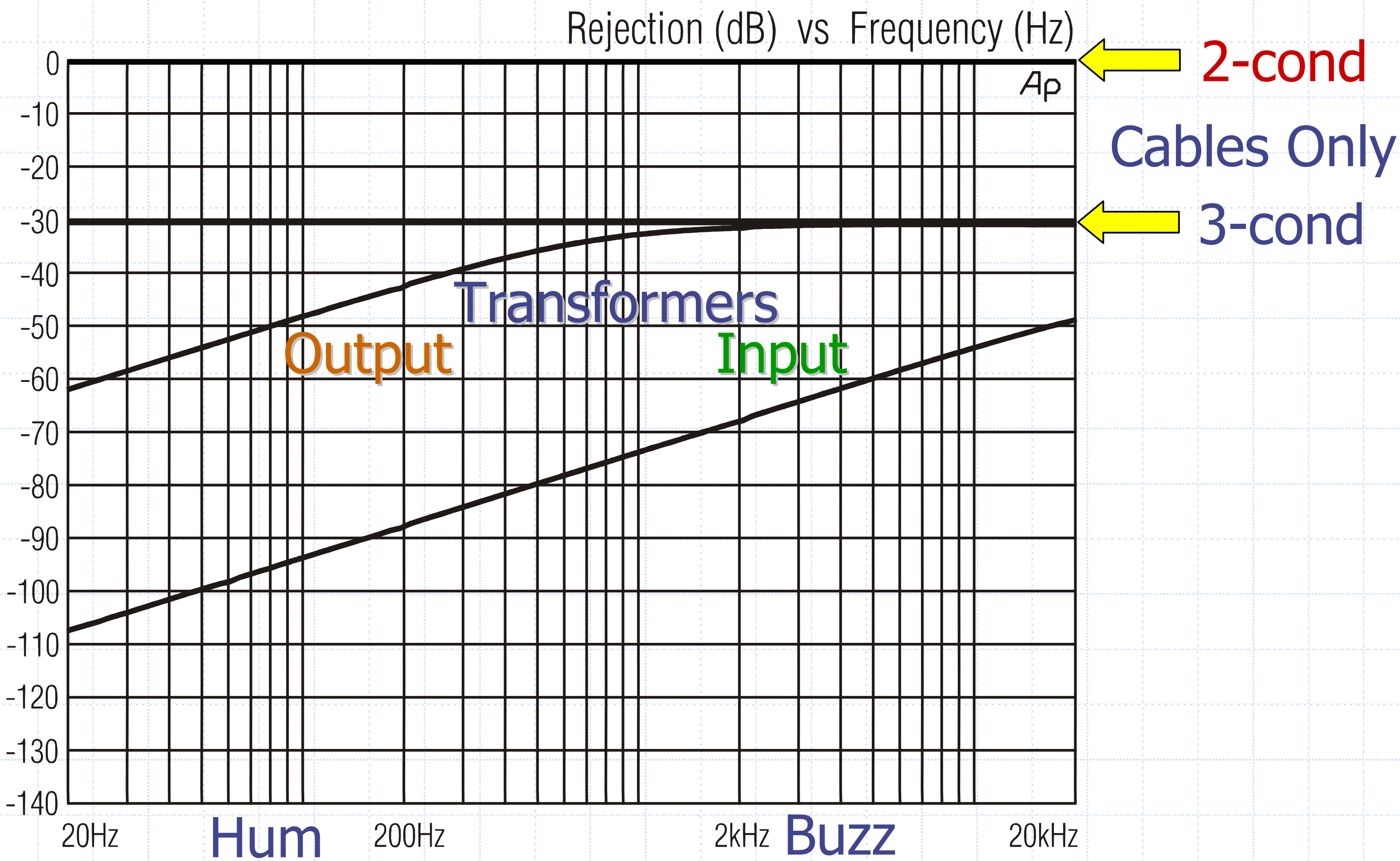


2-c cable and adapter results in <u>**NO**</u> rejection at all



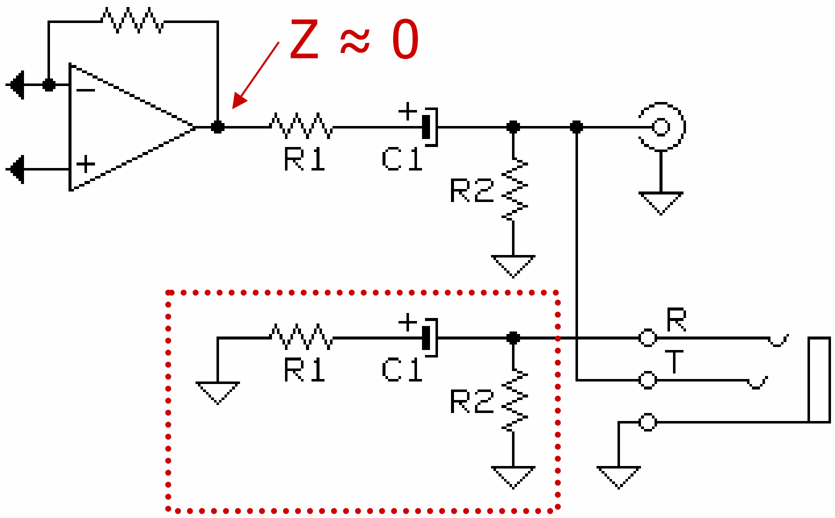
3-c cable results in **30 dB** rejection for typical input

Relative CMRR Performance



“Universal” Consumer Output

- True Balanced Out on TRS (or XLR)
- Unbalanced Out on TS or RCA
- Simultaneous Use Causes Imbalance

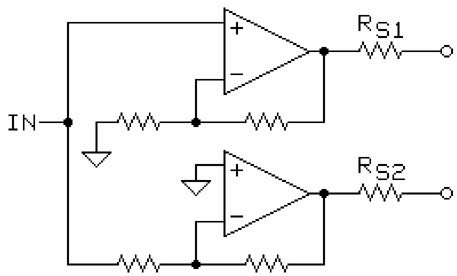


DUPLICATE OF EXISTING OUTPUT NETWORK

