



University of Moratuwa

Wisdom is all wealth

Noise and Interference in Instrumentation

Part 5

Anton F. P. Van Putte, Electronic measurement systems, Taylor & Francis, 2nd Edition

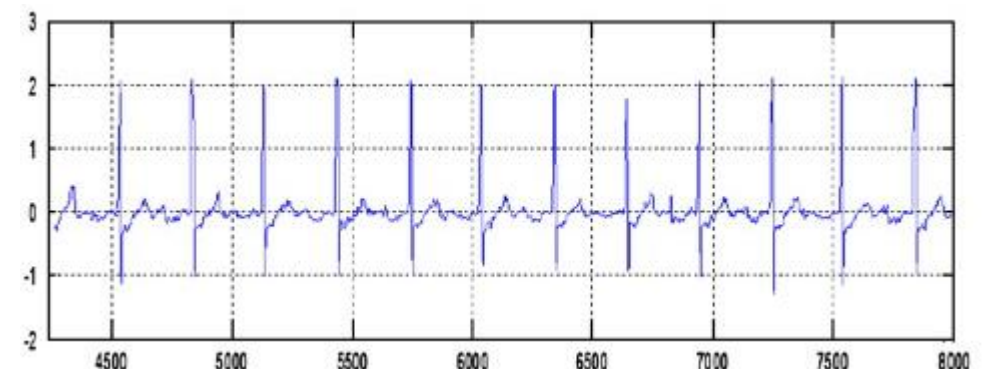
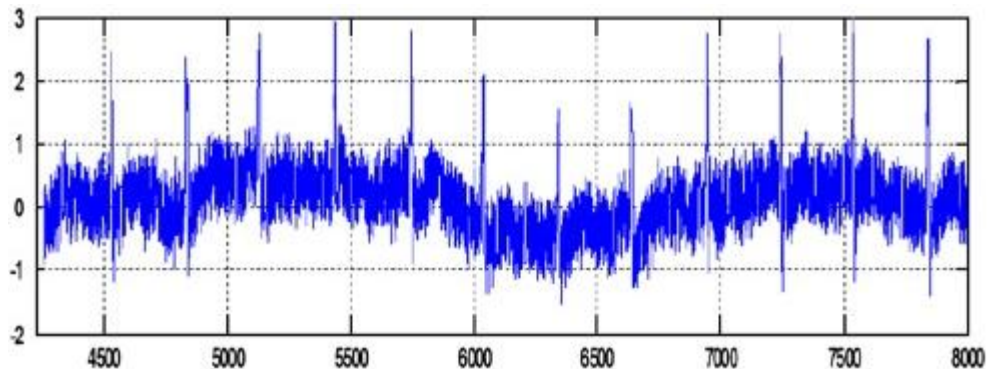
M. M. S. Anand, Electronic instruments and Instrumentation Technology, PHI

John G Webster, Medical Instrumentation- Application and Design, John Wiley & Sons, 4th Edition

R.S. Khandpur, Handbook of biomedical instrumentation, Tata McGraw-Hill, 3rd Edition

Definition of Interference

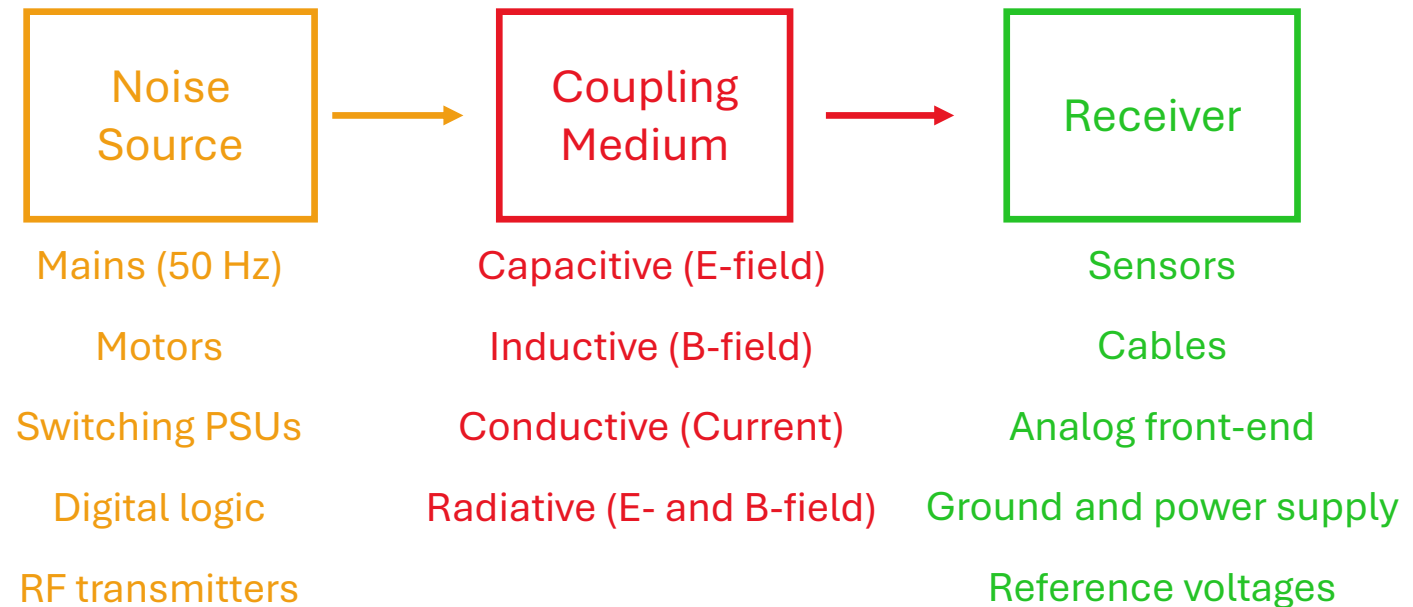
- Unwanted signals that originate from external sources.
 - Usually studied separately from noise that is intrinsic to devices and systems.
- Causes disruption or distortion to the desired signal
- Interference is often more structured and can be traced back to specific sources.
 - Noise is typically continuous and stochastic in nature



Images from: <https://doi.org/10.1016/j.neucom.2013.02.010>

Electrical Interference

- Interference exists only when the following three components exist in order:
 - A noise source, a coupling medium, and a receiver that reflects the coupled noise.
- By breaking/weakening any one link, you can mitigate the impact of noise.
 - Remove or reduce the source:
 - Ex: Move switching regulators away from the analog section.
 - Block the coupling path:
 - Ex: Shield (capacitive), twist wires and shrink loop area (inductive), use single-point grounding, filter the supply (conductive), add ferrites and RF filters (radiative).
 - Make the receiver less sensitive:
 - Ex: Use differential inputs with high CMRR, keep high-impedance nodes short.



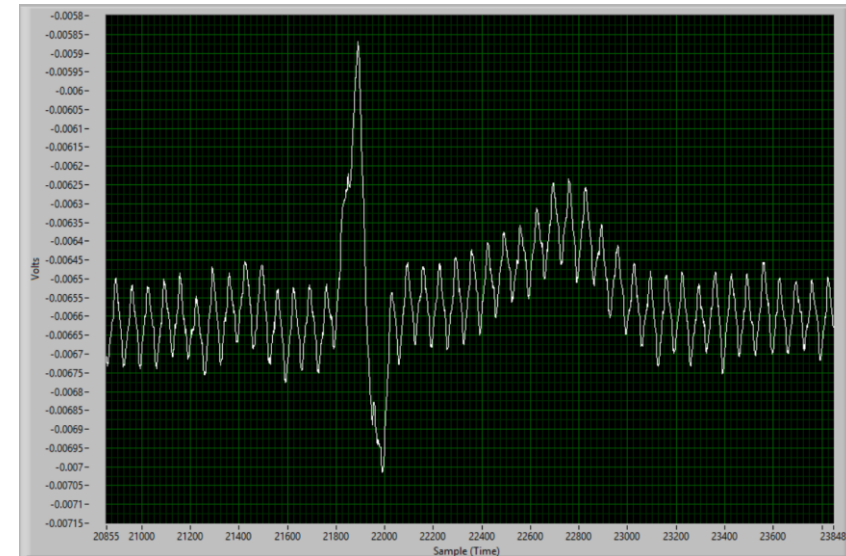
Observing Noise and Interference Effects

- It is important to identify and analyze noise and interference in our electronic systems.
- This enables us to determine the type of noise involved and design appropriate mitigation techniques.
- We can measure and characterize noise using electronic measurement instruments such as:
 - Oscilloscopes
 - Spectrum Analyzers
 - Multimeters

Observing Noise and Interference Effects

Oscilloscope

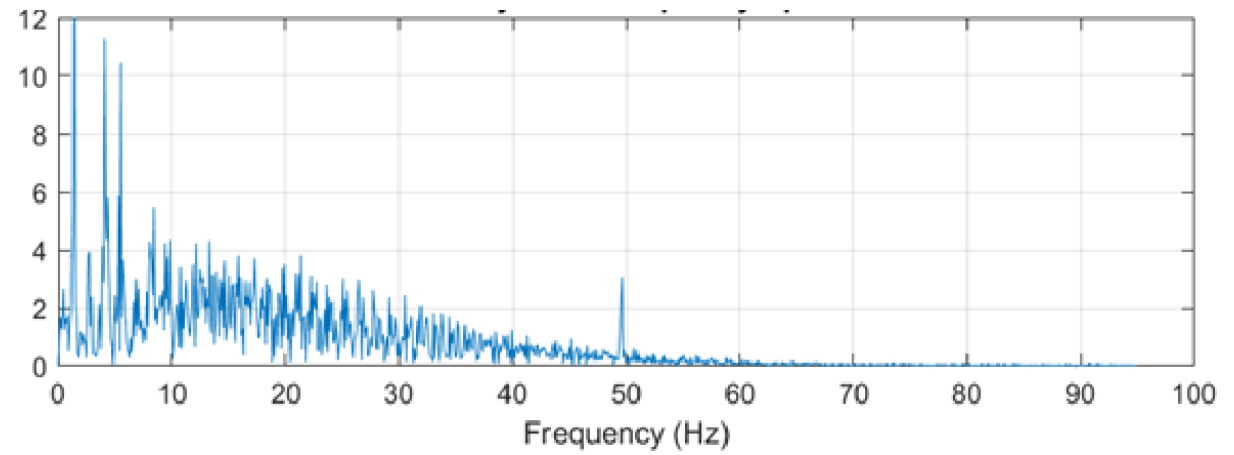
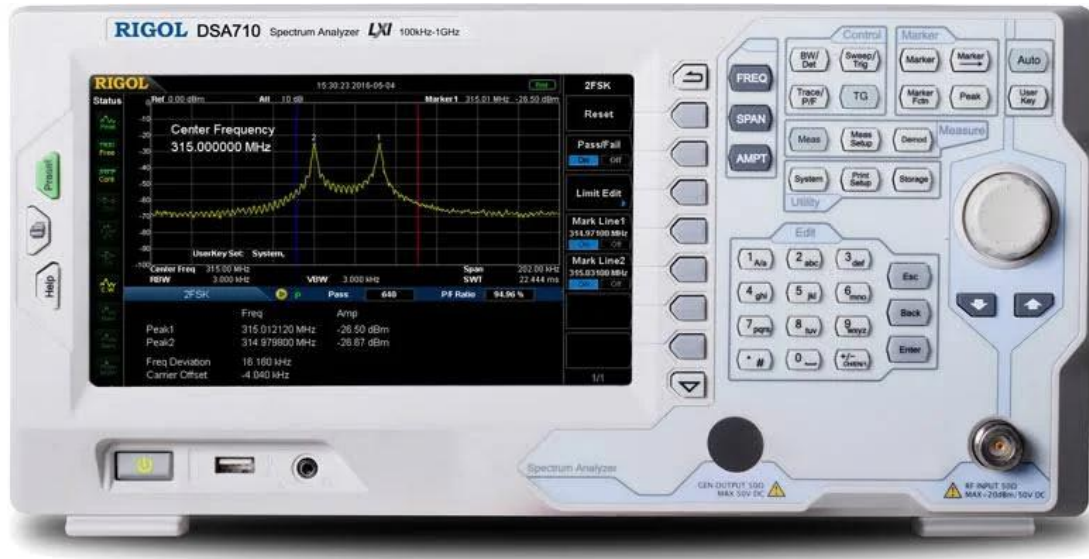
- Displays signal waveforms in time domain and time domain characteristics of noise like:
 - real-time fluctuations,
 - peak to peak amplitudes
- Use Time base and voltage scale settings, triggering techniques to measure signal/noise parameters.
- Image to the right shows powerline interference on top of an ECG signal.



Observing Noise and Interference Effects

Spectrum Analyzer

- Used to analyze frequency domain characteristics of noise by obtaining the noise spectral densities.
- Use frequency range, resolution, and bandwidth settings for signal/noise parameter characterization.
- Spectrum analyzers help to identify interfering frequencies and frequency bands where noise is mostly prominent.
- In the figure to the right, we can see power line interference at 50 Hz.



Observing Noise and Interference Effects

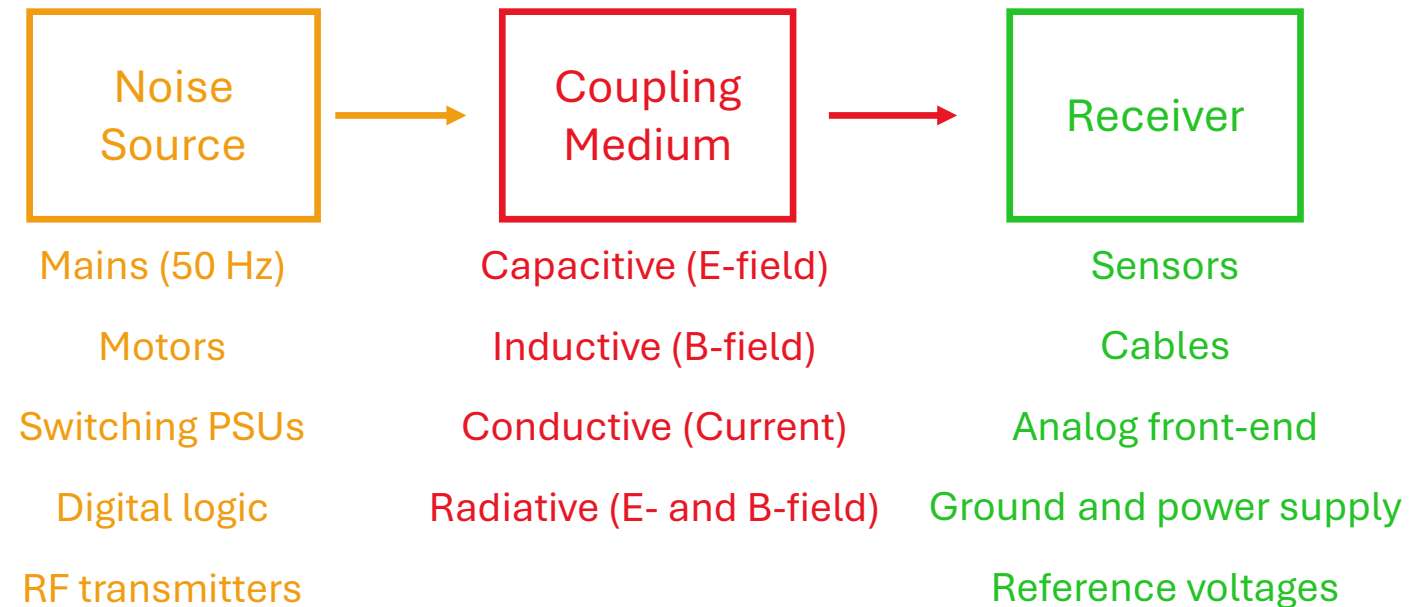
Multimeter

- A precise bench-top multimeter may be used to measure noise RMS in the absence of a signal.
 - However, note that a multimeter's RMS reading only covers noise that falls within its limited bandwidth.
- It can also be used to measure other circuit parameters like resistances, DC offset voltages, ground potential differences, etc.



