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Temperature sensors

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- Characteristics of interests
- Types of temperature sensors
  - 1. Thermistor
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  - 3. Thermocouple
  - 4. Integrated Silicon Linear Sensor
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- Signal Conditioning Circuits (throughout)

Why we need to measure temperature

- Ideal gas law is PV = nRT
- Sensors such as strain, pressure, force, flow, level, and position many times require temperature monitoring in order to insure accuracy.
- As an example, pressure and force are often sensed with resistive Wheatstone bridge configurations. The temperature errors of the resistive elements of these bridges can exceed the actual measurement range of the sensor, making the pressure sensor's output fairly useless unless the temperature of the bridge is known.

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Important Properties

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

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Main single probe types

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

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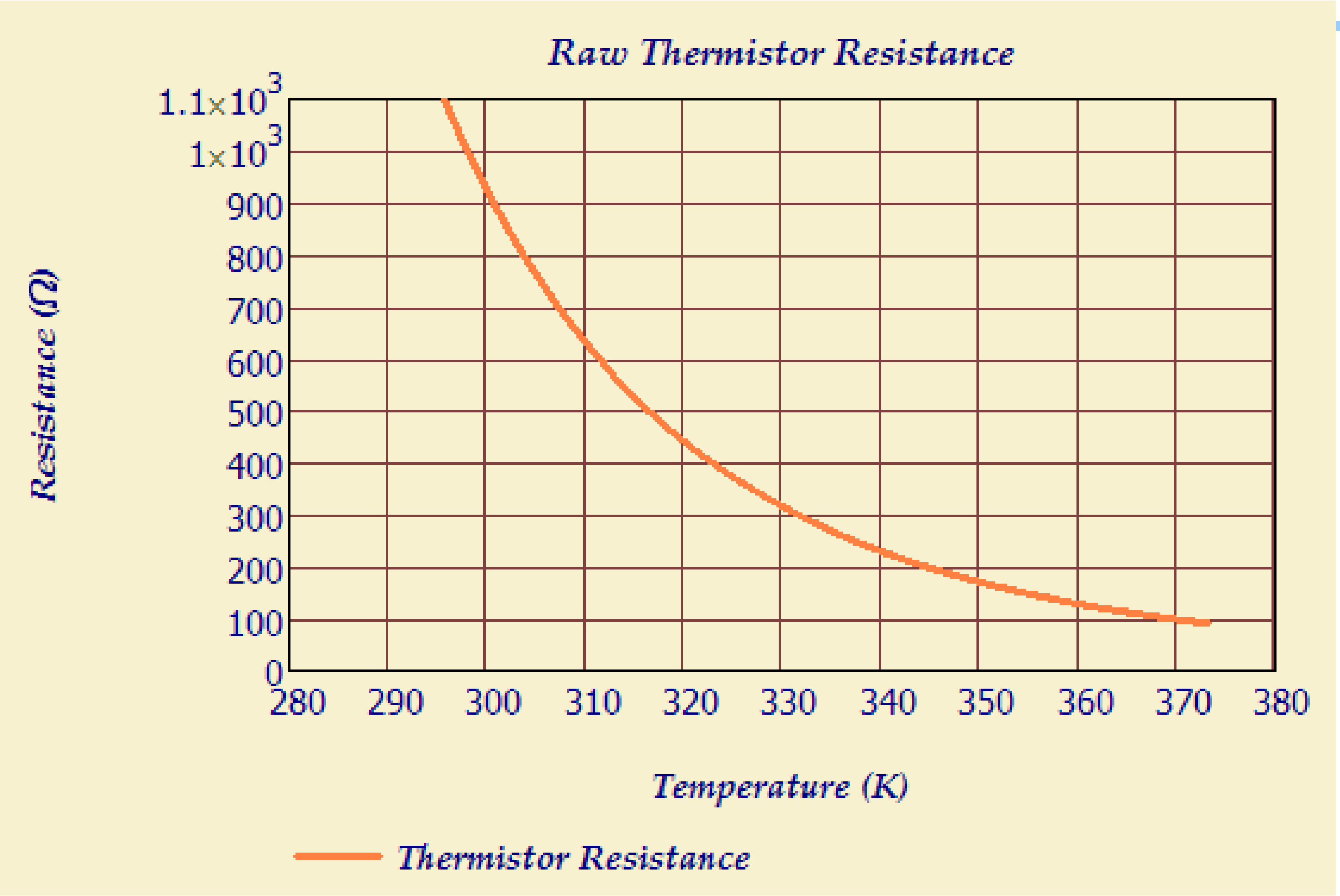
TABLE 1 POPULAR TEMPERATURE SENSORS

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	More than $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
- R-T mode (zero-power mode):
  - nonlinear relationship between R and T

Thermistor resistance vs temperature



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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)
    - β is a curve fitting parameter and itself is temperature dependent.
    - Manufacturers will often give you R_0, T_0 and an average value for β

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Simple exponential Thermistor Model

- Usually T_0 is room temp 25^{o}C = 298.15^{o}K
  - So $R_0 = R_{25}$
- $R_T = R_{25}$ x $\exp[\beta(1/T - 1/298.15)]$
  - where $\beta \approx \mathit{ln}\,(R_{85}/R_{25})\,/(1/358.15-1/298.15)$
- 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; in this case R_T in terms of T.

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

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

Total measurement uncertainty = +/- 0.005^{o}C

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Inverting the equation: T in terms of R

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:

- 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 (resulting in the three term SH eqn)

Aside that has nothing to do with temperature sensors but is useful.

Both differentiating and integrating measured data is difficult because of noise and unknown DC offsets.

- Assume we have a 3rd order Voltage to Temp relationship. i.e., $\underline{V} \approx V_{measured}$ where

  $$\underline{V} = A + B\,T + C\,T^2 + D\,T^3$$

- Then

  $$d\underline{V}/dT = B + 2\,C\,T + 3\,D\,T^2$$

- And

  $$\int \underline{V}\,dT = K + A\,T + 1/2\,B\,T^2 + 1/3\,C\,T^3 + 1/4\,D\,T^4$$

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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.

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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.

$$\Delta C = W \times \theta$$

  - W in Watts
  - θ in ^{o}C /W

Self heating calculation

- $\Delta^{o}C = I^2 R_T \ \theta_{\text{Device to ambient}}$
- Example.
  - $I = 5mA$
  - $R_T = 4k\Omega$
  - $\theta_{\text{Device to ambient}} = 15\ ^{o}C\ /W$
- $\Delta^{o}C = (5e\text{-}3)^2 \times 4e3 \times 15 = 1.5\ ^{o}C$
- This means the temp will read 1.5 degrees higher than ambient

- Now try it for $I = 1mA$ with $R_T = 15k\Omega$
  - $\Delta^{o}C$ = ______________________________

