Temperature Sensors & Measurement

E80 Spring 2014

Contents

- Why measure temperature?
- Characteristics of interest
- Types of temperature sensors
  - 1. Thermistor
  - 2. RTD Sensor
  - 3. Thermocouple
  - 4. Integrated Silicon Linear Sensor
- Sensor Calibration
- Signal Conditioning Circuits (throughout)

Why Measure Temperature?

- Temperature measurements are one of the most common measurements...

- Temperature corrections for other sensors
  – e.g., strain, pressure, force, flow, level, and position many times require temperature monitoring in order to insure accuracy.

Important Properties?

- Sensitivity
- Temperature range
- Accuracy
- Repeatability
- Relationship between measured quantity and temperature
- Linearity
- Calibration
- Response time

Types of Temperature Sensors?

Covered

1. Thermistor
   - Ceramic-based: oxides of manganese, cobalt , nickel and copper
2. Resistive Temperature Device - RTD
   - Metal-based : platinum, nickel or copper
3. Thermocouple
   - junction of two different metals
4. Integrated Silicon Linear Sensor
   - Si PN junction of a diode or bipolar transistor

Not Covered

5. Hot Wire Anemometer

6. Non-Contact IR Single Sensor

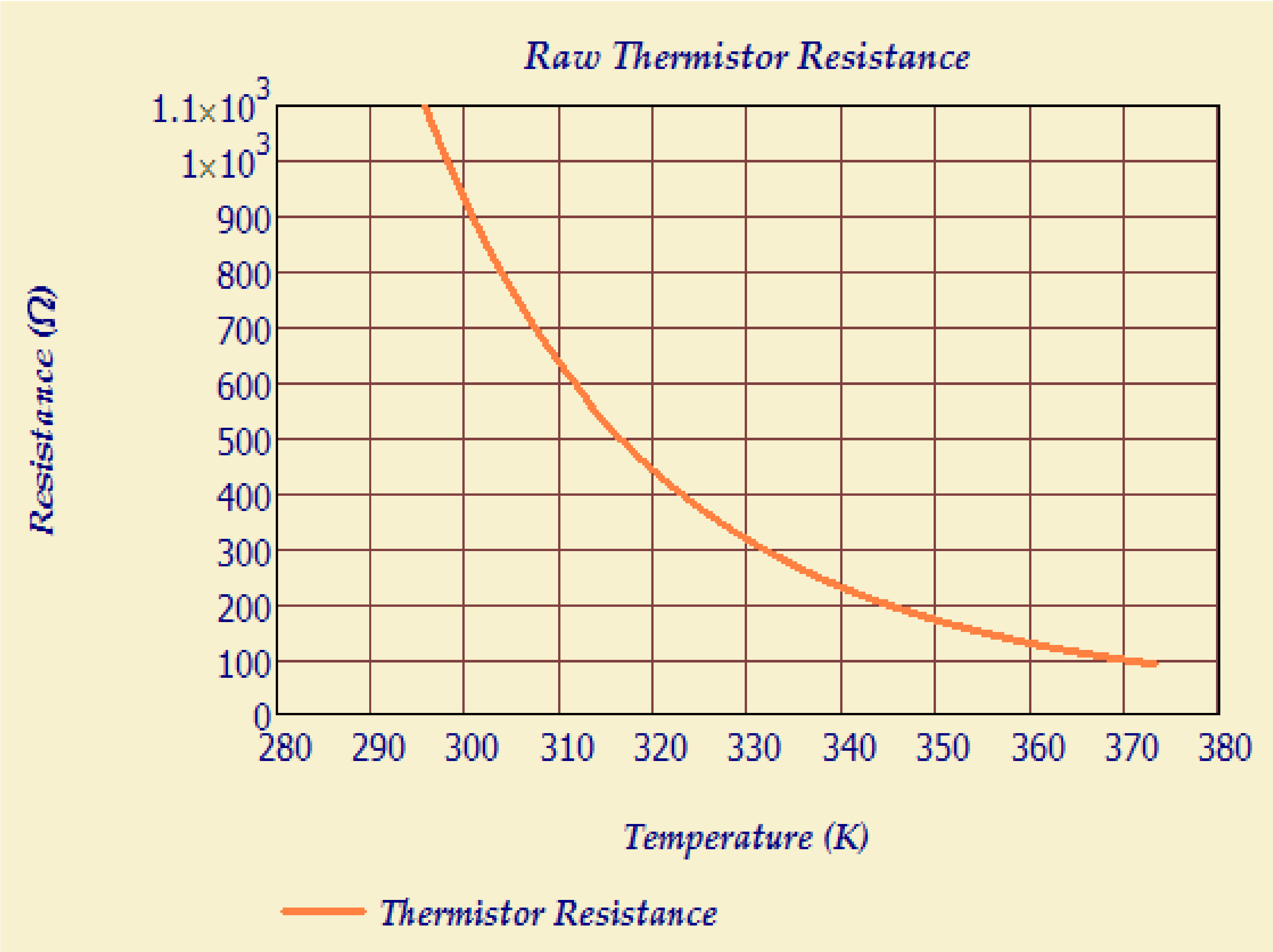
7. IR Camera

TABLE 1 POPULAR TEMPERATURE SENSORS

Parameter	Thermocouple	RTD	Thermistor	Silicon based
Temperature range (°C)	–270 to +1800	–250 to +900	–100 to +450	–55 to +150
Sensitivity	Tens of microvolts per degree Celsius	0.00385Ω/Ω/°C (platinum)	Several Ω/Ω/°C	Uses technology that is approximately –2 mV/°C sensitive
Accuracy (°C)	±0.5	±0.01	±0.1	±1
Linearity	Requires at least a fourth-order polynomial or equivalent look-up table	Requires at least a second-order polynomial or equivalent look-up table	Requires at least a third-order polynomial or equivalent look-up table	At best within ±1°C; no linearization required unless higher accuracy is desired; high accuracy results require a third-order polynomial
Ruggedness	Rugged due to larger-gauge wires and insulation materials, which enhance sturdiness	Susceptible to damage as a result of vibration due to #26 to #30 AWG leads, which are prone to breakage	Thermistor element is housed in a variety of ways; however, the most stable hermetic units are enclosed in glass; generally, thermistors are difficult to handle, but shock and vibration do not affect them	As rugged as any other IC in a plastic package, such as dual-in-line or surface-outline ICs
Responsiveness in stirred oil (sec)	Less than 1	1 to 10	1 to 5	4 to 60
Excitation	None required	Current source	Voltage source	Typically, supply voltage
Form of output	Voltage	Resistance	Resistance	Voltage, current, or digital
Typical size	Bead diameter is five times wire diameter	0.25×0.25 in.	0.1×0.1 in.	From TO-18 transistors to plastic DIPs
Price	$1 to $50	$25 to $1000	>$10	$1 to $10

Part I Thermistor

- High sensitivity
- Inexpensive
- Reasonably accurate
- Lead resistance ignored
- Glass bead, disk or chip thermistor
- Typically Negative Temperature Coefficient (NTC),
  - PTC also possible
- nonlinear relationship between R and T



Raw Thermistor Resistance
1.1×10^3
1×10^3
900
800
700
600
500
400
300
200
100
0
280
290
300
310
320
330
340
350
360
370
380
Resistance (Ω)
Temperature (K)
Thermistor Resistance

Simple Exponential Thermistor Model

- $R_T = R_0 \times \exp[\beta(1/T - 1/T_0)]$
  - R_T is the thermistor resistance (Ω).
  - T is the thermistor temperature (K)
  - Manufacturers will often give you R_0, T_0 and an average value for β
    - β is a curve fitting parameter and itself is temperature dependent.

Simple Exponential Thermistor Model

- Usually T_0 is room temp $25^oC = 298^oK$
  - So $R_0 = R_{25}$

- $R_T = R_{25} \times \exp[\beta(1/T – 1/298)]$
  - where $\beta \approx \mathit{ln}\,(R_{85}/R_{25})\,/(1/358-1/298)$

- Not very accurate but easy to use

Better Thermistor model

- Resistance vs temperature is non-linear but can be well characterised by a 3rd order polynomial

- $\mathit{ln}\ R_T = A + B / T + C / T^2 + D / T^3$

  where A,B,C,D are the characteristics of the material used.

Inverting the equation

The four term Steinhart-Hart equation

$$T = [A_1 + B_1\, \mathit{ln}(R_T/R_0) + C_1\, \mathit{ln}^2(R_T/R_0) + D_1 \mathit{ln}^3(R_T/R_0)]^{-1}$$

Also note:

- Empirically derived polynomial fit
- A, B, C & D are not the same as A_1, B_1 , C_1 & D_1
- Manufacturers should give you both for when $R_0 = R_{25}$
- C_1 is very small and sometime ignored (the three term SH eqn)

R_T VALUE AND TOLERANCE

These thermistors have a narrow tolerance on the B-value, the result of which provides a very small tolerance on the nominal resistance value over a wide temperature range. For this reason the usual graphs of $R = f(T)$ are replaced by Resistance Values at Intermediate Temperatures Tables, together with a formula to calculate the characteristics with a high precision.

