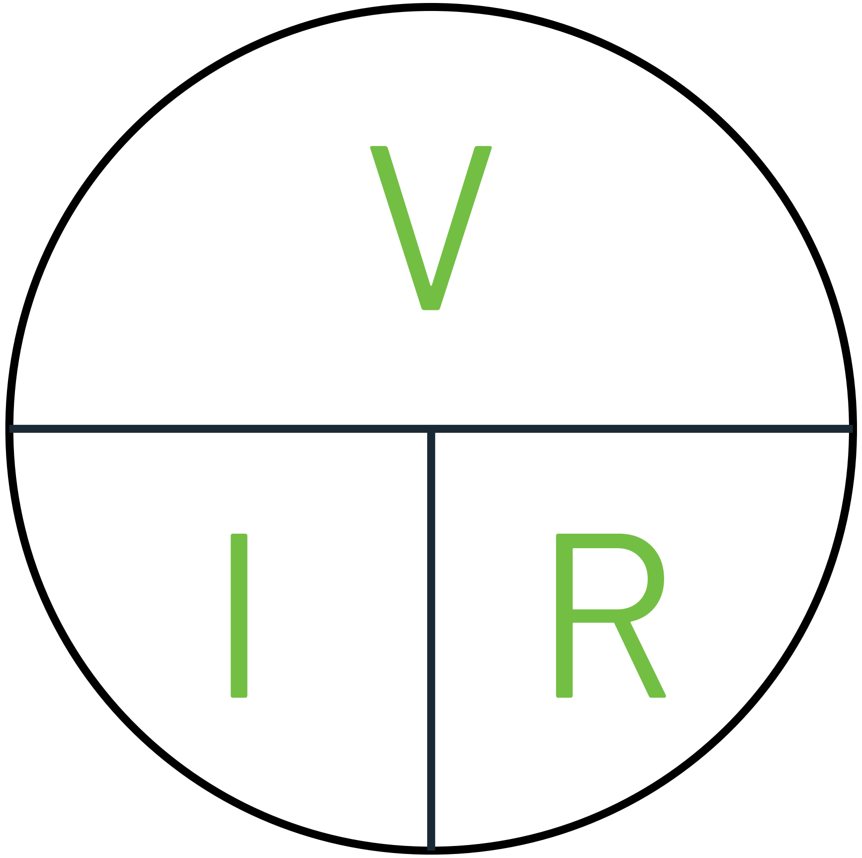
DC Measurement Refresher:

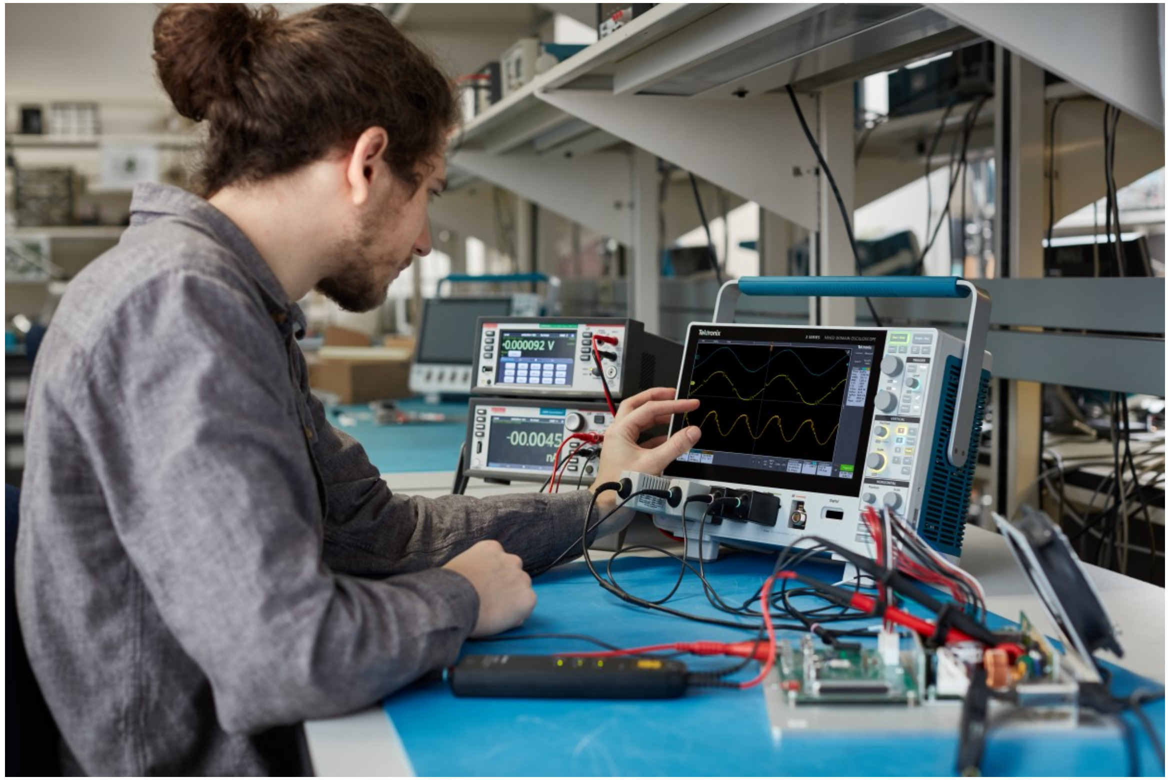
Avoiding Common Errors

Brad Odhner

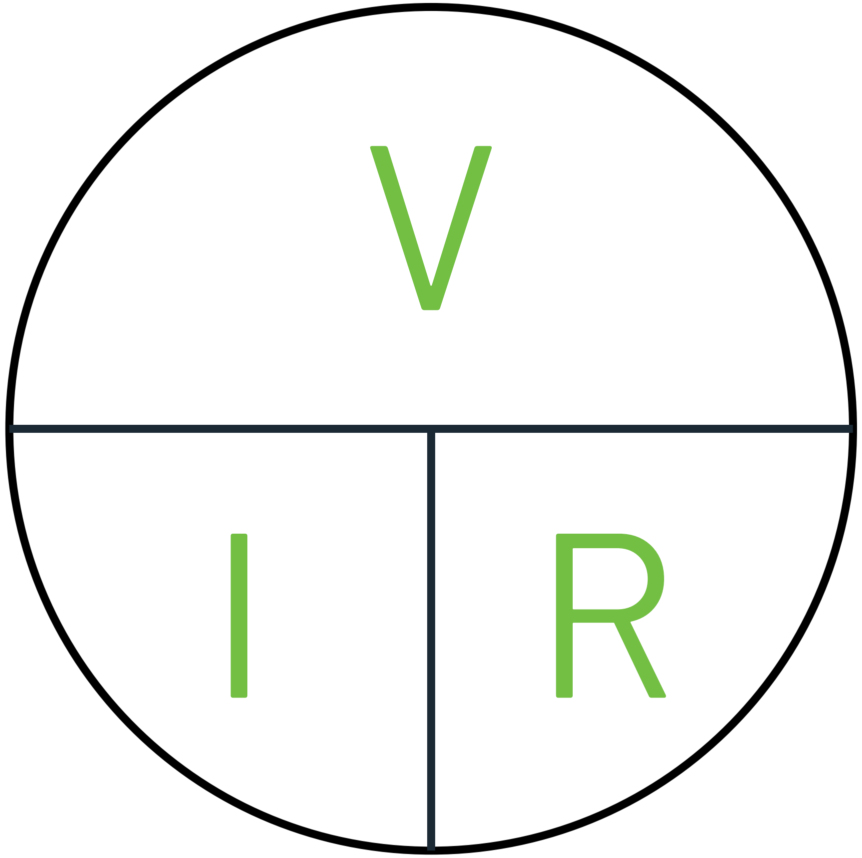
A Tektronix Company

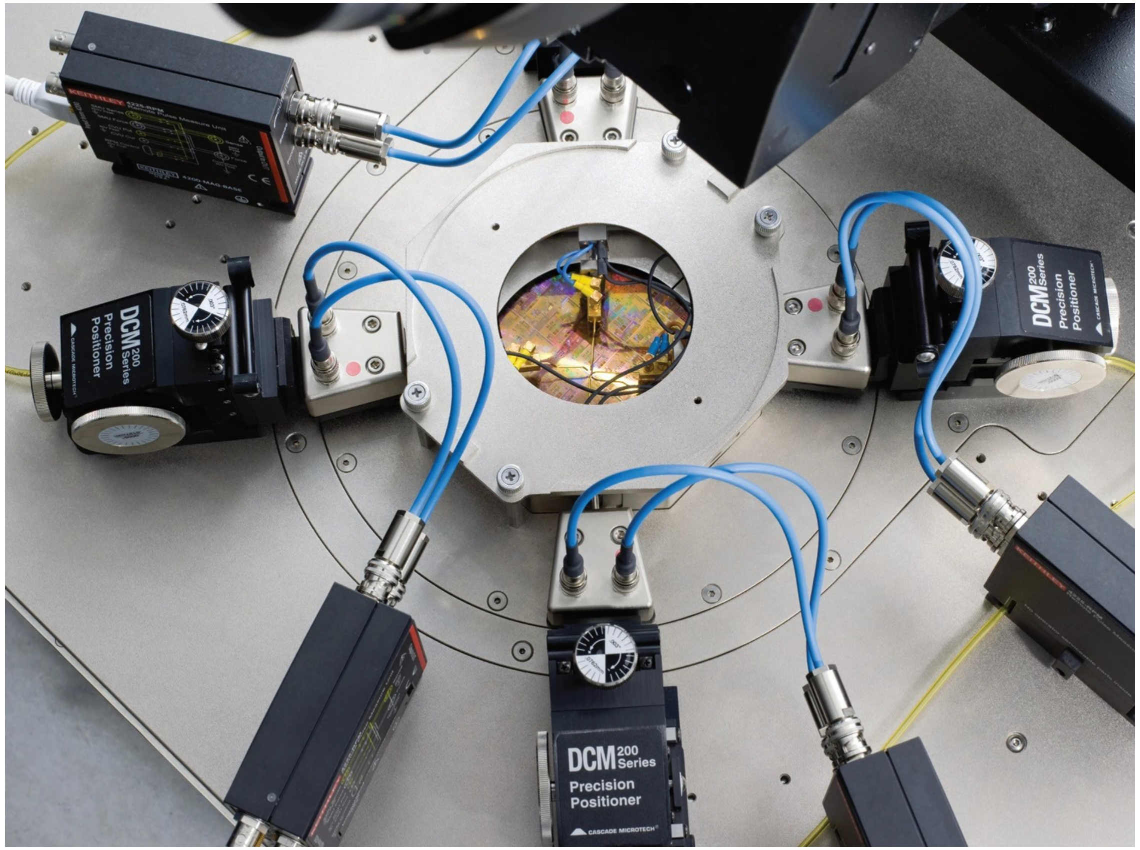
DC Measurement Refresher





DC Measurement Refresher





Agenda

1. Common Instruments
    1. Digital Multimeters
    2. Power Supplies
    3. Source Measure Units
2. Connector Types
    1. Banana
    2. Alligator
    3. Coax / Triax
    4. Phoenix
3. 2-wire vs. 4-wire
    1. 4-point Collinear Probes

Digital Multimeters

DMMS HAVE DIFFERENT CLASSES BASED ON THEIR RESOLUTION

3-½	4-½	5-½	6-½	7-½	8-½
					
Intro Hobbyist / Spot Check	Simple Verification / Hobbyist	Intro Bench / Lower Education	General Purpose / Higher Education	Specialty Purpose	Calibration / Research

½ Digits?

0.000 000 00

½ 1 2 3 4 5 6 7 8

½ Digits?

0.000 000 00

½ 1 2 3 4 5 6 7 8

½ = 0 or 1

= 0-9

½ Digits?

1.100 000 00

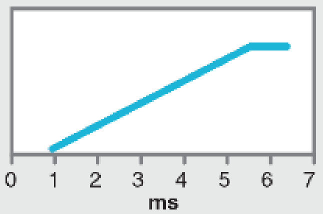
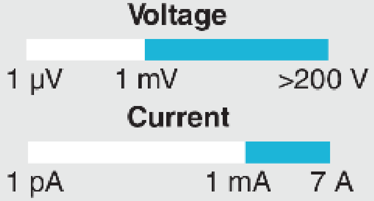
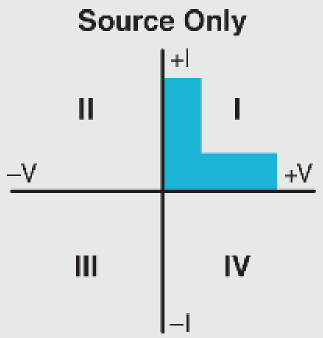
0.000 000 00

½ 1 2 3 4 5 6 7 8

½ = 0 or 1

= 0-9

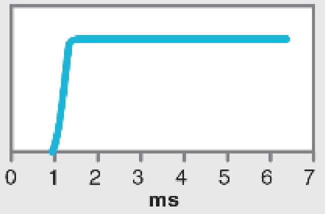
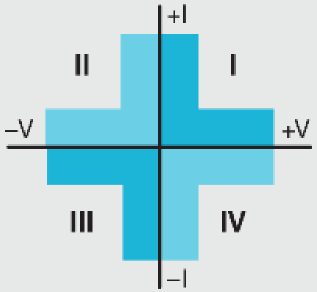
Power Supplies

Speed	
Source/ Measure Precision	100 mV source uncertainty = 3 mV
Voltage and Current Resolution	
Quadrant Operation	

- SUPPLY POWER
  - Slow
  - Stable

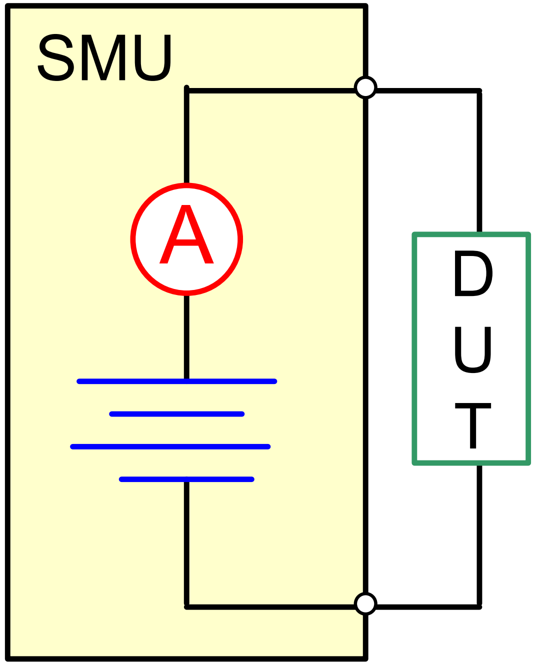
Source Measure Units

SOURCE CURRENT **OR** VOLTAGE
MEASURE CURRENT **AND** VOLTAGE
GENERALLY NOT AS MUCH POWER

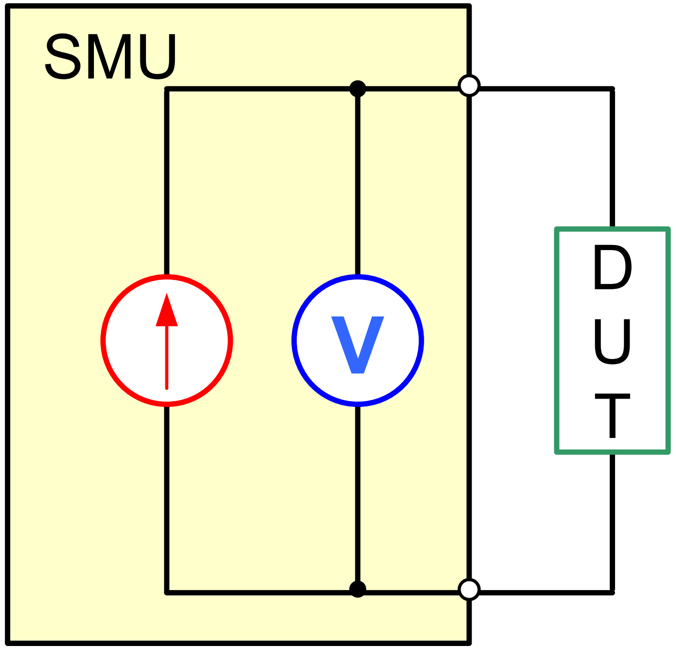
	SMU Instrument
Speed	
Source/ Measure Precision	100 mV source uncertainty = 20 µV
Voltage and Current Resolution	**Voltage** 1 µV >200 V **Current** 1 pA 7 A
4 Quadrant Operation	**Source + Sink** 

Source Measure Units

- SOURCE CURRENT **OR** VOLTAGE
- MEASURE CURRENT **AND** VOLTAGE



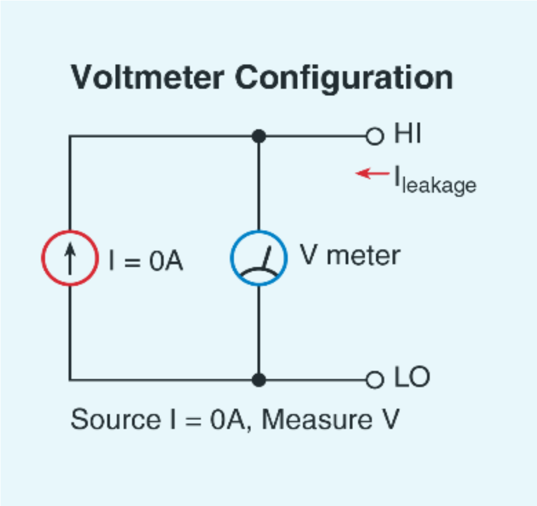
Source V, Measure I



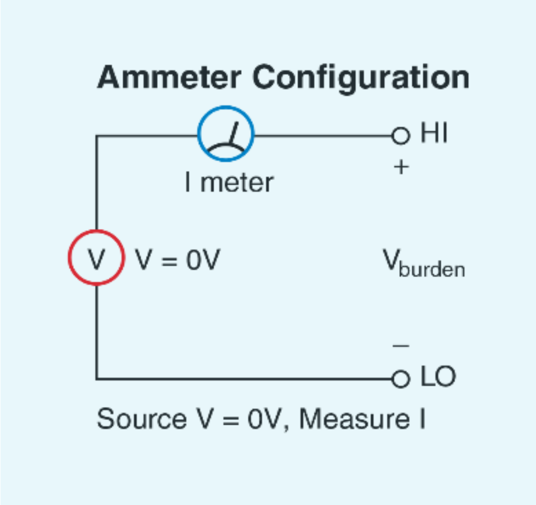
Source I, Measure V

Source Measure Units

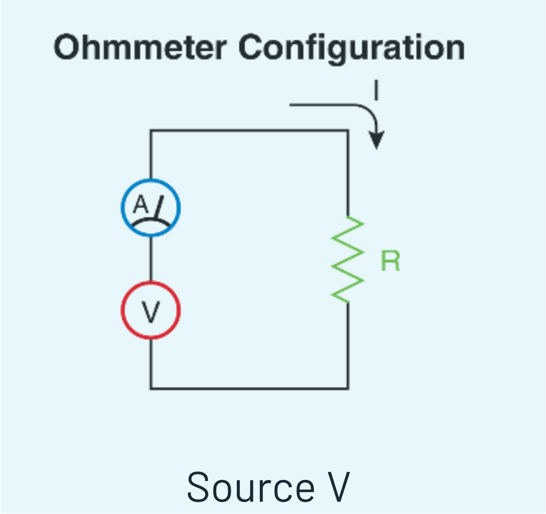
- SOURCE CURRENT **OR** VOLTAGE
- MEASURE CURRENT **AND** VOLTAGE
- CAN ACT AS VOLTMETERS, AMMETERS, OR OHMMETERS


