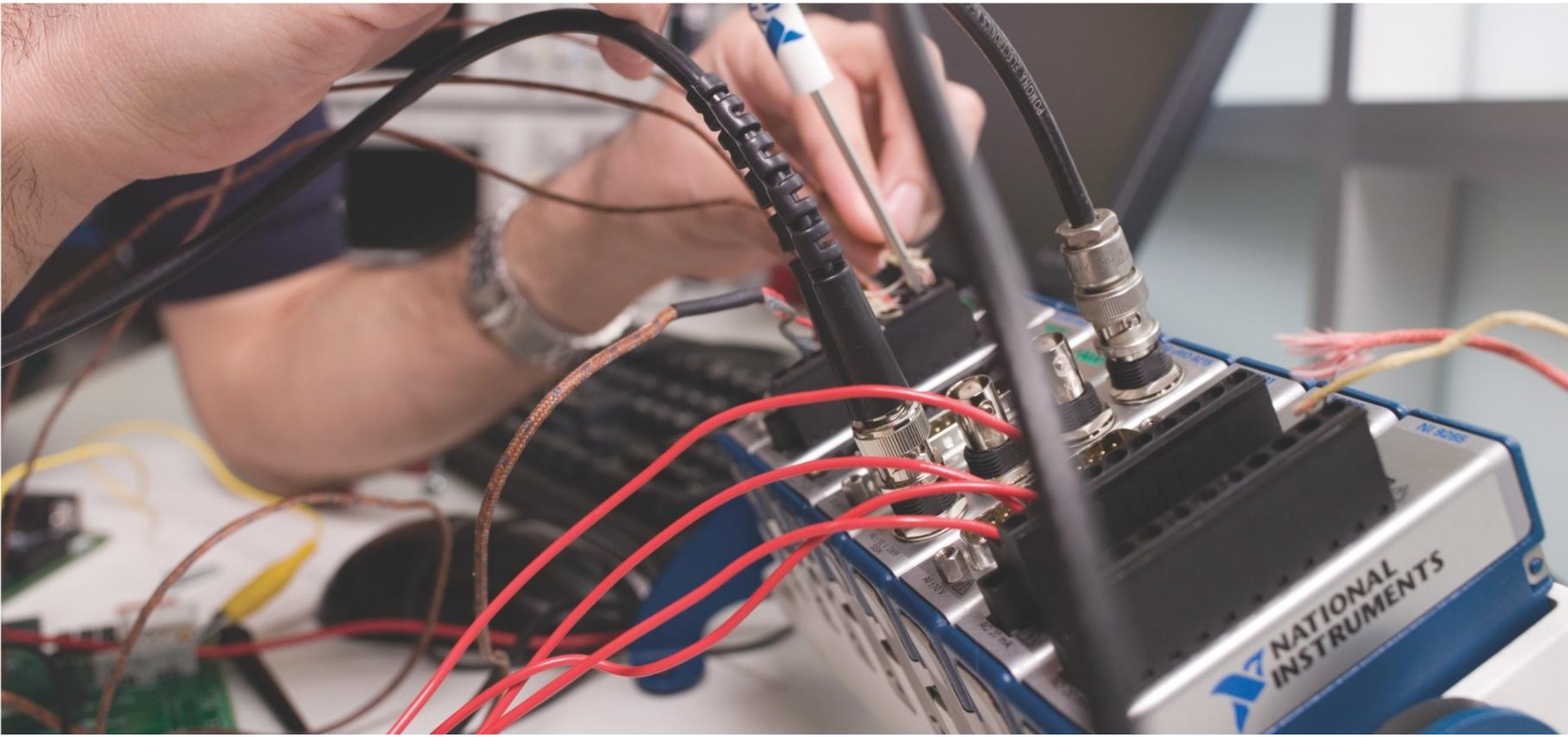


# Sensor Measurement Fundamentals Series

# How to Design an Accurate Temperature Measurement System

Jackie Byrne

Product Marketing Engineer

National Instruments



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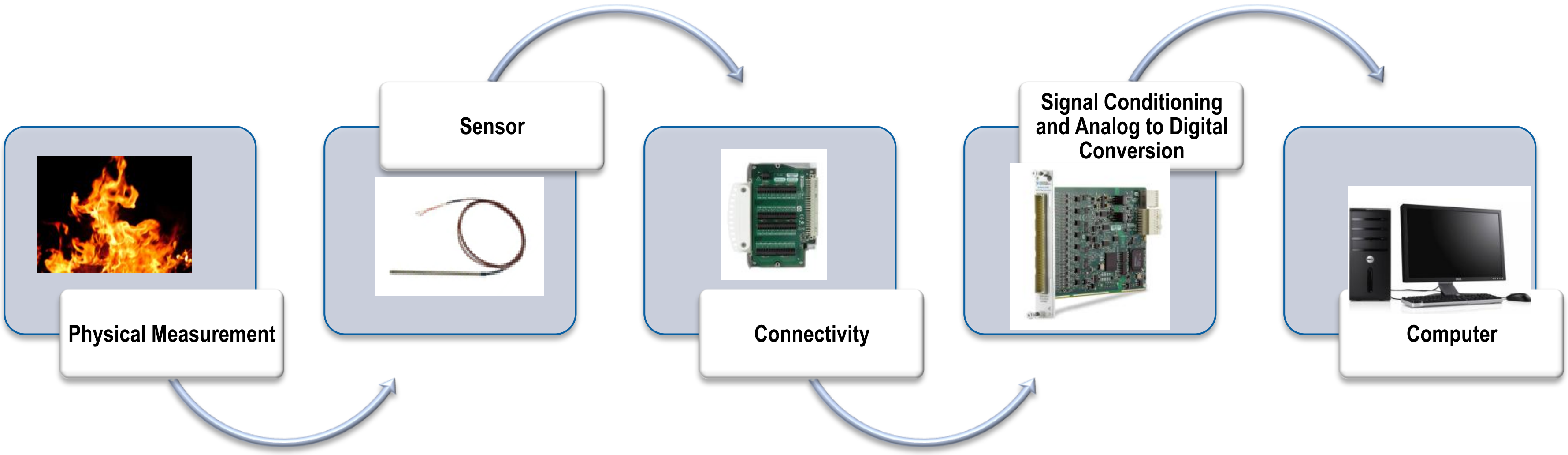
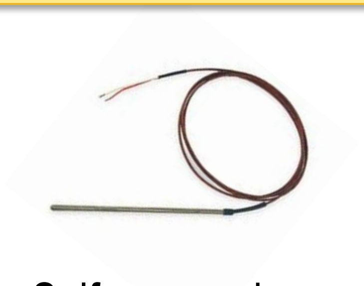
# Sensor Measurements 101



# Choose the Right Temperature Sensor

## Thermocouples



- \+ Self-powered
- \+ Inexpensive
- \+ Rugged
- \+ Temperature range

- \- Low voltage
- \- Requires CJC
- \- Variable accuracy

## RTDs

- \+ High accuracy
- \+ High stability

- \- Expensive
- \- Requires current
- \- Low resistance
- \- Self-heating

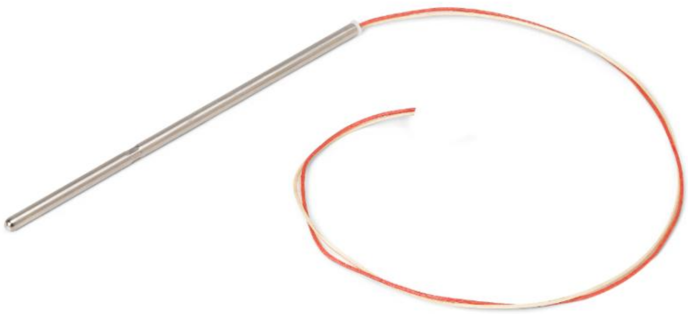
## Thermistors

- \+ High resistance
- \+ High sensitivity
- \+ Low thermal mass

- \- Highly nonlinear output
- \- Limited operating range
- \- Requires current
- \- Self-heating

# Thermocouple Basics

- Junction of two dissimilar metals
- Voltage rises with temperature
- Nonlinear
- Works on the Thermoelectric Effect Principle

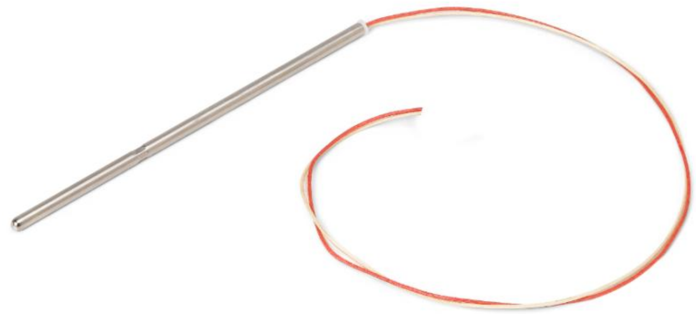
# Thermocouple Types

## American National Standards Institute (ANSI) Conventions

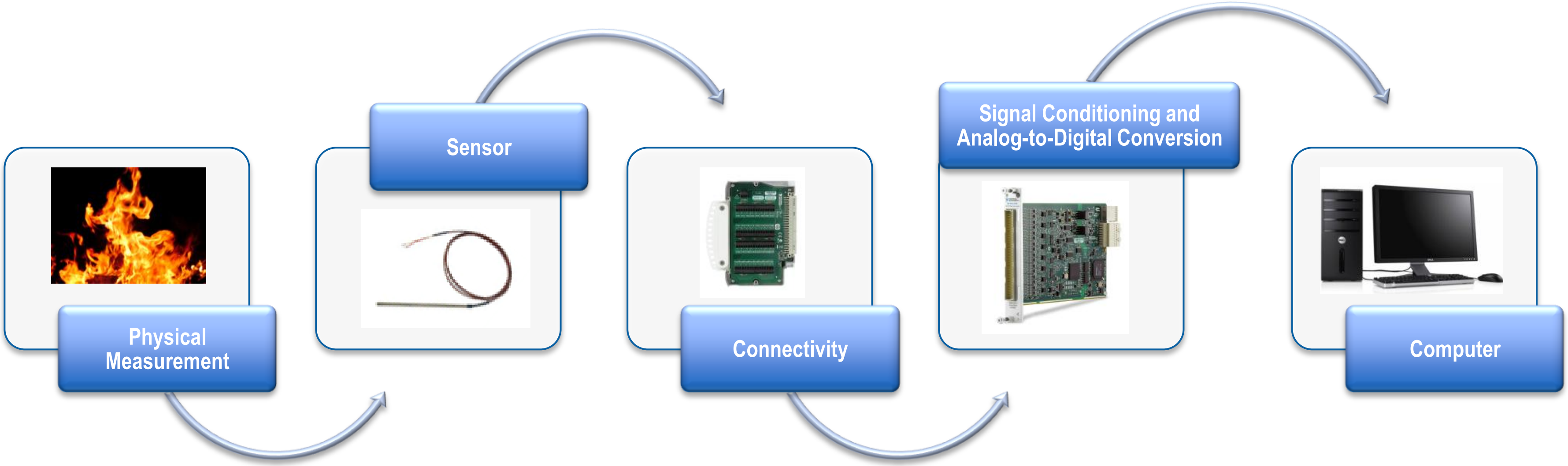
| Thermocouple Type | Conductors—Positive | Conductors—Negative |
|---|---|---|
| B | Platinum—30% rhodium | Platinum—6% rhodium |
| E | Nickel-chromium alloy | Copper-nickel alloy |
| J | Iron | Copper-nickel alloy |
| K | Nickel-chromium alloy | Nickel-aluminum alloy |
| N | Nickel-chromium-silicon alloy | Nickel-silicon-magnesium alloy |
| R | Platinum—13% rhodium | Platinum |
| S | Platinum—10% rhodium | Platinum |
| T | Copper | Copper-nickel alloy |