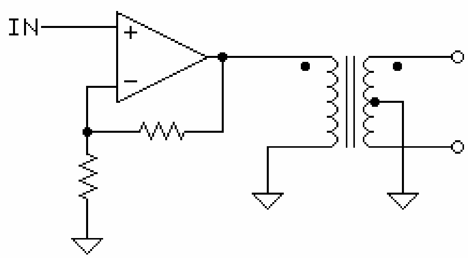
Balanced to Unbalanced Audio

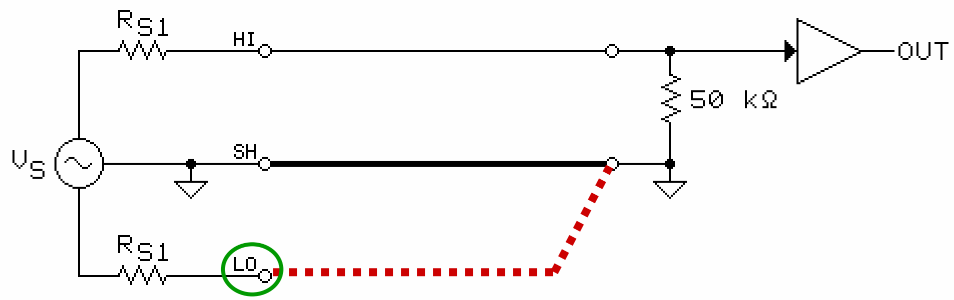
- AKA “Pro to Consumer”
- Signal level difference is legitimate concern
  - Consumer inputs easily over-driven by pro levels
  - Requires voltage <u>loss</u> of 12 dB
  - Lower pro output? – metering & noise degrade
- One wiring method will NOT work for all kinds of line output circuits – it’s risky business!

