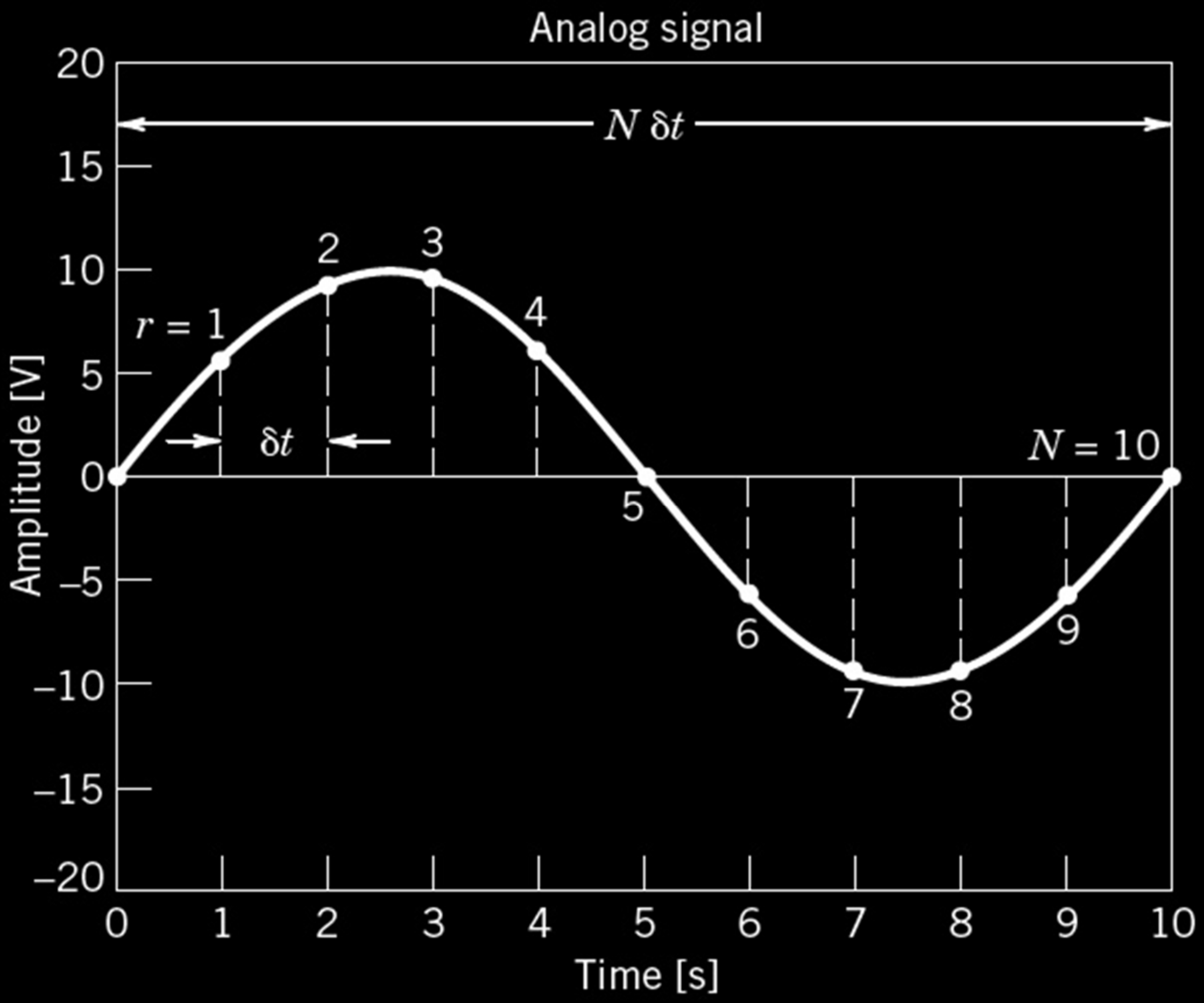
MECE 3320 – Measurements & Instrumentation

Data Acquisition

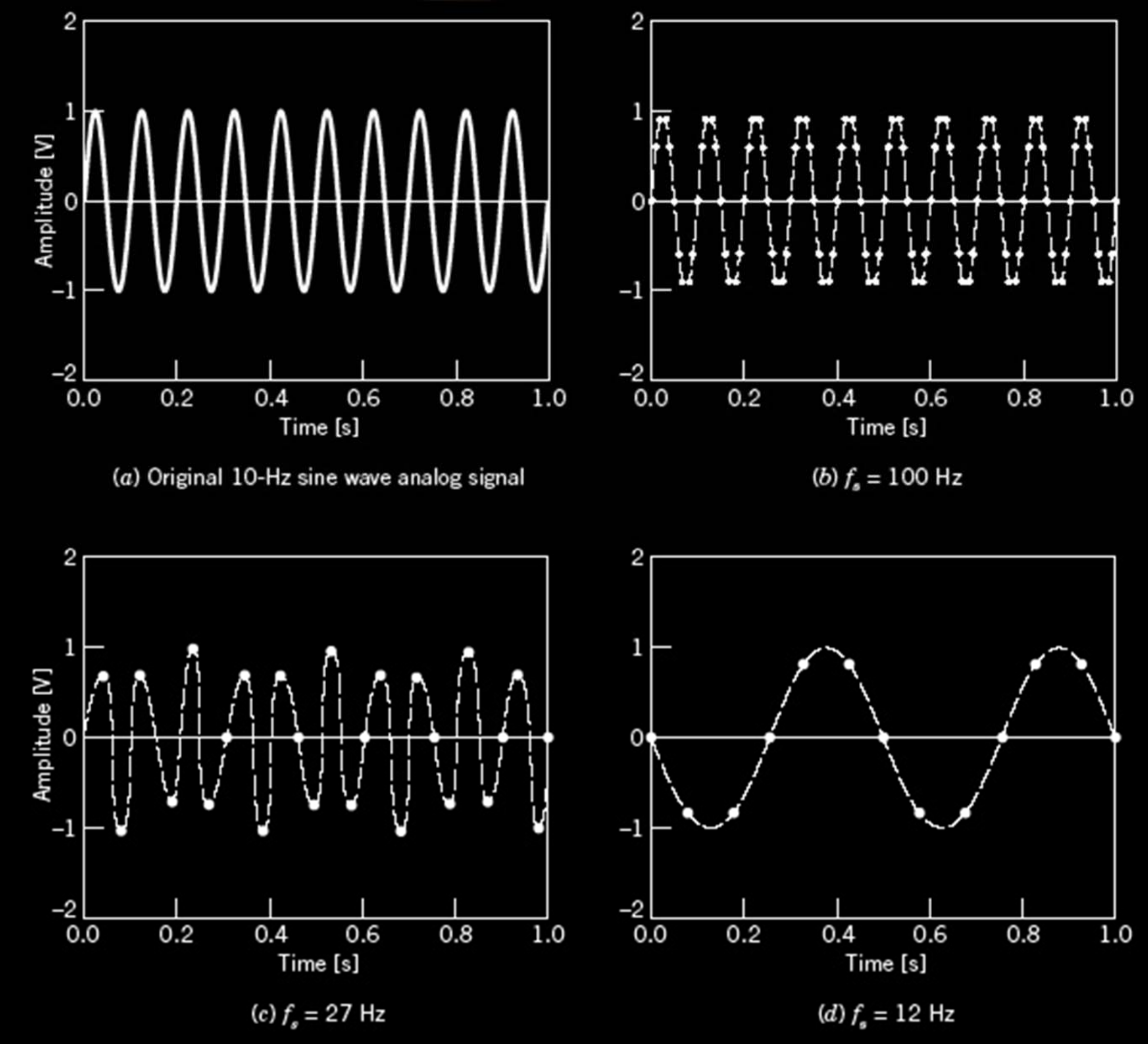
Dr. Isaac Choutapalli
Department of Mechanical Engineering
University of Texas – Pan American