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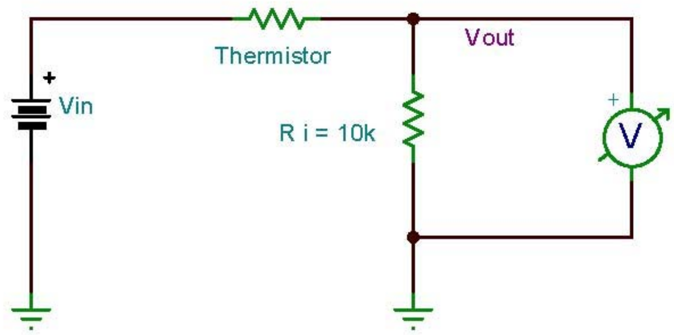
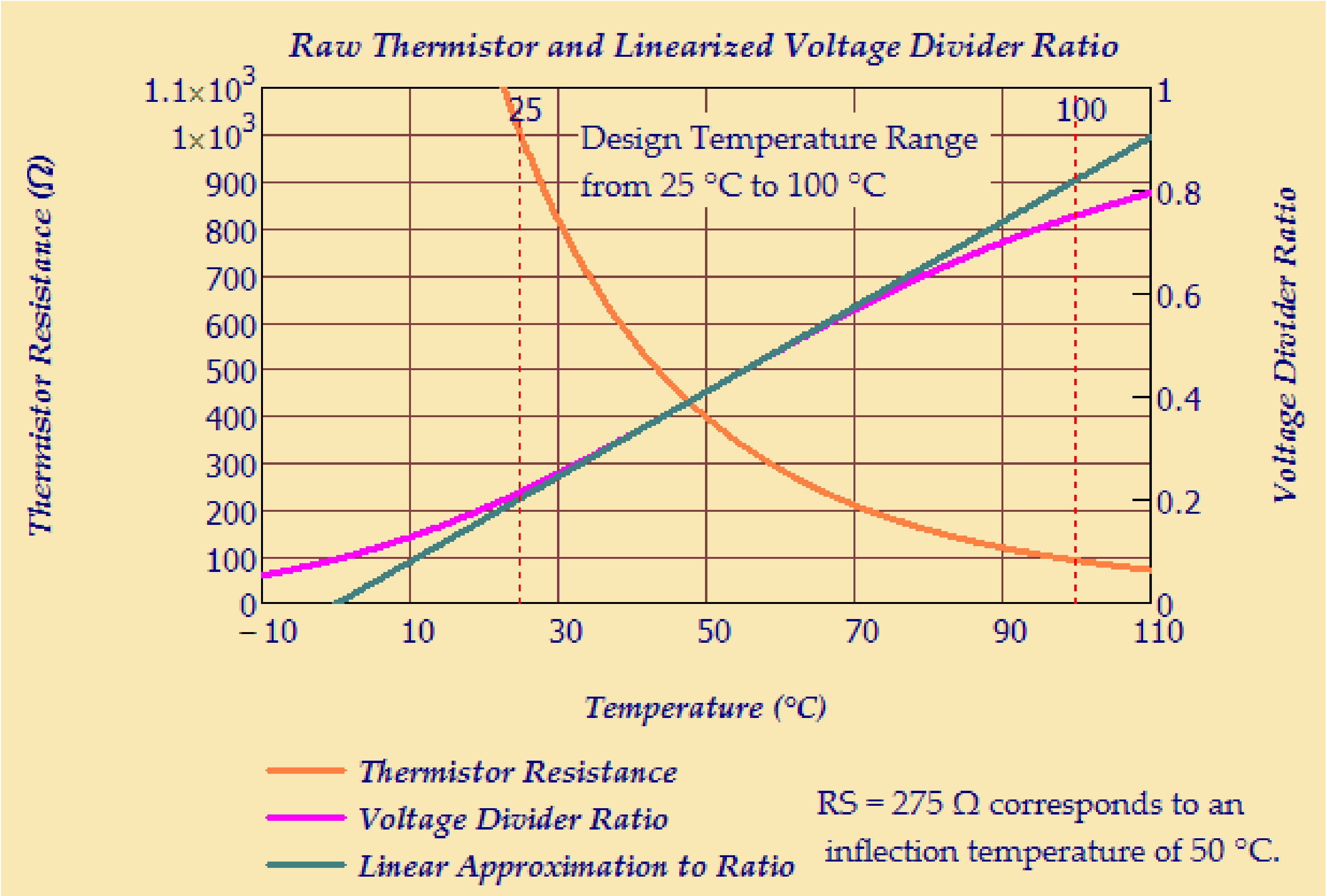
Linearization techniques

- Current through Thermistor is dominated by 10k resistor.



Linearization of a 1kOhm Thermistor



This plot Ti = 50 ^{0}C, Ri = 275 Ω

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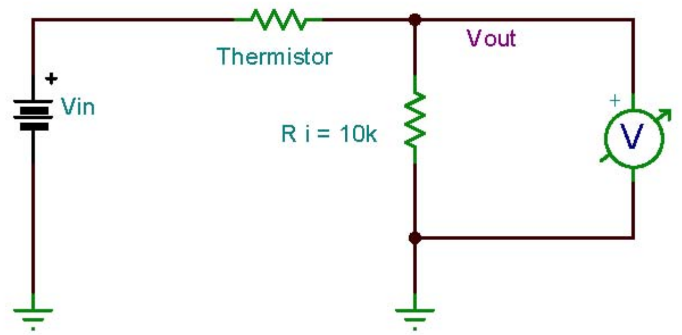
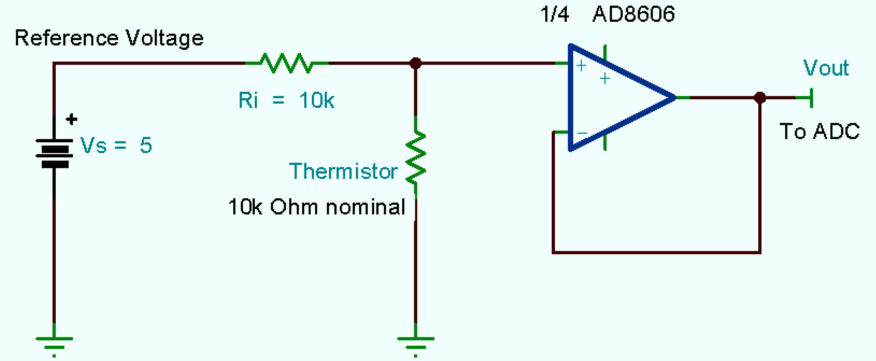
Linearization math

- $V_{out}/V_{in} = R_i/(R_i + R_T)$

- Find T_i from $d(V_{out}/V_{in})/dT = 0$ @T_i
  - then
- $R_T = R_0 \times \exp[\beta/T_i - \beta/T_0] \times (\beta - 2T_i)/(\beta + 2T_i)$
  - where T_0 , R_0 and β are given.
  - For example
    - $T_0 = 25^oC$ (289 ^oK), $R_0 = 1$ kΩ, $\beta = 3560\ ^oK$
    - (NB. covert all temps to same scale)