Ground-Referenced Symmetrical



OR

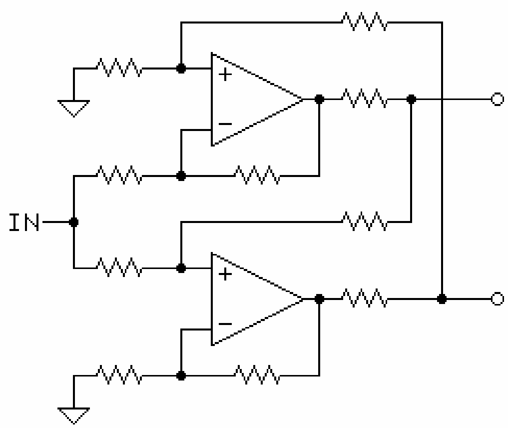


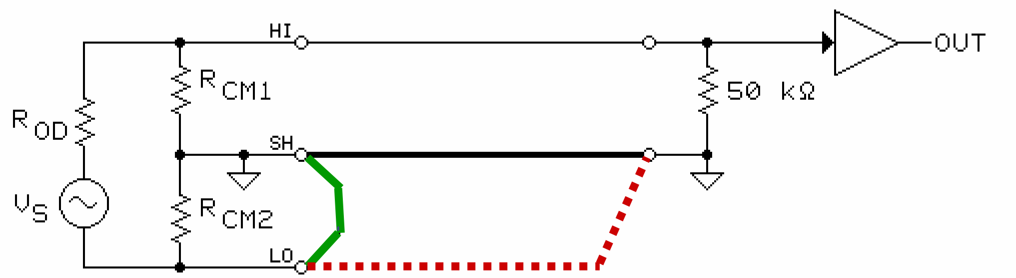


Equivalent Circuit with Unbalanced Receiver

- Driver “unhappy” when either output is grounded
- Unused output must float
- No noise advantage over unbalanced output

“Active Balanced” Floating

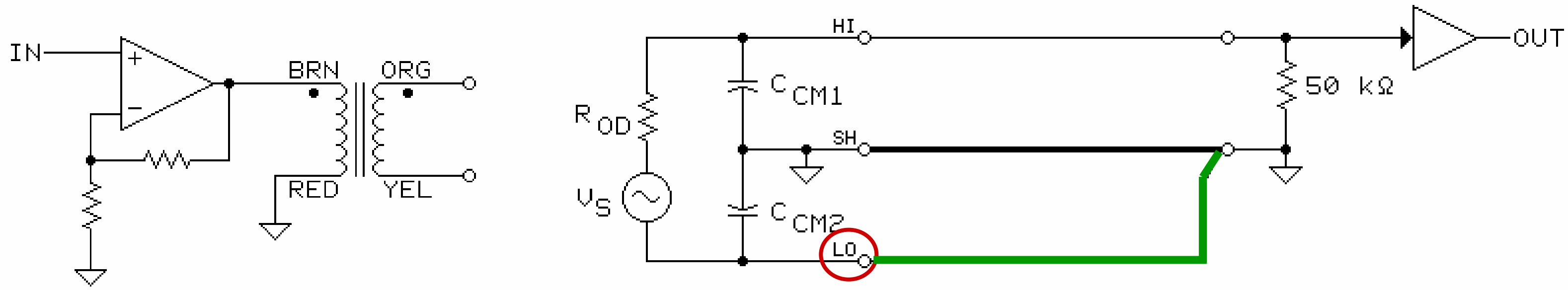




Equivalent Circuit with Unbalanced Receiver

- Either output can be grounded, but **only** at driver
  - Grounding at receiver can make driver unstable or oscillate
- Large level loss if one output left floating
- Identical to unbalanced for noise susceptibility