Voltmeter Configuration

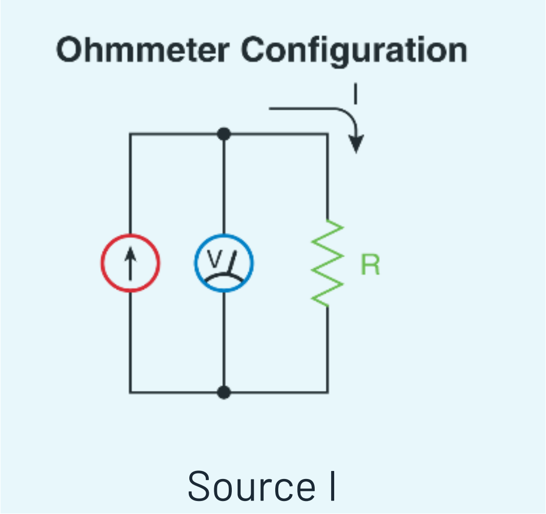
Source I = 0A, Measure V


Ammeter Configuration

Source V = 0V, Measure I

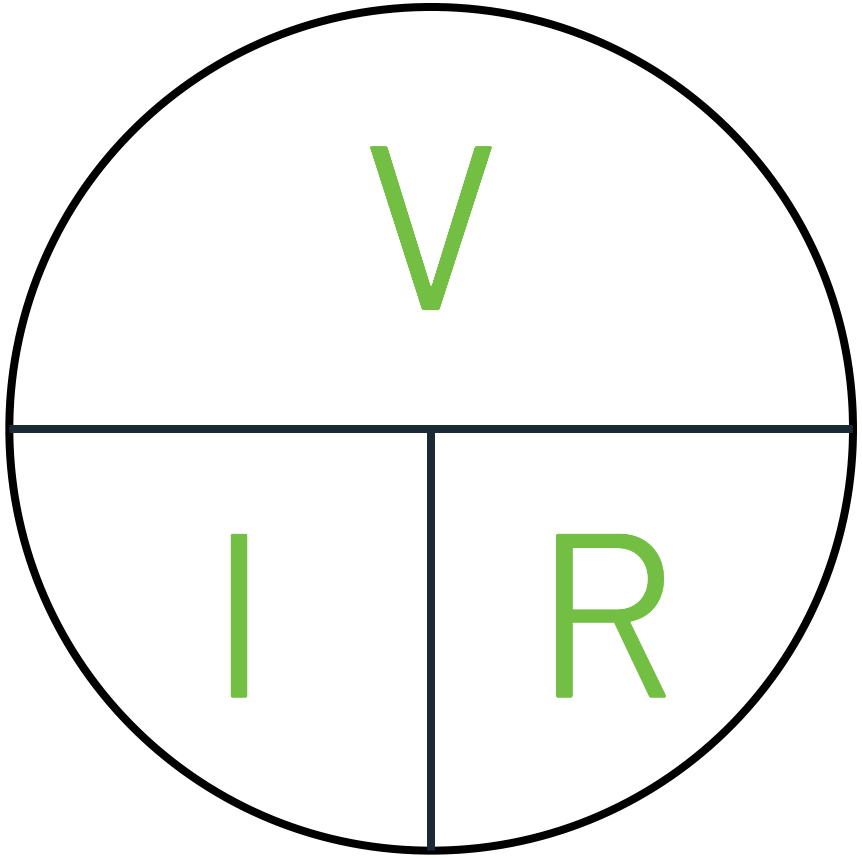

Ohmmeter Configuration

Source V


Ohmmeter Configuration

Source I

Source Measure Units

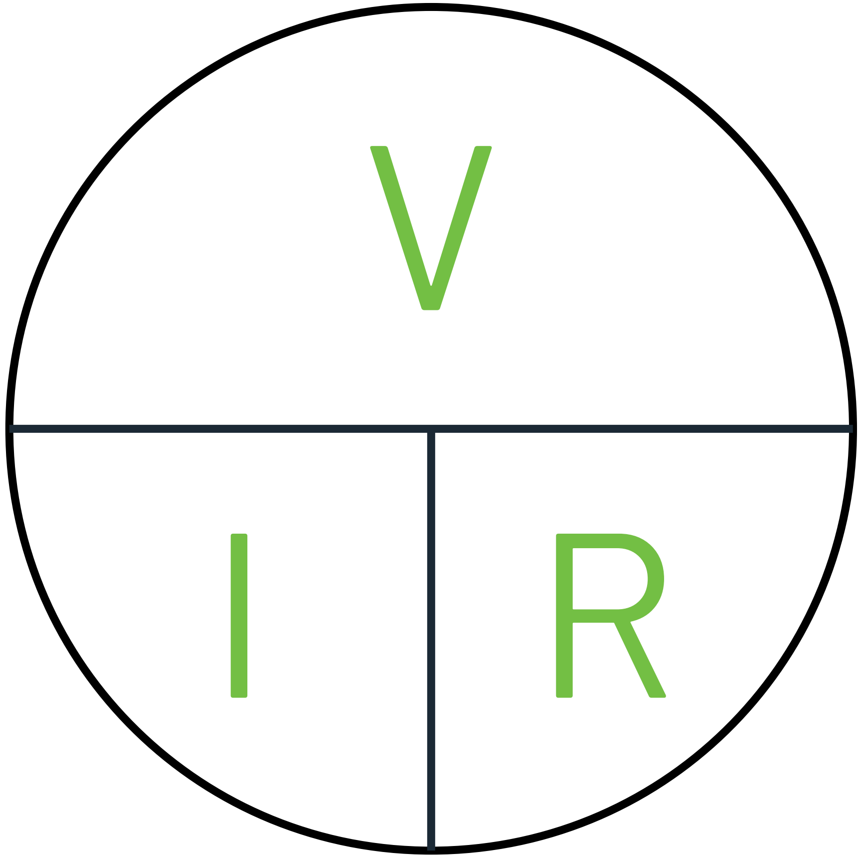


- Source current **or** voltage
- Measure current **and** voltage

$$V = I * R$$

↑ ?

Source Measure Units



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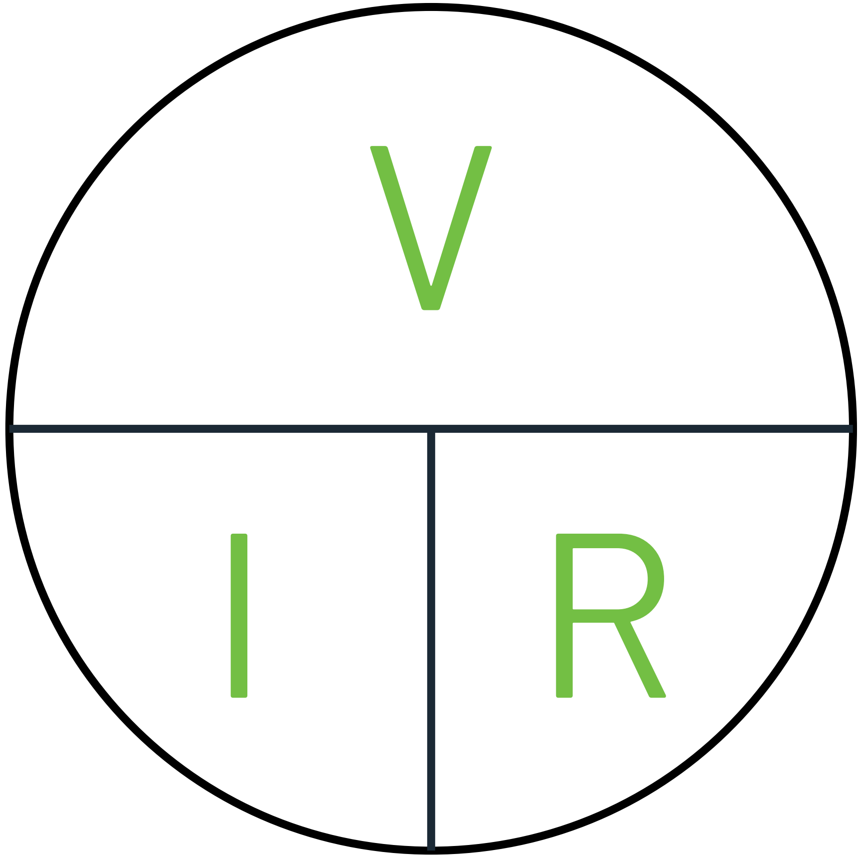
- Measure current **and** voltage

$$\begin{array}{ccccc} V & = & I & * & R \\ \uparrow & & \uparrow & & - \\ & & & \text{or} & \\ & & - & & \uparrow \end{array}$$

Source Measure Units



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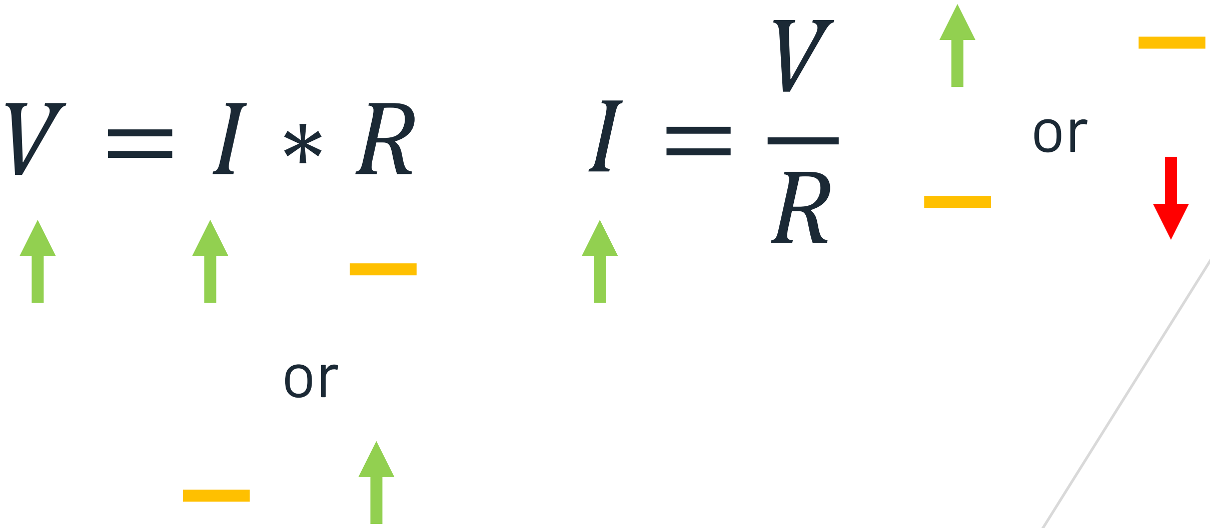

$$V = I * R$$

$$I = \frac{V}{R}$$

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    1. Banana
    2. Alligator
    3. Coax / Triax
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    1. 4-point Collinear Probes

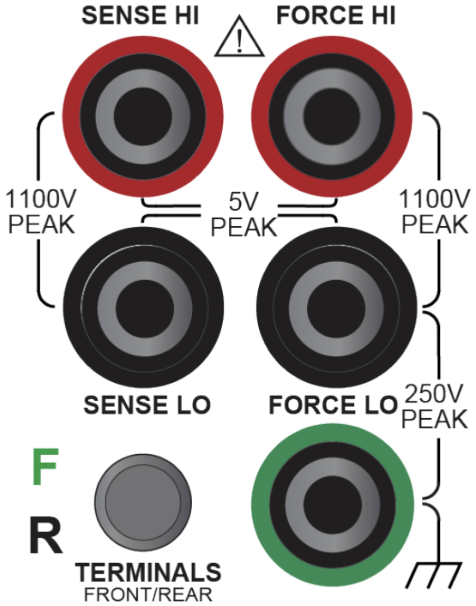
Basic Connectors

Banana
(Safety)

Alligator

Basic Connectors

Banana
(Safety)



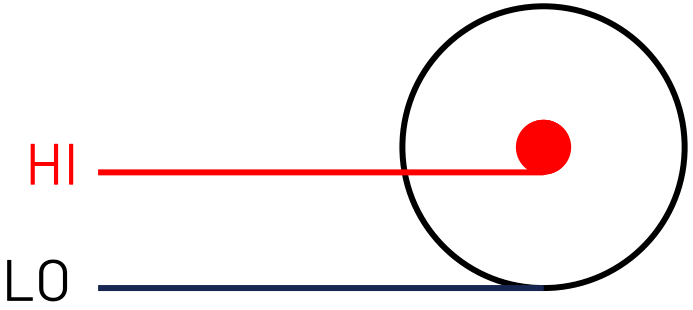
Basic Connectors

Specifications

Working Voltage:	42V peak center conductor to inner shield. 42V peak center conductor and inner shield to outer shell.
Operating Environment:	0°C to 50°C, up to 70% RH at ≤ 35°C.
Contact Resistance:	<0.5Ω.
Insulation Resistance:	$10^{15}\Omega$, center conductor to inner shield (23°C @ <40% RH).

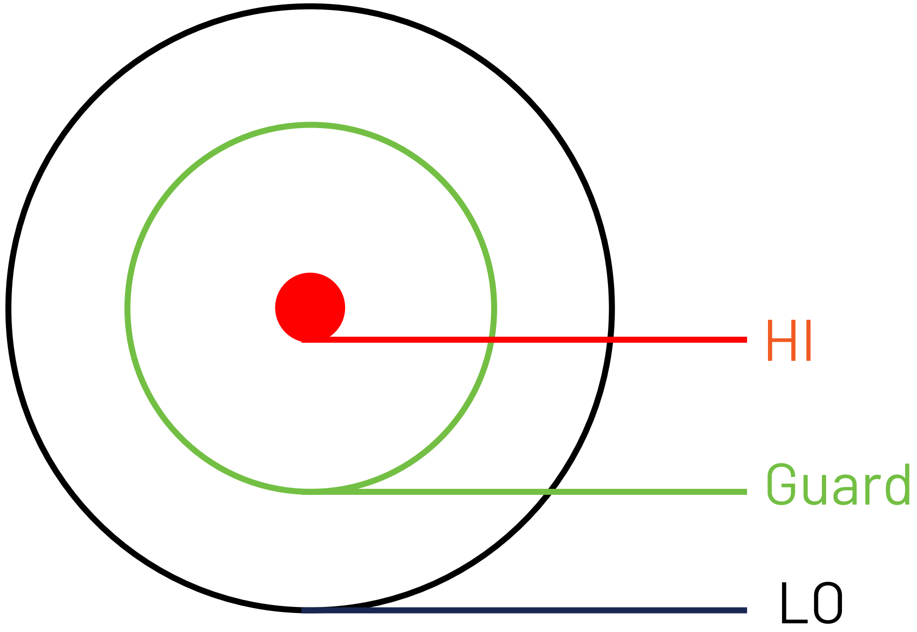
Alligator

Coax Connectors / BNC / SMA



Reduces noise and simplifies cabling

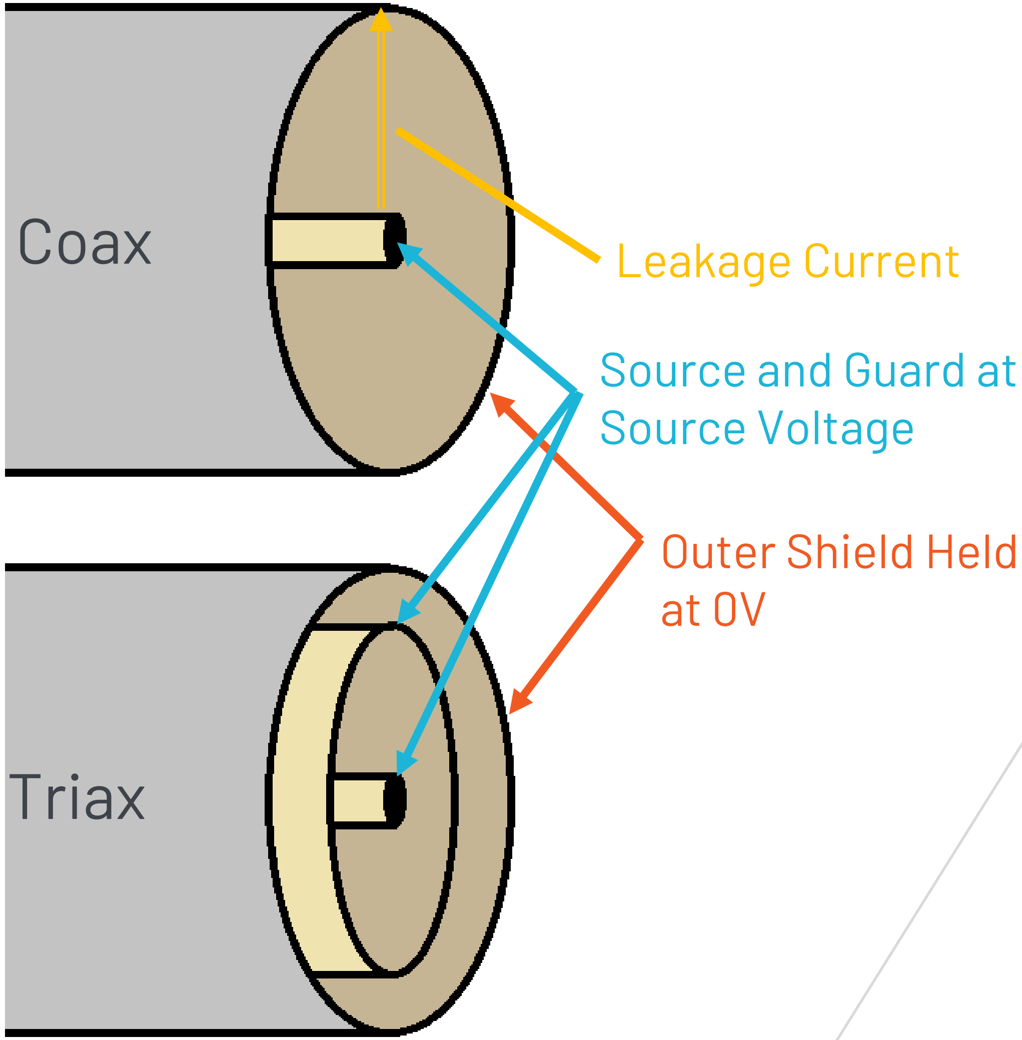
Triax Connectors



Improves accuracy at low currents

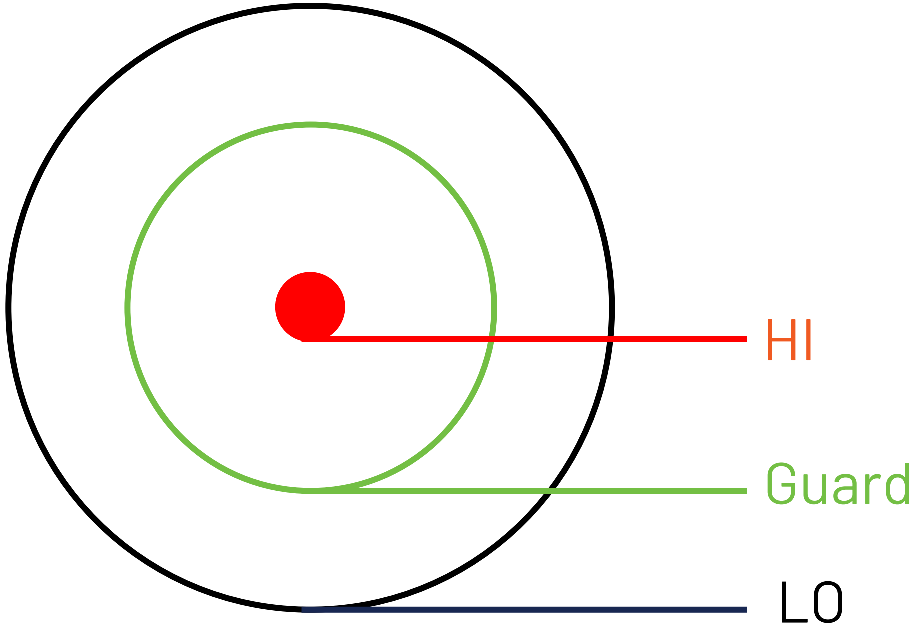
Guarding

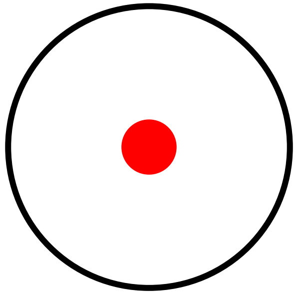
- If there is voltage, there is current!
- Prevents leakage current within the coaxial cable
  - Requires a triaxial cable
  - The inner shield is held at V_{source}
  - Leakage current is now between Guard and Shield and no longer between Source and Shield
  - No leakage between Source and Guard because they are at the same potential

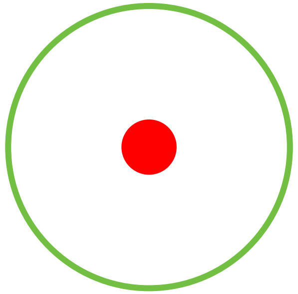


Triax Connectors

ADAPTING TO OTHER CONNECTORS

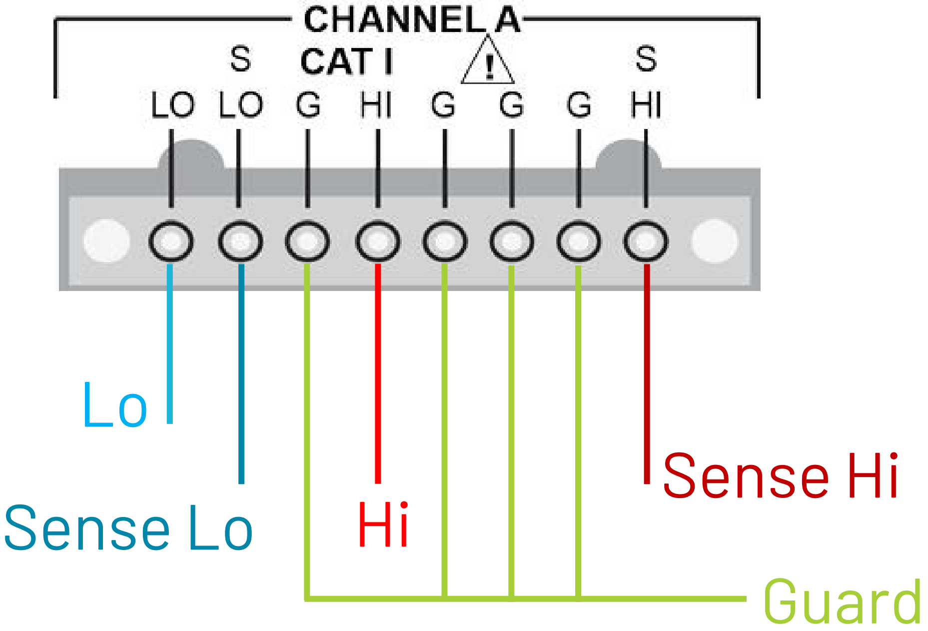




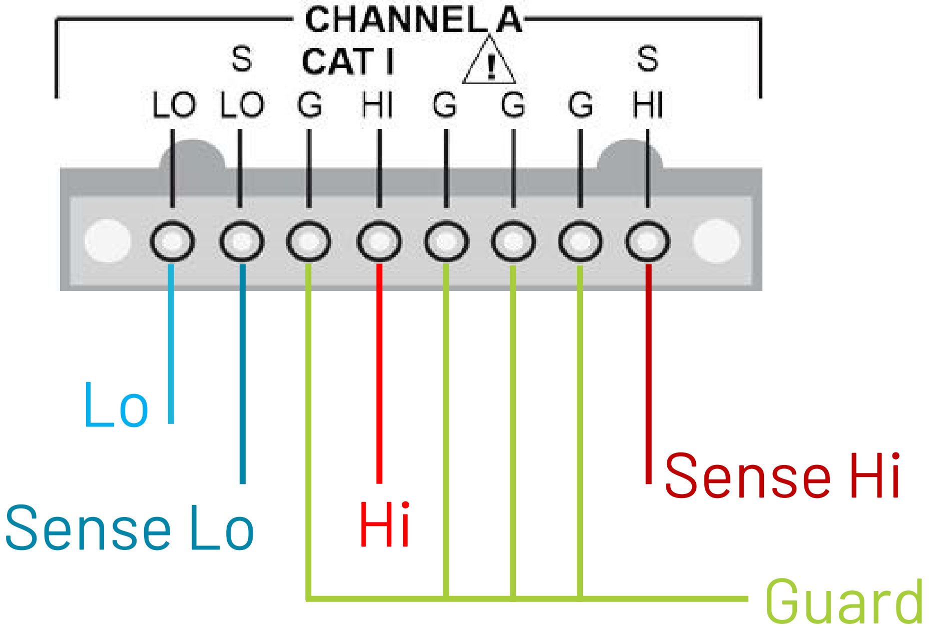


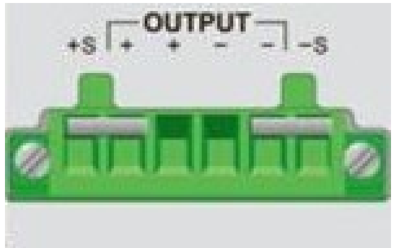
Hazardous voltage can be present!

