Low Level Measurement

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Bona, Oh

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CONTENTS

SECTION 1 Low Level DC Measuring Instruments

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Standard Symbols

Prefixes		
Symbol	**Prefix**	**Exponent**
y	yocto-	10^{-24}
z	zepto-	10^{-21}
a	atto-	10^{-18}
f	femto-	10^{-15}
p	pico-	10^{-12}
n	nano-	10^{-9}
µ	micro-	10^{-6}
m	milli-	10^{-3}
(none)	(none)	10^{0}
k	kilo-	10^{3}
M	mega-	10^{6}
G	giga-	10^{9}
T	tera-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zetta-	10^{21}
Y	yotta-	10^{24}

Quantities		
Symbol	**Unit**	**Quantity**
V	volts	EMF
A	amperes	current
Ω	ohms	resistance
C	coulombs	charge
s	seconds	time
W	watts	power
F	farads	capacitance
Hz	cycles/s	frequency
K	degrees	temperature

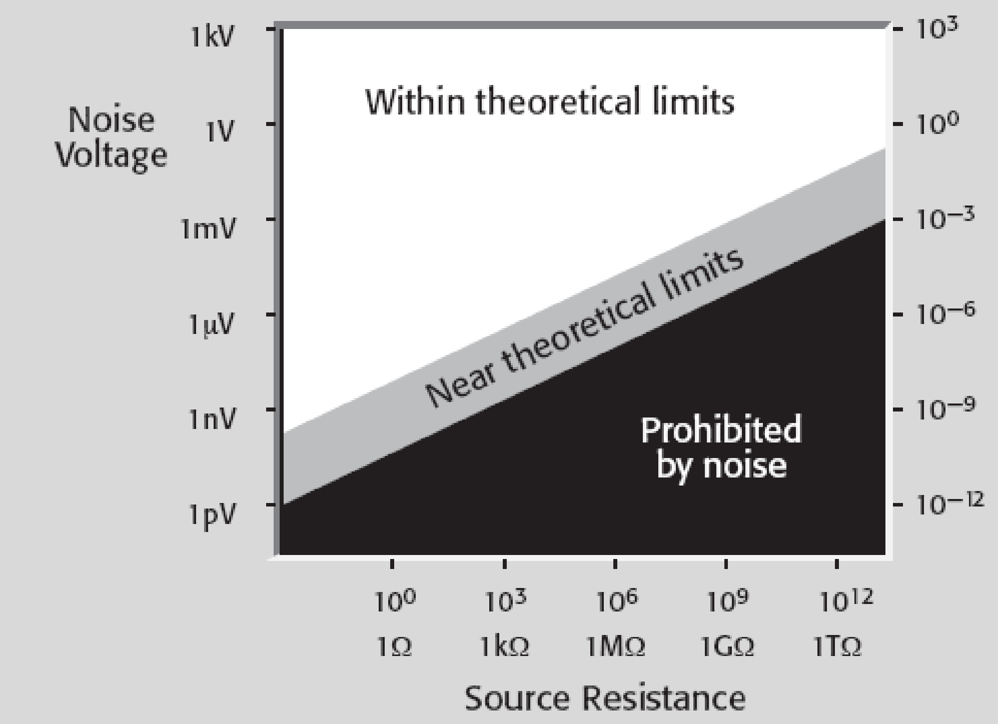
Theoretical Limits of Voltage Measurement

The Rs provides a fundamental limit to how well you can resolve Vs:

$$V_n = \sqrt{4kTBR_s}$$

K - Boltzmann’s constant
T - Absolute temperature of the source
B - Noise bandwidth in hertz
R - Resistance of the source in Ohms

Theoretical Measurement Limits

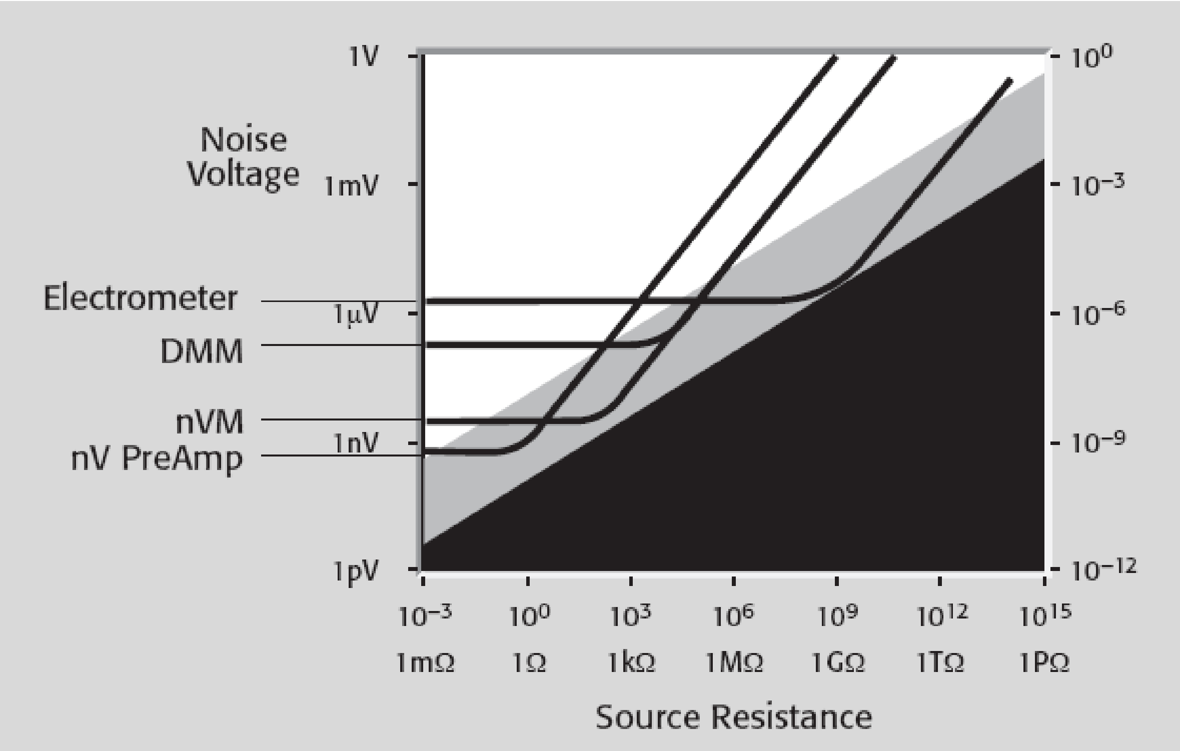


Theoretical Limits of Voltage Measurements

The theoretical limit of sensitivity in any measurement is determined by the noise generated by the resistances present in the circuit

This shows theoretical voltage measurement limits at room temperature (300K) with a response time of 0.1 second to ten seconds

Theoretical Measurement Limits



Typical Digital Multimeter (DMM), Nanovoltmeter (nVM), Nanovolt Preamplifier (nV PreAmp), and Electrometer Limits of Measurement at Various Source Resistances

Instrument Definitions

A number of different types of instruments are available to make DC measurements, including electrometers, DMMs, nanovoltmeters, picoammeters, SMUs (source-measure units), SourceMeter instruments, low current preamps, and micro-ohmmeters.

- Electrometer
- DMM (Digital Multi Meter)
- Nanovoltmeter
- Picoammeter
- Source-Measure Unit
- SourceMeter Instrument

Instrument Definitions - Electrometer

An electrometer is a highly refined DC multimeter. As such, it can be used for many measurements performed by a conventional DC multimeter. Additionally, an electrometer's special input characteristics and high sensitivity allow it to make voltage, current, resistance, and charge measurements far beyond the capabilities of a conventional DMM.

electrometer must be used for

- Currents less than 10nA (1E-8A)
- Resistances greater than 1GΩ (1E9Ω)
- Measuring voltage from a source resistance of 100MΩ or higher
- Measuring current when input voltage drop (burden) of less than a few hundred millivolts is required (when measuring currents from sources of a few volts or less)
- Charge measurement is required

electrometer functions

- **Voltmeter**
  Input resistance is greater than 100Tohm
  Input offset current is less than 3fA
- **Ammeter**
  Detect low current as low as 1fA
  Low voltage burden than DMMs
- **Ohmmeter**
  Measurements up to 10Pohm(1E16)
- **Coulombmeter**
  Detect low charge as low as 10fC

Instrument Definitions – DMM

Digital multimeters vary widely in performance, from low cost handheld 3 1/2 - digit units to high precision system DMMs. DMM simply point out the fact that the vast majority of measurements are made at levels far from theoretical limits, and DMMs are designed to meet these more conventional measurement needs

DMMs functions

- **Voltmeter**
- **Ammeter**
- **AC voltmeter**
- **AC ammeter**
- **Frequency**
- **Temperature**

Instrument Definitions – Nanovoltmeter

A nanovoltmeter is a very sensitive voltage meter. Nanovoltmeter is optimized to provide voltage measurements near the theoretical limits from low source resistances. Compared to an electrometer, the voltage noise and drift are much lower, and the current noise and drift are much higher

Navovoltmeter functions

- **Voltmeter**
  Voltage sensitivity can be as good as 1nV

Instrument Definitions – Picoammeter

A picoammeter is an ammeter built along the lines of the ammeter function of an electrometer. When compared with an electrometer, a picoammeter has a similar low voltage burden, similar or faster speed, less sensitivity, and a lower price. It may also have special characteristics, such as high speed logarithmic response or a built-in voltage source

Picoammeter function

- **Ammeter**

Instrument Definitions – Source-Measure Unit / SourceMeter

As its name implies, a source-measure unit (SMU) has both measuring and sourcing capabilities. Adding current and voltage sourcing capabilities to a measuring instrument provides an extra degree of versatility for many low level measurement applications. The added sourcing functions also make a SMU more convenient and versatile than using separate instruments for such applications as generating I-V curves of semiconductors and other types of devices

Source-Measure Unit functions

- **Measure voltage**
- **Measure current**
- **Source voltage**
- **Source current**

*** SourceMeter – Designed for general-purpose. Many type of model by ranges**

SECTION 2 Low Current and High-Resistance Measurement

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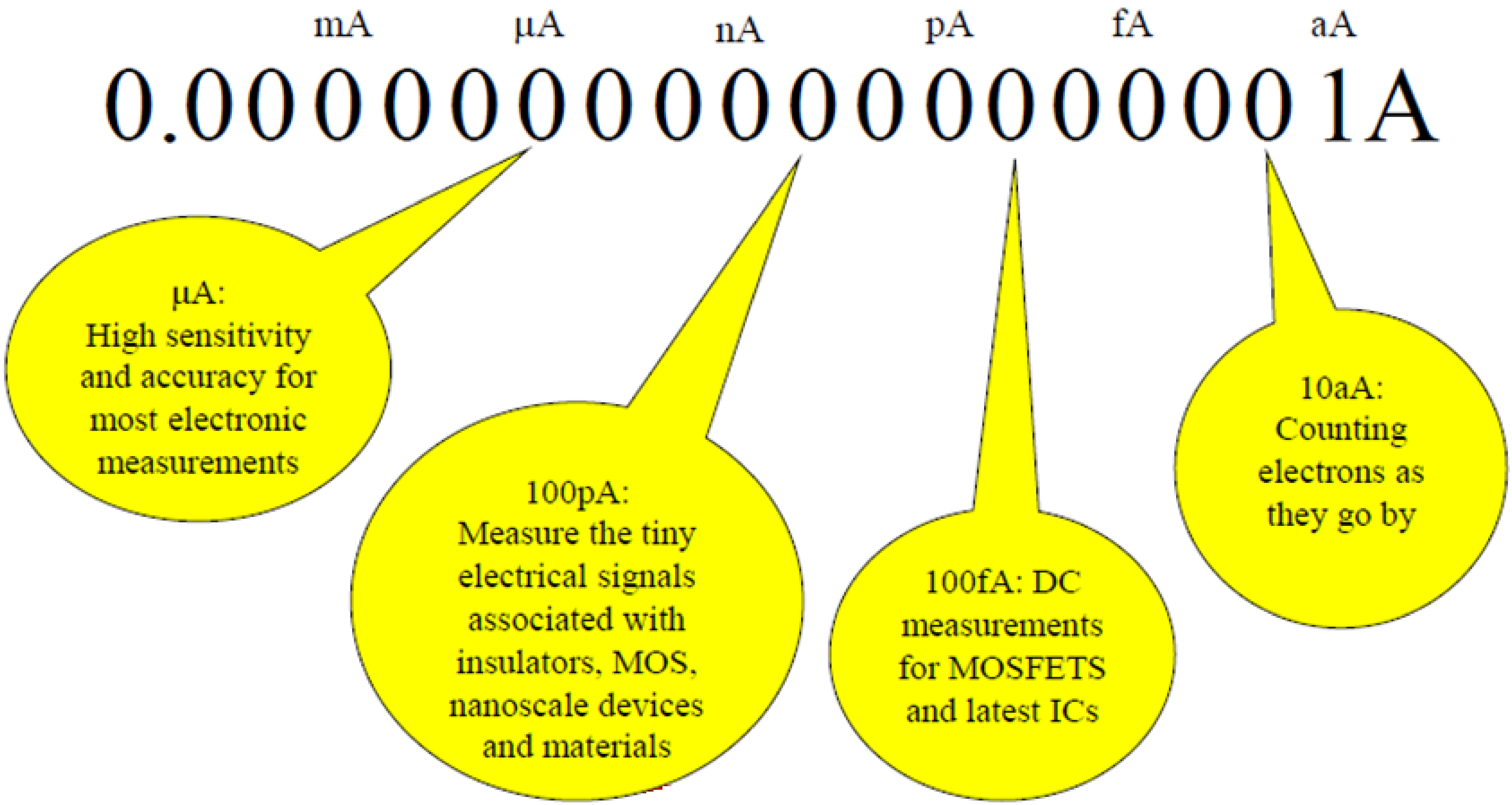
Objectives
Low I High R Products

1. Understand current measurement

2. To know the main difference between an electrometer and a DMM

Realistically, What Can Be Measured?



mA µA nA pA fA aA

0.000000000000000001A

µA:
High sensitivity
and accuracy for
most electronic
measurements

100pA:
Measure the tiny
electrical signals
associated with
insulators, MOS,
nanoscale devices
and materials

100fA: DC
measurements
for MOSFETS
and latest ICs

10aA:
Counting
electrons as
they go by

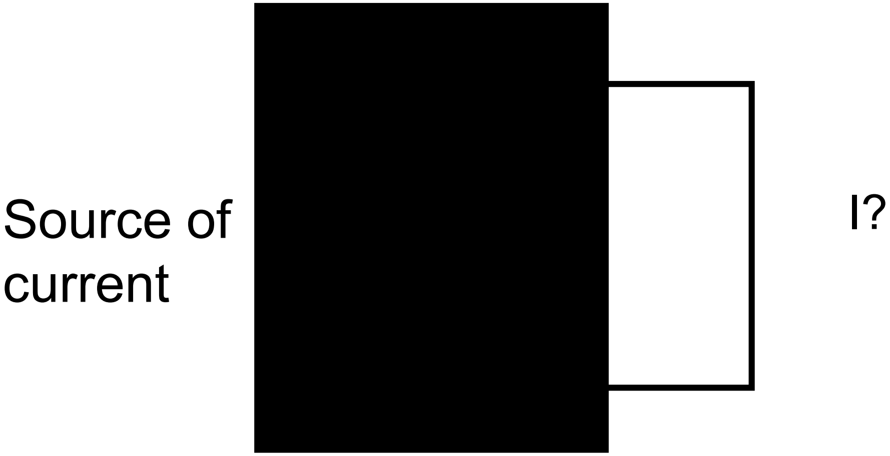
the Low I /High R Measurement

- Low Current Measurement
- High Resistance Measurement
- High Input Impedance On Volt
- Low voltage burden