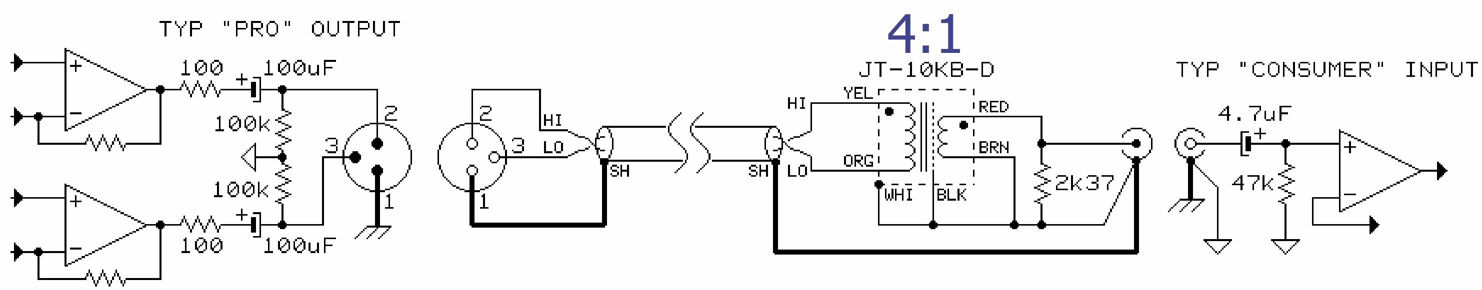
Transformer Floating



Equivalent Circuit with Unbalanced Receiver

- Either output can be grounded – anywhere
- Grounding at receiver gives 70 dB hum improvement
- Low-frequency loss if either output floats!!
  - Also applies to transformer-balanced inputs, regardless of driving source, if either input floats!!