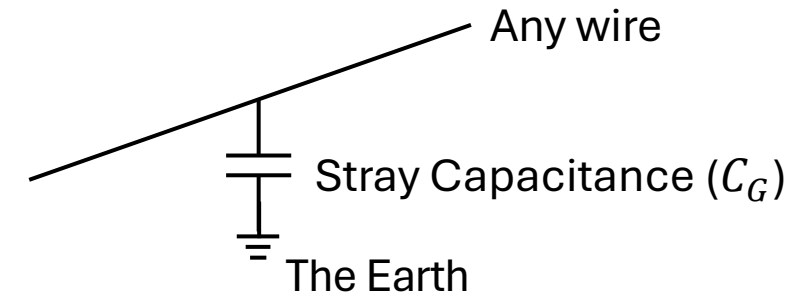
Mitigation Techniques

- Noise mitigation plays a critical role in preserving SNR.
- Techniques include:
 - Shielding
 - Filtering
 - Isolation
 - Differential signaling
 - Proper grounding
 - Proper PCB layouts
- In the next few slides, we look at the different coupling media, and corresponding mitigation techniques.



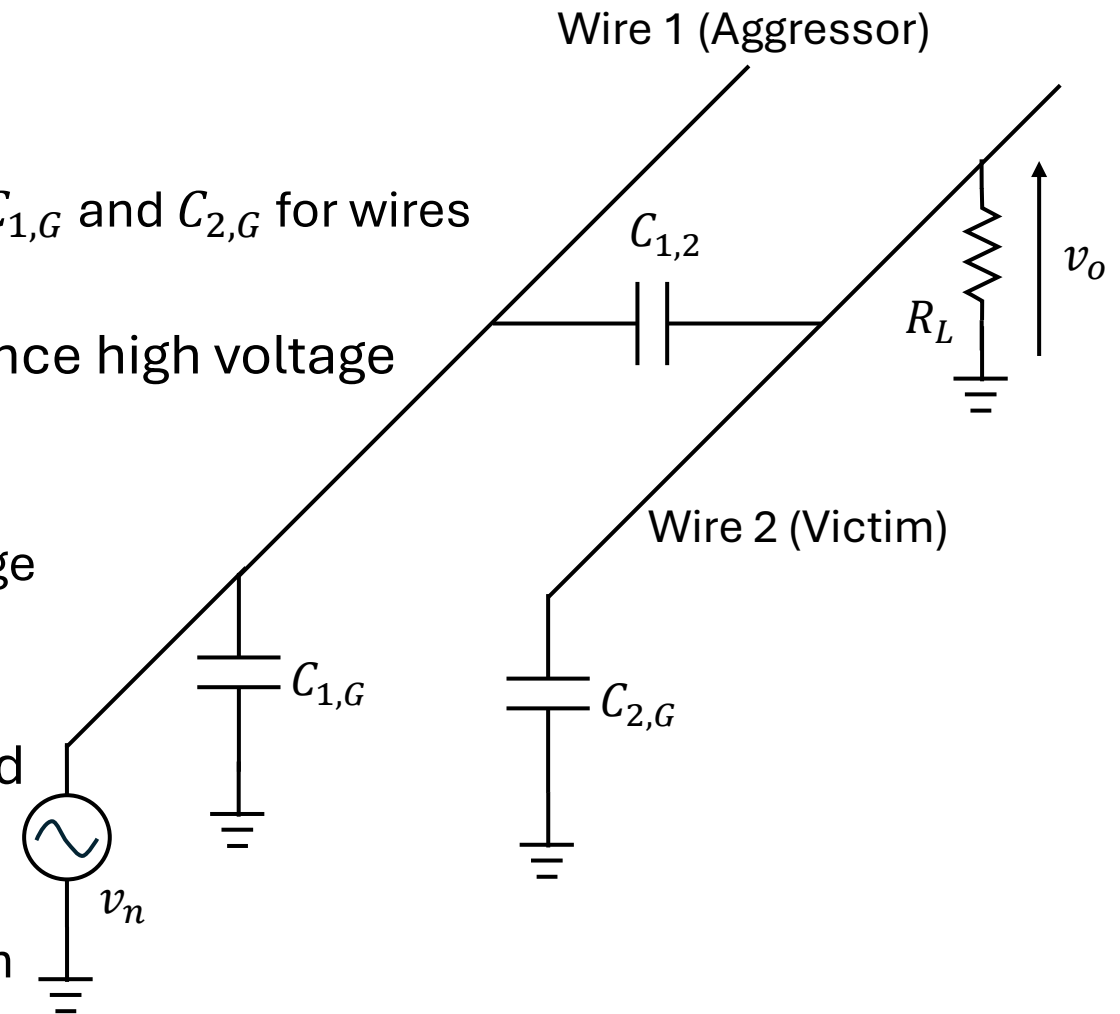
Capacitive Coupling

- Definition: Interference due to the presence of stray capacitances between any two conductive media separated by a dielectric.
 - Ex: Two wires separated by an air gap.
 - The wires are conductors, and the air is a dielectric.
 - Ex 2: A single wire.
 - Any wire has a stray capacitance to earth:
 - Remember, the earth is also a conductor, therefore, two conductors separated by an air gap (dielectric) becomes a capacitor.
- Capacitive coupling can cause interference and crosstalk between nearby wires/traces.
 - Main noise sources (aggressors) include:
 - high voltage lines
 - ex: mains grid
 - high frequency lines
 - ex: PCB traces around switching power supplies
- Shielding and changes to wire routing can mitigate capacitive coupling.



Capacitive Coupling between two wires

- Consider two wires running parallel to each other.
- Any conductor has a stray capacitance to ground.
 - Let's denote these stray capacitances to ground as $C_{1,G}$ and $C_{2,G}$ for wires 1 and 2 respectively.
- Assume the first wire is connected to a low impedance high voltage source v_n .
 - Ex: a power line carrying 230 V_{RMS} 50 Hz.
 - Since it has a low impedance, we assume that voltage generated by this source is spread across the entire wire 1 without attenuation.
- Assume the wire 2 has a resistive load R_L connected to it.
 - Ex: input impedance of an amplifier stage if we assume that the wire 2 carries a sensitive signal from a sensor.

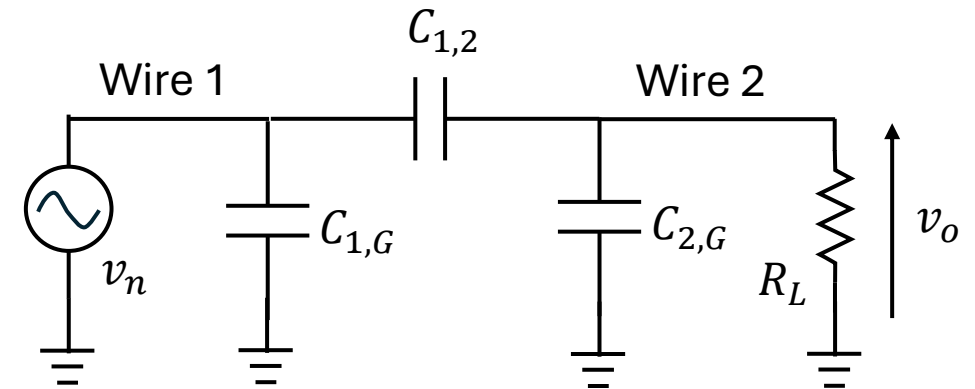


Capacitive Coupling between two wires

- The noise observed at the receiver v_o is:

- $$v_o = v_n \times \frac{Z_{C_{2,G}} || R_L}{Z_{C_{1,2}} + (Z_{C_{2,G}} || R_L)} = v_n \times \frac{1}{1 + \frac{Z_{C_{1,2}}}{Z_{C_{2,G}} || R_L}}$$
 - $$\frac{Z_{C_{1,2}}}{Z_{C_{2,G}} || R_L} = \frac{1 + j\omega R_L C_{2,G}}{j\omega R_L C_{1,2}}$$
- $$\therefore v_o = v_n \times \frac{1}{1 + \frac{1 + j\omega R_L C_{2,G}}{j\omega R_L C_{1,2}}} = v_n \times \frac{j\omega R_L C_{1,2}}{1 + j\omega R_L (C_{1,2} + C_{2,G})}$$

- This resembles the voltage at the output of a highpass filter.



Capacitive Coupling between two wires

At low frequencies and small load impedance

- For situations where the load resistance R_L is much smaller than the impedances of the coupling capacitances, we have:
 - $R_L \ll \left| \frac{1}{j\omega(C_{1,2} + C_{2,G})} \right| \Rightarrow 1 + j\omega R_L(C_{1,2} + C_{2,G}) \approx 1$
 - This is a reasonable assumption because the coupling capacitances are typically very small.
 - The capacitance (C) of a simple parallel plate capacitor is given by $C = \frac{A\epsilon}{d}$ where A and d are the overlapping area and the distance between the parallel plates respectively.
 - The capacitance of a more complex structure follows similar trends.
 - Given the typical distances between conductors, and the low relative permittivity of air (assuming the coupling happens through air – note that this doesn't have to be the case), the capacitances tend to be very small.
 - In addition, we mostly consider capacitive coupling effects from the 230 V supply grid which has a relatively small ω of $2\pi \times 50$
- Therefore, we can approximate $v_o \approx v_n \times j\omega R_L C_{1,2}$

Capacitive Coupling between two wires

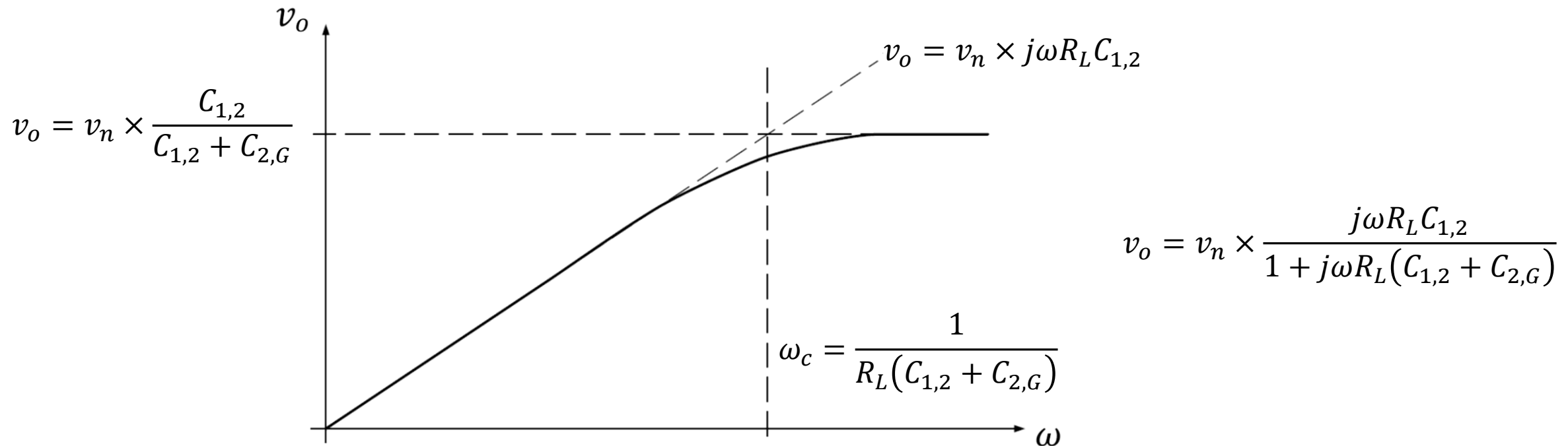
At high frequencies and high load impedance

- However, this approximation does not hold for situations where the noise source has higher frequency (ex: noise from a switching power supply), and if the victim has a high impedance (ex: a high-input-impedance amplifier).
 - Now, $v_o = v_n \times \frac{j\omega R_L C_{1,2}}{1 + j\omega R_L (C_{1,2} + C_{2,G})} = \frac{C_{1,2}}{\frac{1}{j\omega R_L} + (C_{1,2} + C_{2,G})}$
- Since both ω and R_L are now high, we have $\frac{1}{j\omega R_L} \rightarrow 0$
 - Therefore, $v_o \approx v_n \times \frac{C_{1,2}}{C_{1,2} + C_{2,G}}$

Capacitive Coupling between two wires

The transfer function

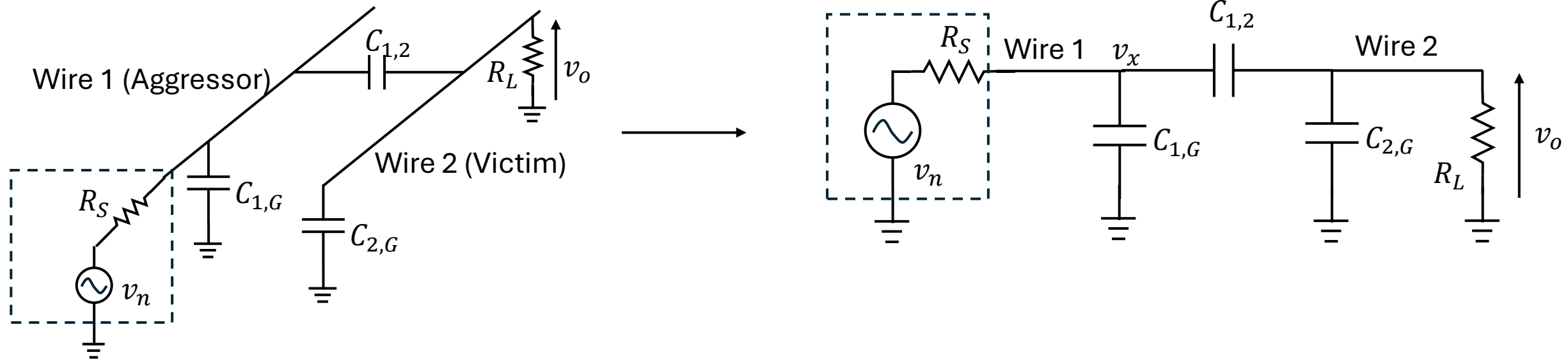
- Transfer function for the noise for the capacitively coupled wires.
- Observe how this resembles the transfer function of a high pass filter, indicating that higher the noise frequency, higher the chance of coupling.
 - Digital signals may have small source voltage, but their fast-switching nature can cause cross-talk between parallel signal lines that run close to each other.



Capacitive Coupling between two wires

Impact of a high impedance source

- If the source (aggressor) has a high source impedance R_S , the voltage at v_x will be a low-pass filtered version of v_n .
 - $v_x = v_n \times \frac{Z}{R_S + Z}$ where $Z = Z_{C_{1,G}} \parallel (Z_{C_{1,2}} + [R_L \parallel Z_{C_{2,G}}])$
- Therefore, the strength of coupling will go down except for the band where the pass bands of the low pass filter ($f < f_{LP}$) and the subsequent high pass filter ($f > f_{HP}$) overlaps.
 - If R_S is large enough that $f_{HP} > f_{LP}$, there will be no overlap, hence coupling will be weak at all frequencies.