Phoenix Connectors



Phoenix Connectors





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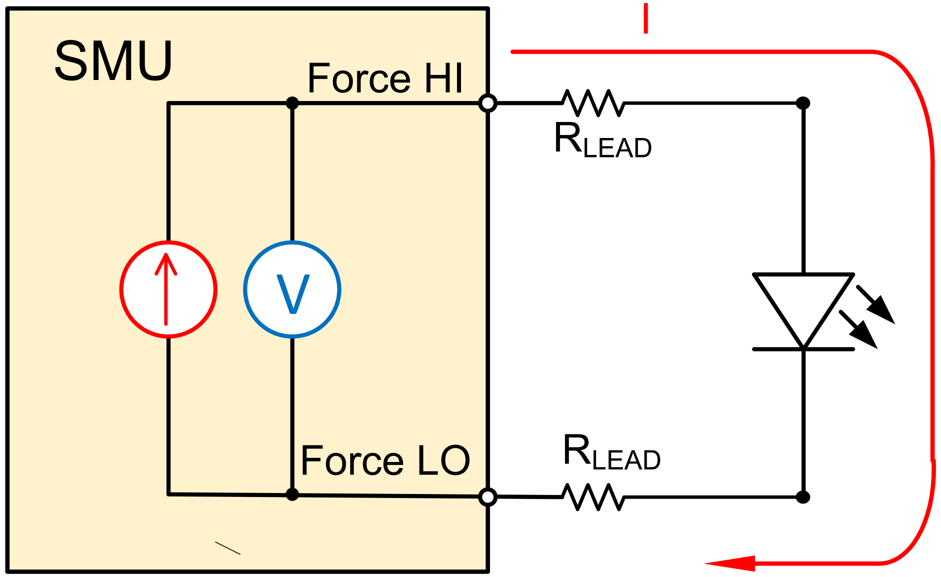
2 Wire vs. 4 Wire Measurements

LOCAL VS REMOTE SENSE / KELVIN CONNECTIONS



2 Wire vs. 4 Wire Measurements

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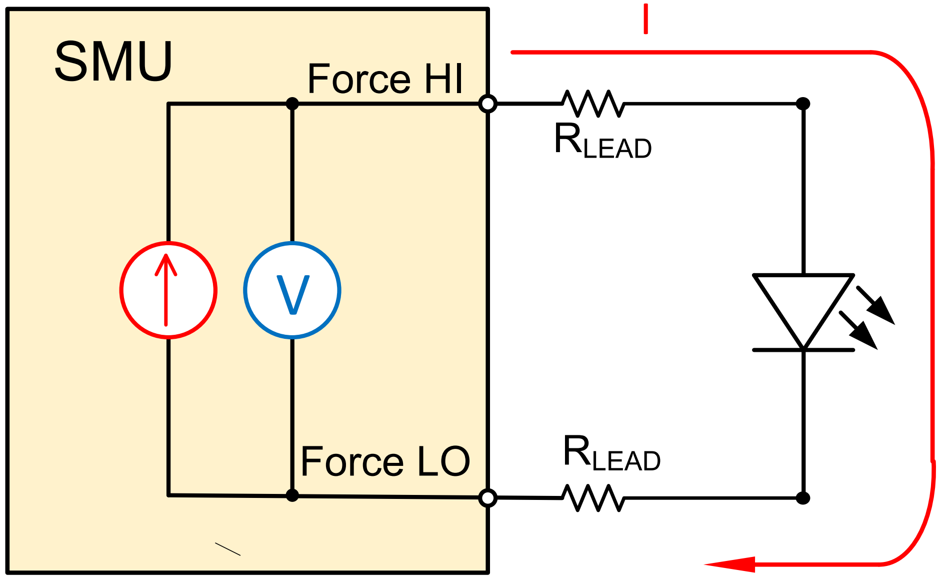


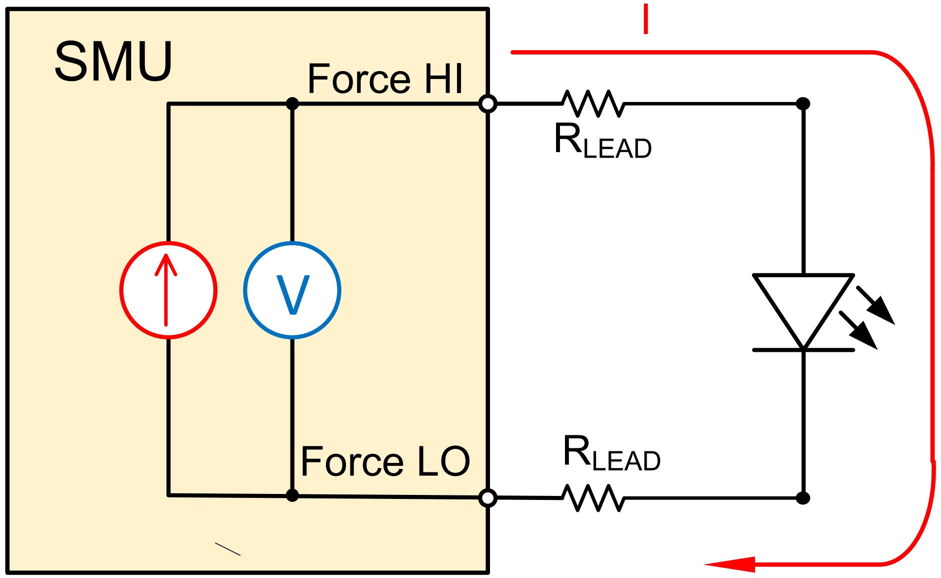
Measured Voltage:

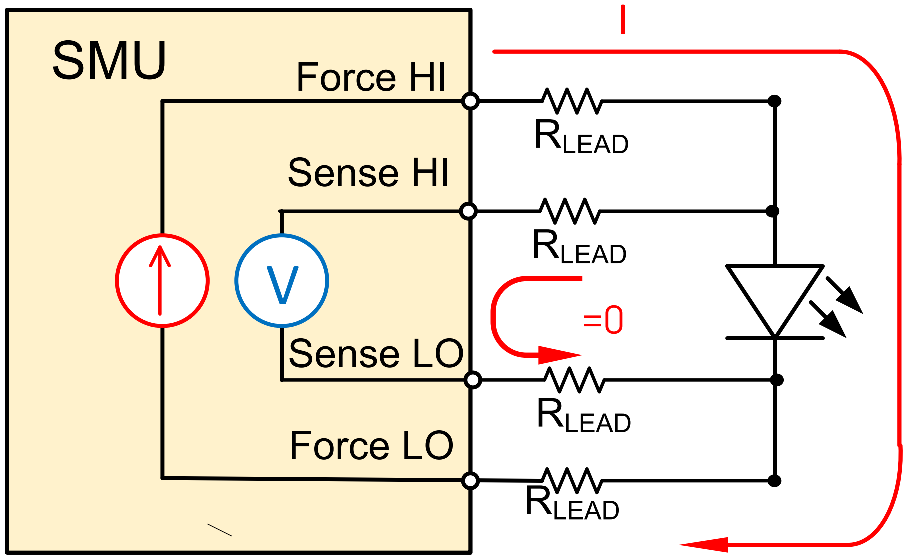
$$V_M = V_{LED} + 2 \times I \times R_{Lead}$$

The voltage drops from the two test leads will be added to the voltage measurement

2 Wire vs. 4 Wire Measurements

LOCAL VS REMOTE SENSE / KELVIN CONNECTIONS





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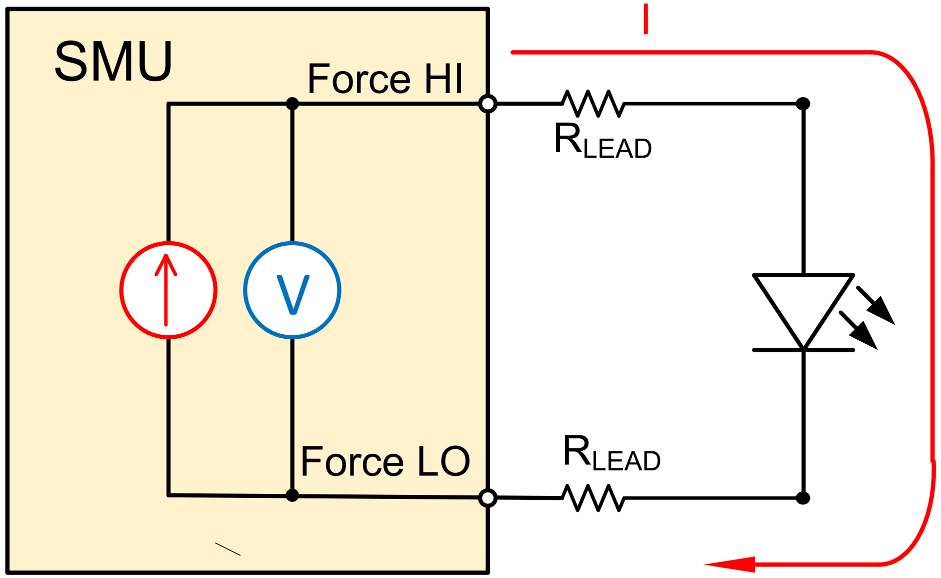
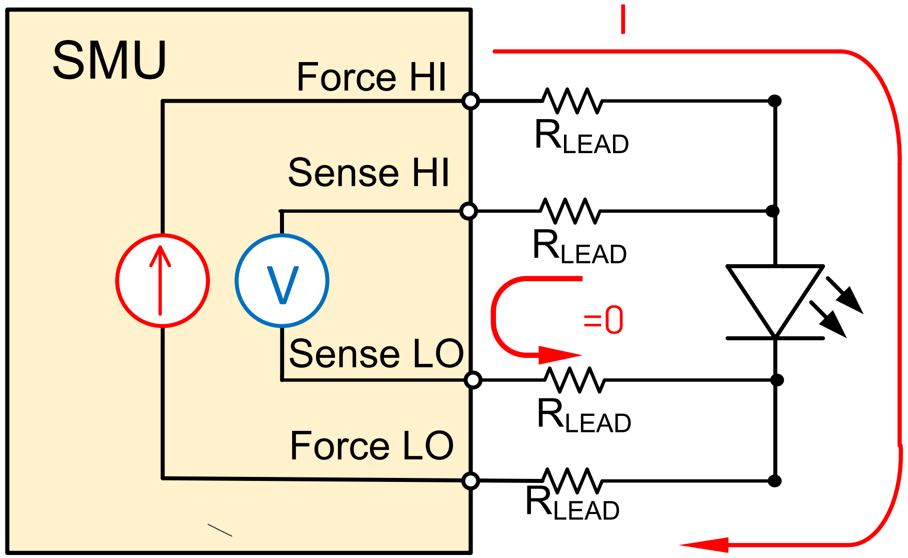




Measured Voltage:

$$V_M = V_{LED} + 2 \times I \times R_{Lead}$$

The voltage drops from the two test leads will be added to the voltage measurement

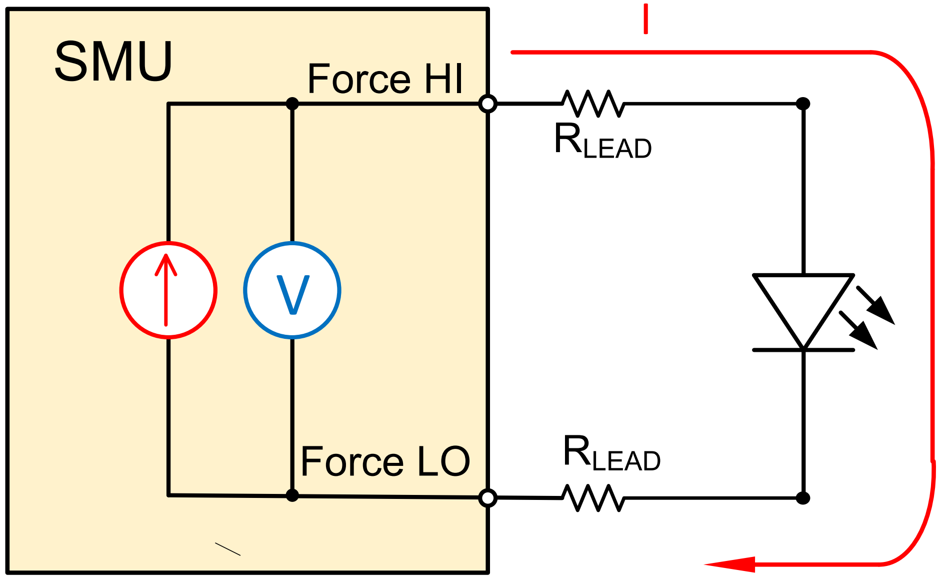
Measured Voltage:

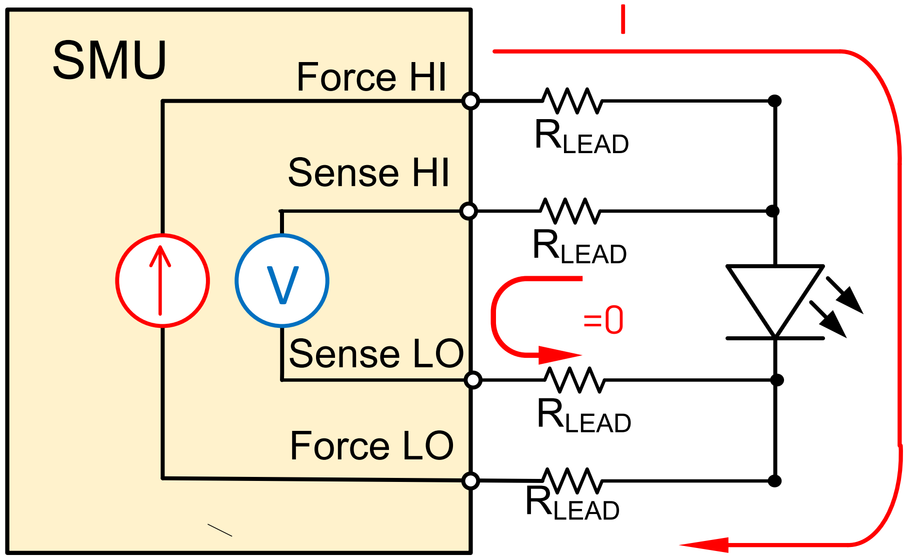
$$V_M = V_{LED}$$

No current flows through the sense leads, so the voltmeter only measures the voltage drop across LED.

2 Wire vs. 4 Wire Measurements

LOCAL VS REMOTE SENSE / KELVIN CONNECTIONS





Measured Voltage:

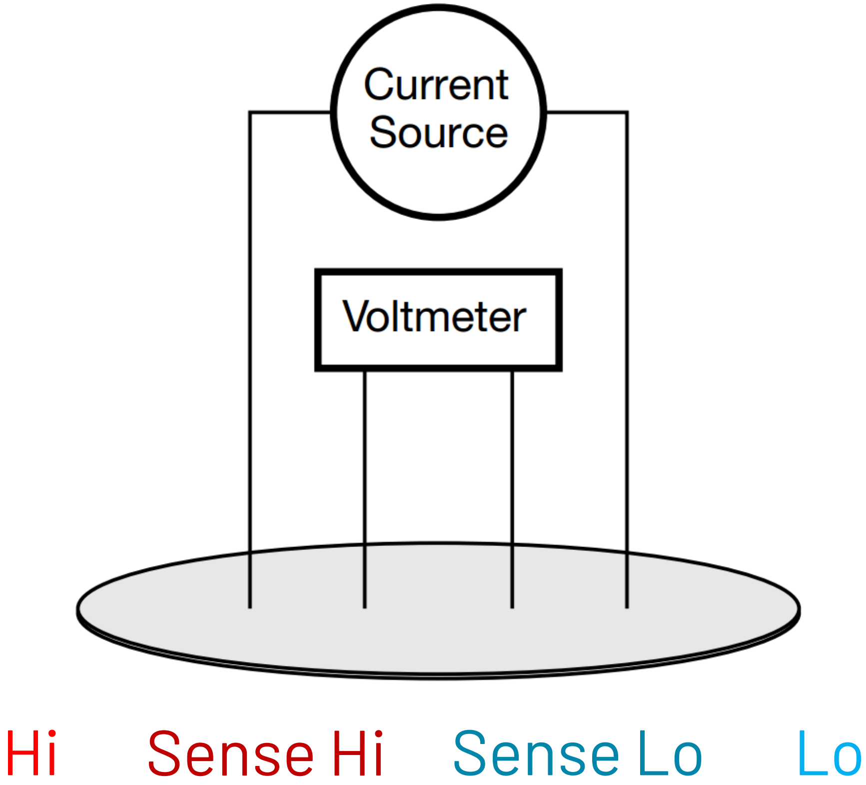
$$V_M = V_{LED} + 2 \times I \times R_{Lead}$$

Hi Sense Hi Sense Lo Lo

The voltage drops from the two test leads will be added to the voltage measurement

4-pt probe Collinear Probe

RESISTIVITY MEASUREMENTS



4-pt probe Collinear Probe

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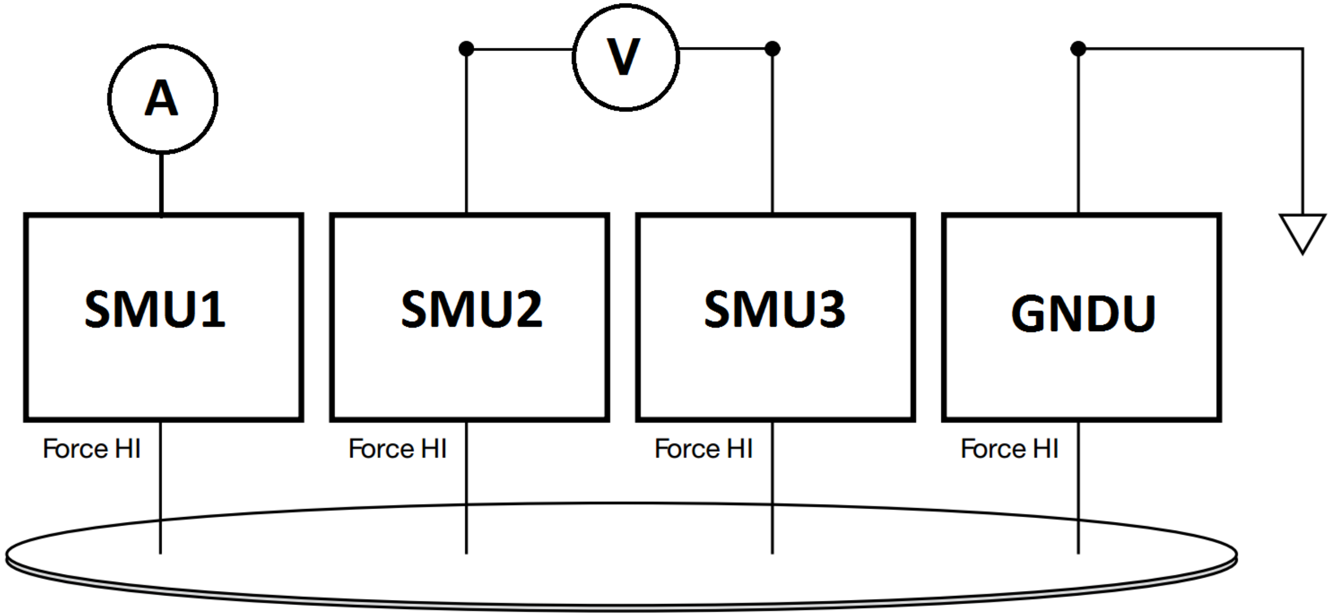
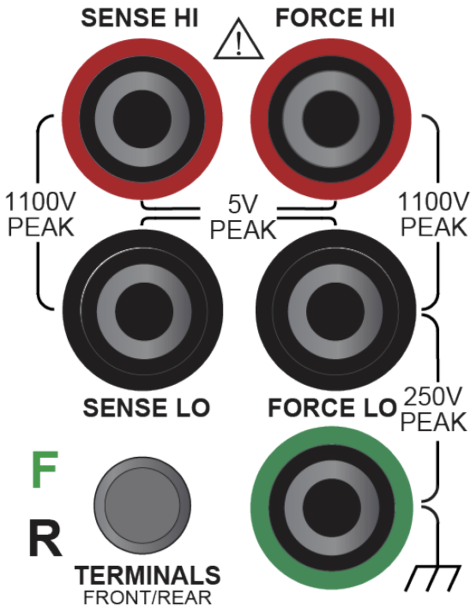
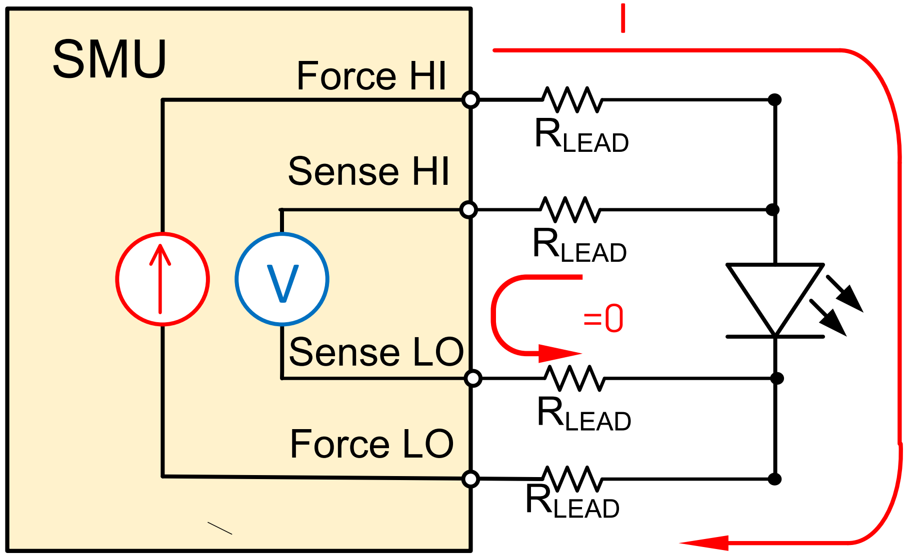