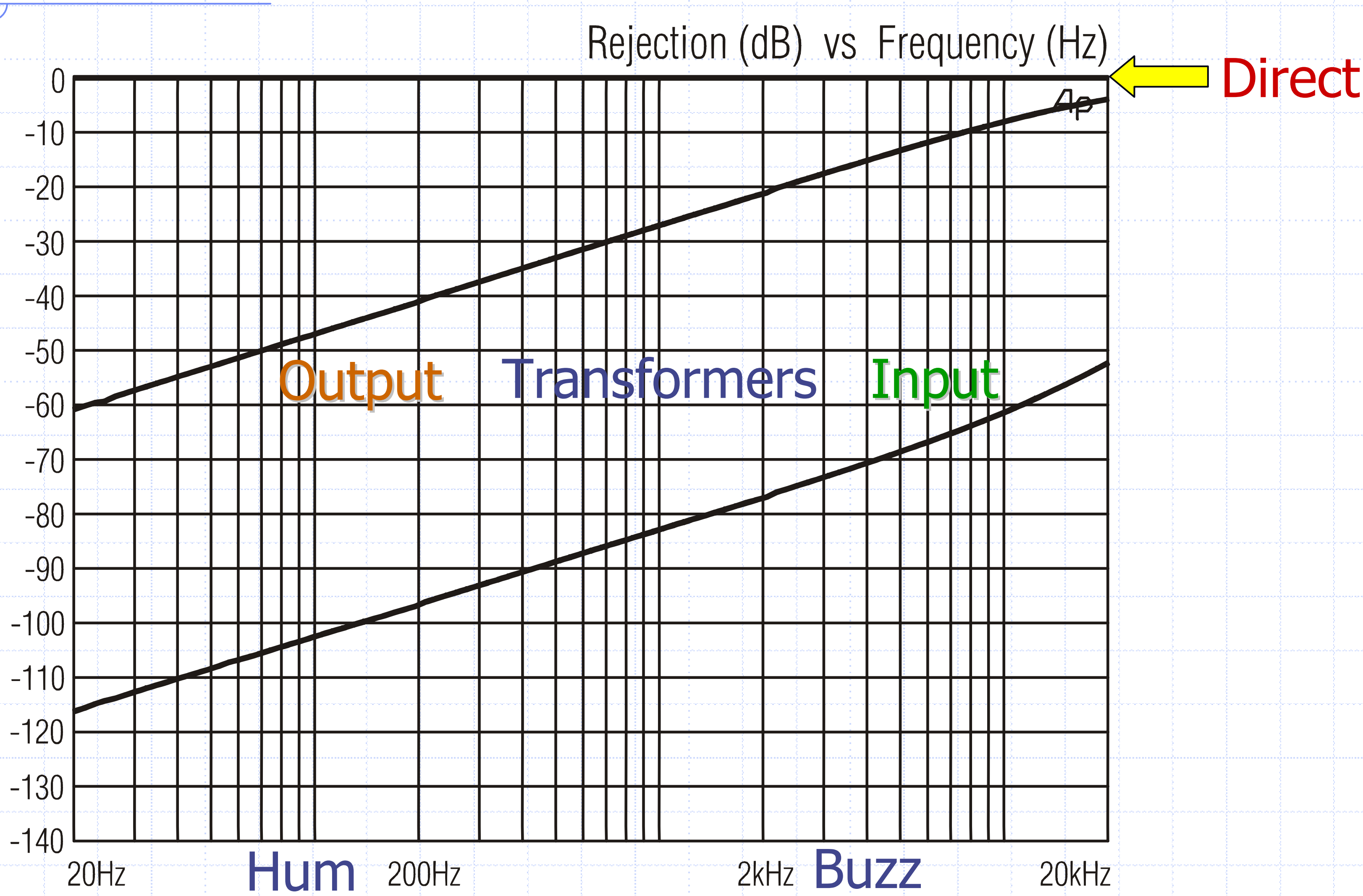
Don’t Worry, Be Happy



ISO-MAX® PC-2XR

- Works with **any** variety of output stage
- Transformer attenuates signal 12 dB
- Superior ground noise rejection

Relative CMRR Performance



RF Interference

- Electromagnetic interference (EMI) difficult to avoid, especially in urban areas
  - Radiated
    - Short-wave, commercial, ham, and CB radio
    - TV and FM broadcast
    - Remote controls, wireless, and cell phones
    - Radar, medical, and industrial RF devices
  - Radiated and/or Conducted
    - AM radio
    - Power line arcing or corona discharge
    - Malfunctioning fluorescent or neon lighting
    - Electric welders, brush motors, relays, and switches

Look Around

- Strongest sources are often within building and conducted via power wiring
- May share branch circuits with your system
- Source may be ***part*** of your system!
- Light dimmers, fluorescent lights, CRT displays, and switch-mode power supplies are most common offenders

RF Immunity

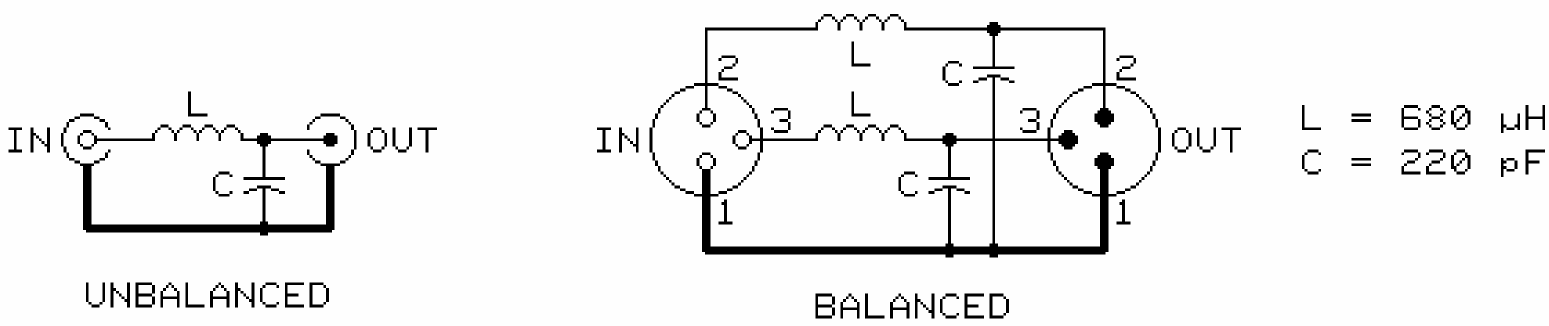
- **Good equipment design requires it**
- Testing now mandated in Europe, but CE mark is no guarantee
- Most equipment today has poor immunity
- Symptoms
  - Background voices, music, tones, clicks, etc.
  - TV signal causes buzz almost identical to 60 Hz
  - "Veiled" or "grainy" quality in audio
  - "Herringbone" patterns in video
  - Otherwise unexplained behavior in digital systems

Adding External RF Immunity

- Ferrite “clamshells” work well above ~ 20 MHz
- Generally most effective at receive end of cable
- More effective if cable looped several times
- For AM radio, low-pass filter usually necessary …

Fair-Rite Products

AM Radio Filter for Audio



- 50 kHz low-pass filters, best at receive end
- Capacitor NP0/C0G ceramic with short leads
  - Increase up to 1000 pF for tough cases
- Inductor I_{MAX} and DCR specs not critical
  - Use miniature toroids on mic lines to avoid hum
  - ±5% L and C for balanced version

Technical/Isolated Grounding

- Conduit touching *any* separately grounded metal can cause noise currents in safety ground system
- "IG" outlets insulate their safety ground from mounting saddle
- Grounded *only* by green wire routed back to electrical panel
- Covered by NEC Article 250-74

Leviton Mfg

Blame the Power Line?