Sampling Concepts



$$f_s = \frac{1}{\delta t}$$

Sampling Rate



(*a*) Original 10-Hz sine wave analog signal

(*b*) $f_s = 100$ Hz

(c) $f_s = 27$ Hz

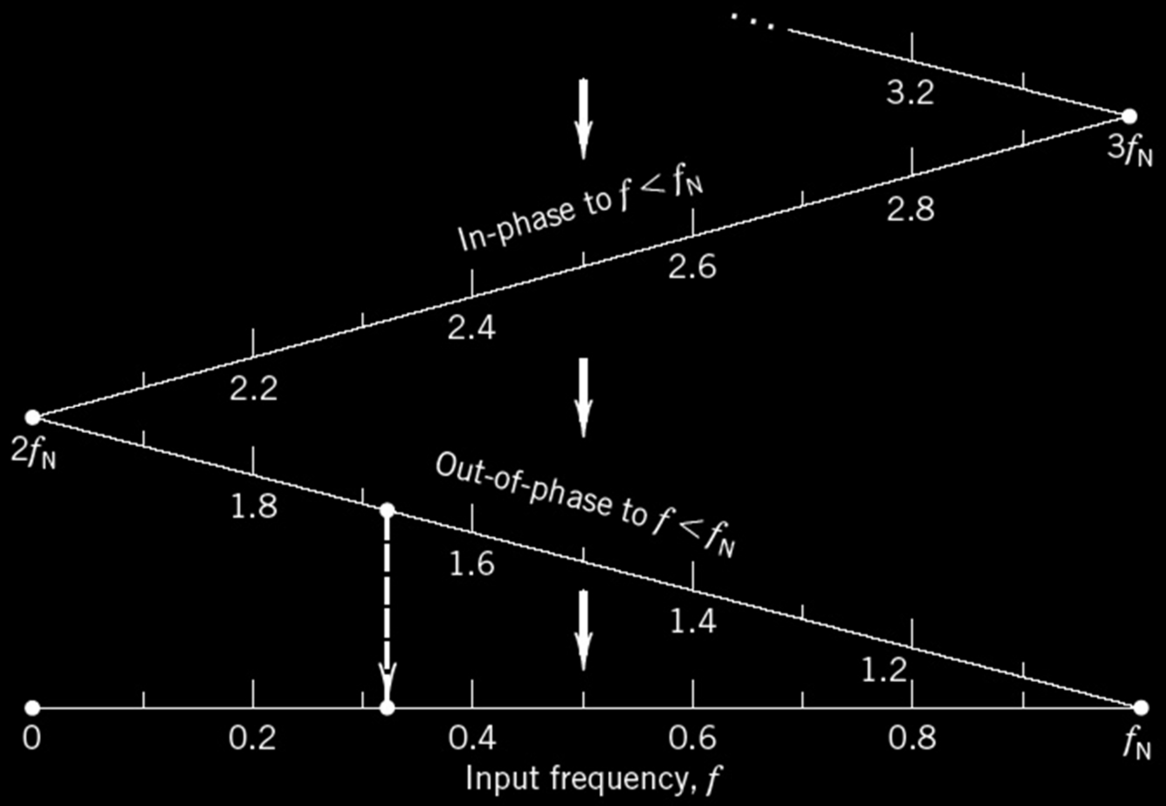
(*d*) $f_s = 12$ Hz

Figure 7.2 The effect of sample rate on signal frequency and amplitude interpretation.

$$f_s > 2\,f_m \text{ or } \delta t < \frac{1}{2\,f_m}$$

(Nyquist Criterion)

Alias Frequencies



Folding diagram

$$\text{Nyquist Frequency, } f_N = \frac{f_s}{2}$$

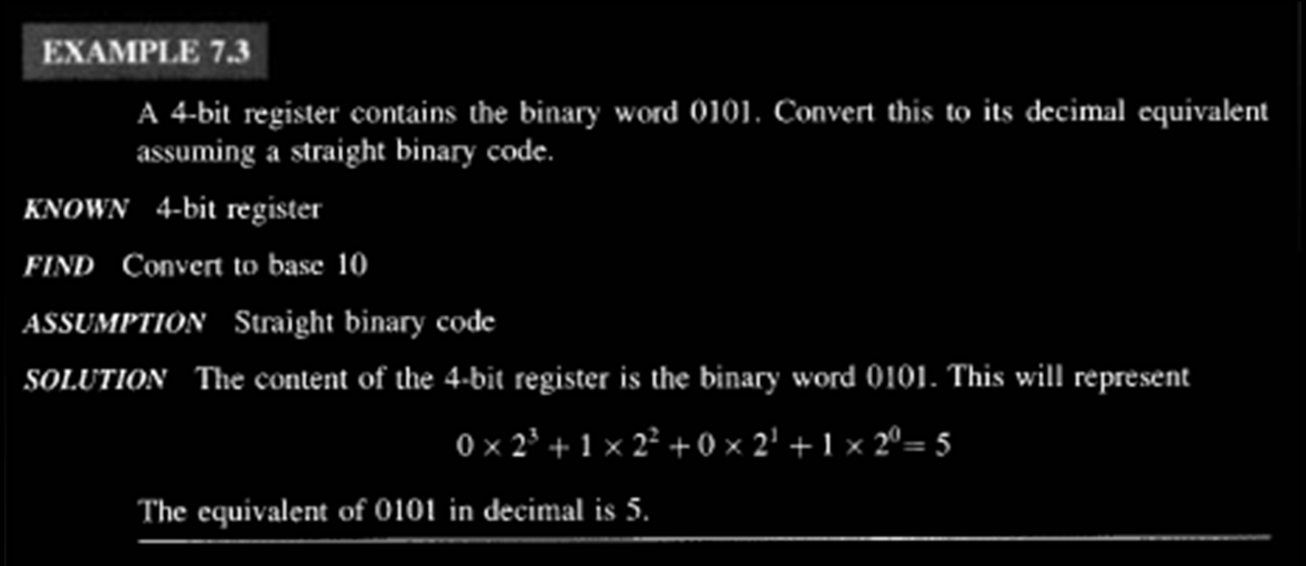
What is the alias frequency if a 10 Hz sine wave is sampled at 12 Hz?

Digital Devices: BITS & WORDS

Digital systems use binary numbering system to represent and transmit signal information.

Bit: a single digit, either 0 or 1
Word: an ordered sequence of bits.
Byte: a specific sequence of 8 bits
Register: memory location where numerical information is stored

M bits can be arranged to represent 2^M combinations of different words.



EXAMPLE 7.3

A 4-bit register contains the binary word 0101. Convert this to its decimal equivalent assuming a straight binary code.

KNOWN 4-bit register

FIND Convert to base 10

ASSUMPTION Straight binary code

SOLUTION The content of the 4-bit register is the binary word 0101. This will represent

$$0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 5$$

The equivalent of 0101 in decimal is 5.

Voltage Measurements

Digital-to-Analog Converter: This is an *M*-bit digital device that converts a digital binary word into analog voltage.

Analog-to-Digital Converter: Converts an analog voltage into a binary number through a process called quantization. Quantization is a process that is discrete, taking place one number at a time.

An *M*-bit *A/D* converter will output an *M*-bit binary number. It can represent 2^M binary numbers.

Most measurements these days require *A/D* converter. So, how do you select an *A/D* converter?

Considerations in Selecting A/D Converter

Resolution (Q) : Smallest voltage increment that will cause a bit change.

$$Q = E_{FSR} / 2^{M}$$

Quantization Error: Any input voltage that falls between two adjacent output codes will result in an error – known as the quantization error. This caused due to the finite resolution of the *A/D* converter. This voltage shows up as a *noise* in the signal.