Hi Sense Hi Sense Lo Lo

2 Wire vs. 4 Wire Measurements

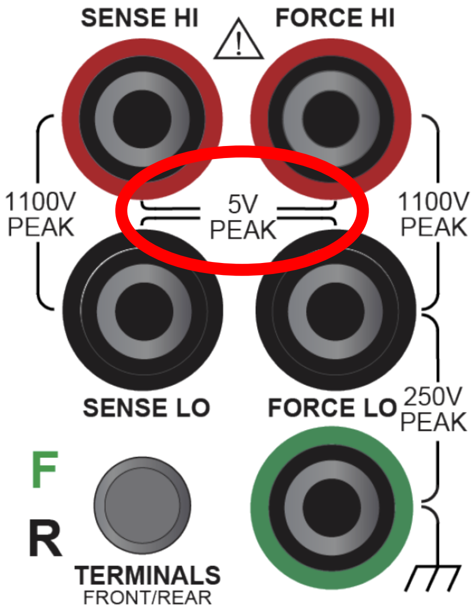
LOCAL VS REMOTE SENSE / KELVIN CONNECTIONS

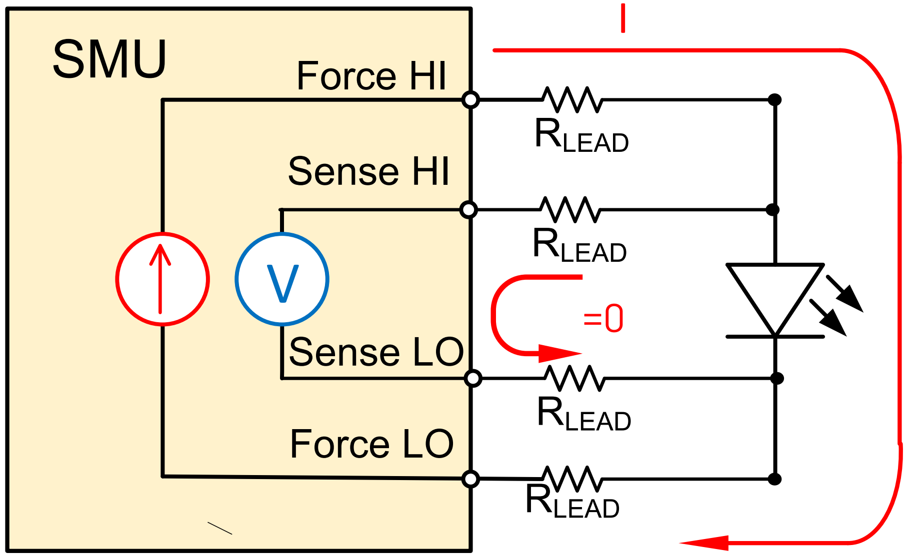




2 Wire vs. 4 Wire Measurements

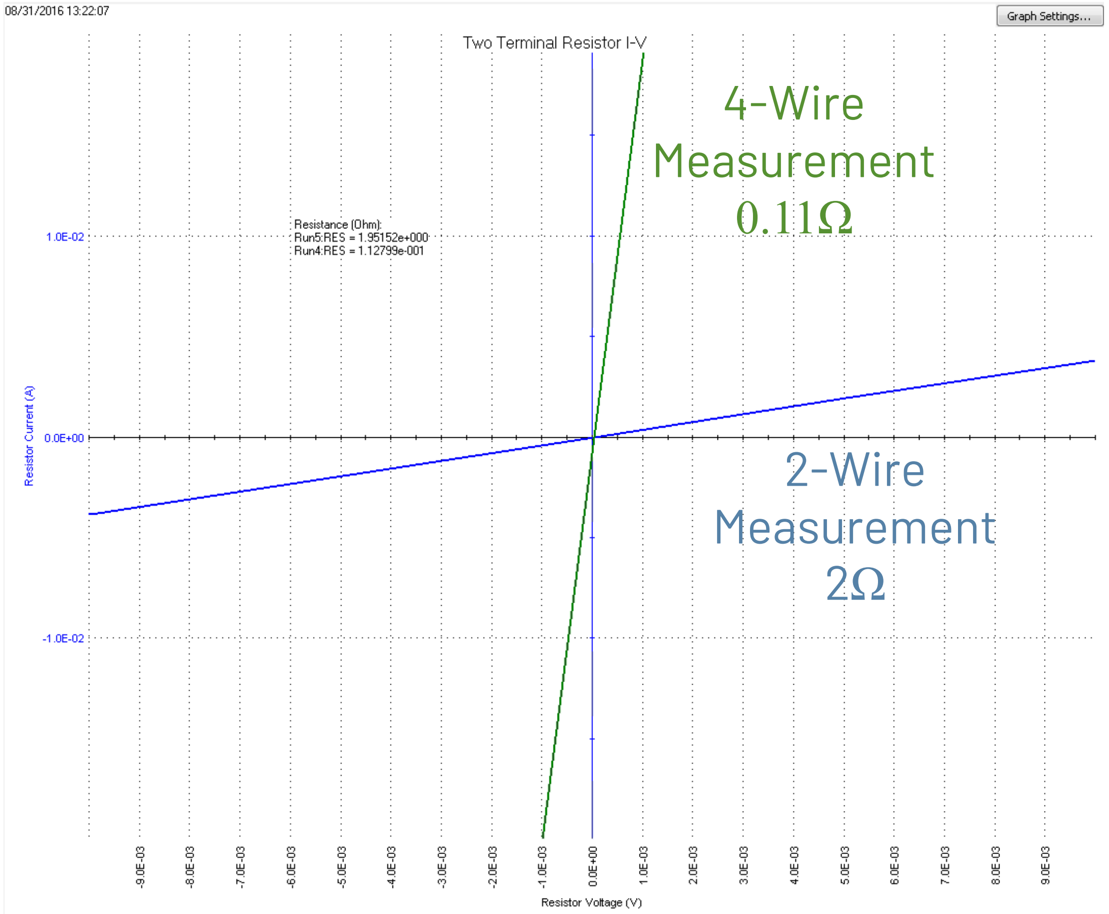
LOCAL VS REMOTE SENSE / KELVIN CONNECTIONS





2 Wire vs. 4 Wire

FOR LOW RESISTANCE OR HIGH CURRENT MEASUREMENTS



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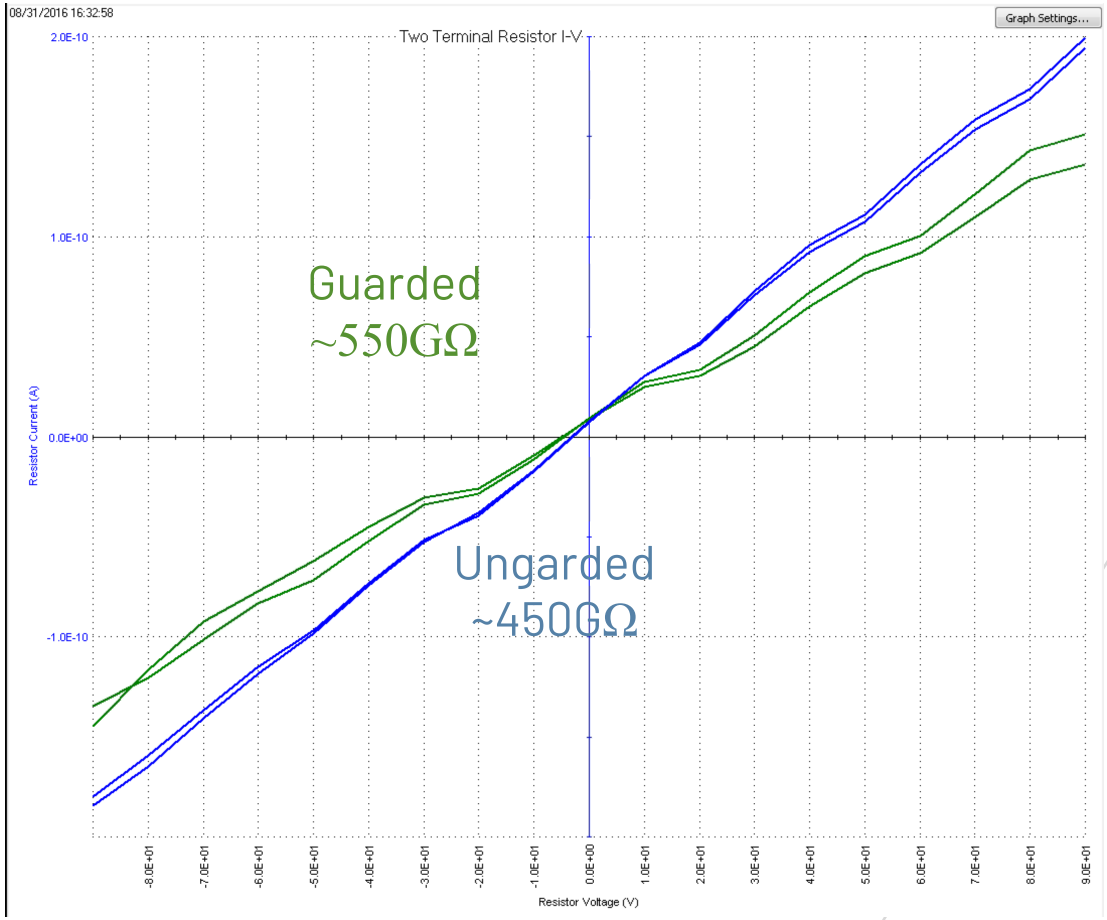
Resistance (Ohm):
Run5:RES = 1.95152e+000
Run4:RES = 1.12799e-001

Guarding

FOR HIGH RESISTANCE OR HIGH VOLTAGE MEASUREMENTS



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THANK YOU

Contact Information

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Tektronix

How to Avoid Common Low Level Measurement Errors

Elizabeth Makley

KEITHLEY
A Tektronix Company

Agenda

- Key Measurement Terms
- What is “Low Level”?
- Sensitive instruments
- Optimizing Low Current Measurements
- Optimizing Low Voltage Measurements

Key Measurement Terms

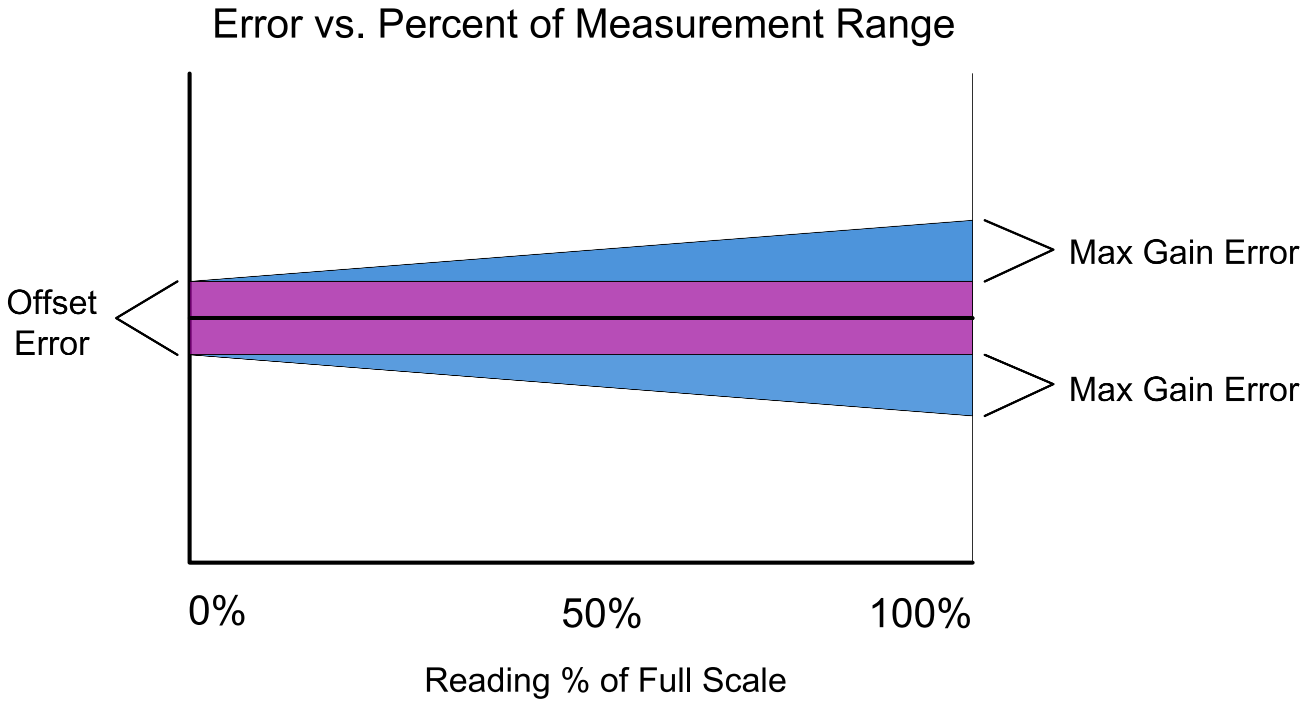
- Resolution vs Accuracy
- Instrumentation Error
- Repeatability and Reproducibility
- NPLCs

Resolution vs Accuracy

- Resolution: The smallest portion of a signal that can be observed
  - The sensitivity of an instrument is the resolution with respect to the measured value
  - For a 6.5 digit DMM on the 10 V range, the resolution is 10 µV
  - This DMM has a 6.5 digit resolution and a sensitivity of 10 µV on the 10 V range
- Accuracy: A measure of how close a measured valued is to an accepted value
  - Absolute accuracy: the accepted value is a primary standard value, like a calibration standard
  - Relative accuracy: the accepted value is a locally established reference value, like a golden sample
  - Calibration is important, this adjusts the instruments ABSOLUTE accuracy

Instrument Accuracy

- Instruments have inherent errors to them
- A typical expression of accuracy is +/- (gain error + offset error).
- At the low end of full scale, the offset term dominates the error.
- At the high end of full scale, the gain term dominates the error.



Repeatability and Reproducibility

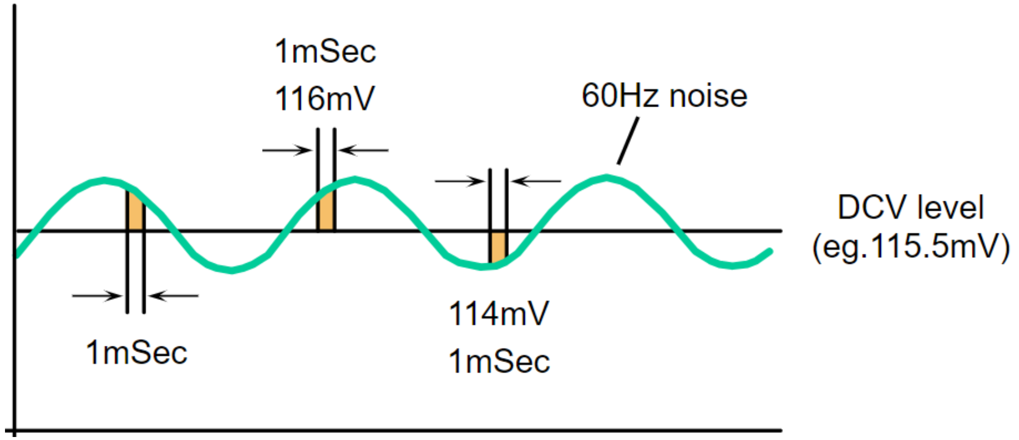
- A measurement is repeatable if…
  - The same setup can get the same measurement over and over again
- A measurement is reproducible if…
  - Equivalent setups can get the same measurement over and over again

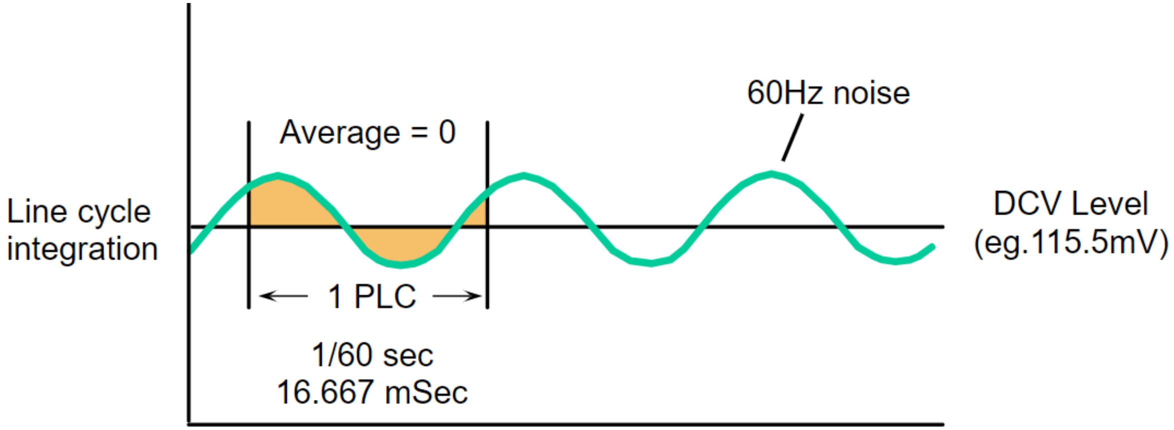
So why optimize your measurements?

- Resolution is determined by your instrument
- Accuracy is limited by your instrument
- But repeatability and reproducibility can be improved by optimizing your test setup!

Power Line Cycle Integration

- NPLC: Number of Power Line Cycles





This ability to reject 60Hz noise at the input is called Normal Mode Rejection Ratio (NMRR).
1Vpp noise @ 60dB NMRR = 1mV error.

Tradeoff: Higher speed means less accuracy

What is a Low Level Measurement?

- Low Current/High Resistance
- Low Voltage/Low Resistance

Low Current or High Resistance

Low Current: <10 nA (10^{-8}A)

- Examples:
  - Gate leakage current of FETs,
  - Testing sensitive nano-electronic DUTs
  - Capacitor leakage current
  - Ion beam current
  - Light measurements with photomultiplier tubes
  - Photodiode current

High Resistance: >1 GΩ (10^{9}Ω)

- Examples:
  - Resistivity of insulators such as paper, rubber, and plastics
  - Insulation resistance testing of devices such as multi-conductor cables, connectors, and printed circuit boards
  - Measuring the resistance of high mega-ohm resistors

Low Voltage or Low Resistance

Low Voltage: <1 µV (10^{-6} V)

- Examples:
  - Measuring differences between voltage standards
  - Microcalorimetry measurements
  - High resolution temperature measurements
  - Hall Voltage and resistivity

Low Resistance: >1 Ω

- Examples:
  - Contact resistance
  - Resistance of superconductors
  - Resistivity of conductors

Sensitive Instruments

What instrument should I use?

Low Current

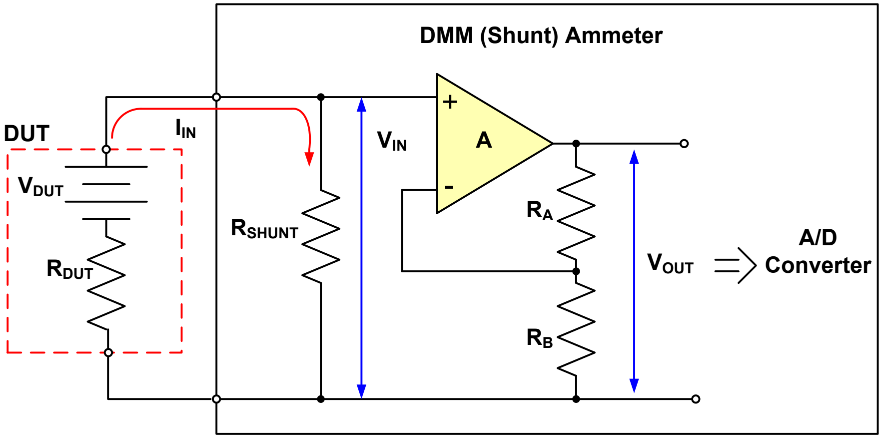
- Electrometer: Precision DC multimeter
- Picoammeter: Measures only low current. Pair with a voltage source for high resistance
- Source Measure Unit (SMU): sources current or voltage while measuring current and voltage

Low Voltage

- Nanovoltmeter: Measures only low voltage. Pair with a current source for low resistance
- Micro-ohmmeter: Ohmmeter that specializes in measuring very small resistances

What about a DMM?