Capacitive Coupling

Mitigation Strategies

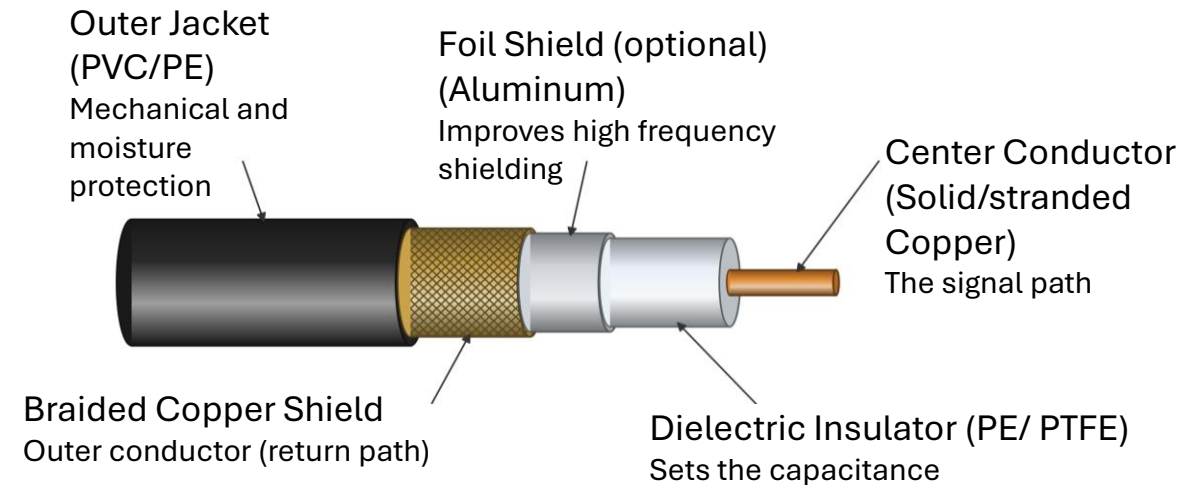
- The capacitance (C) of a simple parallel plate capacitor is given by $C = \frac{A\epsilon}{d}$ where A and d are the overlapping area and the distance between the parallel plates respectively.
 - The capacitance of a more complex structure follows similar trends.
 - In general, the capacitance can hence be reduced by increasing the distance between the conductors, minimizing the overlap area, and by using a material with low relative permittivity in between.
- A conductive shield connected to the signal reference terminates the aggressor's electric field lines on the shield instead of the victim.

Shielding

- Shielding blocks external electromagnetic interference due to capacitive coupling.
 - Remember, the concept of a Faraday Cage!
- Different types of shielding include foil, metallic braiding, and combination shielding.
- Shielding is essentially implemented by encasing cables and equipment in conductive material and maintaining this conductive casing at a fixed (typically) potential.
 - Maintaining at a single potential is typically done by grounding the shield.
 - However, there could be other forms of shields that are actively driven to cancel out interference.
 - Ex: Driven guard rings.



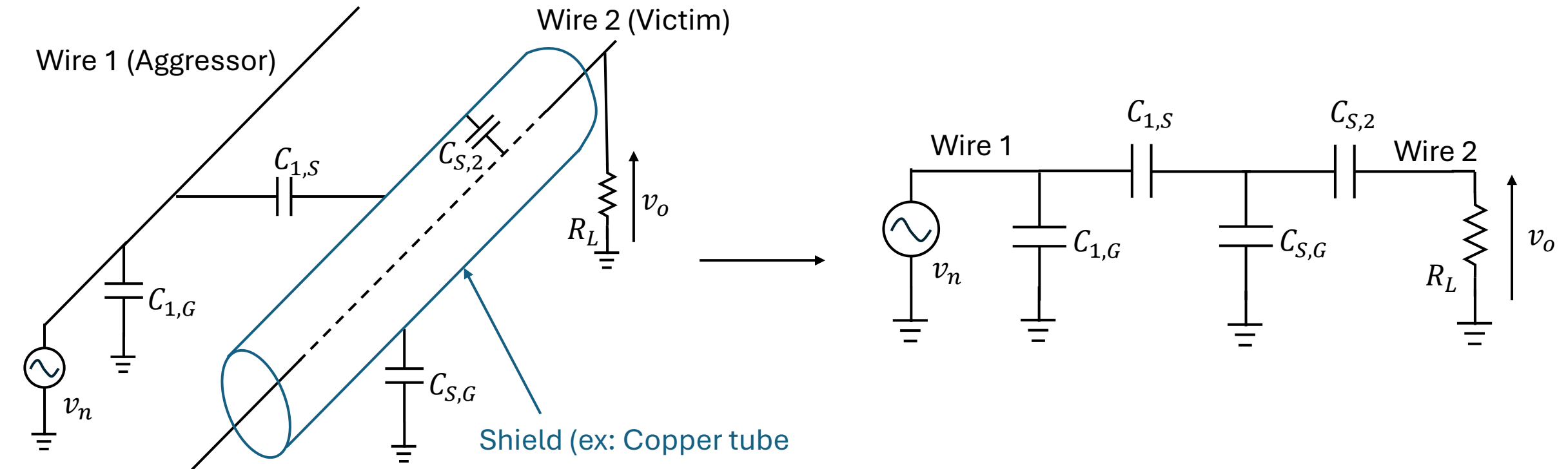
Wikipedia



Shielding

Reduce Capacitive Coupling

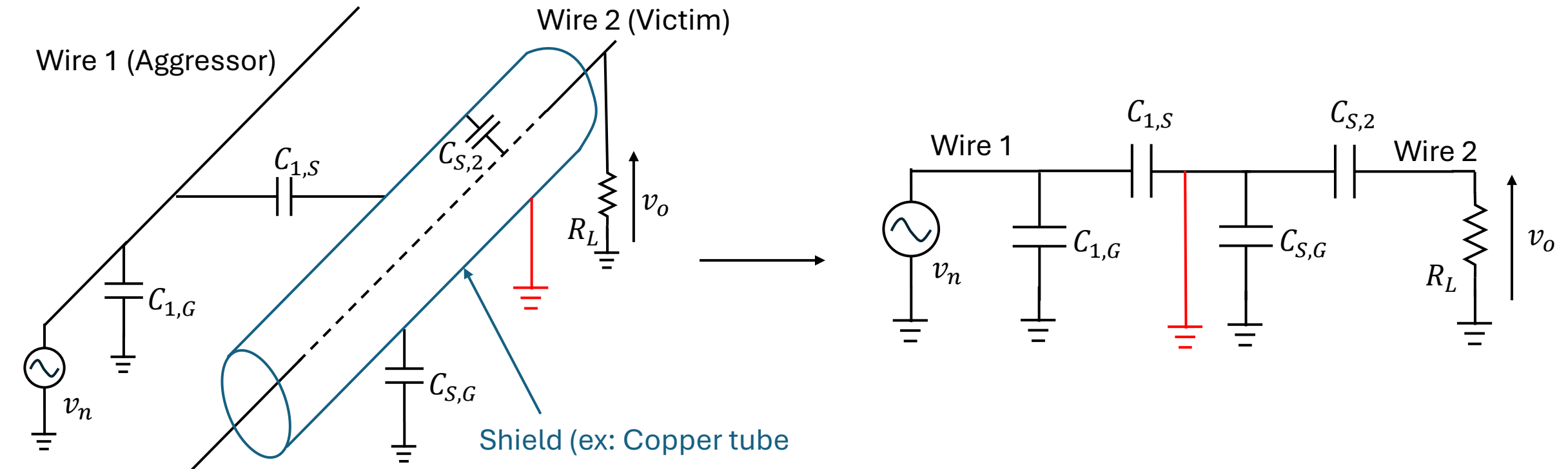
- A simple copper tube may be applied around a wire as the shield
 - However, as can be seen with the equivalent figure to the right, this only adds an extra capacitance and merely changes the effective capacitor divider ratio.
 - It does not prevent capacitive coupling onto wire 2 unless we make a modification.



Shielding

Reduce Capacitive Coupling

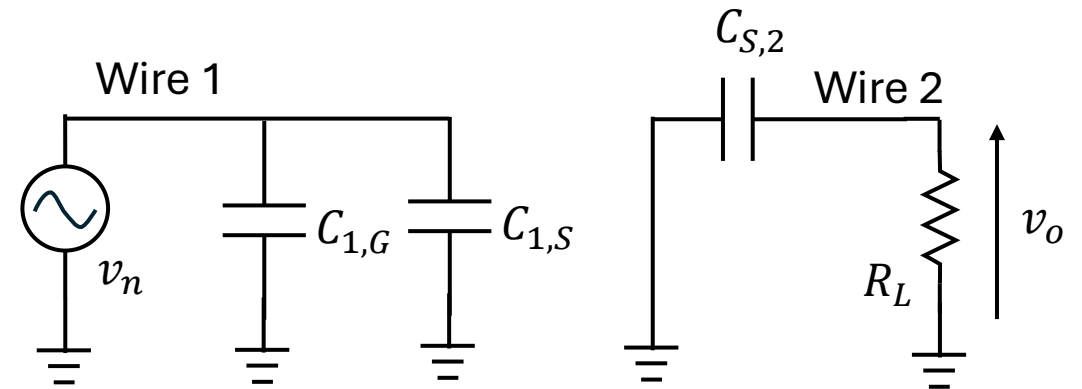
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 - Connect the shield to ground!



Shielding

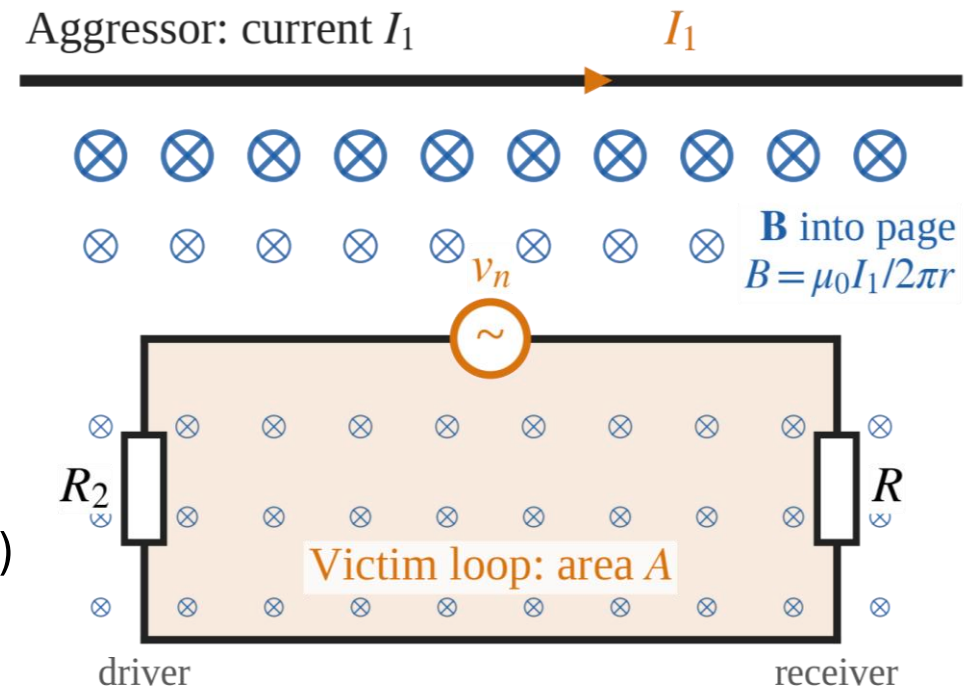
Reduce Capacitive Coupling

- A simple copper tube may be applied around a wire as the shield
 - However, as can be seen with the equivalent figure to the right, this only adds an extra capacitance and merely changes the effective capacitor divider ratio.
 - It does not prevent capacitive coupling onto wire 2 unless we make a modification.
 - Connect the shield to ground!
 - Now there will be no coupling between the source and the victim wire as long as the shield remains at the constant GND potential despite external or internal interference.



Inductive (Magnetic) Coupling

- This is the magnetic counterpart of capacitive coupling.
 - A changing current in one conductor (the **aggressor**) creates a changing magnetic field around it.
 - A changing field passing through a loop of another circuit (the **victim**), induces a voltage (Faraday's law).
 - The victim is the loop, not the wire:
 - What matters is the area enclosed between the signal path and its return path.
 - The induced voltage appears in series with the victim loop.
- Typical aggressors:
 - large or fast-changing currents
 - mains and power cables, transformers, motors
 - switching-converter current loops
- Mitigation:
 - distance,
 - small loop area (twisting, or placing wires close to each other)
 - orientation,
 - magnetic shielding

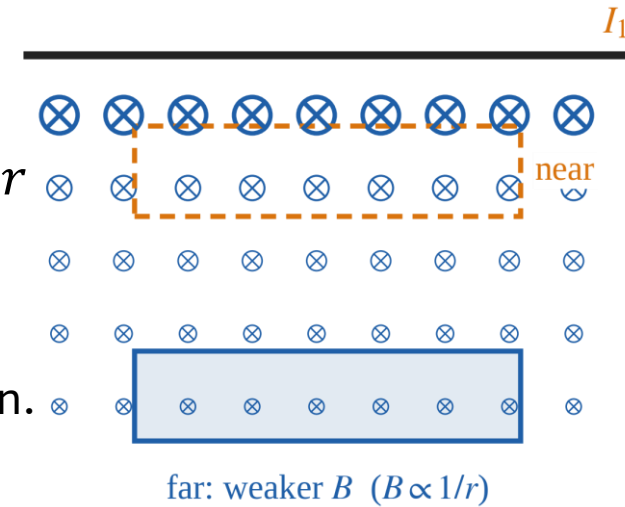


Inductive Coupling

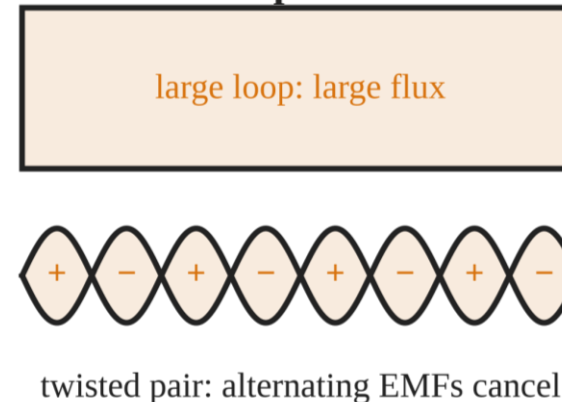
Reduce Inductive Coupling

- Formula for the induced EMF in a loop with area A lying at an angle θ to a sinusoidally changing magnetic field with amplitude $B(r)$ and angular frequency ω is given by $v_n = j\omega B(r)A \cos\theta$.
 - r is the radial distance from the source of the magnetic field and B falls as $1/r$ for a single wire source.
- Mitigation:
 - Every term in the formula $v_n = j\omega B(r)A \cos\theta$ is a lever for inductive coupling mitigation.
 - Reduce B by increasing distance from the aggressor
 - Route the aggressor's outgoing and return conductors together so their fields cancel.
 - Victim's loop area A is set by how far away its return path is from its signal path.
 - Keep them close to each other.
 - Twisting cables don't reduce loop area but causes the induced EMFs in each loop to cancel out against the next.
 - Make $\theta \rightarrow 90^\circ$ by running sensitive loops at right angles to the field (ex: cross a mains cable at 90°)

