Lesson 7
Signal Conditioning

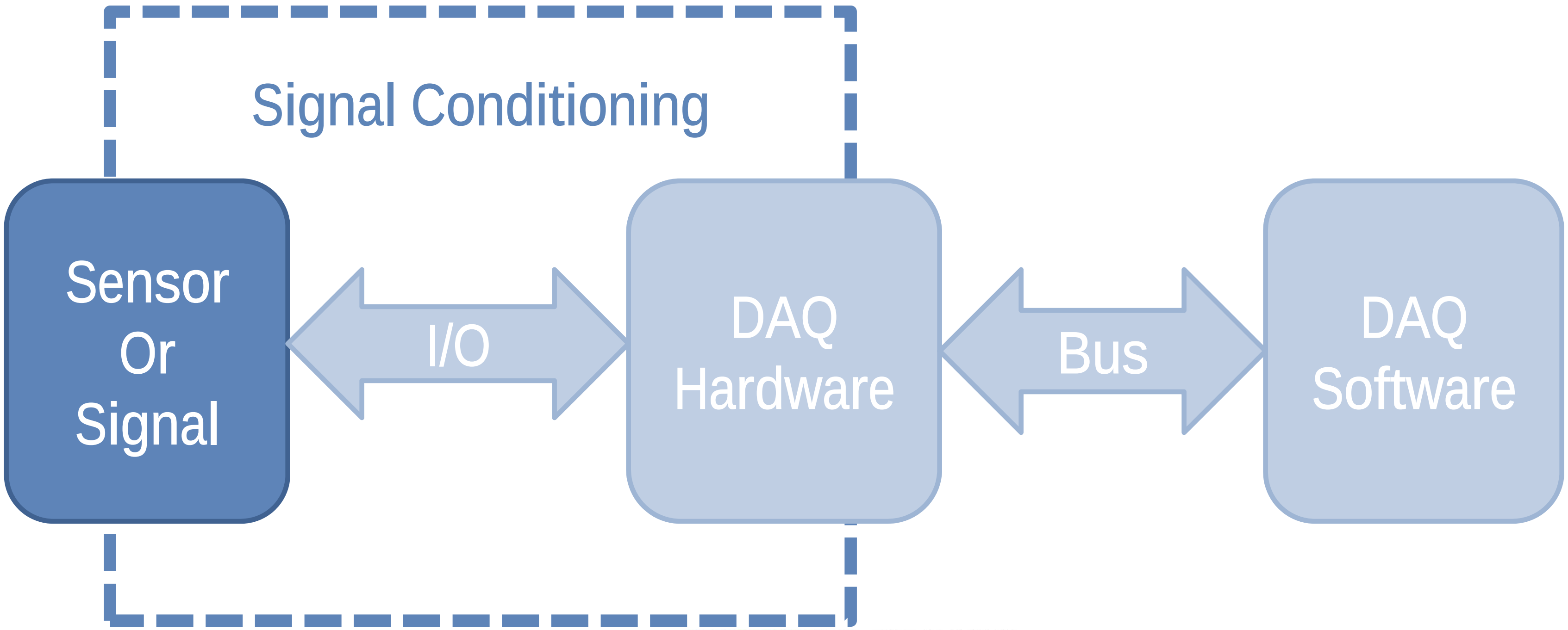
TOPICS

A. Overview of Signal Conditioning
B. Signal Conditioning Systems
C. Signal Conditioning for Voltage Measurements
D. Temperature Measurements
E. Strain, Pressure, Load, and Torque Measurements
F. Sound and Vibration Measurements

Signal Conditioning Overview

Sensors and signals sometimes require signal conditioning before being they can be properly measured

- Different sensors require different signal conditioning

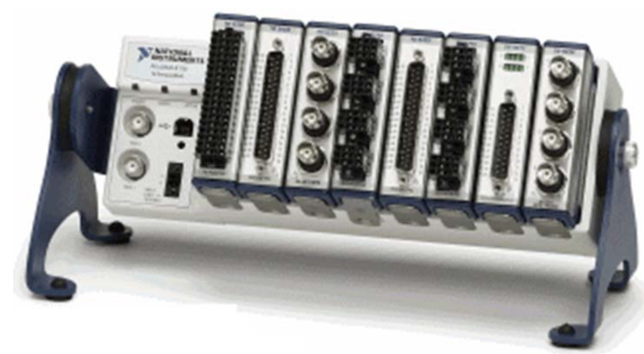


National Instruments
Signal Conditioning Systems

	Low to Medium Channel Count	High Channel Count
Integrated Signal Conditioning	 CompactDAQ	 PXI (SC Express, DSA)
Front End Signal Conditioning	 SCXI	

CompactDAQ – Integrated, Low to Medium Channel Count

- Connectors, signal conditioning, and DAQ integrated into chassis and modules
- Ideal for portable measurement systems
- Hot-swappable modules
- Up to 24-bit accuracy
- Input rates up to 500kS/s for analog
- Cross-platform devices
  - CompactRIO
  - CompactDAQ
  - USB sleeve



PXI Express – Integrated, High Channel Count

- Integrated signal conditioning for bridge, thermocouple, vibration, etc
- Dedicated bandwidth per device
- Up to 24-bit resolution
- Programmable gain and filter settings
- NIST-traceable calibration certificates
- >500 channels per chassis
- Device and multi-chassis synchronization using PXI platform

SCXI – Front-end, High Channel Count

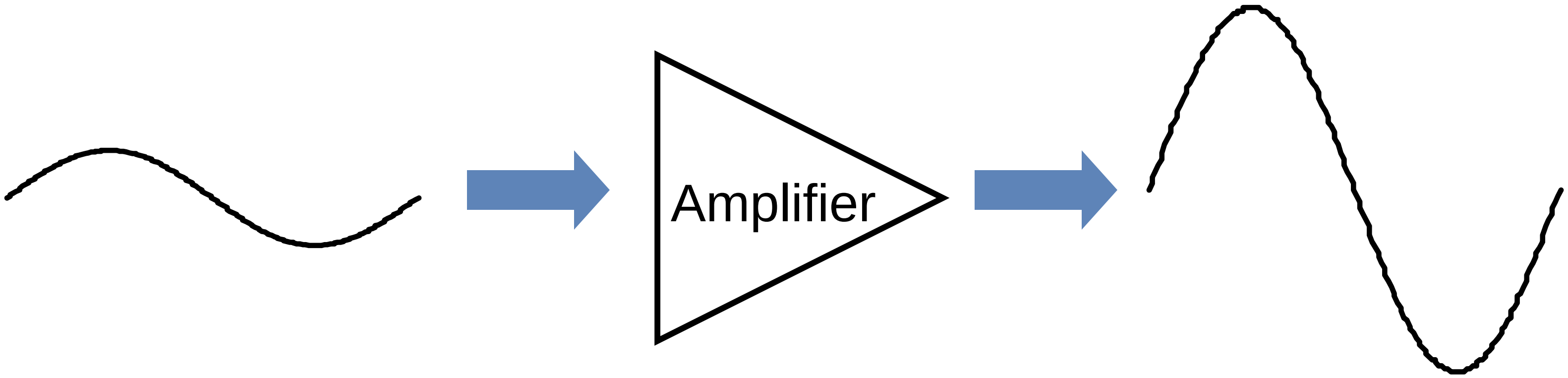
- Front-end signal conditioning platform for multifunction DAQ devices
- Multiplexer, matrix, and general-purpose switching
- Wide range of analog and digital conditioning options
- Reconfigurable desktop, rack-mount and portable solution
- Several chassis options; ideal for high channel-count systems

Signal Conditioning for Voltage Measurements

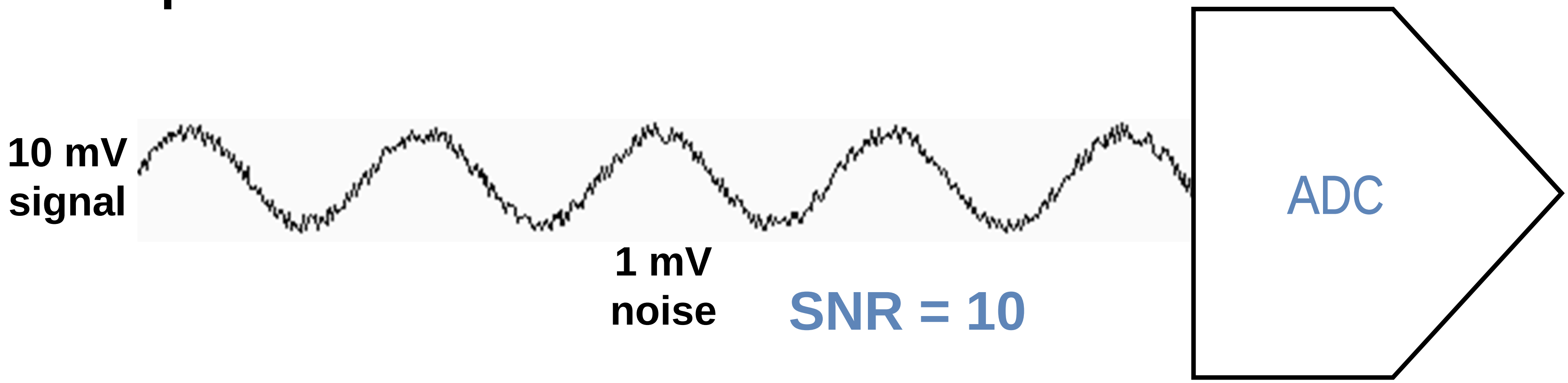
- Amplification
- Attenuation
- Isolation
- Filtering

Amplification

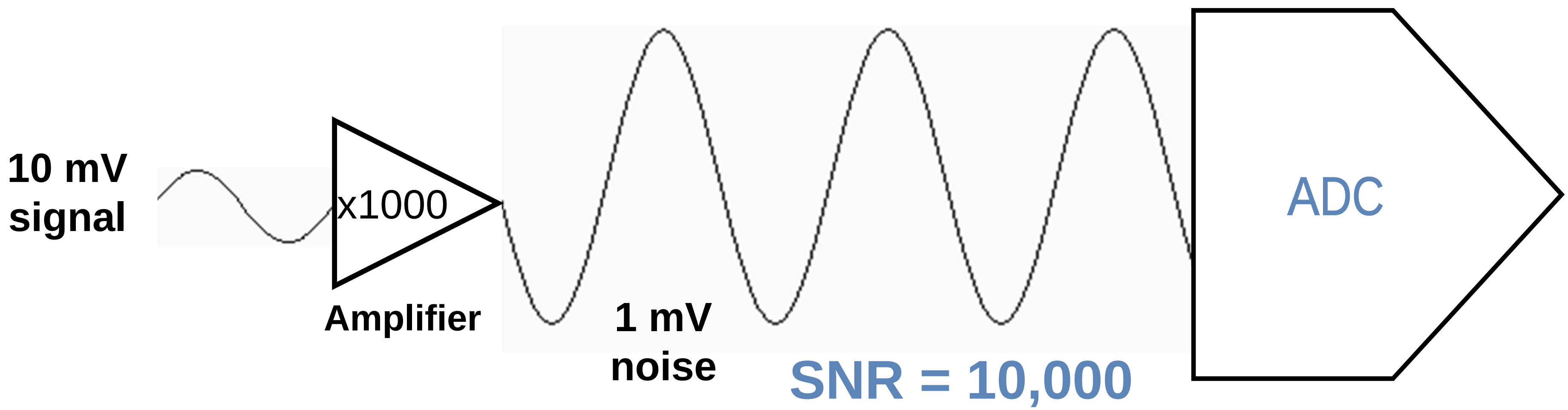
- Used on low-level signals
- Maximizes use of Analog-to-Digital Converter (ADC) range and increases accuracy
- Increases Signal-to-Noise Ratio (SNR)