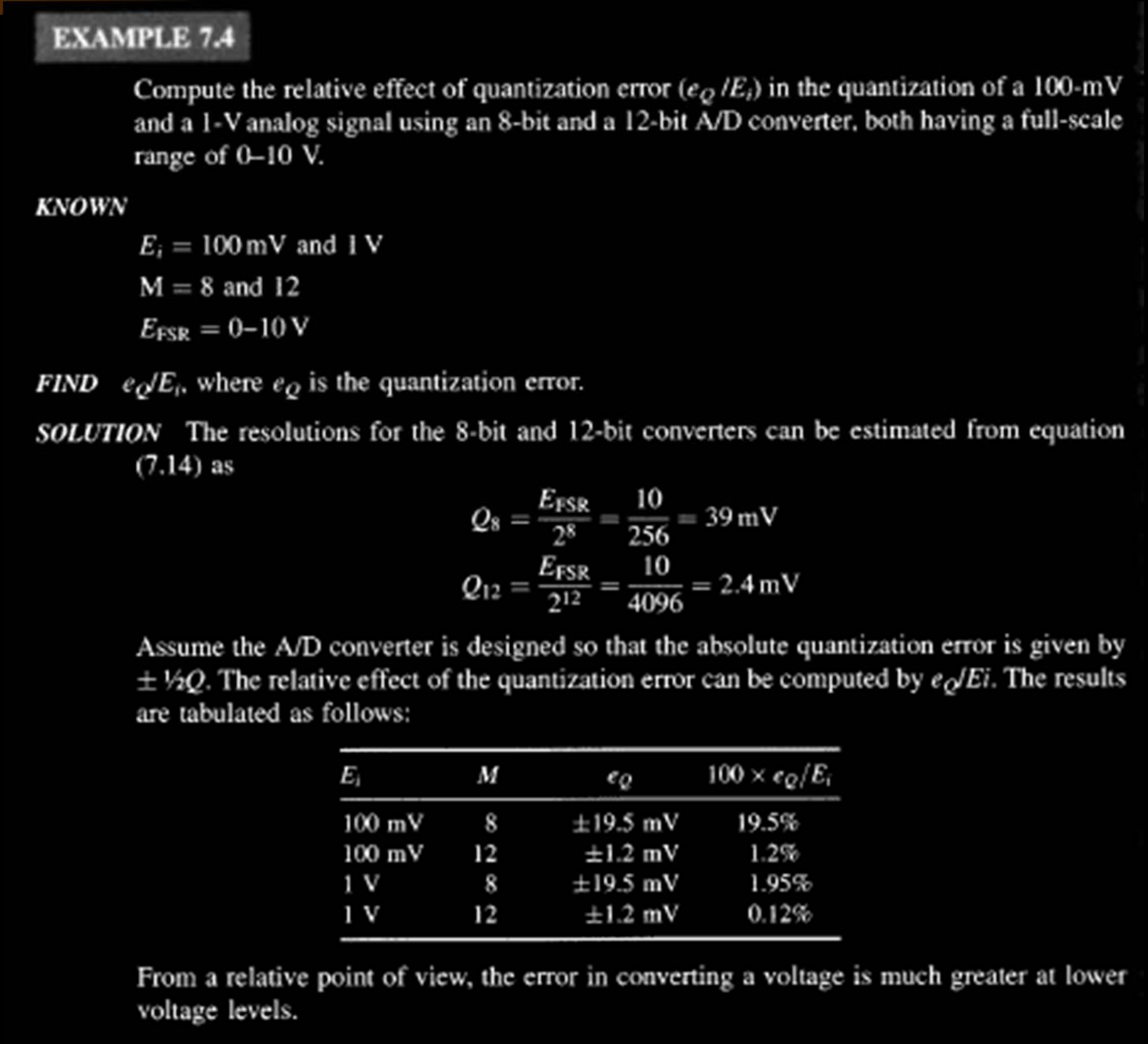
The A/D converter resolution is also specified in terms of signal-to-noise (SNR) ratio.

$$SNR[dB] = 20 \log 2^{M}.$$

Saturation Error: If the incoming or outgoing voltage exceeds, the specified range on the A/D converter, it is known to have saturated and the error is called saturation error.

Conversion Error: Errors that arise during the process of converting an analog signal to digital. These errors include linearity, hysteresis, sensitivity, zero and repeatability errors.

Considerations in Selecting A/D Converter



EXAMPLE 7.4

Compute the relative effect of quantization error (e_Q/E_i) in the quantization of a 100-mV and a 1-V analog signal using an 8-bit and a 12-bit A/D converter, both having a full-scale range of 0–10 V.

KNOWN

$E_i = 100\,\text{mV}$ and $1\,\text{V}$

$M = 8$ and 12

$E_{FSR} = 0\text{–}10\,\text{V}$

FIND e_Q/E_i, where e_Q is the quantization error.

SOLUTION The resolutions for the 8-bit and 12-bit converters can be estimated from equation (7.14) as

$$Q_8 = \frac{E_{FSR}}{2^8} = \frac{10}{256} = 39\,\text{mV}$$

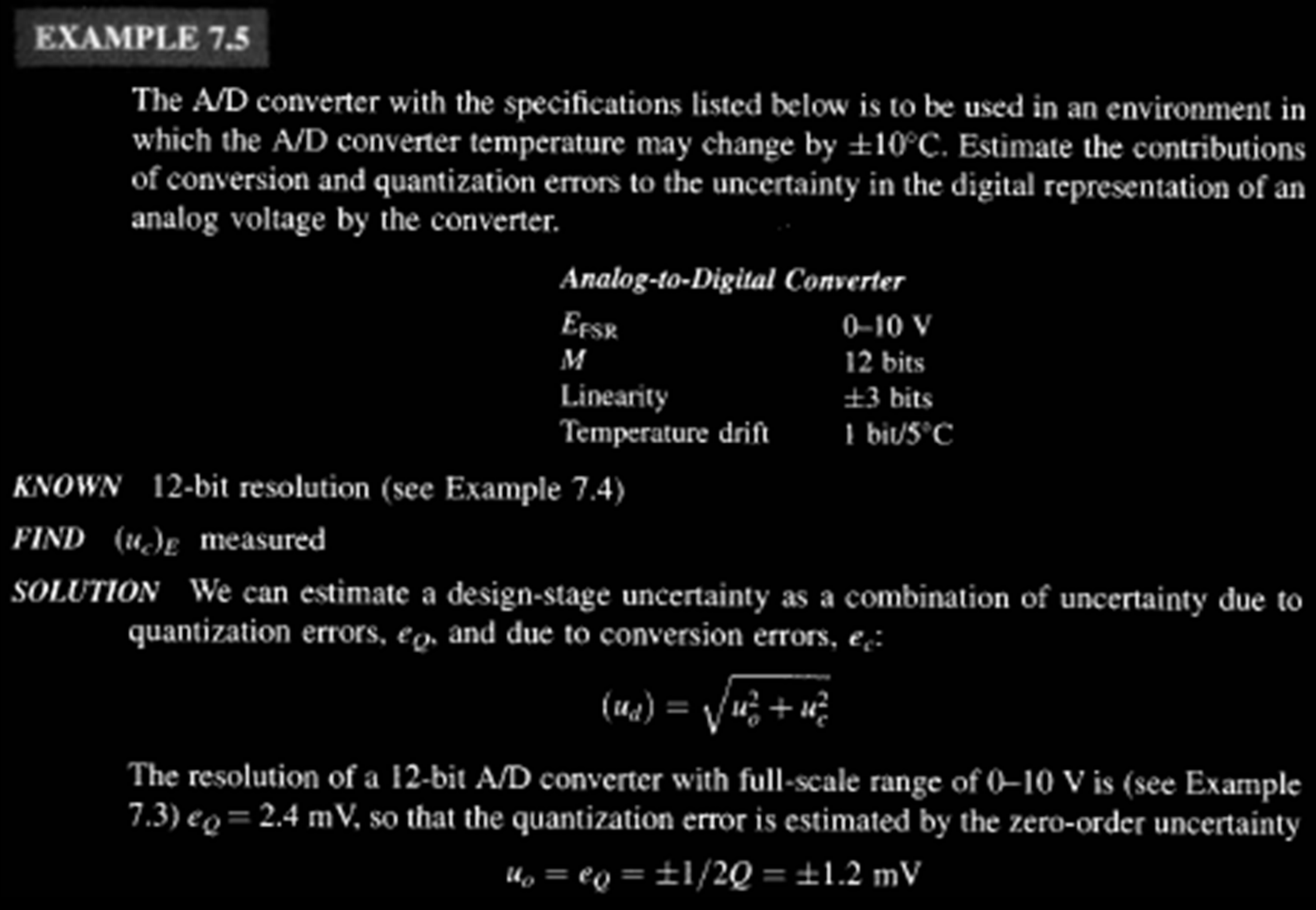
$$Q_{12} = \frac{E_{FSR}}{2^{12}} = \frac{10}{4096} = 2.4\,\text{mV}$$

Assume the A/D converter is designed so that the absolute quantization error is given by $\pm \frac{1}{2}Q$. The relative effect of the quantization error can be computed by e_Q/Ei. The results are tabulated as follows:

E_i	M	e_Q	$100 \times e_Q/E_i$
100 mV	8	±19.5 mV	19.5%
100 mV	12	±1.2 mV	1.2%
1 V	8	±19.5 mV	1.95%
1 V	12	±1.2 mV	0.12%

From a relative point of view, the error in converting a voltage is much greater at lower voltage levels.

Considerations in Selecting A/D Converter



EXAMPLE 7.5

The A/D converter with the specifications listed below is to be used in an environment in which the A/D converter temperature may change by ±10°C. Estimate the contributions of conversion and quantization errors to the uncertainty in the digital representation of an analog voltage by the converter.