Ammeter Type	Instruments	Typical Sensitivity	Typical Voltage Burden
Shunt	DMMs	µA to nA	<1V
Feedback	Electrometers Picoammeters SMUs SourceMeters	pA to fA	<1mV

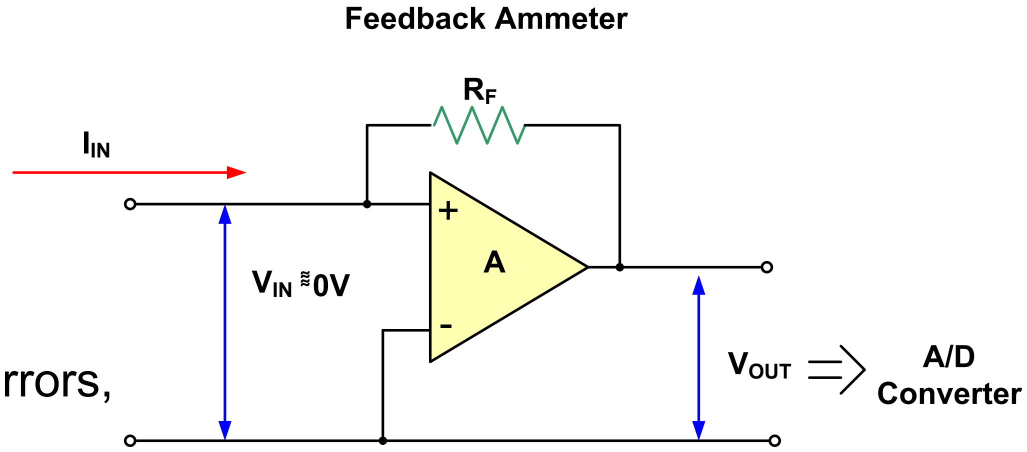


$$V_{OUT} = I_{IN}R_{SHUNT}(1+R_A/R_B)$$

To minimize loading errors,

$R_{SHUNT} << R_{DUT}$

$V_{DUT} >> V_{IN}$



$$V_{OUT} = - I_{IN}R_F$$

Keithley's Sensitive Instrument Offerings

Low Current

- Electrometer: Keithley 6514/6517/6430

- Picoammeter: Keithley 6400 Series

- Source Measure Unit (SMU): 2400 Series, 2600B Series

Low Voltage

- Nanovoltmeter: Keithley 2182A

- Low Resistance Configuration: Keithley 2182A paired with 6200 Series Low Current Source

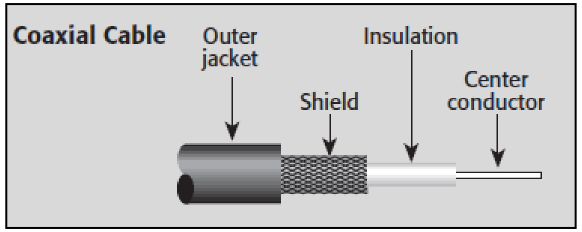
////////////

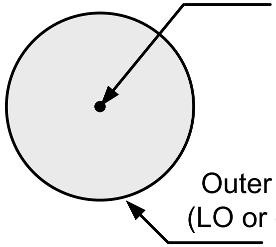
Optimizing Low Current Measurements

- Device Connections
- Measuring Offset Current
- Settling Time
- Shielding
- Guarding
- Generated Currents
- Noise and Source Impedance

Connecting to the Device

Coaxial Cables

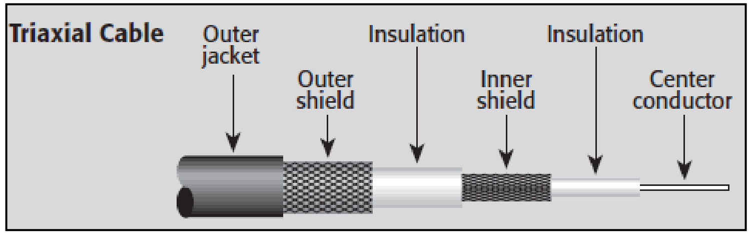


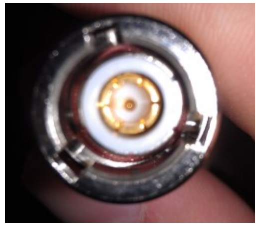


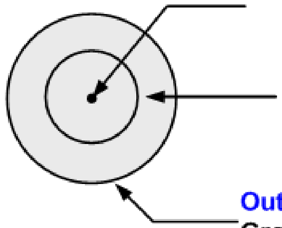
Center Conductor (HI)

Outer Shield
(LO or ground)

Triaxial Cables







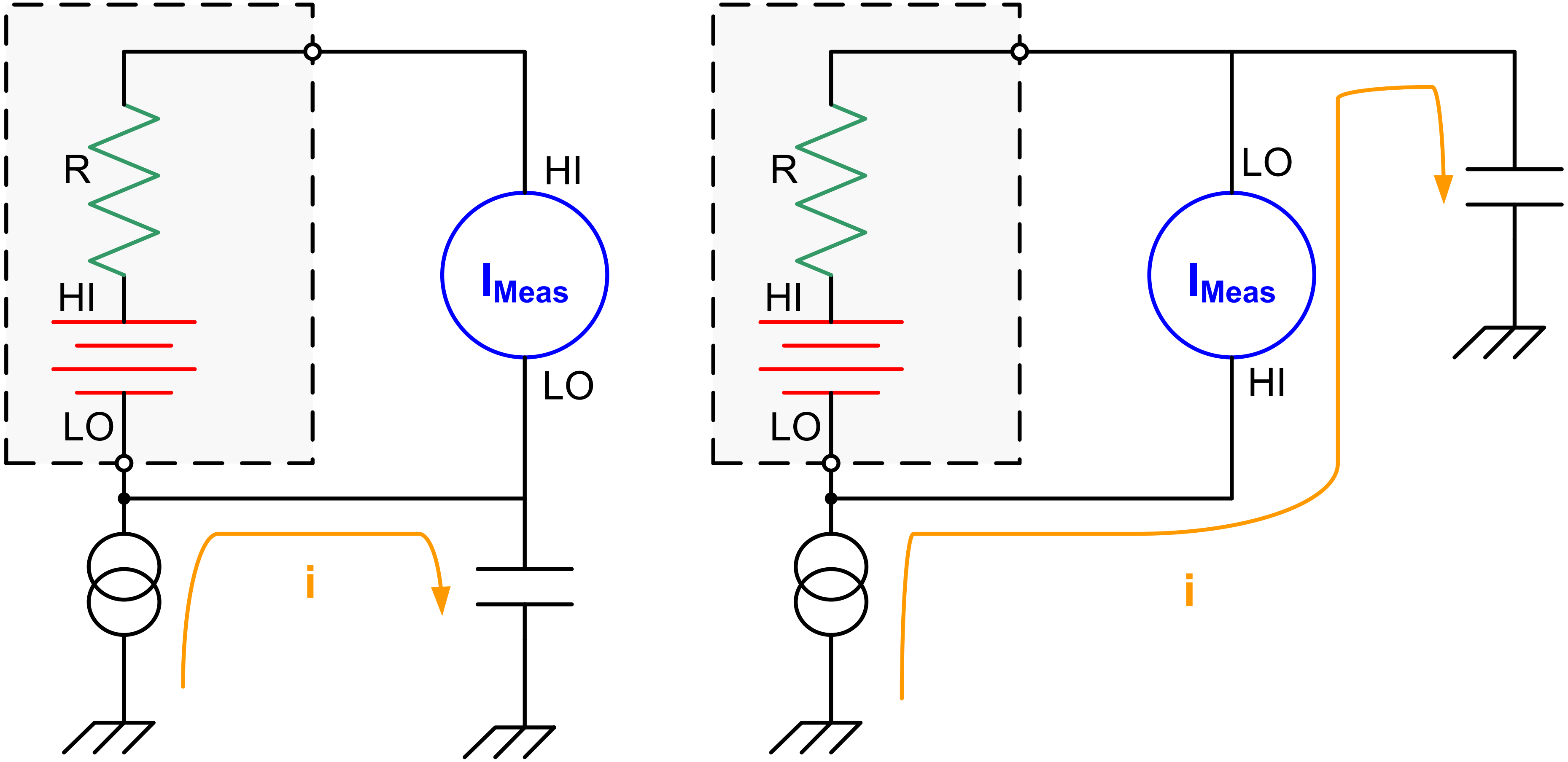
Center Conductor:
HI terminal for both Electrometer/Picoammeter and SMU

Inner Shield: LO terminal for Electrometer/Picoammeter
Guard terminal for SMU

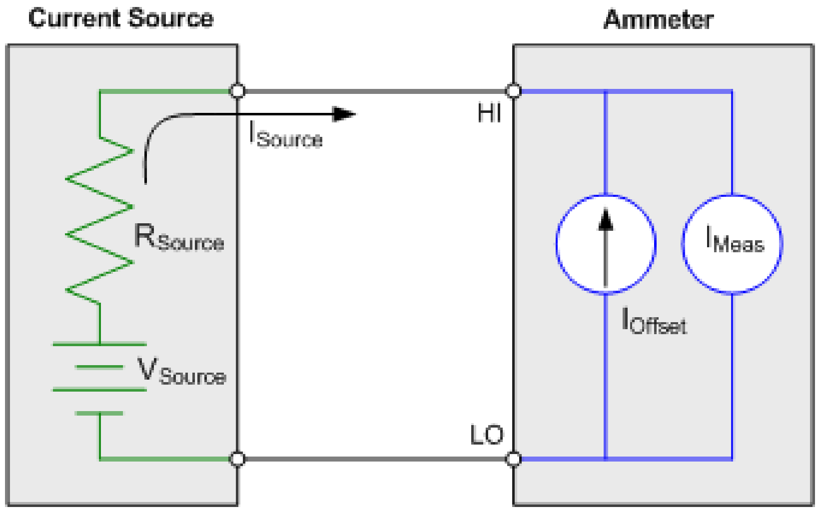
Outer Shield:
Ground for Electrometer Ammeter/Picoammeter
Ground for SMU

- Use low noise cable to minimize offsets
- The insulation resistance of all connectors, internal wiring, terminals, and sockets should be as high as possible to avoid errors due to leakage current
- Keep connections short and simple
- Use shielded cables and test fixtures to prevent electrostatic pick-up
- When testing light sensitive components, use a light-tight test fixture

Connecting to the Device



Measuring offset current



Caution: Changing connections generates current in the circuit. For making ultra-low current measurements, it may be necessary to wait for a few minutes to hours for the spurious currents to decay after changing connections to the circuit.

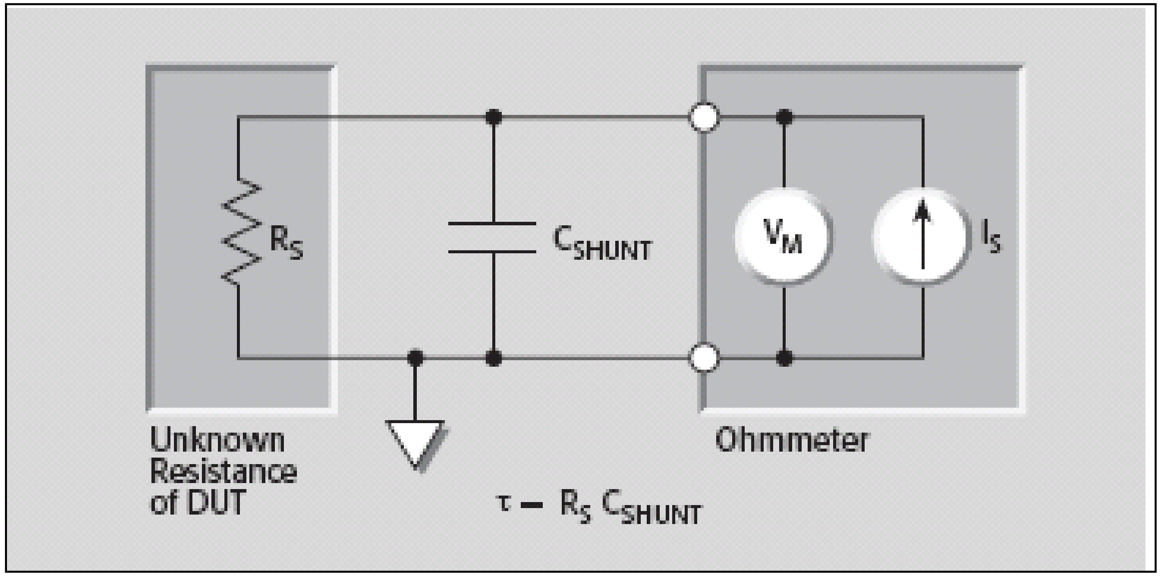
Procedure for Measuring Offset Current of Bench Instrument:

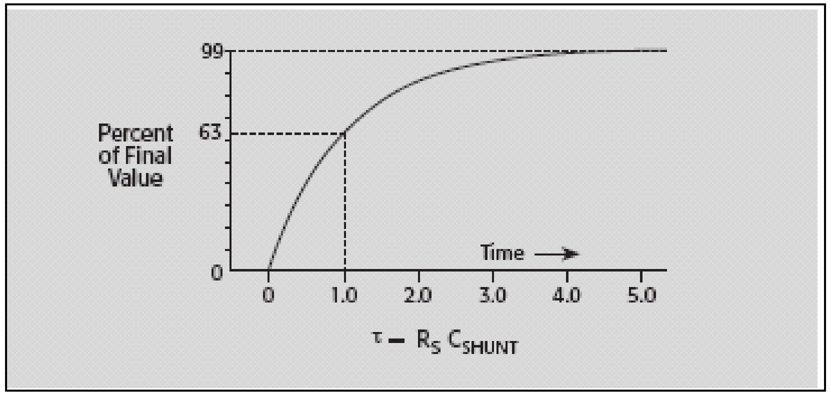
1. Allow instrument to warm up for 1 hour.
2. Place metal cap on the input terminal.
3. Select the lowest current range.
4. Allow about five minutes.
5. Take a measurement by observing the reading on the front panel.
6. Verify the reading is within the instrument's specifications.
7. Press the REL function to subtract the offset from subsequent readings.

Procedure for Measuring Offset Current of the Entire System:

1. Measure the current of the ammeter with a metal cap over the HI terminal.
2. Add cables/adaptors one at a time and repeat the test after each new piece.
3. Connect to the test fixture or probe station with the probes up and repeat the test.
4. In addition to measuring the current offset, apply voltage and measure leakage current.

Settling time





The settling time is the result of the RC time constant, or τ.

$$\tau = R_S C_{SHUNT}$$

Example:

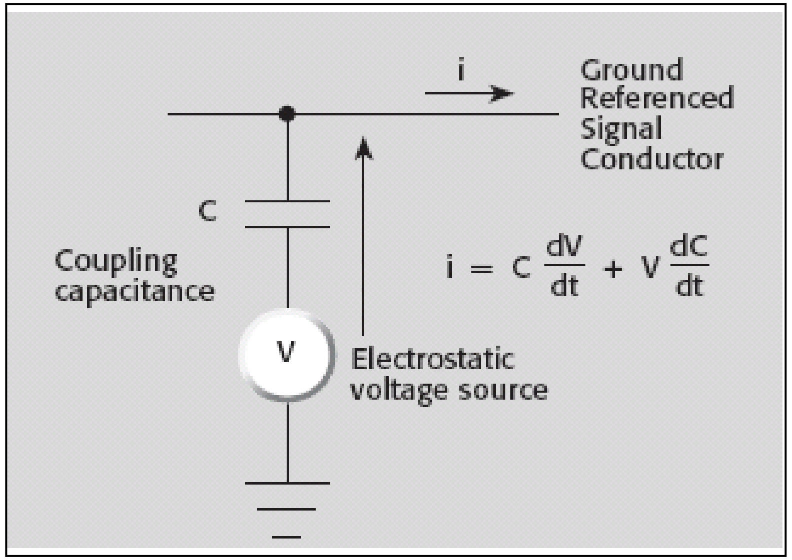
If $C_{SHUNT} = 10$ pF

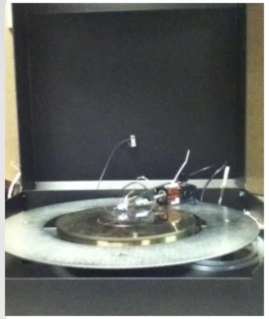
$R_S = 1\text{T}\Omega$ (or 1e12 Ω)

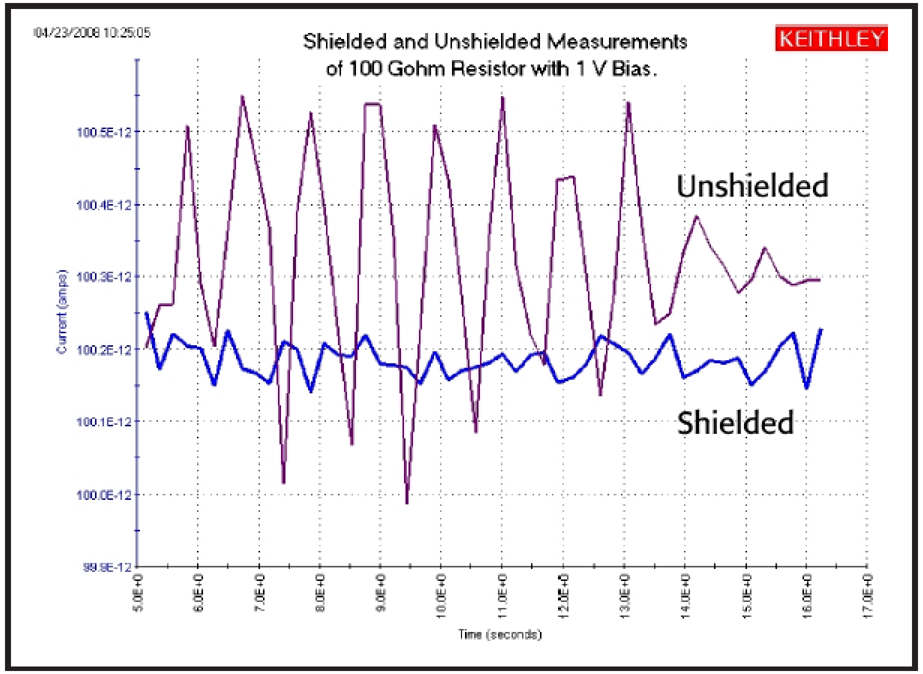
Then, $\tau = 10\text{pF} \times 1\ \text{T}\Omega = 10$ seconds.

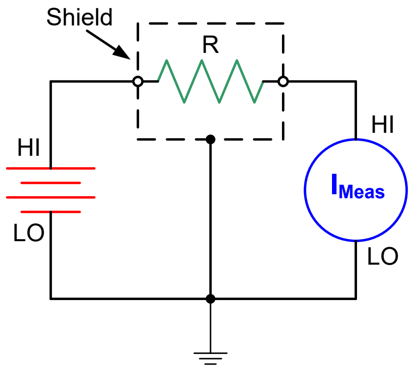
Therefore, a settling time of 50 seconds would be required for the reading to settle with 1% of final value!