Amplification

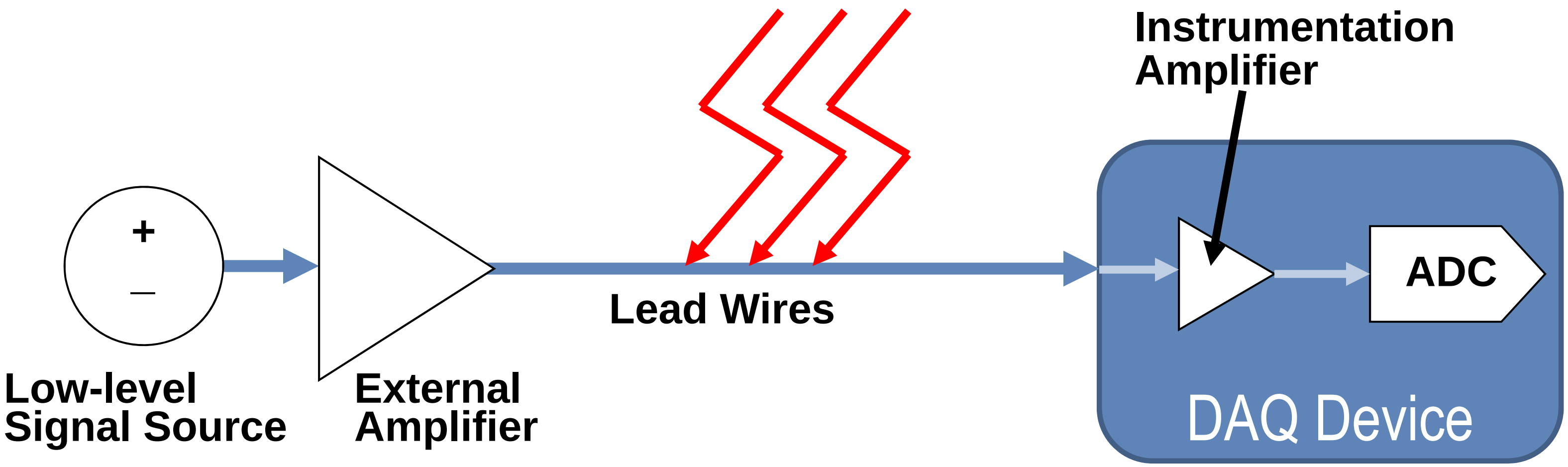


Increase Signal-to-Noise Ratio (SNR) with amplifier



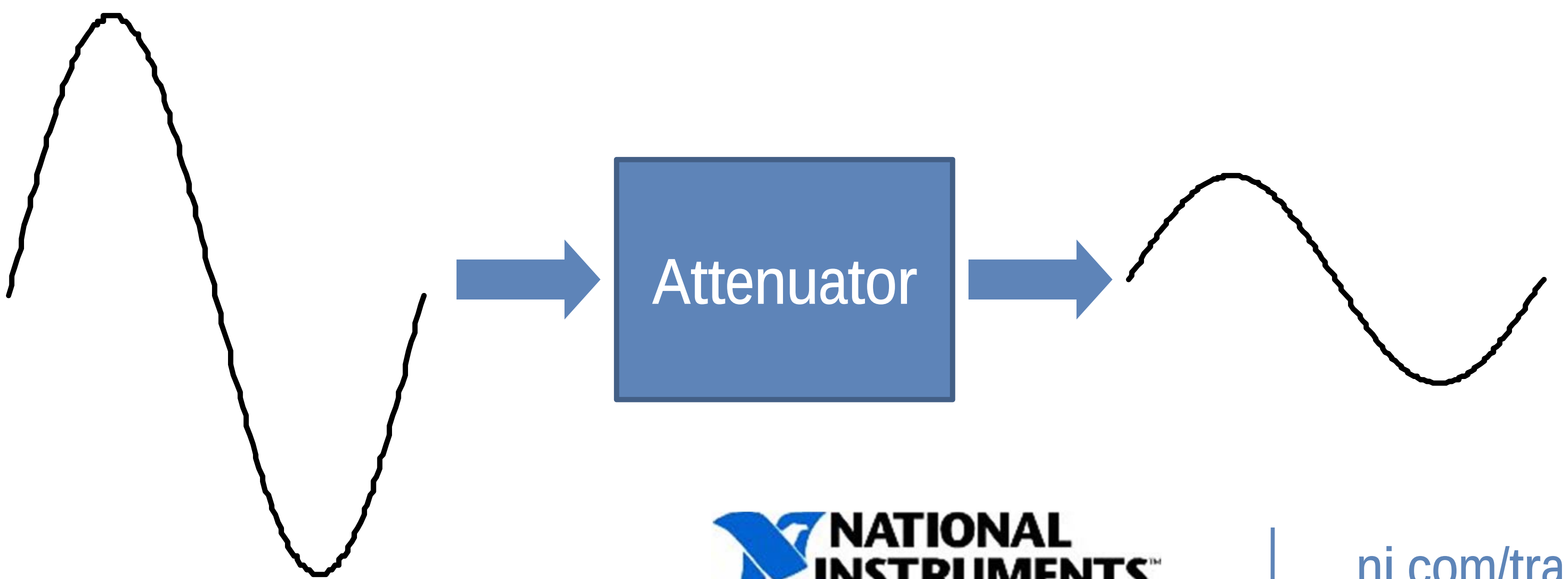
Amplification

- Amplify the low-level voltages near the signal source to reduce the effects of noise
- Configure the minimum and maximum in DAQmx programming so DAQ device will automatically select the proper amplification to best utilize DAQ device resolution

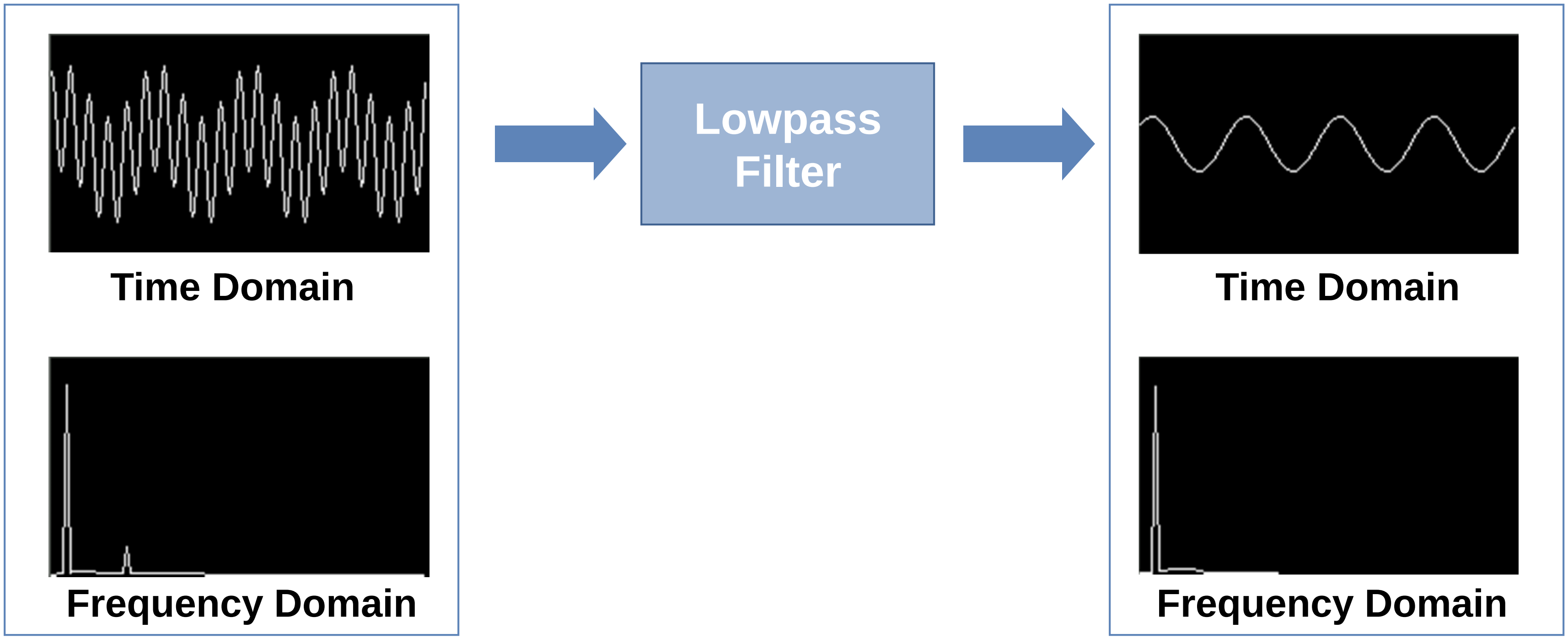


Attenuation

- Decreases the input signal amplitude to fit within the range of the DAQ device
- Necessary when input signal voltages are beyond the range of the DAQ device



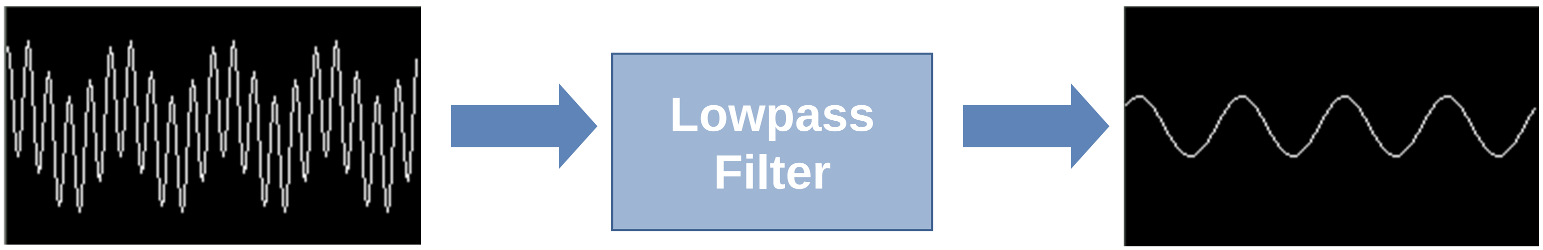
Filtering



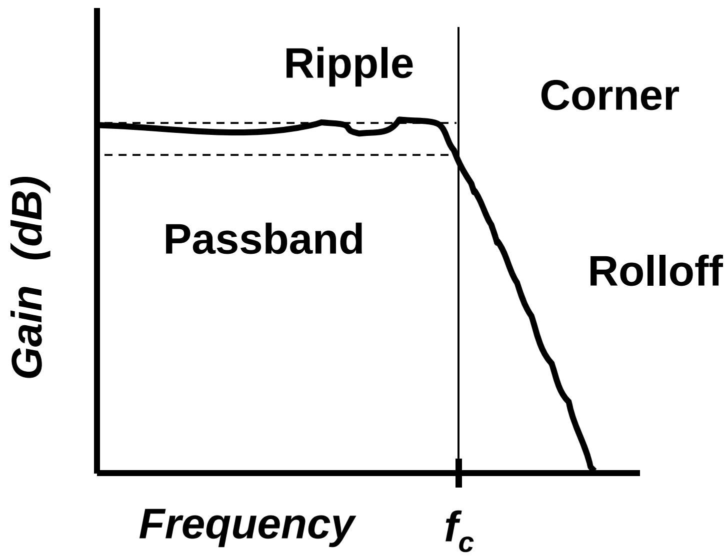
Removes noise

Blocks unwanted frequencies

Filtering



Bode Plot

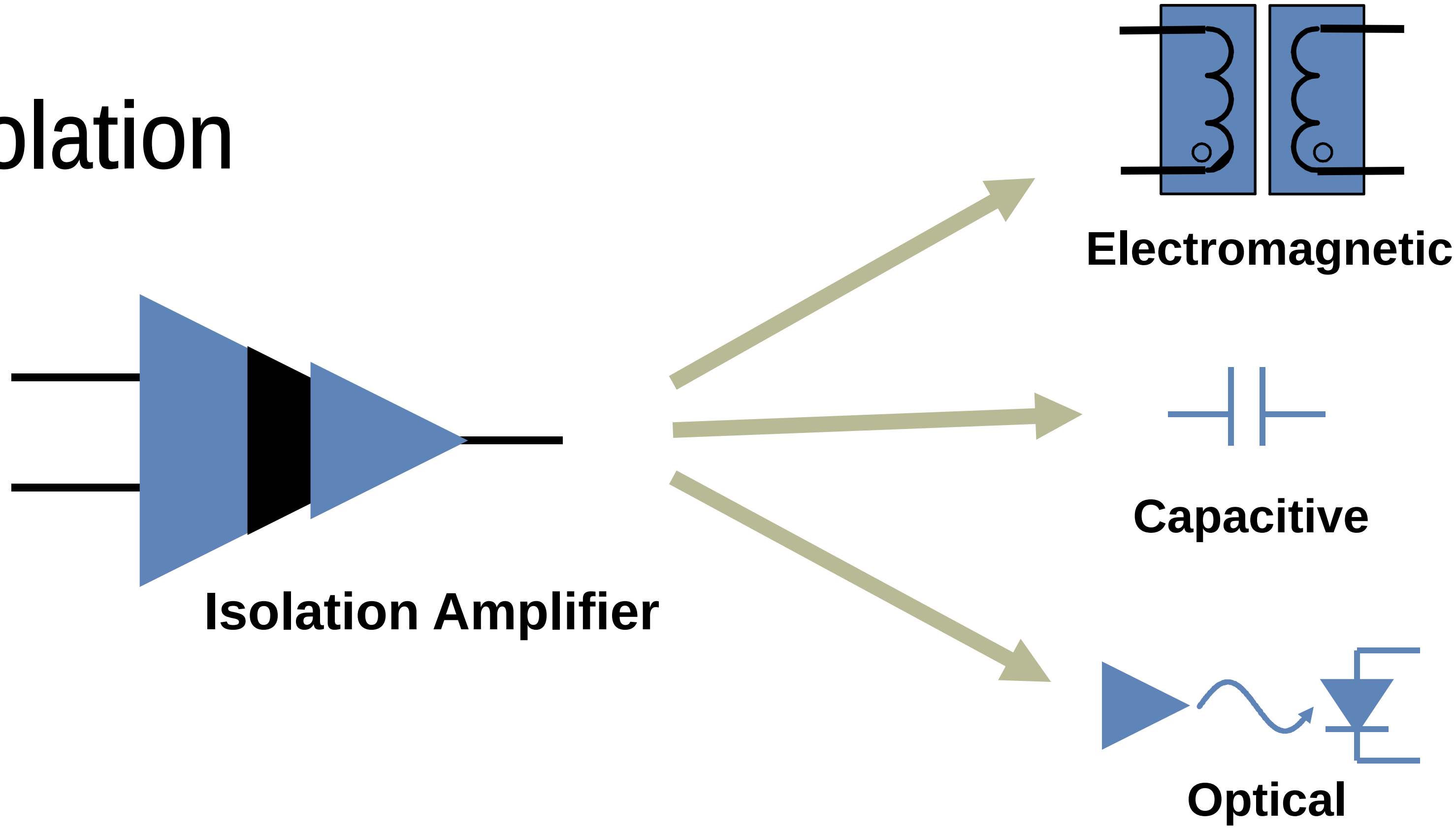


- Passband – frequencies the filter lets pass
- Ripple - filter's effect on the signal's amplitude
- Corner – frequency where the filter begins blocking the signal
- Rolloff – how sharply the filter cuts off unwanted frequencies