"Today's residential systems contractors face unprecedented challenges where high resolution, trouble-free operation is required. From inducing AC ground loops, video hum bars, static bursts, damage from AC line surges and variable audio and video performance, comprehensive control and conditioning of AC power is no longer an option."

… product training description
by well-known manufacturer

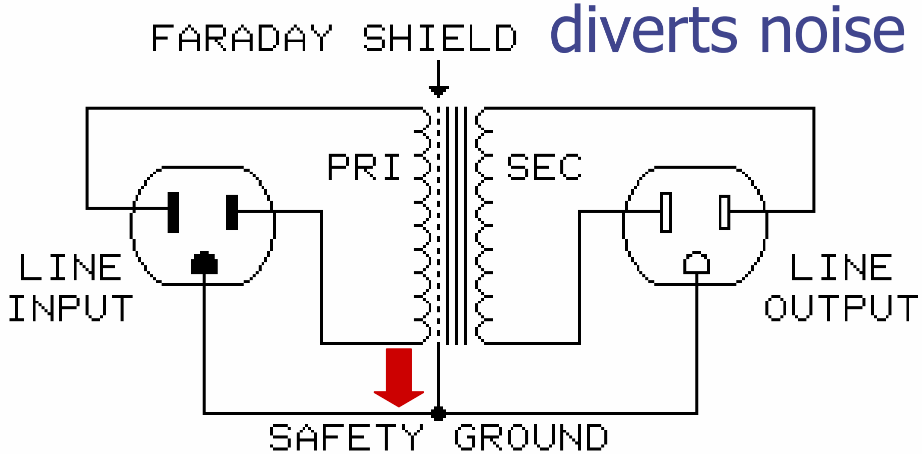
Power Filters, Conditioners, and Isolation Transformers

Since most noise is coupled from the power line, "purification" has great intuitive appeal

1. Purifier and load <u>must</u> be safety grounded
   - Purifier *adds* noise current to safety ground
   - Often makes **system** noise worse
2. Touted noise reduction specs are <u>unrealistic</u>
   - Measurements made in lab on *ground plane*
   - Real-world grounding uses wires or conduit

May help if installed at power service entrance where system grounds converge

Power Isolation Transformer



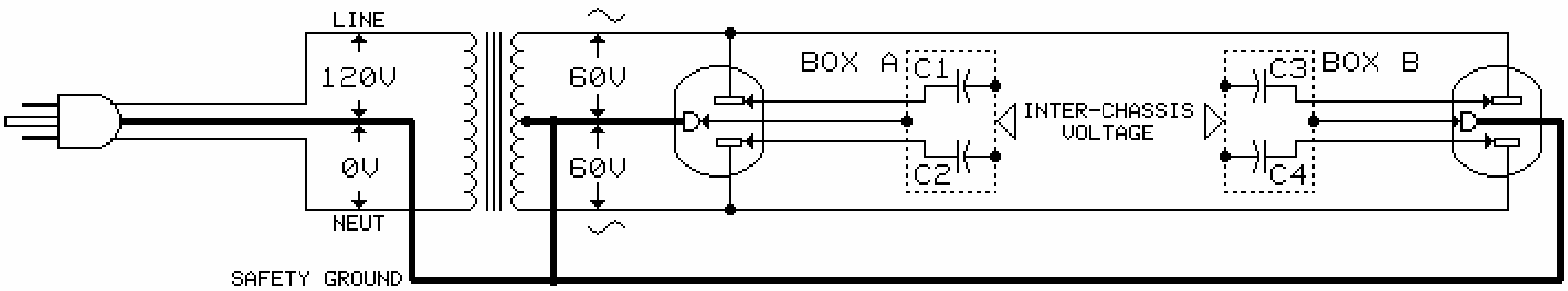
diverts noise away from secondary

and adds it to safety ground

"Balanced Power"