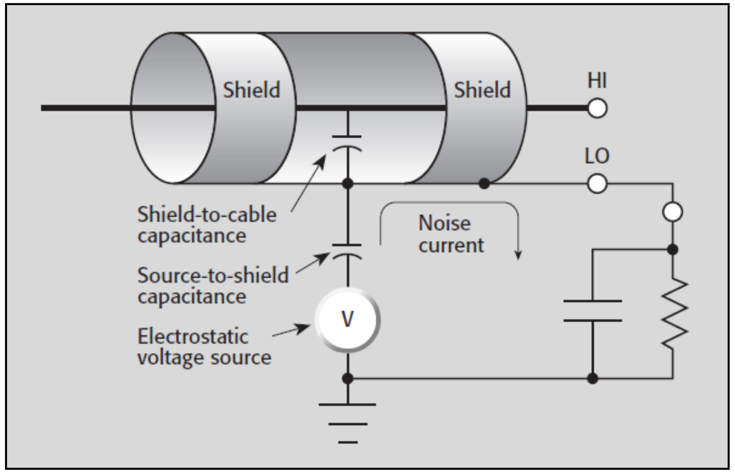
Electrostatic Interference and Shielding



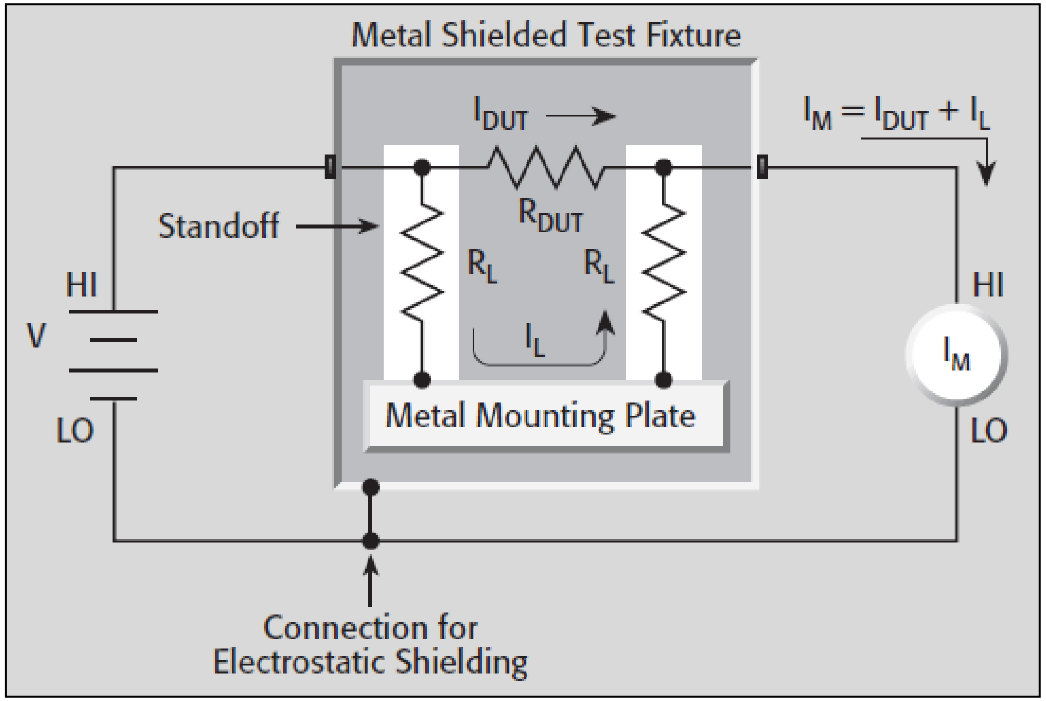


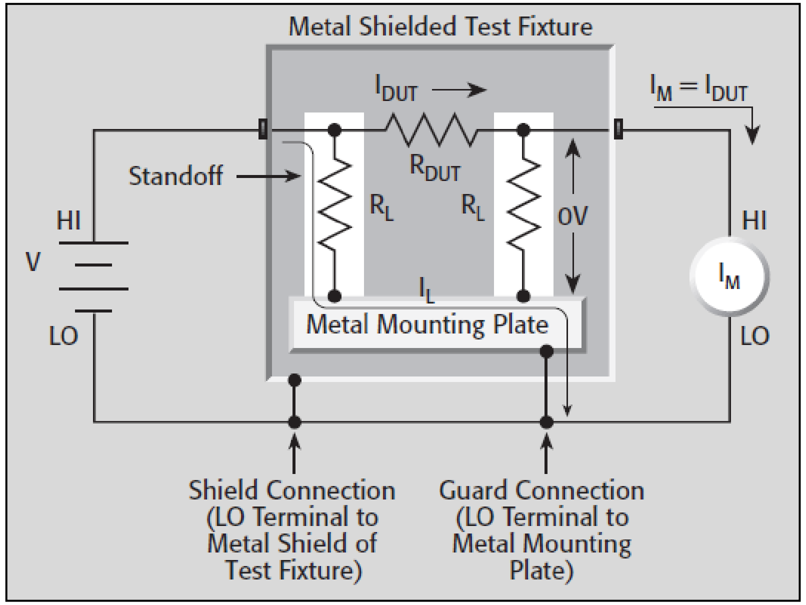


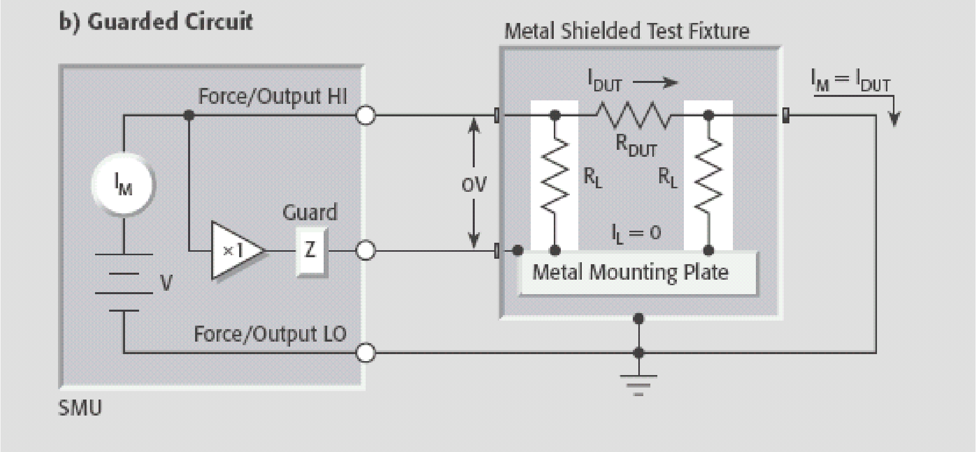




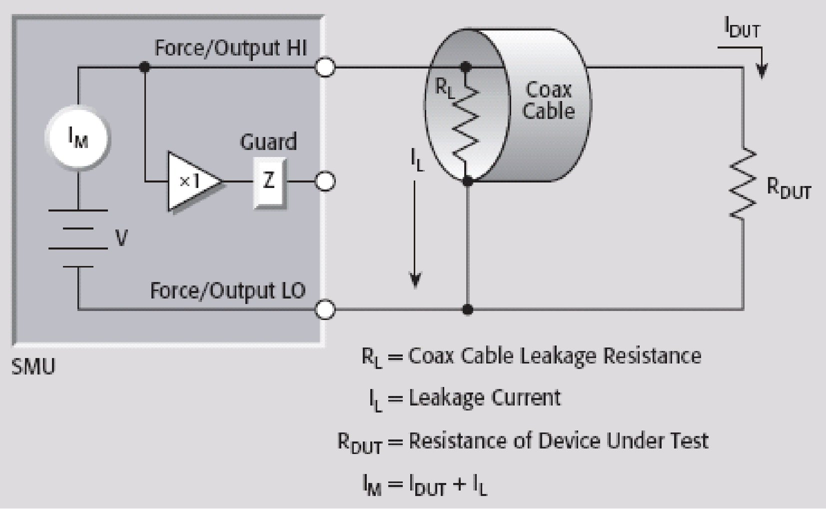
Leakage Current and Guarding






b) Guarded Circuit

Leakage Current and Guarding

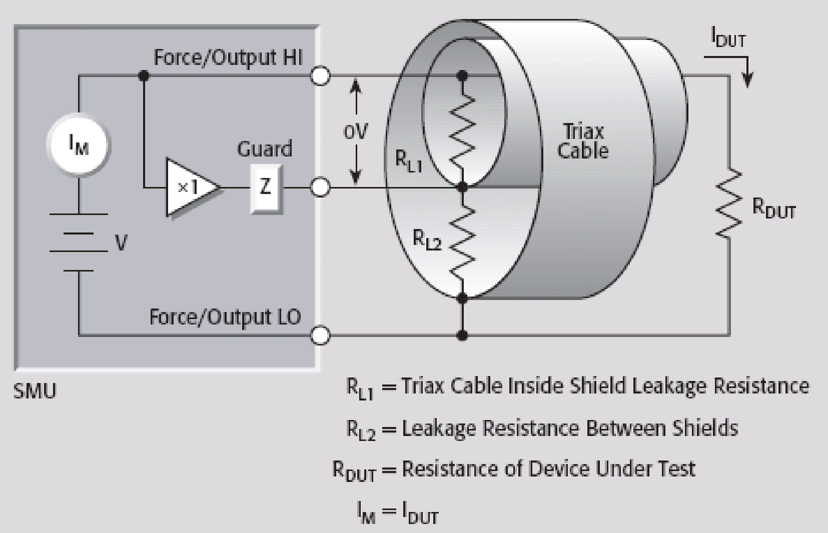


R_L = Coax Cable Leakage Resistance

I_L = Leakage Current

R_{DUT} = Resistance of Device Under Test

$I_M = I_{DUT} + I_L$

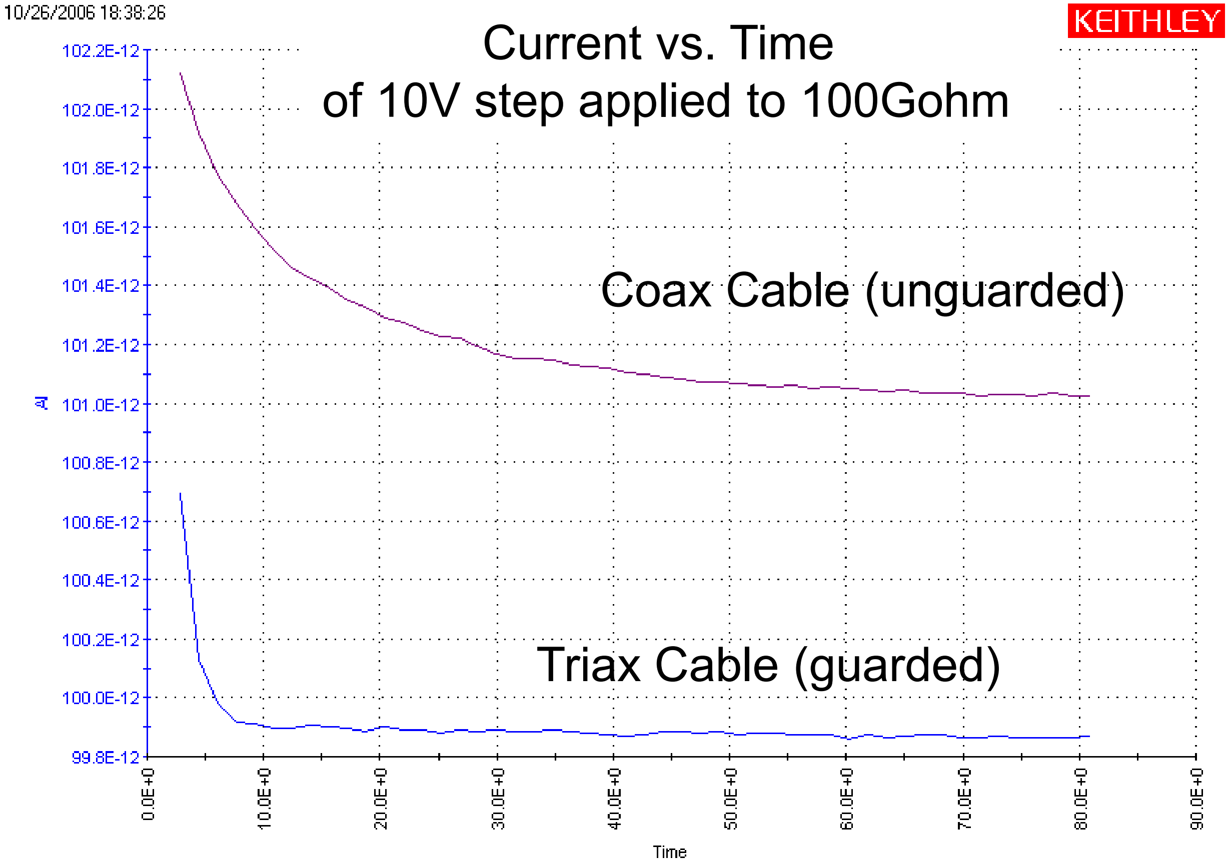


R_{L1} = Triax Cable Inside Shield Leakage Resistance

R_{L2} = Leakage Resistance Between Shields

R_{DUT} = Resistance of Device Under Test

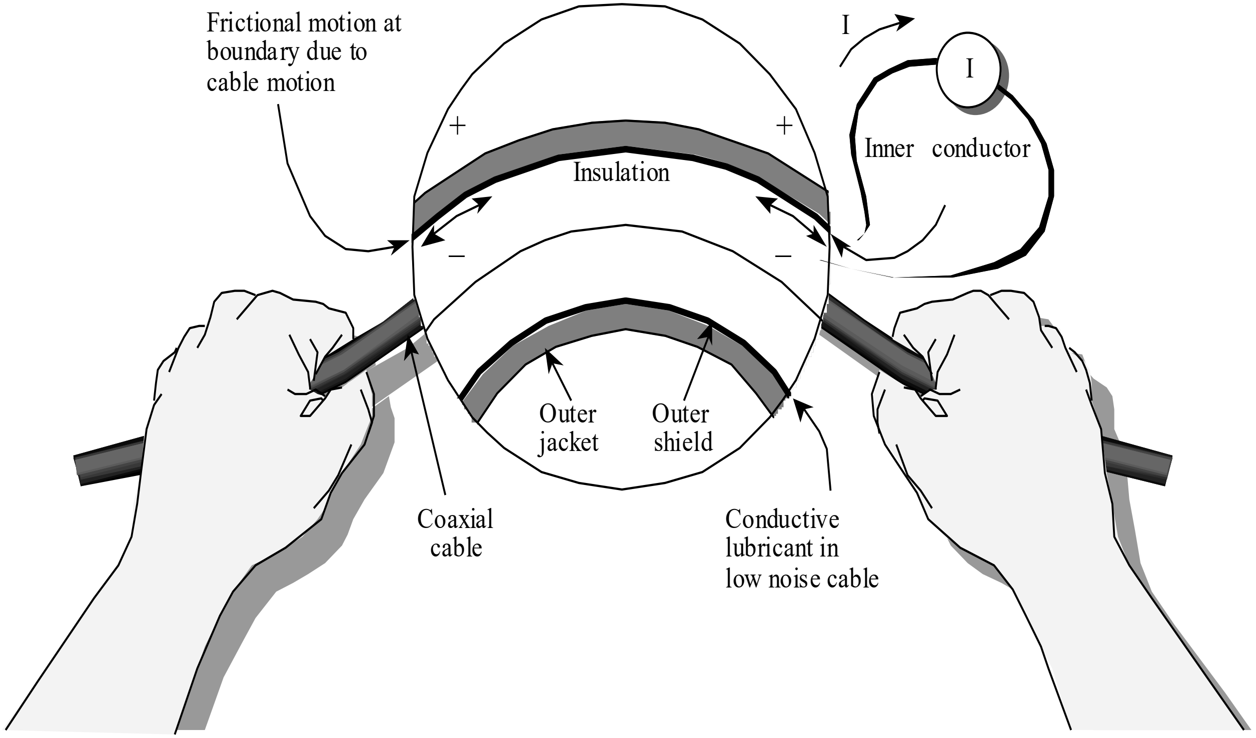
$I_M = I_{DUT}$



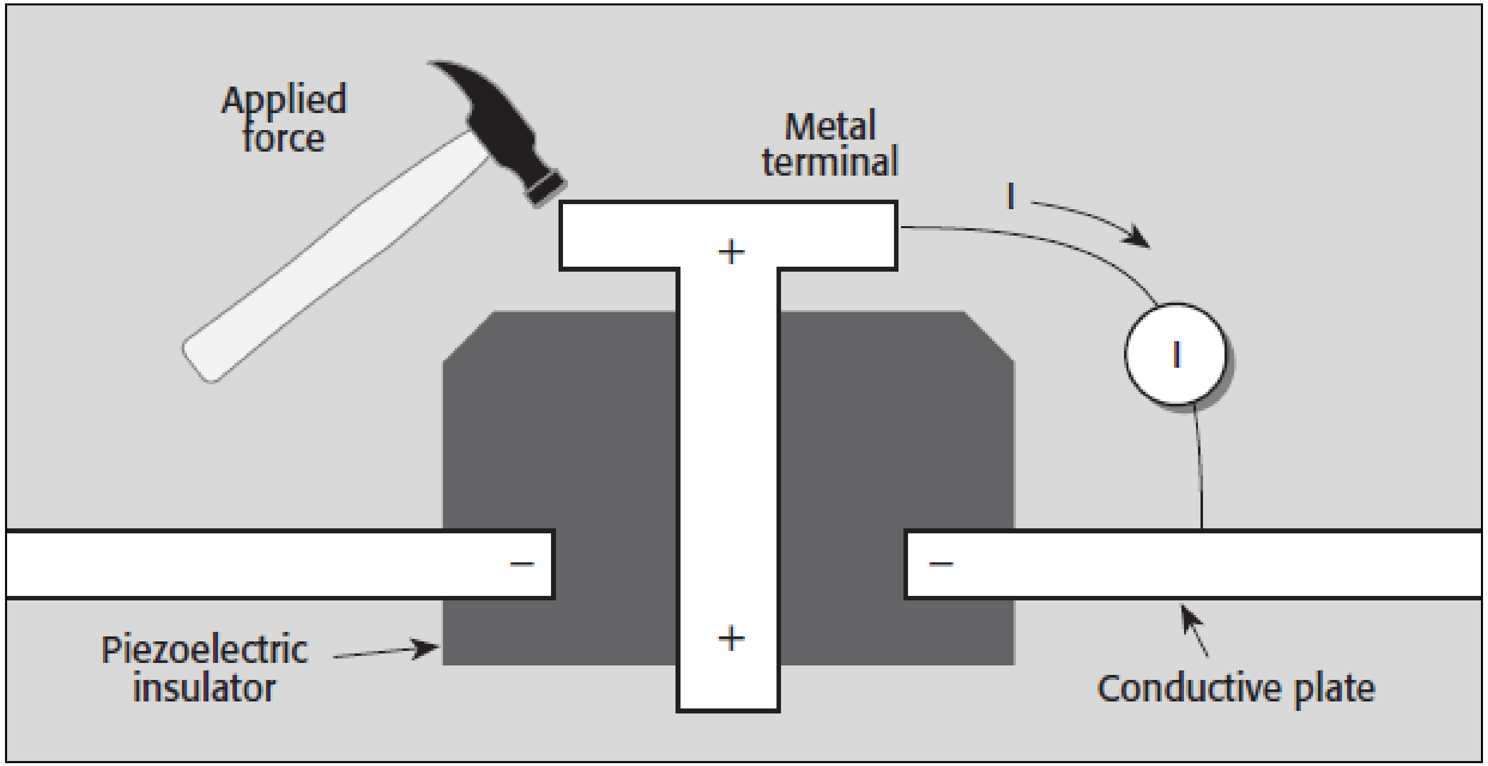
Current vs. Time
of 10V step applied to 100Gohm

Triboelectric Effects

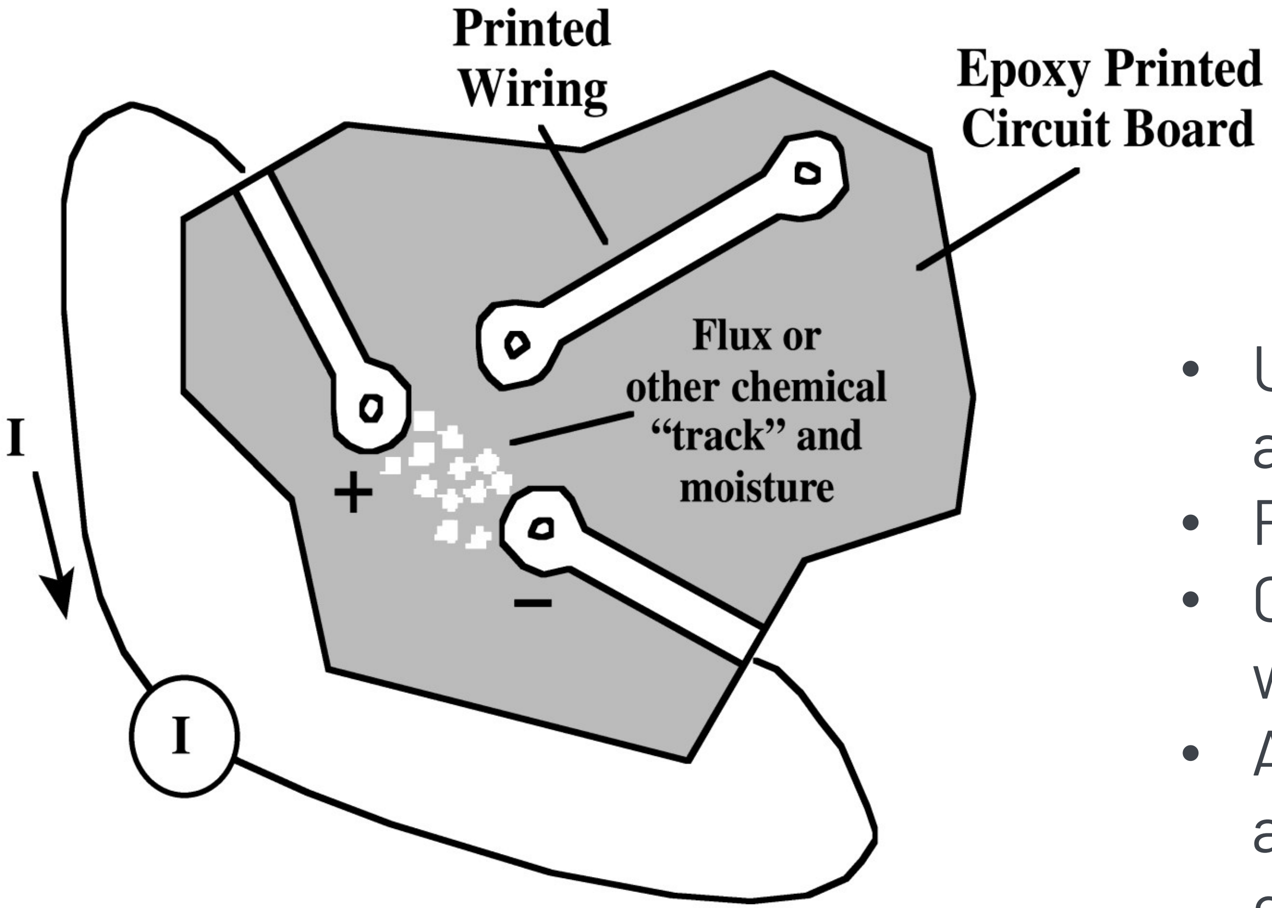
- Current caused by friction between insulators and conductors
- Reduce the effect by:
  - Use the low noise cables that are supplied with the sensitive ammeter.
  - Keep all connections away from temperature changes.
  - Remove or mechanically decouple vibration sources such as motors, pumps, and other electromechanical devices.
  - Securely mount or tie down electronic components, wires, and cables.
  - Mount the ammeter or preamps as close as possible to the DUT.