# Variations of Thermocouples

- Temperature range
- Accuracy
- Length
- Diameter
- Environment
- Cost



# Measurement Hardware




| NI Hardware for Thermocouple Measurements | | | | |
|---|---|---|---|---|
| NI 9213 | C Series | 16 channels | High density | CJC amplification filtering |
| NI PXIe-4353 | SC Express | 32 channels | High accuracy | |

# Achieve High Accuracy by Minimizing Sources of Error

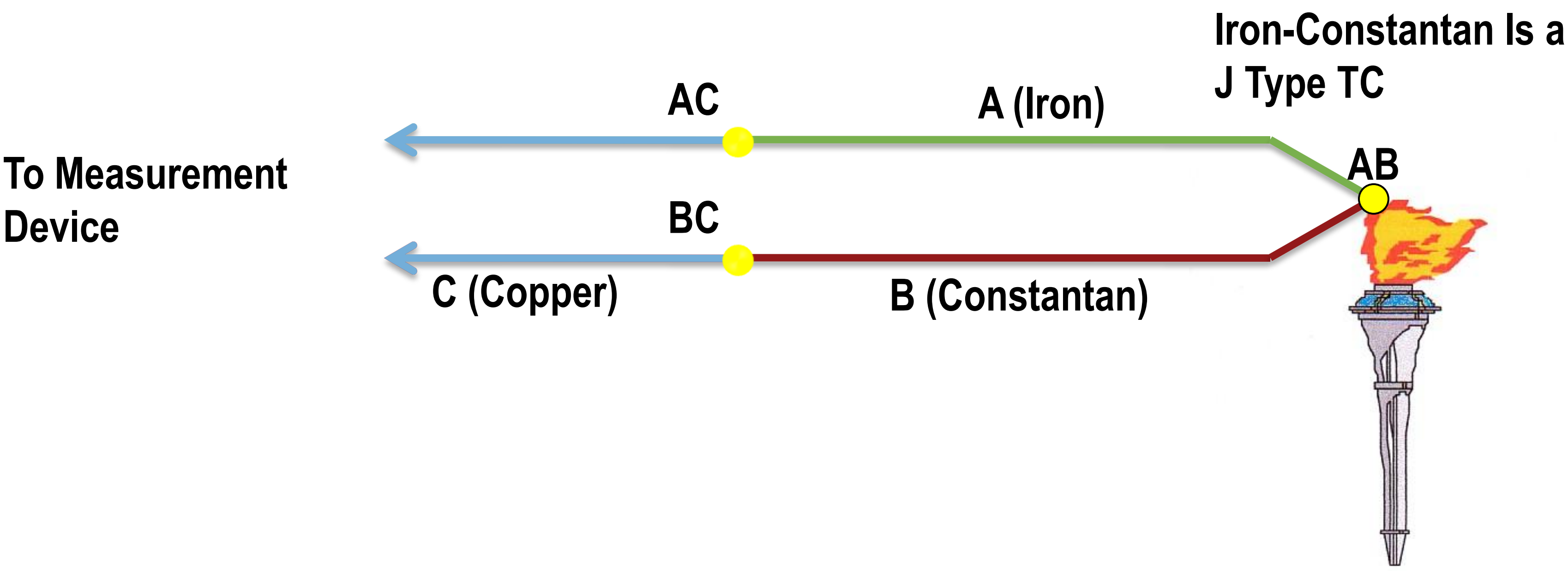
1. Cold-Junction Compensation
2. Noise
3. Device Offset
4. Thermocouple

# Achieve High Accuracy by Minimizing Sources of Error

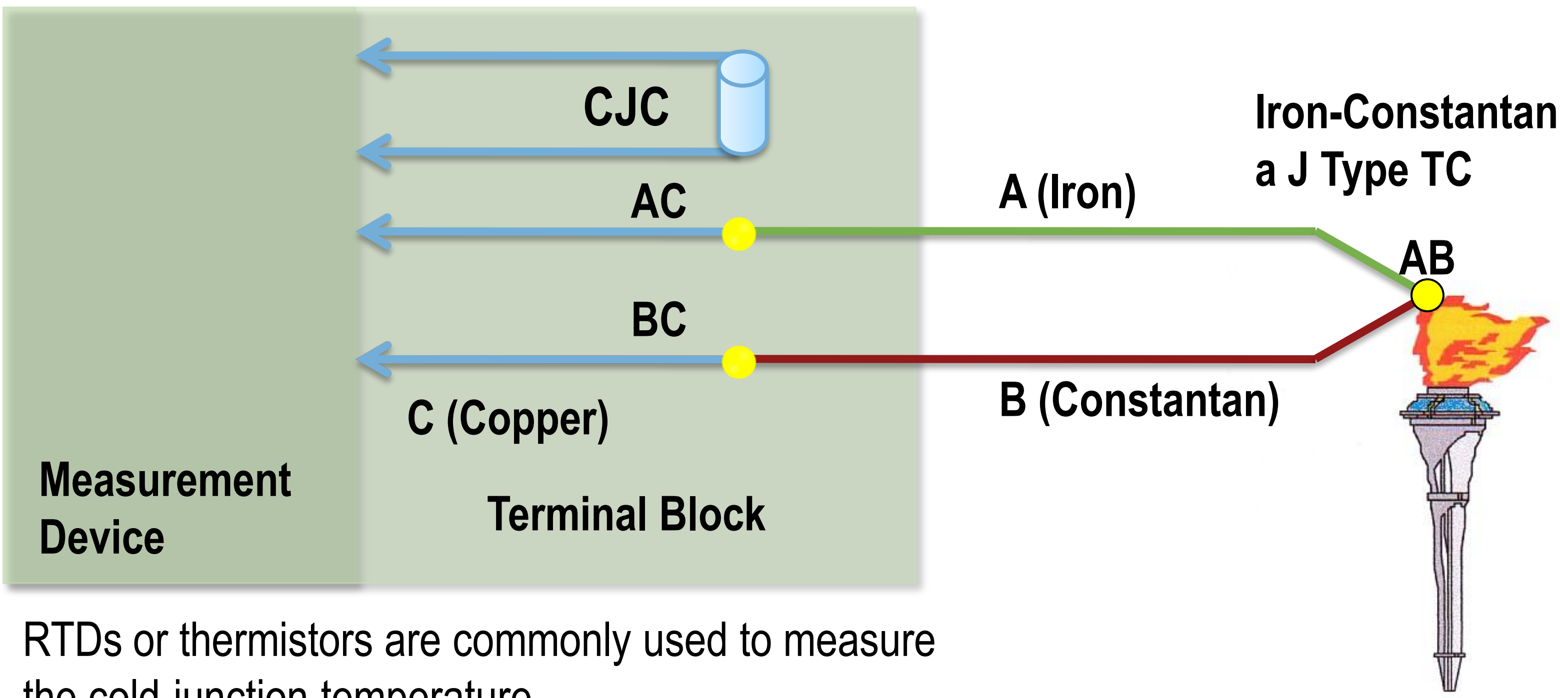
1. **Cold-Junction Compensation**
2. Noise
3. Device Offset
4. Thermocouple

# Cold-Junction Compensation

- AB is measuring temperature
- AC and BC generate another voltage
- Voltage at AC and BC are required to determine AB