Linearization techniques





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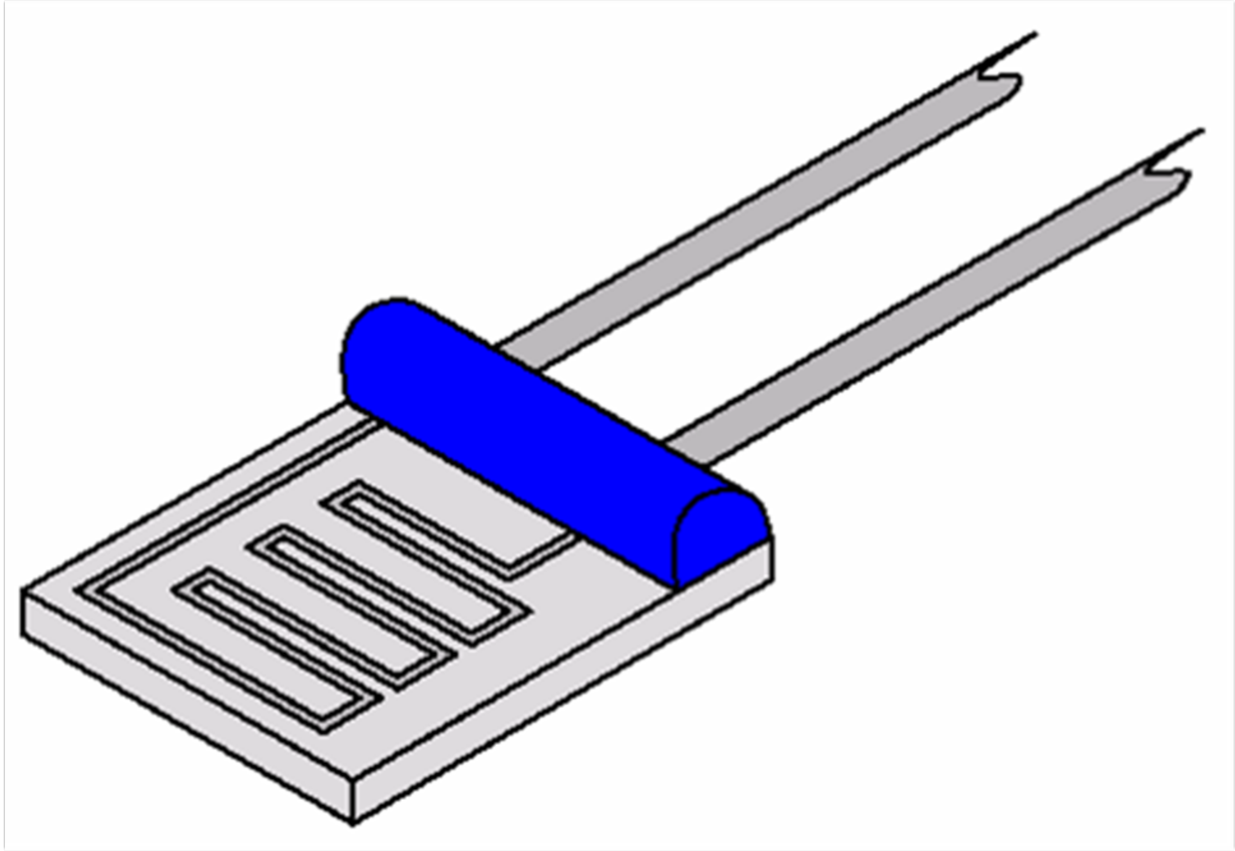
Part II RTD

- Resistive temperature devices (or detectors)



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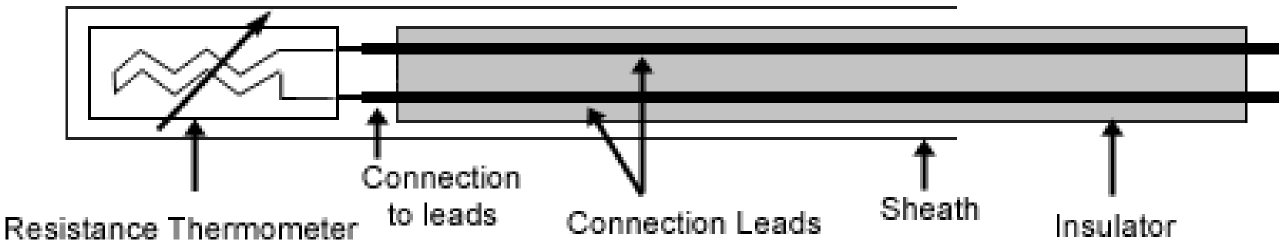
pRTD, cRTD and nRTD

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



- Copper and nickel as also used but not as stable

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RTD are almost linear

- RTDs have a + slope of α relating the Resistance vs Temp (i.e., resistance increases with temperature) so that
- $R_T = R_0(1+ \alpha)(T - T_0)$
- Recognized standards for industrial platinum RTDs are
  - IEC 6075 and ASTM E-1137 α = 0.00385 Ω/Ω/°C

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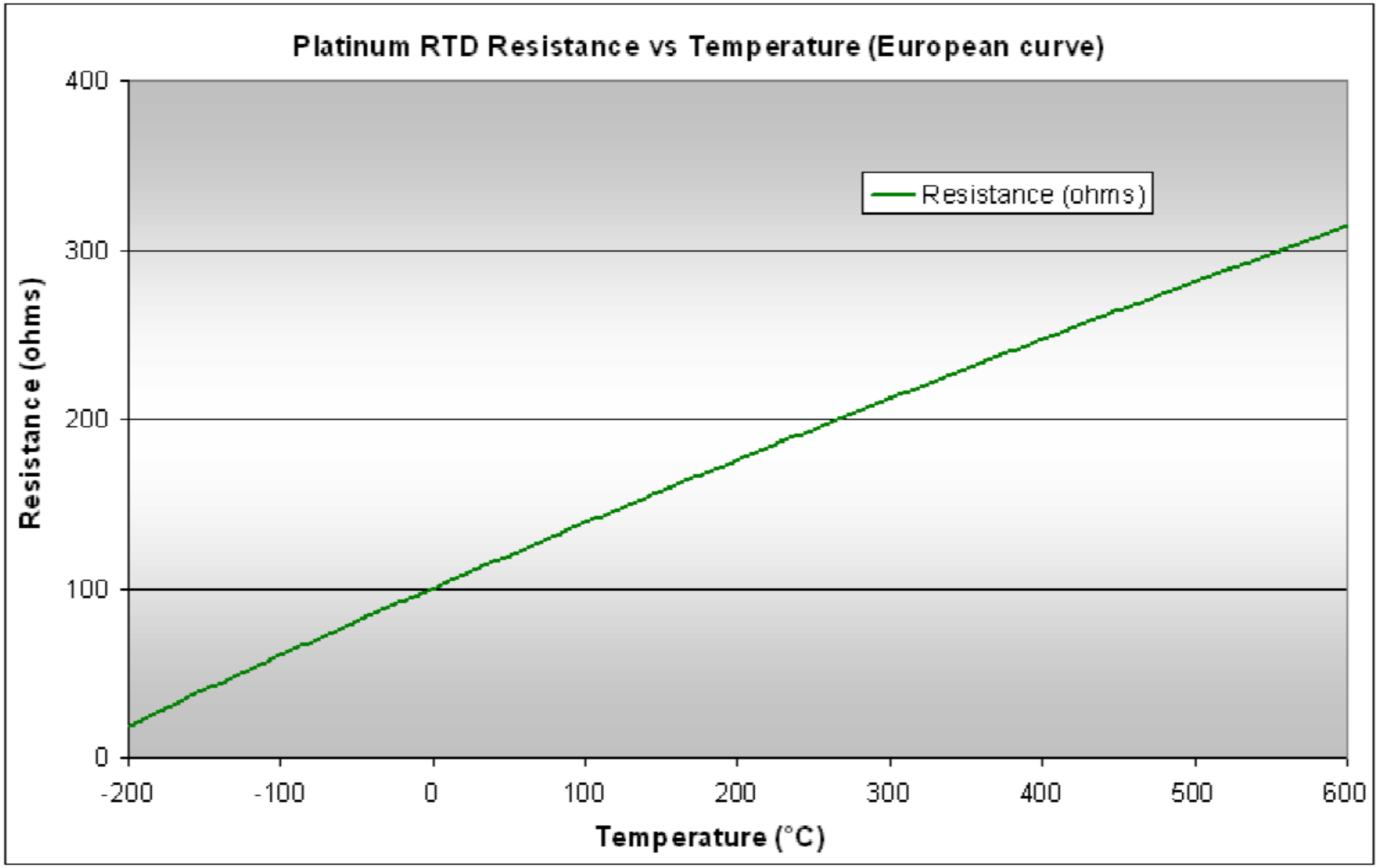
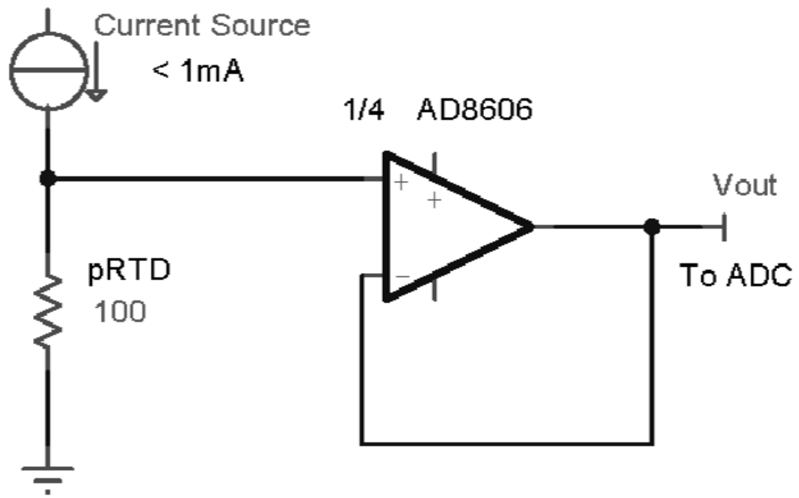
Linearity: The reason RTDs are so popular