FORMULAE TO DETERMINE NOMINAL RESISTANCE VALUES

The resistance values at intermediate temperatures, or the operating temperature values, can be calculated using the following interpolation laws
(extended "*Steinhart and Hart*"):

$$R_{(T)} = R_{ref} \times e^{(A + B/T + C/T^2 + D/T^3)} \quad (1)$$

$$T_{(R)} = \left(A_1 + B_1 \ln \frac{R}{R_{ref}} + C_1 \ln^2 \frac{R}{R_{ref}} + D_1 \ln^3 \frac{R}{R_{ref}}\right)^{-1} \quad (2)$$

where:

A, B, C, D, A_1, B_1, C_1 and D_1 are constant values depending on the material concerned; see table below.

R_{ref} is the resistance value at a reference temperature (in this event 25 °C).

T is the temperature in K.

http://www.eng.hmc.edu/NewE80/PDFs/VIshayThermDataSheet.pdf

Thermistor Calibration

3-term Steinhart-Hart equation

$T = [A_1 + B_1\, ln(R_T/R_0) + D_1 ln^3(R_T/R_0)]^{-1}$

How do we find A1, B1 and D1?

Minimum number of data points?

Linear regression/Least Squares Fit (Lecture 2)

Thermistor Problems: Self-heating

- You need to pass a current through to measure the voltage and calculate resistance.

- Power is consumed by the thermistor and manifests itself as heat inside the device
  - **$P = I^2 R_T$**
  - You need to know how much the temp increases due to self heating by P so **you need to be given θ =** the temperature rise for every watt of heat generated.

Heat flow

- Very similar to Ohms law. The temperature difference (increase or decrease) is related to the power dissipated as heat and the thermal resistance.

$$\Delta C = P \times \theta$$

  - P in Watts
  - θ in ^{o}C /W

Self Heating Calculation

- $\Delta^{o}C = P \times \theta = (I^2 R_T)\, \theta_{\text{Device to ambient}}$
- Example.
  - $I = 5mA$
  - $R_T = 4k\Omega$
  - $\theta_{\text{Device to ambient}} = 15\ ^{o}C/W$
- $\Delta^{o}C =$

Self Heating Calculation

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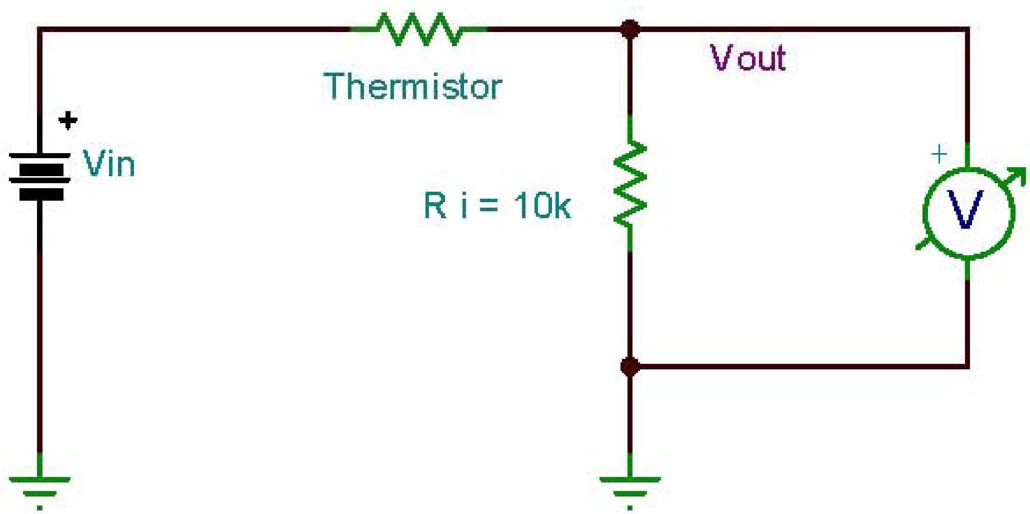
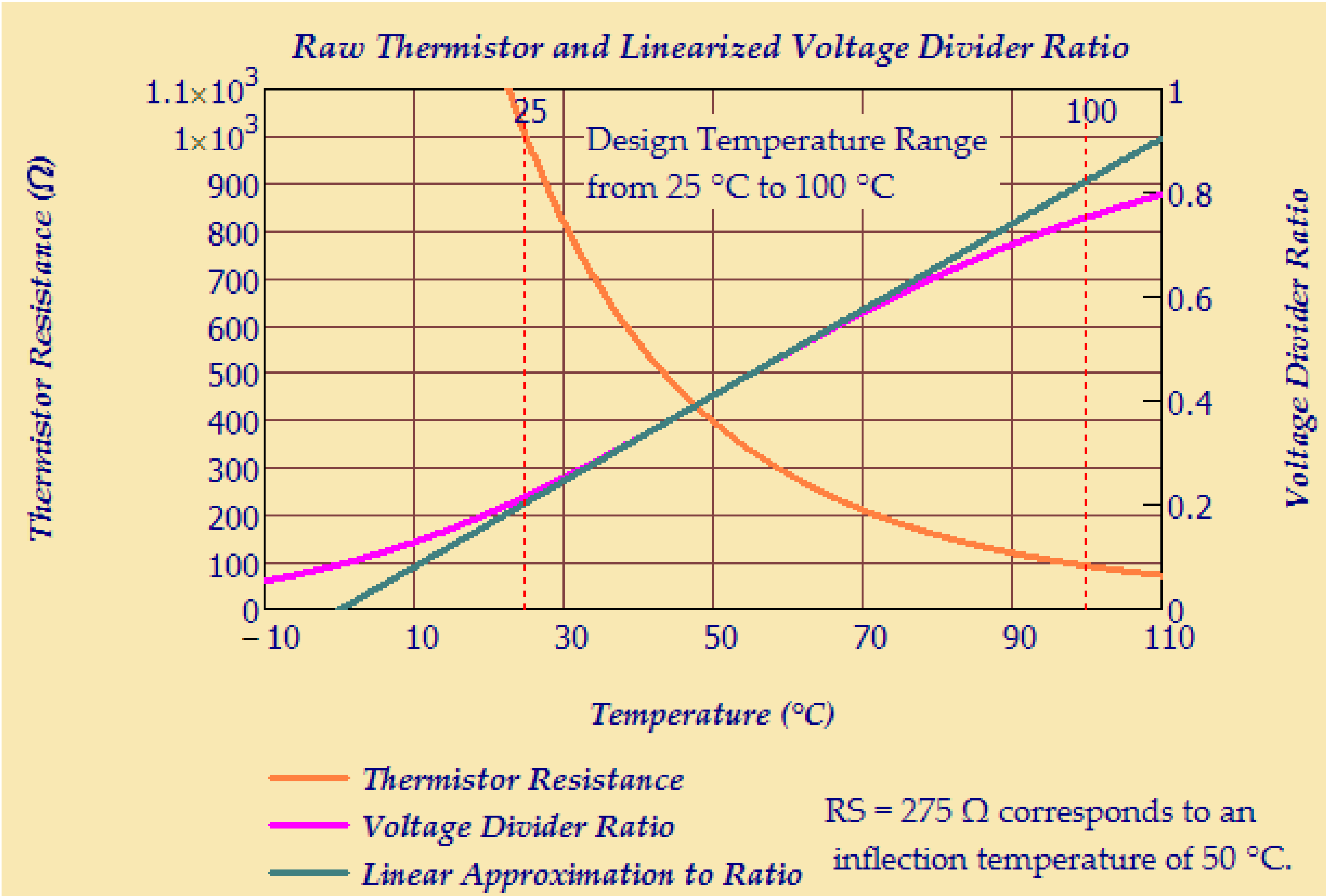
- Example.
  - $I = 5mA$
  - $R_T = 4k\Omega$
  - $\theta_{\text{Device to ambient}} = 15\ ^{o}C\ /W$
- $\Delta^{o}C = (0.005)^2 \times 4000 \times 15 = \underline{1.5\ C}$

Linearization Techniques

- Current through Thermistor is dominated by 10k Ω resistor.