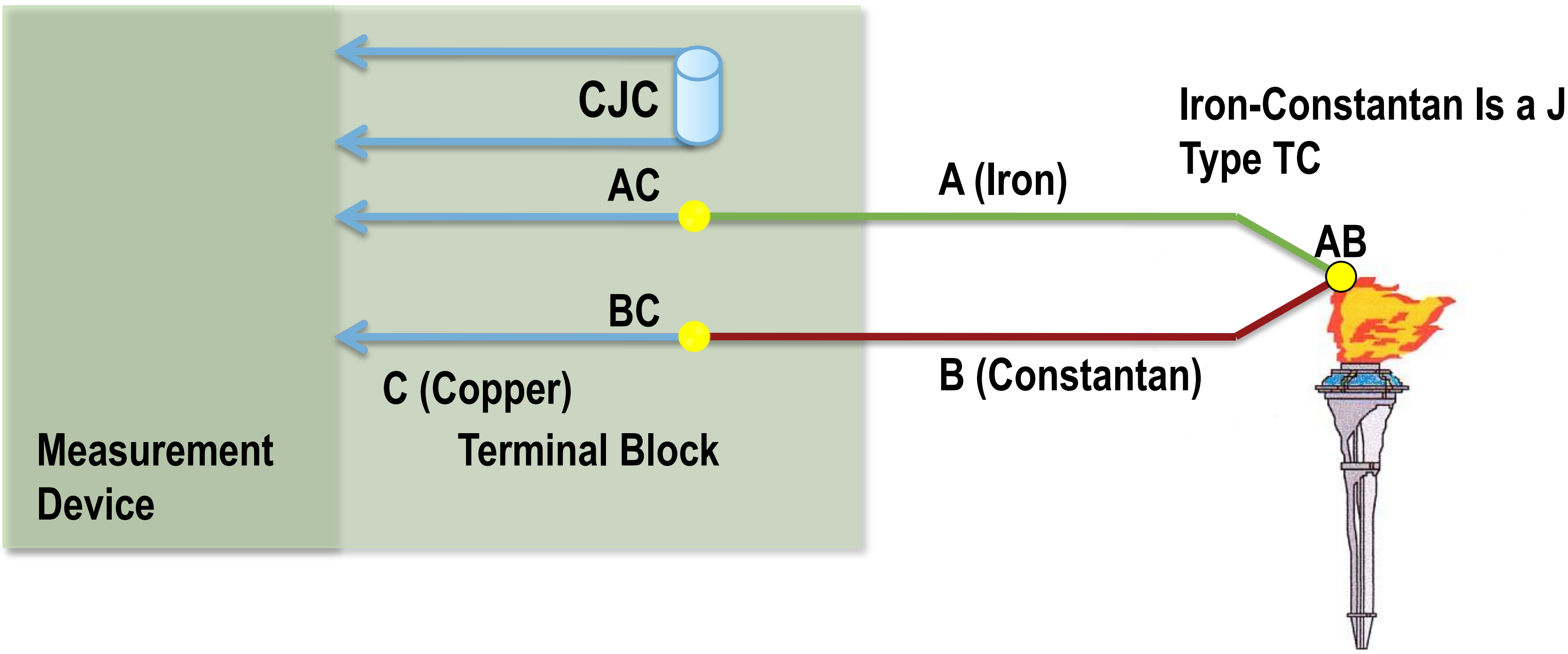
# Cold-Junction Compensation




RTDs or thermistors are commonly used to measure the cold-junction temperature

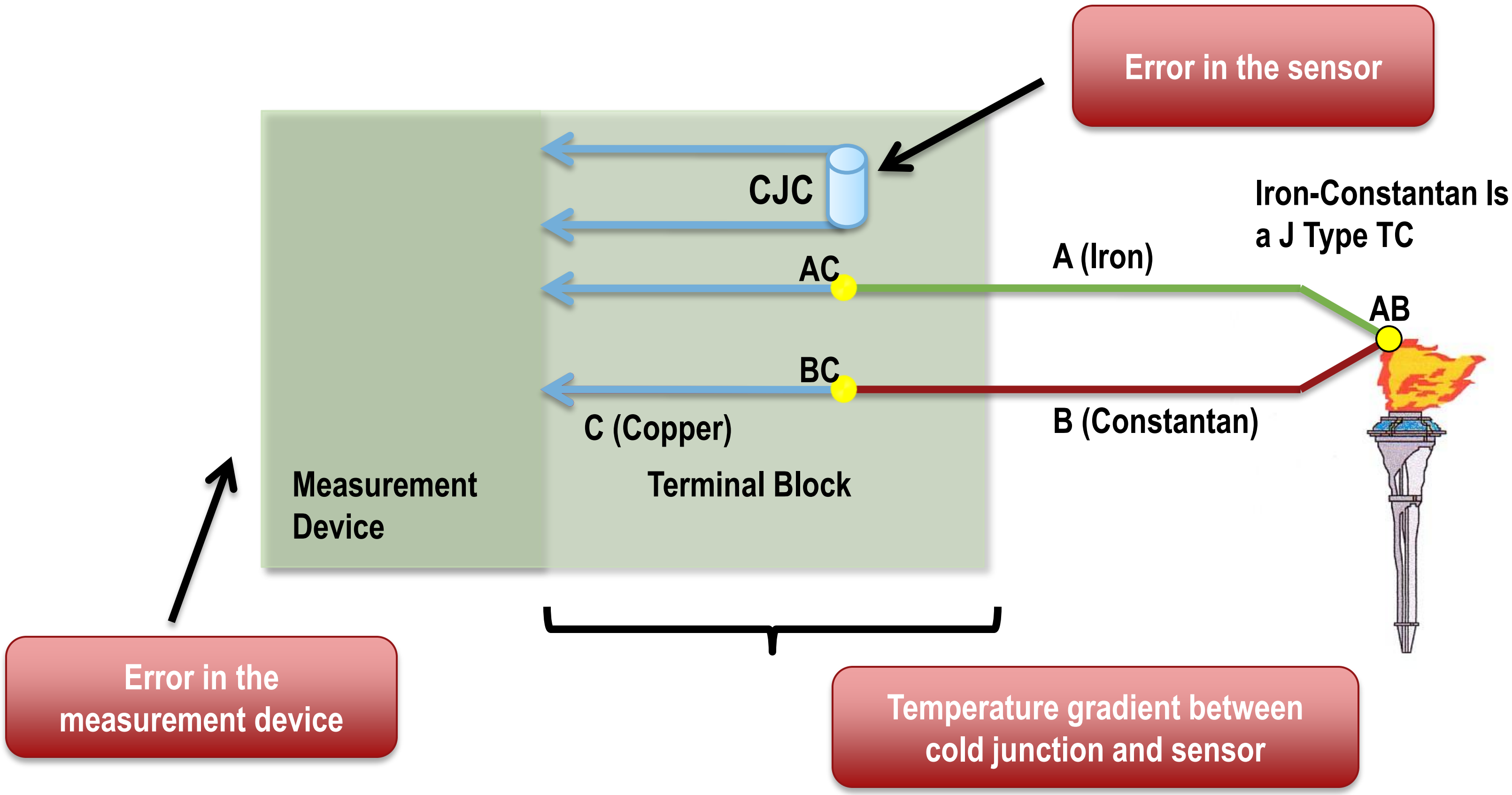
# Cold-Junction Compensation Error

- Difference between the actual temperature at the cold junction and the temperature measured by the device



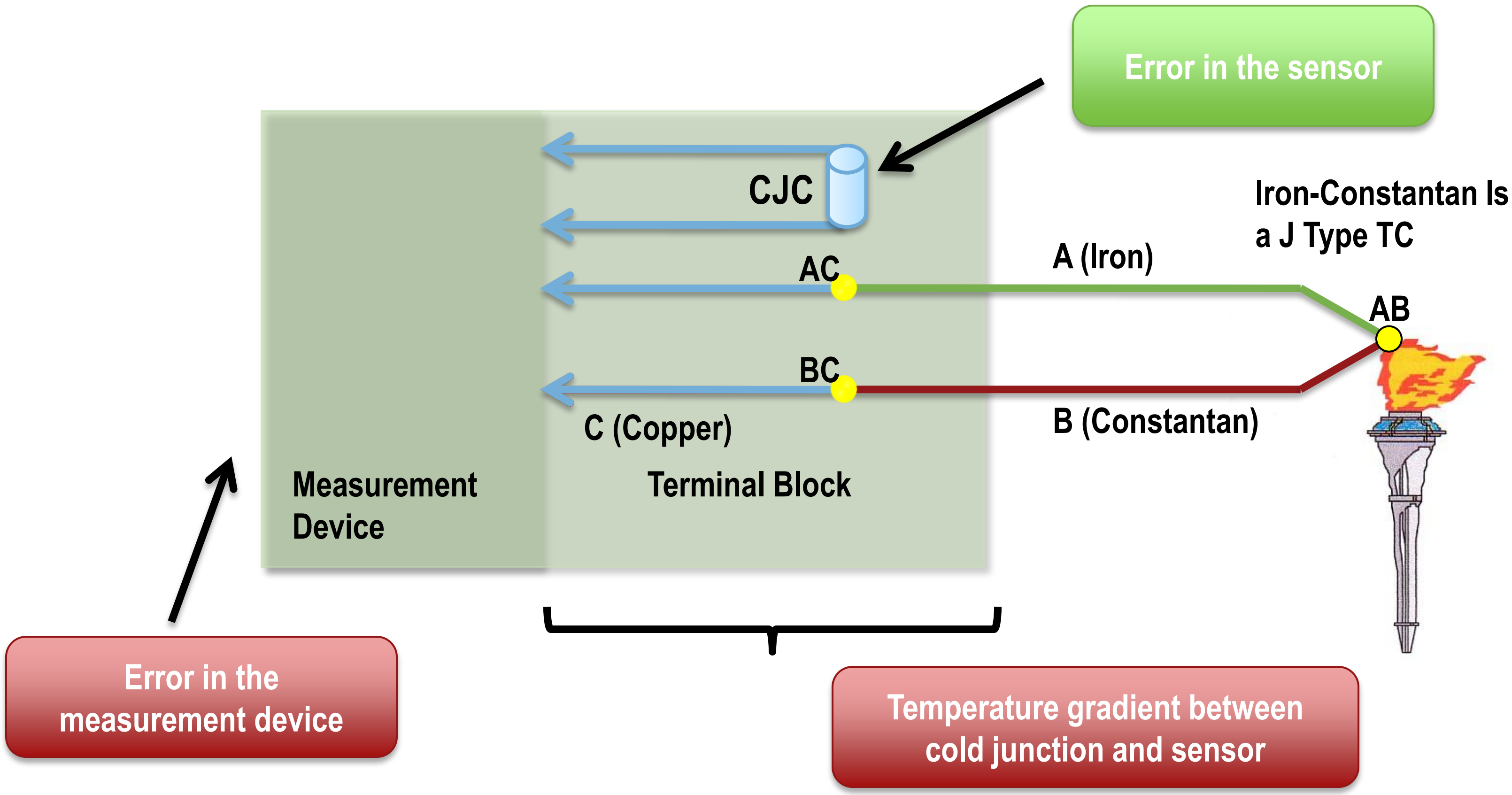
# Cold-Junction Compensation Error

- Difference between the actual temperature at the cold junction and the temperature measured by the device



# Cold-Junction Compensation Error

- Difference between the actual temperature at the cold junction and the temperature measured by the device