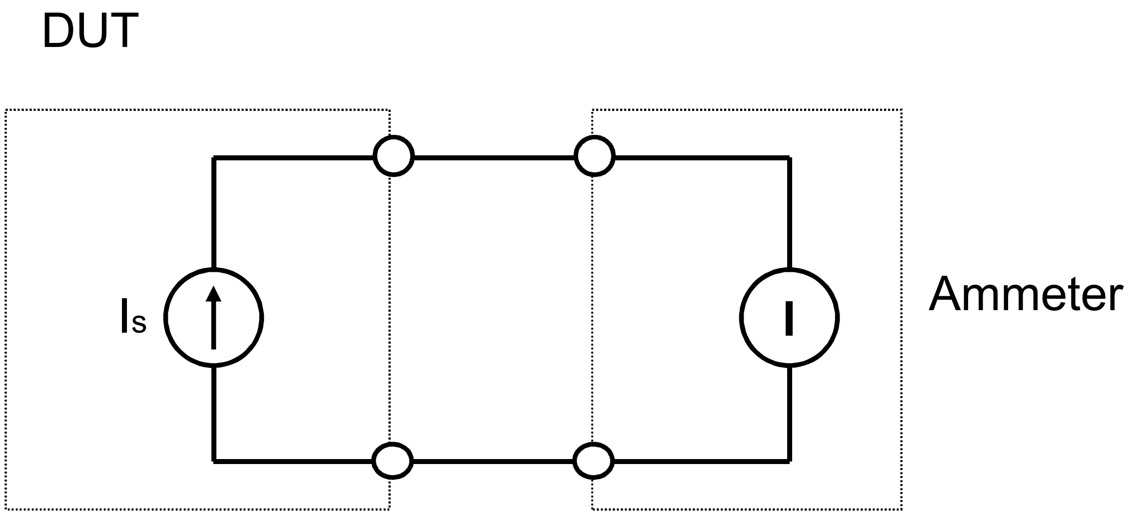
  - Feedback ammeter not a shunt ammeter

  - 1mV vs 200mV for DMM

Current Measurement

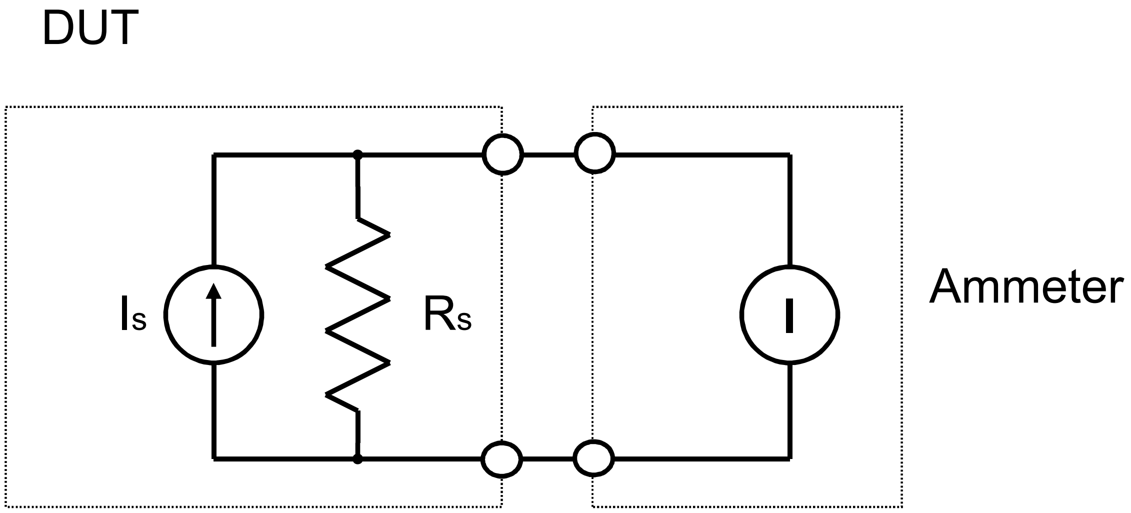


Current Measurement



Goal: $I = I_s$

Current Measurement



Two main problems:

1. Source is not ideal, I_s is dependent upon load
2. Ammeter is not ideal, it is not an absolute short

Theoretical Limits of Current Measurement

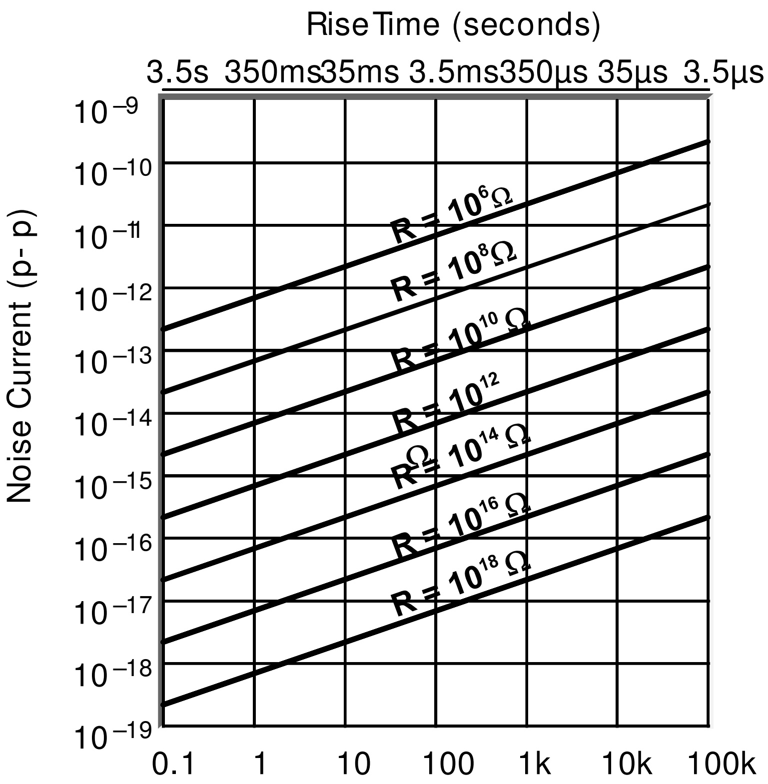
The Rs provides a fundamental limit to how well you can resolve Vs:

$$I_n = \sqrt{4kTBR_s} \,/\, R_s$$

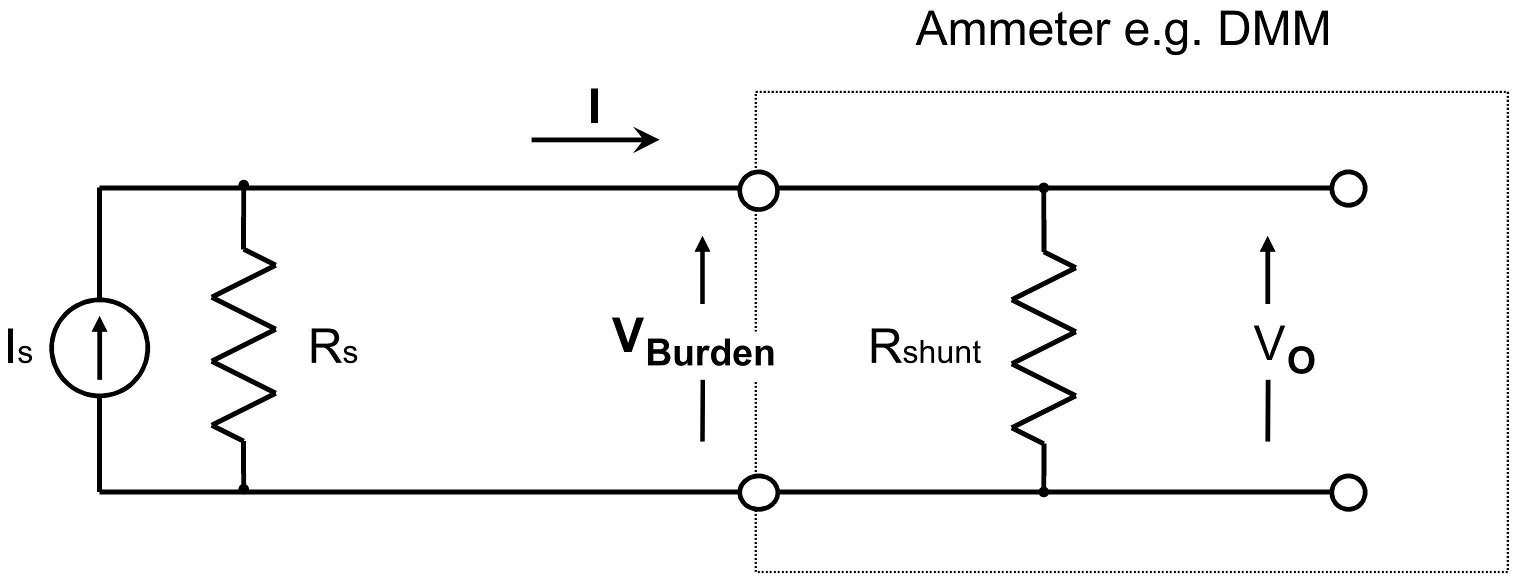
K - Boltzmann's constant
T - Absolute temperature of the source
B - Noise bandwidth in hertz
R - Resistance of the source in Ohms

Johnson Current Noise

The Rs provides a fundamental limit to how low Is you can measure



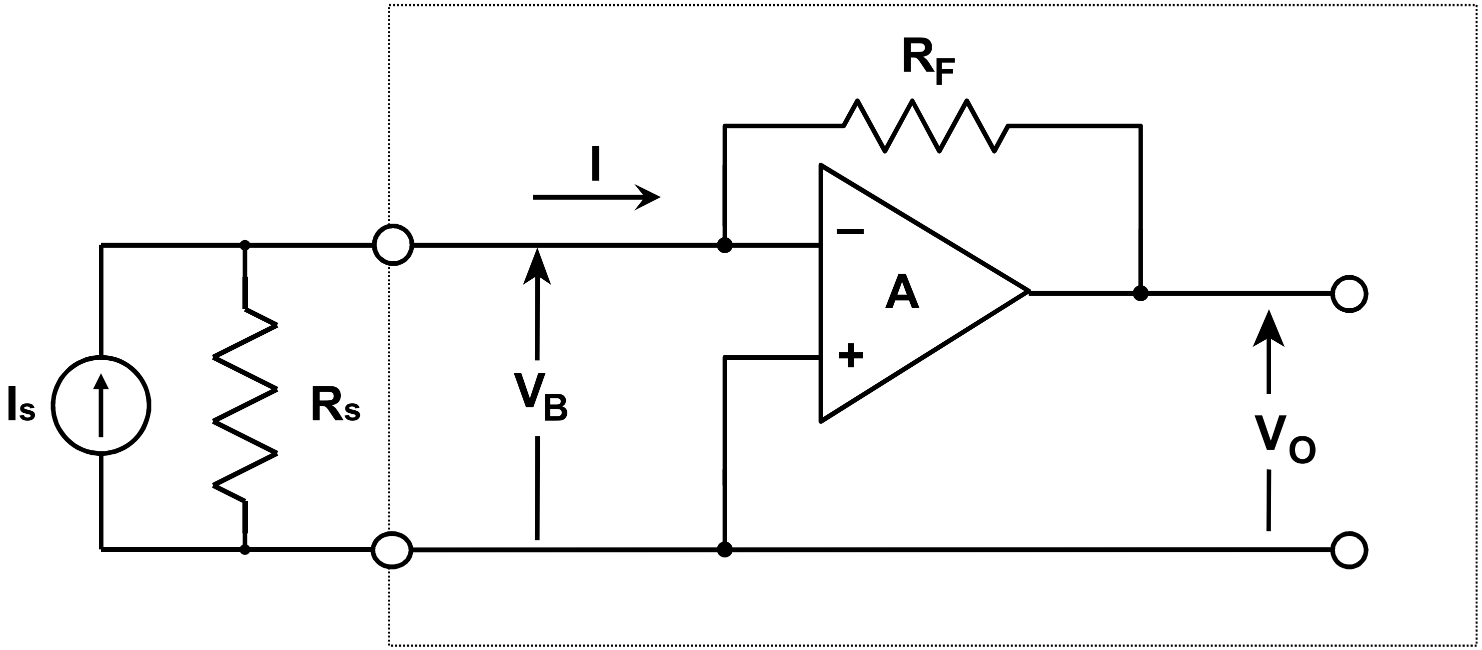
Shunt Ammeter



$$V_O = I \cdot R_{shunt} = V_B$$

Feedback Ammeter

Ammeter e.g. Picoammeter, Electrometer, SMU



SECTION 3 Low Voltage/ Low Resistance Measurement

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Objectives
Low Voltage / Low Resistance

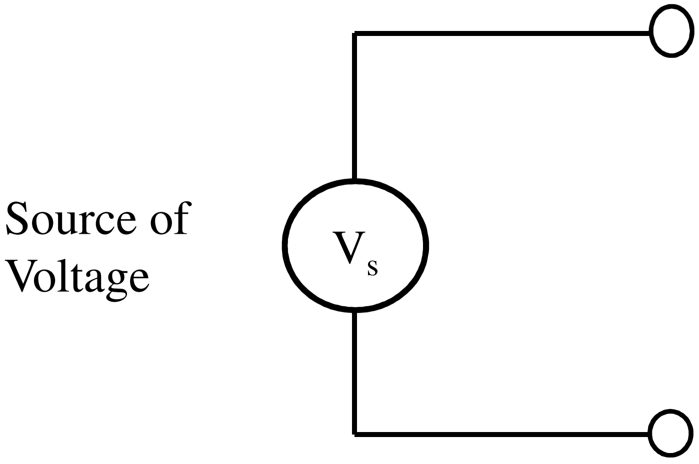
1. Understand voltage measurement

2. Have detail understanding of what “leak resistance” error is and why “4-wire measurements” is the solution for it

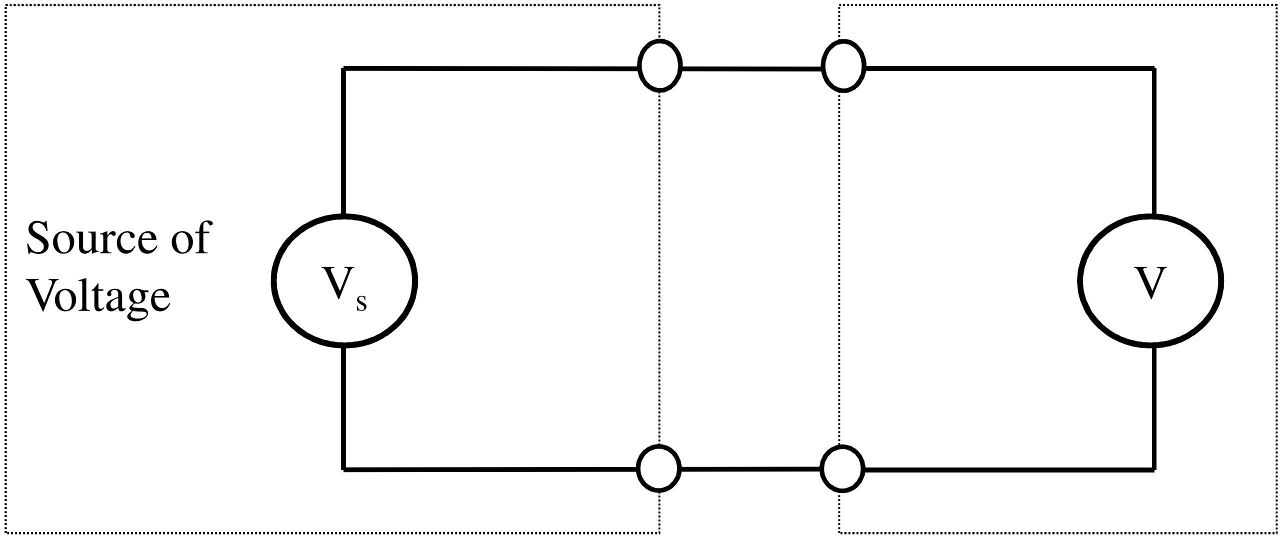
3. Have detail understanding of what “thermal emf error” is