Analog-to-Digital Converter

E_{FSR}	0–10 V
M	12 bits
Linearity	±3 bits
Temperature drift	1 bit/5°C

KNOWN 12-bit resolution (see Example 7.4)

FIND $(u_c)_E$ measured

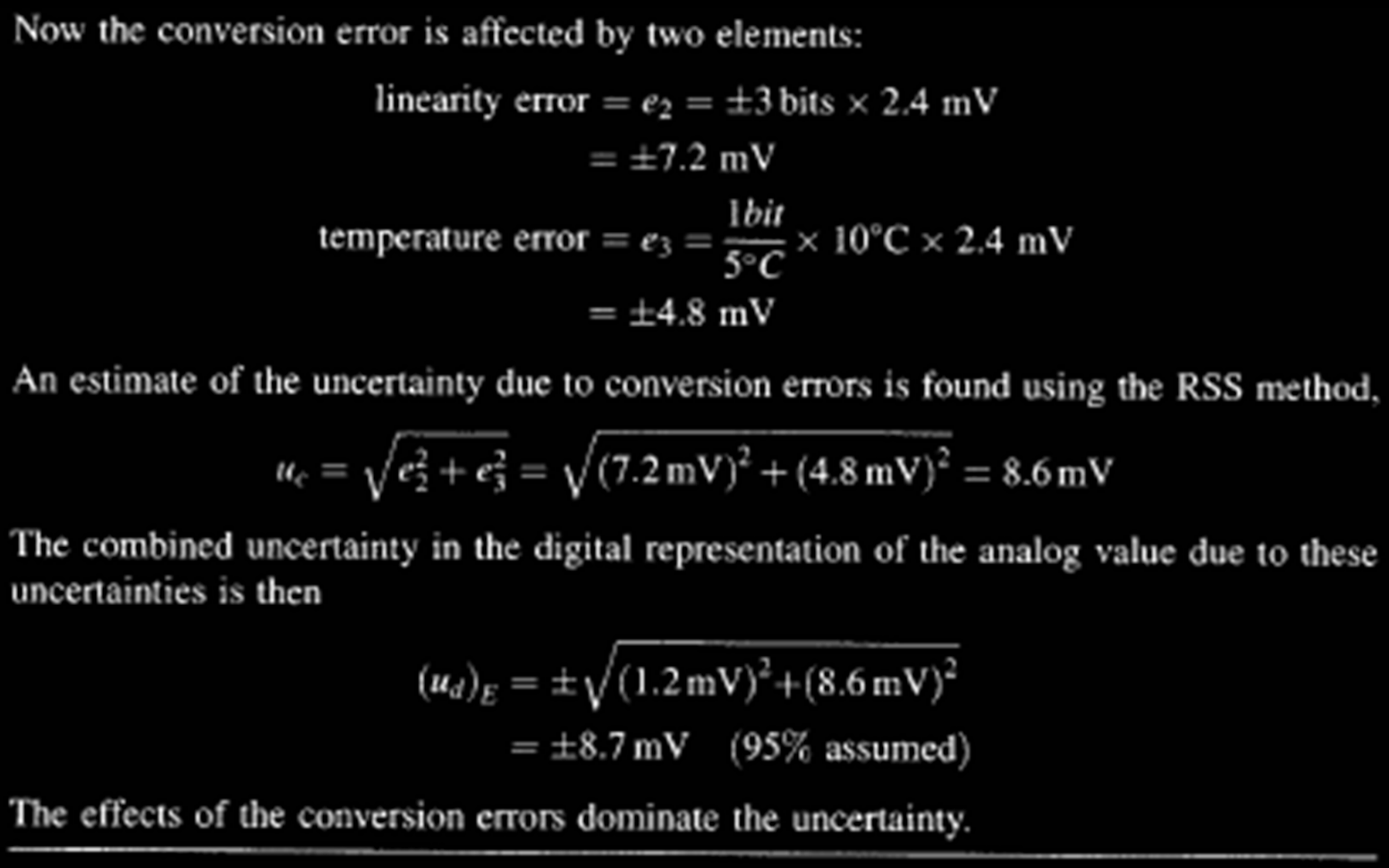
SOLUTION We can estimate a design-stage uncertainty as a combination of uncertainty due to quantization errors, e_Q, and due to conversion errors, e_c:

$$(u_d) = \sqrt{u_o^2 + u_c^2}$$

The resolution of a 12-bit A/D converter with full-scale range of 0–10 V is (see Example 7.3) $e_Q = 2.4$ mV, so that the quantization error is estimated by the zero-order uncertainty

$$u_o = e_Q = \pm 1/2Q = \pm 1.2 \text{ mV}$$

Considerations in Selecting A/D Converter



Now the conversion error is affected by two elements:

$$\text{linearity error} = e_2 = \pm 3\,\text{bits} \times 2.4\text{ mV}$$
$$= \pm 7.2\text{ mV}$$
$$\text{temperature error} = e_3 = \frac{1 bit}{5°C} \times 10°\text{C} \times 2.4\text{ mV}$$
$$= \pm 4.8\text{ mV}$$

An estimate of the uncertainty due to conversion errors is found using the RSS method,

$$u_c = \sqrt{e_2^2 + e_3^2} = \sqrt{(7.2\,\text{mV})^2 + (4.8\,\text{mV})^2} = 8.6\,\text{mV}$$

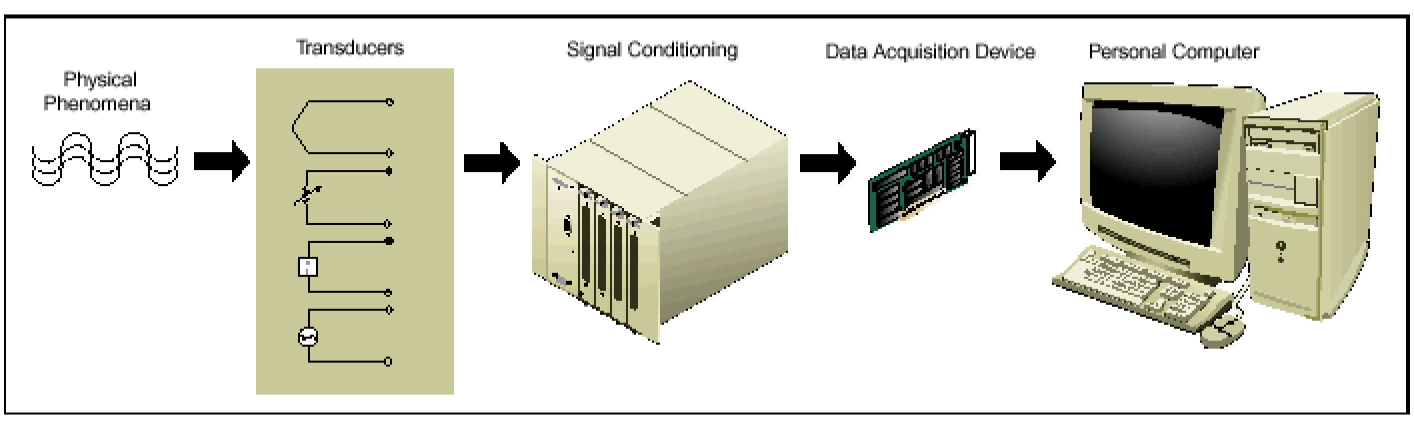
The combined uncertainty in the digital representation of the analog value due to these uncertainties is then

$$(u_d)_E = \pm\sqrt{(1.2\,\text{mV})^2 + (8.6\,\text{mV})^2}$$
$$= \pm 8.7\,\text{mV} \quad (95\%\ \text{assumed})$$

The effects of the conversion errors dominate the uncertainty.