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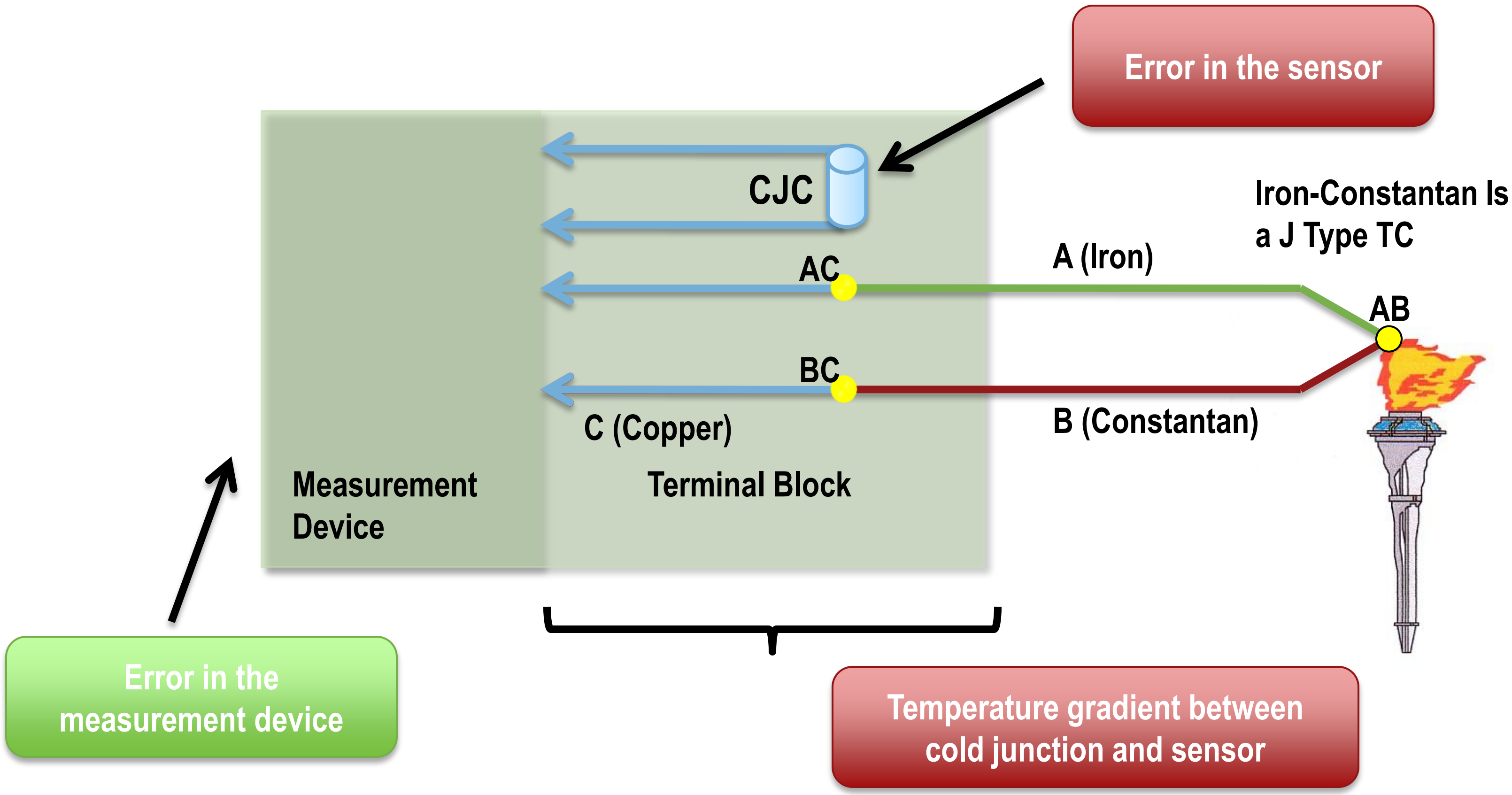
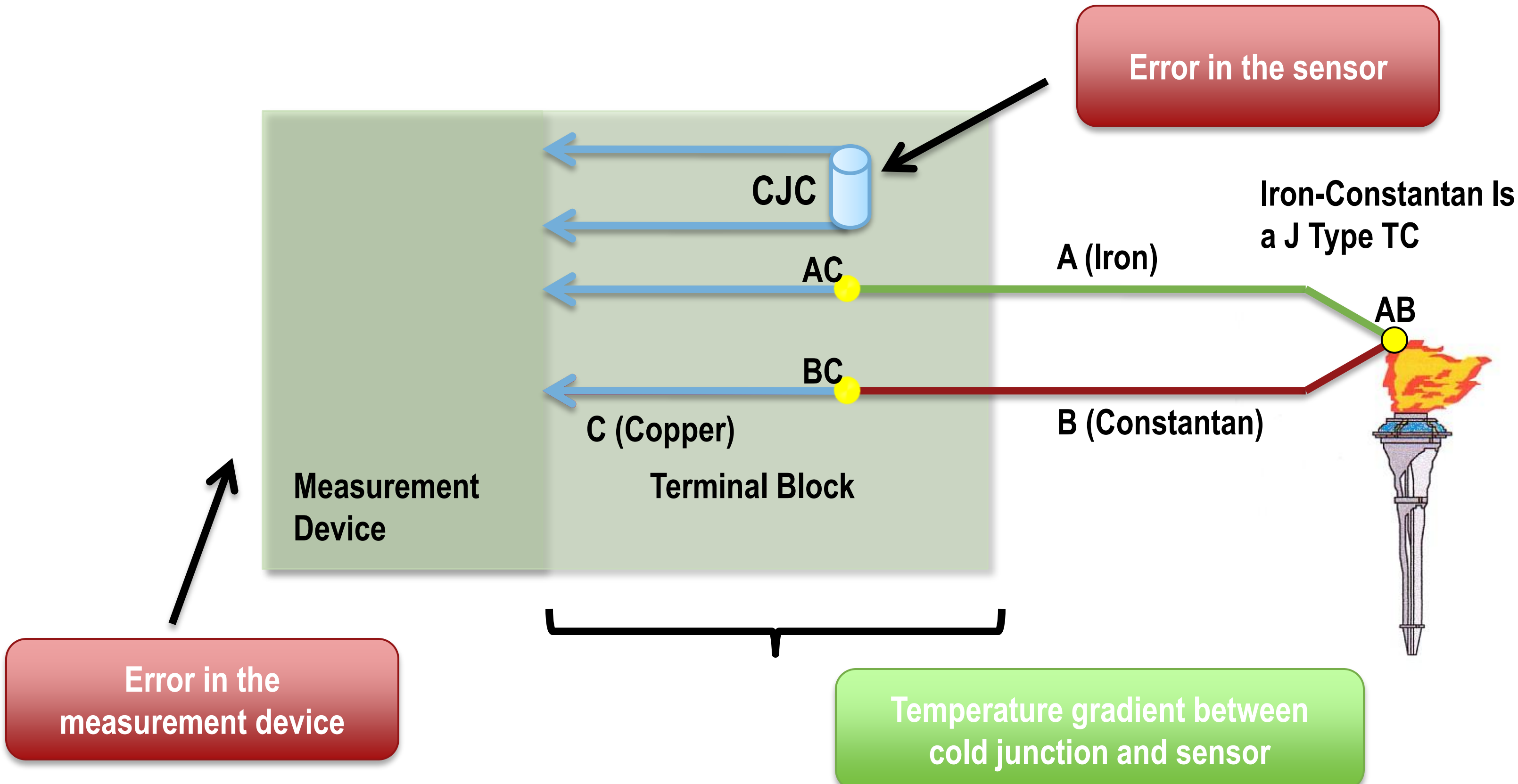
# Cold-Junction Compensation Error

- Difference between the actual temperature at the cold-junction and the temperature measured by the device

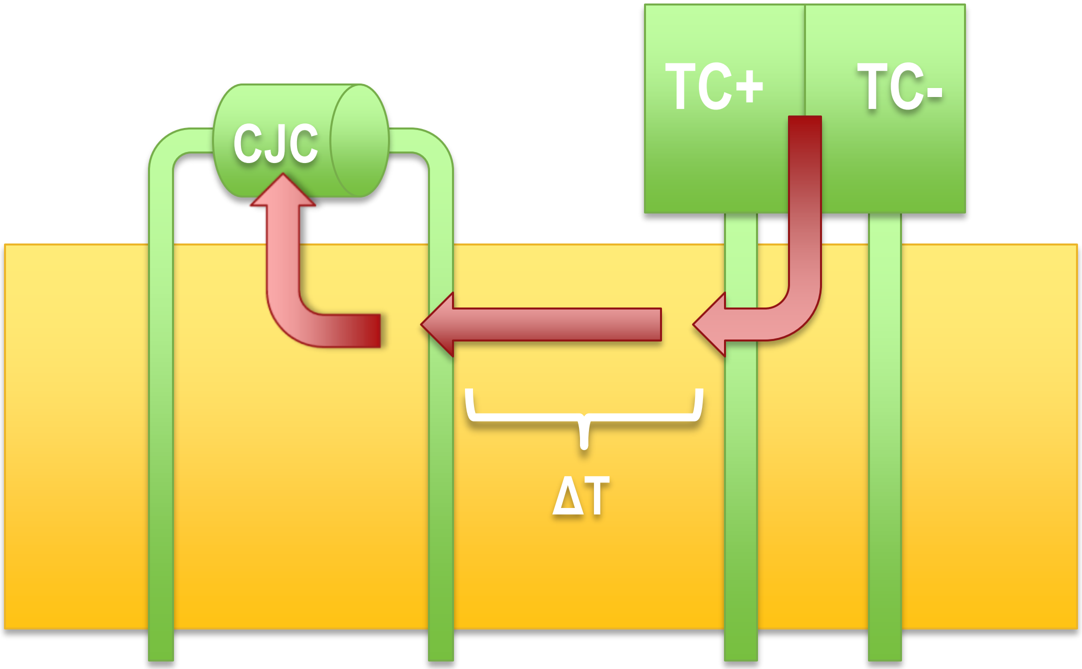


# Cold-Junction Compensation Error

- Difference between the actual temperature at the cold-junction and the temperature measured by the device

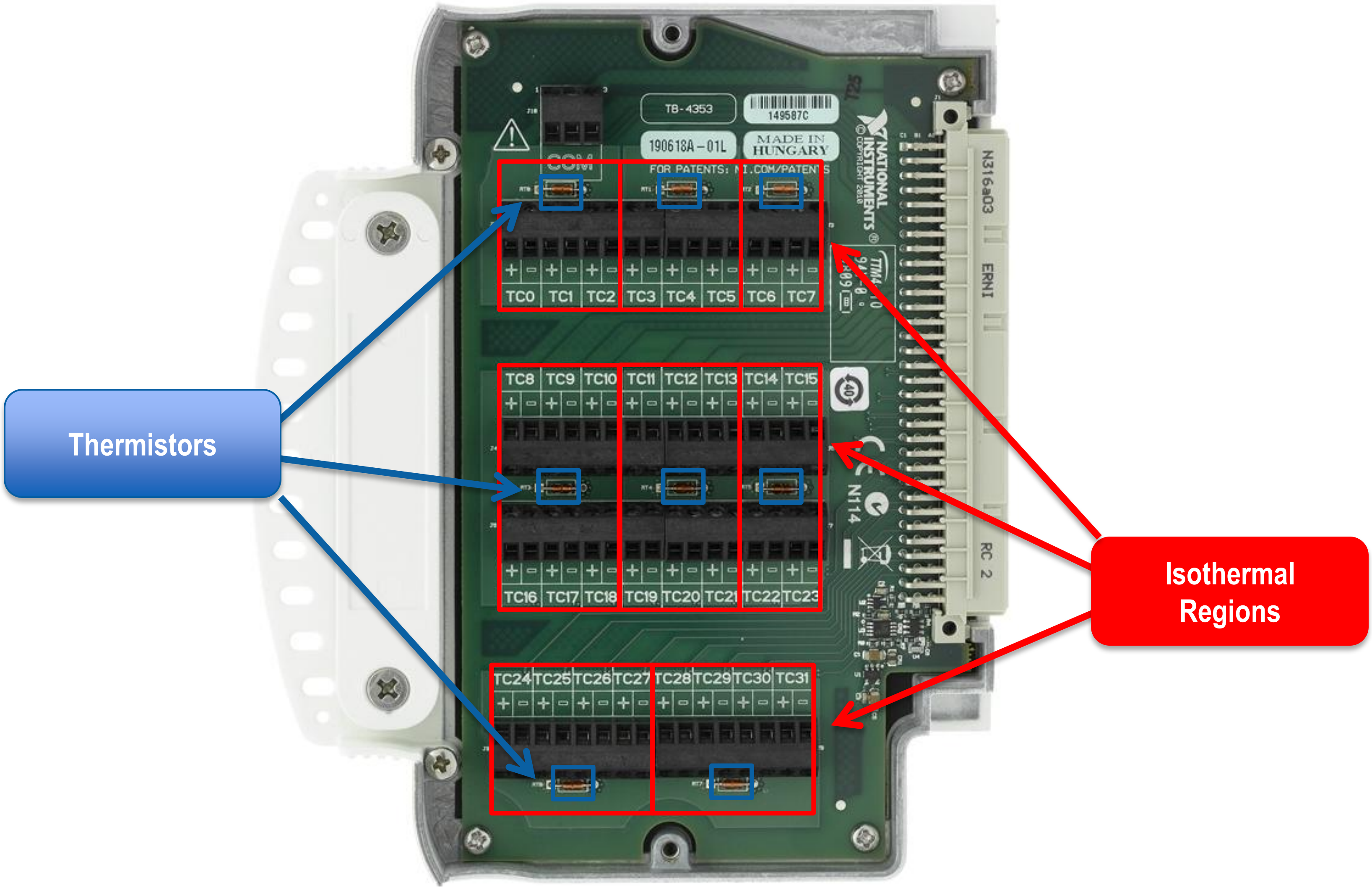


# Minimizing Isothermal Error: Design




Temperature difference between the actual temperature at the cold junction and the temperature at the thermistor

- CJC thermally connected to thermocouple terminals
- CJC as close as possible to thermocouple terminals
- Low ratio of channels to CJC sensors