4. Identify the solution/measurement techniques employed on each Low R product (Delta Mode)

Voltage Measurements



Voltage Measurements

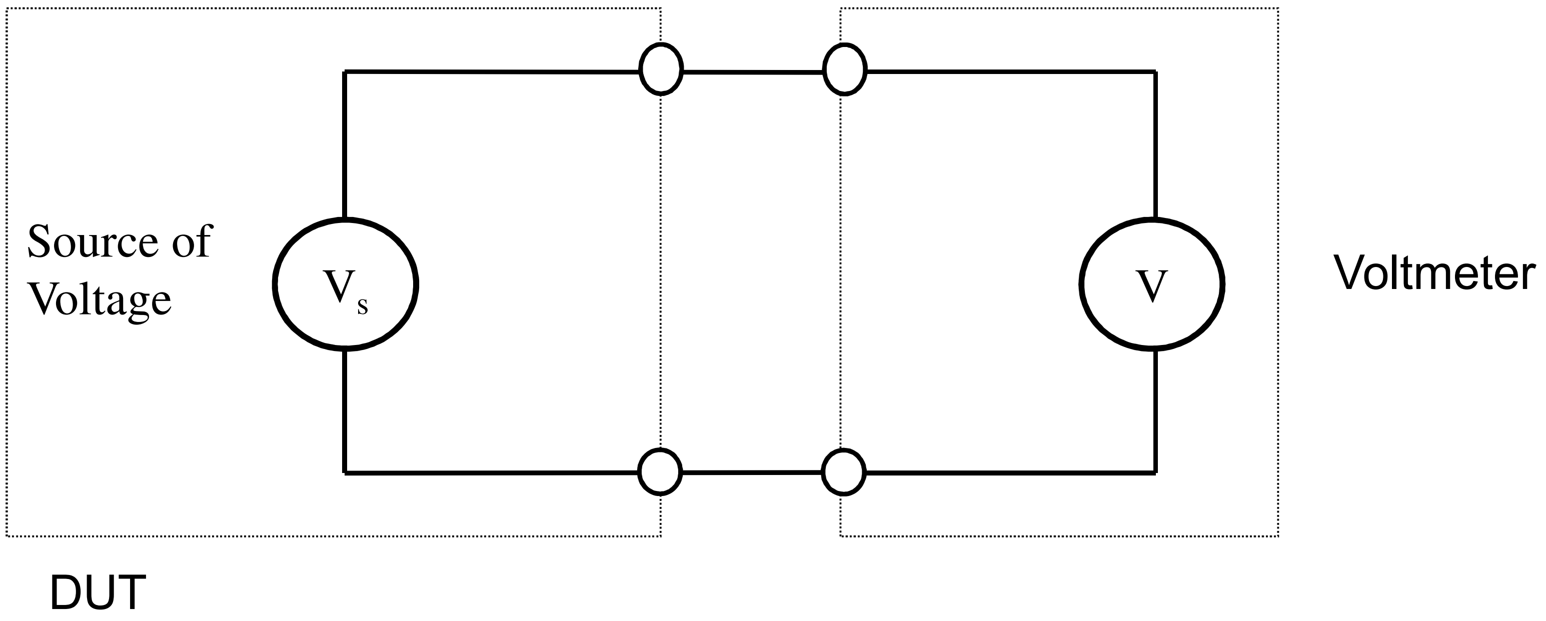


Voltmeter

DUT

Goal: $V = V_s$

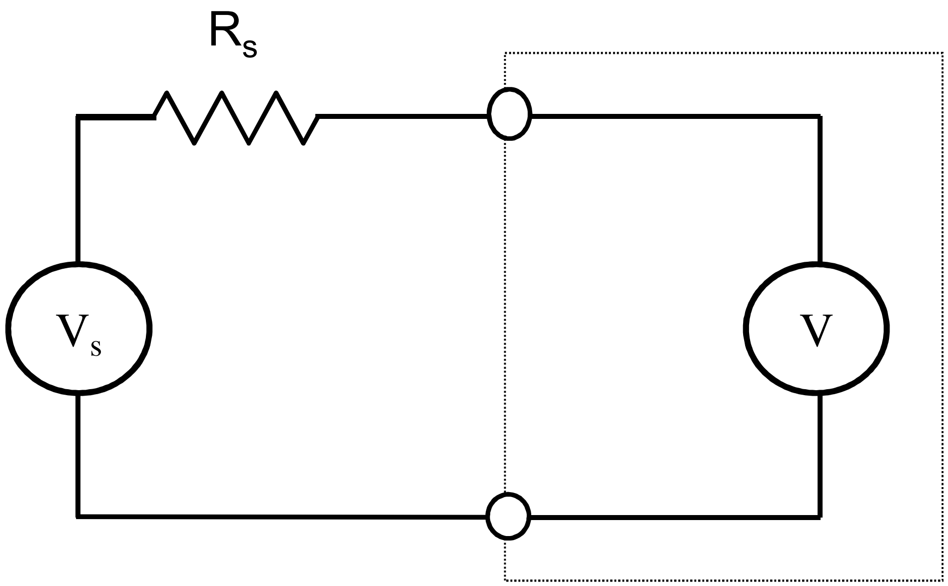
Voltage Measurements



Two main problems:

1. Source is not ideal, V_s is dependent upon load
2. Voltmeter is not ideal, it is not an absolute open

Thevenin Equivalent Model

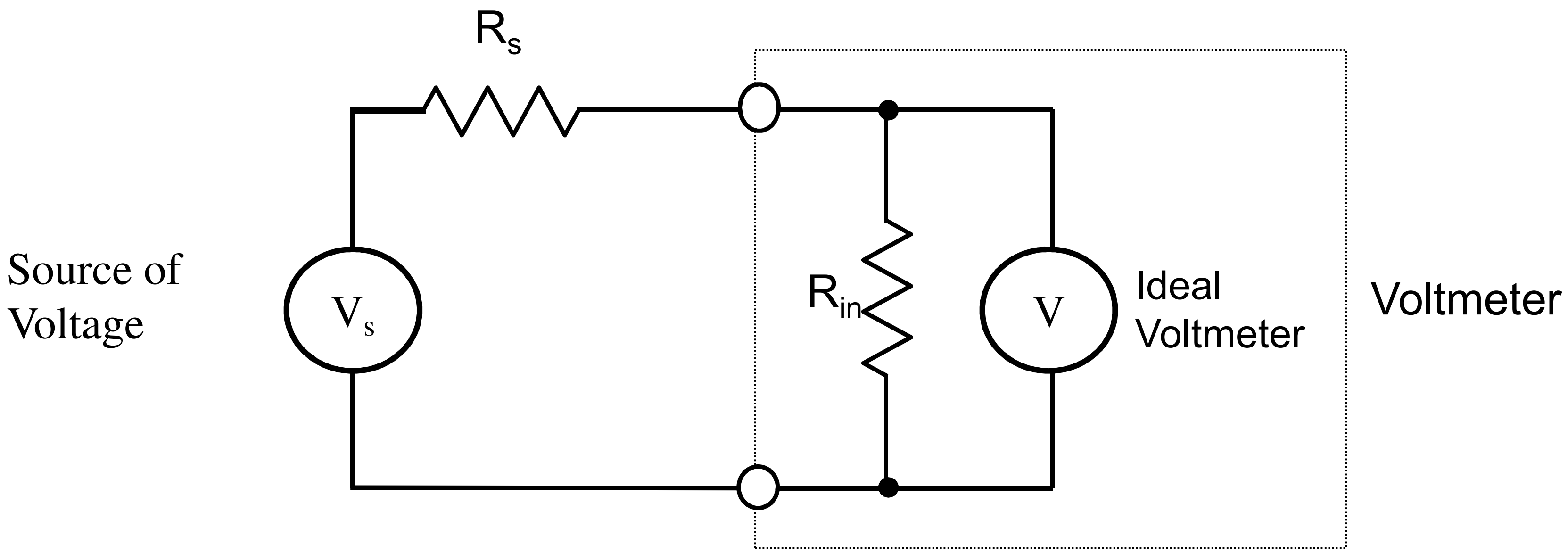


Ideal voltage source

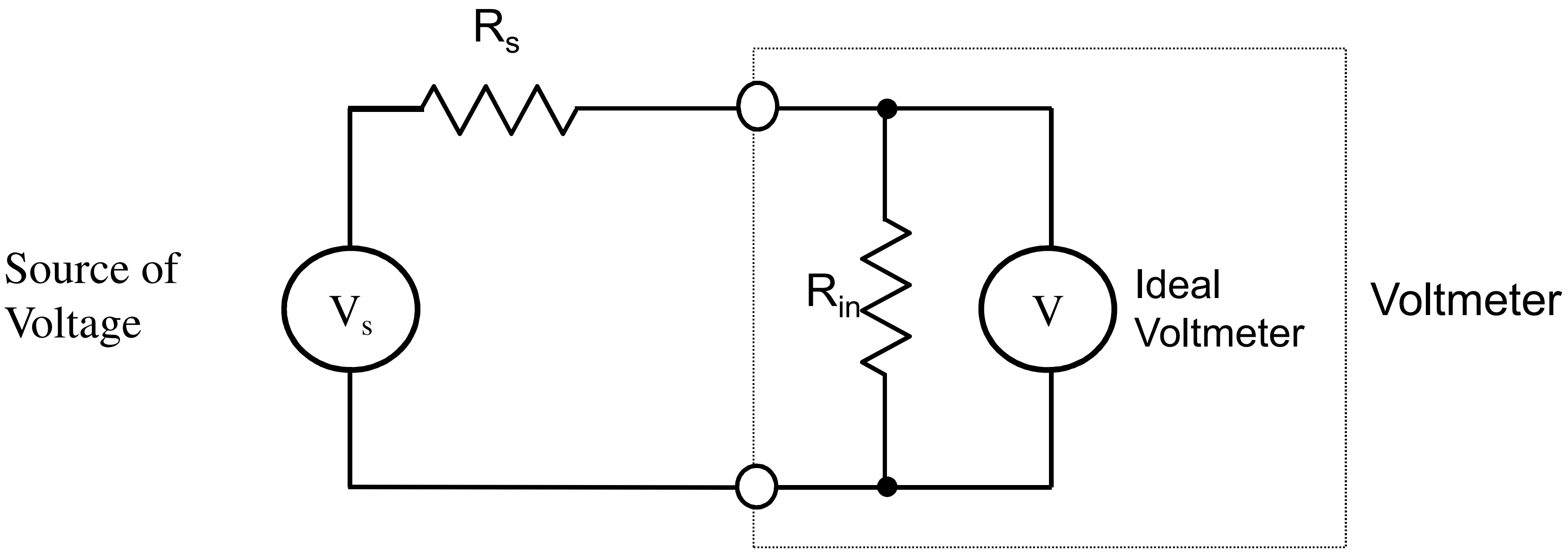
Voltmeter

- V_S Open-Circuit Voltage
- R_S Thevenin Equivalent Source Resistance

Thevenin Equivalent Model

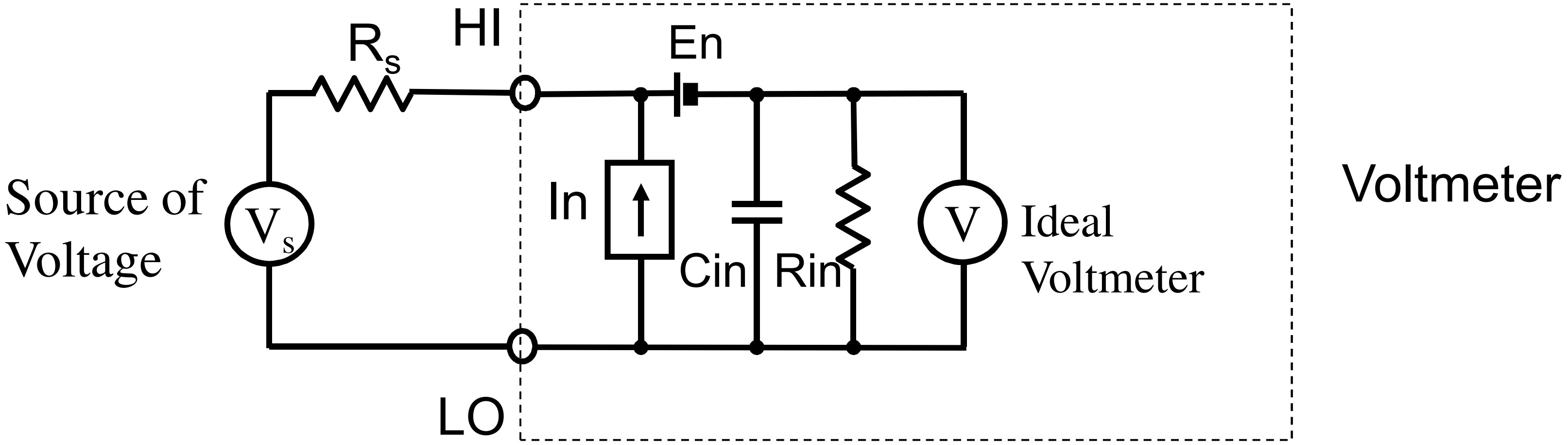


Thevenin Equivalent Model

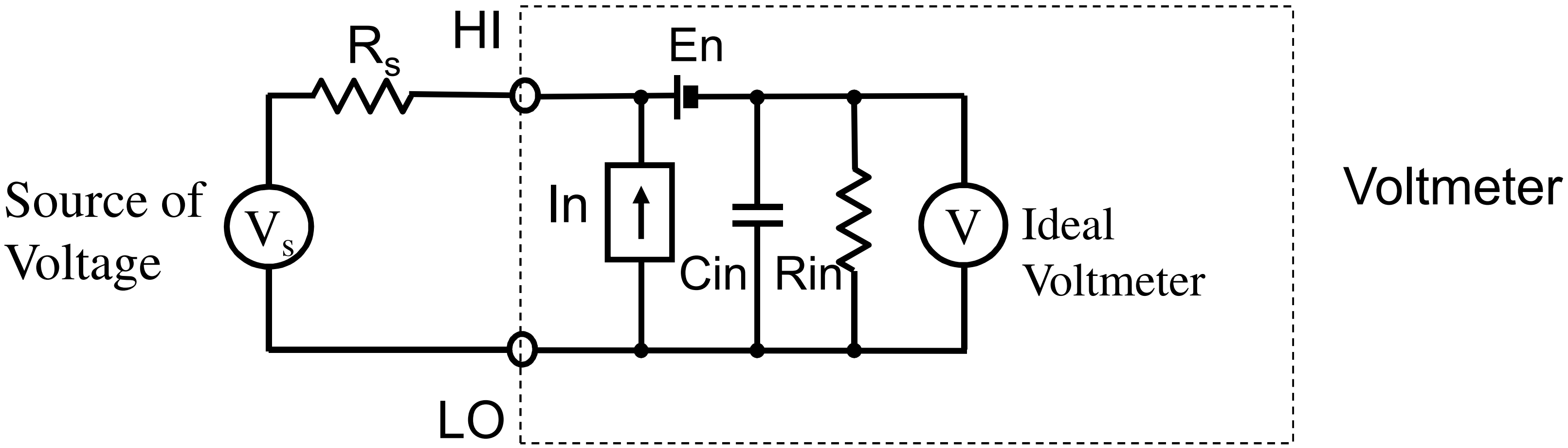


$$V = V_S \left[\frac{R_{in}}{R_S + R_{in}} \right]$$

Voltage Measurements



Voltage Measurements



$$V = V_S * \left[\frac{R_{IN}}{R_S + R_{IN}}\right] + e_N + I_N * \left[\frac{R_S\ R_{IN}}{R_S + R_{IN}}\right]$$