- *Symmetrical* power idea has seductive appeal
  - 120-volts between two 60-volt legs like 240-volts between two 120-volt "phases" of utility power
- In ideal world, it would completely <u>cancel</u> leakage currents into safety ground system
  - Equal and opposite voltage swings across equal capacitances would result in zero net current
  - In real equipment, capacitances from each leg to chassis are very <u>un</u>equal, more often a 3:1 ratio
- Actual noise reduction generally under 10 dB and rarely exceeds 15 dB
  - May be cost-effective in certain video applications

Symmetrical AC Power

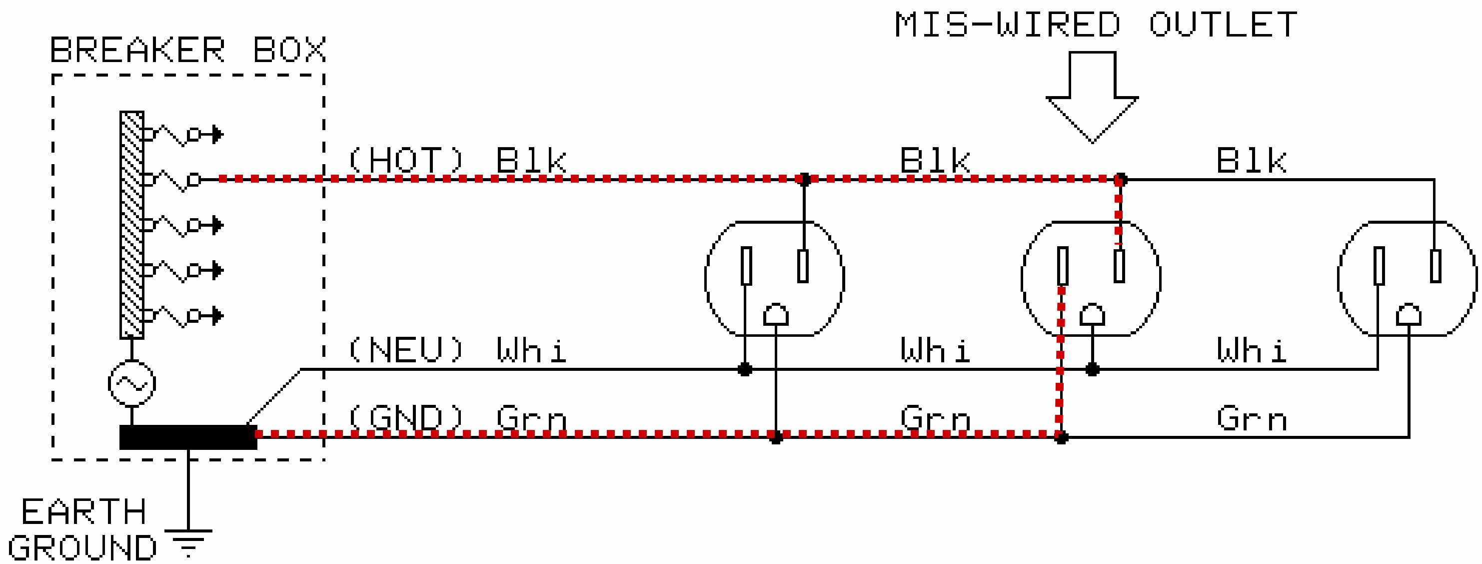


Ground current cancels *only* if C1=C2, C3=C4, etc.

Do They Work?

- Improvements, if any, are generally marginal
- More cost-effective to identify and treat point(s) where power line couples to signal
- Many benefits ascribed to “power treatment” schemes are actually due to plugging all system equipment into the same outlet strip or branch circuit – always a good idea!