Filtering – Examples

- Remove/reject unwanted noise within certain frequency range
  - 50/60 Hz noise rejected by lowpass 4Hz filter
  - Some DAQ devices have built-in programmable filters
- Prevent noise caused by aliasing from higher frequencies
  - Implement an anti-aliasing filter with a lowpass filter to remove frequency components greater than one half the sampling frequency (Nyquist Theorem)

Isolation



Pass signal from its source to measurement device without a physical connection

- Blocks high common-mode signals
- Breaks ground loops
- Protects your instrumentation

Isolation – Referencing / Common-Mode Voltage

- Floating signals – reference to your instrumentation
- Common-mode voltage – can damage your amplifier
- Ground loops – caused by multiple reference points

Isolation Specifications

Isolation Committees – UL, IEC

Component requirements
Spacing requirements
Testing procedures

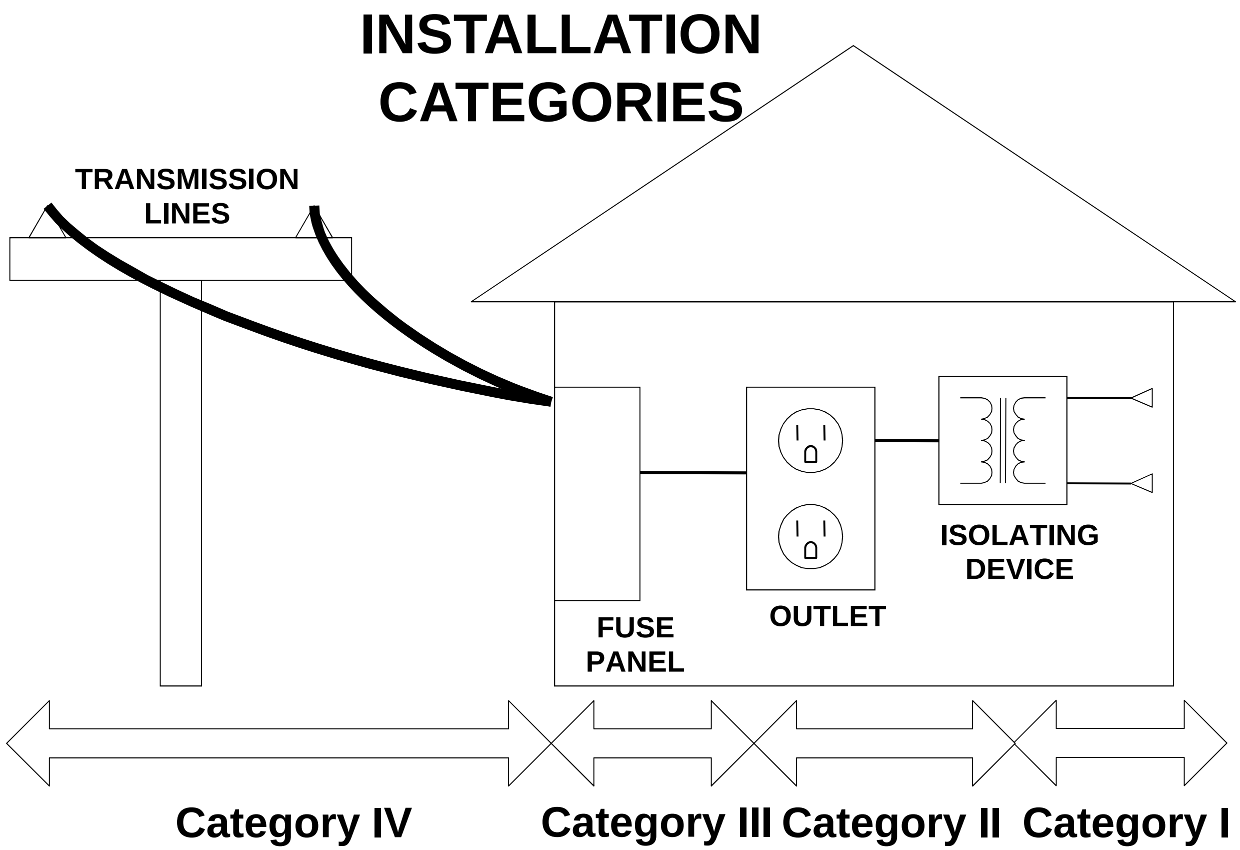
Safe Working Voltage

Defines acceptable normal voltage you can apply

Installation Rating

Defines the possible transients your system can accept

Installation Ratings



Most Common Sensor Measurements

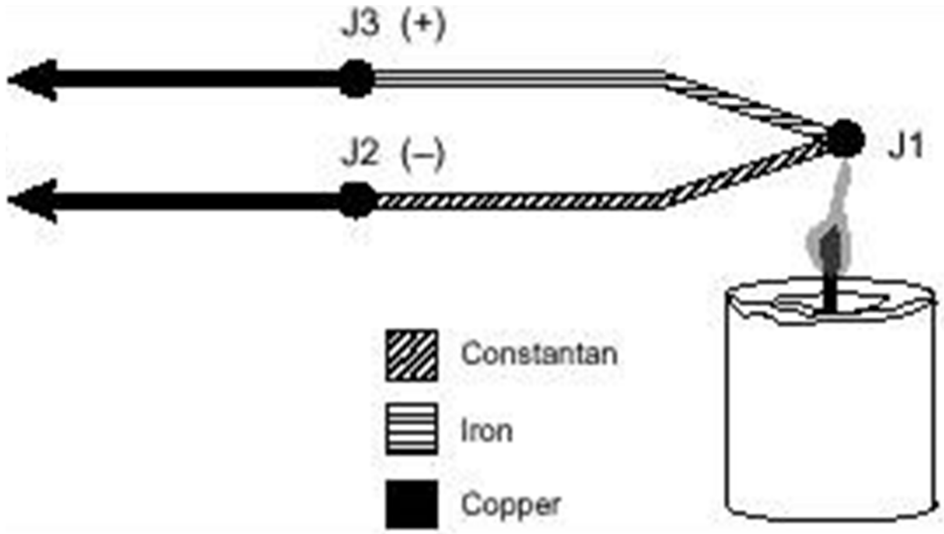
- Temperature
- Strain, pressure, load, and torque
  - Bridge-based measurements
- Sound and vibration
  - Closely related measurements

Temperature Sensor Measurements

Temperature Sensors

- Thermocouple
- Resistance Temperature Detectors (RTD)
- Thermistor (thermally sensitive resistors)

Thermocouple Construction

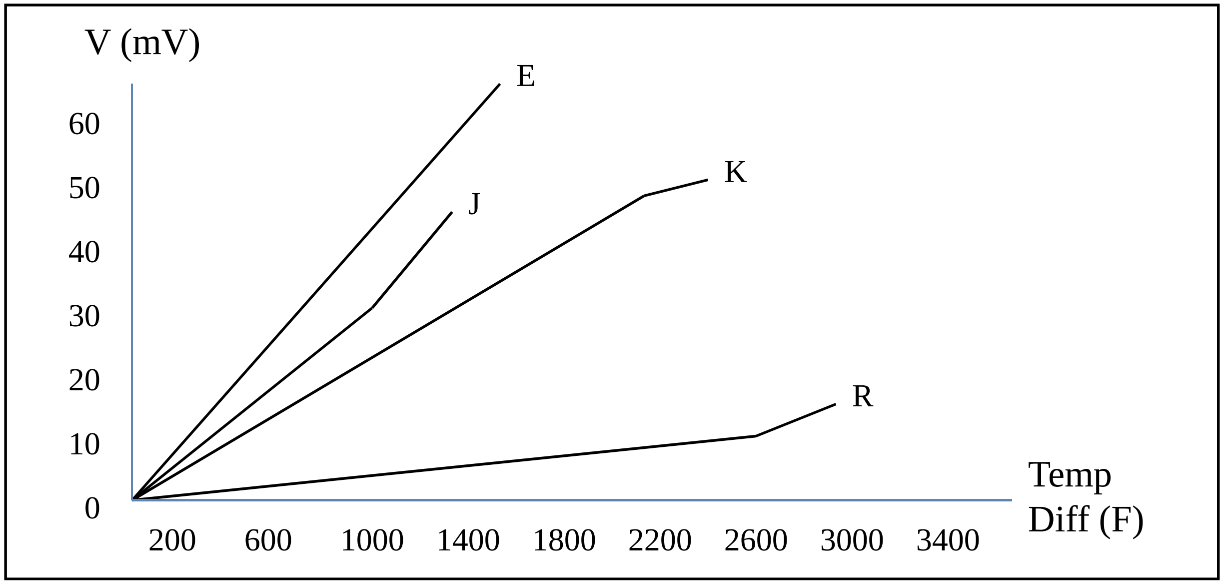


To DAQ Device

J-type Thermocouple

- 2 wires of *dissimilar metals* twisted and bonded together
  - J1: “hot” junction, T_{HJ}
  - J2 & J3: “cold” junctions, T_{CJ}

Thermocouple Output



- Voltage signal of a thermocouple is proportional to temperature at the hot junction
- The voltage vs. temperature relationship is nonlinear over large temperature ranges

Thermocouple Color Codes

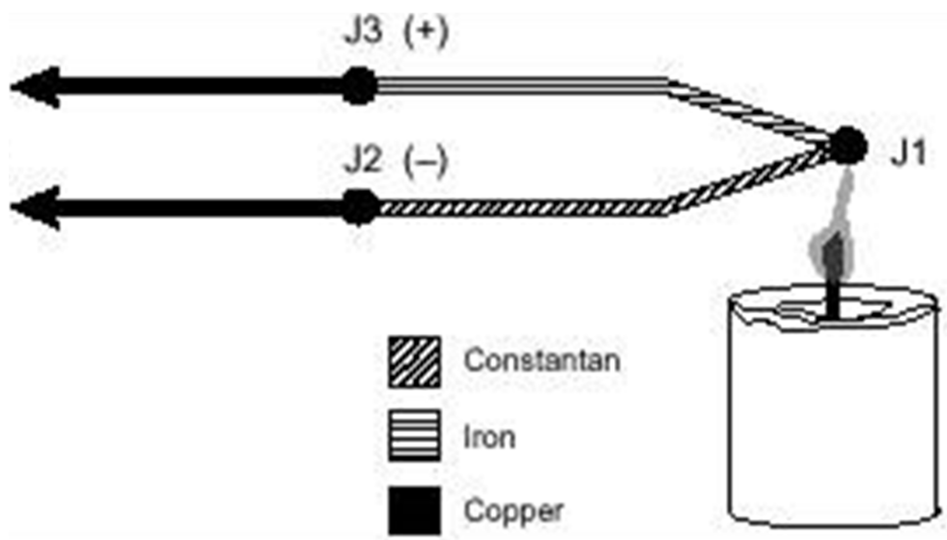
Type	Material		Color Code		Overall Jacket		Range (°C)	
Thermocouple Grade	*Positive Wire*	*Negative Wire*	*Positive Wire*	*Negative Wire*	*Extension*	*Overall Jacket*	*min*	*max*
J	Iron	Constantan	White	Red	Black	Brown	0	750
K	Chromel	Alumel	Yellow	Red	Yellow	Brown	-200	1250
T	Copper	Constantan	Blue	Red	Blue	Brown	-200	350
E	Chromel	Constantan	Purple	Red	Purple	Brown	-200	900

Note: Unlike most leads, the red lead for thermocouples is negative

Thermocouple Operation

- Due to the “Seebeck Effect,” dissimilar metals in contact produce a voltage (mV) proportional to the temperature difference between the hot (J1) and cold junctions (J2, J3)