Theoretical Limits of Voltage Measurement

The Rs provides a fundamental limit to how well you can resolve Vs:

$$V_n = \sqrt{4kTBR_s}$$

K - Boltzmann's constant
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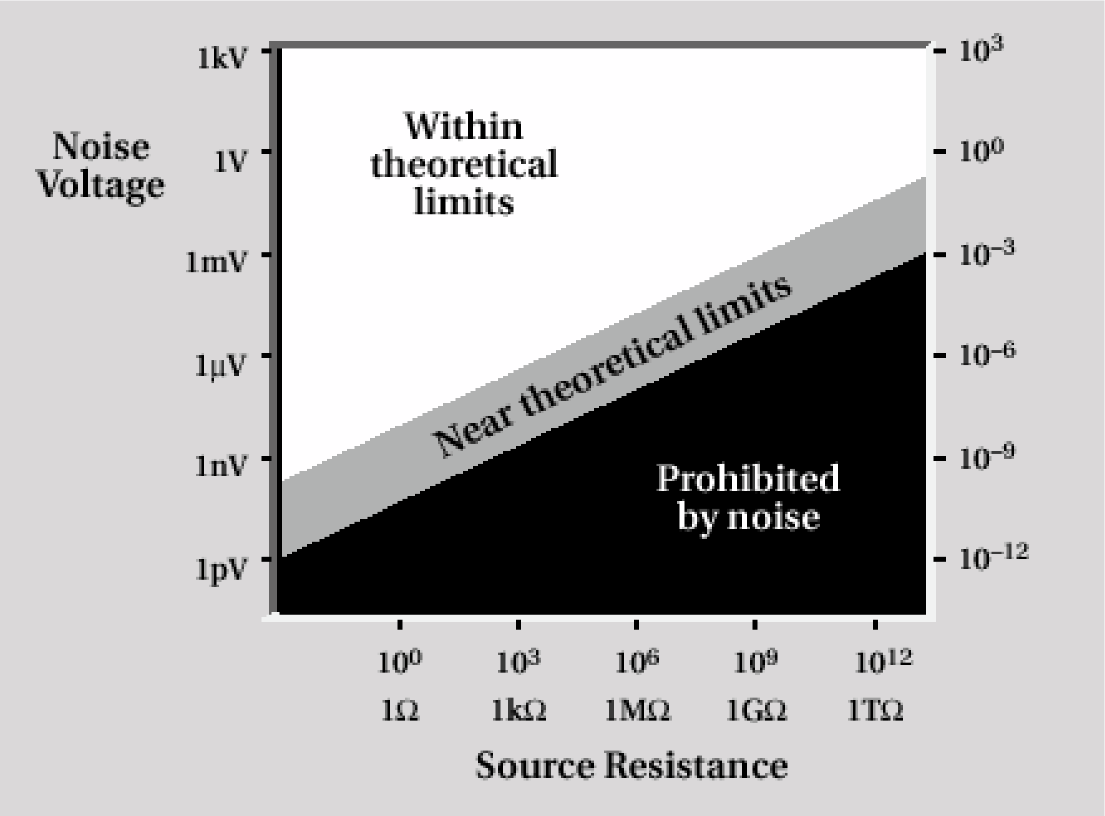
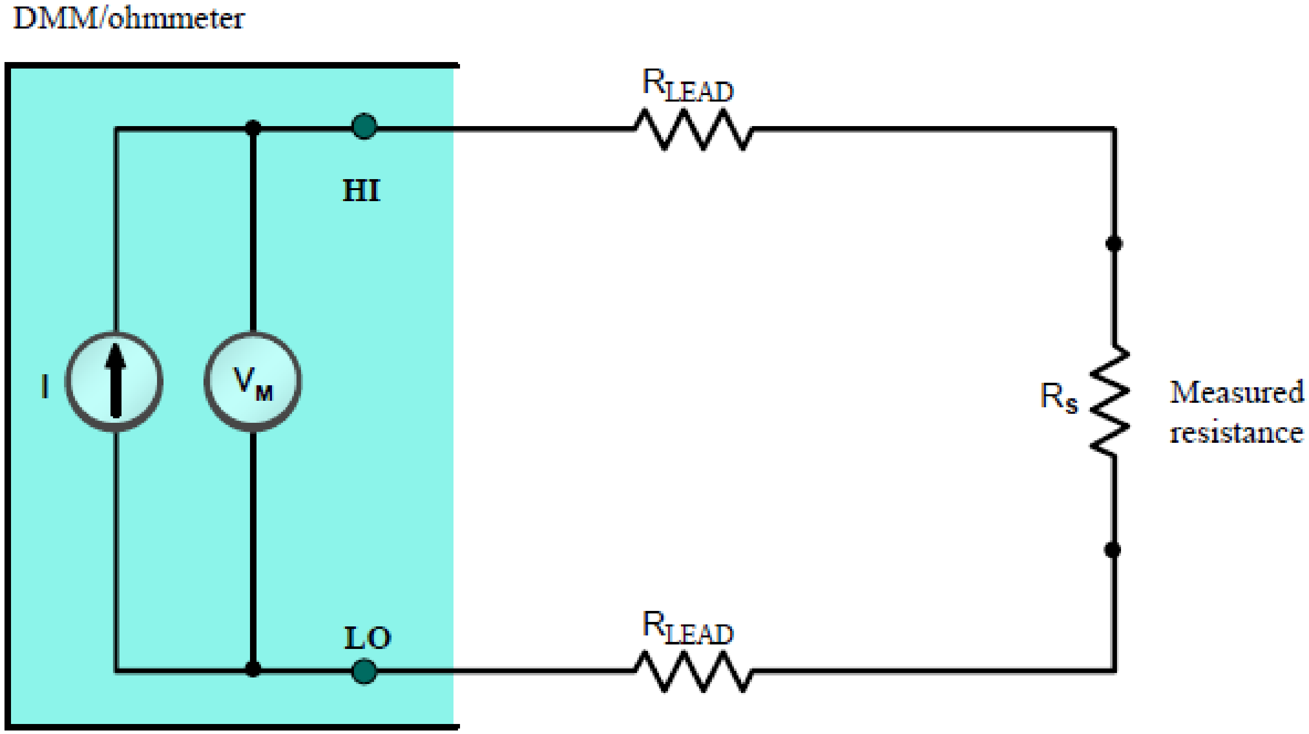
Theoretical Limits of Voltage Measurement



Lead Resistance in 2Wire Ohms Circuit



$$R_{measured} = R_S + R_{LEAD} + R_{LEAD}$$

Lead Resistance Error

- Typical Lead Resistance: 1 -10mOhm

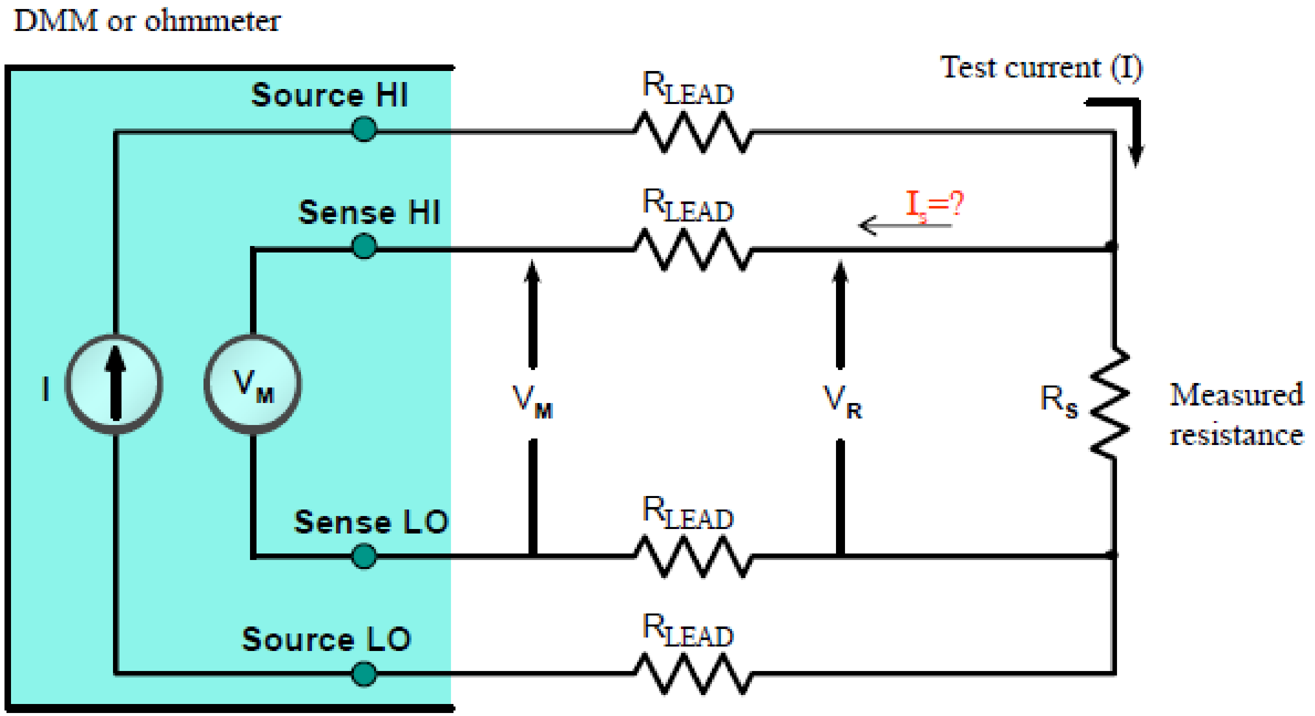
- Typical Low Ohms measurement can be 100mOhms

- Assuming Rs = 100mOhm, Rlead=10mOhm, Rmeasured is:

  - Rmeasured = Rs + Rlead + Rlead
  - Rm = 100e-3 +10e-3 + 10e-3
  - Rm = 120e-3 Ohm

- **Error = 20%**

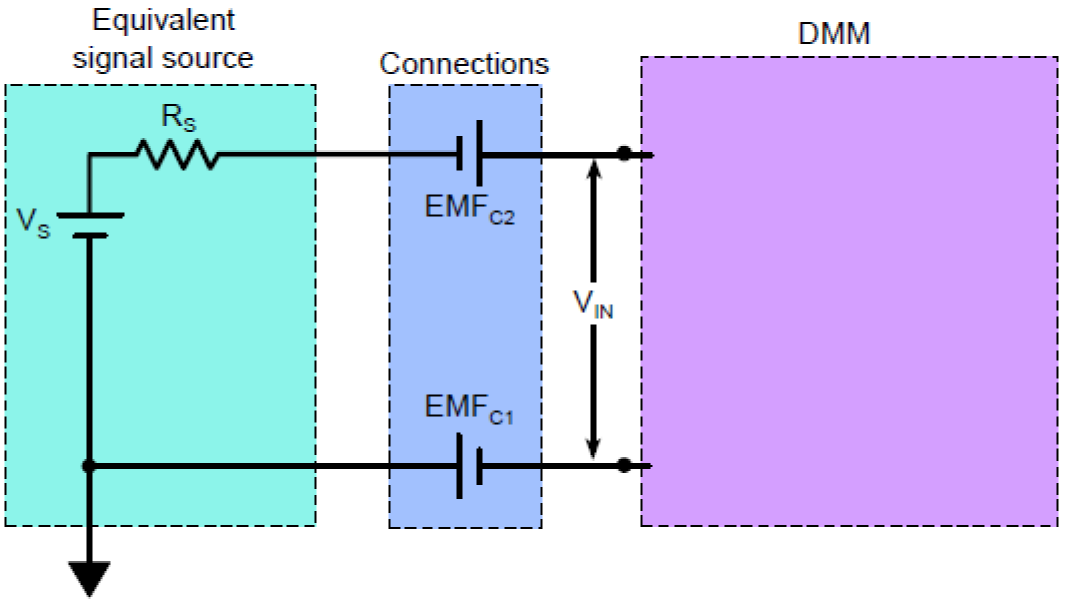
4-wire Ohms – to minimize Lead Resistance Errors



V_M = Voltage measured by meter
V_R = Voltage across resistor
Because sense current is negligible, $V_M = V_R$

and measured resistance = $\dfrac{V_M}{I} = \dfrac{V_R}{I}$

Thermal EMF errors



- Unwanted Thermocouples are created when

  - Dissimilar metal are connected together

  - Temperature gradients exist in the circuit

Thermal EMF Methods

- Current-Reversal Method

  - Thermoelectric EMFs can be canceled by making two measurements with currents of opposite polarity