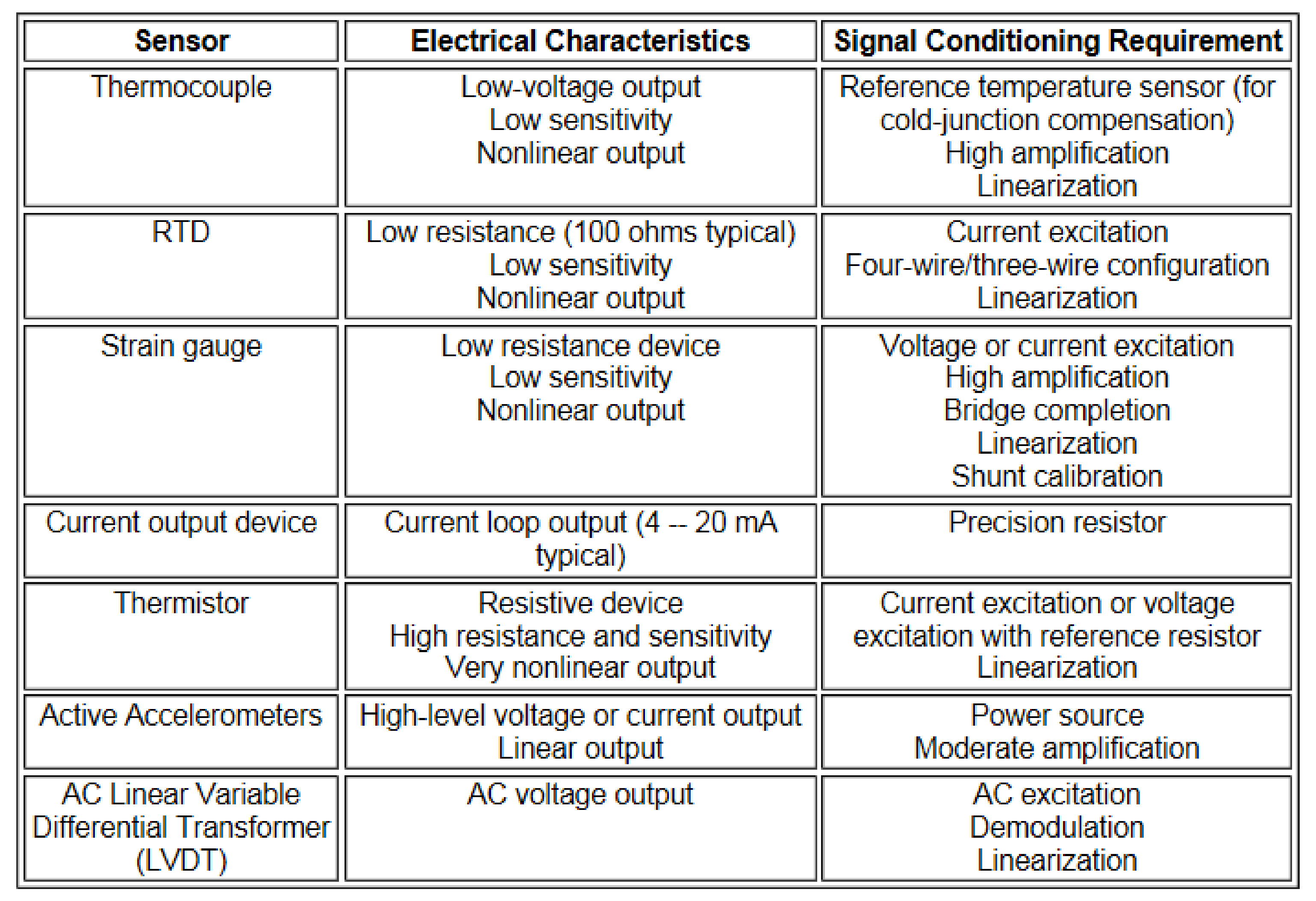
Signal Conditioning[+]

- Many real-world sensors and transducers require signal conditioning before a computer-based measurement system can effectively and accurately acquire the signal.
- Front-end signal conditioning system can include functions such as signal amplification, attenuation, filtering, electrical isolation, simultaneous sampling, and multiplexing.
- Many transducers require excitation currents or voltages, bridge completion, linearization, or high amplification for proper and accurate operation.



[+] *National Instruments*

Signal Conditioning[+]

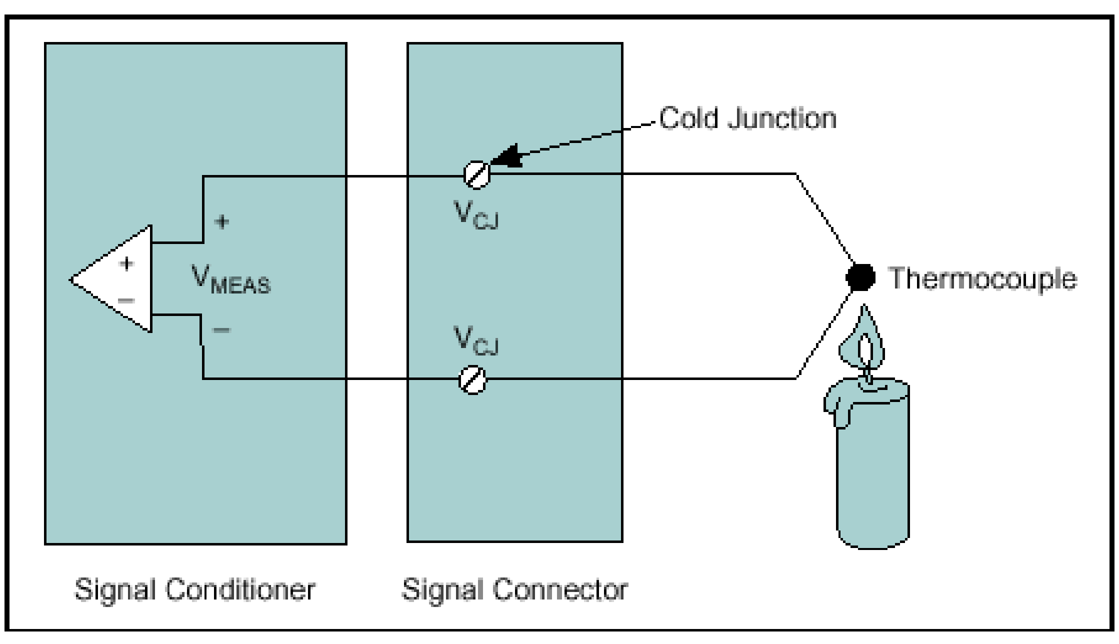


Sensor	Electrical Characteristics	Signal Conditioning Requirement
Thermocouple	Low-voltage output Low sensitivity Nonlinear output	Reference temperature sensor (for cold-junction compensation) High amplification Linearization
RTD	Low resistance (100 ohms typical) Low sensitivity Nonlinear output	Current excitation Four-wire/three-wire configuration Linearization
Strain gauge	Low resistance device Low sensitivity Nonlinear output	Voltage or current excitation High amplification Bridge completion Linearization Shunt calibration
Current output device	Current loop output (4 -- 20 mA typical)	Precision resistor
Thermistor	Resistive device High resistance and sensitivity Very nonlinear output	Current excitation or voltage excitation with reference resistor Linearization
Active Accelerometers	High-level voltage or current output Linear output	Power source Moderate amplification
AC Linear Variable Differential Transformer (LVDT)	AC voltage output	AC excitation Demodulation Linearization

[+] *National Instruments*

Thermocouples

- Most popular transducer for measuring temperature .
- A thermocouple operates on the principle that the junction of two dissimilar metals generates a voltage that varies with temperature.
- Measuring this voltage is difficult because connecting the thermocouple to the terminals of a DAQ board creates what is called the reference junction or cold junction.



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Thermocouples

- There are two general approaches to cold-junction compensation -- hardware and software compensation.
- Hardware compensation uses a special circuit that applies the appropriate voltage to cancel the cold-junction voltage.
- Cold-junction compensation in software, on the other hand, is very flexible and requires only knowing the ambient temperature. If you use an additional sensor to directly measure the ambient temperature at the cold junction, you can compute the appropriate compensation for the unwanted thermoelectric voltages.

$^{+}$*National Instruments*

Thermocouples - Sensitivity

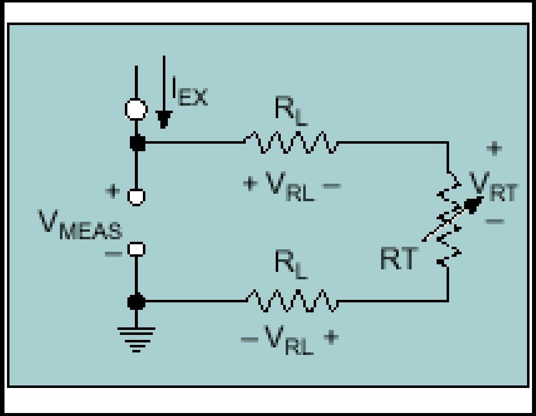
- Thermocouple outputs are very low level and change only 7 to 50 µV for every 1 °C change in temperature.
- You can increase the sensitivity of the system with a low-noise, high-gain amplification of the signal.
- For example, a plug-in DAQ board with an analog input range of ±5 V, an amplifier gain of 100, and a 12-bit analog-to-digital converter (ADC) has the following resolution.

$$\frac{10\ \text{V}}{(2^{12})\cdot 100} = 24.4\ \mu\text{V/bit}$$

$^{+}$*National Instruments*

RTD's

- An RTD consists of a wire coil or deposited film of pure metal whose resistance increases with temperature.
- Known for its stability and accuracy over a wide temperature range.
- The most popular type is made of platinum and has a nominal resistance of 100 ohms at 0 °C.