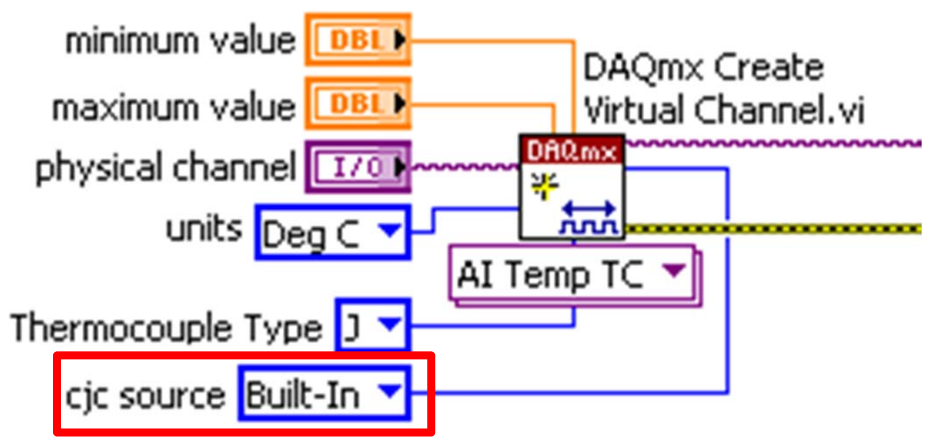
To DAQ Device



J-type Thermocouple

Cold Junction Compensation Signal Conditioning

- CJC signal conditioning accounts and corrects for the voltage added at cold junctions
- Some NI DAQ devices use a direct-reading sensor at the reference junction
  - Direct-reading sensor measures the reference-junction temperature
  - Software adds the appropriate voltage value to the measured voltage to cancel out the cold junction voltage



Additional Signal Conditioning for Thermocouples

- Filtering
  - Thermocouples output low voltage (mV) signals, making them susceptible to noise
  - Use lowpass filter to remove 60 Hz power line noise, etc
- Amplification
  - Improve noise performance by amplifying the low voltage signals near the signal source
- Isolation
  - Thermocouples commonly mounted/soldered directly to a conductive material (i.e. steel, water) making them susceptible to common-mode noise and ground loops

Exercise 7-1: Thermocouple Measurement

To read the temperature from a thermocouple with the NI 9219.

GOAL

Exercise 7-1: Thermocouple Measurement

- How does the VI and NI 9219 compensate for voltages added at cold junctions?

DISCUSSION

Active and Passive Temperature Sensors

Thermocouples are passive temperature sensors

- Do not require excitation

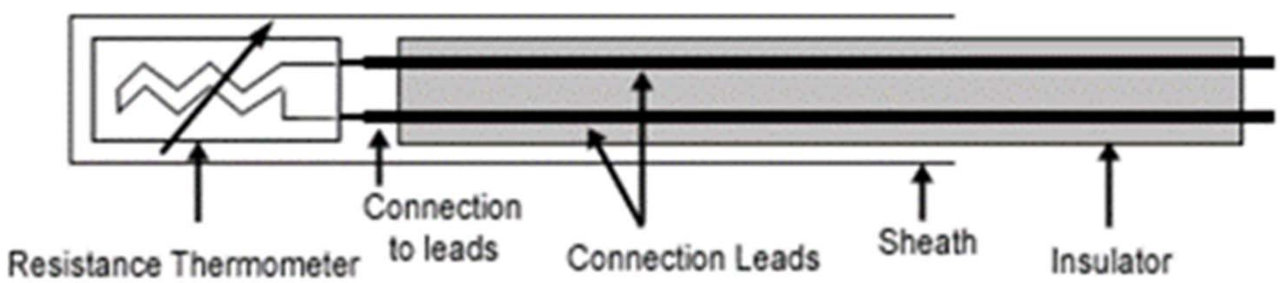
RTDs and Thermistors are active temperature sensors

- Require current or voltage excitation

Excitation – A sensor that requires excitation must receive a voltage or current from an external source

Resistance Temperature Detectors (RTDs)

- Operate on the principle of changes in electrical resistance of pure metals
- Characterized by a linear positive change in resistance with temperature



Physical Architecture of an RTD

Thermistors

Thermistors (thermally sensitive resistors)

- Similar to RTDs in that they are electrical resistors whose resistance changes with temperature
- Manufactured from metal oxide semiconductor material which is encapsulated in a glass or epoxy bead

Wire Varieties

RTDs and thermistors come in the following wire varieties

- Two-wire
- Three-wire
- Four-wire

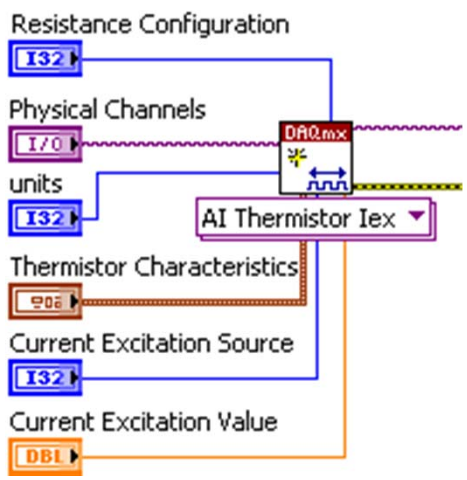
Each requires a different wiring to DAQ device

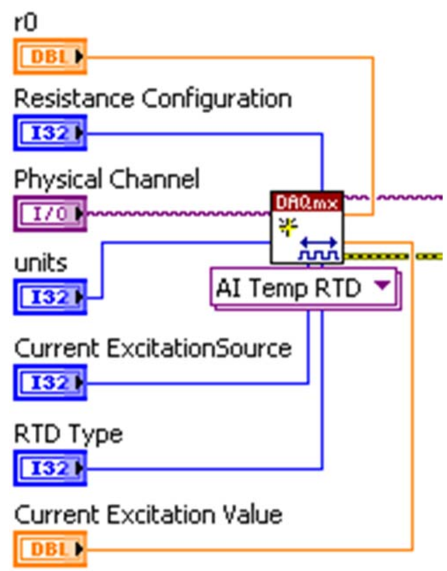
Additional Signal Conditioning for RTDs and Thermistors

- Lowpass filter
  - Both sensors output low voltage (mV) signals
  - Use lowpass filter to remove 60 Hz power line noise, etc
- Amplification
  - Improve noise performance by amplifying the low-voltage signals near the signal source

RTD and Thermistor Example

Use the DAQmx Create Virtual Channel to configure RTD and thermistor parameters





Temperature Sensor Comparison

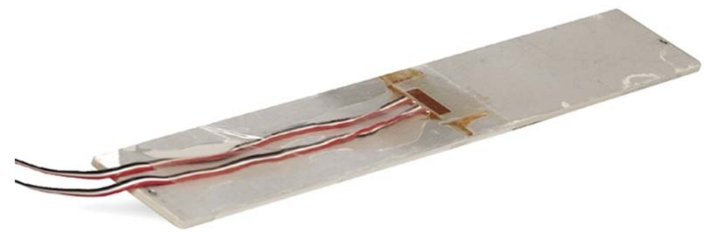
	Thermocouple	RTD	Thermistor
Temperature Range	-267°C to 2316°C	-260°C to 850°C	-100°C to 500°C
Accuracy	Good	Best	Good
Linearity	Better	Best	Good
Sensitivity	Good	Better	Best

E. Strain, Pressure, Load, and Torque Measurements

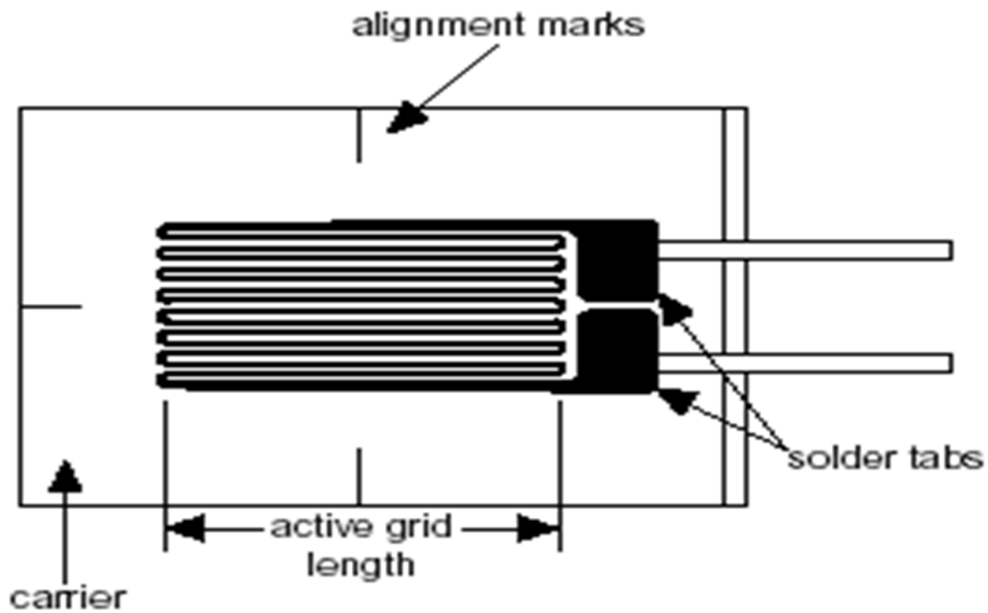
- Strain is the amount of deformation of a body due to an applied force
- Strain (ε) is defined as the fractional change in length as shown below

$$\varepsilon = \frac{\Delta L}{L}$$

Strain Gage Construction



- Strain gages measure strain
- Thin wire or metal foil in a zigzag pattern is fastened to a “carrier”

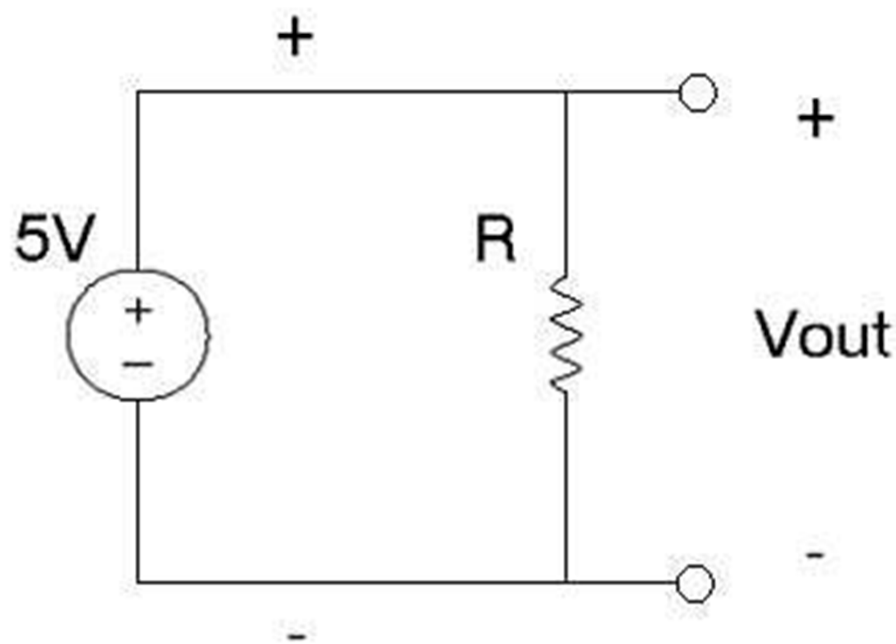


Strain – Gage Factor

- Fundamental parameter of the strain gage is its sensitivity to strain
- Expressed as the gage factor (GF)
- Gage factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain)

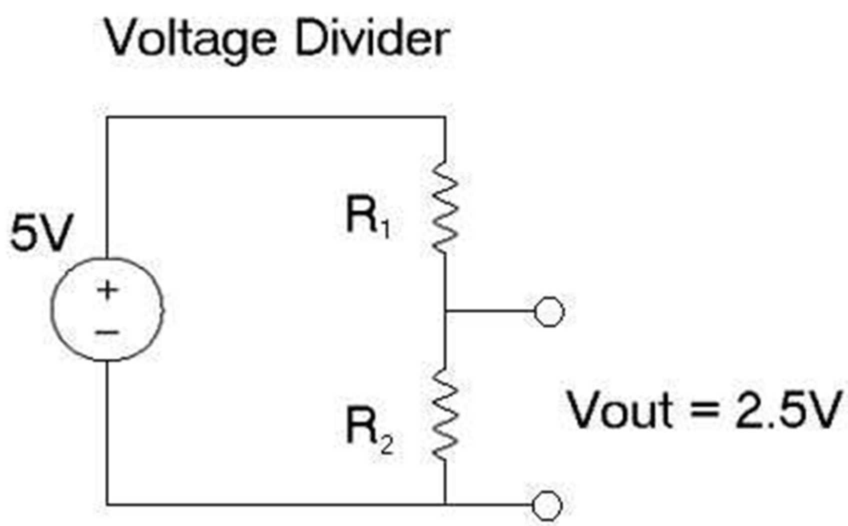
$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