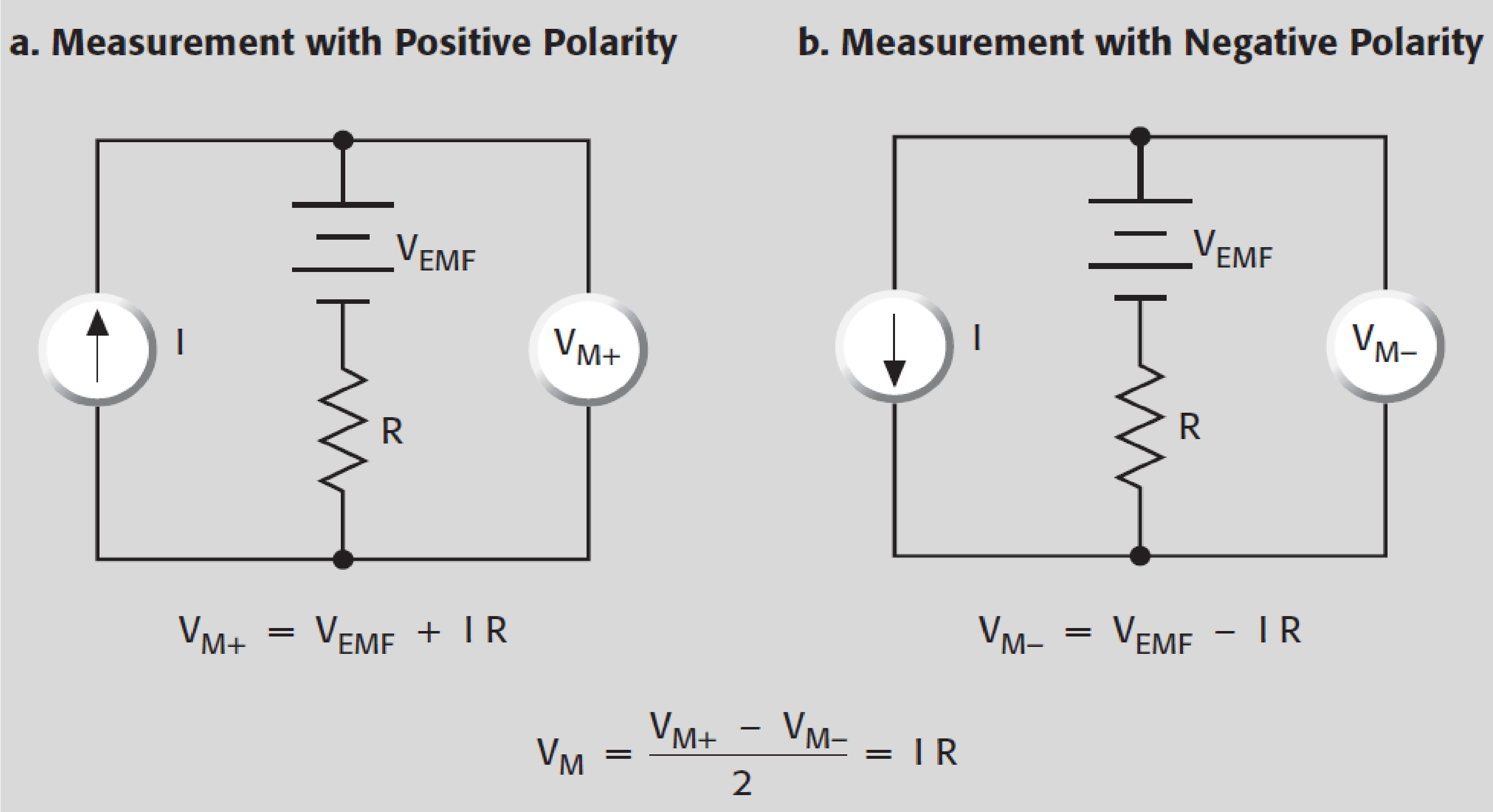
- Offset-Compensated Ohms Method

  - Measurements are alternated between a fixed source current and zero current

- Delta Method

  - Three voltage measurements to make each resistance calculation.

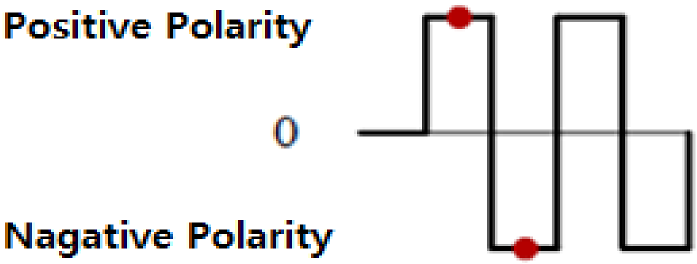
Current-Reversal Method



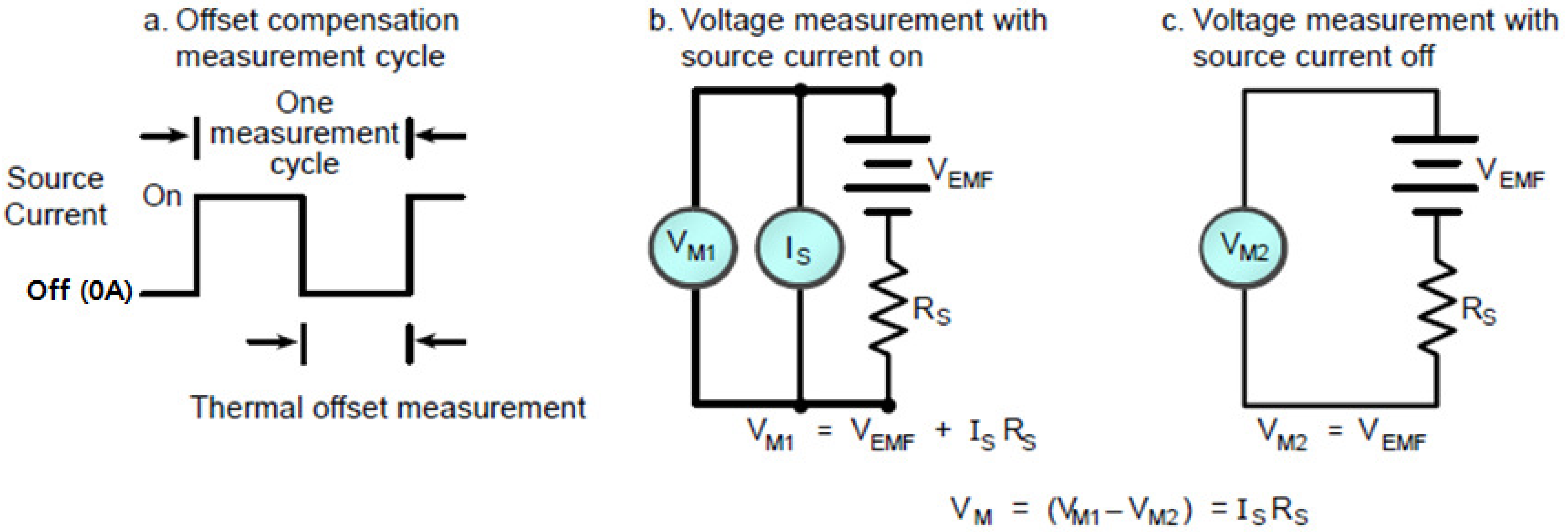
$$V_{M+} = V_{EMF} + IR$$

$$V_{M-} = V_{EMF} - IR$$

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



Offset Compensation to minimize Thermal EMFs errors



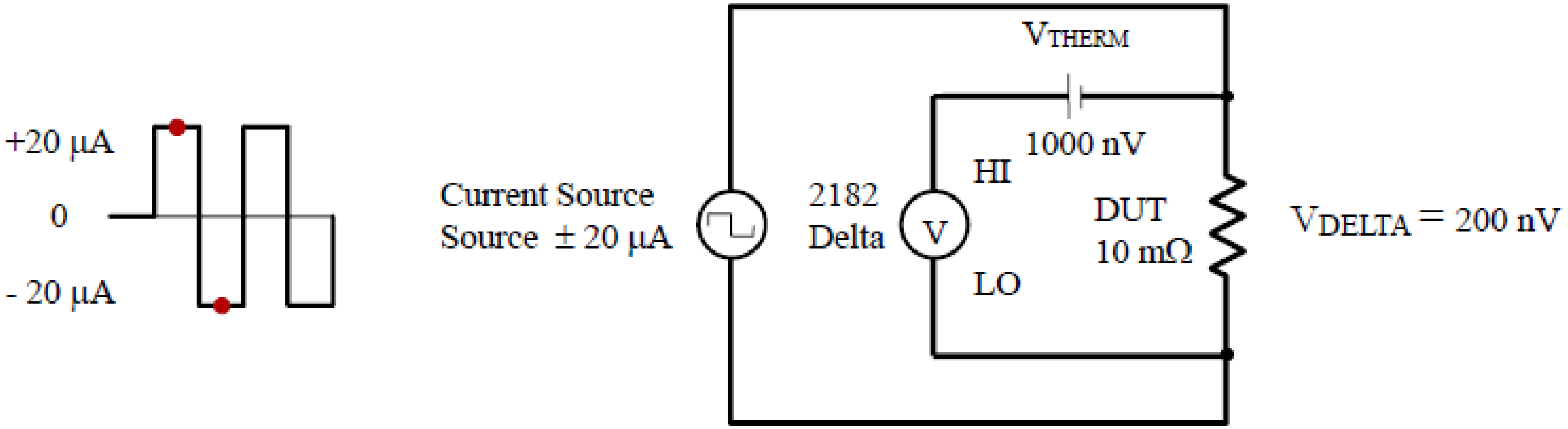
$V_{M1} = V_{EMF} + I_S R_S$

$V_{M2} = V_{EMF}$

$$V_M = (V_{M1} - V_{M2}) = I_S R_S$$

Delta Mode (Current Reversal Method)
To minimize Thermal EMFs

Note: This Method is used with 2400 & 2182



At + 20 µA :

$V_1 = 200\text{ nV} + 1000\text{ nV}$
$= 1200\text{ nV}$

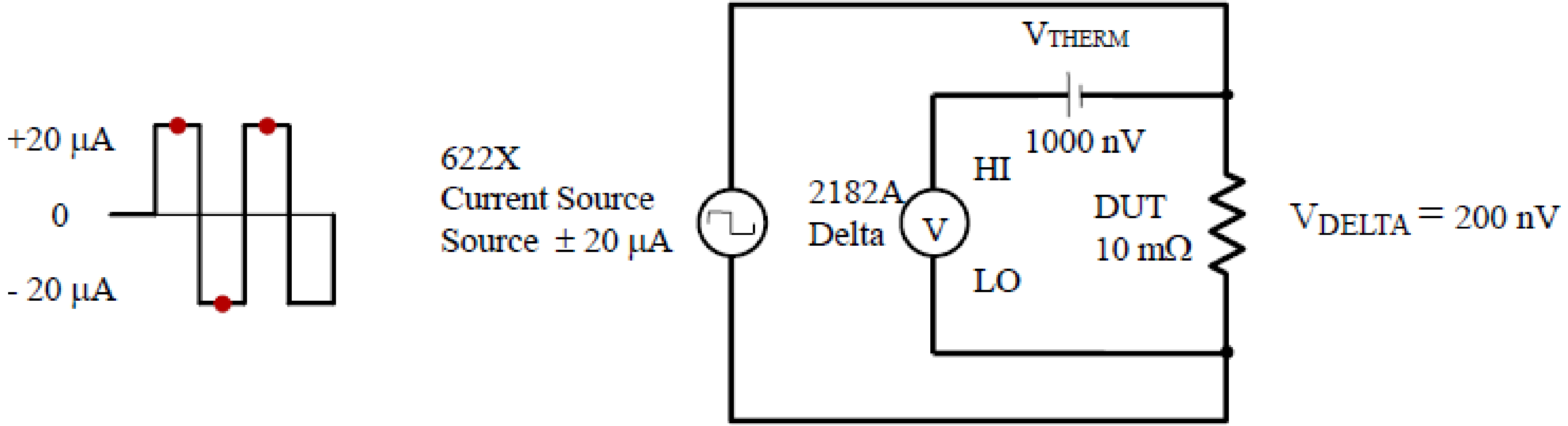
At - 20 µA :

$V_2 = -200\text{ nV} + 1000\text{ nV}$
$= 800\text{ nV}$

$$V_{DELTA} = \frac{V_1 - V_2}{2} = \frac{1200\text{ nV} - 800\text{ nV}}{2} = 200\text{ nV}$$

By reversing current, Delta Mode significantly reduces effects from thermal voltages.

Improved Delta Mode eliminates the effects of Thermal EMFs



At + 20 μA :

$V_1 = 200\text{ nV} + 1000\text{ nV}$
$= 1200\text{ nV}$

At - 20 μA :

$V_2 = -200\text{ nV} + 1010\text{ nV}$
$= 810\text{ nV}$

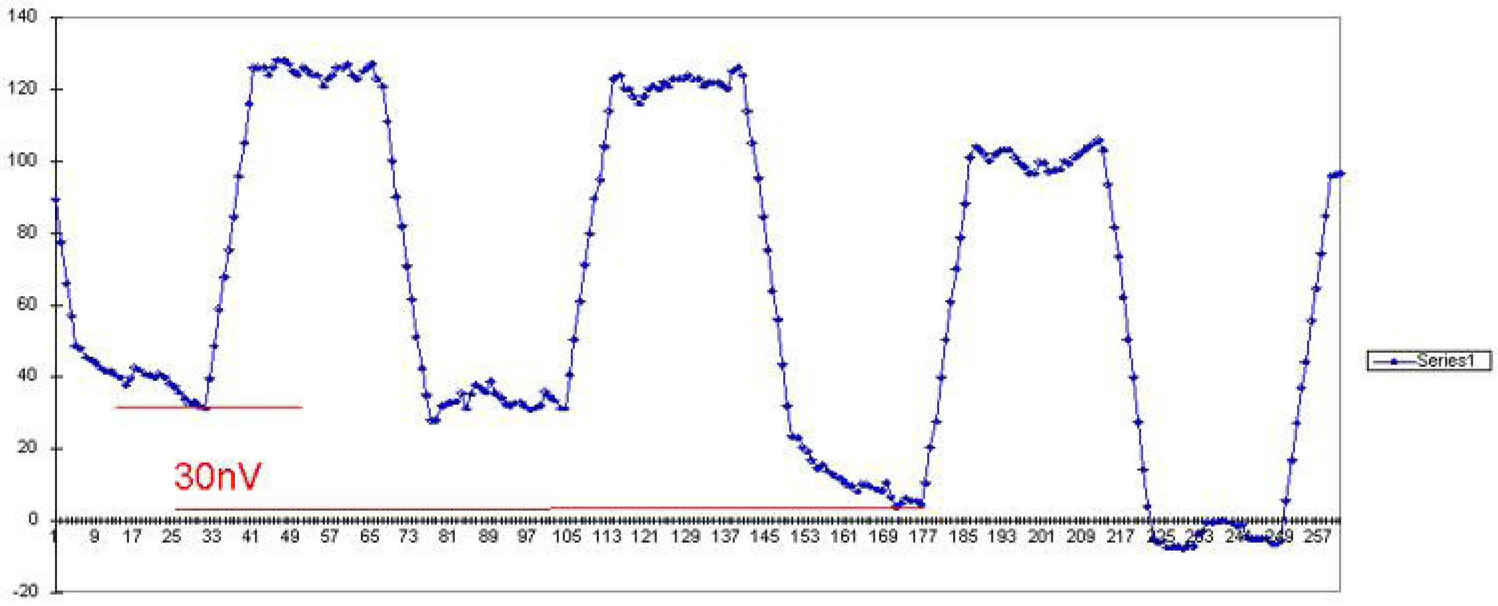
At + 20 μA :

$V_3 = 200\text{ nV} + 1020\text{ nV}$
$= 1220\text{ nV}$

$$V_{DELTA} = \frac{\frac{V_1 - V_2}{2} + \frac{V_3 - V_2}{2}}{2} = \frac{195\text{ nV} + 205\text{ nV}}{2} = 200\text{ nV}$$