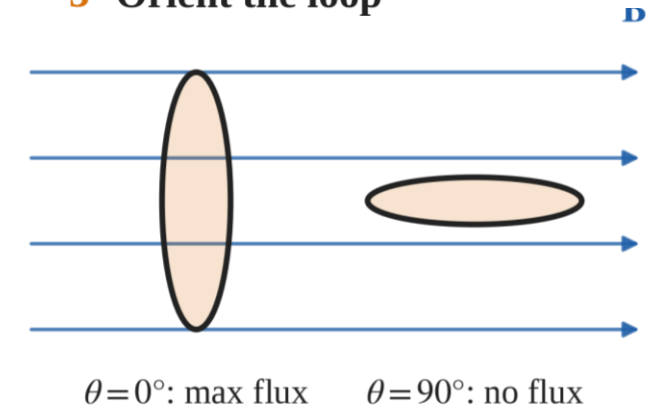
1 Increase distance



2 Reduce loop area



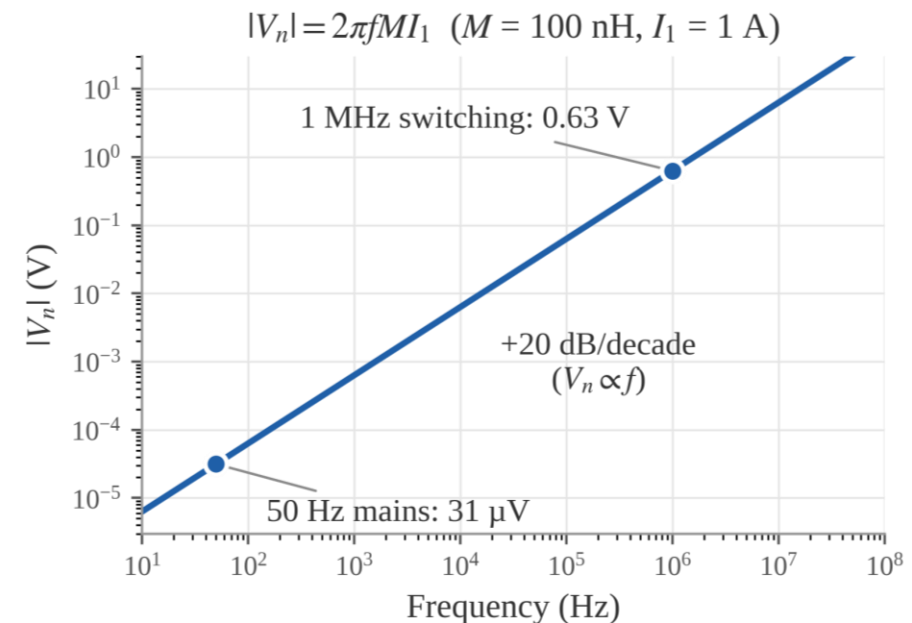
3 Orient the loop



Inductive Coupling

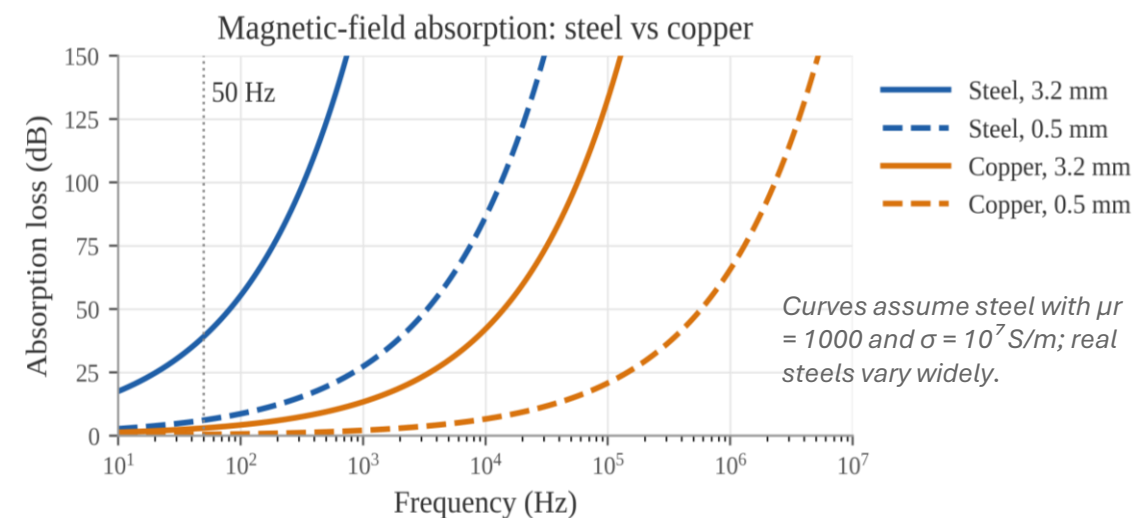
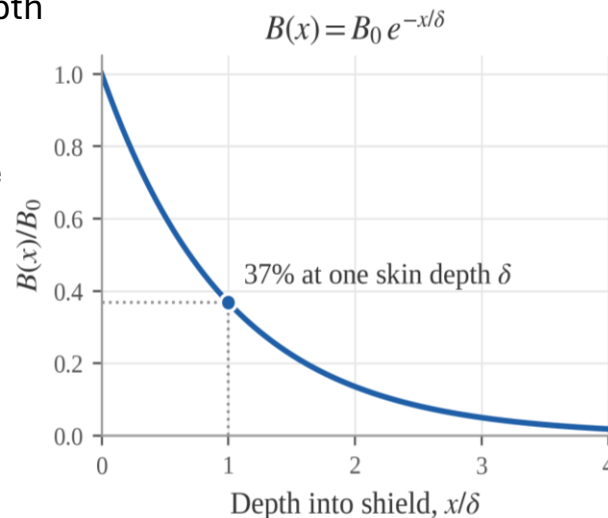
Reduce Inductive Coupling

- The induced voltage due to inductive coupling rises in proportion to frequency of the aggressor.
 - $v_n = M_{1,2} \frac{di_1}{dt}$ where $M_{1,2}$ is the mutual inductance between the aggressor and the victim, and i_1 is the current on the aggressor. – Indicates that faster changing currents/edges couple more than slower ones.
- Example:
 - Consider a wire carrying 50 Hz mains current forming a mutual inductance of 100 nH with a nearby conductor. Assume the mains wire is carrying an RMS current of 1 A.
 - We have $v_n(t) = 100 \times 10^{-9} \times \frac{d}{dt} (1\sqrt{2} \times \sin(2\pi \times 50t))$
 - $\therefore V_{n_{RMS}} = 100 \times 10^{-9} \times 2\pi \times 50 \times 1 = 31.4 \mu V$
 - Now consider the same coupling (100 nH mutual inductance), and same current on the aggressor (1 A RMS), but oscillating at $f = 1$ MHz.
 - Now, $V_{n_{RMS}} = 0.63$ V which is a 20000-fold increase, and a practical concern with switching power supplies.
 - Even when they carry lower currents than the AC mains, their sheer switching frequency causes them to couple a lot of interference via inductive coupling.



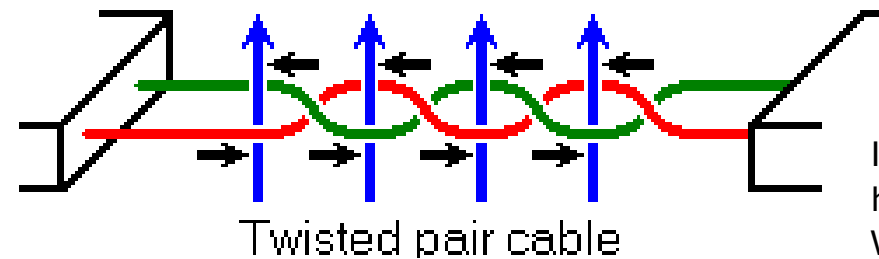
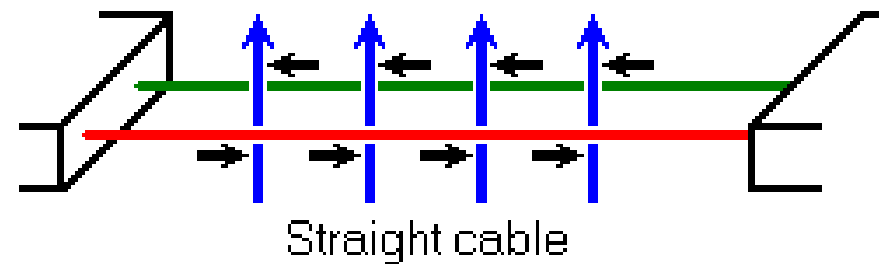
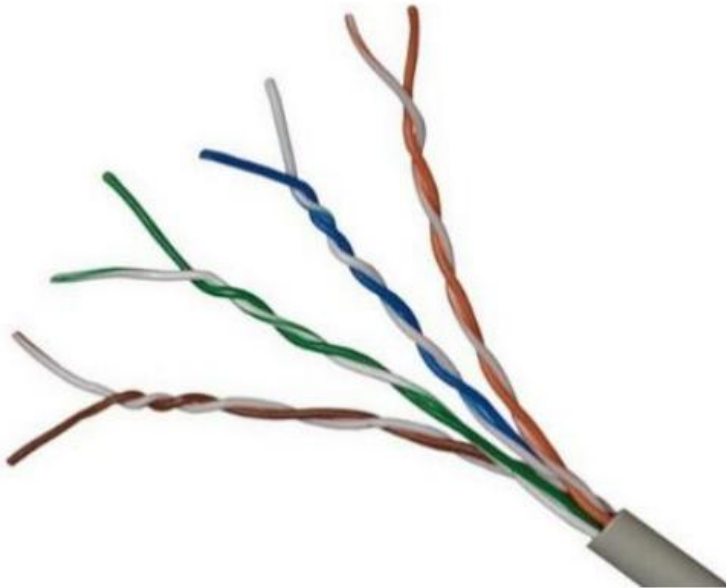
Shielding Magnetic Fields

- Electric fields are easy to shield - Almost any thin, grounded conductor works.
- However, thin conductors may **not** be able to stop low-frequency magnetic fields.
 - Magnetic fields penetrate conductors and are mainly attenuated by absorption.
 - A shield absorbs/attenuates the magnetic field B along the thickness of the shield x as:
 - $B(x) = B_0 e^{-x/\delta}$, with $\delta = 1/\sqrt{\pi f \mu \sigma}$ is the 'skin-depth'
 - Here f is the frequency of the interference, and μ and σ are the magnetic permeability and the electrical conductivity of the shielding material respectively.
- At 50 Hz copper has a skin depth of ≈ 9 mm
 - $\therefore$ a 0.5 mm copper shield is almost transparent.
- Steel's high permeability shrinks the skin depth to under 1 mm.
 - $\therefore$ steel is used for low-frequency magnetic shielding.
- 0.5 mm thick copper only becomes effective in the hundreds of kHz and above.
- Practical message:
 - At mains frequency (50 Hz), it is usually much easier to reduce inductive pickup with distance, small loop areas, twisting and orientation than with a shield.



Twisted Pair Cables

- Voltage induced in the cables due to external magnetic fields can cause currents to flow in wires, causing interference in the signal.
- By twisting the pair of cables, the induced current direction will be alternate, thereby cancel each other out.
 - This will cancel out the interference.



→ **Magnetic field**
→ **Induced noise current**

Image retrieved from:
<https://www.researchgate.net/post/What-is-the-basic-idea-behind-the-twisted-pair-Why-are-the-two-wires-twisted-How-does-this-arrangement-compensate-undesirable-disturbances>

Capacitive vs Inductive Coupling

Aspect	Capacitive coupling	Inductive coupling
Coupling field	Electric field (E)	Magnetic field (B)
Coupling element	Stray capacitance $C_{1,2}$	Mutual inductance $M_{1,2}$
Aggressor	Node with a large or fast voltage change $\frac{dv}{dt}$	Conductor with a large or fast current change $\frac{di}{dt}$
Typical aggressors	Mains wiring near the patient, switch nodes, clock lines	Power and mains cables, transformers, motors, switching-converter loops
Noise in the victim	Current injected into the victim node: $i_n = C_{1,2} \frac{d}{dt} v_1$	Voltage in series with the victim loop: $v_n = M_{1,2} \frac{d}{dt} i_1$
Model coupled noise as	Current source (High source impedance)	Voltage source (low source impedance)
Most vulnerable victims	High-impedance nodes (electrodes, op-amp inputs)	Low-impedance circuits with a large loop area
Geometry that matters	Spacing and parallel length of conductors	Loop area, distance, orientation
Shielding	Thin grounded conductor works well	Thin conductors are poor at low frequency (needs steel or mu-metal)
Main fixes	Grounded shield, spacing, lower victim impedance	Twisting and small loops, distance, orientation

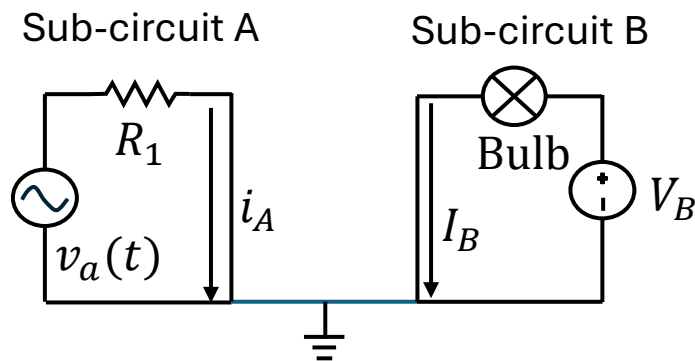
Conductive Coupling

- Conductive coupling happens when current from one circuit (a complete loop) flows through some impedance it shares with another circuit (a separate complete loop).
 - Any practical wire or PCB trace has a non-zero impedance:
 - Purely resistive at low frequencies.
 - Inductive reactance added in series with resistance at high frequencies.
 - If a single wire or PCB trace is shared between two subcircuits, currents from both circuits flow through this shared, common wire/trace.
 - Since it has non-zero impedance, a potential drop appears across the length of this wire/trace in response to currents flowing through it.
 - At low frequencies, the voltage drop $\Delta V = I \times R$ and at high frequencies, the voltage drop $\Delta V = I \times (R + j\omega L)$.

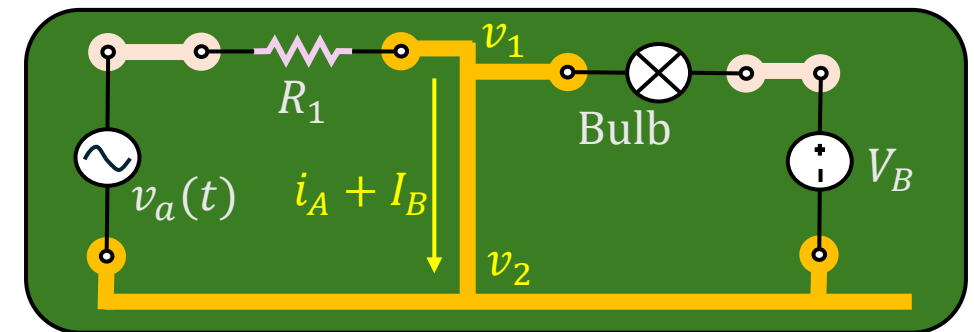
Conductive Coupling

Shared Ground Return

- Consider the following schematic.
 - Two sub-circuits share the same ground connection.
 - One possible implementation in PCB is shown on the right.
 - We will later look at a different implementation that will mitigate this effect.
 - The ground trace spreads throughout the PCB and multiple components connect to it at multiple points.
 - The two sub-circuits now share a common trace, and due to its finite impedance $Z_{1,2}$, and a total current $i_A + I_B$ flowing through it, a potential difference of $\Delta V = v_1 - v_2 = Z_{1,2} \times (i_A + I_B)$ is formed across it.
 - Consequently, if we assume the magnitude of i_A to be large, although the bulb is powered by a DC source V_B , it will begin to flicker at the frequency of the source $v_a(t)$.