NI PXIe-4353 High-Accuracy Thermocouple Module

# Minimizing Isothermal Error: Setup

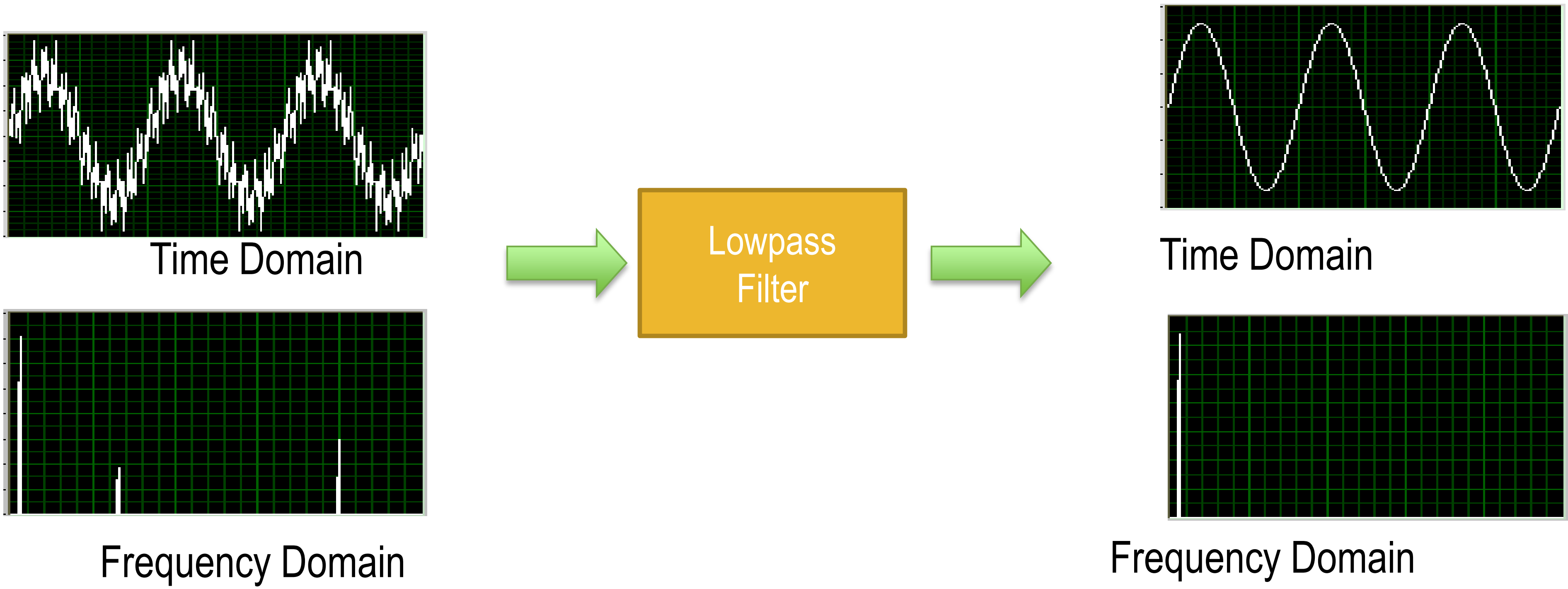
- ✓ Keep the ambient temperature as stable as possible
- ✓ Keep the measurement device in a stable and consistent orientation
- ✓ Minimize adjacent heat sources and airflow across the measurement device
- ✓ Avoid running thermocouple wires near hot or cold objects
- ✓ Run thermocouple wiring together near the measurement device
- ✓ Allow thermal gradients to settle after temperature change in system power or in ambient temperature
- ✓ Use the smallest gauge thermocouple wire suitable for the application
- ✓ Only use extension wires that are made of the same conductive material as the thermocouple wires

# Achieve High Accuracy by Minimizing Sources of Error

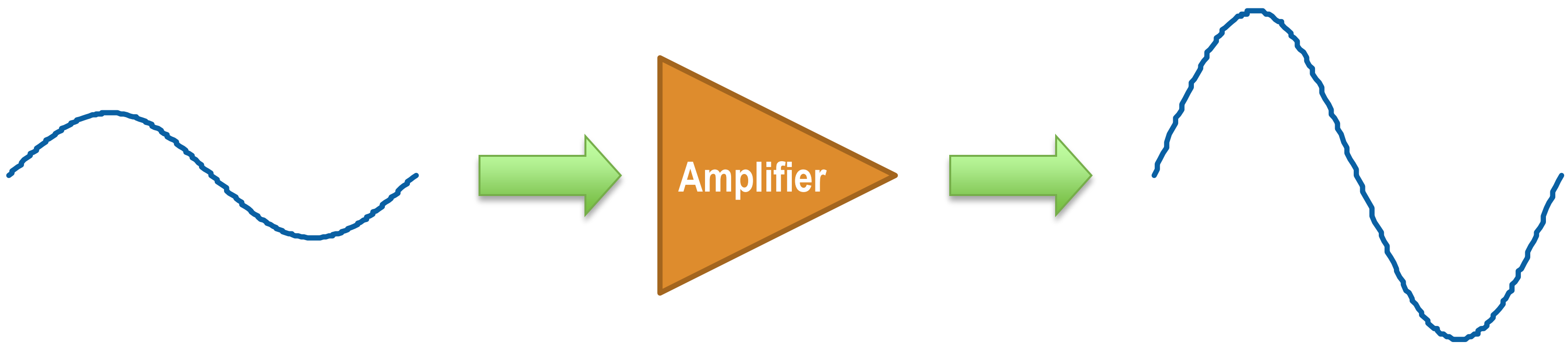
1. Cold-Junction Compensation
2. **Noise**
3. Device Offset
4. Thermocouple

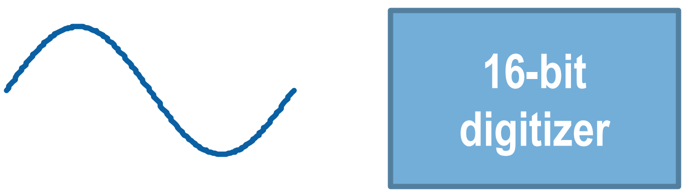
# Lowpass Filtering Removes Noise

- Rejects unwanted noise within a certain frequency range
- Implemented in software or hardware



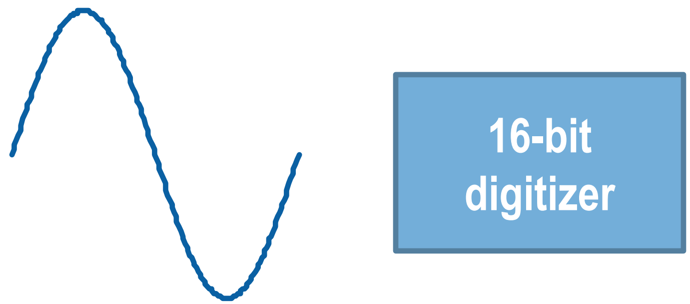
# Amplification Increases Resolution




10 mV
signal

Four levels
of resolution
(2 bits)




10 V
signal

65,536 levels
of resolution
(16 bits)



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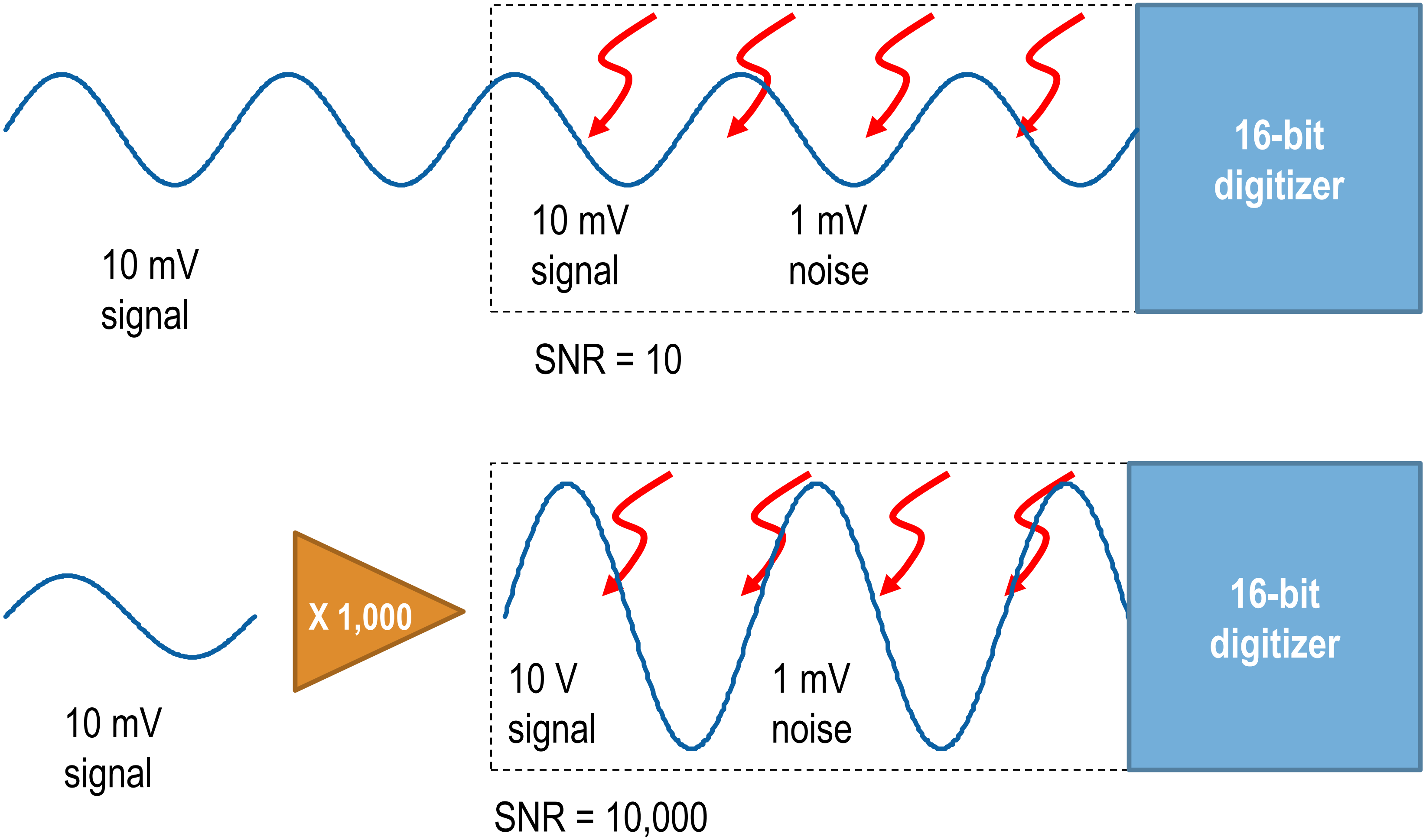
# Amplification Increases SNR