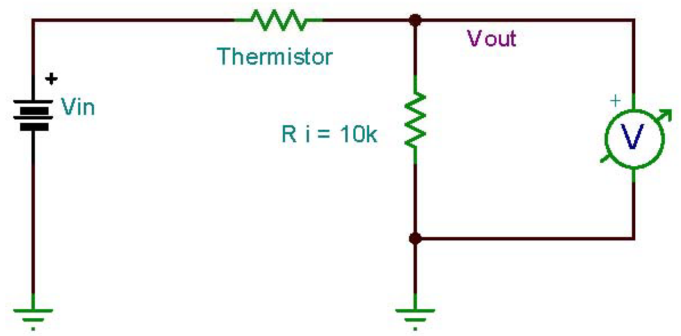


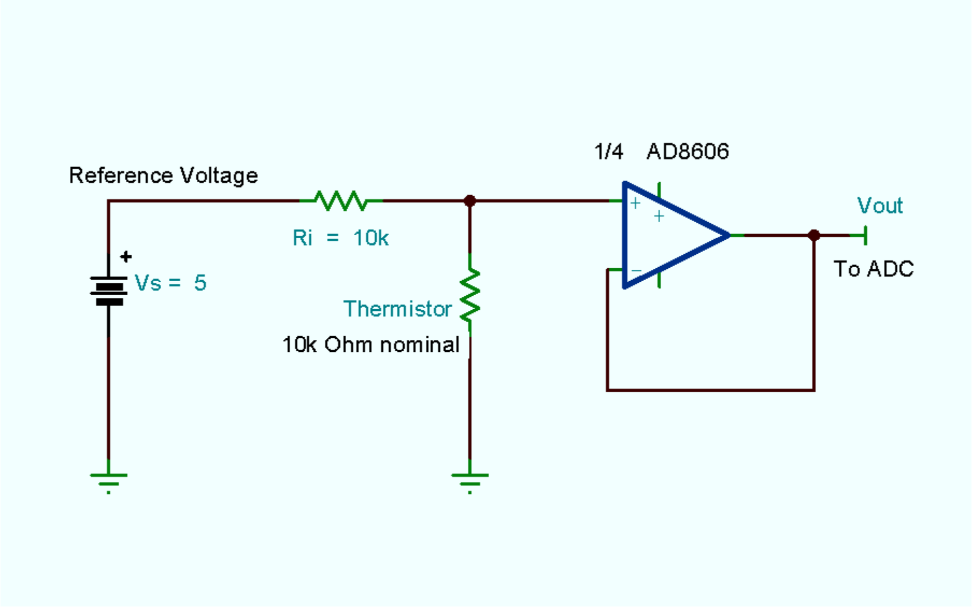
Linearization of a 1O k-Ohm Thermistor



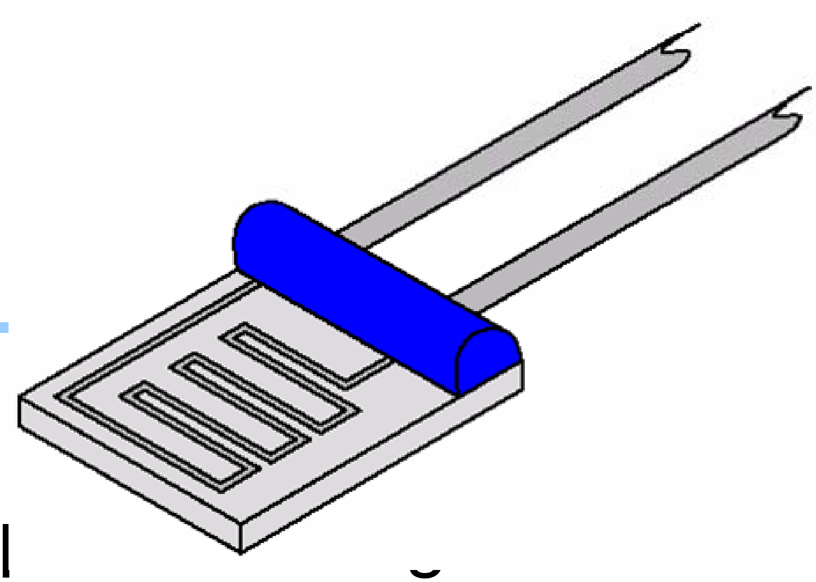
This plot Ti = 50 ^{0}C, Ri = 275 Ω

Linearization techniques





Part II RTD

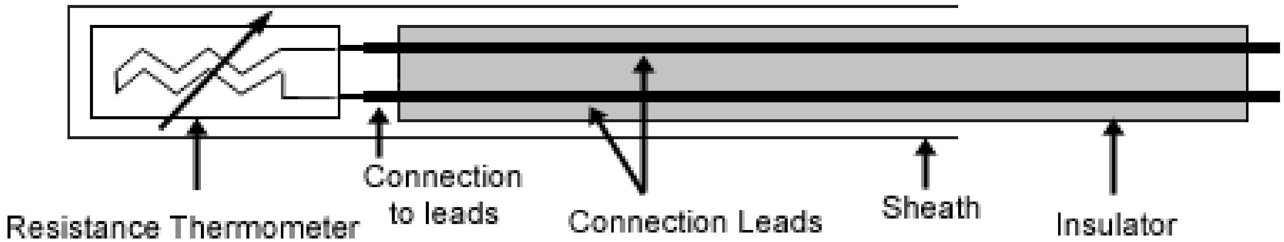


- Accurate & Stable
- Reasonably wide tem
- More Expensive
- Positive temperature constant
- Requires constant currant excitation
- Smaller resistance range
  - Self heating is a concern
  - Lead wire resistance is a concern