Measuring the resistance is easy using a constant current source



NB You can also use a simple voltage divider and linearize it inside the ADC processor

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With long wires precision is a problem

- Two-wire circuits,
- Three-wire circuits and
- Four-wire circuits.
- Most of the following circuits can be understood using GΩhms law (Gough's version of Ohms Law) which I define as
- "No current = No voltage drop; or
- No voltage drop = No current"

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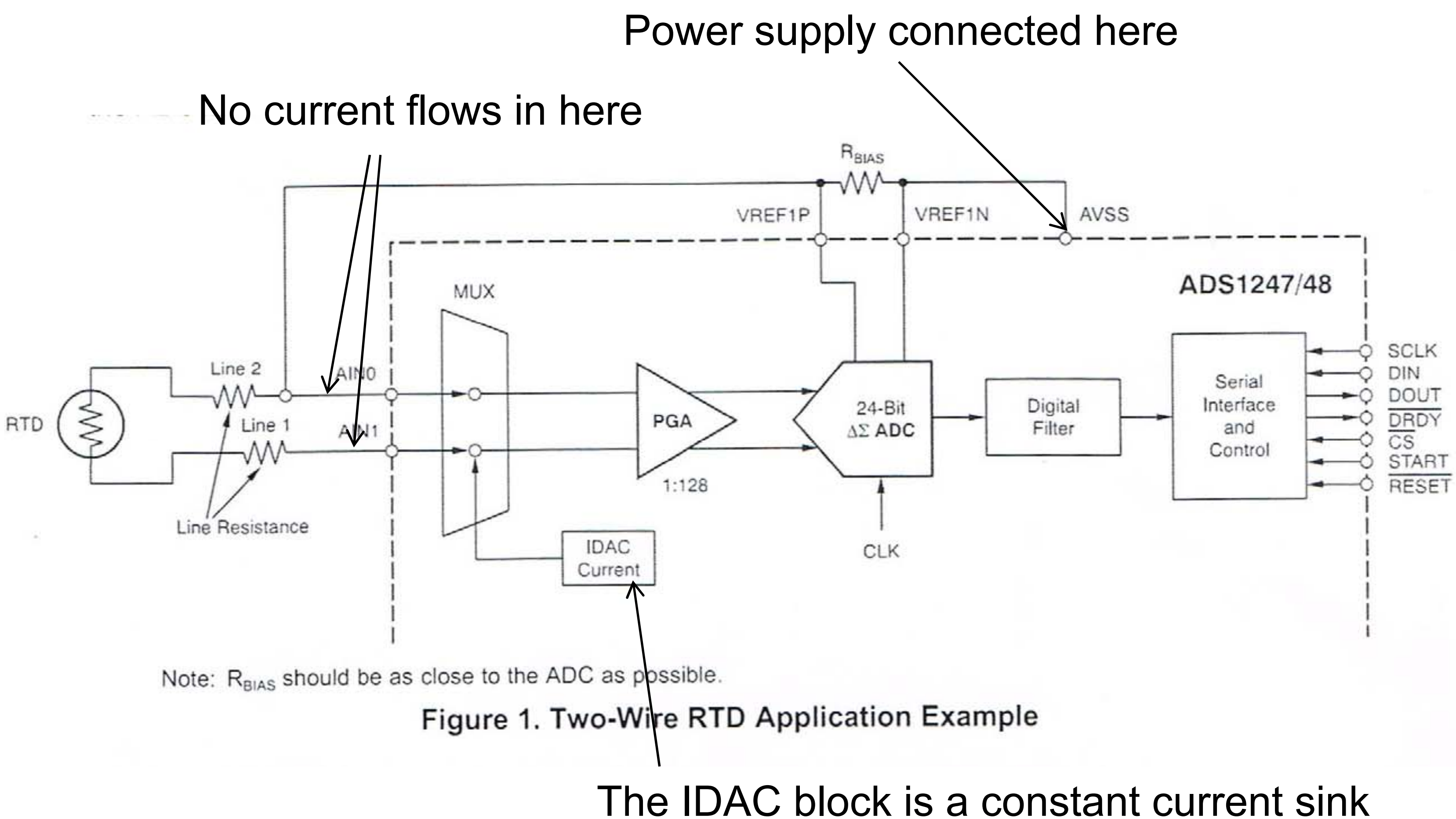
Two wire: lead resistances are a problem



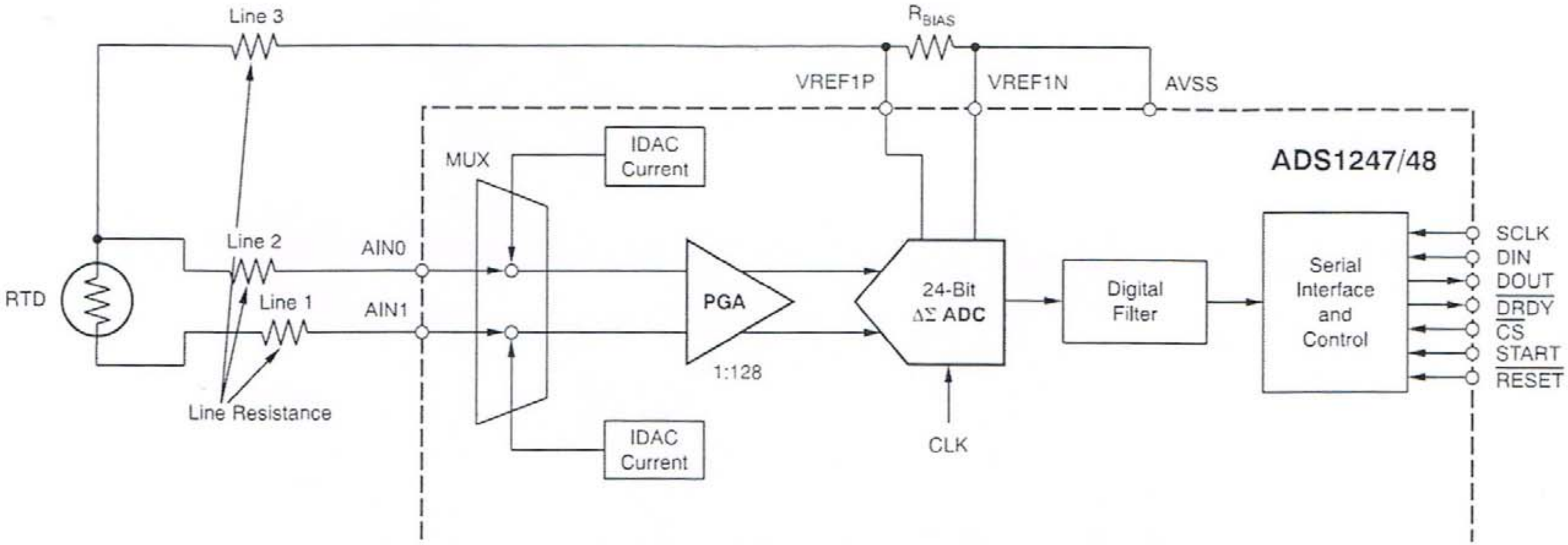
Note: R_{BIAS} should be as close to the ADC as possible.