- Because RTDs are passive resistive devices, you must pass a current through the RTD to produce a voltage that a DAQ board can measure

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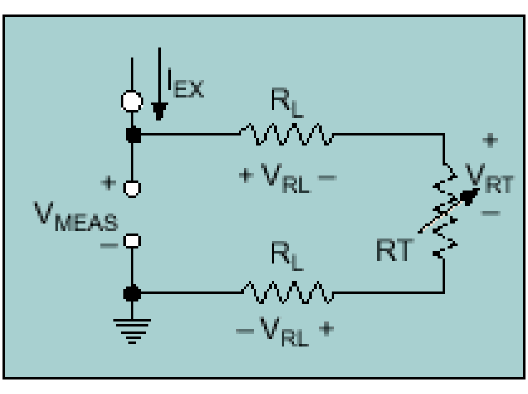
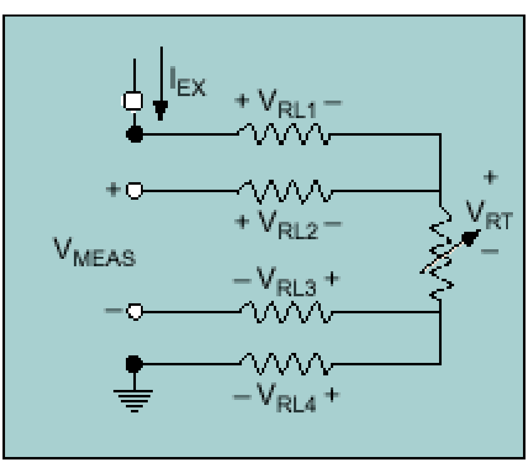
RTD's



- ❖ Because RTDs are passive resistive devices, you must pass a current through the RTD to produce a voltage that a DAQ board can measure.
- ❖ With a 2-wire RTD, labeled RT, the voltage drops caused by the excitation current, I_{EX}, passing through the lead resistance, R_L, add to the measured voltage, V_{MEAS}.



- ❖ With a 4-wire RTD, one pair of wires carries the excitation current through the RTD; the other pair senses the voltage across the RTD.
- ❖ Because only negligible current flows through the sensing wires, the lead resistance error is very small.

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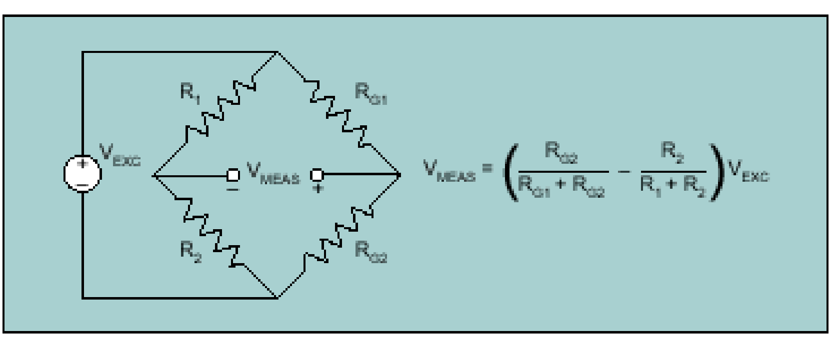
Strain Gages

- ❖ Strain gauges are also used in sensors that detect force or other derived quantities, such as acceleration, pressure, and vibration.
- ❖ Most common type is the bonded resistance strain gauge, which consists of a grid of very fine foil or wire.
- ❖ The electrical resistance of the grid varies linearly with the strain applied to the device. When using a strain gauge, you bond the strain gauge to the device under test, apply force, and measure the strain by detecting changes in resistance.



$$V_{MEAS} = \left(\frac{R_{G2}}{R_{G1} + R_{G2}} - \frac{R_2}{R_1 + R_2}\right) V_{EXC}$$

- ❖ Strain gauges can occupy one, two or four arms of the bridge, with any remaining positions filled with fixed resistors.

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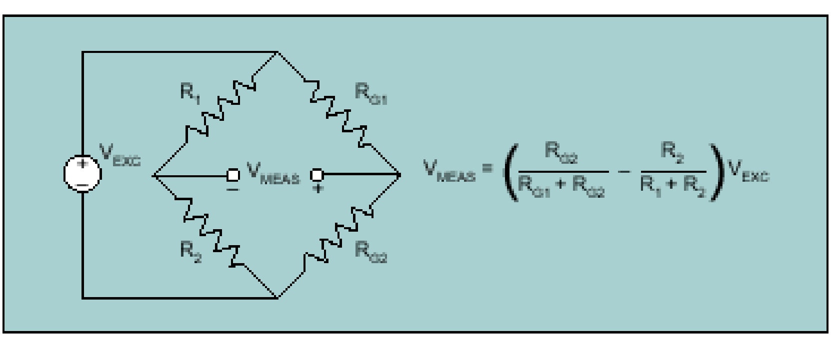

- When the ratio of R_{G1} to R_{G2} equals the ratio of R_1 to R_2, the measured voltage V_O is 0 V. This condition is referred to as a balanced bridge. As strain is applied to the gauge, their resistance values change, causing a change in the voltage at V_{MEAS}.

$^+$*National Instruments*

Accelerometers

- An accelerometer is a device commonly used to measure acceleration and vibration.
- It consists of a known mass attached to a piezoelectric element. As the accelerometer moves, the mass applies force to the element and generates a charge. By reading this charge, you can determine acceleration.
- Accelerometers are directional, measuring acceleration along only one axis. To monitor acceleration in three dimensions, we should choose a multi-axis accelerometer.
- Accelerometers are available in two types, passive and active.
- Passive accelerometers send out the charge generated by the piezoelectric element. Because the signal is very small, passive accelerometers require a charge amplifier to boost the signal.
- Active accelerometers include internal circuitry to convert the accelerometer charge into a voltage signal, but require a constant current source to drive the circuitry.

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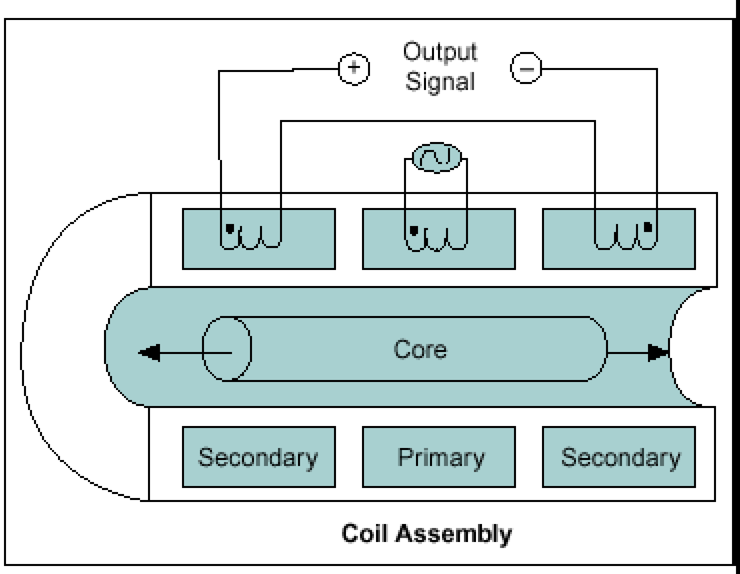
LVDT's

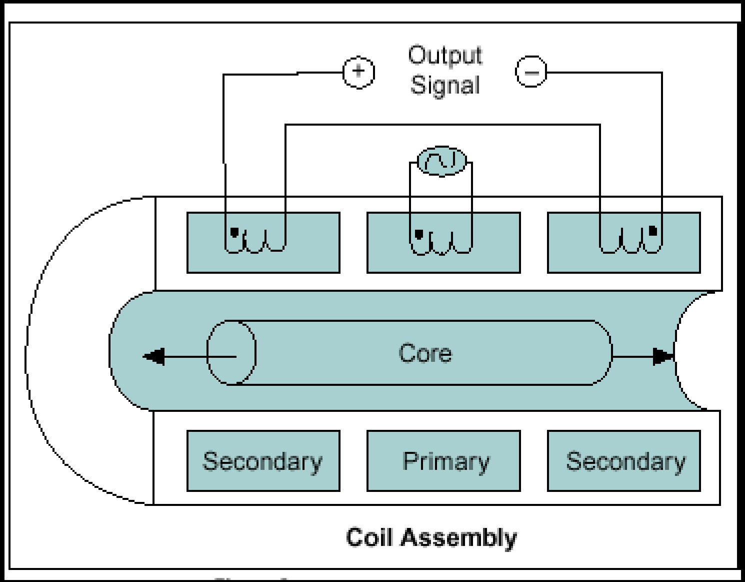
- A linear voltage differential transformer (LVDT) is a device commonly used to measure linear displacement.