More complicated signal conditioning

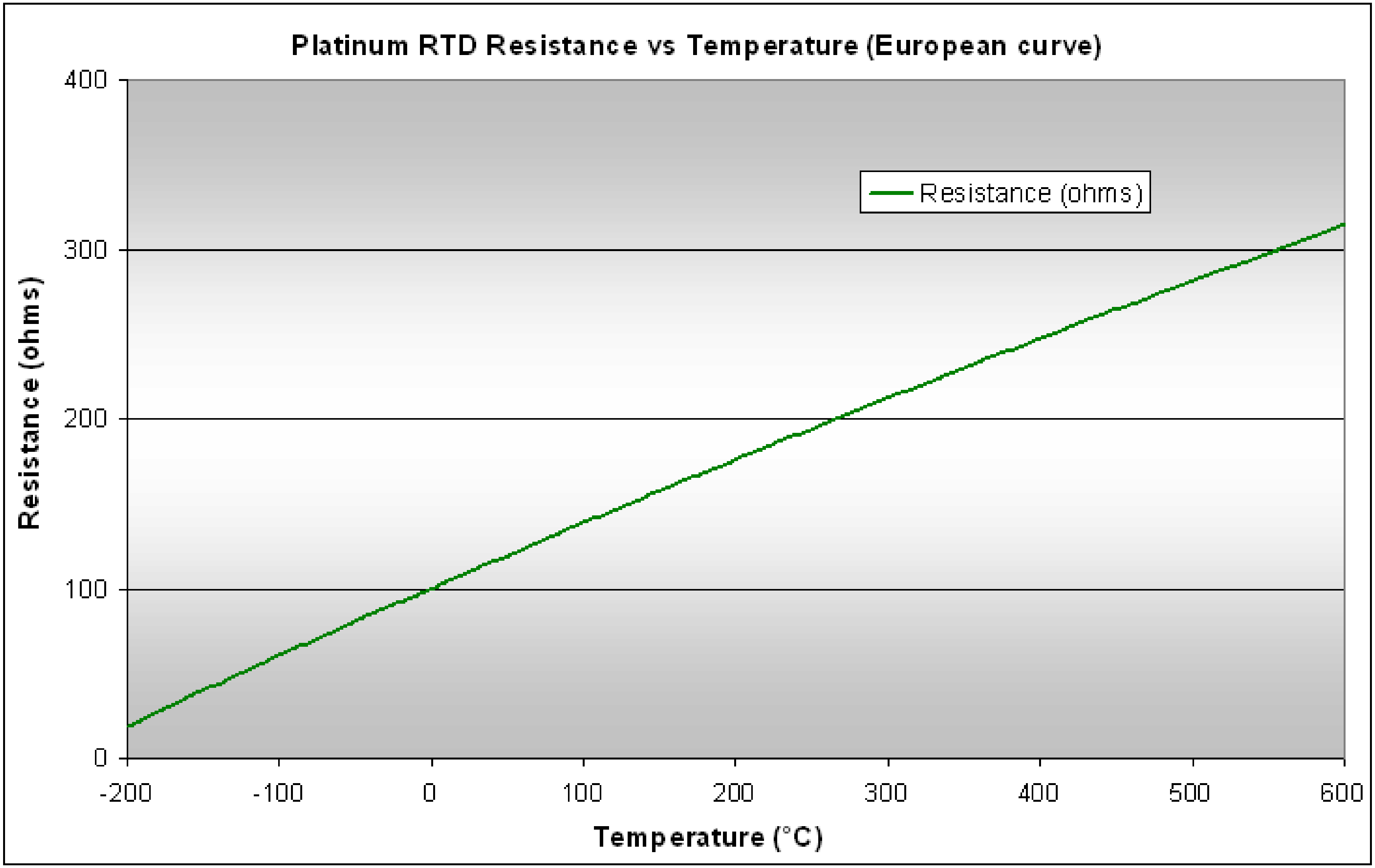
pRTD, cRTD and nRTD

- The most common is one made using platinum so we use the acronym pRTD



- Copper and nickel as also used but not as stable

Linearity: The reason RTDs are so popular



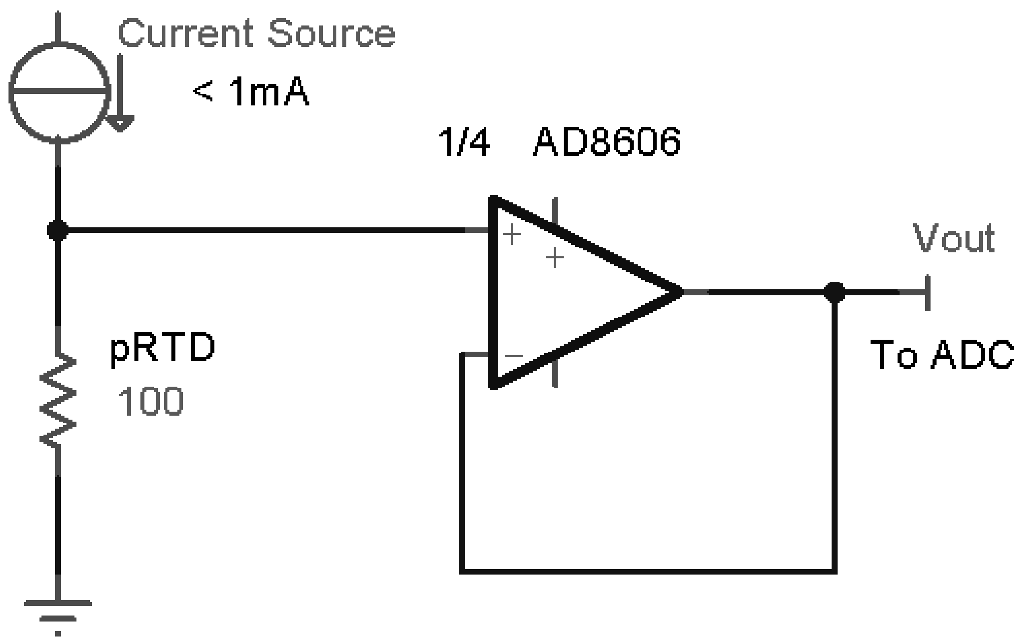
RTD are almost linear

- Resistance increases with temperature (+ slope)

  $R_T = R_0(1+ \alpha)(T - T_0)$

- Recognized standards for industrial platinum RTDs are
  – IEC 6075 and ASTM E-1137 α = 0.00385 Ω/Ω/°C

Measuring the resistance needs a constant current source



Read AN 687 for more details (e.g. current excitation circuit):
http://ww1.microchip.com/downloads/en/AppNotes/00687c.pdf
http://www.control.com/thread/1236021381
on 3-wire RTD

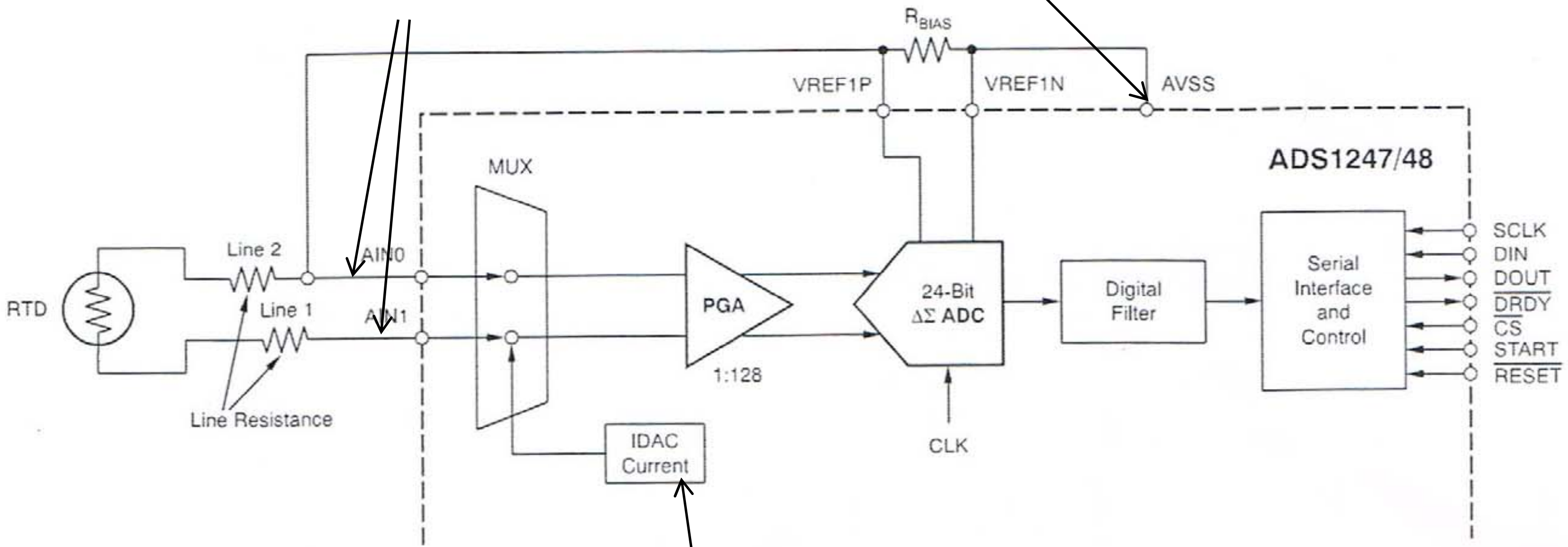
With long wires precision is a problem

- Two wire circuits,
- Three wire circuits and
- Four wire circuits.

Two wire: lead resistances are a problem

Power supply connected here

No current flows in here



Note: R_{BIAS} should be as close to the ADC as possible.

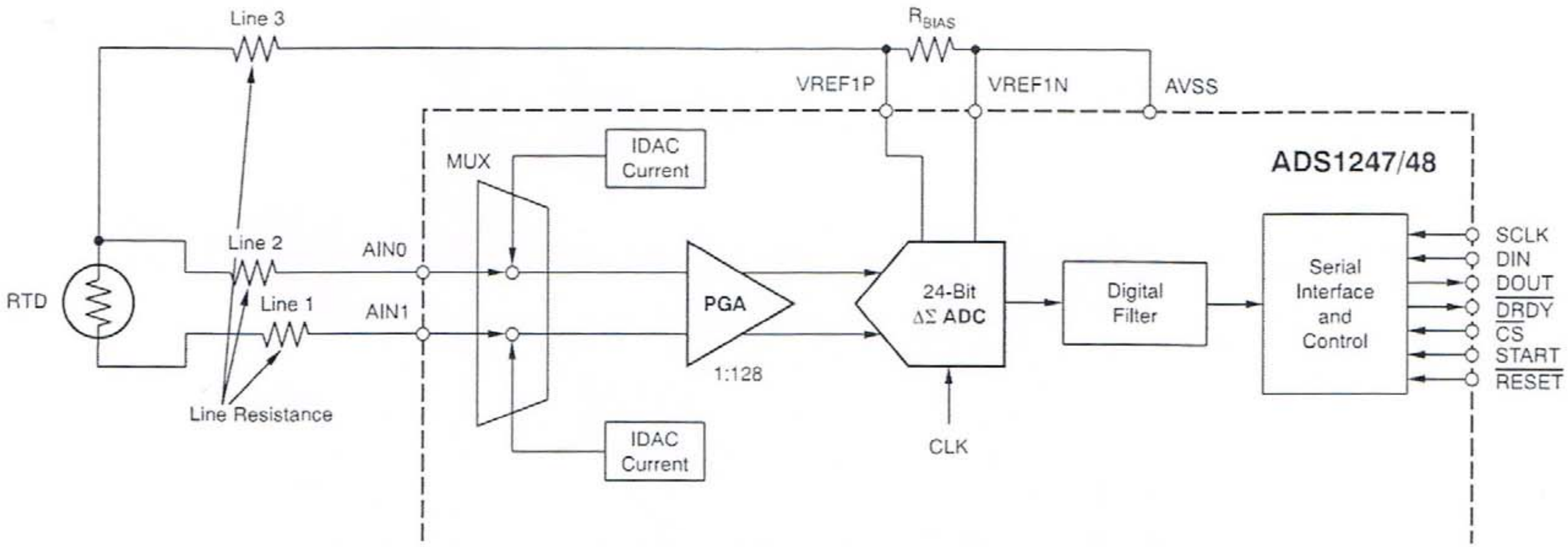
Figure 1. Two-Wire RTD Application Example