Figure 1. Two-Wire RTD Application Example

Three wire with two current sinks

3 **Three-Wire RTD Application**

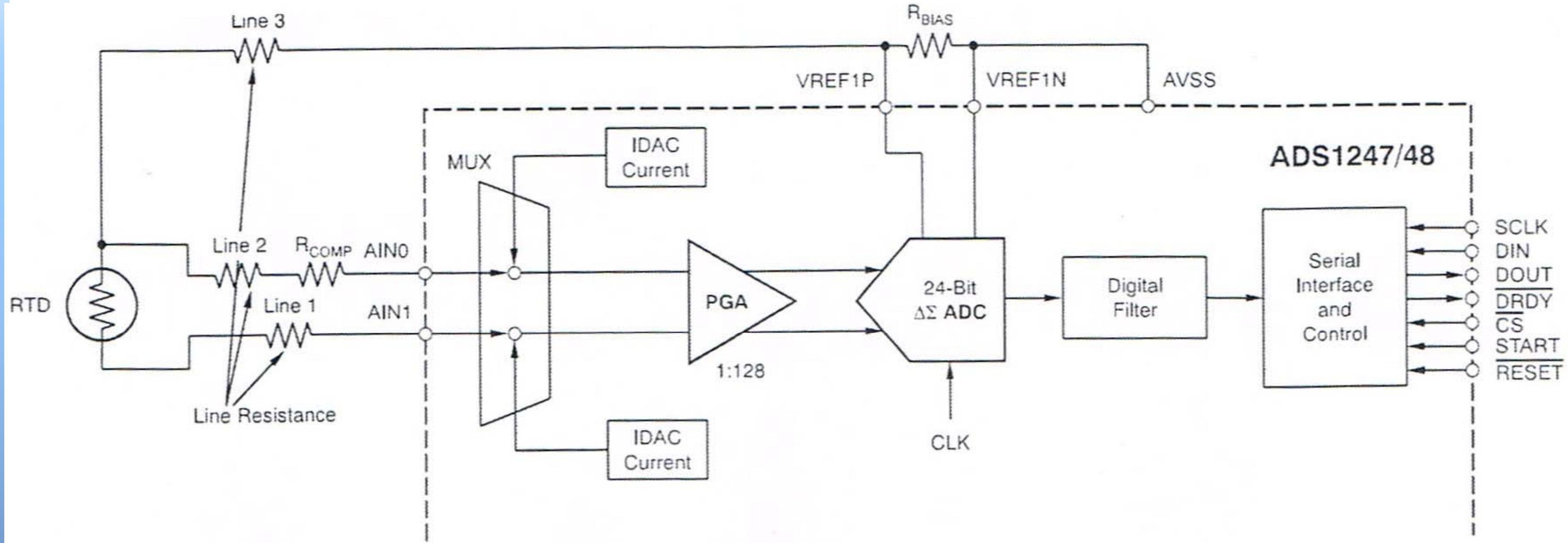
Figure 2 illustrates an example of a three-wire RTD application using either the ADS1247 or ADS1248.



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

Figure 2. Three-Wire RTD Application Example

Three wire with compensation with two current sinks



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

Figure 3. Three Wire RTD Application Example with Hardware Compensation

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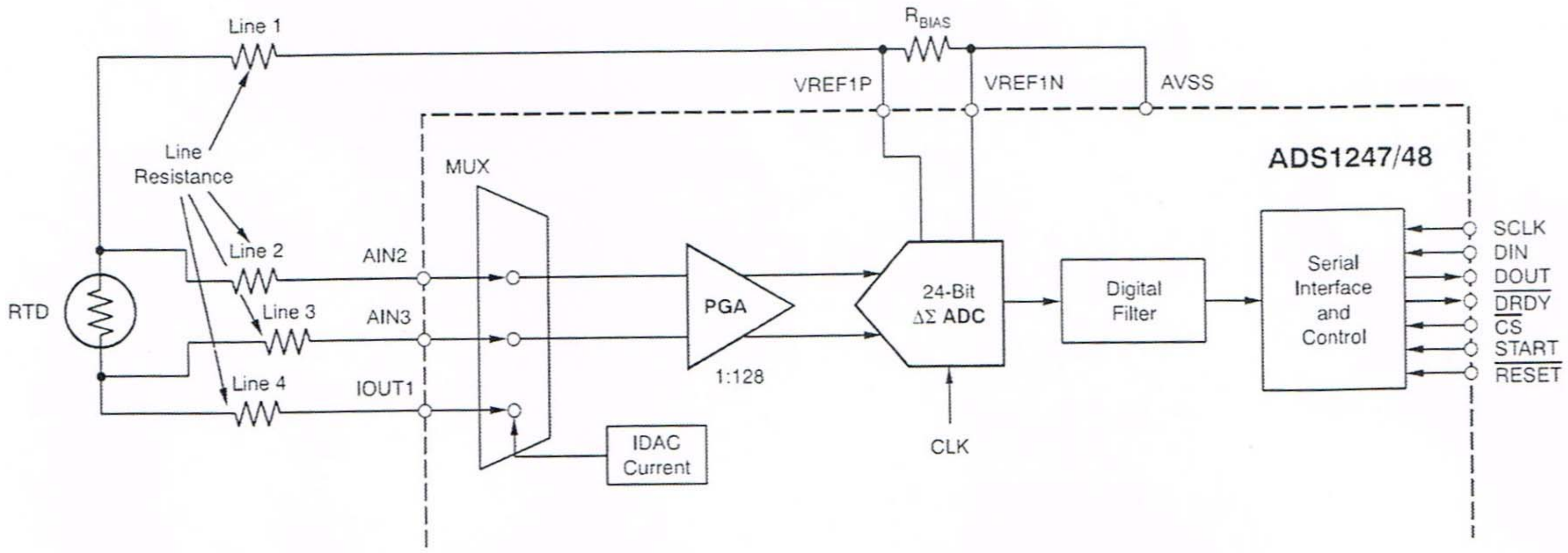
Four wire with one current sink.