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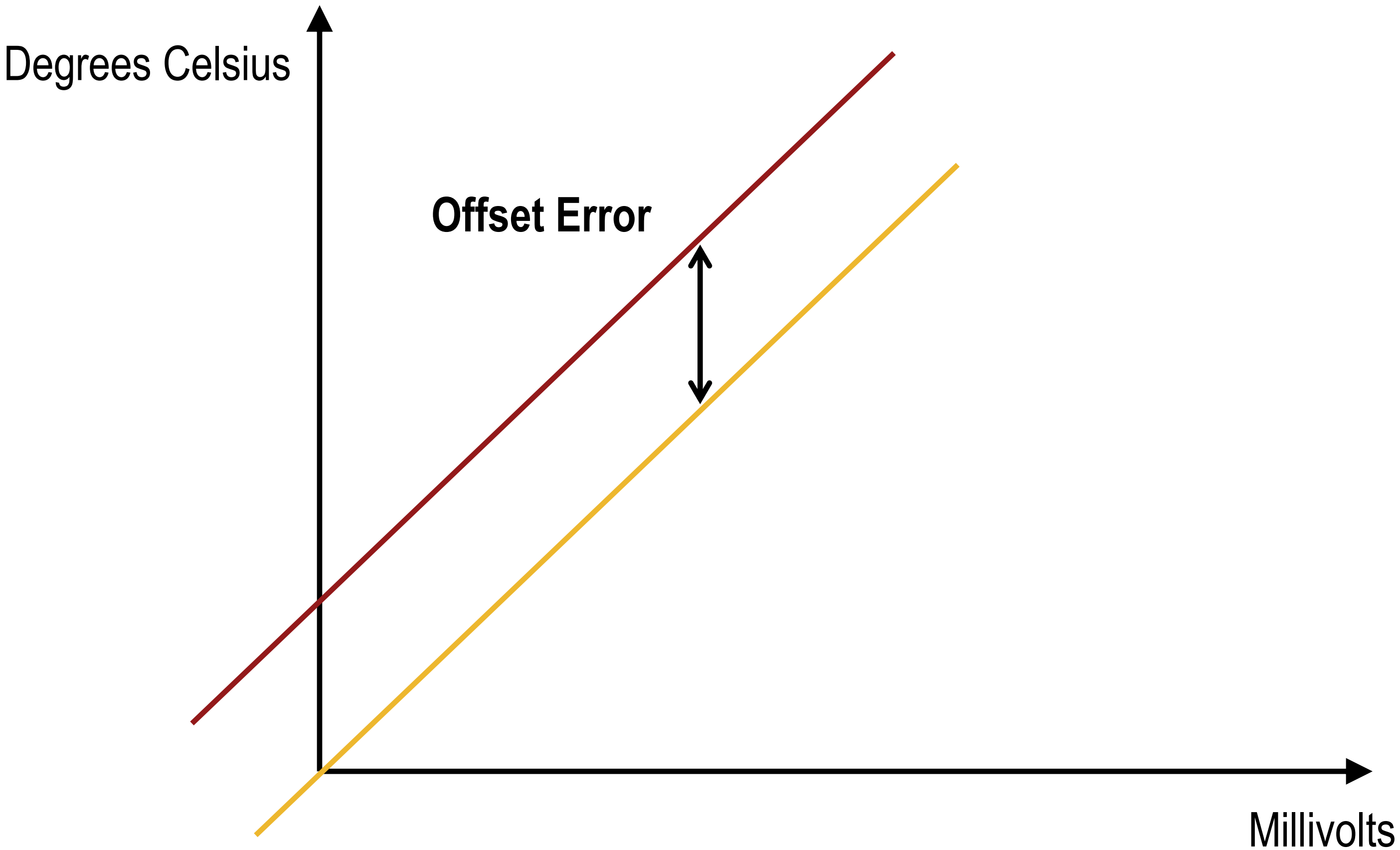
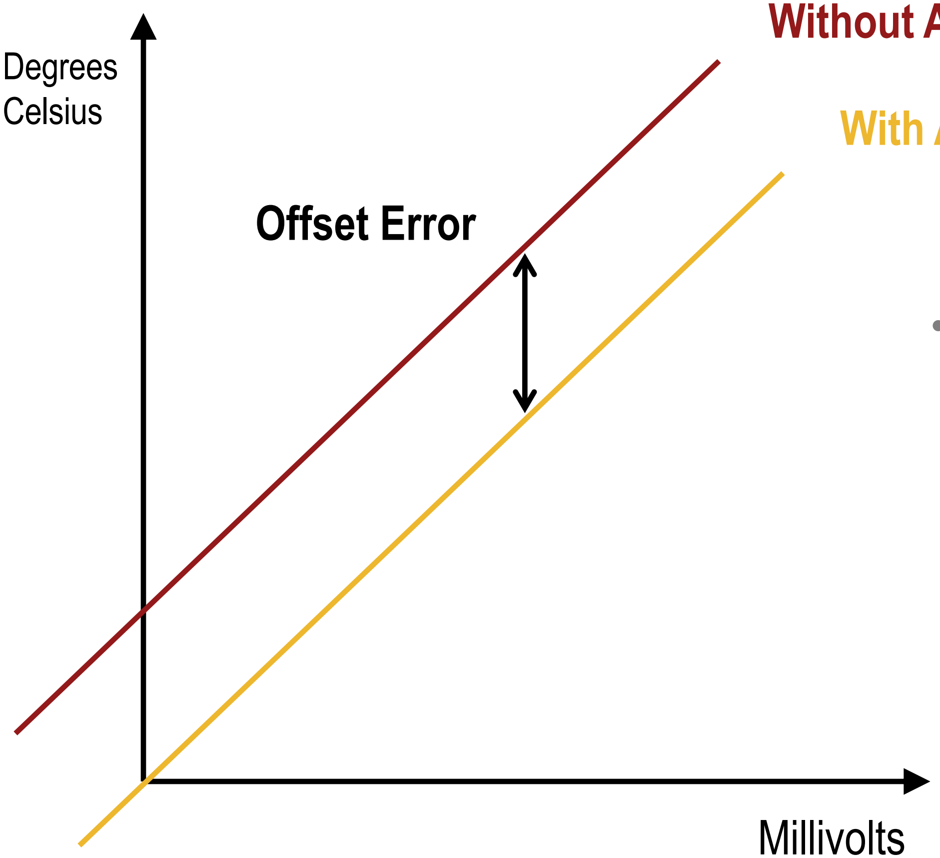
# Achieve High Accuracy by Minimizing Sources of Error

1. Cold-Junction Compensation
2. Noise
3. **Device Offset**
4. Thermocouple

# Device Offset Error

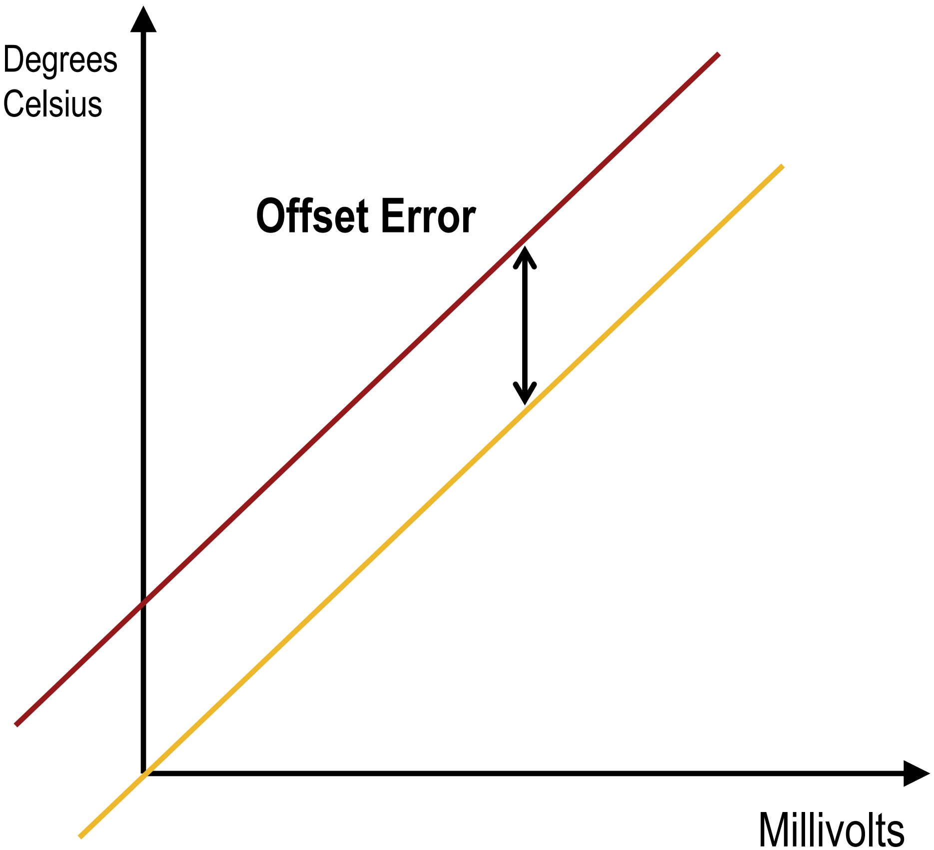


# Compensate for Device Offset




- Use built-in autozero feature
  - Measures internal offset automatically
  - Reduces the offset error and drift to negligible levels

# Compensate for Device Offset




- Be aware of offset error contribution to overall accuracy
- Ensure that device is regularly calibrated

# Achieve High Accuracy by Minimizing Sources of Error

1. Cold-Junction Compensation
2. Noise
3. Device Offset
4. **Thermocouple**

# Thermocouple Errors

$\Delta T$

- Gradient across the thermocouple wire can introduce errors due to impurities in the metals