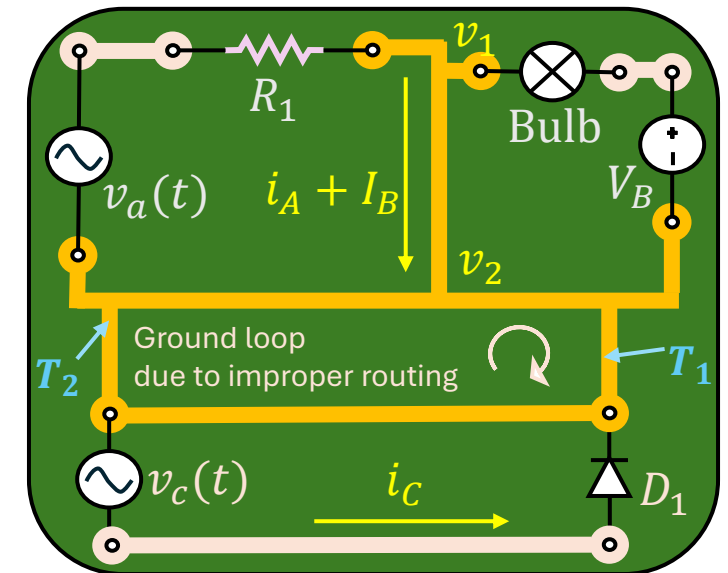
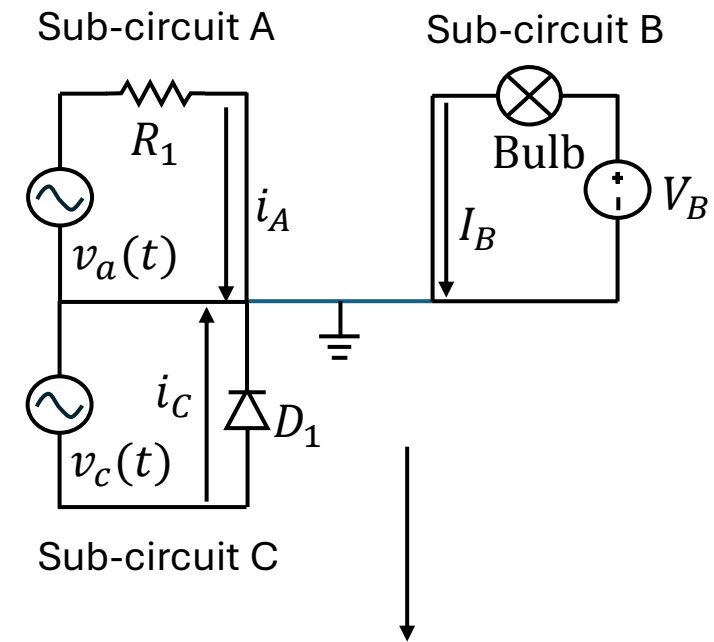
Schematic – Two circuits sharing the same ground



One possible implementation in PCB

Ground Loop Interference

- Ground loops occur when multiple ground connections close a loop.
 - Potential differences within a ground loop due to:
 - EMF induced by magnetic flux through the loop area (inductive coupling).
 - Ground-potential differences from other circuits' currents in shared ground impedance (conductive coupling).
 - These potential differences cause currents to flow inside the loop as well as into connected nodes.
- Generally, multiple wires/traces connecting together at different points can lead to loops.
 - However, **ground** loops get special attention due to their ubiquity.
 - Ground connections in a circuit are highly susceptible to loop formation because it is almost always a network of multiple nodes connecting to each other at different points in the circuit.
 - Improper grounding, multiple ground points connected inappropriately, long ground connections, devices powered via sources with separate grounds that are interconnected can all create ground loops, hence ground loop interference.



Removing **either** T_1 **or** T_2 will fix ground loop

Ground Loop Interference

- Long ground conductors are prone to capacitive, inductive, and conductive interference:
 - Long ground conductors have higher impedance (both resistance and inductance) hence can cause potential drops as currents flow through them.
 - Long conductors enclose larger loop areas which can inductively couple noise.
 - Since ground conductors have low impedances, the induced EMF drives a large circulating current.
 - Ground conductors can capacitively couple noise, but this coupling is weak due to their low impedances.
 - However, as length of the ground conductor increases, it will have higher stray capacitance, hence capacitive coupling too increases.
- Ground loops can be both large-scale (between devices) or within a single PCB.

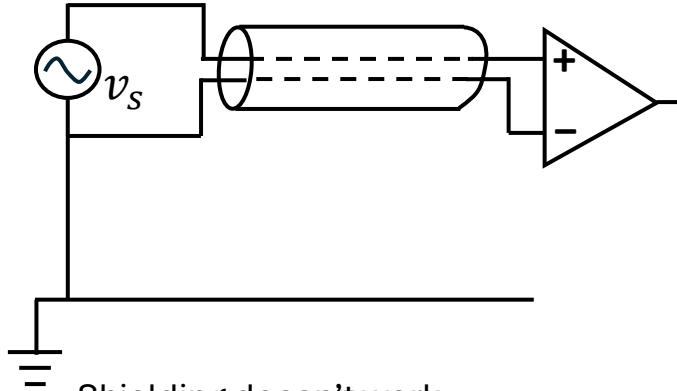
Ground Loop Interference

Improper Shielding

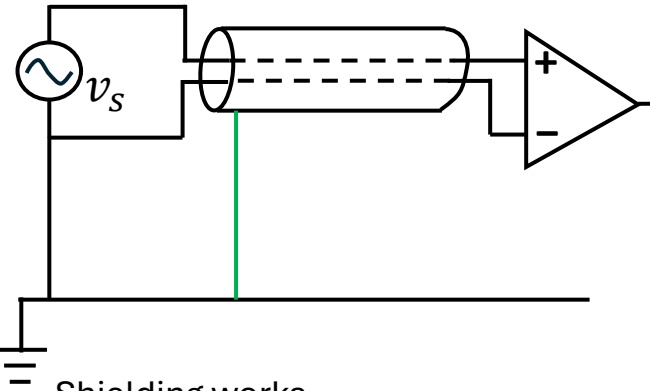
- Improper use of a shield for capacitive coupling mitigation can lead to unintentional ground loops.
 - For the shield to work, it should be connected to the signal reference node.
 - However, if you connect the shield to the reference node at both ends, a ground loop may be formed.
 - Potential differences between the grounding points will result in a current flowing in the shield.
 - These potential differences could be due to the loop picking up **magnetic** fields **inductively**, or due to currents from other circuitry flowing through this shared ground connection with non-zero impedance (explained before).
 - This potential difference will add directly in **series** with the signal source in either of the following situations (due to conductive coupling):
 - If the shield itself is used as the return line for a signal
 - ex: coaxial cable where signals go in the center core and return on the shielding
 - If the source end and receiver end are connected to a shared ground rail at separate points.
 - If there is no conductive path, capacitive coupling will still happen (most significant for high impedance sources like electrodes) between the shield and the inner core; the opposite of what the shield was designed to do.
- Note: At higher frequencies, grounding both ends of the shield may be necessary because of the possibility of the shield acting as an antenna.

Ground Loop Interference

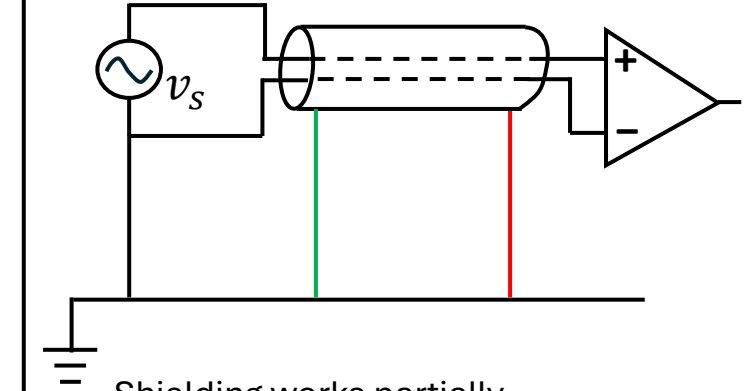
Improper Shielding



Shielding doesn't work
(Shield not connected to reference)

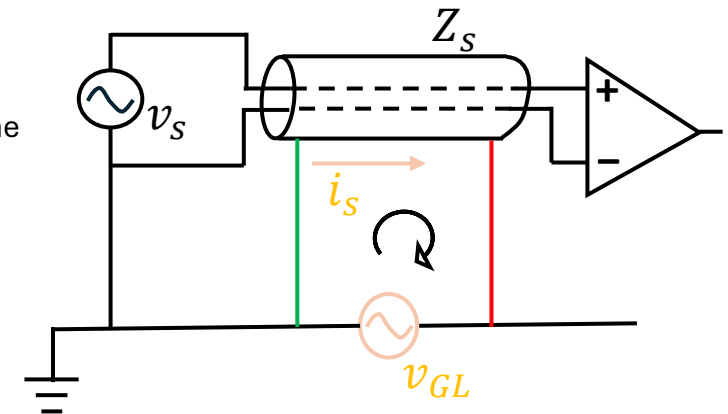


Shielding works
(Shield connected to reference at one end)



Shielding works partially
(Shield connected to reference at both ends)

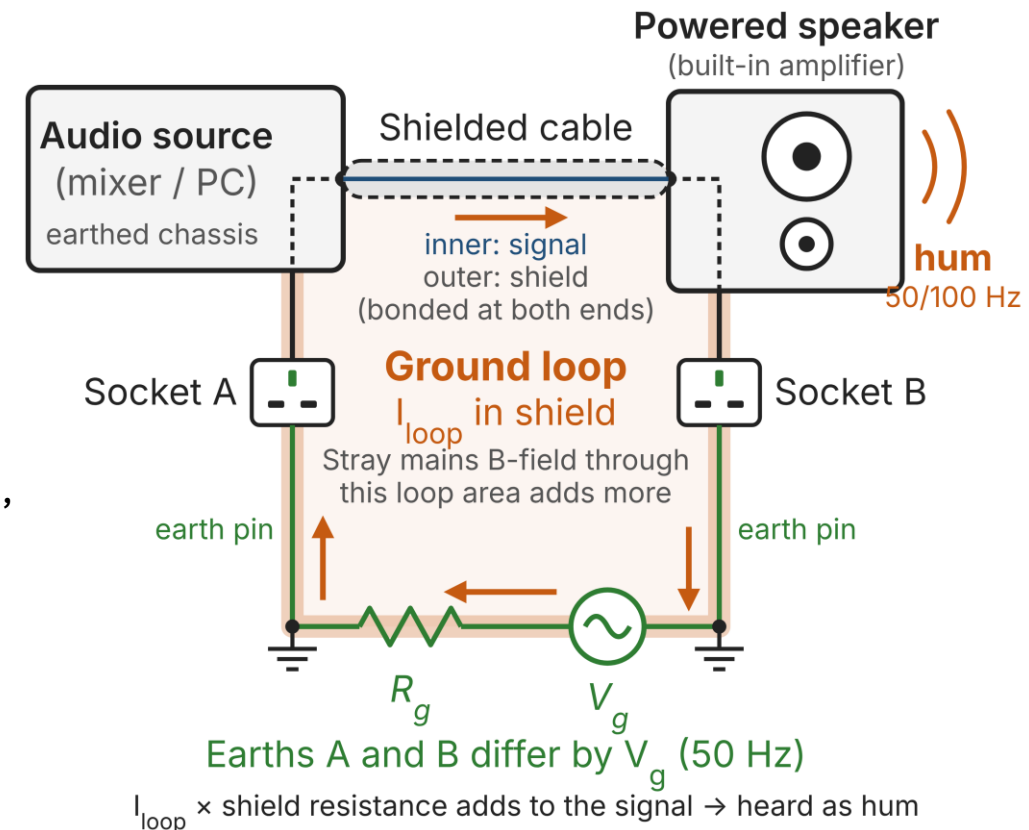
- Ground loop is formed.
- Current flows in the shield due to inductive and conductive coupling from other sources in the same circuit (or outside for inductive coupling).
- Consider this as a source V_{GL} connected in the loop.
 - The voltage v_{GL} will cause a current $i_s = v_{GL}/Z_s$ to flow along the shield.
 - Here Z_s is the shield's impedance.
- Therefore, the shield is no longer at reference potential.
- A portion of this voltage will be capacitively coupled onto the signal and return wires inside the shield, appearing mostly as common-mode noise.



Ground Loop Interference

How ground loops can form due to Earth

- Example scenario where a large scale ground loop forms between devices:
 - In audio systems, ground loops often cause a **loud hum** in speakers.
 - The audio source (mixer/PC) is connected to earth ground via its power socket.
 - A powered speaker which may be at another location is also connected to earth ground via a separate power socket.
 - The cable connecting the mixer/PC and the speaker has a grounded shield (cable ground),
 - This is connected to earth ground at both ends via the chassis of each device.
 - Therefore, the earth and the shield complete a ground loop.
 - Due to the sheer size of this ground loop, it can easily induce a lot of inductively coupled noise.
 - In addition, the two earth grounds may be at different potentials, leading to conductively coupled interference.
 - In medical devices such as EEG or ECG systems, ground loops can introduce low-frequency noise into delicate μV – mV level signals, leading to corrupted or unreliable measurements.



Ground Loop Interference

Mitigation Techniques

- Several techniques are available to mitigate ground loops and their resulting interference.
 - Single-point Grounding
 - Use a single ground point so there is no closed loop for current to circulate (effective at low frequency).
 - However, single point grounds require longer ground connections.
 - At high frequency, long ground leads have high impedance (and stray capacitance between them), so single-point grounding stops working ($\because$ inductive reactance rises with frequency $\Rightarrow$ larger voltage drops along long wires).
 - Isolation Techniques
 - Use isolation transformers, ground loop isolators, and optocouplers that break the conductive path, thus preventing ground loops.
 - Differential inputs with high Common-mode rejection
 - Ground loop interference appears as common mode noise in differential mode inputs (ex: Difference amplifiers)
 - When the reference oscillates, the entire circuit referenced to it oscillates, hence both inputs to the amplifier.
 - Differential inputs and high CMRR to amplifiers can reject this noise.
 - Proper Grounding Practices
 - Short, thick ground wires.
 - Cable Management
 - Use twisted pair cables and avoid ground loops in cable routing.

Ground Loop Interference

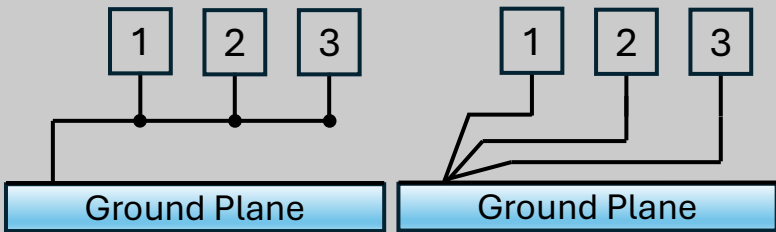
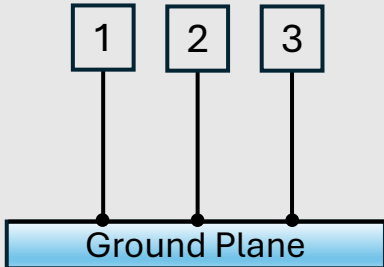
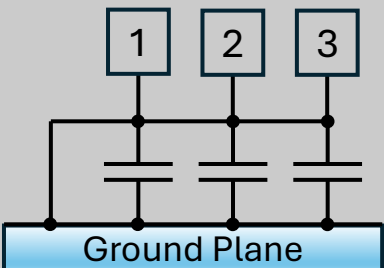
Mitigation Techniques – Proper Grounding

- A well-designed grounding system can provide protection against interference.
- There can be two types of grounds in an electronic instrument:
 - Safety grounds
 - Usually at earth potential.
 - Safety grounds carry fault currents and should not be used as signal grounds.
 - Signal grounds
 - May or may not be at earth potential.
 - Ex: A battery powered device may not have its reference tied to earth.