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

Figure 4. Four-Wire RTD Application Example

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4 wire with precision current source

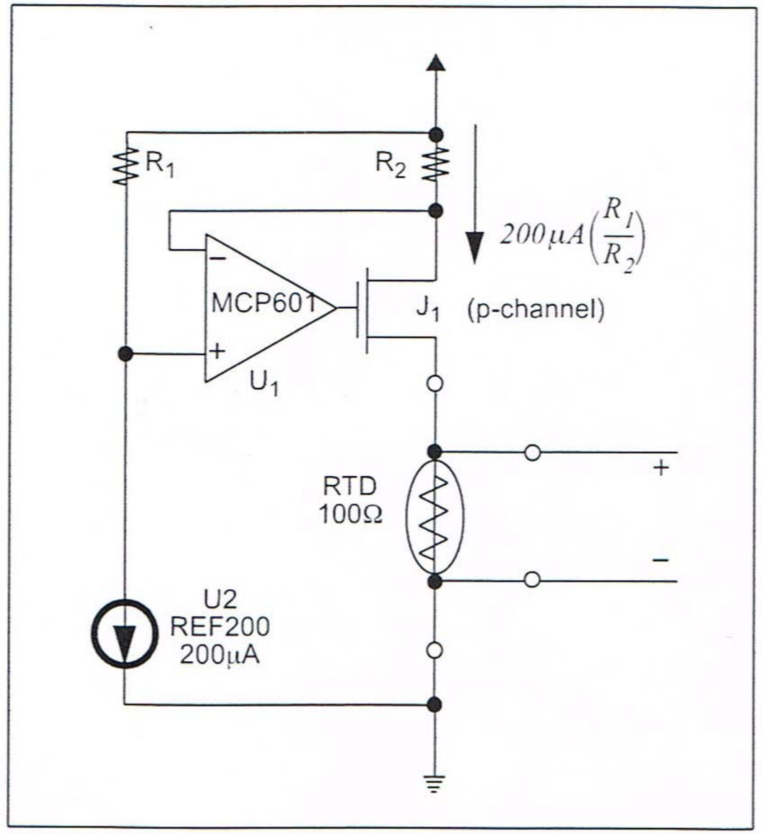

FIGURE 8: *An 4-wire RTD can be used to sense the temperature of the isothermal block. RTDs require a precision current excitation as shown here.*

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

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Experimentally

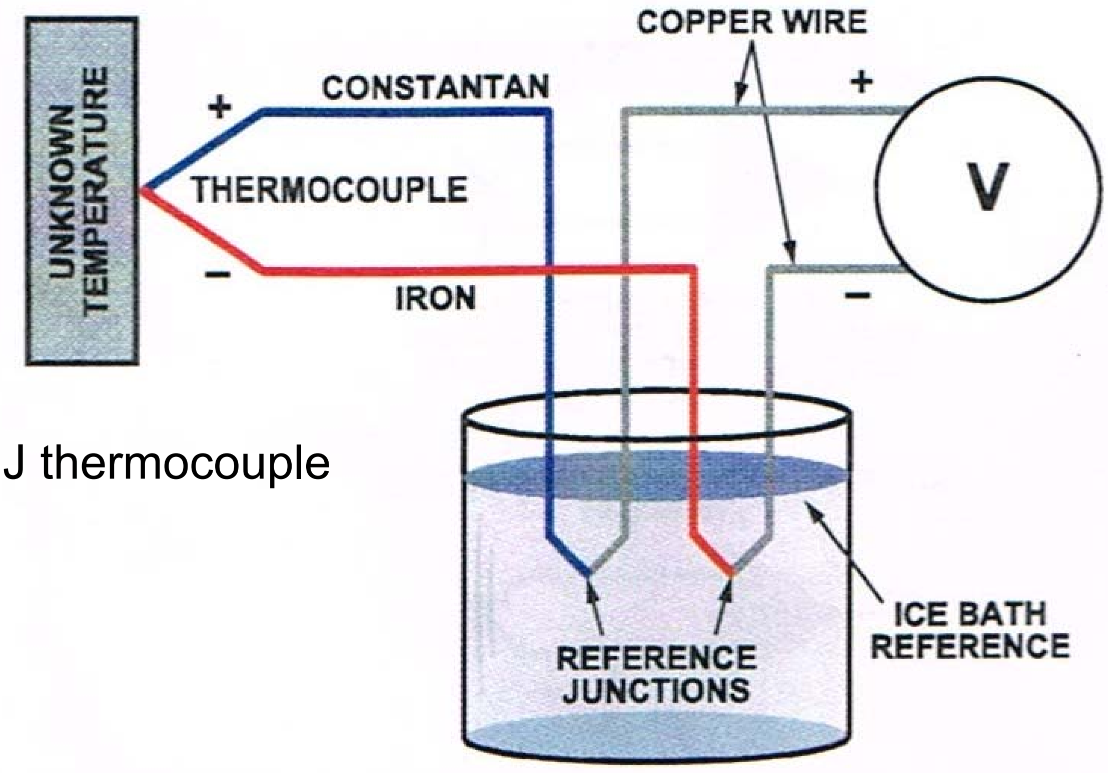
- Mostly you need to derive temperature (+/-) from the measured resistance (+/-).
- Easiest way is to construct a Look-Up table inside LabVIEW or your uP
- Precision, accuracy, errors and uncertainties need to be considered.

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



Type J thermocouple

Figure 2. Basic iron-constantan thermocouple circuit.