A Real Problem, the N-G Swap



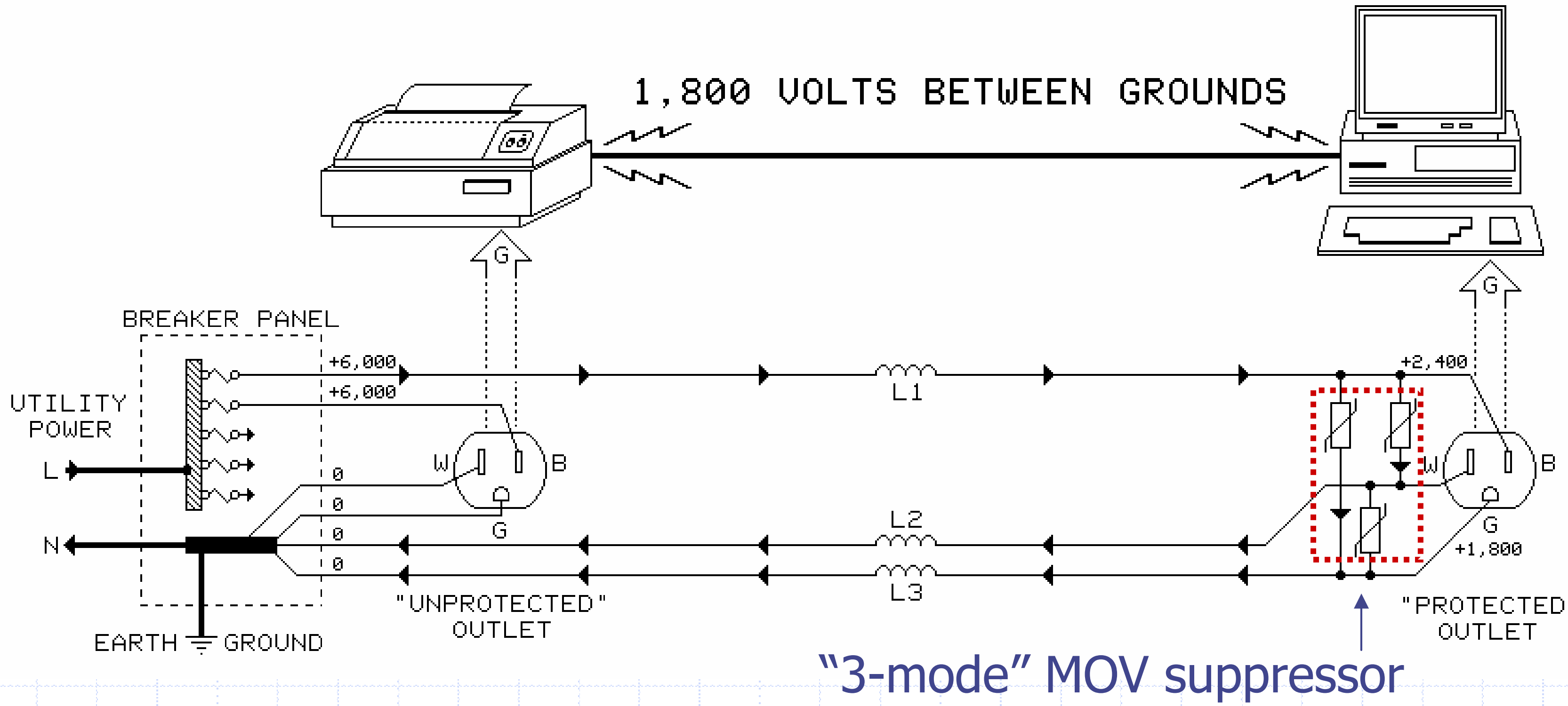
- *Load current* flows in safety ground wiring
- Voltage drops create **severe** noise problems
- *Not* detectable with simple testers

AEMC

About Surge Suppression

- Fear and pseudo-science are often used to sell surge protection devices
- Mindless use of *conventional* suppressors can actually <u>increase</u> equipment damage risk!
- The most widely-used suppressors employ three MOV (*metal-oxide varistor*) devices that divert surges into the safety ground system
- Surges generate brief but **extreme** voltage differences in the safety ground system
- Equipment interfaces are often damaged …

Surge Suppression DANGER!



Think Different …

- To protect from lightning induced surges, install devices at main power service entry
- To protect sub-circuits or equipment, install **series-mode** suppressors
  - They present a *high impedance* to the surge
  - They do <u>not</u> dump currents into safety ground

SurgeX

Thanks for Your Attention!

"Handbook for Sound Engineers"
includes Whitlock chapters on:

- ► Audio Transformers
- ► Microphone Preamplifiers
- ► Grounding and Interfacing

Think of a question later?

whitlock@jensen-transformers.com