The IDAC block is a constant current sink

Three wire with two current sinks

3 Three-Wire RTD Application

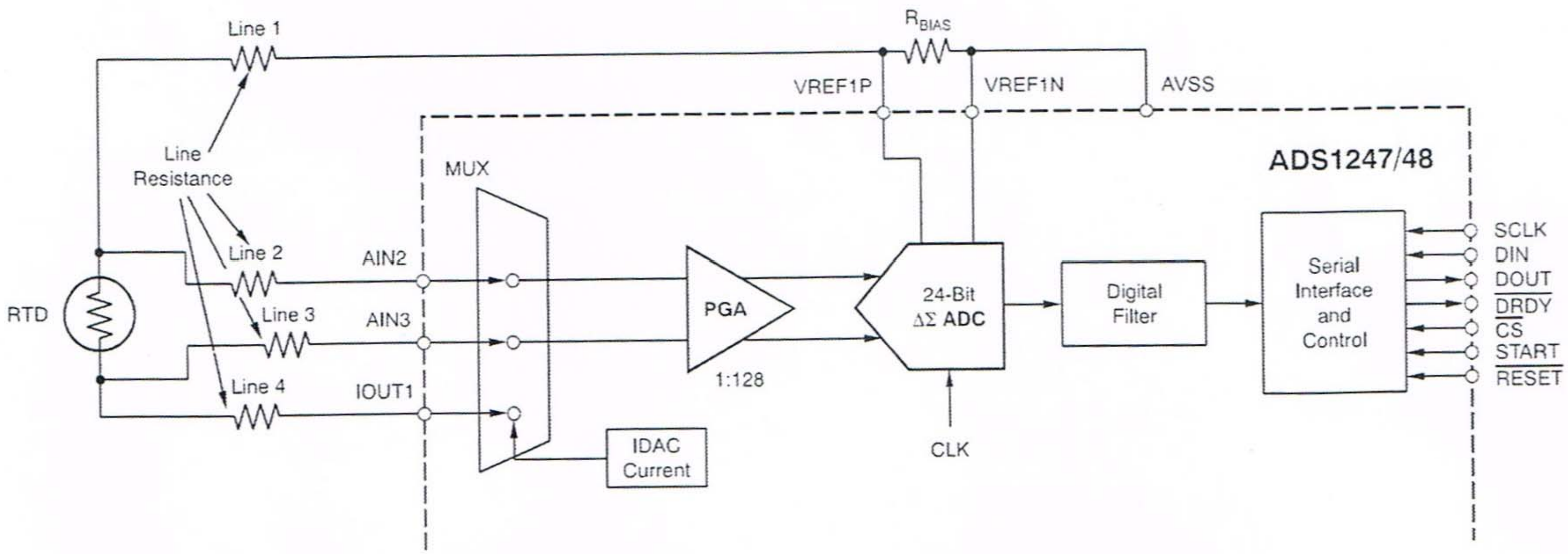
Figure 2 illustrates an example of a three-wire RTD application using either the ADS1247 or ADS1248.



Note: R_{BIAS} should be as close to the ADC as possible.

Figure 2. Three-Wire RTD Application Example

Four wire with one current sink.



Note: R_{BIAS} should be as close to the ADC as possible.

Figure 4. Four-Wire RTD Application Example

4 wire with precision current source

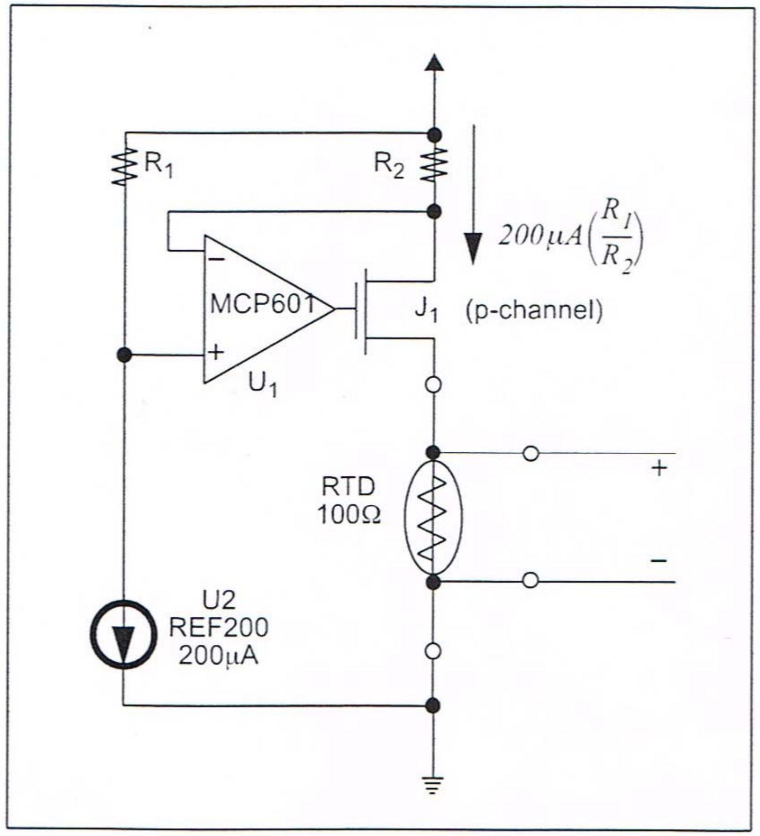


FIGURE 8: An 4-wire RTD can be used to sense the temperature of the isothermal block. RTDs require a precision current excitation as shown here.

Mathematical Modelling the RTD

- The Callendar-Van Dusen equation

$R_T = R_0 (1 + A T + B T^2 + C T^3(T-100)$ for $T < 0\ ^oC$

$= R_0 (1+ A T + B T^2)$ for $T > 0\ ^oC$

  – where R_0 is the resistance at $T_0 = 0\ ^oC$ and

- For platinum
- $A = 3.9083 \times e\text{-}3\ ^oC^{-1}$
- $B = -5.775 \times e\text{-}7\ ^oC^{-2}$
- $C = -4.183 \times e\text{-}12\ ^oC^{-4}$

Experimentally

- Derive temperature (+/-) from the measured resistance.
- Easiest way is to construct a Look-Up table inside LabView or your uP
- Precision, accuracy, errors and uncertainties need to be considered.

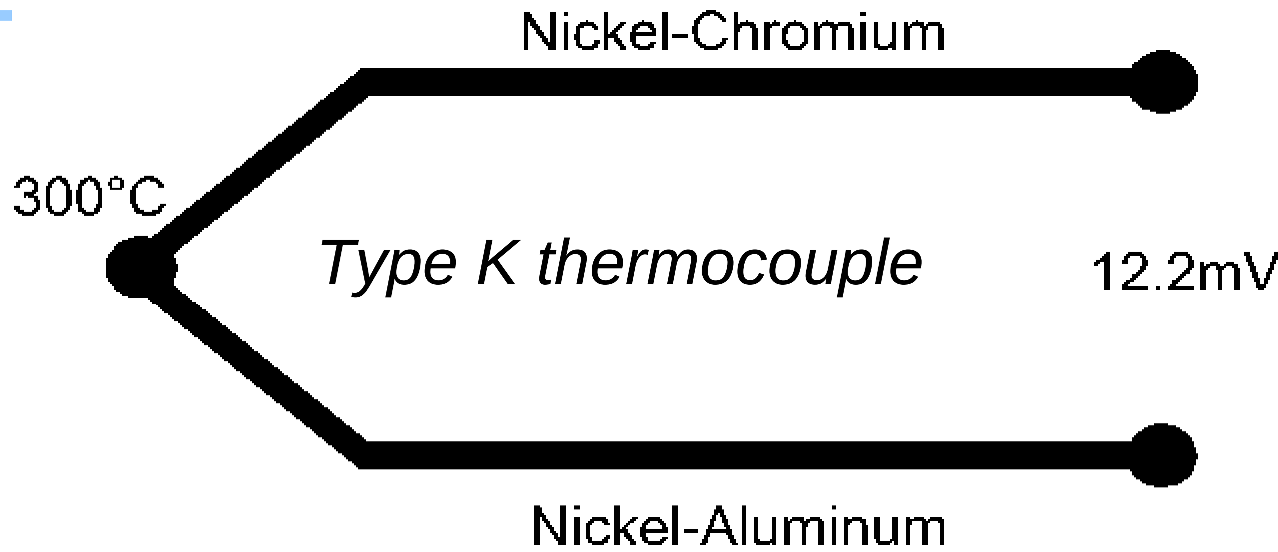
Experimental uncertainties

- For real precision, each sensor needs to be calibrated at more than one temperature and any modelling parameters refined by regression using a least mean squares algorithm.
  - LabView, MATLAB and Excel have these functions
- The 0^{o}C ice bath and the ~100 ^{o}C boiling de-ionised water (at sea level) are the two most convenient standard temperatures.