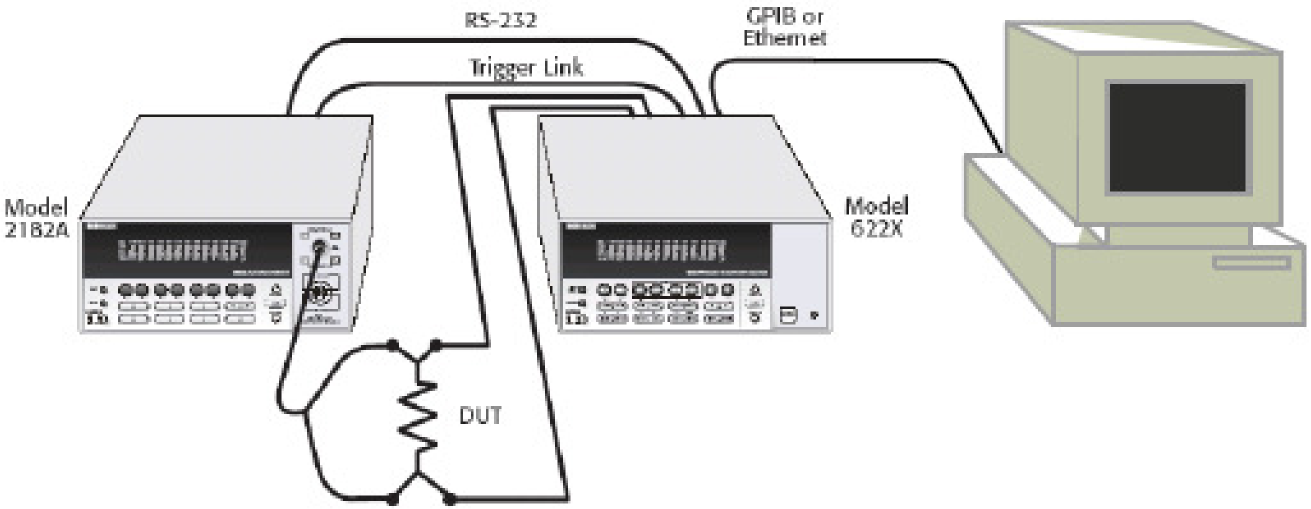
Improved Delta Mode eliminates effects from thermal voltage *drift*

Why fast current reversal



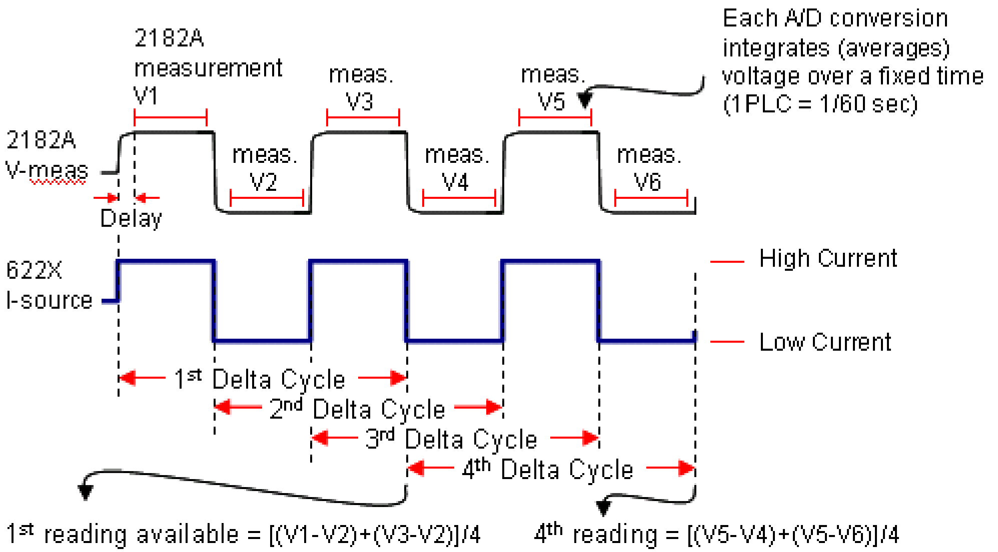
Offset Drift >30nV/10Sec
Must do reversals fast – speed is critical
2182A is the lowest noise nanovoltmeter at 10rds/sec (1PLC)

The BEST Low Resistance Solution EVER!
6220 or 6221/2182A Delta Mode



622X controls the 2182A. The pair act as a single instrument.

Why is Delta Mode so IMPORTANT?



1st reading available = [(V1-V2)+(V3-V2)]/4

4th reading = [(V5-V4)+(V5-V6)]/4

Up to 300 successive readings can be averaged to reduce noise further.

- Delta Mode ability opens up many big opportunities:

- Serves Traditional low resistance Applications

- Superconductivity, metal reliability & research (Source current -> low voltage measure)

- low power DUTs, which are difficult to measure without heating, altering or destroying:

Limit current -> still low voltage measure

How Low V Challenges Relate to Low R Challenges

- Recall the fact that Low R measurements are performed by using a test current and measuring the voltage drop across the DUT

- Therefore Low R and Low V measurements share the fundamental measurement challenges – most notably “thermal emf errors”

- However, since Low V measurement does not involve using a test current, special techniques such as Offset Compensation and Current Reversal –cannot be performed for Low V measurements

- Accurate Low V measurements mostly depend on instrument resolution/accuracy, noise specs and other test set ups

SECTION 4 Source of Measurement Error

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Source of Measurement Error

- **Electrostatic Interference**
- **Leakage Current**
- **Generated Currents:**

  - Offset Currents: Internal and External

  - Triboelectric Effects

  - Piezoelectric Effects

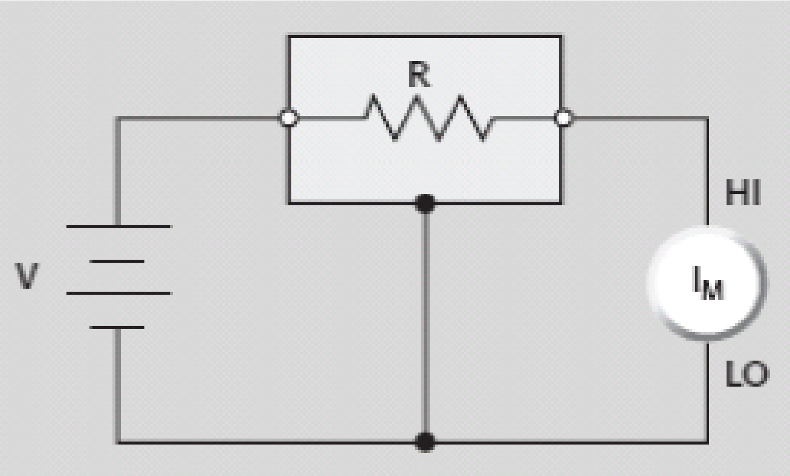
  - Contamination and Humidity

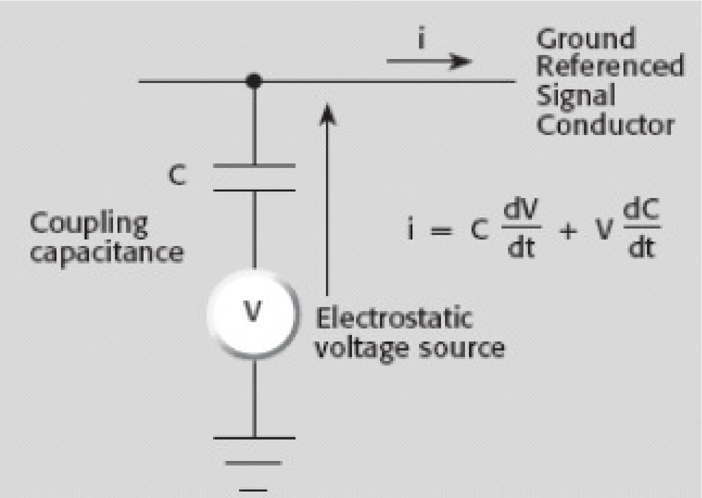
- **Source Impedance:**

  - Source Resistance

  - Source Capacitance

Electrostatic Interference





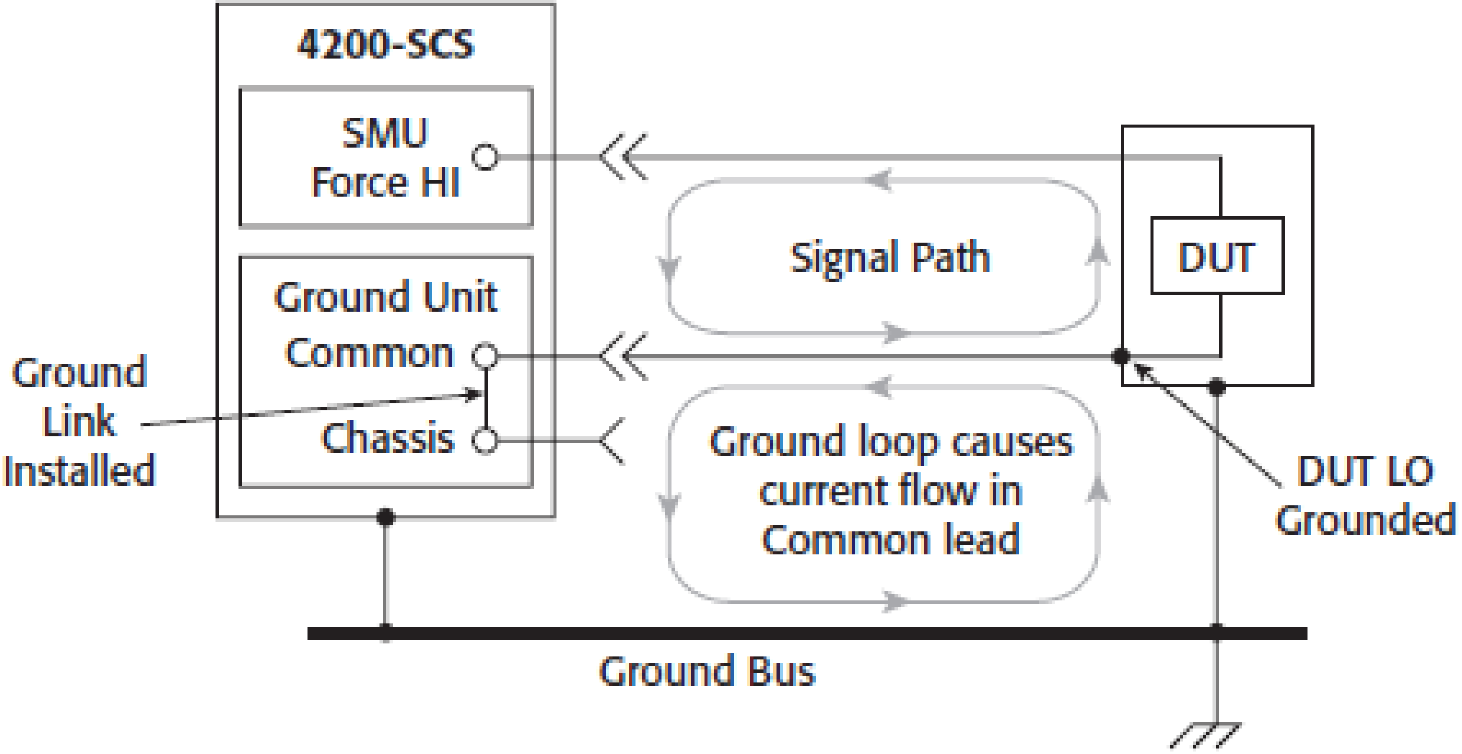
- **To reduce electrostatic interference effects:**

- Build a shield to enclose the circuit or device being measured

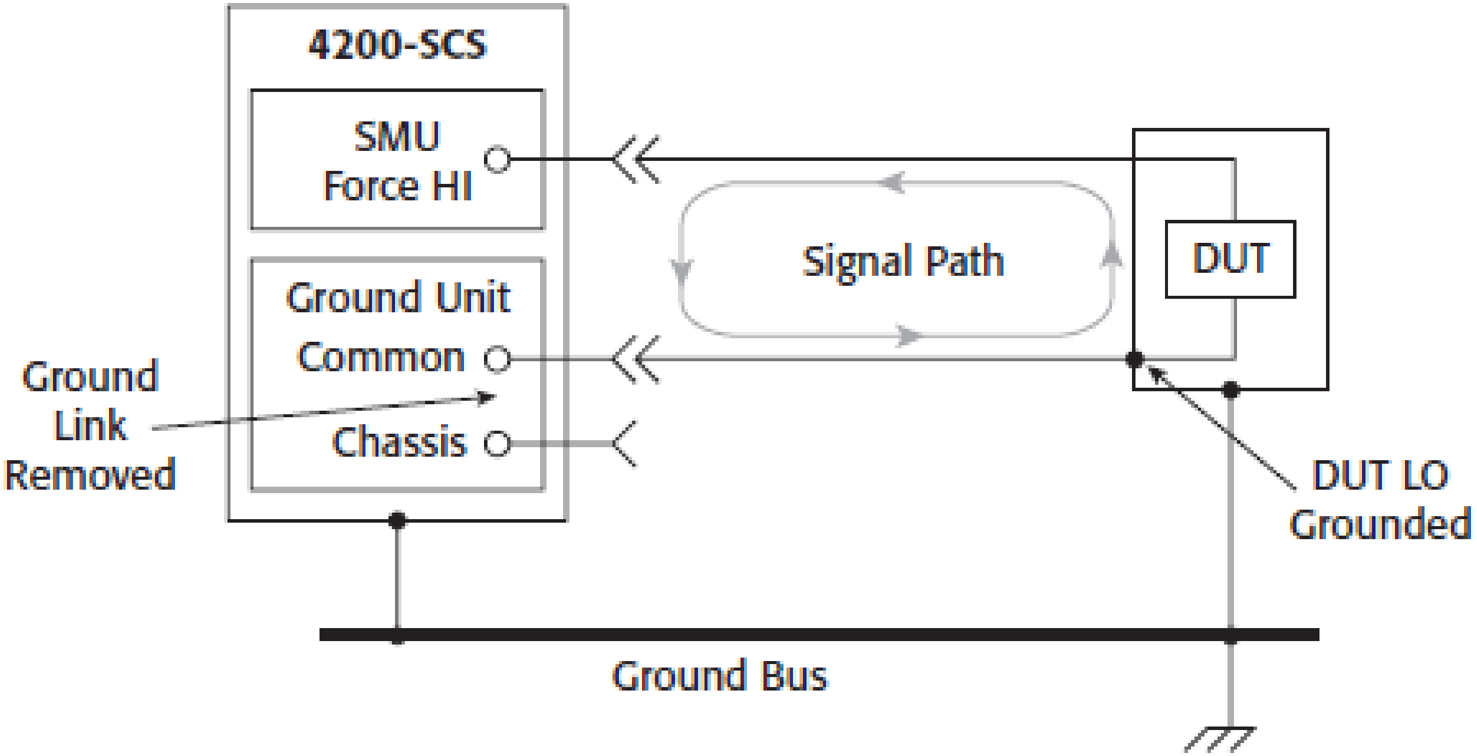
- Shield can be just a simple metal box or meshed screen that encloses the test circuit