- When an AC excitation voltage is applied to the primary winding, a voltage is induced in each secondary winding through the magnetic core.

⁺*National Instruments*

LVDT's



- The position of the core determines how strongly the excitation signal couples to each secondary winding.
- When the core is in the center, the voltage of each secondary coil is equal and 180 degrees out of phase, resulting in no signal.
- As the core travels to the left of center, the primary coil is more tightly coupled to the left secondary coil, creating an output signal in phase with the excitation signal.
- As the core travels to the right of center, the primary coil is more tightly coupled to the right secondary coil, creating an output signal 180 degrees out of phase with the excitation voltage.

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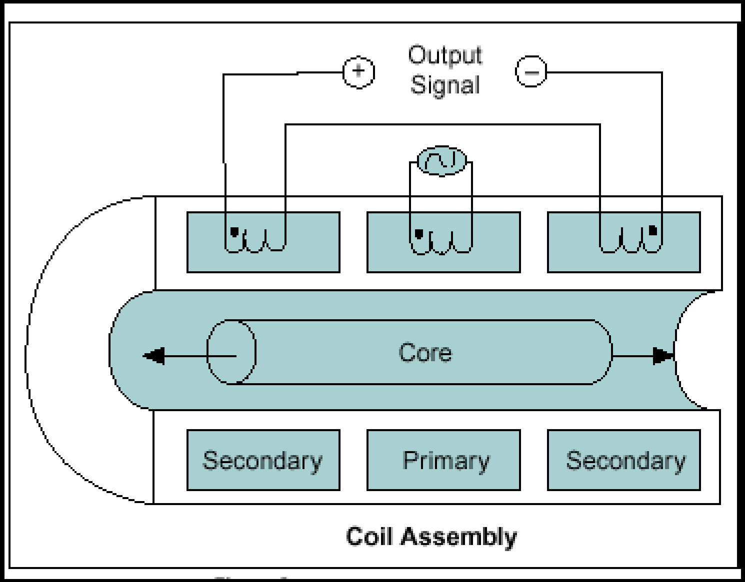
LVDT's



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Data Acquisition System Components

Analog signals usually require ***Signal Conditioning*** for proper interface with a digital system.

Filters: Controls the frequency content of the signal being sampled. A *low-pass filter* only allows frequencies that are lower than the *cut-off frequency*. A *high-pass filter* only allows signals that are above the cut-off frequency. A *band-pass filter* only allows signals that are within the specified band.

Amplifier: Low voltage signals are amplified and high-voltage signals are attenuated before the A/D conversion

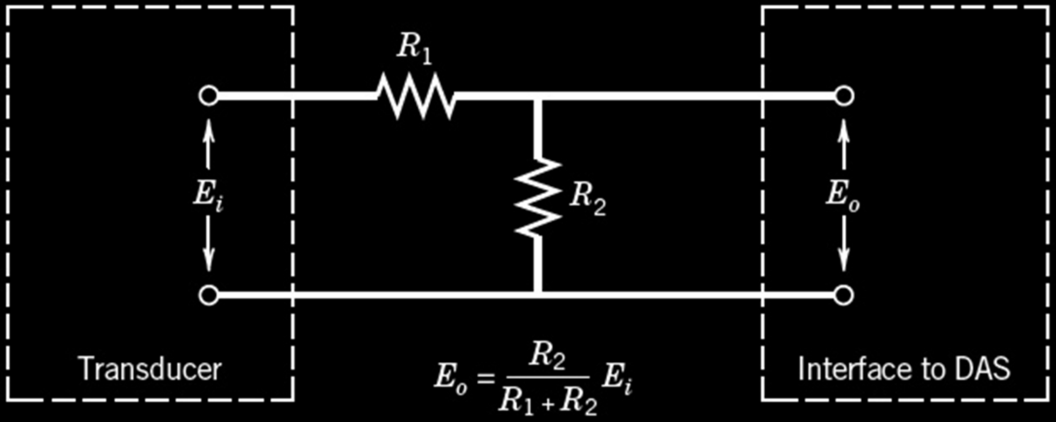


Figure 7.15 Voltage divider circuit for signal amplitude attenuation.

Data Acquisition System Components

Shunt Circuit: A circuit to convert current signal into voltage signal using a shunt resistor.

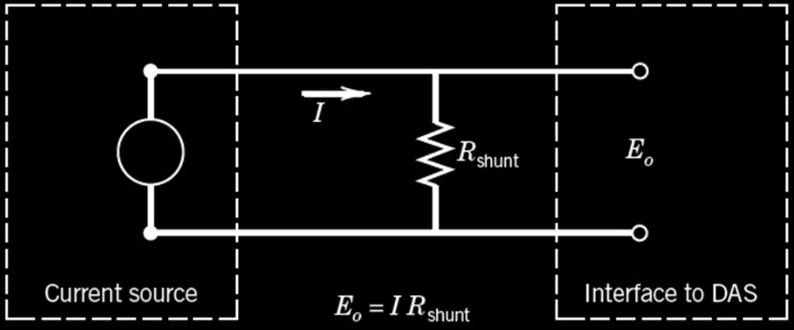


Figure 7.16 Simple shunt resistor circuit.

Offset Nulling Circuit: Subtracts a small voltage to zero out a transducer output signal.

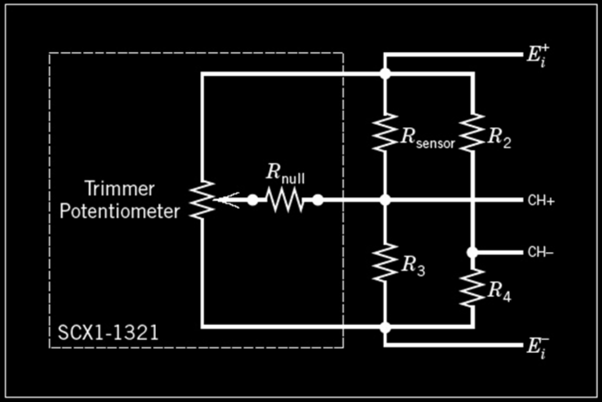


Figure 7.17 Circuit for applying a null offset voltage. (Courtesy of National Instruments, Inc.)

The other DAQ system components are Multiplexer, A/D & D/A converters, central bus, memory etc.