Piezoelectric Effect and Stored Charge

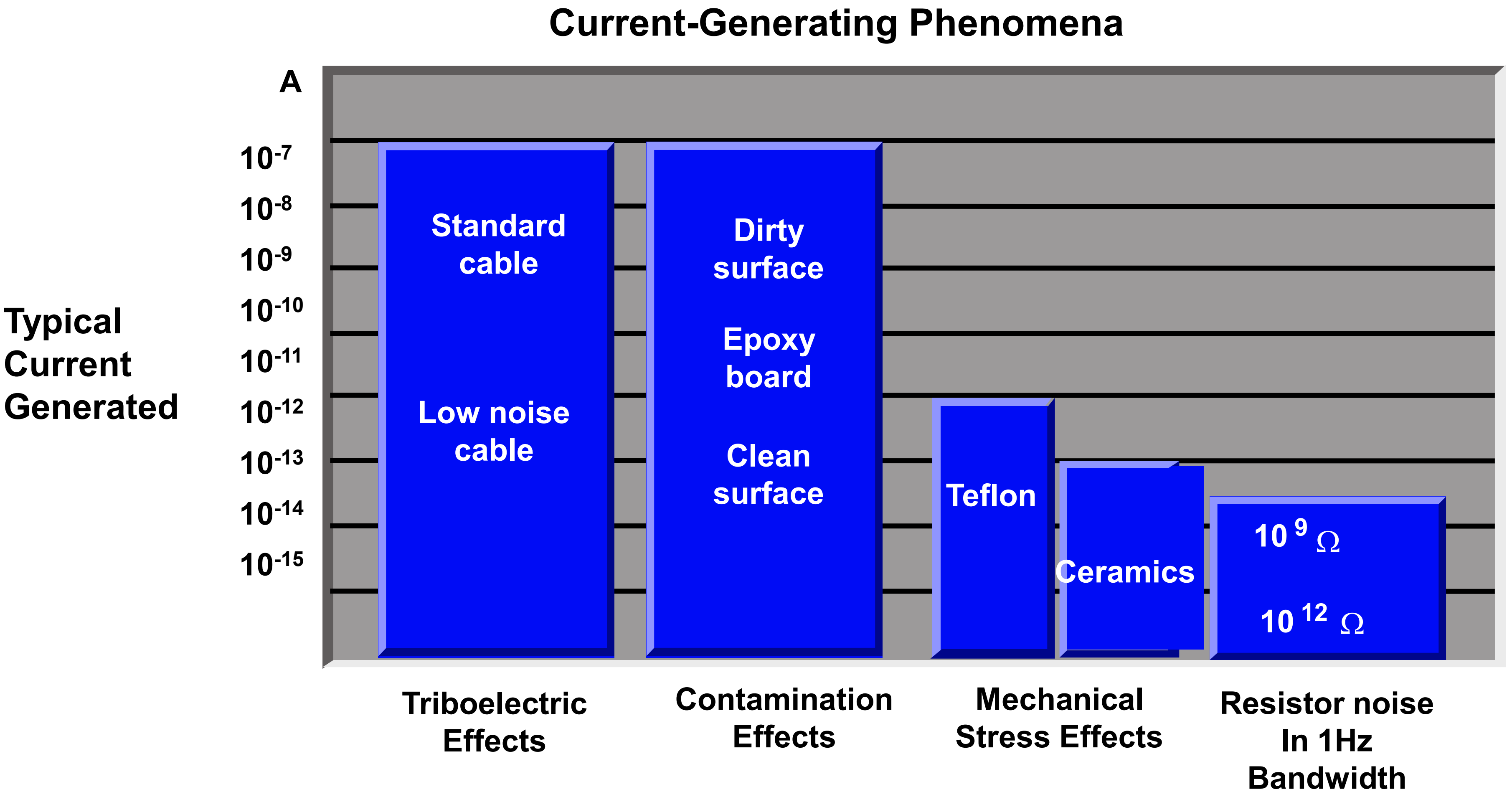


Contamination and Humidity

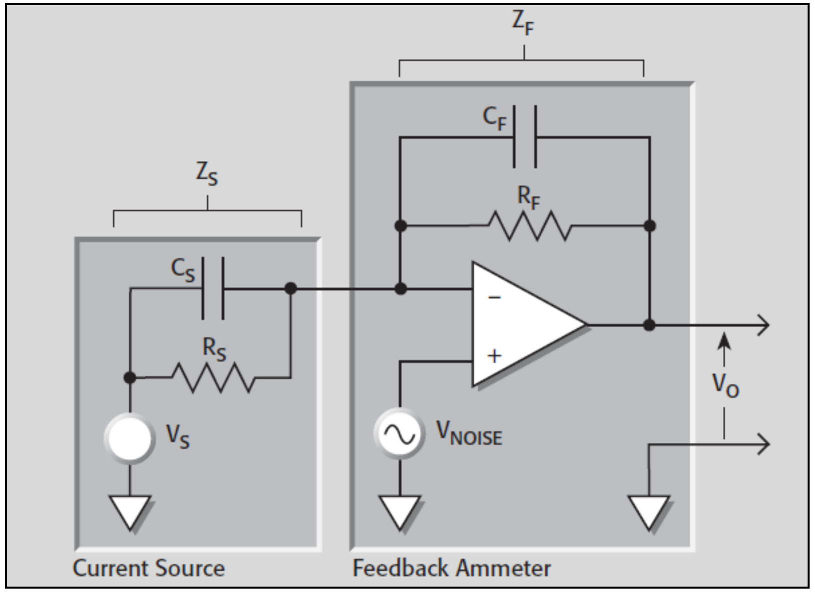


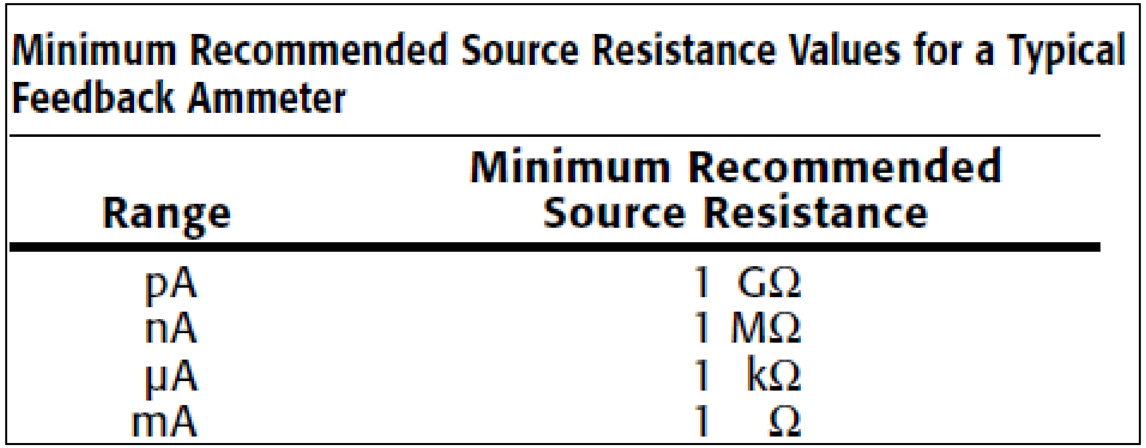
- Use insulators that resist water absorption
- Reduce humidity
- Clean components and fixturing with a proper solution
- Avoid touching the circuitry with anything that may deposit contaminants

Generated Currents



Noise and Source Resistance





Minimum Recommended Source Resistance Values for a Typical Feedback Ammeter

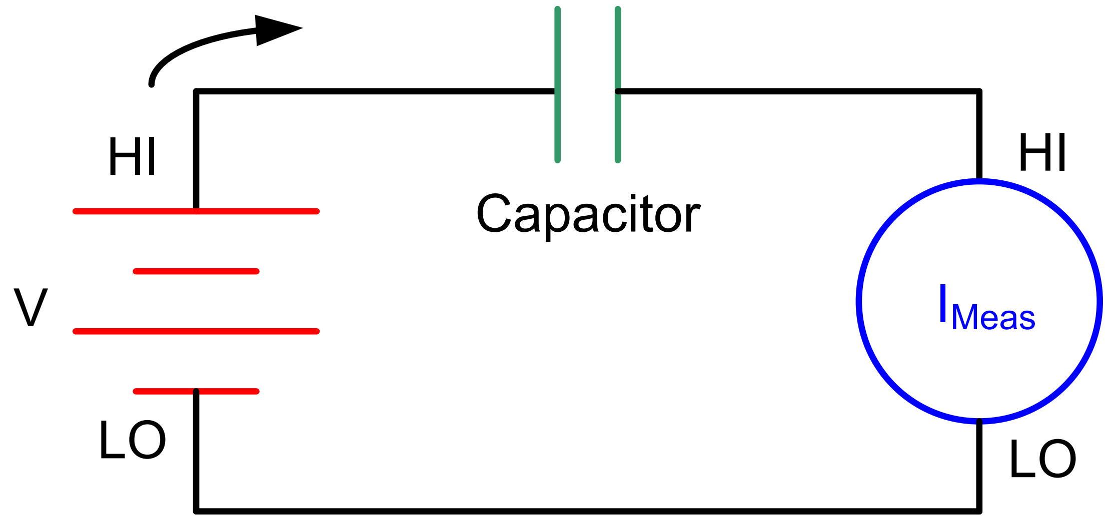
Range	Minimum Recommended Source Resistance
pA	1 GΩ
nA	1 MΩ
μA	1 kΩ
mA	1 Ω

The noise gain of the circuit can be given by the following equation:

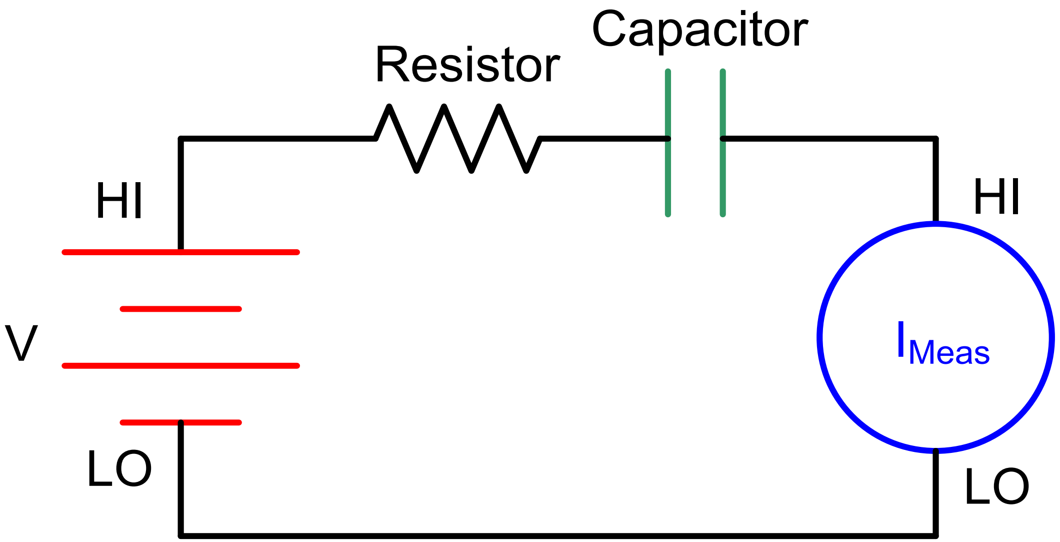
Output V_{NOISE} = Input V_{NOISE} $(1 + R_F/R_S)$

Noise and Source Capacitance

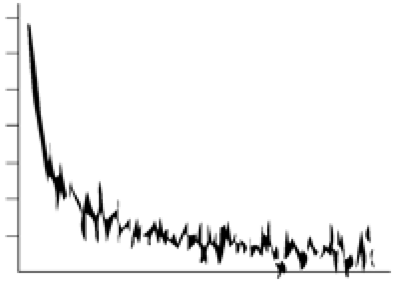
$i = V/R(1 - e^{-t/RC})$



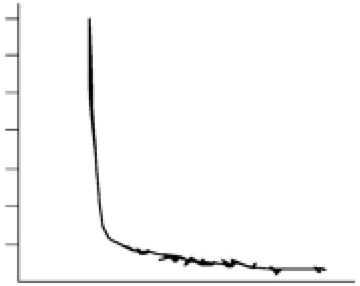
No series resistance. Measurements may be noisy.



Series resistance added to reduce noise.



Without Series Resistance



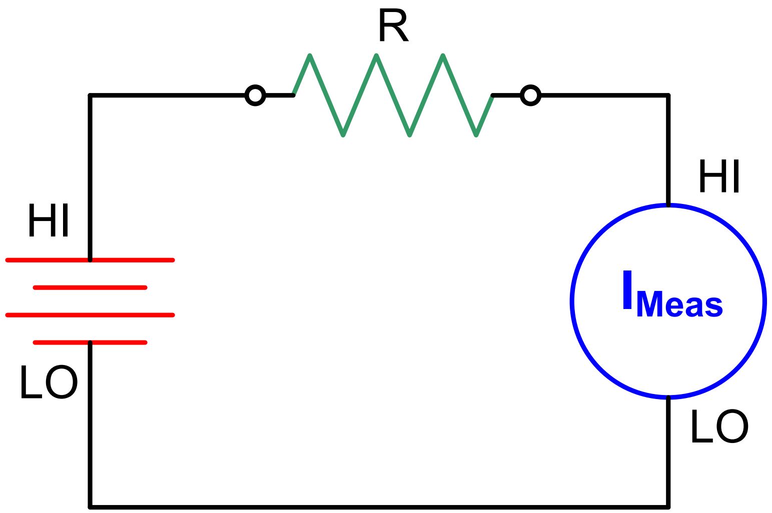
With Series Resistance

Optimizing Low Voltage Measurements

- Device Connections
- Offset Voltage and Zero Drift
- Thermal EMFs
- RFI/EMI
- Noise
- Magnetic Fields
- Ground Loops

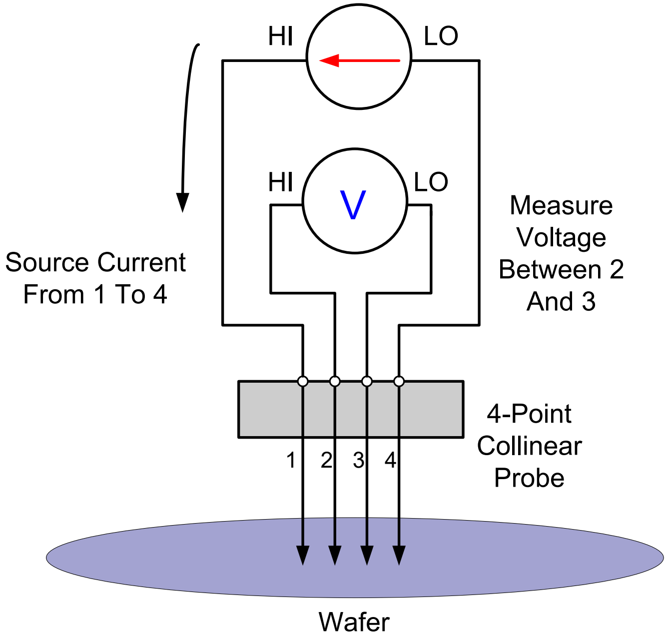
4 Wire Method to Measure Low Resistance

2-wire: Source V, Measure I



Useful for **Insulators**

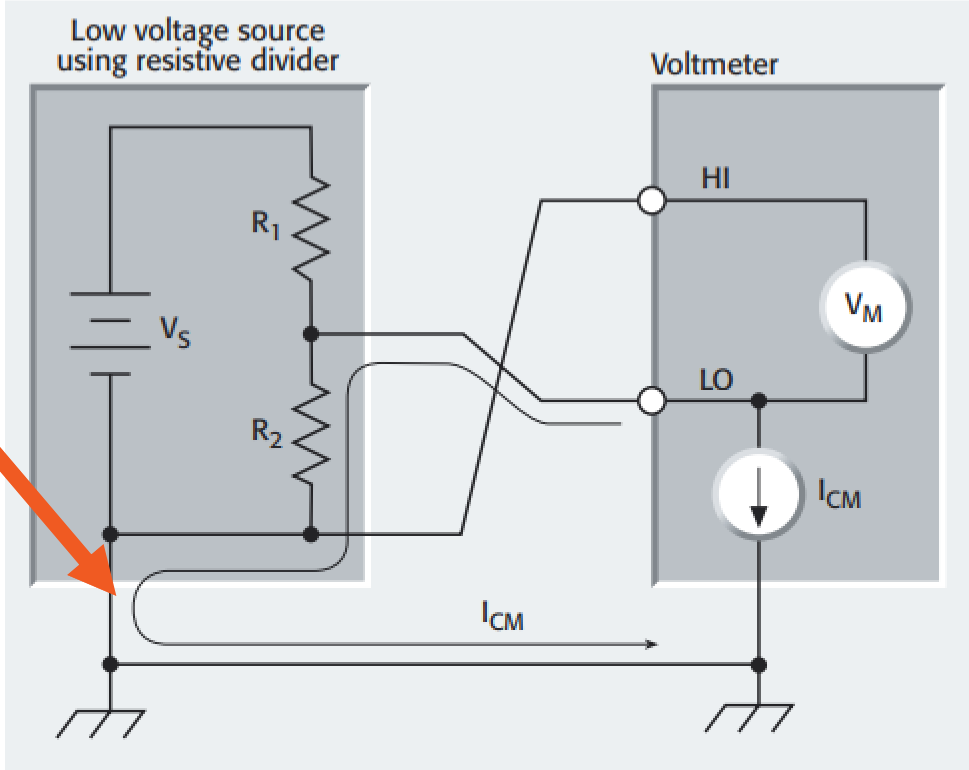
4-wire: Source I, Measure V



Useful for **Semiconductors** and **Conductors**

Other Connection Considerations

- Common-Mode Current
  - Don’t swap leads
- Thermal EMFs
  - Don’t use dissimilar metals
- Non-ohmic contacts
  - Use quality contact metal such as indium or gold
  - Reduce effects with RFI shielding and appropriate grounding



Offset Voltage and Zero Drift

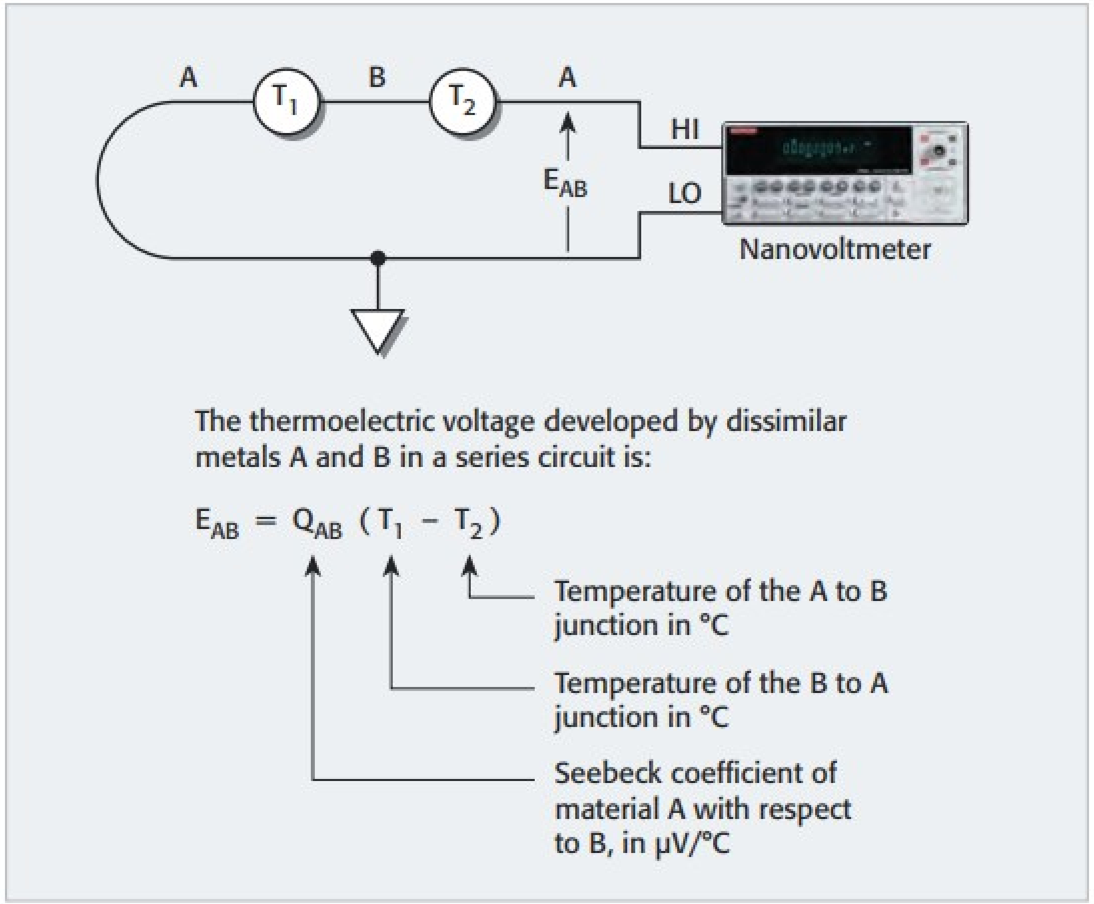
Measuring Voltmeter Offset Voltage:

1. Turn on the power and allow the instrument to warm up for the time specified in the service manual.
2. Place an appropriate short on the input of the voltmeter as suggested in the manual of the instrument.
3. Set the voltmeter to the most sensitive voltage range and zero or REL the meter.
4. Verify the voltage is within specification.