Part III Thermocouples

- High temperature range
- Inexpensive
- Withstand tough environments
- Multiple types with different temperature ranges
- Requires a reference temperature junction
- Fast response
- Output signal is usually small
- Amplification, noise filtration and signal processing required

Seebeck Effect



$$Emf = \int_{T_1}^{T_2} S_{12} \cdot dT = \int_{T_1}^{T_2} (S_1 - S_2) \cdot dT$$

Thermocouples are very non-linear

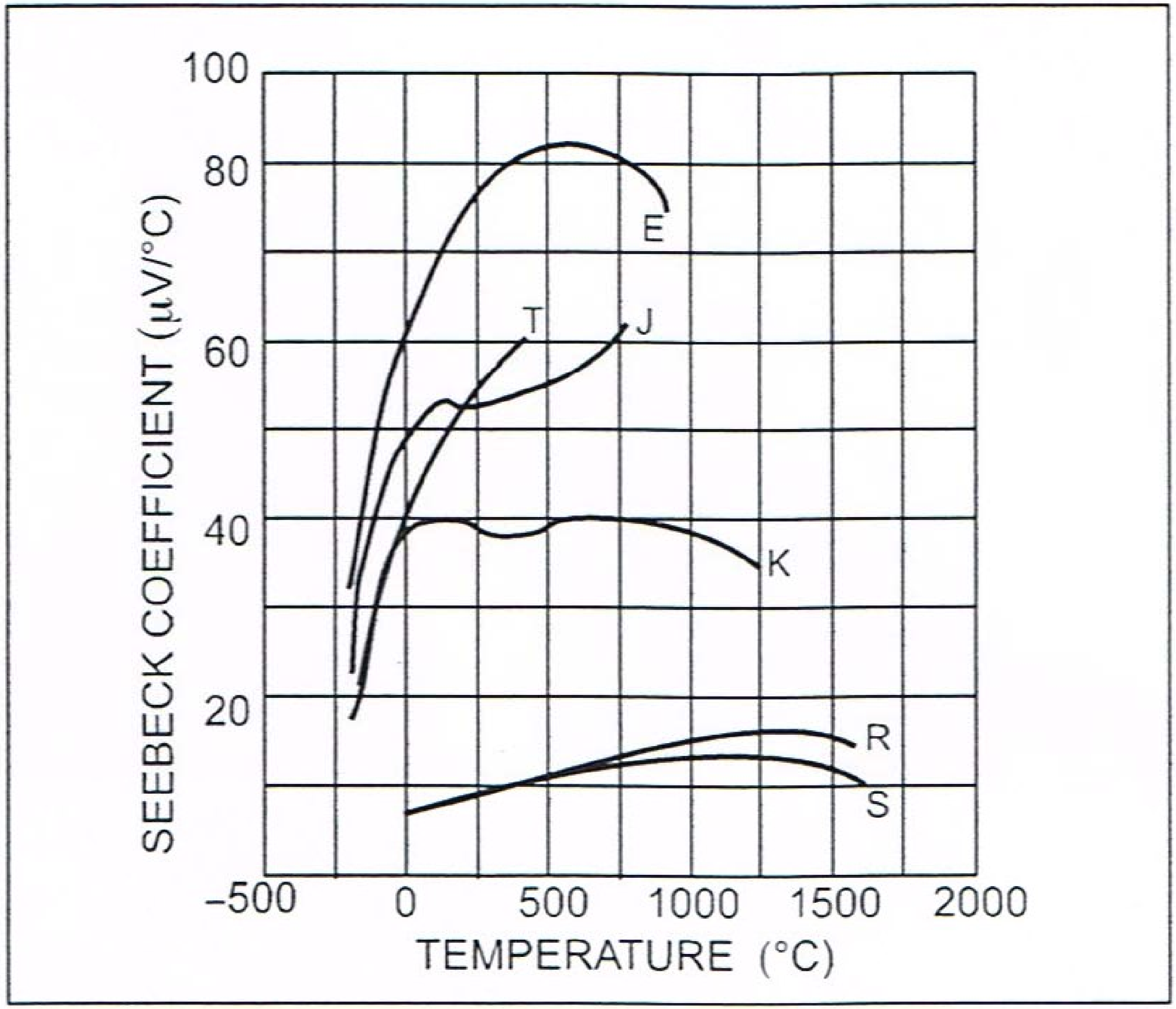


FIGURE 2: *Seebeck coefficient of various thermocouples versus temperature*

Mathematical Model

- To cover all types of thermocouples, we need a 6 - 10th order polynomial to describe the relationship between the voltage and the temperature difference between the two junctions

- Either
- $T = a_0 + a_1 \times V + a_2 \times V^2 +++++ a_{10} V^{10}$

- Or

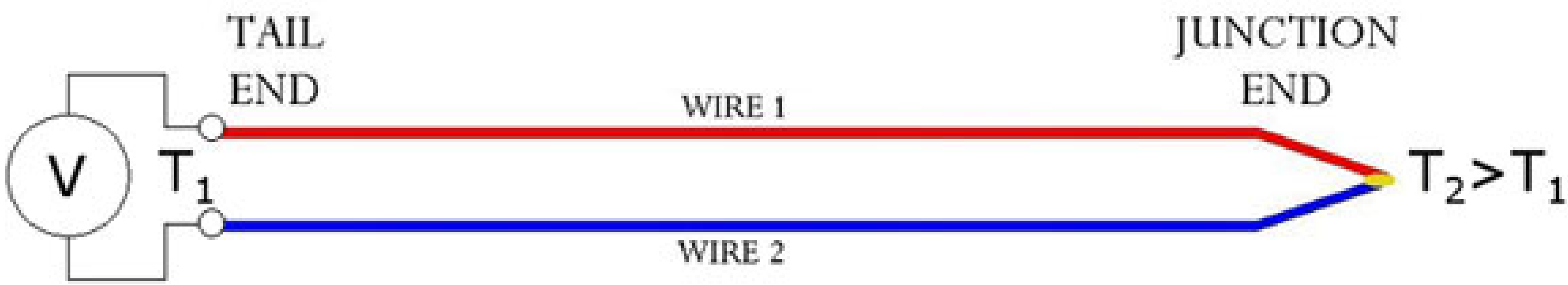
- $V = b_0 + b_1 \times T + b_2 \times T^2 +++++ b_{10} T^{10}$
  $+ \alpha o \exp(\alpha 1 (T-126.9686)^2)$ for $T > 0^oC$

10^{th} order polynomial fit: Find T from measured Voltage

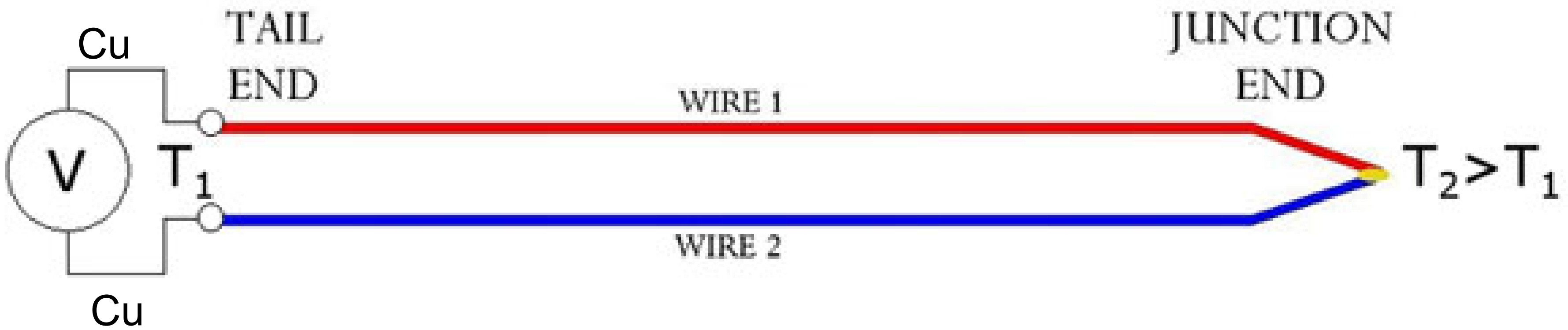
	Thermocouple Type					
	E	J	K	R	S	T
Range	0° to 1000°C	0° to 760°C	0° to 500°C	-50° to 250°C	-50° to 250°C	0° to 400°C
a_0	0.0	0.0	0.0	0.0	0.0	0.0
a_1	1.7057035E-2	1.978425E-2	2.508355E-2	1.8891380E-1	1.84949460E-1	2.592800E-2
a_2	-2.3301759E-7	-2.00120204E-7	7.860106E-8	-9.3835290E-5	-8.00504062E-5	-7.602961E-7
a_3	6.543558E-12	1.036969E-11	-2.503131E-10	1.3068619E-7	1.02237430E-7	4.637791E-11
a_4	-7.3562749E-17	-2.549687E-16	8.315270E-14	-2.2703580E-10	-1.52248592E-10	-2.165394E-15
a_5	-1.7896001E-21	3.585153E-21	-1.228034E-17	3.5145659E-13	1.88821343E-13	6.048144E-20
a_6	8.4036165E-26	-5.344285E-26	9.804036E-22	-3.8953900E-16	-1.59085941E-16	-7.293422E-25
a_7	-1.3735879E-30	5.099890E-31	-4.413030E-26	2.8239471E-19	8.23027880E-20	
a_8	1.0629823E-35		1.057734E-30	-1.2607281E-22	-2.34181944E-23	
a_9	-3.2447087E-41		-1.052755E-35	3.1353611E-26	2.79786260E-27	
a_{10}				-3.3187769E-30		
Error	+/-0.02°C	+/-0.05°C	+/-0.05°C	+/-0.02°C	+/-0.02°C	+/-0.03°C

TABLE 7: NIST Polynomial Coefficients of Voltage-to-temperature conversion for various thermocouple type