Data Acquisition Boards

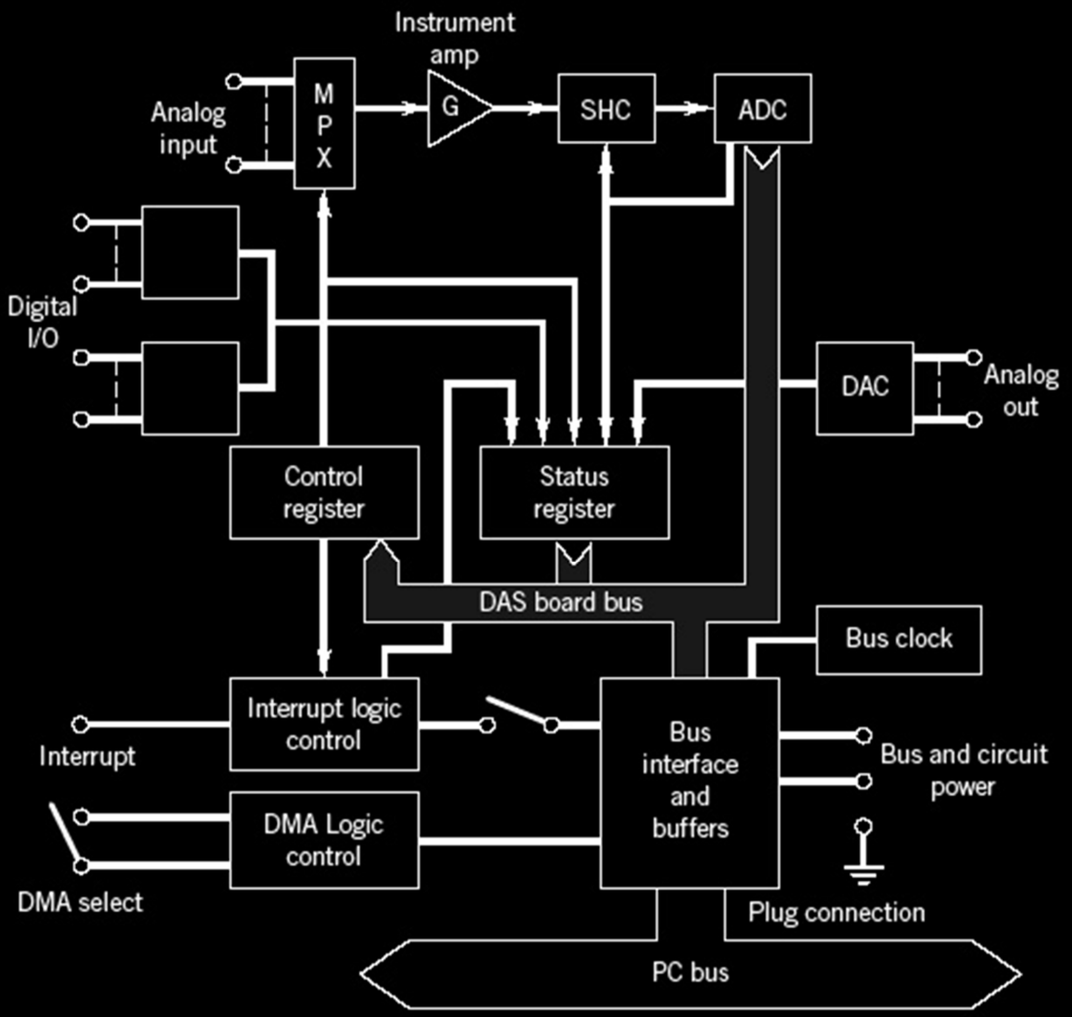
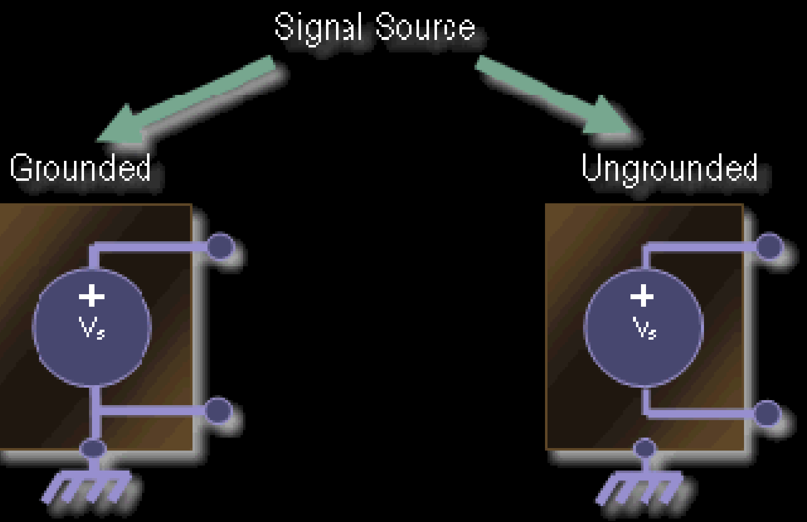
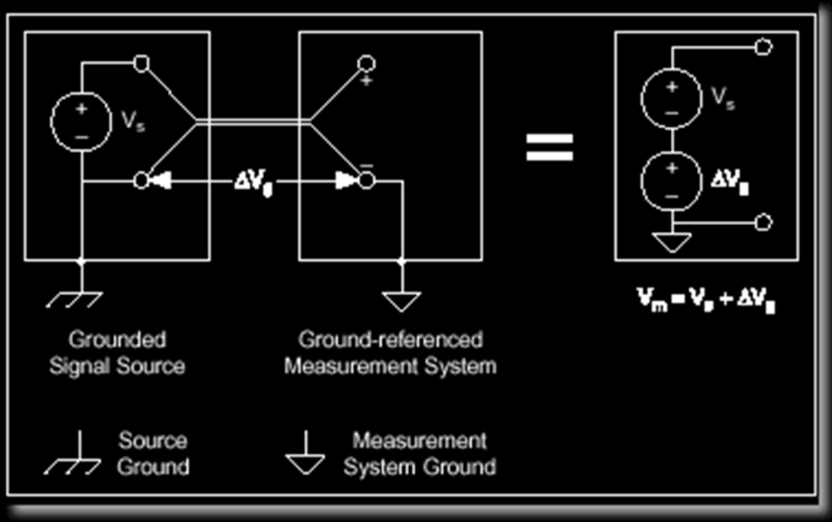


Figure 7.22 Typical layout for a data-acquisition plug-in board. (Courtesy of National Instruments, Inc.)

Analog Input Signals





Source: National Instruments

Common-Mode Voltage (CMV): The voltage that arises due to the voltage difference between the *source ground* and the *board ground* in a single-ended connection.

Floating Source: Signal sources that are not referenced to any ground. e.g. batteries, thermocouple signals etc.

Single & Differential Ended Connections

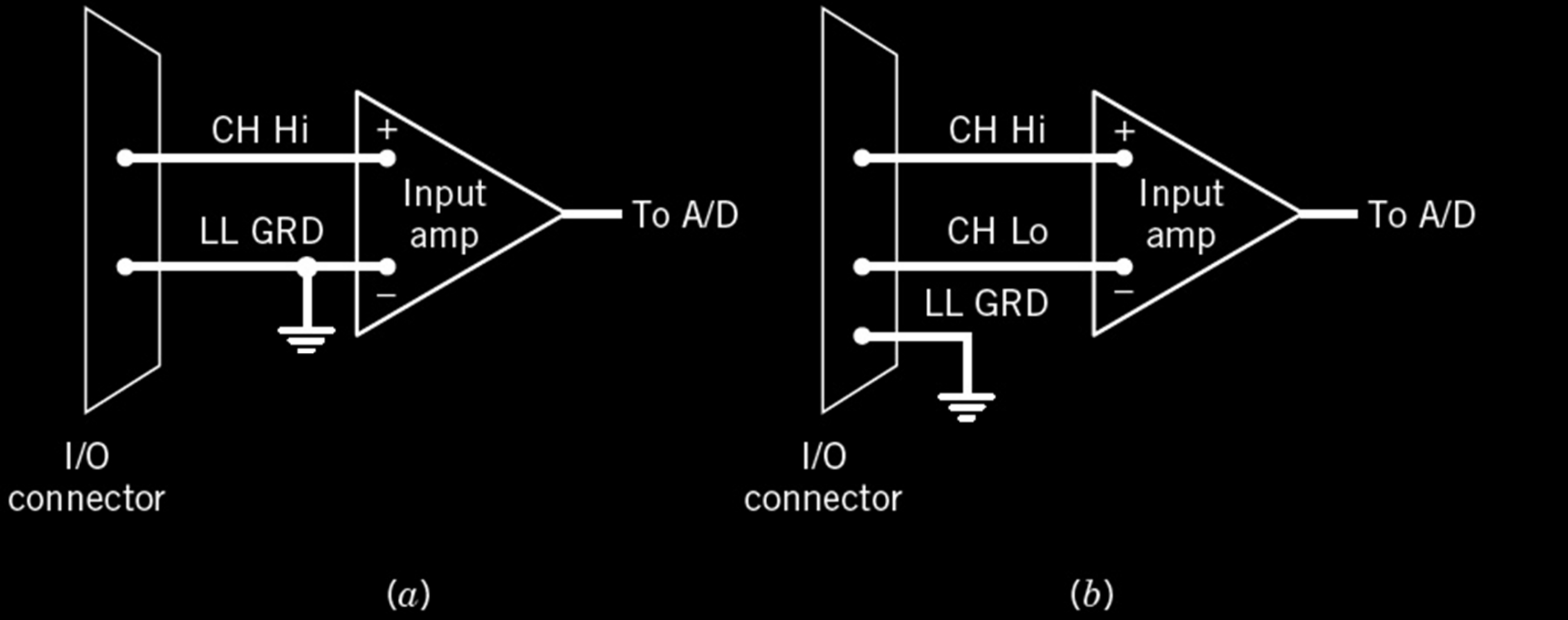


Figure 7.25 (a) Single-ended connection. (b) Differential-ended connection.