Reducing Zero Drift and Transient Temperature Effect:

- Reduce temperature gradients in the environment
- Insulate the test circuit to slow down temperature changes so they don't cause a large transient effect

Thermoelectric EMFs



The thermoelectric voltage developed by dissimilar metals A and B in a series circuit is:

$$E_{AB} = Q_{AB}\,(T_1 - T_2)$$

T_2: Temperature of the A to B junction in °C

T_1: Temperature of the B to A junction in °C

Q_{AB}: Seebeck coefficient of material A with respect to B, in µV/°C

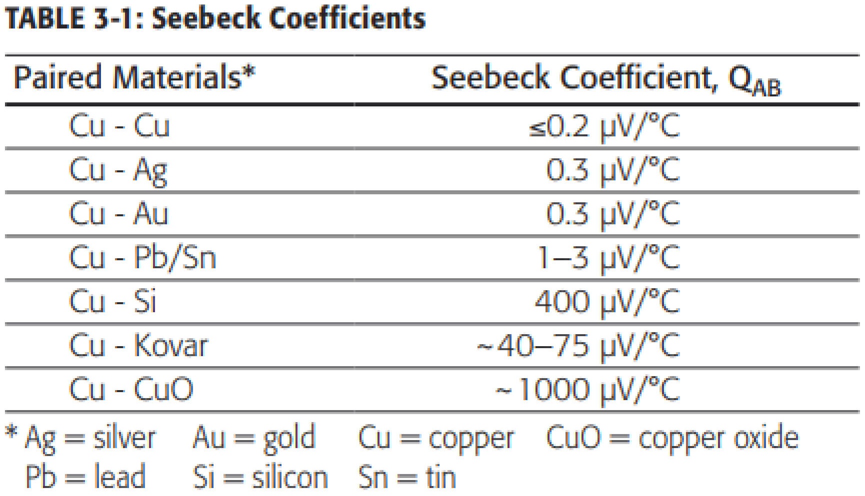


TABLE 3-1: Seebeck Coefficients

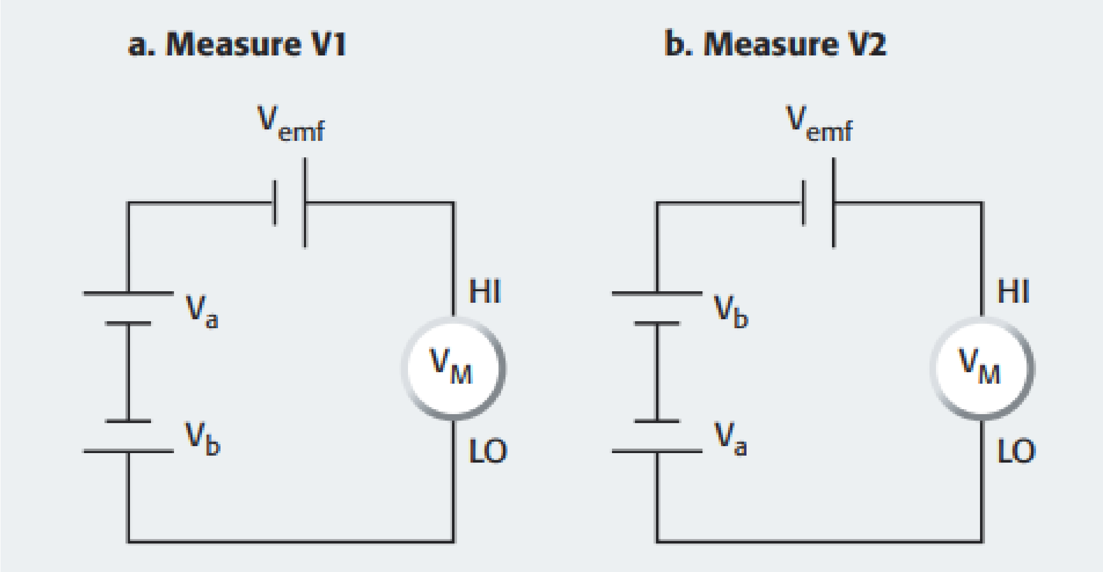
Paired Materials*	Seebeck Coefficient, Q_{AB}
Cu - Cu	≤0.2 µV/°C
Cu - Ag	0.3 µV/°C
Cu - Au	0.3 µV/°C
Cu - Pb/Sn	1–3 µV/°C
Cu - Si	400 µV/°C
Cu - Kovar	~40–75 µV/°C
Cu - CuO	~1000 µV/°C

* Ag = silver Au = gold Cu = copper CuO = copper oxide
Pb = lead Si = silicon Sn = tin

Reduce Thermal EMFs:

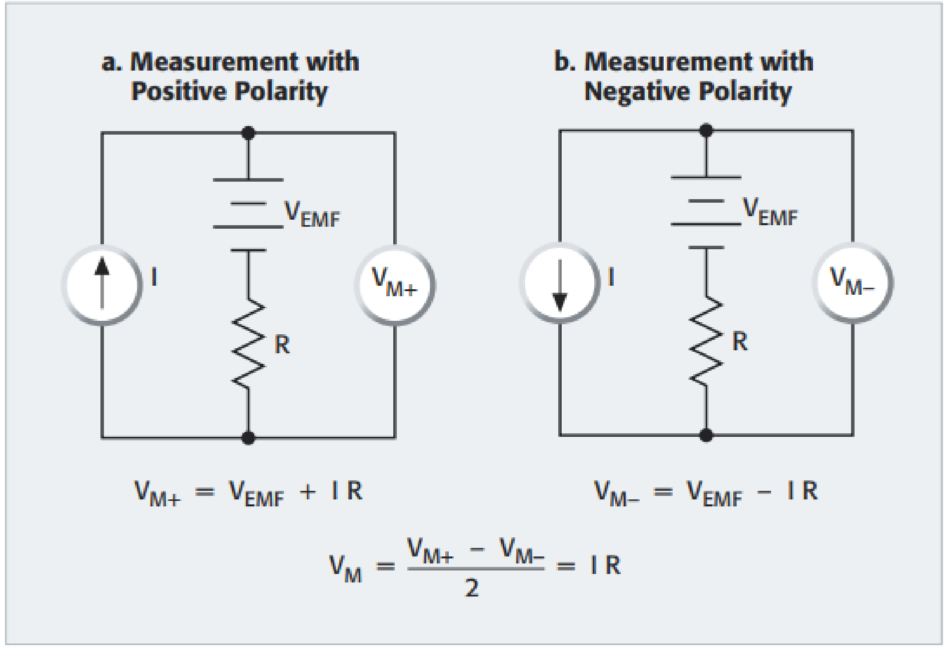
- Avoid dissimilar metals in the circuit
- Keep temperature constant and allow circuit to reach thermal equilibrium
- Insulate circuit to prevent temperature fluctuations
- Use current reversal or delta method

Current Reversal and Delta Method



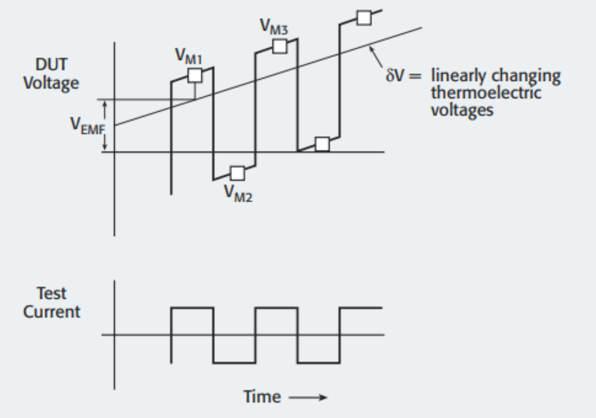
$$V_1 = V_{emf} + V_a - V_b \qquad V_2 = V_{emf} + V_b - V_a$$

$$\frac{V_1 - V_2}{2} = \frac{V_{emf} + V_a - V_b - V_{emf} - V_b + V_a}{2} \text{ or } V_a - V_b$$



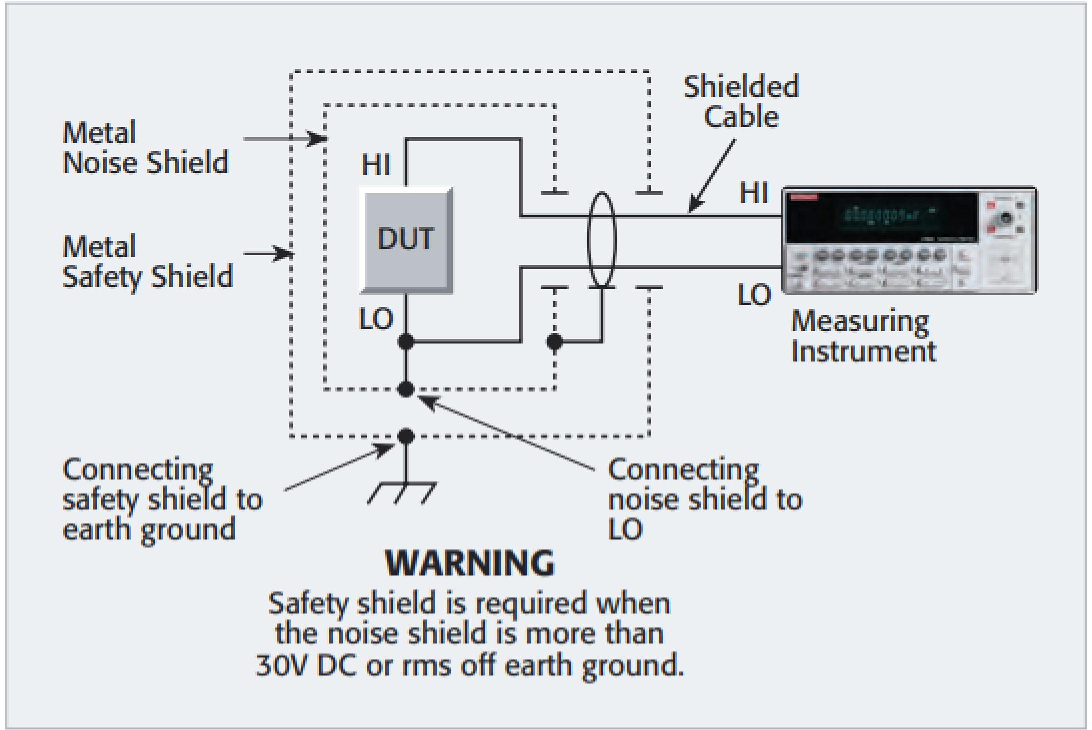
$$V_{M+} = V_{EMF} + IR \qquad V_{M-} = V_{EMF} - IR$$

$$V_M = \frac{V_{M+} - V_{M-}}{2} = IR$$



RFI/EMI

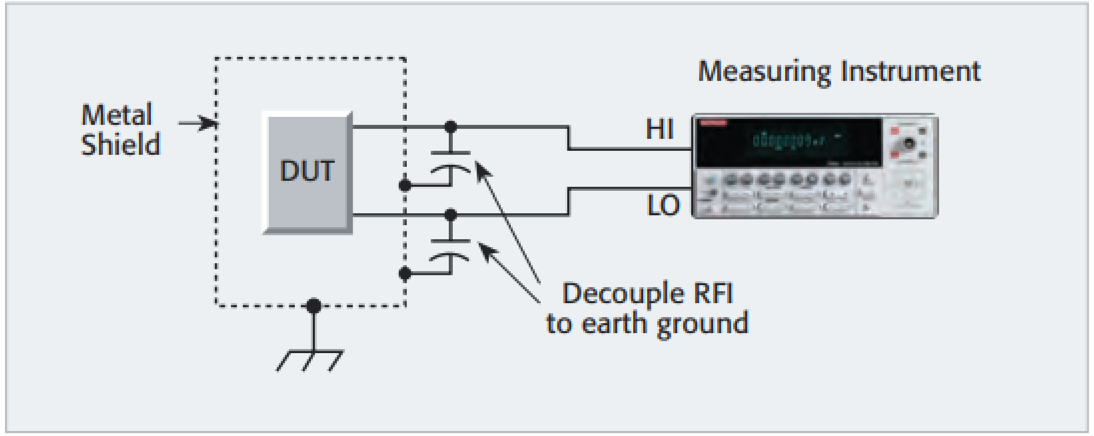
FIGURE 3-6: Shielding to Attenuate RFI/EMI Interference



WARNING

Safety shield is required when the noise shield is more than 30V DC or rms off earth ground.

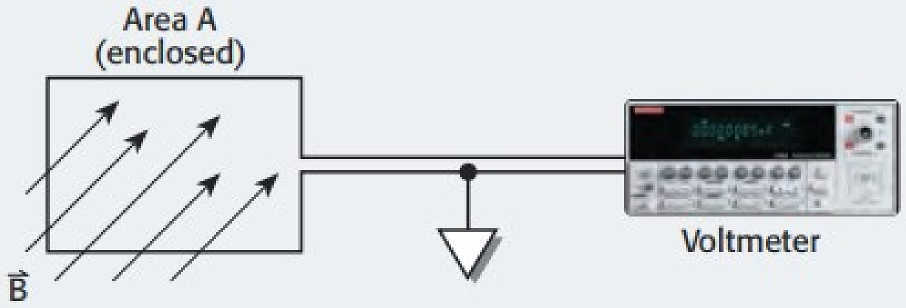
FIGURE 3-7: Shielded Connections to Reduce RFI/EMI



Noise

Johnson Noise AKA Thermal Noise or White Noise	1/f Noise	Line Cycle Interference
Noise due to motion of electrons due to thermal energy	Varies inversely with frequency, most often associated with carbon composition resistors and semiconductors	Noise picked up from the 50 or 60 Hz lines powering surrounding electrical devices
• Reduce temperature of the source resistance • Decrease bandwidth of measurement by increasing filtering or integrate over more line cycles		• Use line cycle integration (NPLC)

Magnetic Fields



The voltage developed due to a field passing through a circuit enclosing a prescribed area is:

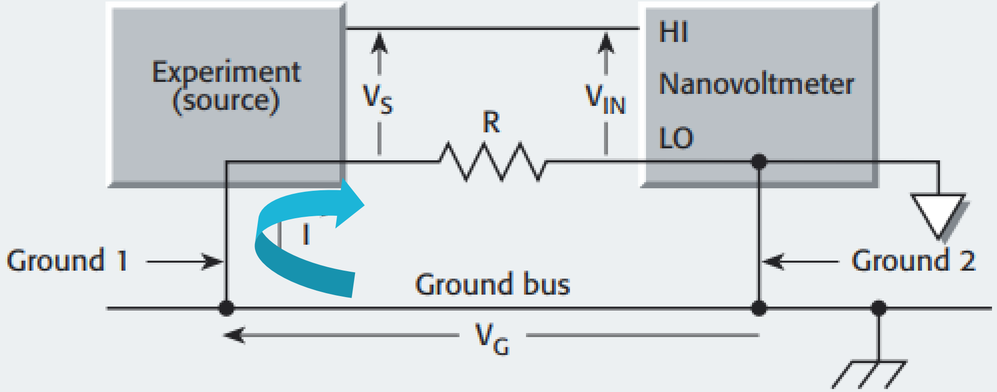
$$V_B = \frac{d\phi}{dt} = \frac{d(\vec{B}A)}{dt} = \vec{B}\frac{dA}{dt} + A\frac{d\vec{B}}{dt}$$

where: V_B = induced voltage
A = loop area
$\vec{B}$ = magnetic flux density
$\phi = \vec{B}A$ = magnetic flux

Reduce effects from magnetic fields by…

- Keeping leads short and loops in the circuit small
- Twist wires together
- Avoid significant magnetic fields
- Tie the circuit down to avoid movement
- Magnetically shield wires (Mu-metal)
- Isolate circuit from other circuits carrying large currents that may generate magnetic fields

Ground Loops



Input voltage to the nanovoltmeter is:

$V_{IN} = V_S + V_G$

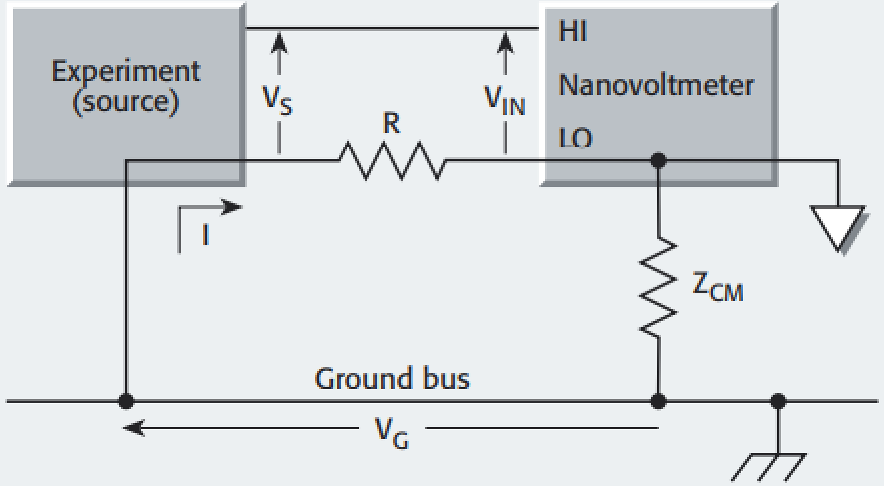
where $V_G = IR$

R = Resistance of input LO connection (typically around 100mΩ)

I = Current passing through input LO connection due to ground voltages (V_G) in the ground bus (magnitude may be amperes)

V_S = Source voltage (desired signal)

V_G may exceed V_S by orders of magnitude.

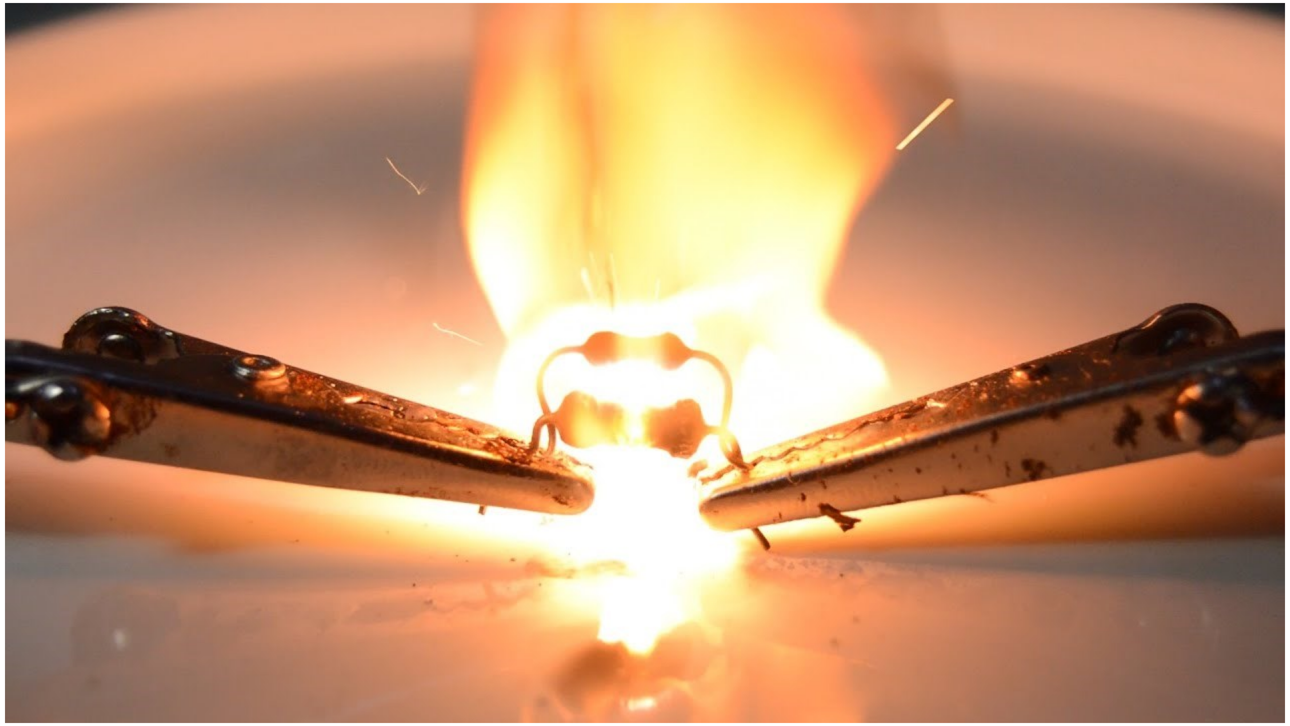


$V_{IN} \approx V_S$, since V_G is now insignificant compared to V_S.

Z_{CM} = Common mode impedance of nanovoltmeter

Device Heating

- For temperature sensitive devices
  - Keep currents low
  - Use pulsing features to reduce power delivered to the device



Low Level Measurements Summary

- Choose an instrument sensitive enough to measure either low current or low voltage
- Make good connections to the device and use high quality connectors, cables and test fixtures
- Verify the capabilities of the test system. Check for errors in instruments, as well as incorrect setups (swapped leads, ground loops, freely moving cables). Check the environment for sources of errors
- Apply the proper measurement techniques to avoid measurement errors caused by environmental factors and noise

Additional Resources

- Low Level Measurements Handbook
- Sensitive Instruments Product Pages
- Optimizing Low Current Measurements
- Low Current Measurements Application Note
- Capacitor Leakage Current Measurements
- Resistivity of Insulating Materials
- Low Voltage Measurement Techniques
- Delta Mode White Paper
- Differential Conductance White Paper
- Understanding Low Voltage Measurements

Thank you

- **Elizabeth Makley,** Elizabeth.Makley@keithley.com
- Product Applications Engineer