Grounding Techniques

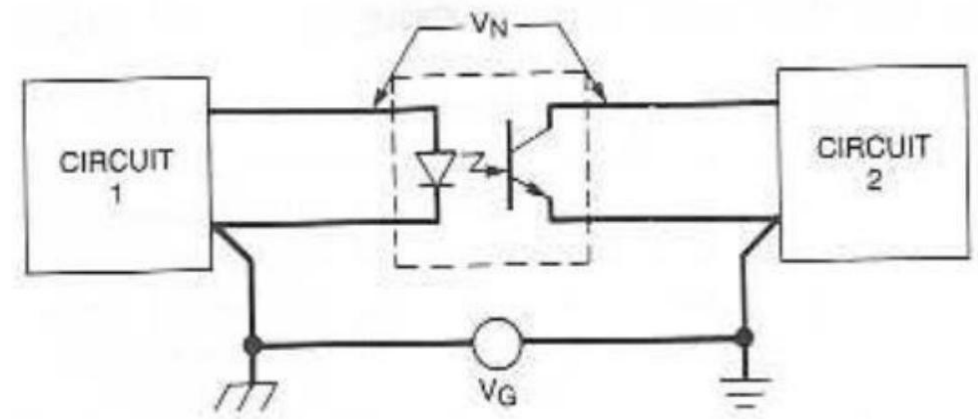
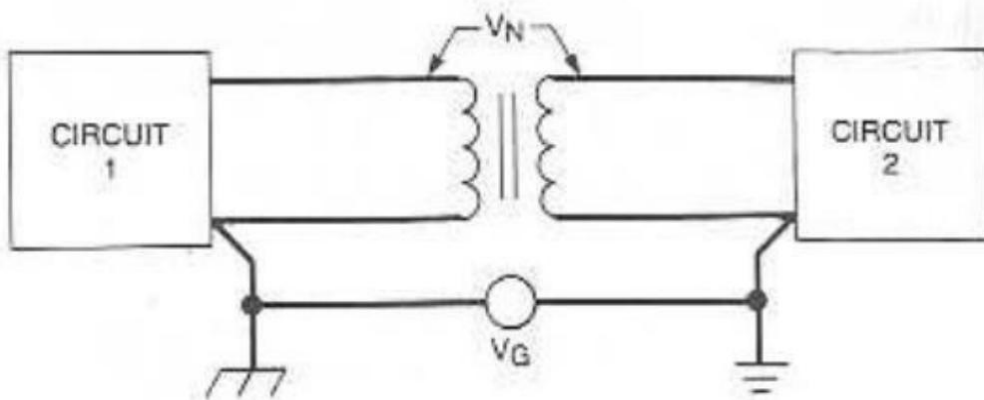
Signal Ground

- Grounding can be done in multiple ways:

Type		Description	Pros	Cons	Use case
Single Point Grounding		All modules connect to ground at a single common point.	- Eliminates ground loops at low frequency. - Simple concept.	- Long return paths cause high inductance at high frequency. - Not effective for RF/EMI suppression.	- Low-frequency analog systems. - Audio circuits.
Multipoint Grounding		Each module connects to the ground plane at multiple points directly.	- Very low impedance. - Excellent for RF and digital systems.	- Multiple connections can create ground loops at low frequency. - Can cause hum in audio/low-frequency systems.	- High-frequency digital circuits. - RF systems.
Hybrid Grounding		Single-point at low frequency, multipoint (capacitive coupling) at high frequency.	- Reduces ground loops at low frequency. - Provides low impedance path at high frequency.	- More complex to design. - Requires careful capacitor selection and layout.	- Mixed-signal systems (analog + digital). - EMI-sensitive equipment.

Isolation Techniques

- Using isolation transformers or optical isolators can separate different parts of a system.
 - This prevents conductive coupling as they share no conductor.
 - Reduces effects of noise.
- An isolation transformer (left) passes a signal magnetically.
- An optocoupler (right) passes a signal as light.
- The ground difference V_G appears across the barrier, and not in the signal.
 - Therefore, no ground loop => No current will flow.



Isolation Techniques

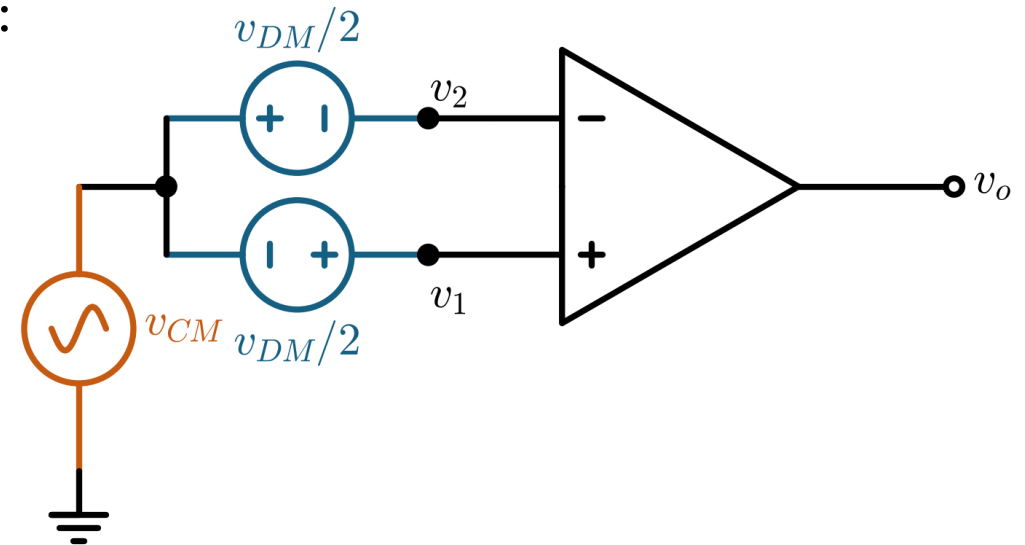
How They Work

- Isolation breaks the conductive (galvanic) path between two circuits but still passes the signal or power across a barrier.
- The ground-potential difference V_G then appears across the barrier, not in the signal path:
 - No ground-loop current.
- Acts as a safety barrier:
 - Blocks dangerous currents and high voltages.
- Limits:
 - The barrier has a few pF of capacitance, so fast common-mode transients still couple.
 - The isolated side needs isolated power too (isolated DC–DC converter or battery)
- Medical devices isolate the patient-connected part from mains to meet μA -level leakage limits (IEC 60601-1)
- A battery-powered wearable is isolated by design, but **not** while connected to a PC or charger by USB

Method	Crosses the barrier as	Typical use
Transformer	Magnetic field	AC signals, power (isolated DC–DC)
Optocoupler	Light (LED → photodetector)	Digital and control signals
Capacitive isolator	HF carrier across small capacitors	Fast digital buses (SPI, UART)

Common-Mode and Differential-Mode Signals Refresher

- Any pair of lines v_1 , v_2 (measured to ground) can be split into two parts:
 - Differential mode: $v_{DM} = v_1 - v_2$
 - This is the difference between voltages on the two lines (usually the wanted signal).
 - Differential mode current flows out on one line and returns on the other.
 - Common mode: $v_{CM} = \frac{v_1 + v_2}{2}$
 - This is the voltage that fluctuate equally on both lines relative to ground (usually unwanted - interference).
 - This is calculated as the average of the signals on the two lines.
 - Common mode current flows the same way on both lines and returns through ground/earth.
- Therefore, we can re-write the voltages on the two lines as:
 - $v_1 = \left(v_{CM} + \frac{v_{DM}}{2}\right)$ and $v_2 = \left(v_{CM} - \frac{v_{DM}}{2}\right)$



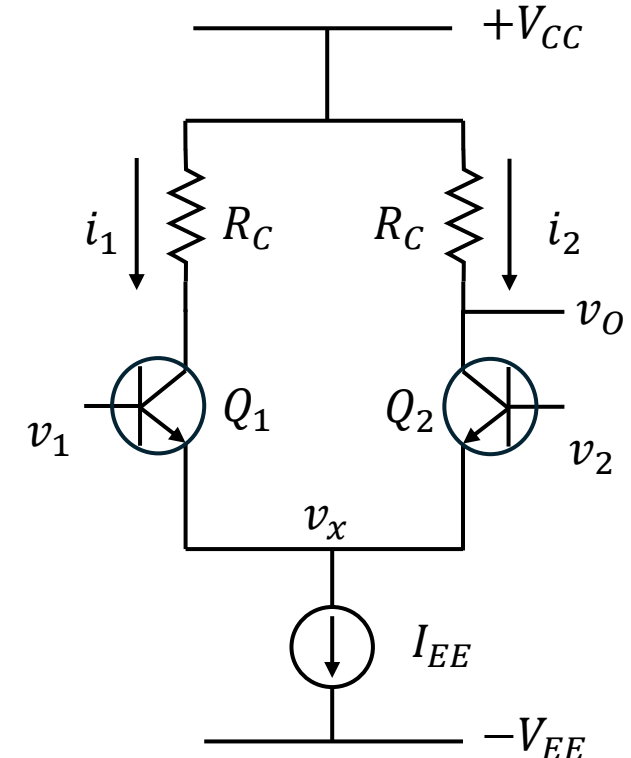
Common-Mode and Differential-Mode Signals

Refresher

- A differential amplifier ideally responds only to v_{DM} .
- However, a practical amplifier responds to both v_{CM} and v_{DM} .
 - $v_O = G_{DM}v_{DM} + G_{CM}v_{CM}$
 - Here, v_O is the voltage at the output of the amplifier, G_{DM} is called the differential mode gain, and G_{CM} is called the common-mode gain.
- Shifting both inputs by the same amount moves v_{CM} but leaves v_{DM} unchanged.
 - This shift is the interference we want to ignore.
- We define common mode rejection ratio $CMRR = \left| \frac{G_{DM}}{G_{CM}} \right|$
 - Referred to the input, the common mode **error** is $\frac{v_{CM}}{CMRR}$
 - Ex: 1 V of common mode noise at 100 dB CMRR looks like 10 μ V of differential mode signal.
 - i.e., the common mode voltages can move the output of an amplifier due to the non-zero G_{CM} in practical amplifiers.
- CMRR measurement:
 - Tie the inputs together and get the common-mode gain G_{CM} .
 - Drive v_{DM} alone to get G_{DM} .

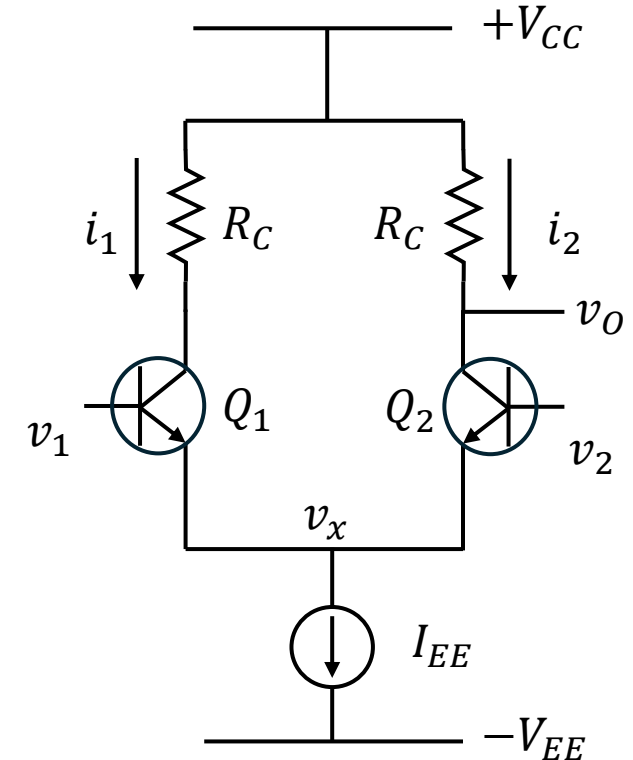
Where an Op-Amp's G_{CM} Comes From

- Inside almost every op-amp the first stage is a differential pair with a tail current source (I_{EE}).
 - A differential input only steers the fixed tail current I_{EE} between the two matched transistors Q_1 and Q_2 .
 - i.e., when i_1 **increases** by Δi , i_2 must **decrease** by the same amount.
 - Since at quiescent state, $i_1 = i_2 = I_{EE}/2$, for a small increase in i_1 current:
 $i_1 = \frac{I_{EE}}{2} + \Delta i$, we have $i_2 = \frac{I_{EE}}{2} - \Delta i$
 - In response, the collector voltages swing, scaling the $(v_1 - v_2)$ by the factor $G_{DM} = g_m \cdot \frac{R_C}{2}$.
 - The derivation for the above formula (Not important for your exam):
 - Things we know:
 - $\Delta i_1 + \Delta i_2 = 0$ (1) ($\because i_1 + i_2 = I_{EE}$)
 - Ohm's law through second branch: $v_O = V_{CC} - i_2 R_C$
 - If we consider a small signal differential, $\Delta v_O = -\Delta i_2 R_C$ (2)
 - Assuming transconductance of Q_1 is g_m , from small signal model:
 - $\Delta i_1 = g_m \Delta v_{be1} = g_m \Delta(v_1 - v_x)$ (3)
 - Assuming Q_1 and Q_2 are a matched pair, transconductance of Q_2 is also g_m . Therefore, from small signal model:
 - $\Delta i_2 = g_m \Delta v_{be2} = g_m \Delta(v_2 - v_x)$ (4)



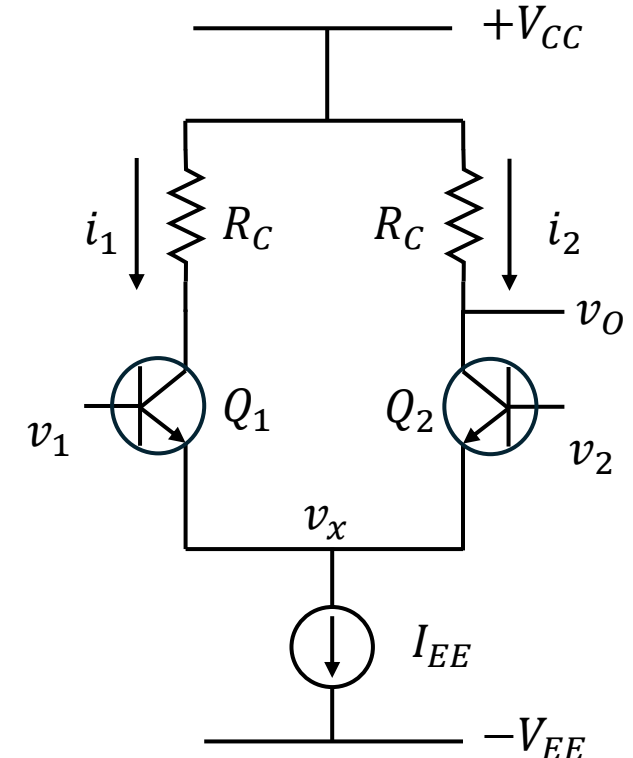
Where an Op-Amp's G_{CM} Comes From

- We want to find a relationship between a small change in the input voltages Δv_1 , Δv_2 and the corresponding change in the output voltage Δv_O .
- From (3) – (4):
 - $\Delta i_1 - \Delta i_2 = g_m \Delta(v_1 - v_2)$ (5)
- From (1), (5):
 - $\Delta i_2 = -g_m \Delta(v_1 - v_2)/2$ (6)
- From (6), (2):
 - $\Delta v_O = \frac{g_m R_C}{2} \Delta(v_1 - v_2)$
 - Since $\Delta(v_1 - v_2) = \Delta v_{DM}$ (the change in the differential signal).
 - $\Delta v_O = \frac{g_m R_C}{2} \Delta v_{DM}$
 - Hence,
 - $G_{DM} = \frac{g_m R_C}{2}$



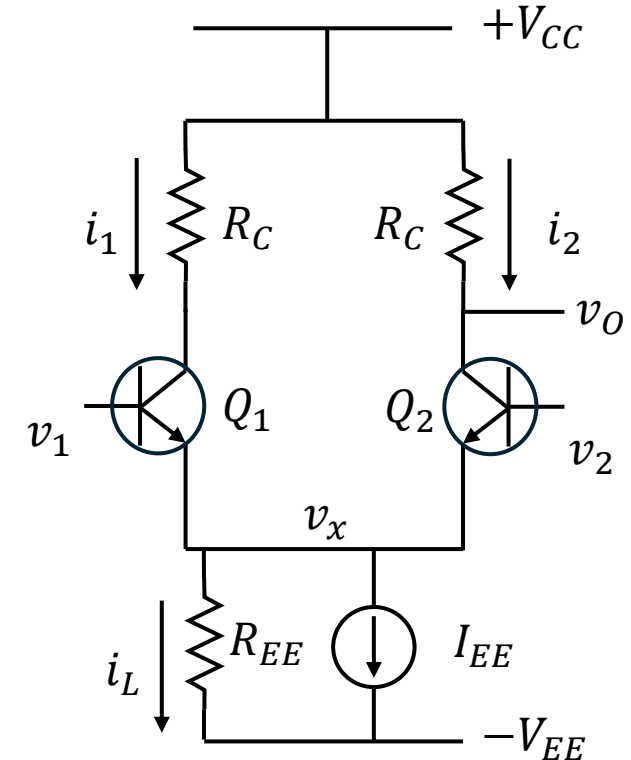
Where an Op-Amp's G_{CM} Comes From

- The G_{DM} is the differential mode gain of the op-amp.
- A common-mode input is when both input voltages v_1 and v_2 rise or fall together.
 - This tries to raise both currents i_1 and i_2 simultaneously.
 - However, the ideal tail source resists any change in total current.
 - Therefore, theoretically, the common mode gain of an op-amp is zero.
 - Let's now consider a practical tail current source implemented by biasing a transistor to the active region.