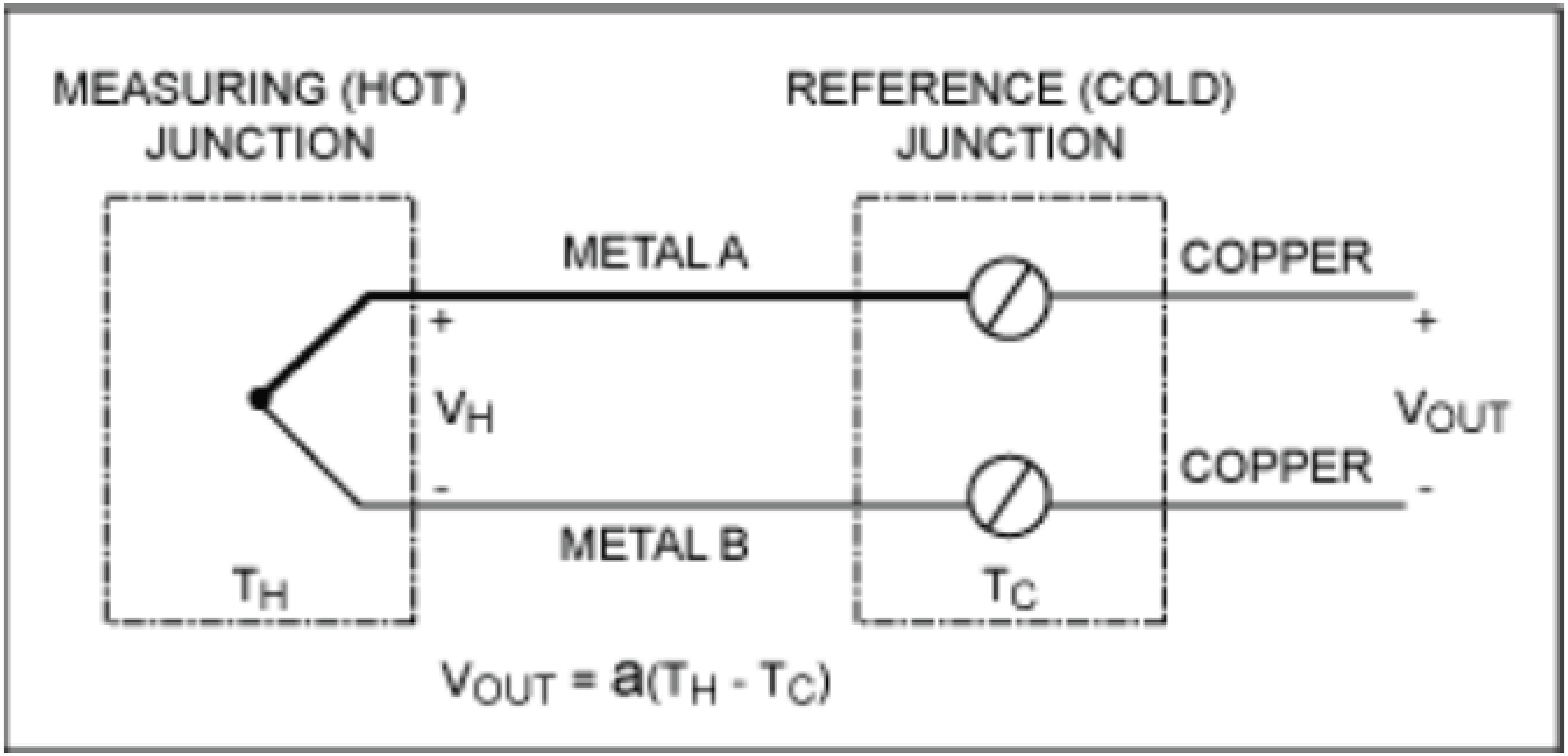
What happens when we connect a meter?



What happens when we connect a meter?

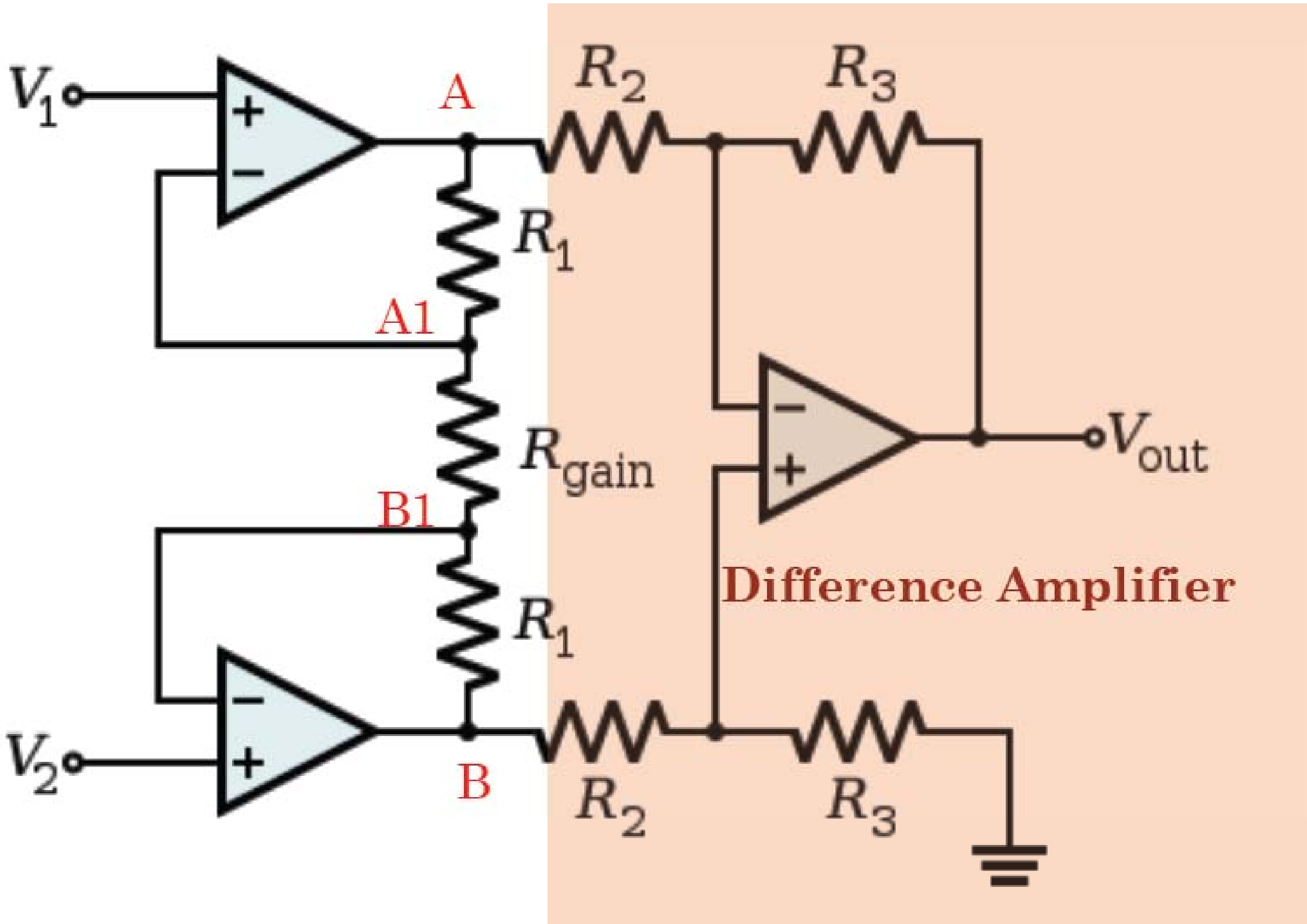


Cold Junction Compensation



Can we read the voltage directly from our DAQ or meter?

Instrumentation Amplifier

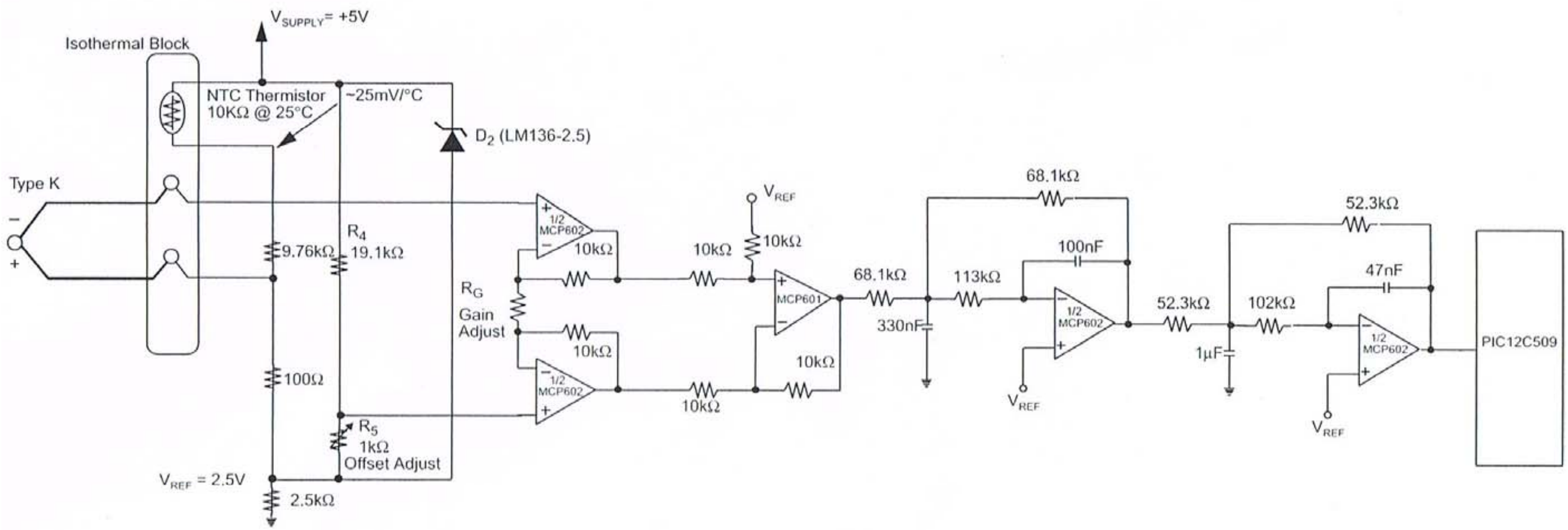


One more thing...