$\Delta T$ Measured voltage $\propto$

# NI Solutions for Thermocouples

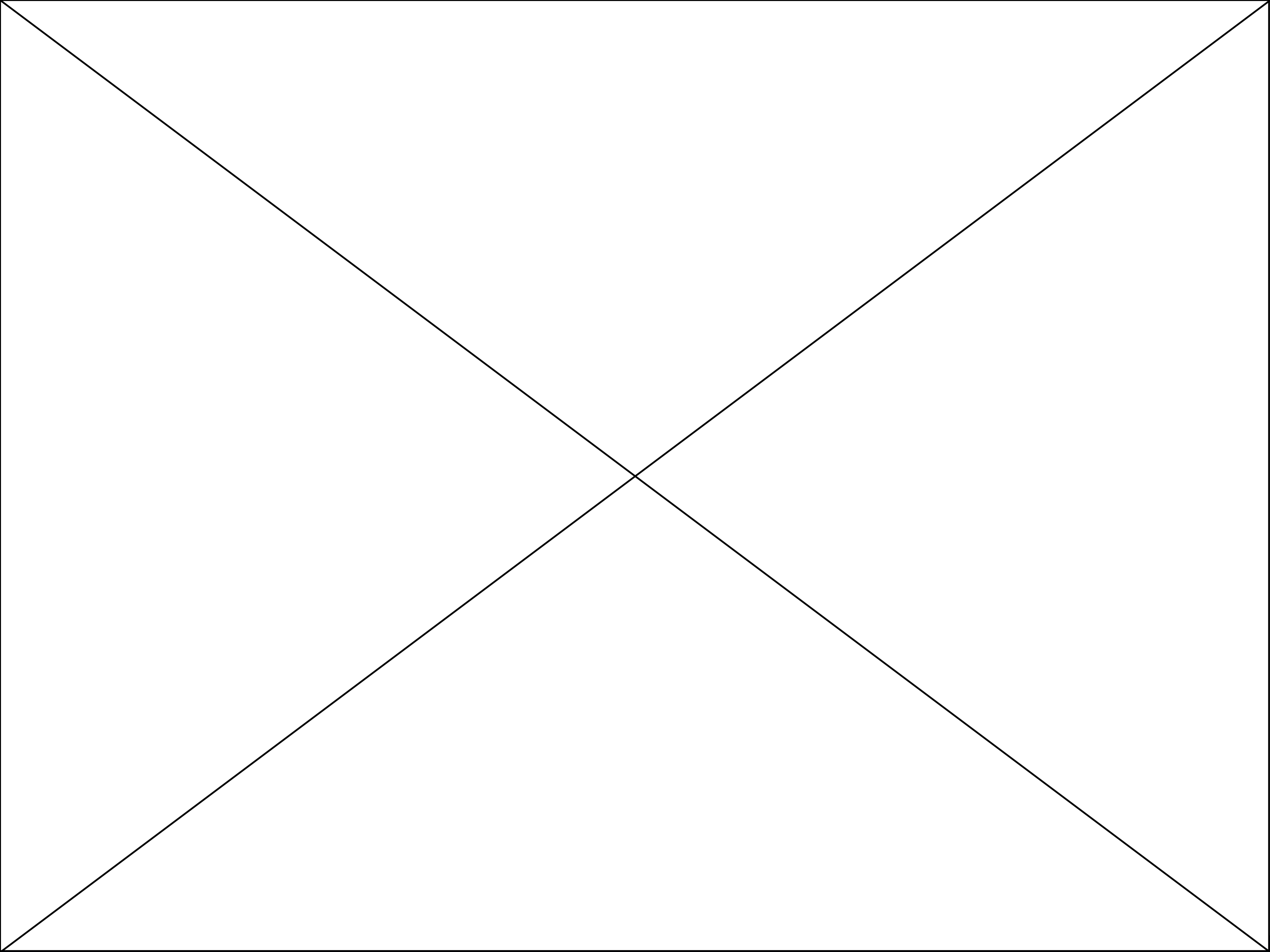
NI SC Express


NI USB-TC01: single-channel


NI CompactDAQ

NI CompactRIO

# Hardware Demonstration

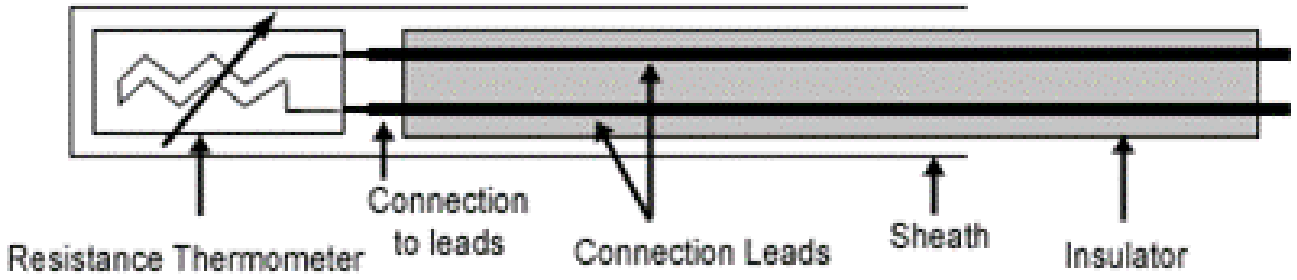


# Choose the Right Temperature Sensor

| Thermocouples | RTDs | Thermistors |
|---|---|---|
|  |  |  |
| + Self-powered | + High accuracy | + High resistance |
| + Inexpensive | + High stability | + High sensitivity |
| + Rugged | | + Low thermal mass |
| + Temperature range | | |
| - Low voltage | - Expensive | - Highly nonlinear output |
| - Requires CJC | - Requires current | - Limited operating range |
| - Variable accuracy | - Low resistance | - Requires current |
| | - Self-heating | - Self-heating |

# RTD—Resistance Temperature Detector

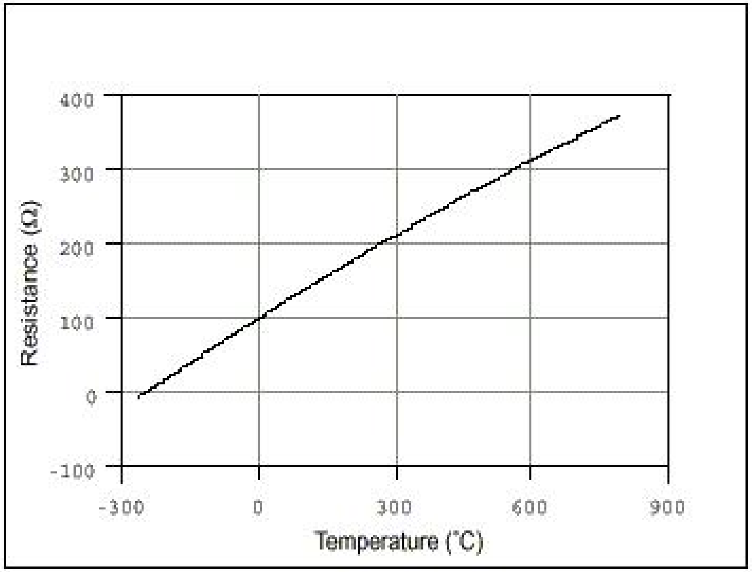
- Device made up of coils or films of metal (usually platinum)
- Typical resistance is 100 Ω at 0 °C
- Resistance varies with temperature; typical measurement range till 850 °C




Working Principle: Passing current through an RTD generates a voltage across the RTD. By measuring this voltage, you can determine its resistance and, thus, its temperature.

# RTD Fundamentals

- Resistance of an RTD is nearly α temperature
- Materials used—nickel and copper, but platinum is the most common because of its wide range, stability, and accuracy. A 100 Ω platinum RTD is commonly referred to as Pt100.




Temperature—
Resistance Curve for Platinum RTDs

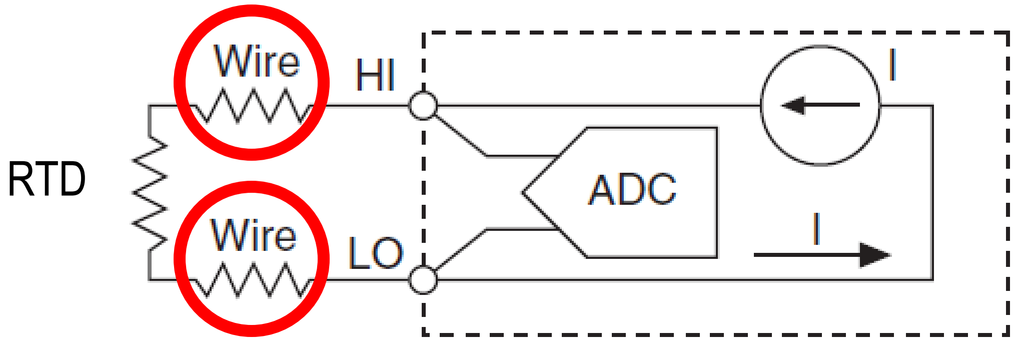
# Measuring Temperature With RTDs

- Step 1: Current excitation
- Step 2: Read voltage generated across the RTD's terminals
- Step 3: Convert voltage reading to temperature
- Tip: To avoid self-heating (resistive heating), minimize the excitation current as much as possible.

# 3 Ways to Connect Your RTD

- 2-Wire Mode
- 3-Wire Mode
- 4-Wire Mode

# 2-Wire Mode



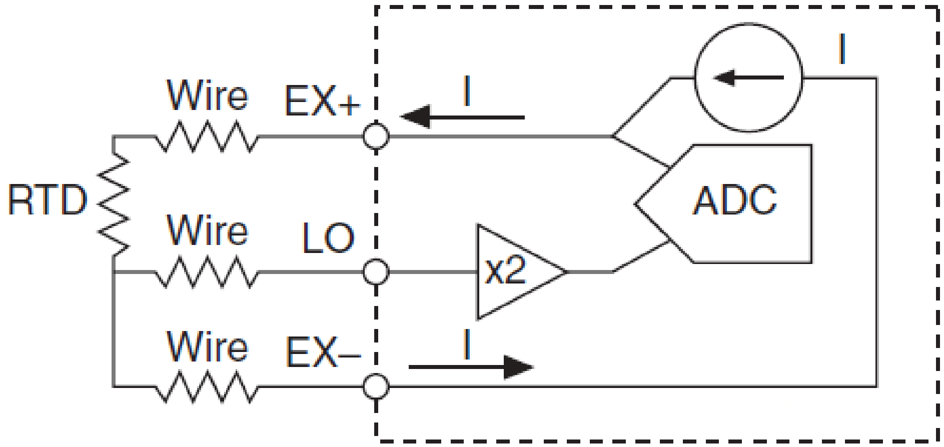

- The DAQ device typically sources the excitation current
- If not, use jumpers to short the excitation and channel pins together

- *Disadvantage: No compensation for lead-wire resistance.*

# 3 Ways to Connect Your RTD

- 2-Wire Mode
- 3-Wire Mode
- 4-Wire Mode

# 3-Wire Mode

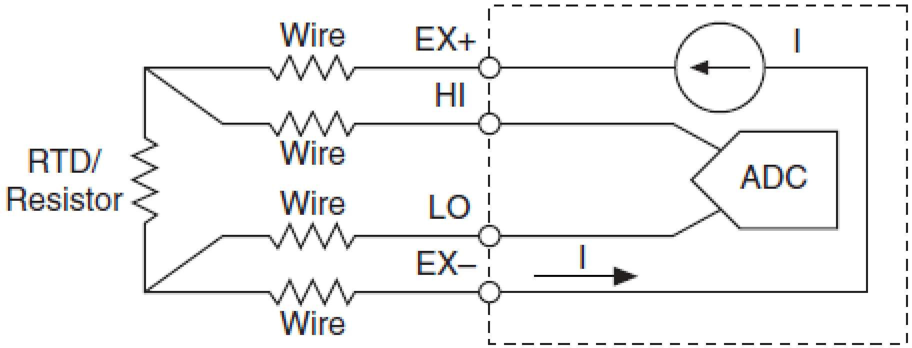



- Temperature measured between EX+ and LO
- Lead wire resistances compensated for *if they are the same for all three wires*
- Gain applied to voltage across negative lead wire as reference to cancel resistance error

# 3 Ways to Connect Your RTD

- 2-Wire Mode
- 3-Wire Mode
- 4-Wire Mode

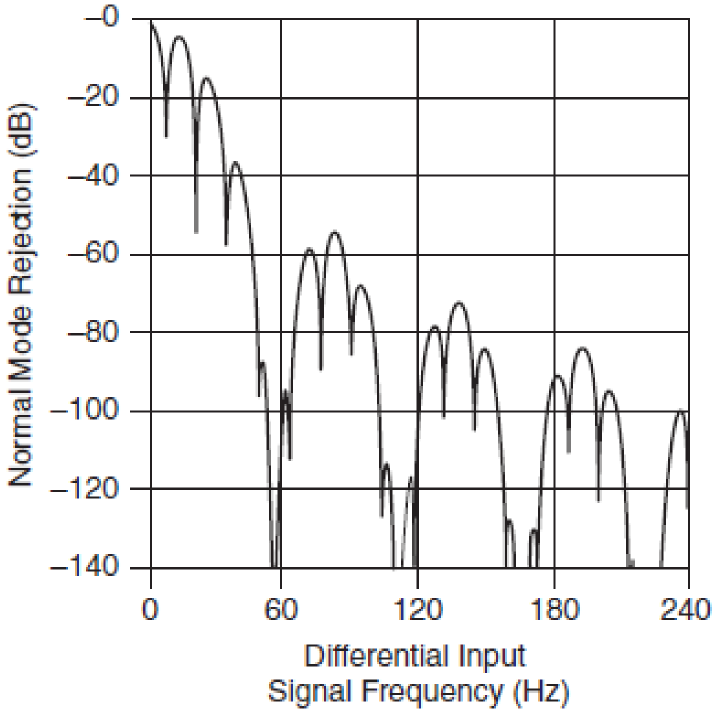
# 4-Wire Mode




- Lead wire resistance does not affect this mode because a negligible amount of current flows across the HI and LO terminals
- *Thus most accurate RTD measurements are obtained using this mode*

# RTD Noise Considerations

- Filtering is required to remove the effect of noise arising due to the power line in lab and industry settings.