- Shield should be connected to measurement circuit LO, which is not necessarily earth ground

Ground Loops



Eliminating Ground Loops



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Leakage Current

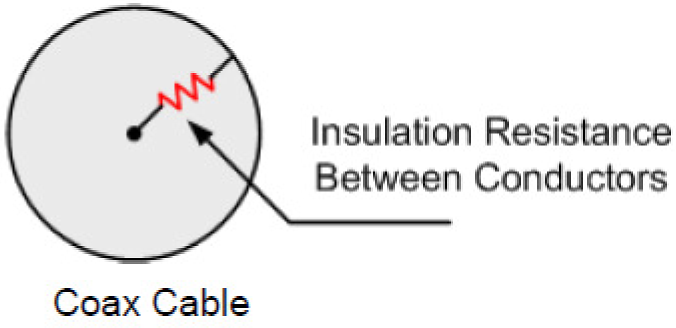
- **Leakage current is an error current that flows (leaks) through insulation resistance when a voltage is applied.**
- **To reduce leakage currents:**

- Use good quality insulators in the test circuit

  (e.g. Teflon ®, polyethylene)

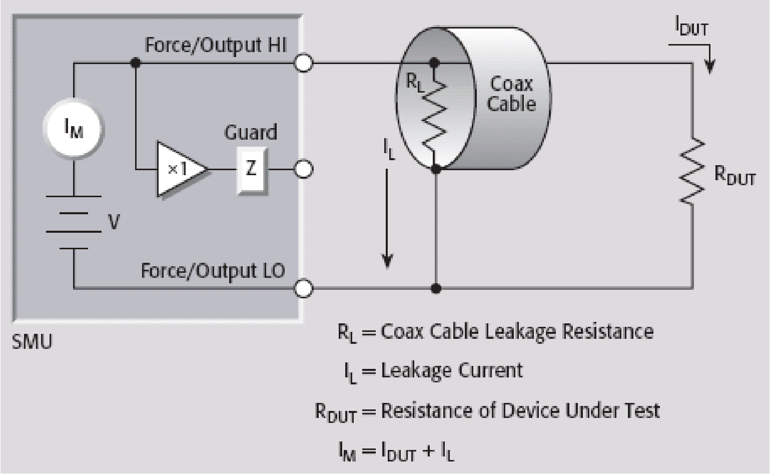
- Reduce the humidity in the test lab

- Use guarding



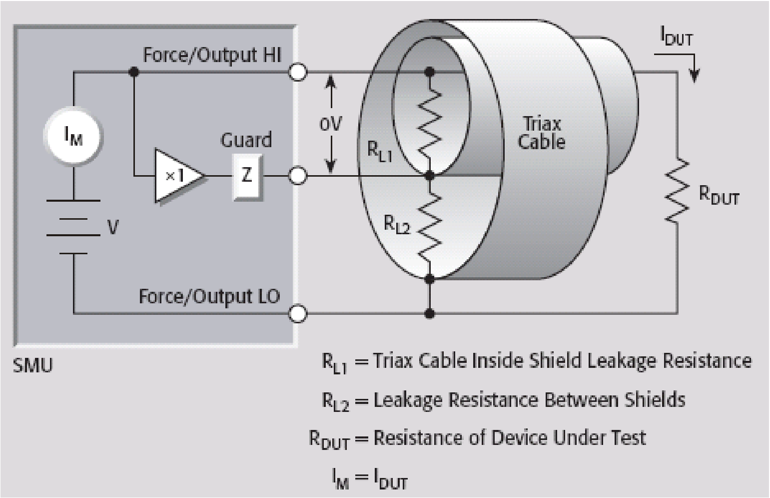
Using Guard to Reduce Leakage - Cable

Unguarded Configuration



R_L = Coax Cable Leakage Resistance
I_L = Leakage Current
R_{DUT} = Resistance of Device Under Test
$I_M = I_{DUT} + I_L$

Guarded Configuration

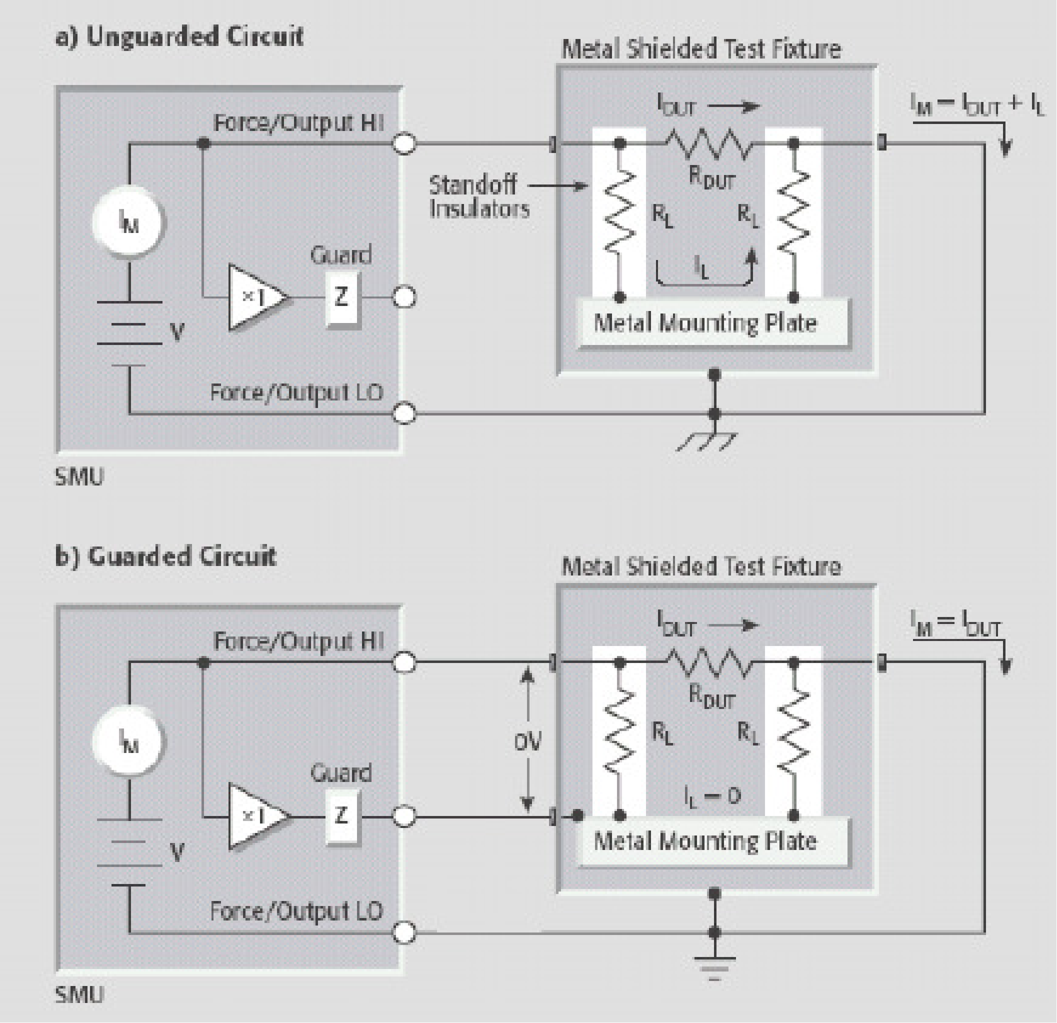


R_{L1} = Triax Cable Inside Shield Leakage Resistance
R_{L2} = Leakage Resistance Between Shields
R_{DUT} = Resistance of Device Under Test
$I_M = I_{DUT}$

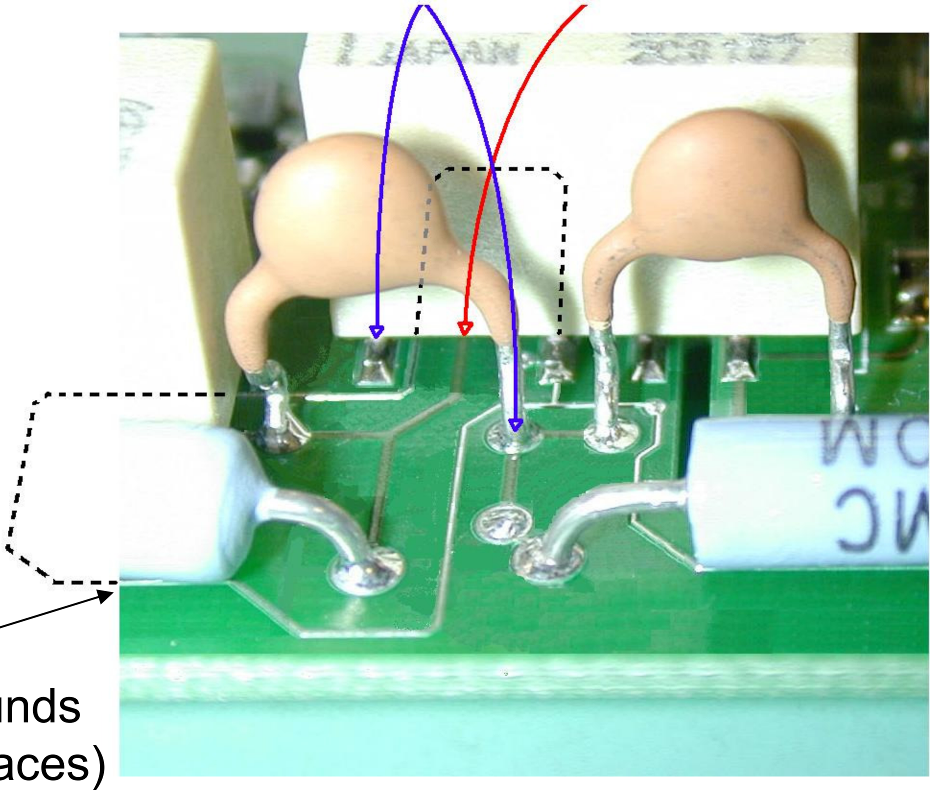
In the unguarded circuit, the leakage resistance of the coax cable is in parallel with the DUT (RDUT), creating an unwanted leakage current (IL). This leakage current will degrade very low current measurements.

In the guarded circuit, the inside shield of the triax cable is connected to the guard terminal of the SMU. The differencein potential between the Force/Output HI terminal and the Guard terminal is nearly 0V, so the leakage current (IL) is eliminated.

Using Guard to Reduce Leakage - Circuit



Using Guard to Reduce Leakage – Circuit application



Nearby Voltages

Sensitive Node (HI)

Guard
(Entirely surrounds
the sensitive traces)

Generated Currents

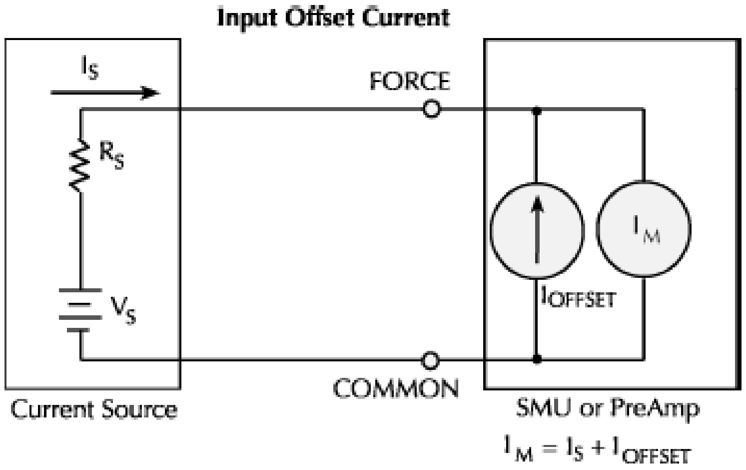
- **Any extraneous generated currents in the test system will add to the desired current, causing errors.**
- **Offset Currents**

  - Internal Offsets: Input offset current of ammeter

  - External Offsets: Insulators and cables:
- **Triboelectric Effects**
- **Piezoelectric and Stored Charge Effects**
- **Contamination and Humidity**

Effect	Generated Current Range
Triboelectric	1fA to 10nA
Mechanical stress (Teflon)	1fA to 1pA
Mechanical stress (Ceramics)	100aA to 100fA
Clean epoxy circuit board	100fA
Dirty epoxy circuit board	100pA

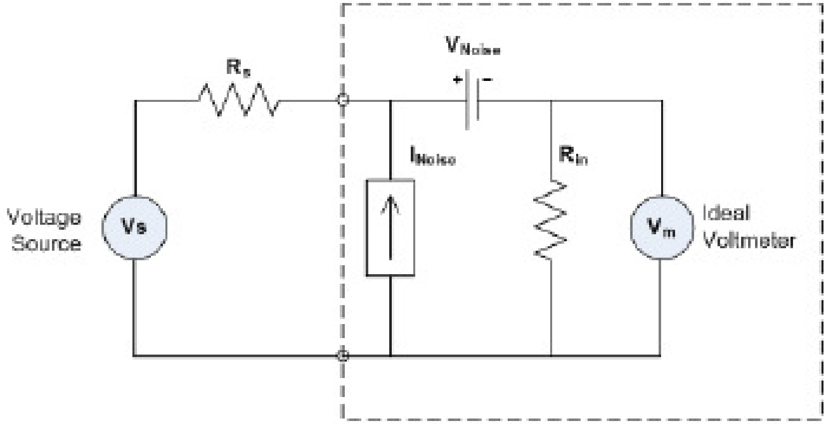
Offset Currents
Internal Offsets



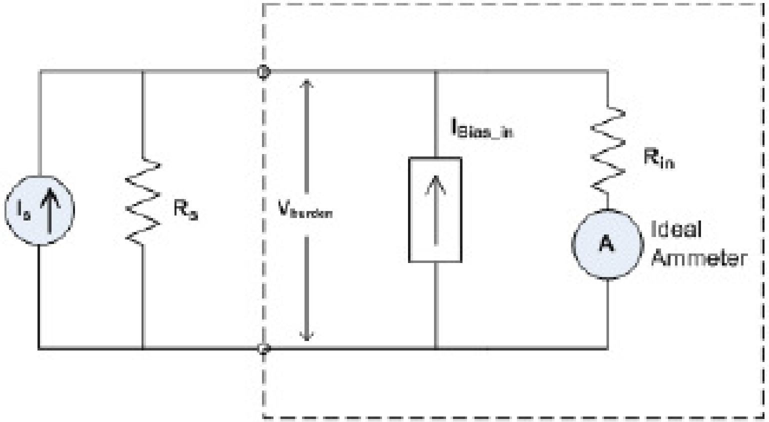
- Input Offset Current is a small current that flows from the ammeter.
- This current is caused by bias currents of active devices and leakage currents through insulators within the instrument.
- Input offset current can be brought down to within spec by performing a system calibration.