- Low voltage signal…
- Long leads…

- What problems could arise?

Thermocouple
with compensation and filtering



Look-up table is easier than using a polynomial

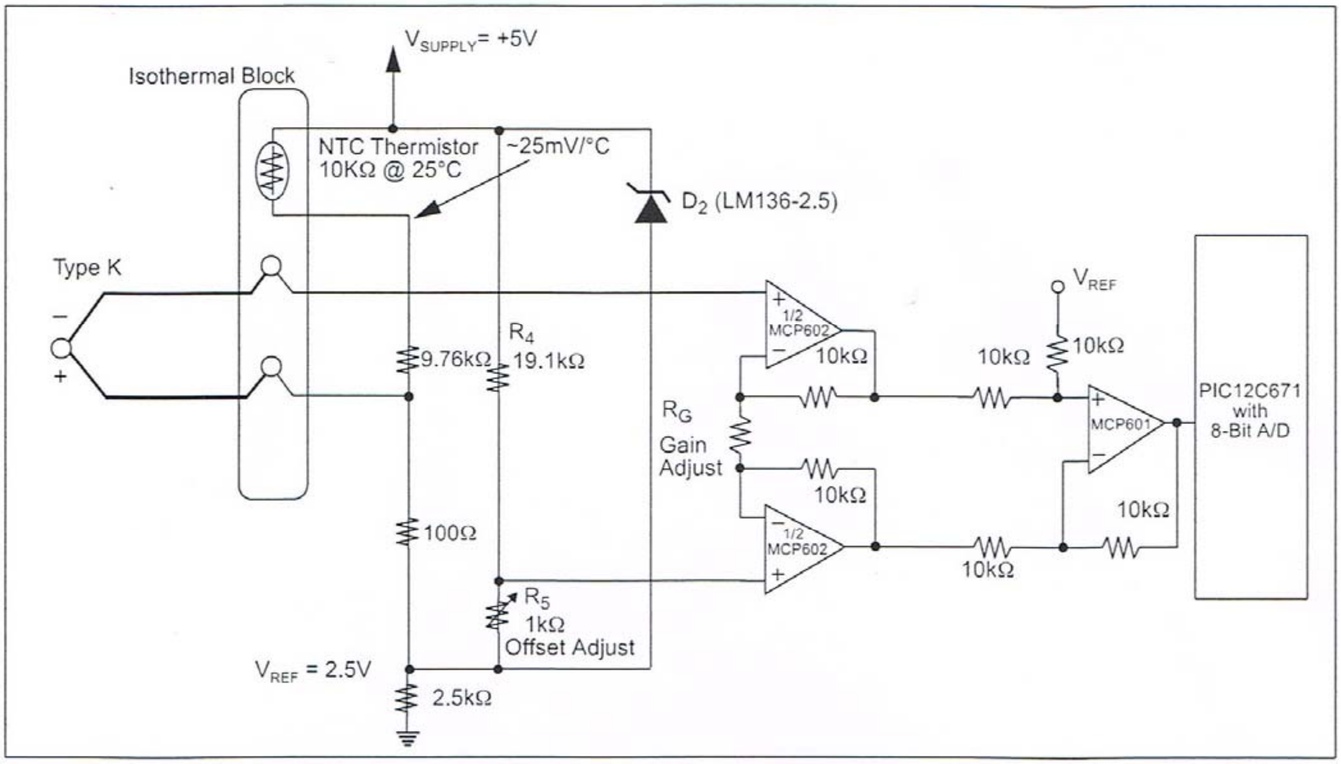


FIGURE 15: *This circuit will provide 8-bit accurate temperature sensing results using a thermocouple. In this circuit, the A/D Converter is included in the PIC12C671 microcontroller.*

°C	0	10	20	30	40	50	60	70	80	90	100
500	20.644	21.071	21.497	21.924	22.360	22.776	23.203	23.629	24.055	24.480	24.905
600	24.905	25.330	25.766	26.179	26.602	27.025	27.447	27.869	28.289	28.710	29.129
700	29.129	29.548	29.965	30.382	30.798	31.213	31.628	32.041	32.453	32.865	33.275
800	33.275	33.685	34.093	34.501	34.906	35.313	35.718	36.121	35.524	36.925	37.326
900	37.326	37.725	38.124	38.522	38.918	39.314	39.708	40.101	40.494	40.885	41.276

TABLE 6: *Type K thermocouple output voltage look-up table. All values in the table are in millivolts.*

What does 8 bit accuracy mean?

- Eight bits = 2^8-1 levels = 255 levels
- Assume supply voltage between 0 and 5 volts
- Minimum V step between each level ≈ 20mV
- Temp range say 0 to 400 ^{o}C
- Minimum temperature step ≈ 1.6 ^{o}C

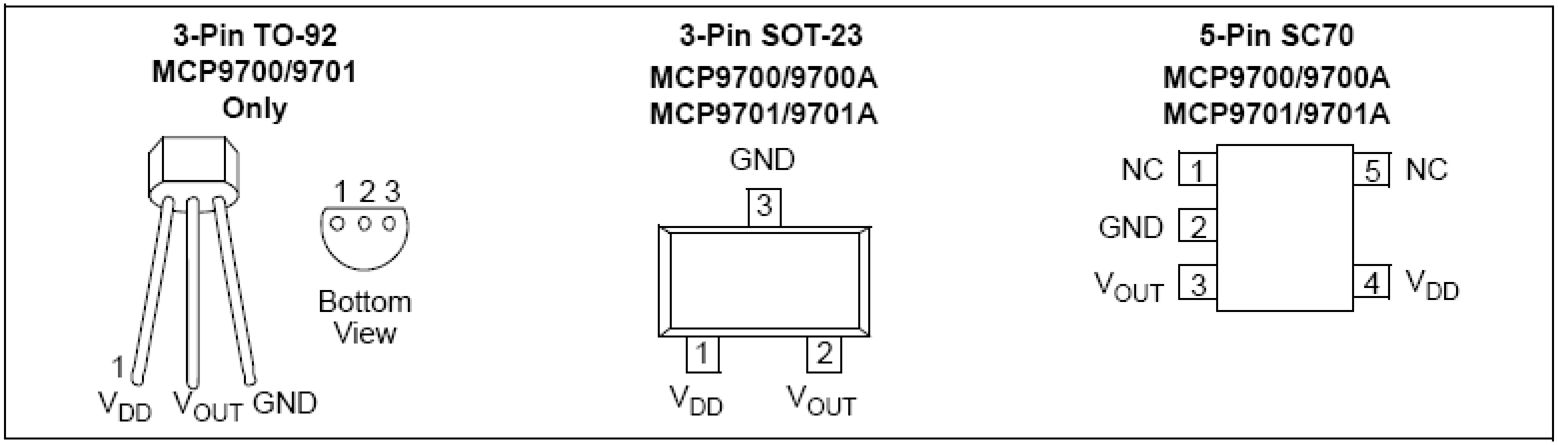
  – This determines the quantisation error regardless the accuracy of the sensor

i.e., Temp = T +/- 0.8^{o}C

Part IV Silicon Detectors

- Integrated form
- -40°C to +150°C
- Limited accuracy +/- 2 degree
- Linear response (no calibration is required)
- Direct interface with ADC

Package Type



References

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- Wikipedia
- Microchip Application Notes AN679, AN684, AN685, AN687
- Texas Instruments SBAA180
- Omega Engineering www.omega.com (sensor specs, application guides, selection guides, costs)
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- Baker, Bonnie, "**Designing with temperature sensors, part two: thermistors**," *EDN*, Oct 20, 2011, pg 24.
- Baker, Bonnie, "**Designing with temperature sensors, part three: RTDs**," *EDN*, Nov 17, 2011, pg 24.
- Baker, Bonnie, "**Designing with temperature sensors, part four: thermocouples**," *EDN*, Dec 15, 2011, pg 24.

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