# Choose the Right Temperature Sensor

## Thermocouples

+ Self-powered
+ Inexpensive
+ Rugged
+ Temperature range

- Low voltage
- Requires CJC
- Variable accuracy

## RTDs

+ High accuracy
+ High stability

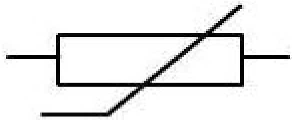
- Expensive
- Requires current
- Low resistance
- Self-heating

## Thermistors

+ High resistance
+ High sensitivity
+ Low thermal mass

- Highly nonlinear output
- Limited operating range
- Requires current
- Self-heating

# What Is a Thermistor?



- Thermally sensitive devices whose resistance varies with temperature
- Made from metal-oxide semiconductors
- 2000 Ω to 10000 Ω at 25 °C
- Up to 300 °C—ideal for low-temperature applications
- Extremely sensitive:  (~200 Ω/°C)
- Thermistors with negative temperature coefficients (NTCs) are normally used

# Thermistor Versus RTD

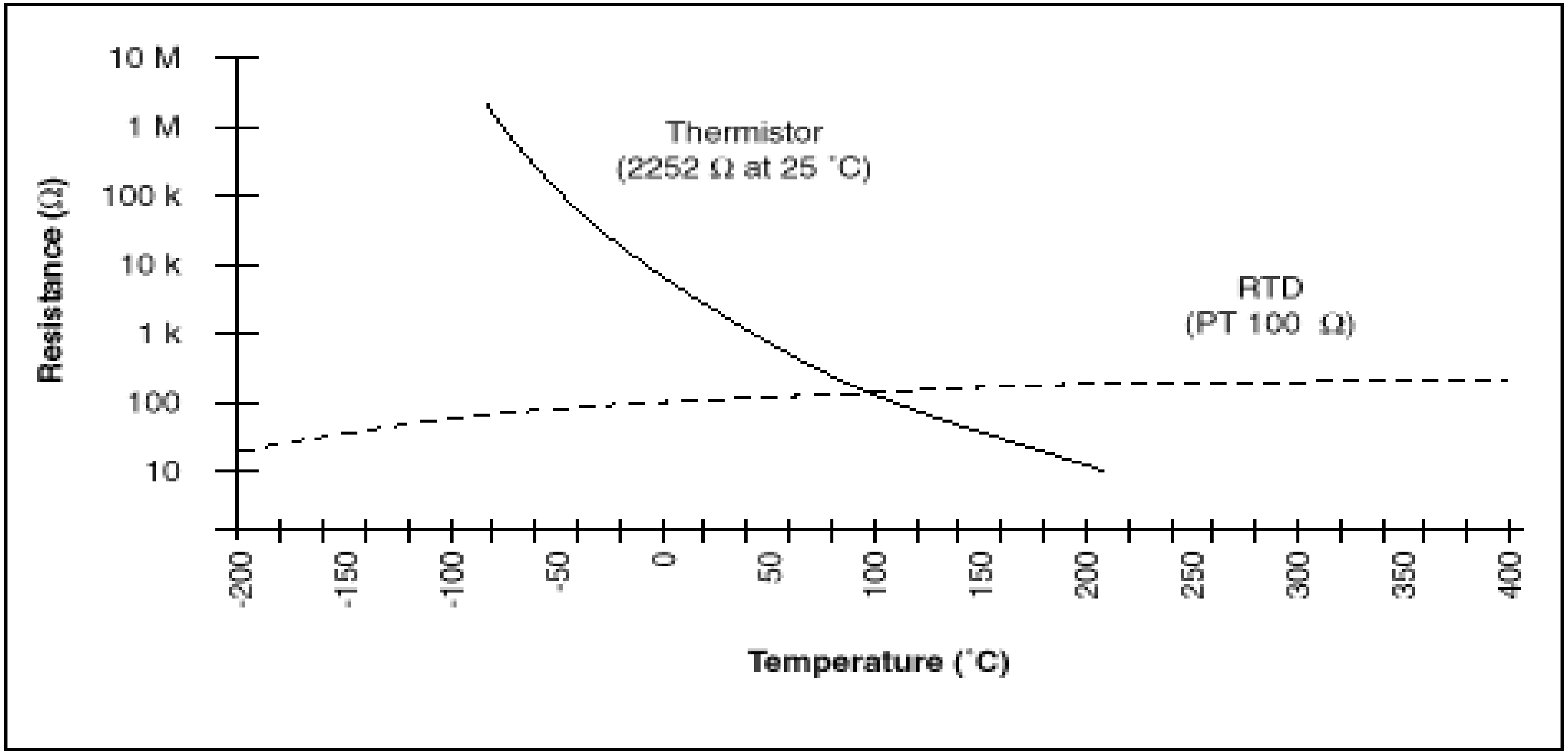
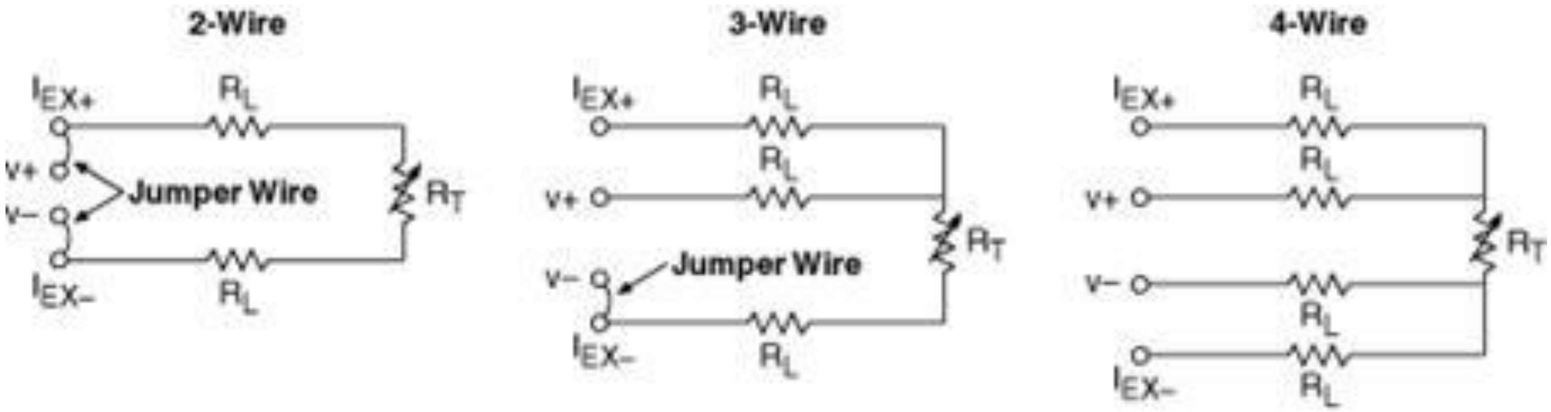



Figure 1. Resistance-Temperature Curve of a Thermistor

# How to Measure Temperature Using a Thermistor

A thermistor measurement is very similar to RTD measurements because they operate on similar principles.



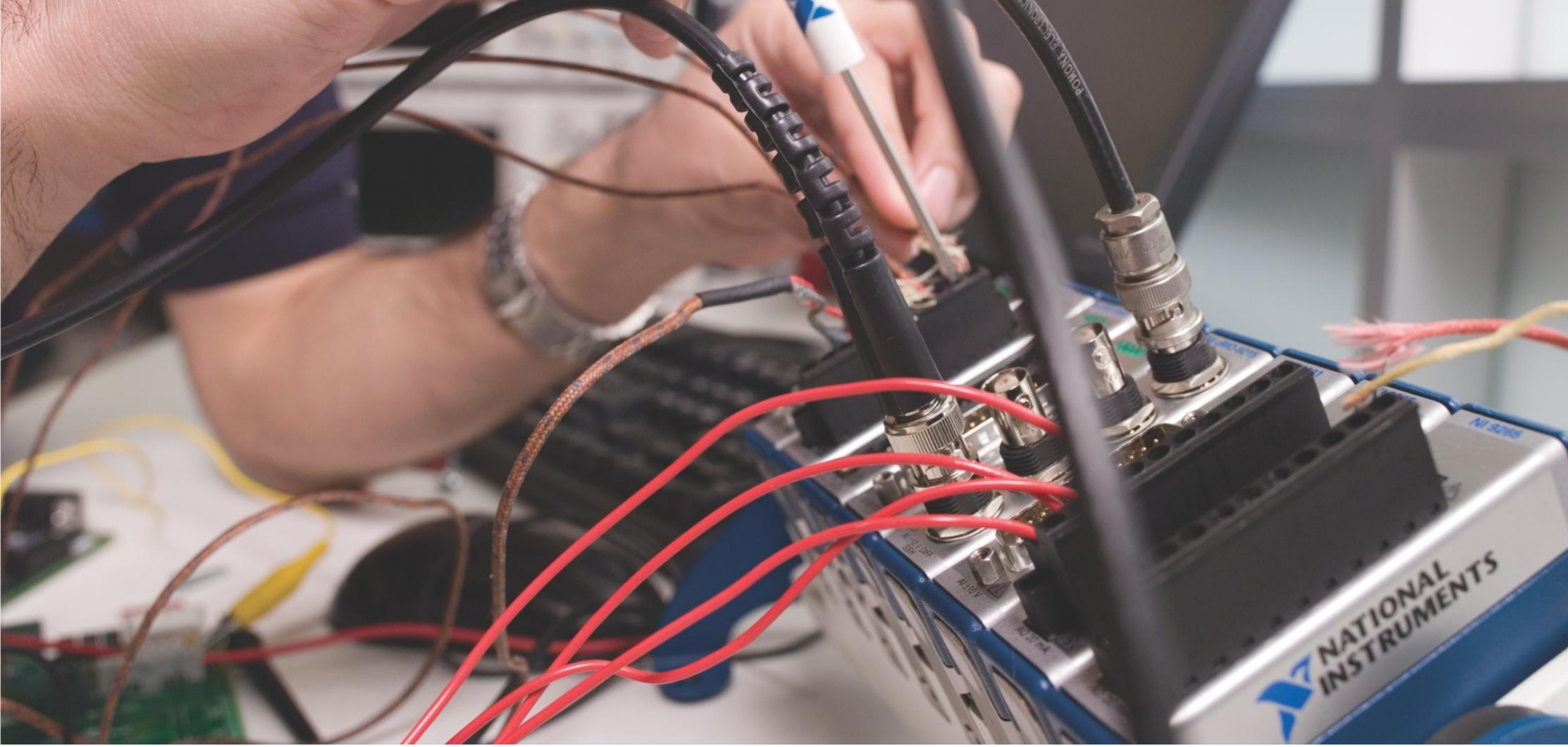

**2-, 3-, and 4-Wire Connection Diagrams**

# Achieve High Accuracy With Thermistors

- Very accurate and stable due to high nominal resistance
- High resistance/sensitivity
- Low thermal mass
- Relatively recent standardization among vendors
- Require current source
- Self-heating

# Technologies Behind NI Temperature Acquisition

- 24-bit resolution
- Amplification
- Multiple cold-junction-compensation channels
- Hardware/software lowpass filtering and 50/60 Hz noise rejection
- Open thermocouple detection
- Differential input channels
- Unlimited expansion capabilities




ni.com/temperature