Noise and Source Impedance

Instrument Type	V-meter R_{IN}	V_{noise}	I_{noise} / Input Bias Current	V_{burden} of Ammeter
DMM	10MΩ -10GΩ	1µV	100pA	Hundreds of mV
Nanovoltmeter	10GΩ	10nV	50pA	N/A
Picoammeter	N/A	N/A	50fA	Hundreds of µV
Electrometer	200TΩ	50µV	3fA	Tens of µV

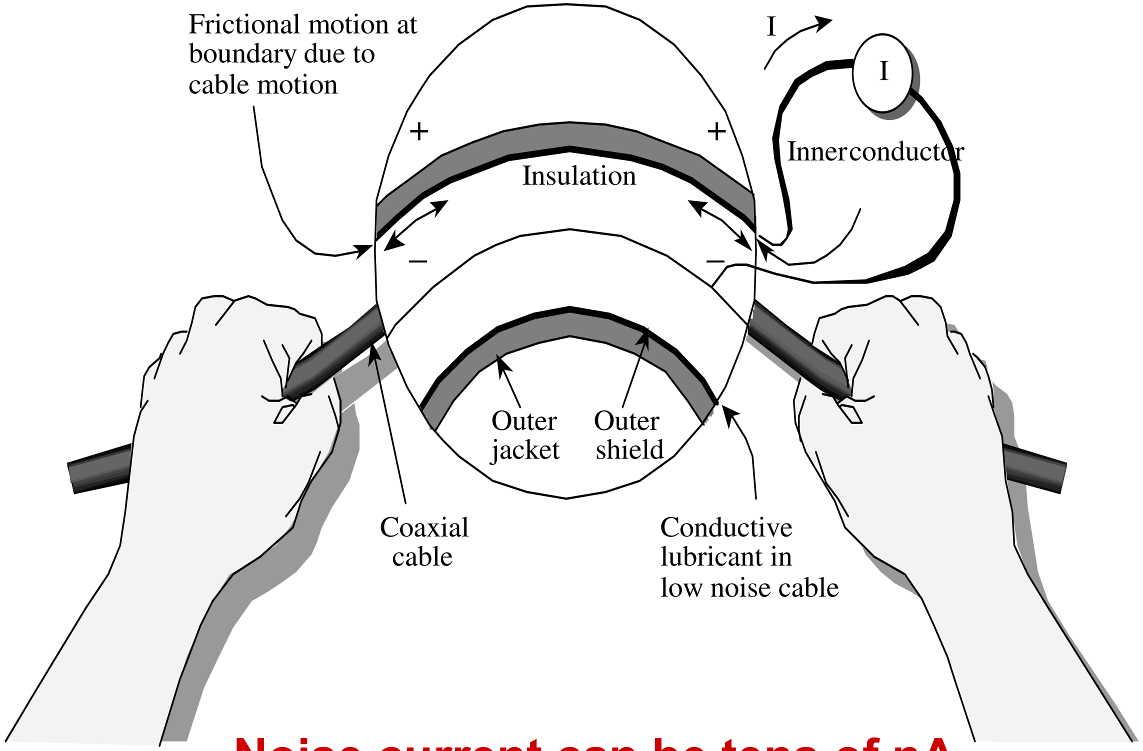


Voltmeter



Ammeter

Triboelectric Effect



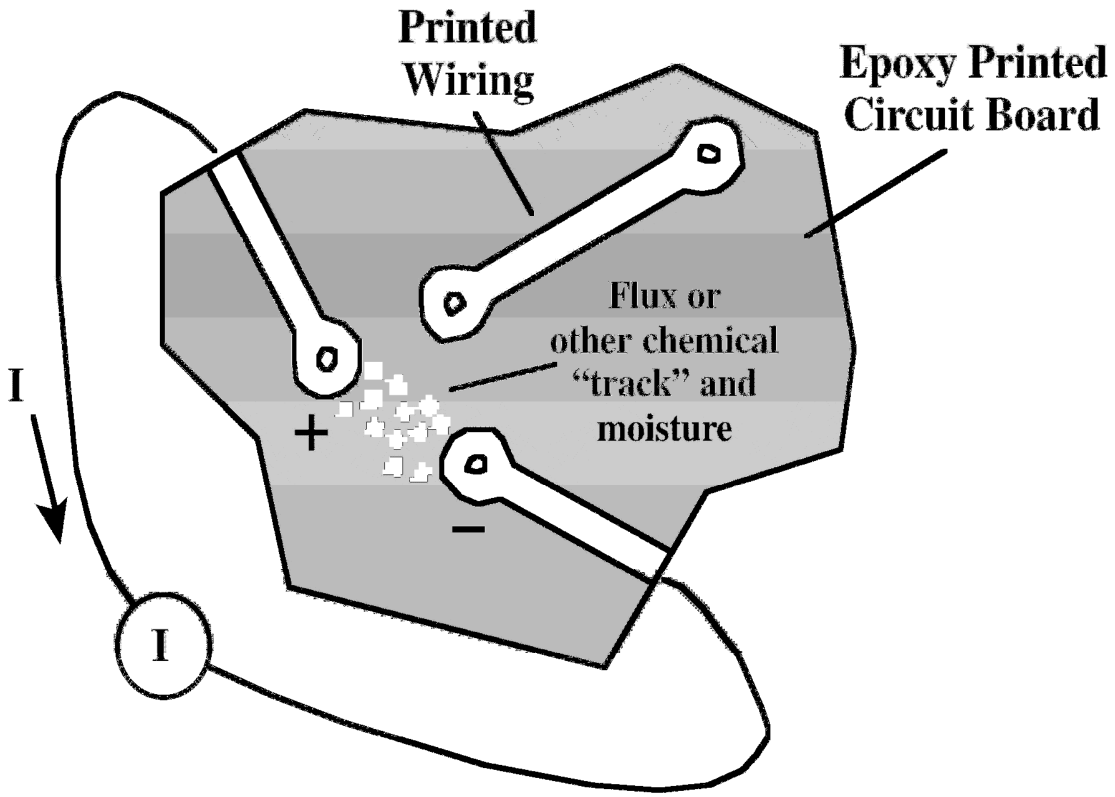
Noise current can be tens of nA

Triboelectric currents are generated by charges created between a conductor and an insulator due to friction. Free electrons rub off the conductor and create a charge imbalance that causes current to flow.

Reducing Triboelectric Noise

- Use low noise cable
- 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.
- If 10nA of noise won’t affect your results, don’t need to worry about this

Contamination Effect

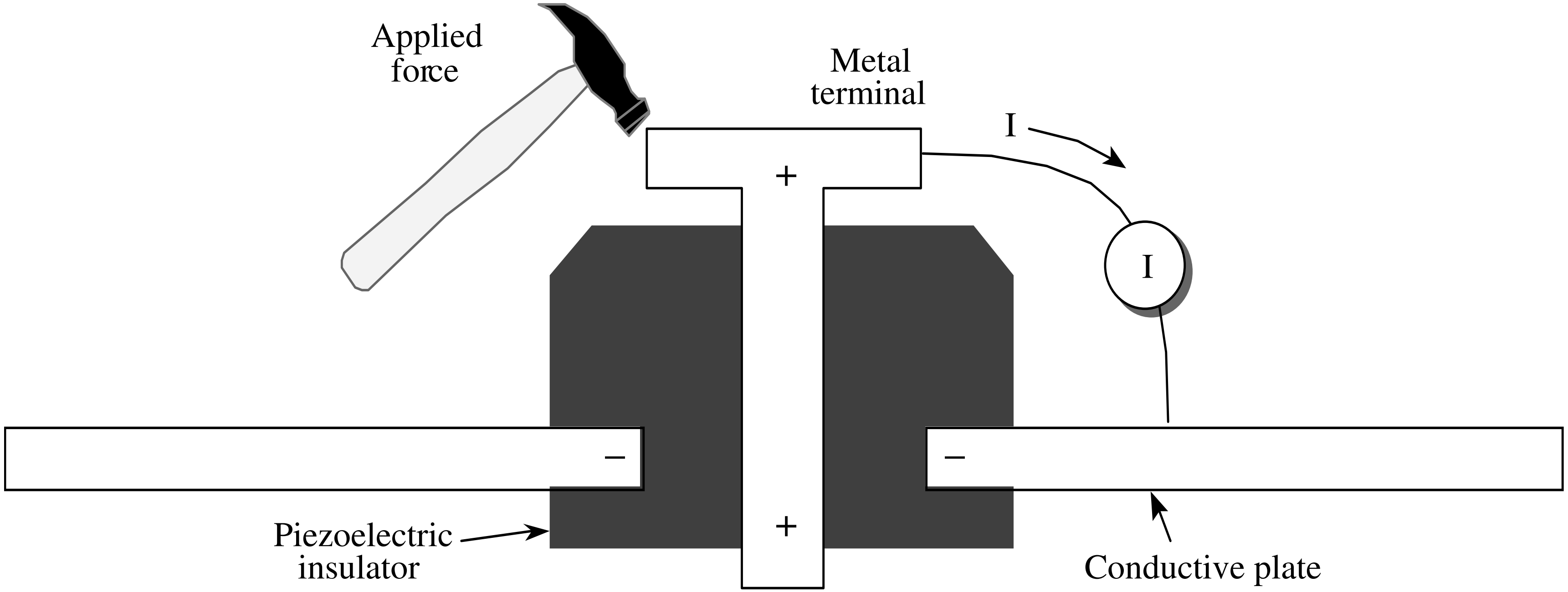


Noise current can be tens of nA

Minimizing contamination effect

- Use air as insulator when feasible
- Avoid touching insulators surrounding sensitive current nodes or use gloves
- Use as little flux as possible when soldering
- Clean around soldered regions with virgin solvent and clean swabs
- Be especially careful if circuit will operate in high humidity environment
- Increasing levels of care can reduce it to fA levels

Mechanical Stress Effects

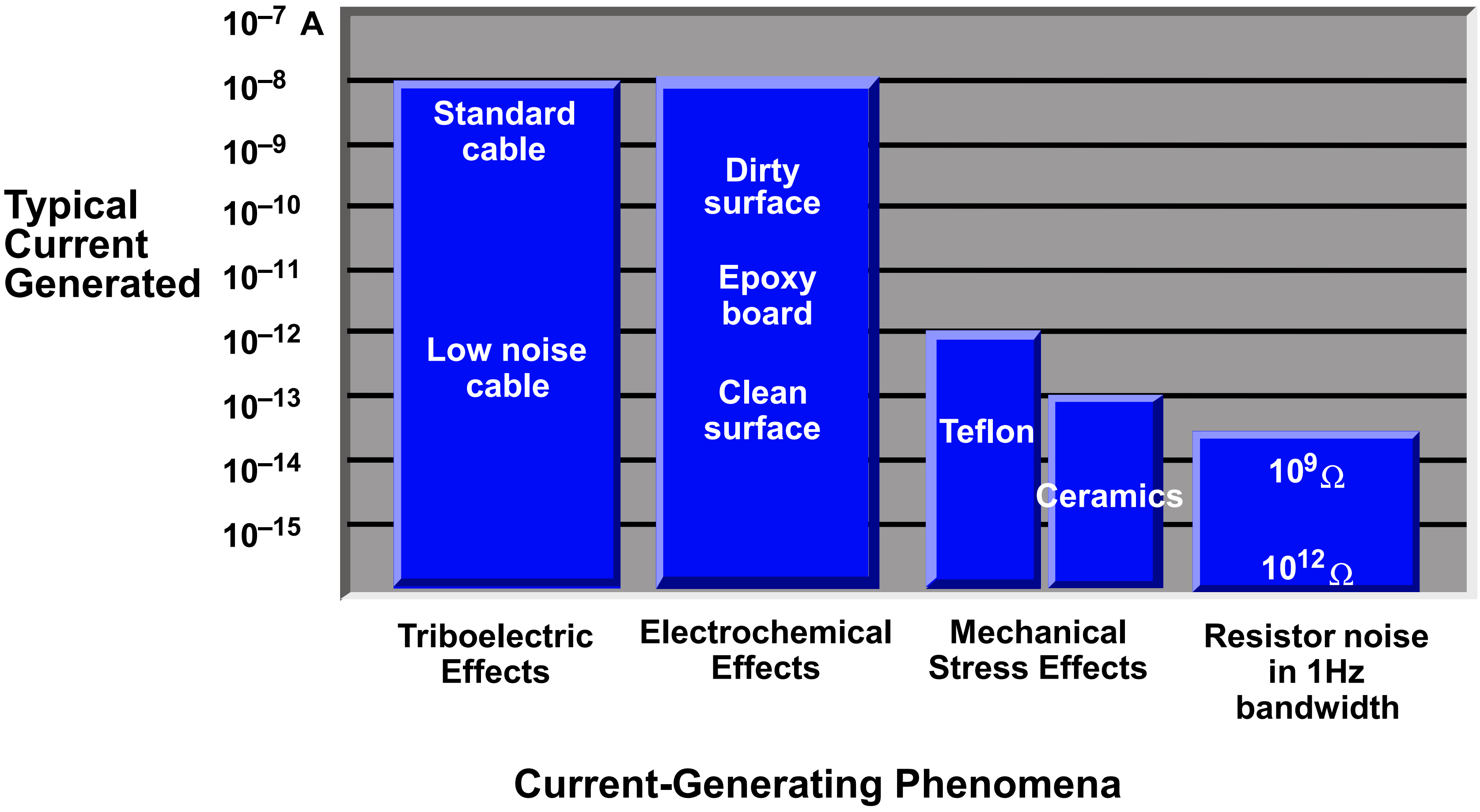


Noise current can be tens of pA

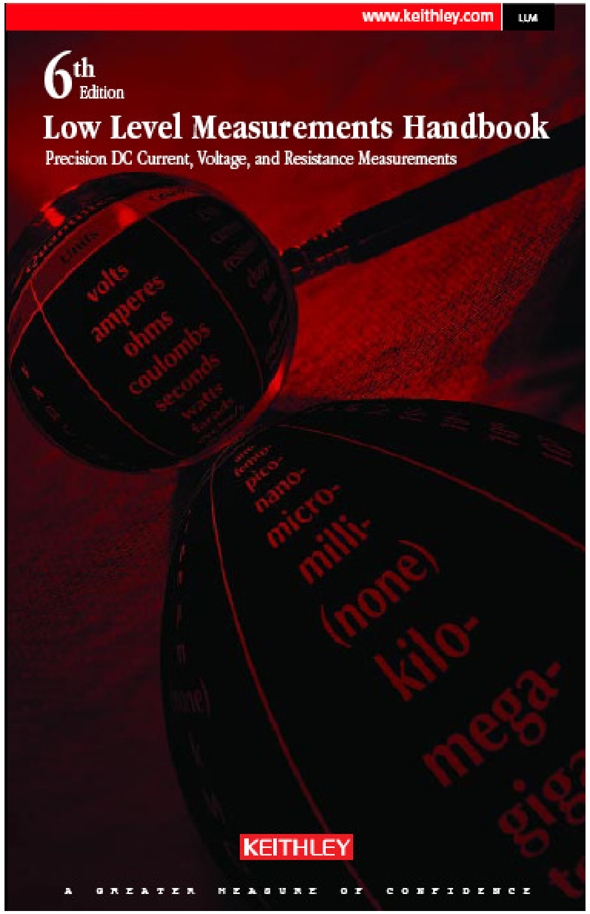
Reducing Stress Effects

- Avoid high-strain connections, such as measurement cables stretched or bent tightly around corners
- Isolate system from vibrations
- Don’t “stress” over this unless you need noise and error below 10pA

Typical Magnitudes of Generated Currents



Low Level Measurements Handbook



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FORCE of the FUTURE

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