Strain – Circuit Basics



The voltage drop across the resistor is equal to the sourced voltage (5V)

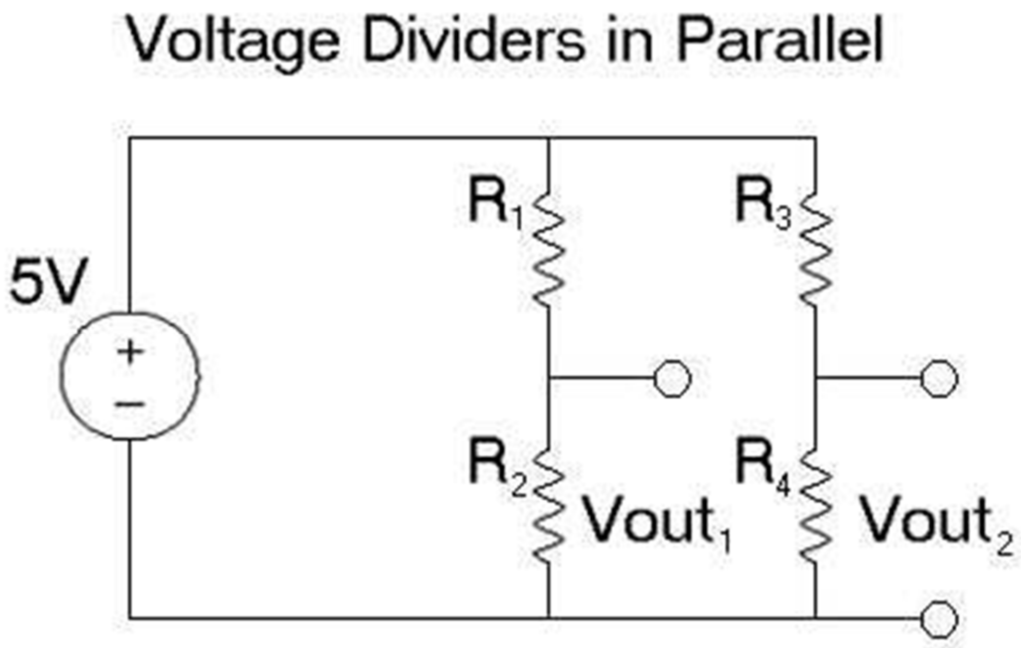
Strain – Circuit Basics



$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)$$

If R_1=R_2 then voltage is dropped equally across the resistors (2.5V across each)

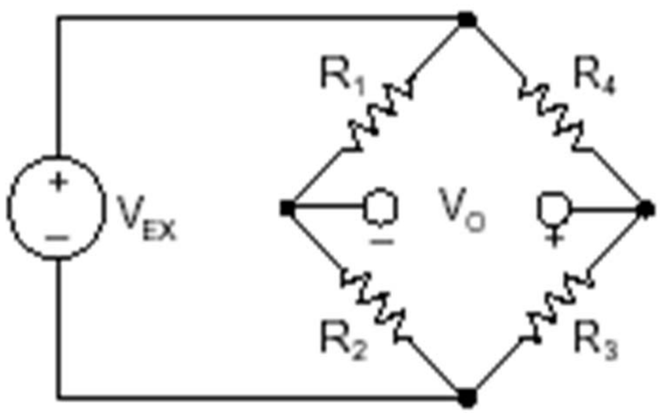
Strain – Circuit Basics



If all resistors are equal then voltage is dropped equally across them (2.50 V across each)

Strain – Circuit Basics

Wheatstone Bridge



$$V_o = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] \bullet V_{EX}$$

If all resistors are equal then no voltage is read.

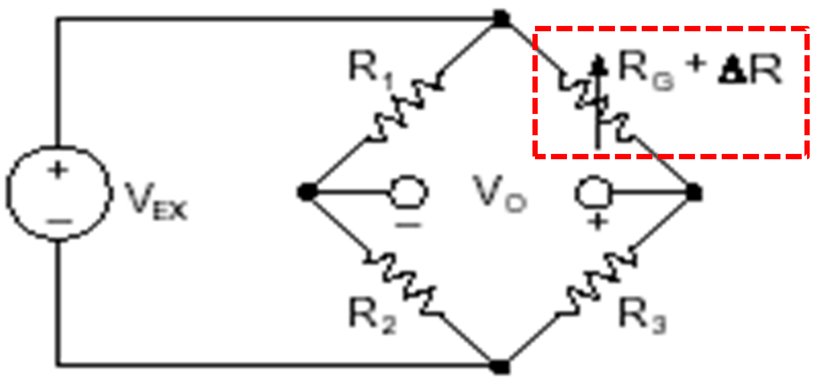
If one or more resistors change, voltage is returned.

Wheatstone Bridge measures small changes in resistance

Strain – Circuit Basics

If you replace a resistor with an active strain gage in the Wheatstone Bridge, any changes in the strain gage resistance will unbalance the Bridge

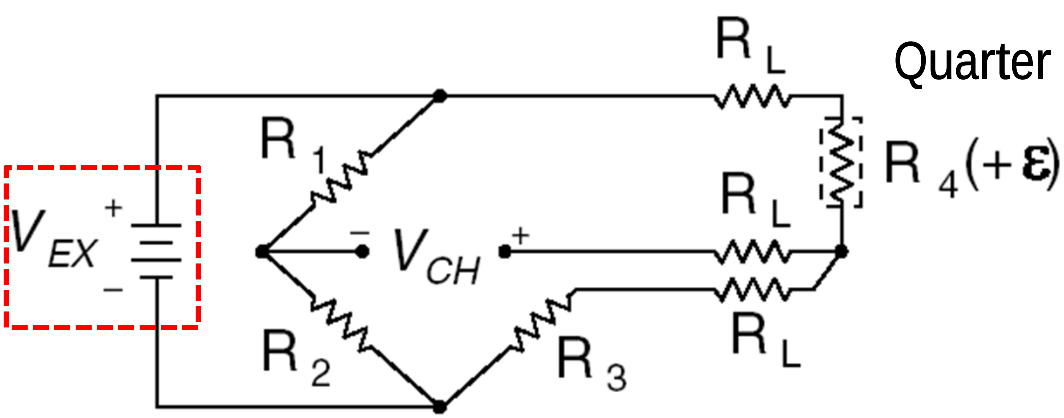
Quarter Bridge Strain Gage



$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{4}\left(\frac{1}{1 + GF \bullet \frac{\varepsilon}{2}}\right)$$

Required Signal Conditioning for Strain Gages

- Excitation
  - Strain gages require voltage excitation levels of between 2.5 V and 10 V
- Bridge Completion
  - Must complete the Wheatstone Bridge in the DAQ device



Quarter Bridge Strain Gage

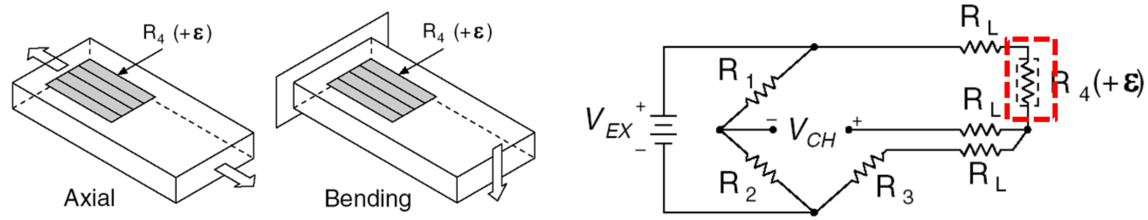
Bridge Terminology

Bridge Configuration	# of Active Elements	# of Active Elements outside Terminal Block
Quarter-bridge	1	1
Half-bridge	2	2
Full-bridge	4	4

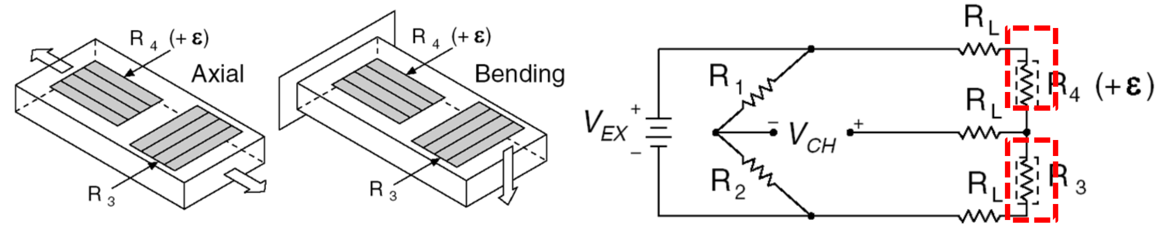
Alignment and wiring of active elements can enhance or minimize certain strains

Bridge Completion

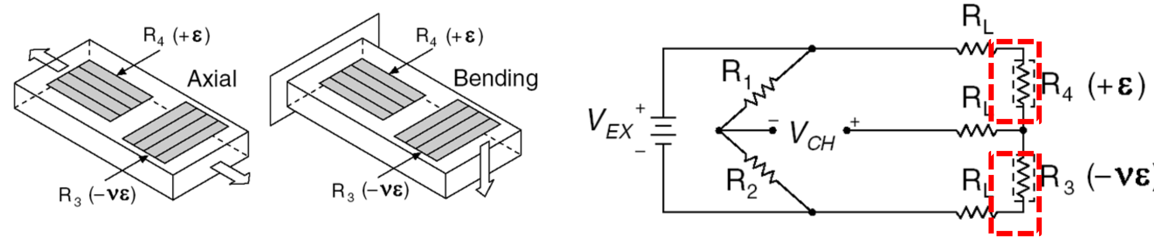
- Quarter Bridge I



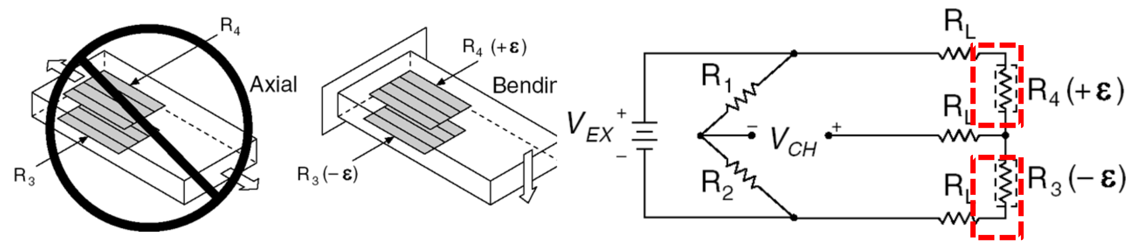
- Quarter Bridge II



- Half Bridge I



- Half Bridge II



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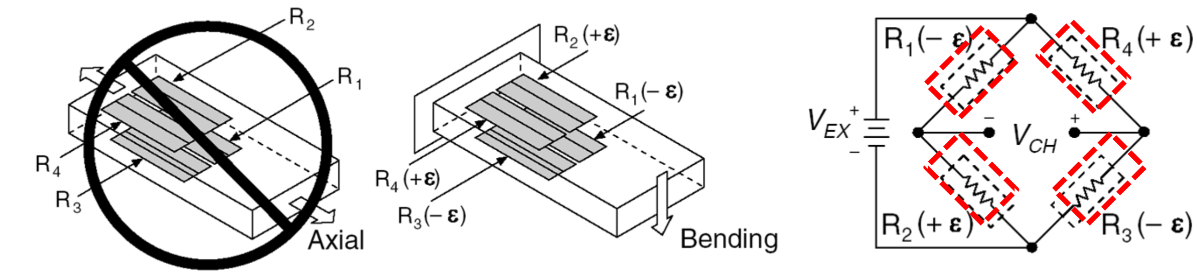
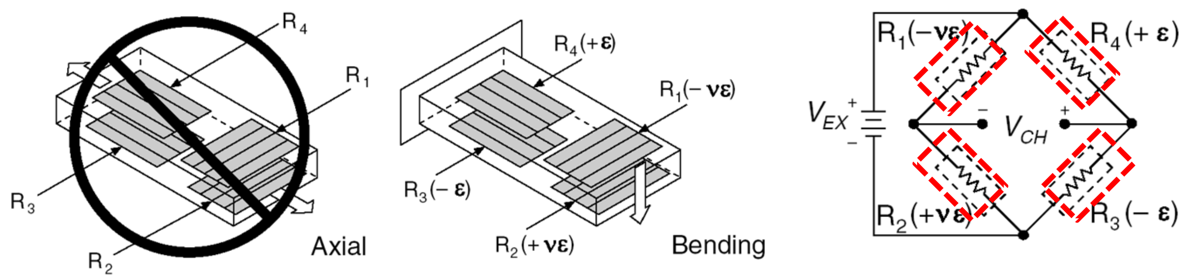
Bridge Completion (cont.)