Thermocouples are very non-linear

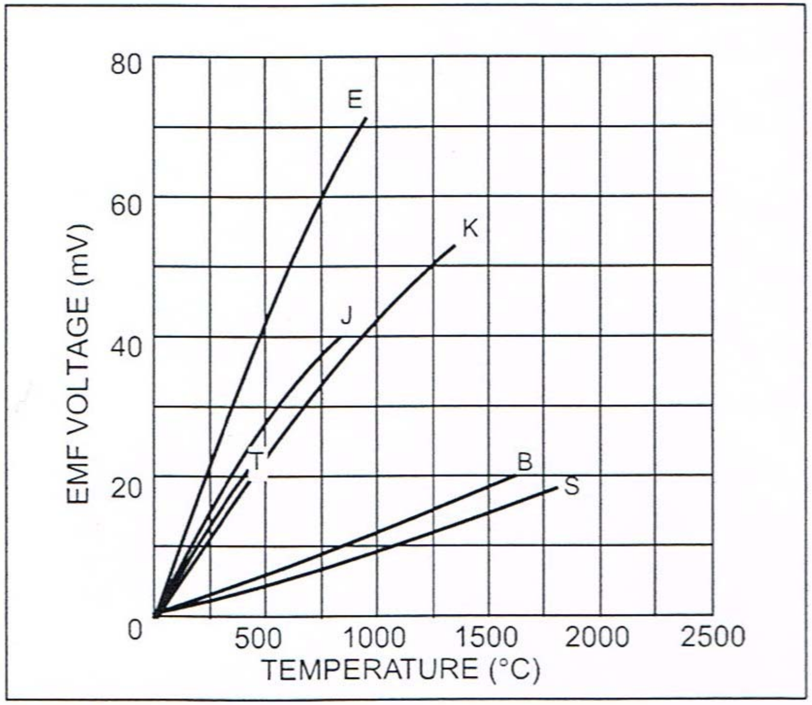


FIGURE 1: EMF voltage of various thermocouples versus temperature

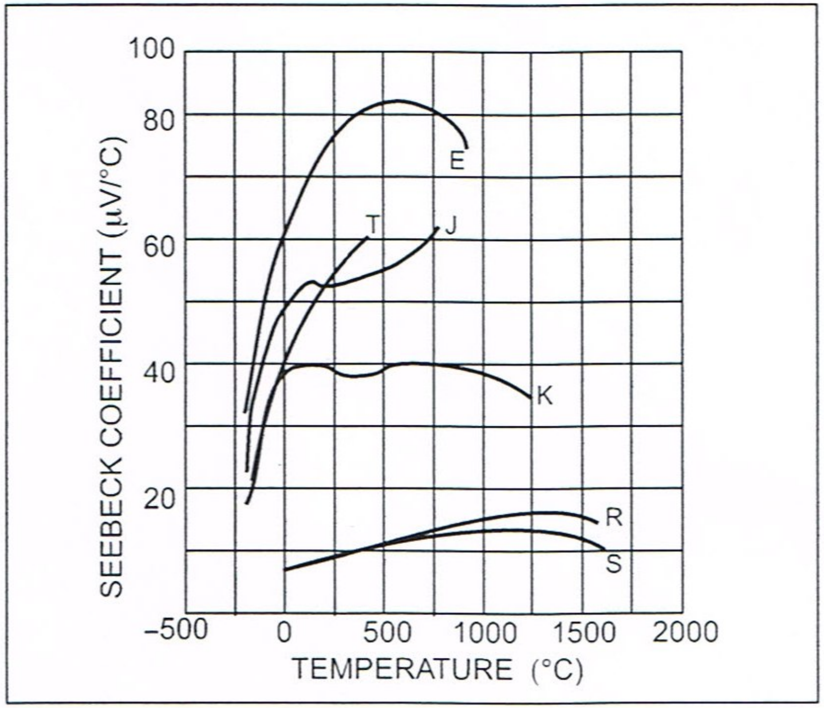


FIGURE 2: Seebeck coefficient of various thermocouples versus temperature

Type K and E

- Type K (chromel {90% nickel and 10% chromium}—alumel {95% nickel, 2% manganese, 2% aluminium and 1% silicon}) is the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C. Doesn’t like high temperatures

- Type E (chromel–constantan) has a high output (68 µV/°C) which makes it well suited to cryogenic use. Additionally, it is non-magnetic. Wide range is −50 to 740 °C and Narrow range is −110 to 140 °C.

Type J and R

- Type J (iron–constantan) has a more restricted range than type K (−40 to +750 °C), but higher sensitivity of about 55 µV/°C.
- Type R (platinum–rhodium alloy) containing 87% platinum + 13% rhodium for the positive conductor and pure platinum for the other conductor. Type R thermocouples are used up to 1600 °C.

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Type S and T

- Type S (platinum-rhodium alloy) containing 90% platinum + 10% rhodium for the positive conductor and pure platinum for the other conductor. In particular, type S is used as the standard of calibration for the melting point of gold (1064.43 °C).
- T (copper – constantan) thermocouples are suited for measurements in the −200 to 350 °C range. Since both conductors are non-magnetic, there is no Curie point and thus no abrupt change in characteristics. Type T sensitivity of about 43 μV/°C.

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Mathematical Model

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

- Either
- $V = b_0 + b_1 \times T + b_2 \times T^2 +++++ b_{10} T^{10}$

  $+ bo \exp(\alpha 1 (T-126.9686)^2)$ for $T > 0^oC$

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

Approximating noisy data with a polynomial having an arbitrary number of coefficients

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```
% MATLAB script
% Assume we have measured at least 432 samples of the Voltage for monotonically increasing
% temperature T (say every one degree from 0 to 434 degrees C) and then fit a 10th order polynomial

% Find the first 10 coefficients

number_of_coeffs = 10;
polycoeffs = polyfit([1:432], Vmeasured , number_of_coeffs)

% Since there is no semicolon, command above will print out all 10
% coefficents for you to check.

% Recreate the noise free approximation from the coefficients

Vsmooth = polyval(polycoeffs,[1:432]);

% Compare with the original data

Error = Vmeasured - Vsmooth;