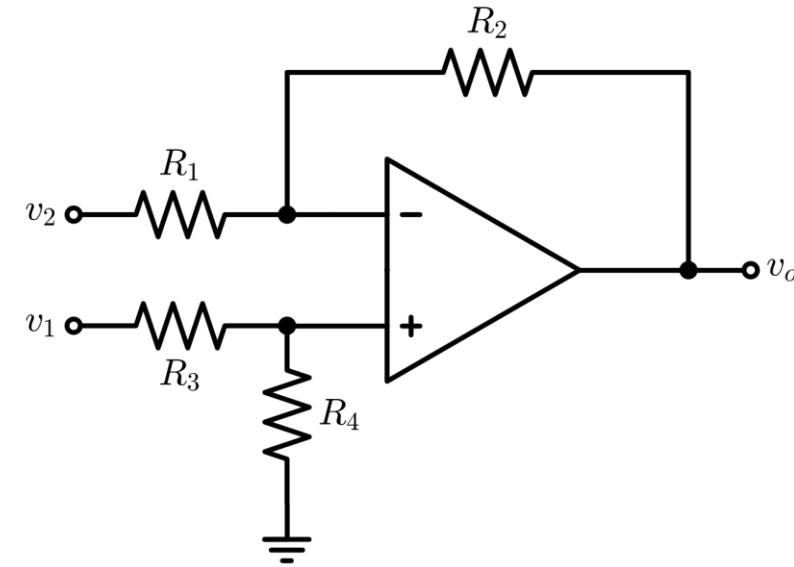
Where an Op-Amp's G_{CM} Comes From

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 - However, the ideal tail source resists any change in total current.
 - Therefore, theoretically, the common mode gain of an op-amp is zero.
 - Let's now consider a practical tail current source implemented by biasing a transistor to the active region.
 - It has a finite output impedance R_{EE} , and therefore by increasing the voltage v_x , excess current i_L can flow through the tail current source.
 - This is exactly what happens when both v_1 and v_2 increase at the same time, causing v_x to increase, and thereby allowing more current to flow on both branches.
 - When both inputs increase by Δv , the output increases, scaled by G_{CM}
 - $G_{CM} \approx -\frac{R_C}{2R_{EE}}$ (G_{CM} is the common mode gain)
 - $\therefore$, $CMRR \approx g_m R_{EE}$ and an ideal current source ($R_{EE} \rightarrow \infty$) gives infinite CMRR.
 - CMRR falls with frequency because stray capacitance across the tail source lowers its impedance: check the datasheet curve at 50 Hz



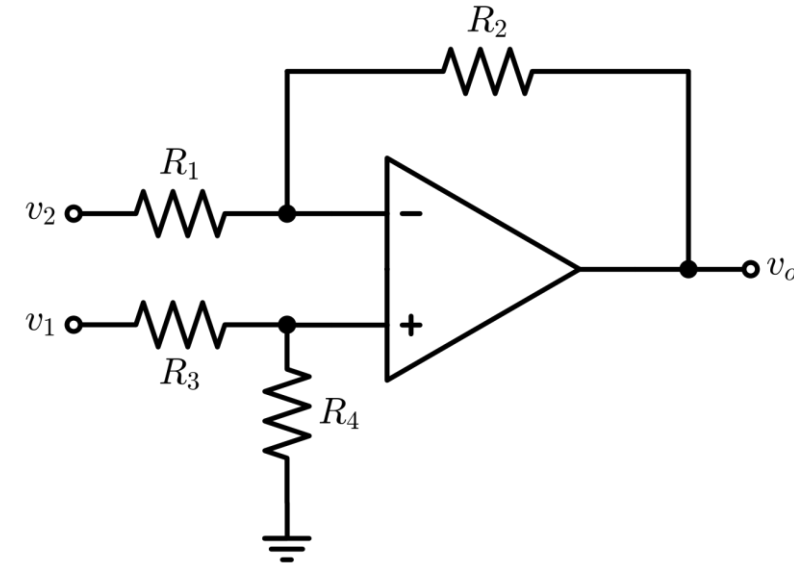
Difference Amplifier and CMRR

- Consider the following op-amp topology for a difference amplifier.
 - Through superposition principle, we can obtain v_O .
 - Consider only v_1 (i.e., set v_2 to zero):
 - v_1 sees a non-inverting amplifier after the R_3/R_4 divider.
 - Therefore, v_O due to v_1 only: $v_{O|v_1} = v_1 \times \frac{R_4}{R_3+R_4} \times \left(1 + \frac{R_2}{R_1}\right)$
 - Consider only v_2 (i.e., set v_1 to zero):
 - v_2 sees an inverting amplifier.
 - Therefore, v_O due to v_2 only: $v_{O|v_2} = -v_2 \times \frac{R_2}{R_1}$
 - Therefore, $v_O = v_{O|v_1} + v_{O|v_2} = v_1 \left(\frac{R_4}{R_3+R_4} \right) \left(1 + \frac{R_2}{R_1} \right) - v_2 \left(\frac{R_2}{R_1} \right)$
 - Let $A = \left(\frac{R_4}{R_3+R_4} \right) \left(1 + \frac{R_2}{R_1} \right)$ and $B = \frac{R_2}{R_1}$
 - Then, $v_O = Av_1 - Bv_2$



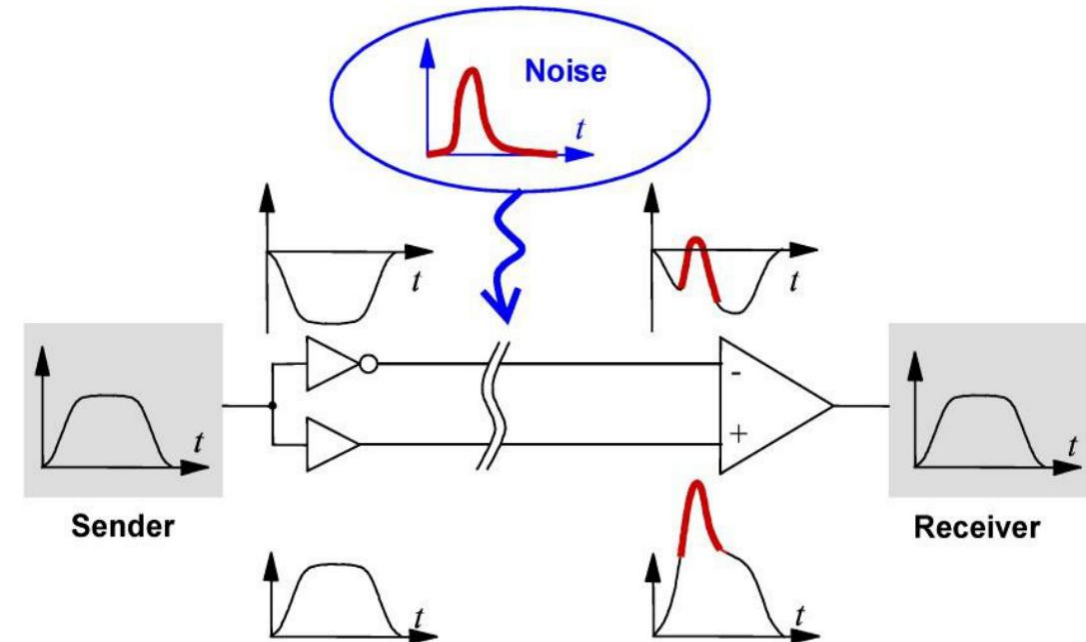
Difference Amplifier and CMRR

- Calculate the common mode and differential mode gains.
 - Substitute $v_1 = v_{CM} + \frac{v_{DM}}{2}$ and $v_2 = v_{CM} - \frac{v_{DM}}{2}$
 - You will find that $v_o = (A - B)v_{CM} + \frac{(A+B)}{2}v_{DM}$
 - i.e., $G_{CM} = (A - B)$ and $G_{DM} = \frac{A+B}{2}$
- Since $A - B = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}$
 - If we have matched resistor ratios $\frac{R_2}{R_1} = \frac{R_4}{R_3} = G$, we find that $G_{DM} = \frac{A+B}{2} = G$, and $G_{CM} = A - B = 0$.
 - i.e., for matched resistor ratios, the common-mode gain G_{CM} of a difference amplifier is zero!
 - Therefore, ideally, the difference amplifier should be able to get rid of the common mode signals.
 - However, real resistors have tolerance.
 - If the two ratios R_2/R_1 and R_4/R_3 differ by a fraction δ , i.e., $R_2/R_1 = G$ and $R_4/R_3 = G(1 + \delta)$,
 - We get $G_{CM} = A - B \approx \frac{G\delta}{1+G}$, hence a CMRR of $\frac{1+G}{\delta}$
 - Therefore, even with a perfect op-amp, the resistors can limit the CMRR.
 - On top of this, the source impedances of signal sources can further destroy this matching.



Differential Signaling

- Differential signaling can be used to reduce common-mode noise by transmitting signals on two complementary lines.
 - This is especially useful when signals are transmitted over longer distances.
 - Long wires have higher chance of picking up common-mode interference.
 - The signal on one line is the inverted version of the signal on the other.
 - At the receiver, the two signals will be subtracted.
 - If the receiver has high CMRR, any common mode noise will be cancelled out as they act similarly on both lines.
 - Differential signaling works best when the two lines are matched and routed together
 - Ex: Twisted pairs, differential PCB pairs
- Examples:
 - USB, Ethernet, RS-485
 - In the ECG, the instrumentation amplifier input is differential



Electromagnetic Interference (EMI)

- Electromagnetic interference refers to electromagnetic disturbances, radiated or conducted from an external source.
 - Sources may be natural or artificial:
 - Natural sources: Lightning, Solar flares
 - Artificial sources: Motors, transformers, electronic devices.
- EMI can be mitigated via:
 - Shielding (using conductive or magnetic materials to enclose electronic components),
 - Filtering (Using capacitors, inductors and ferrite beads to filter out unwanted frequencies and the residual interference the shielding couldn't attenuate).

Power Line Interference (PLI)

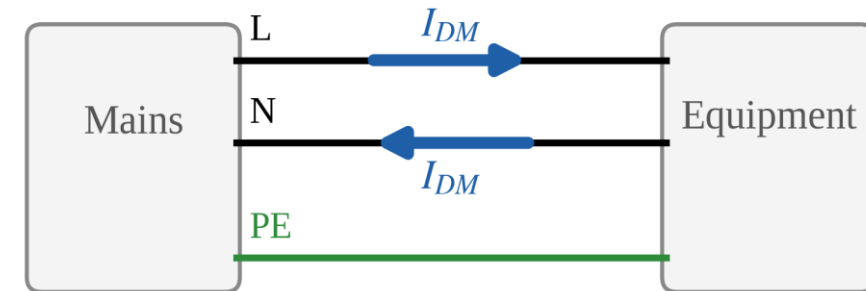
- Power line interference refers to the interference from the mains wiring.
 - It is a form of EMI and can couple into circuits capacitively, inductively and conductively.
- Appliances and machinery can directly shift the reference voltage (ground) levels via conductive coupling.
 - This includes 50 Hz noise as well as its harmonics.
- Conductively coupled power line interference can be mitigated via:
 - transformer isolation,
 - power-line filters (for higher frequency conducted noise),
 - proper grounding.
- Inductively and capacitively coupled powerline interference can be mitigated via techniques previously discussed under inductive and capacitive coupling sections.
 - Ex: Shielding, twisted pairs, ground loop mitigation, etc.

Power Line Filters (EMI Filters)

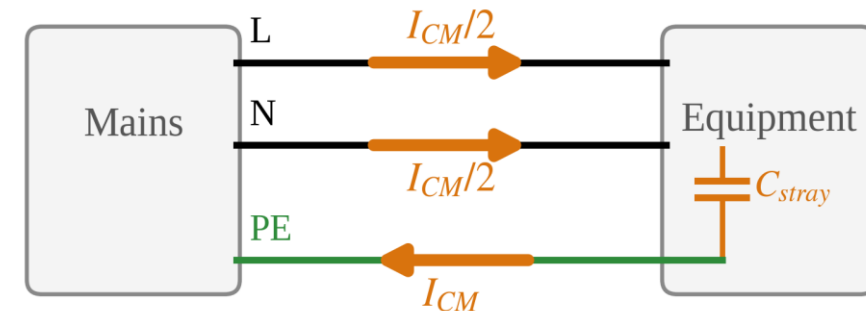
Mitigating Conductively Coupled PLI

- Conductively coupled noise travels in two modes:
 - Common mode (CM):
 - Flows in the same direction on the live and neutral wires, and returns through earth (PE-Protective Earth) via stray capacitance.
 - Ex:
 - Nearby lightning induces nearly the same voltage on live and neutral.
 - Additionally, a nearby lightning strike can lift the local earth relative to remote earth (at the transformer)
 - This leads to ground potential differences.
 - Differential mode (DM):
 - Flows into the device on the live wire (L) and returns on the neutral wire (N).
 - Live/neutral imbalance converts part of the common-mode disturbance into differential mode.

Differential-mode noise



Common-mode noise

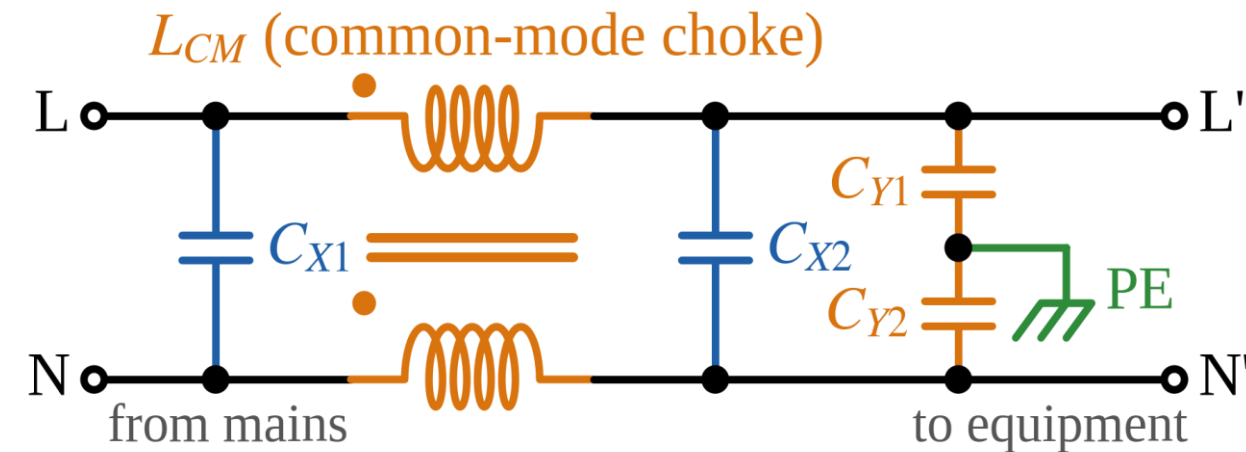


Power Line Filters (EMI Filters)

Mitigating Conductively Coupled PLI

- Conductively coupled power line interference is mitigated via power line filters.
 - These are passive LC low-pass filters fitted at the AC power inlet of mains-powered equipment.
 - These help prevent interference from the grid reaching the device, and also prevent noise from the device going back into the grid and affecting other devices on the grid.
 - Often built into the IEC power-entry module.
- Note:
 - Power line filters do not remove the 50 Hz power line voltage itself.
 - It is designed to pass 50 Hz.
 - It attenuates conducted noise from ~10 kHz to ~30 MHz.

Inside a Power Line Filter



Common-mode choke (L_{CM})

- Two identical windings on one core: one in L, one in N.
- 50 Hz load current and DM noise flow in opposite directions in the L and N wires.
 - $\therefore$ fluxes cancel $\Rightarrow$ low impedance against passing current $\Rightarrow$ 50 Hz and DM noise pass freely.
- CM noise flows in the same direction in the L and N wires.
 - $\therefore$ fluxes add $\Rightarrow$ high impedance against passing current $\Rightarrow$ CM noise is blocked.