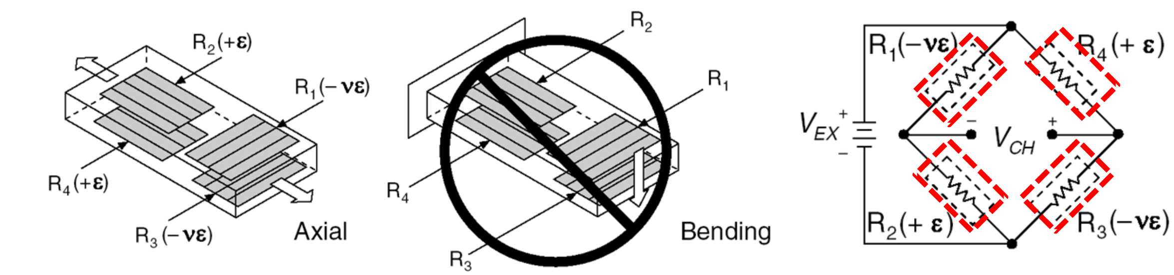
- Full Bridge I



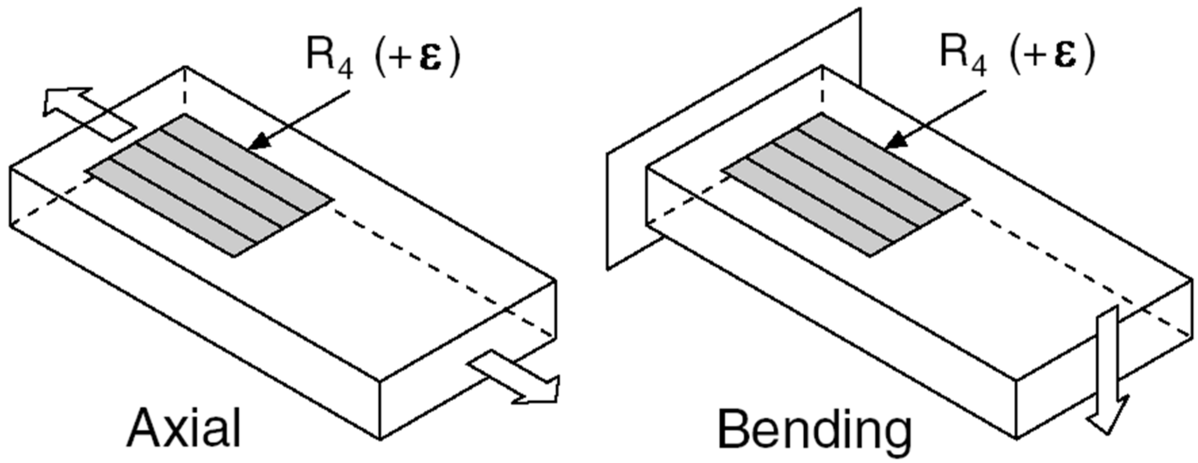
- Full Bridge II

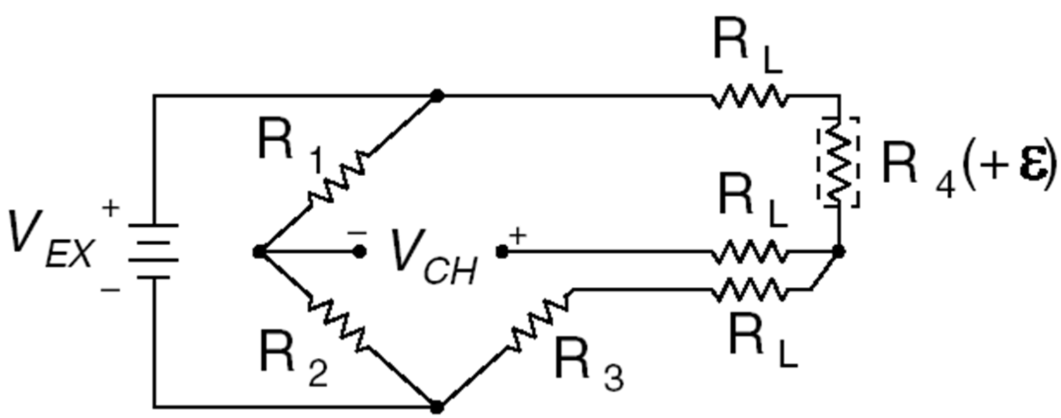


- Full Bridge III



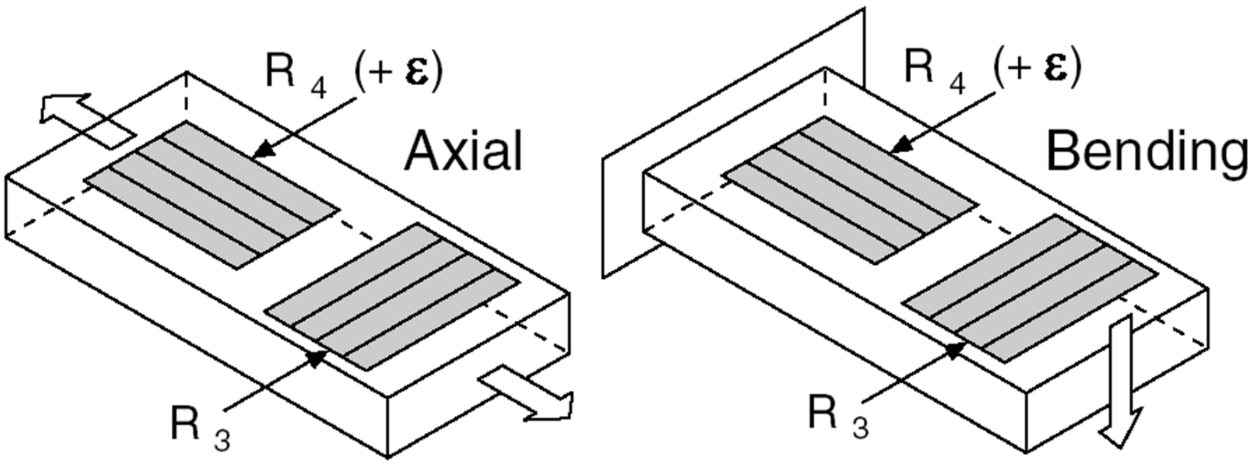
Quarter Bridge I



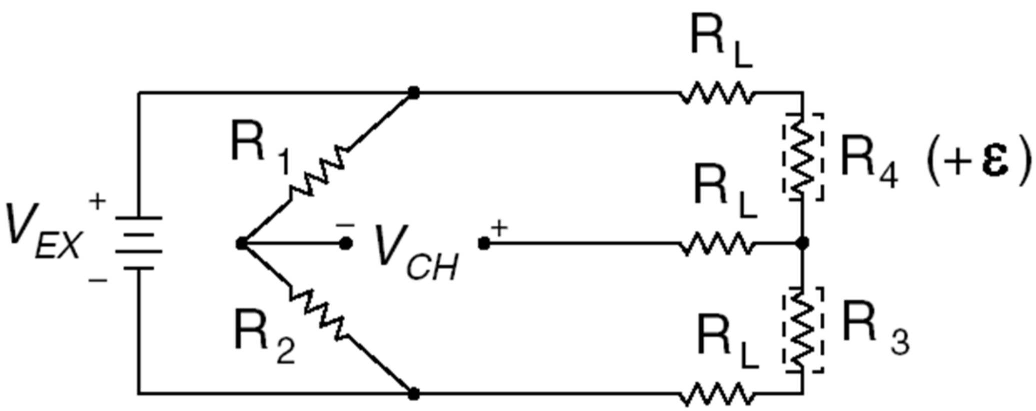


The single active element is mounted in the principle direction of axial or bending strain

Quarter Bridge II

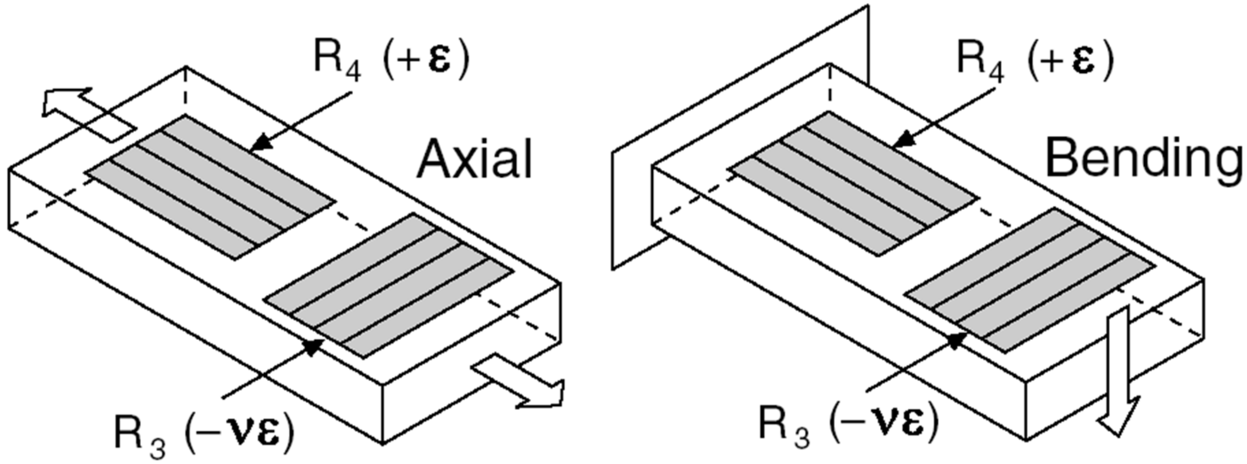


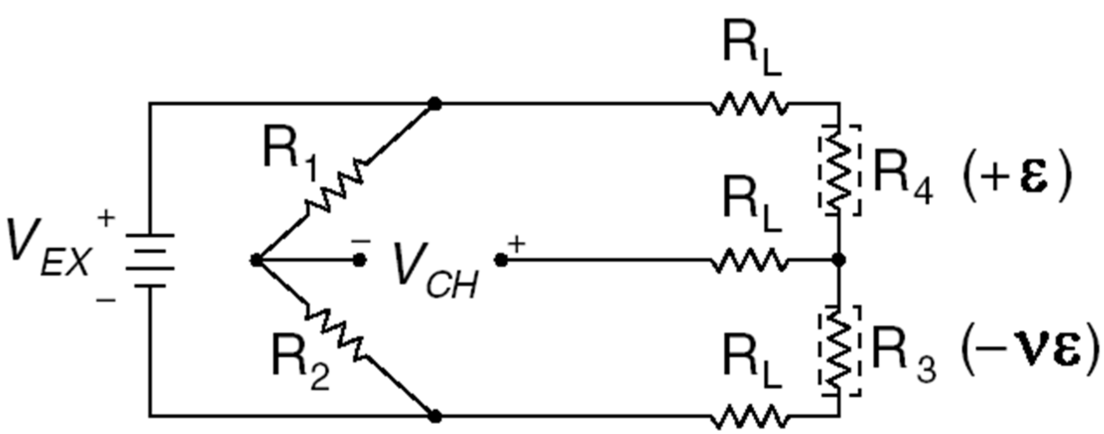
R4 is mounted in the direction of axial strain – measures tensile strain (+ε)



R3 (dummy) is mounted in close thermal contact with strain specimen, but not bonded to it – compensates for temperature

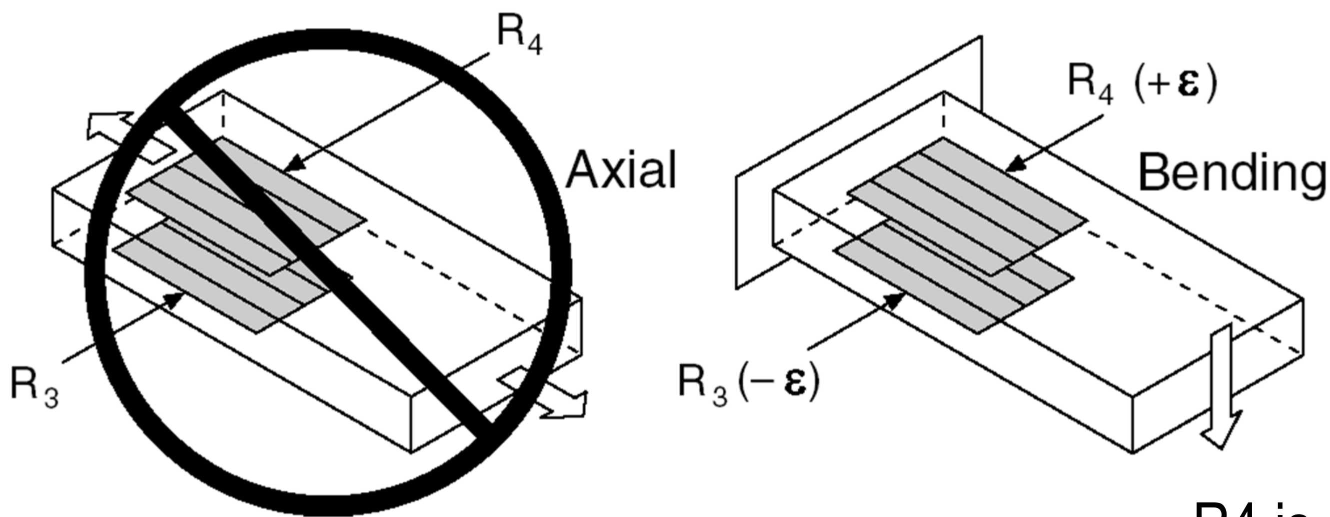
Half Bridge I

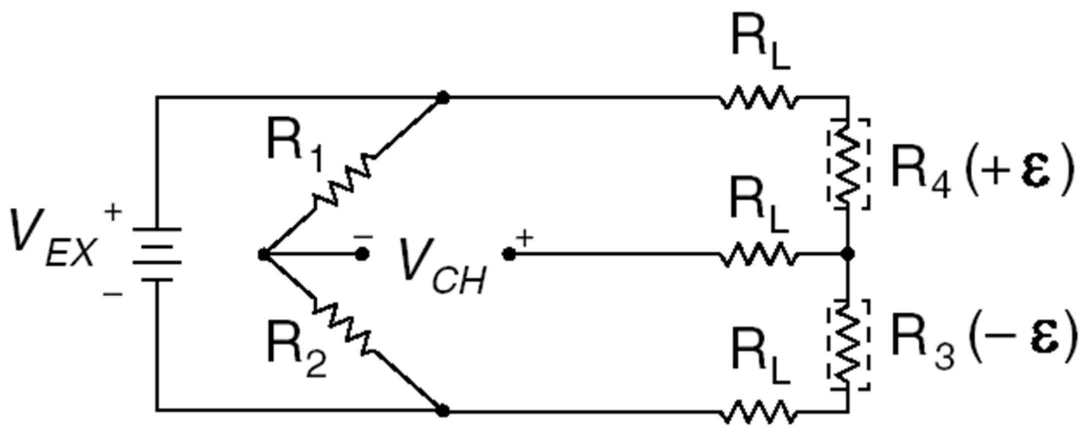




- R4 is mounted in the direction of axial strain – measures tensile strain (+ε)
- R3 measures compression from Poisson effect (-υε)

Half Bridge II

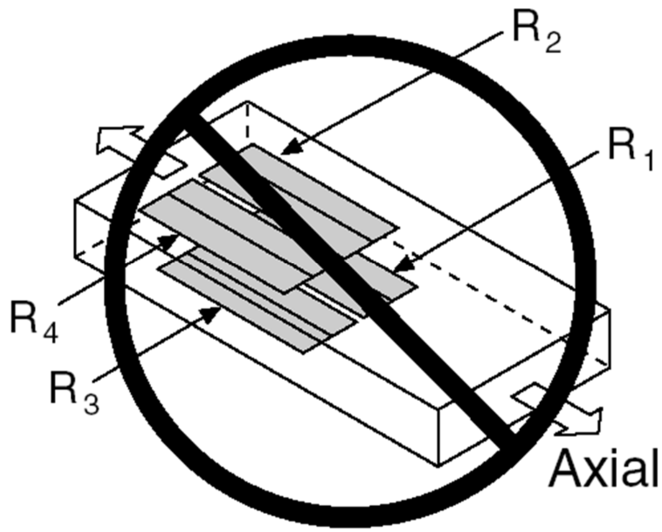


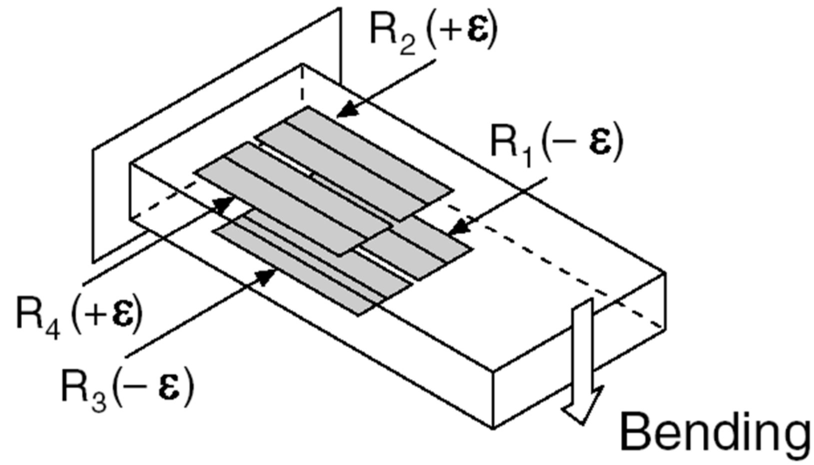


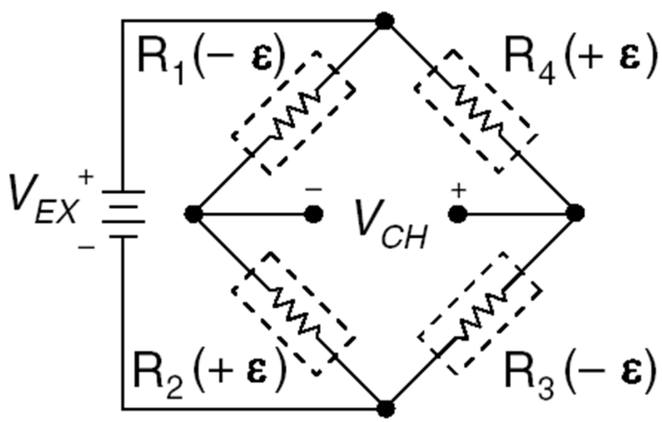
R4 is mounted on top – measures tensile strain (+ε)

R3 is mounted on bottom - measures compressive strain (-ε)

Full Bridge I



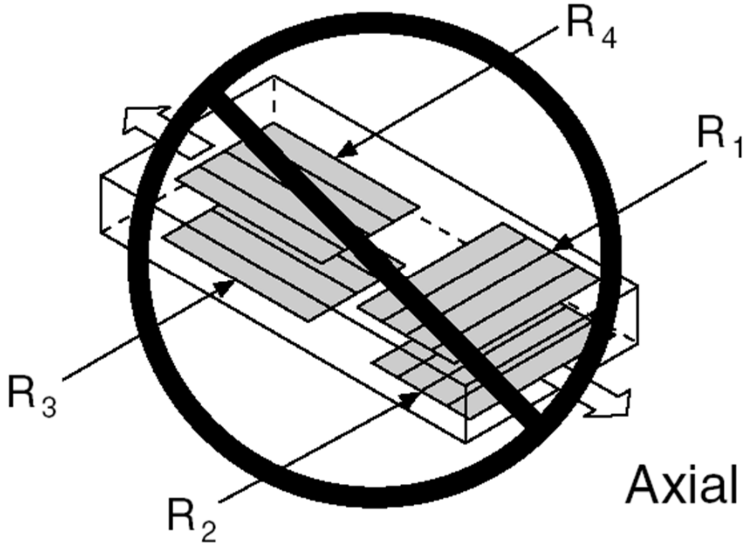


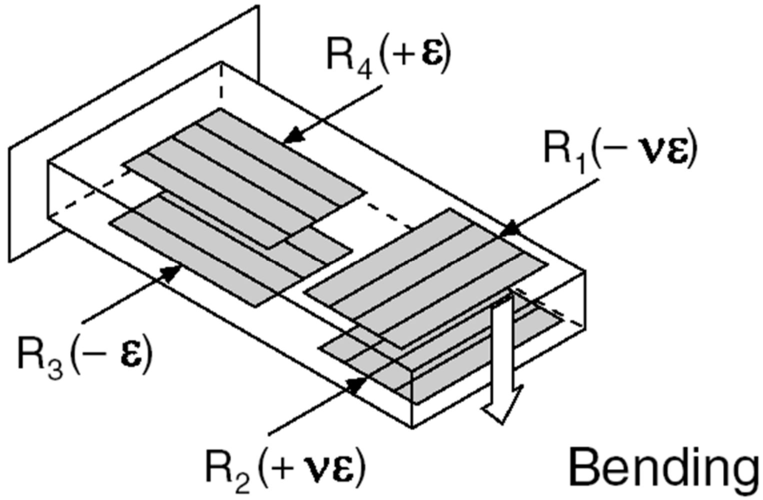


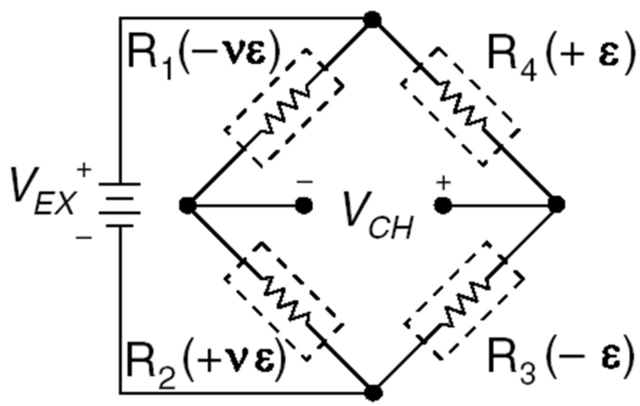
R2 and R4 measure tensile strain (+ε)

R1 and R3 measure compressive strain (-ε)

Full Bridge II

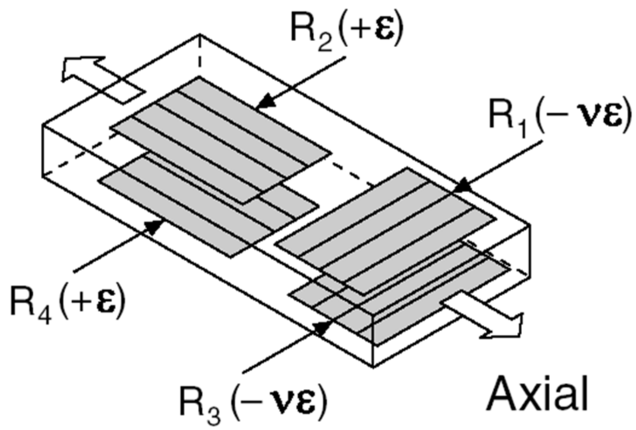


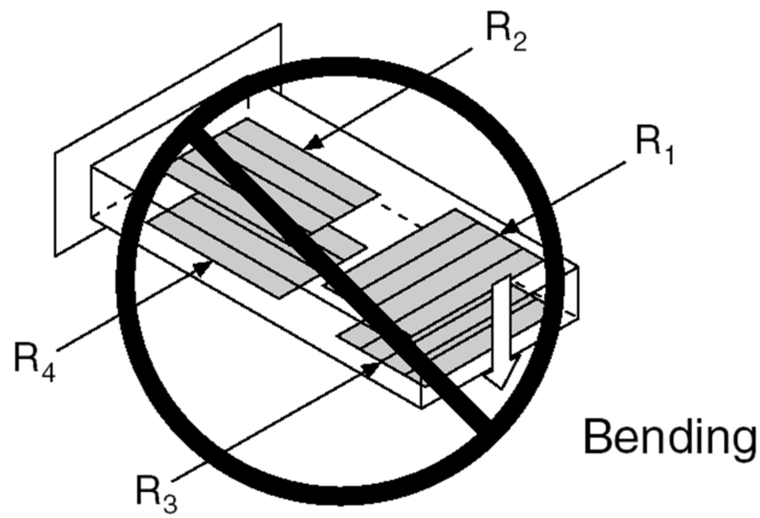


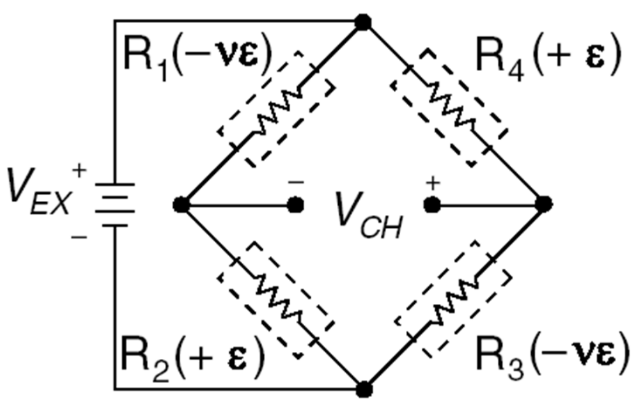


- R1 measures compressive Poisson effect ($-\upsilon\varepsilon$)
- R2 measures tensile Poisson effect ($-\upsilon\varepsilon$)
- R3 measures compressive strain ($-\varepsilon$)
- R4 measures tensile strain ($+\varepsilon$)