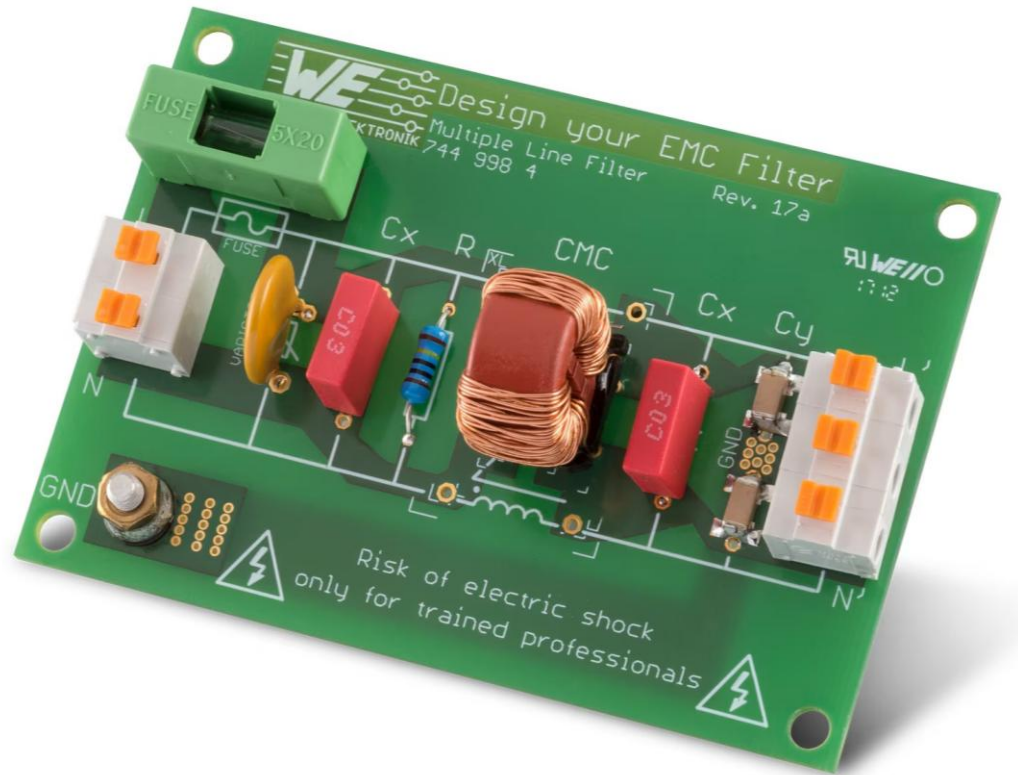
X capacitors (C_X): line-to-line

- Added across L and N.
 - $\therefore$ Short-circuits DM noise.
 - Values are chosen to only short circuit to higher frequencies and not 50 Hz.
 - Typically 0.1–0.47 μF
- Safety class X:
 - If an X capacitor fails short, it only blows the fuse (no shock hazard).
- A bleeder resistor discharges them after unplugging

Y capacitors (C_Y): line-to-earth

- Added across L and protective earth (PE), and another across N and PE.
 - $\therefore$ Diverts CM noise to earth
 - Typical values: 1–4.7 nF
 - Medical equipment have μA -level leakage limits (IEC 60601-1), so Y capacitors are kept very small or omitted
- Safety class Y:
 - Y capacitors are **designed** to fail as **open** circuits.
 - Otherwise, a failure would put live voltage on the earthed chassis $\Rightarrow$ shock hazard.

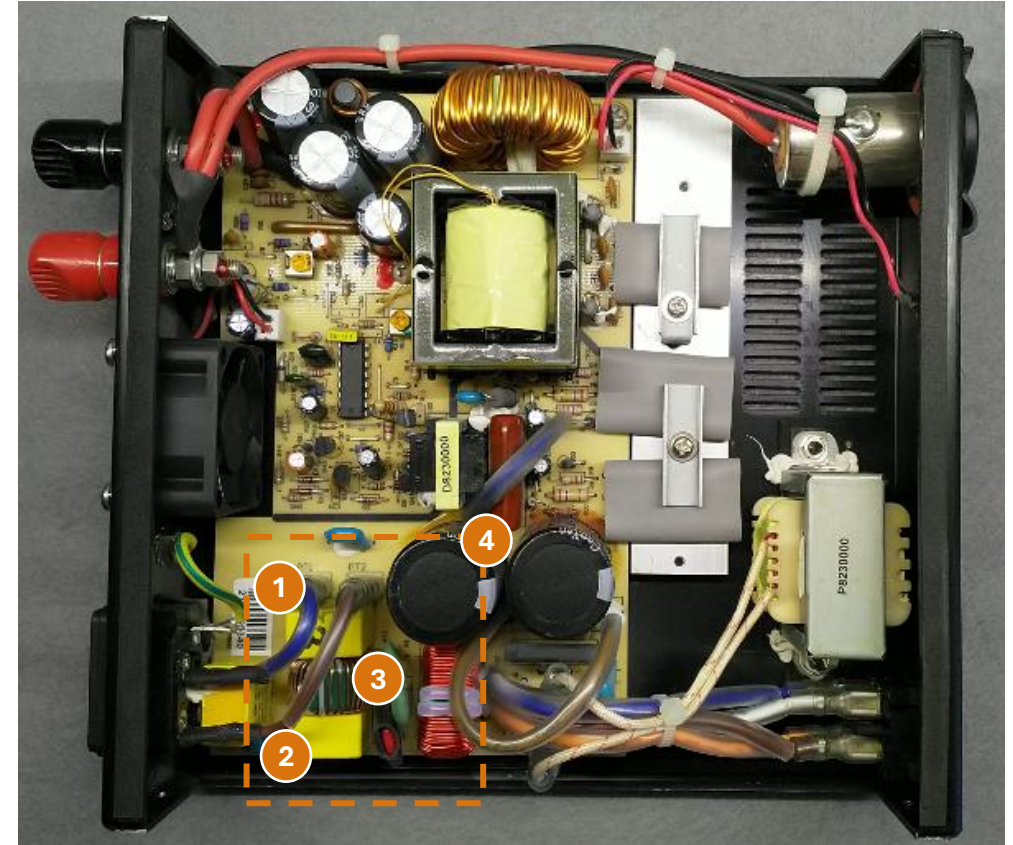
Power Line Filters in Practice



EMC filter demo board: the silkscreen follows the filter schematic, from input (L, N) to output (L', N'):

Fuse → Varistor (surge) → C_x → R (bleeder) → CMC (common-mode choke) → C_x → C_y to GND (PE)

Image: Würth Elektronik

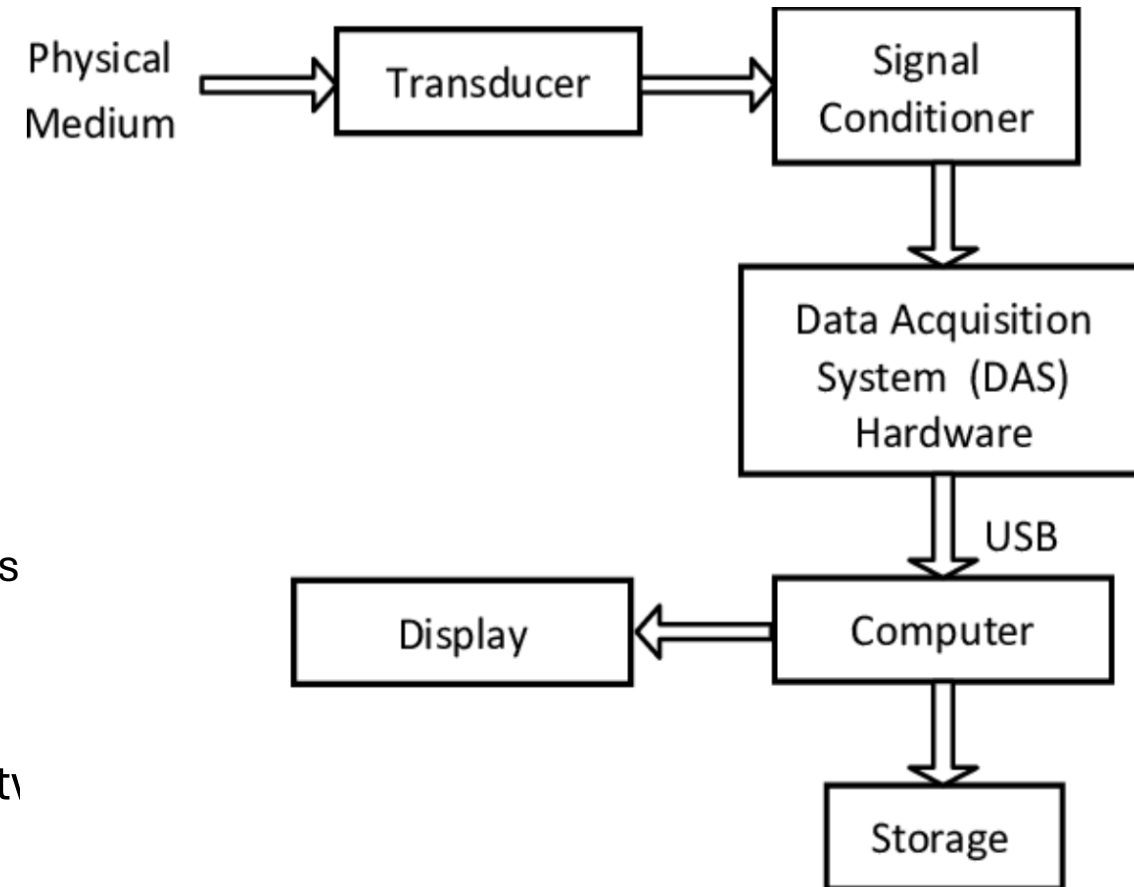


Input EMI filter of a bench power supply (dashed box):

- 1 PE wire (green/yellow) 2 X capacitors (yellow boxes)
- 3 Common-mode choke (toroid) 4 Y capacitor (blue disc)

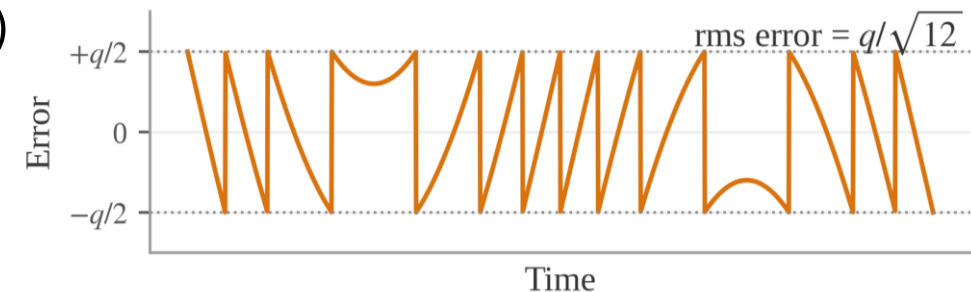
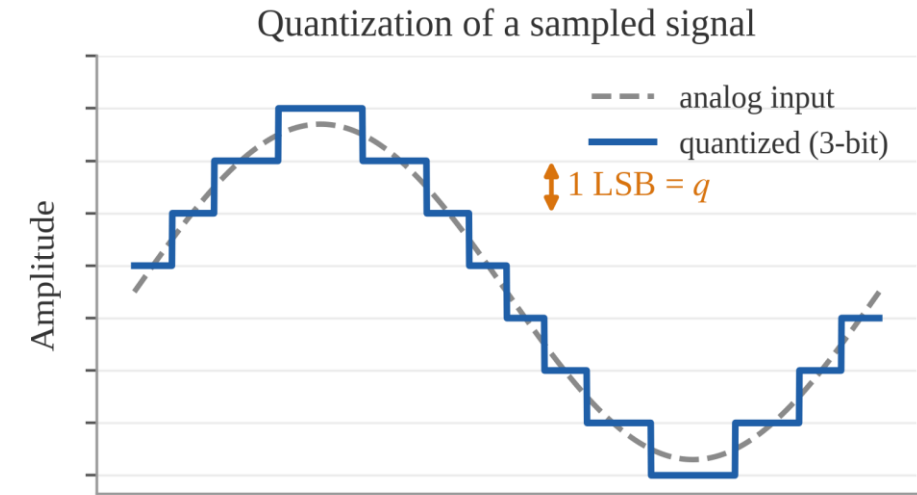
Data Acquisition Systems and Noise

- Data acquisition (DAQ) systems convert physical phenomena into **digital** data for analysis.
- Noise can enter at every block, and noise added early is amplified by the later stages.
 - Internal Noise:
 - Thermal noise, shot noise and flicker noise within the system components
 - Power Supply Noise:
 - Noise from unstable power sources.
 - Ex: ripple currents, switching noise
 - Signal Transmission Line:
 - Noise picked up during signal transmission from sensors
 - Ex: Capacitively coupled noise.
- Fixes:
 - Shielding & layout, low-noise parts, decoupling, short t



ADC Quantization Noise

- An N -bit ADC rounds each sample to one of 2^N levels:
 - step $q = V_{FS}/2^N$ (1 LSB).
 - V_{FS} is the full-scale voltage – The voltage which is divided into the 2^N levels.
- The rounding error lies within $\pm \frac{q}{2}$ and behaves like white noise and has an RMS of $\frac{q}{\sqrt{12}}$ when the signal spans multiple LSBs.
 - $\therefore$ Quantization Noise (RMS) $\Rightarrow \frac{V_{FS}}{2^N \times \sqrt{12}}$.
 - You can arrive at this formula by obtaining the mean square error that you can get knowing that the error e for each sample is $-\frac{q}{2} < e < \frac{q}{2}$, and considering the error is uniformly distributed, i.e., equal probability of getting any value between that range.
- Design rule:
 - Refer the ADC noise to the input (divide by the front-end gain) and keep it below the analog noise.
 - See next slide for examples



ADC Quantization Noise

- ECG examples:

- Assuming a V_{FS} of 3.3 V, calculate the noise floor set by a 12-bit vs 24-bit ADC.

- 12-bit $\Rightarrow$ ADC Noise RMS $= \frac{V_{FS}}{2^N \times \sqrt{12}} = \frac{3.3}{2^{12} \times \sqrt{12}} \approx 233 \mu V_{RMS}$

- Therefore, needs a gain of a few hundred to bring it below 1 μV at the input.
- At that gain however, electrode offset voltage would saturate the amplifier.

- 24-bit $\Rightarrow$ ADC Noise RMS $= \frac{V_{FS}}{2^N \times \sqrt{12}} = \frac{3.3}{2^{24} \times \sqrt{12}} \approx 56 \text{ nV}_{RMS}$

- This is already negligibly small! - However, note that this is only considering the quantization noise. A real ADC will have a much higher noise floor due to its inherent thermal noise, etc..

ADC Reference Voltage

- Importance of noise-free ADC reference.
 - The V_{FS} is set by the V_{REF} of an ADC - Usually, $V_{FS} = V_{REF}$ (unipolar ADCs like the ones in microcontrollers), but there are other ADC types (bipolar ADCs, ex: ADS1292) where $V_{FS} = 2V_{REF}$.
 - If there is noise on the V_{REF} voltage, every sample that you measure will reflect that noise in addition to the actual noise in the signal from other noise sources.
 - $\therefore$ Never use VDD directly from a switching converter as the V_{REF} .
 - It is not recommended to use the separate AVDD as the reference voltage either.
 - Some ADCs have an internal stable reference that you can use.
 - If not, use a reference IC that is powered by the AVDD.
 - It is recommended to add a decoupling capacitor to the ADC reference voltage pin to filter out noise.
 - Recommended value usually given in the datasheet.

Filtering: LP, HP, BP, NF

- Use filtering for any noise or interference that could not be mitigated by other means.
 - Low pass filtering:
 - To remove high frequency noise
 - High pass filtering:
 - To remove low frequency noise
 - Bandpass filtering:
 - To filter out a certain part of the frequency
 - Notch filtering:
 - To remove a narrow band of frequency