Full Bridge III







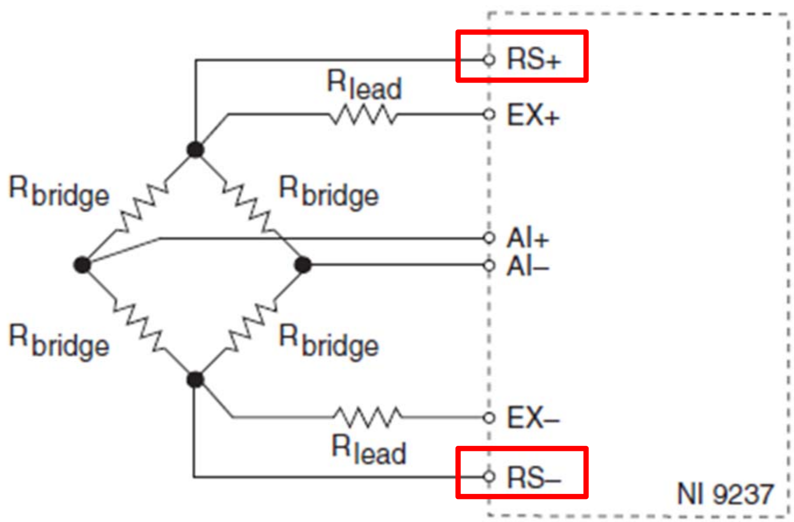
- R1 measures compressive Poisson effect (-υε)
- R2 measures tensile strain (+ε)
- R3 measures compressive Poisson effect (-υε)
- R4 measures tensile strain (+ε)

Optional Signal Conditioning for Strain Gages

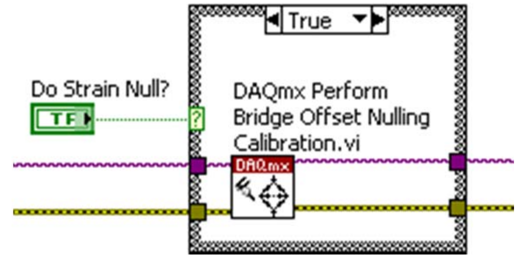
- Remote Sensing
- Offset Nulling
- Shunt Calibration
- Amplification
- Filtering

Remote Sensing

- If strain gage circuit is far from the signal conditioner and excitation source, it might introduce a source of error caused by a voltage drop from the resistance in the connecting wires
- Use remote sensing to compensate for this error



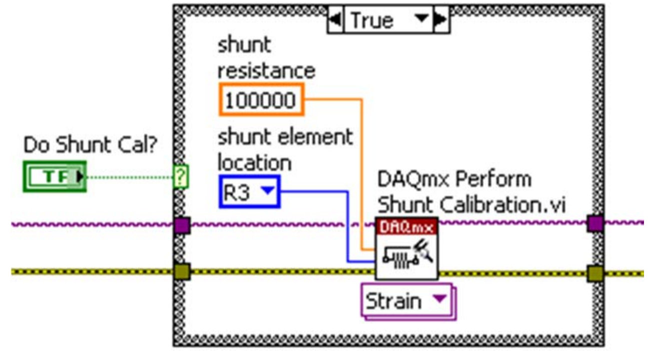
Offset Nulling



Purpose

- Ensures that ~zero volts are produced at rest (no strain)
  Offset Nulling
- Essentially an offset calibration
- Can be performed in HW or SW
- Compensates for inherent bridge imbalance
- Coarse and fine potentiometers are used to perform nulling in hardware

Shunt Calibration



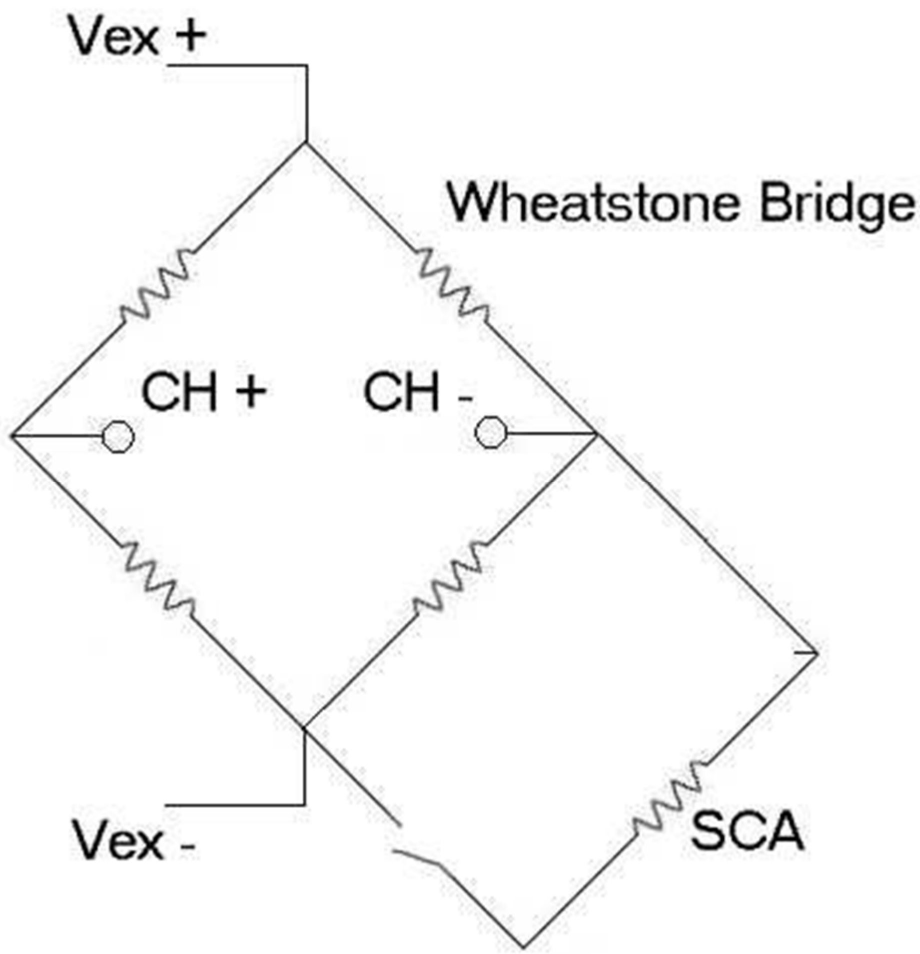
Purpose

- Verify the output of a strain gage measurement system relative to some predetermined mechanical input or strain

Shunt Calibration

- Essentially a gain calibration
- Known resistance is introduced to the circuit and the measured strain is compared to the expected value
- Correction factor is applied to all subsequent readings

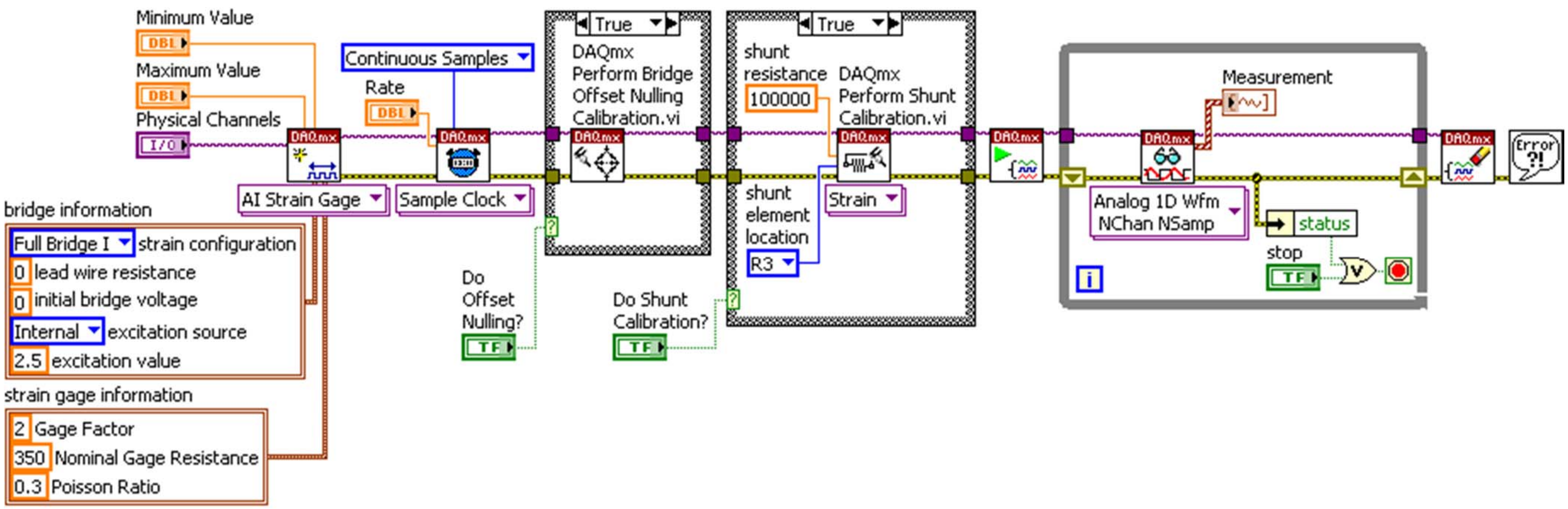
Shunt Calibration Circuit



- Shunt resistor is in parallel to one of the bridge resistors
- The shunt circuit is engaged when the switch is closed (done programmatically)

Strain Gage Example

- Configure bridge information and strain gage information
- Includes options for offset nulling and shunt calibration



Load, Pressure, Torque

Strain gages also used in common load cells, pressure sensors, and torque sensors

- Load cell
  - Uses array of strain gages to measure deformation, in proportional to force, of a structural member
- Pressure sensor
  - Uses strain gages mounted to a diaphragm to measure the deformation, in proportion to pressure, of the diaphragm
- Torque sensor
  - Uses strain gages affixed to a torsion bar to measure the shear stress, in proportion to torque, of the bar

Exercise 7-2: Strain Measurement

To acquire data from a strain gage connected to the NI 9219 and apply offset nulling for more accurate strain measurements.

GOAL

Exercise 7-2: Strain Measurement

- What are possible consequences of not performing offset nulling?

DISCUSSION

Sound and Vibration Measurements

Sound and vibration are closely related

- Vibration occurs when a mass oscillates mechanically about an equilibrium point
- Sound consists of pressure waves generated by vibrating structures. Pressure waves can also induce the vibration of structures

Examples

- Electrical power turbine
- Airplane wing surface
- Musical instruments

Sound and Vibration Measurements

Wide range of applications ,common examples

- Acoustic and vibration testing
  - i.e. noise, vibration, and harshness
- Audio testing
  - i.e. measuring the sound of an audio speaker
- Machine monitoring
  - i.e. predicting failure on power turbines

Sound and Vibration Measurements

Sound sensor

- Microphones measure sound pressure level

Vibration sensor

- Accelerometers measure acceleration typically based on piezoelectric theory

Sound and vibration sensors both measure oscillations

- Similar theory, measurement, and signal conditioning
- Typically both microphones and accelerometers have an integrated amplifier to boost the signal before acquisition

Sound and Vibration Signal Conditioning

- Excitation (current)
- AC coupling to remove DC offset
- Flexible gain settings for different signal ranges
- Lowpass filter to reduce noise and prevent aliasing

Benefits of NI sound & vibration DAQ hardware

- 24-bit resolution for improved dynamic range
- Each channel has its own ADC for synchronized measurements

Sound and Vibration Analysis Examples

Sound and Vibration Measurement Suite contains functions and graphs for analysis and visualization

- Sound Quality, Spectral Analysis, Zoom Power Spectrum, and Frequency Response
- ANSI and IEC-compliant full and fractional octave analysis
- Order analysis tracking and extraction including tachometer processing
- Waterfall, cascade, shaft centerline, orbit, bode, and polar plots
- Universal File Format (UFF58) file I/O support

Summary—Quiz

1. Name 5 types of signal conditioning.

Summary—Quiz Answers

1. Name 5 types of signal conditioning.

   CJC Compensation
   Bridge Completion
   Offset Nulling
   Amplification
   Filtering
   Isolation
   …

Summary—Quiz

2. The arrangement of the strain gages is inconsequential.
   a) True
   b) False

Summary—Quiz Answer

2. The arrangement of the strain gages is inconsequential.
   a) True
   b) False

Summary—Quiz

3. Offset nulling is never necessary because most Wheatstone bridge measurements output exactly 0 V when no strain is applied.
   a) True
   b) False

Summary—Quiz Answer

3. Offset nulling is never necessary because most Wheatstone bridge measurements output exactly 0 V when no strain is applied.

   a) True

   b) False

Summary—Quiz

4. Which of the following types of signal conditioning can apply to thermocouple measurements?
   a) CJC compensation
   b) Amplification
   c) Excitation
   d) Filtering
   e) Isolation

Summary—Quiz Answers

4. Which of the following types of signal conditioning can apply to thermocouple measurements?
   a) CJC compensation
   b) Amplification
   c) Excitation
   d) Filtering
   e) Isolation