%Now think about how you might use this concept to differentiate and to integrate
```

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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

Filtering out the noise:
thermocouples are very noisy

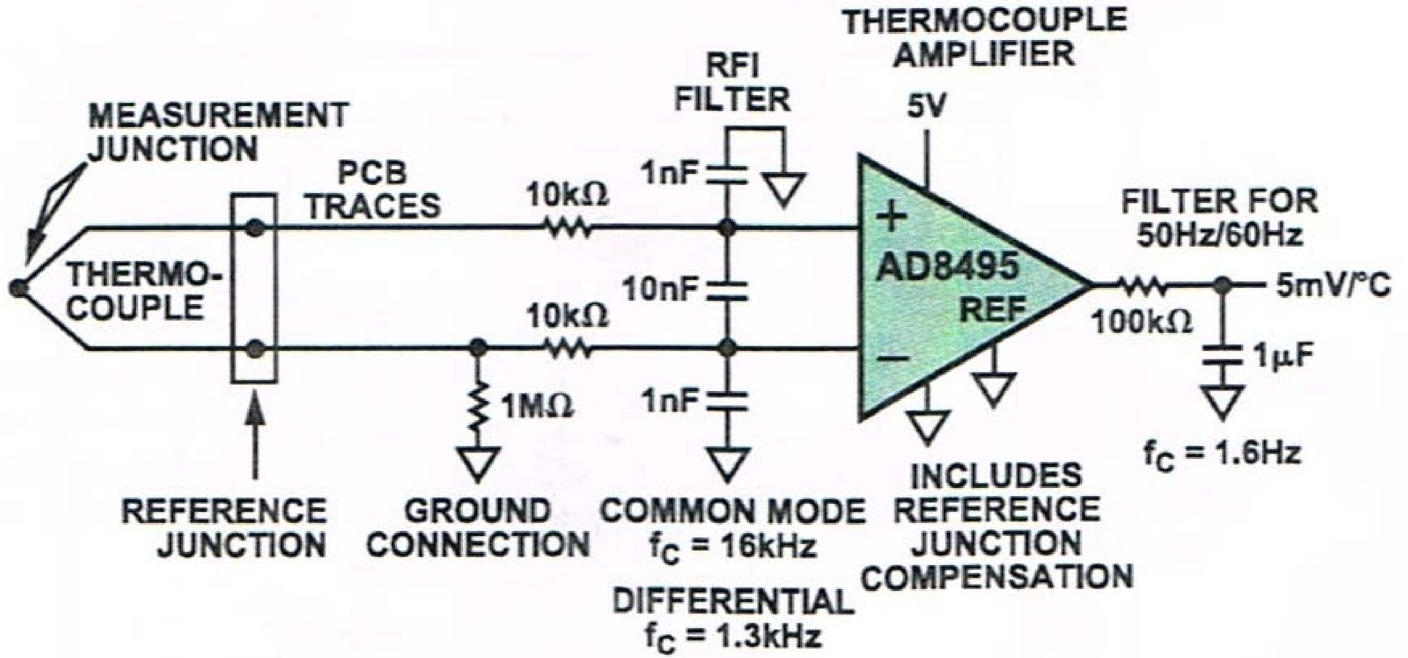
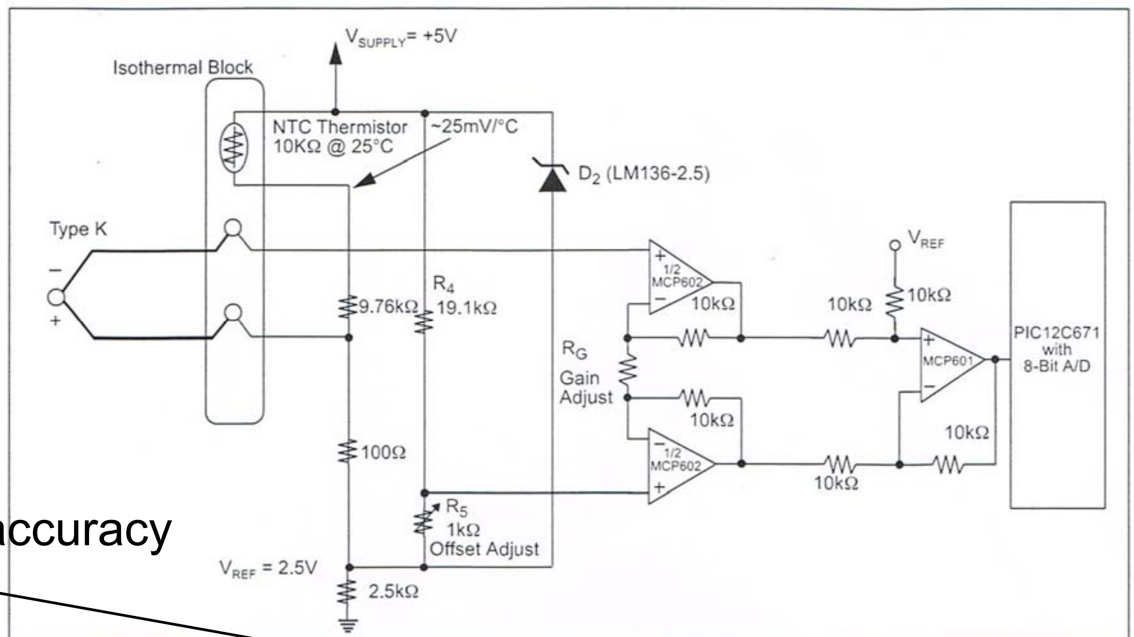


Figure 6. Measurement solution 1: optimized for simplicity.

Look-up table with hardware compensation is easier than using a polynomial



Note 8 bit accuracy

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 required say 0 to 400 ^{o}C
- Minimum temperature step ≈ 1.6 ^{o}C
- i.e., Temp = T +/- 0.8^{o}C
  - This determines the quantisation error of the result regardless the accuracy of the sensor
  - However since the Temp often changes quite slowly you can use averaging to increase the apparent accuracy

Thermocouple
with compensation and filtering

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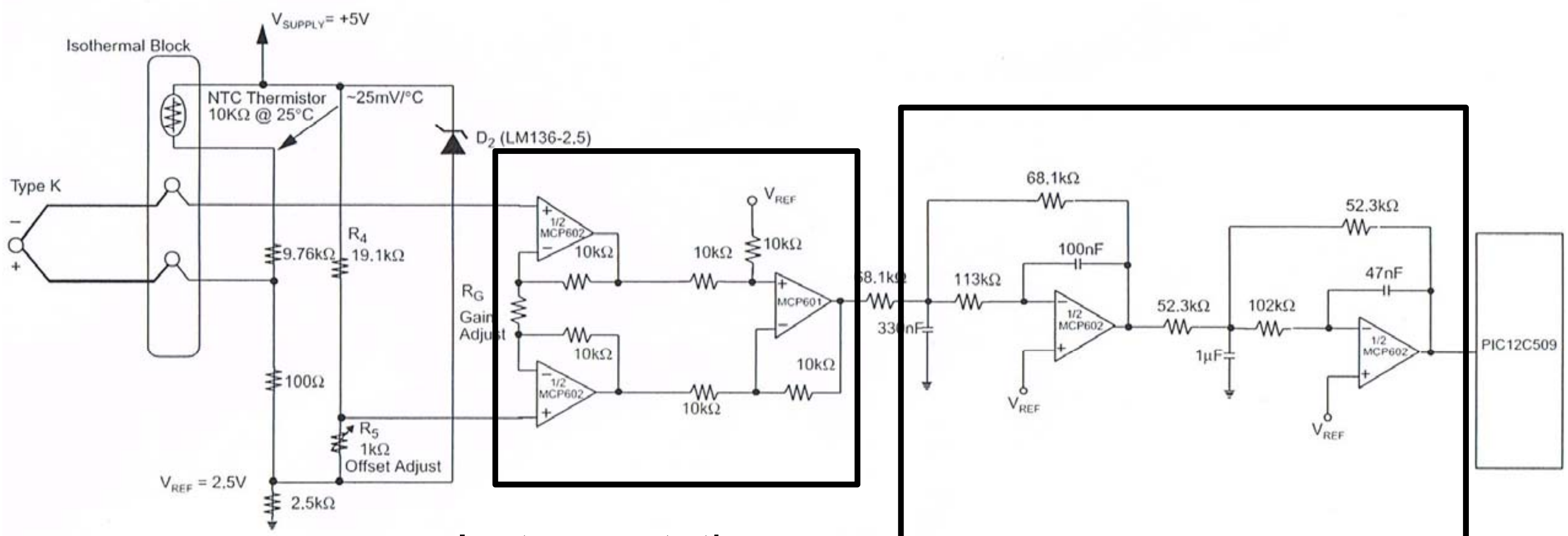
Thermocouples are very noise prone & usually need filtering



Instrumentation amp

Low pass filter

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Using a uP to toggle between sensors

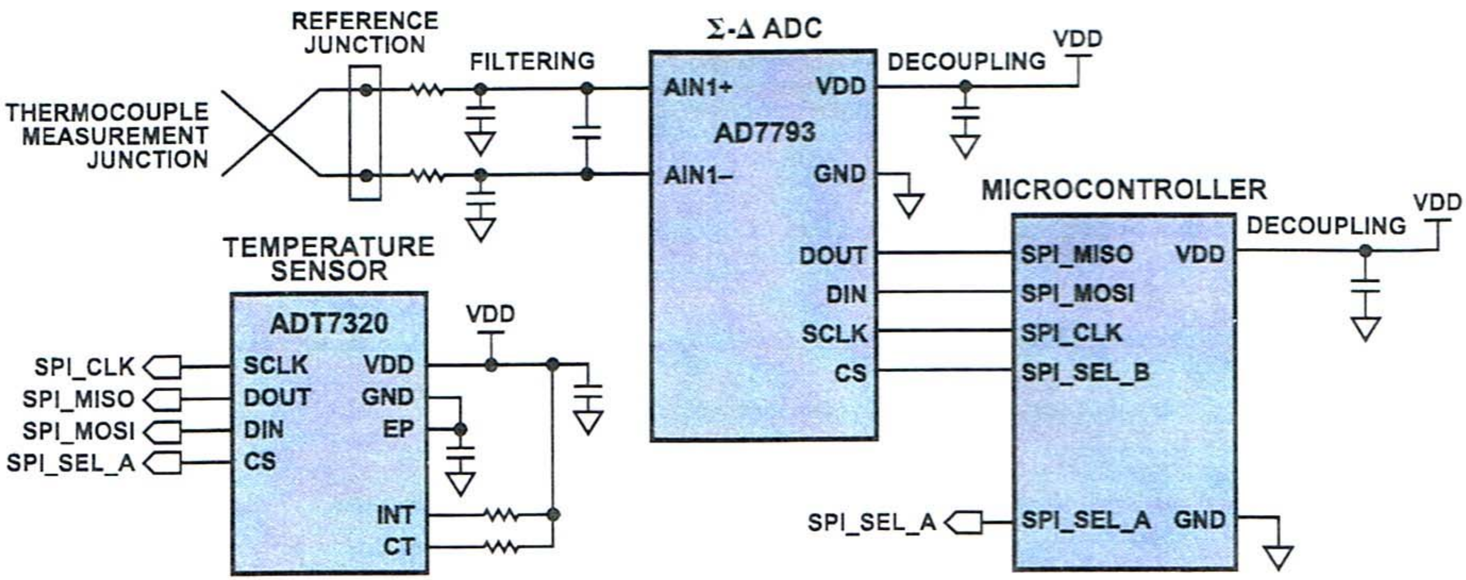

Figure 8. Measurement solution 2: Optimized for accuracy and flexibility.

Useful when the reference junction is not close to the preamp & ADC

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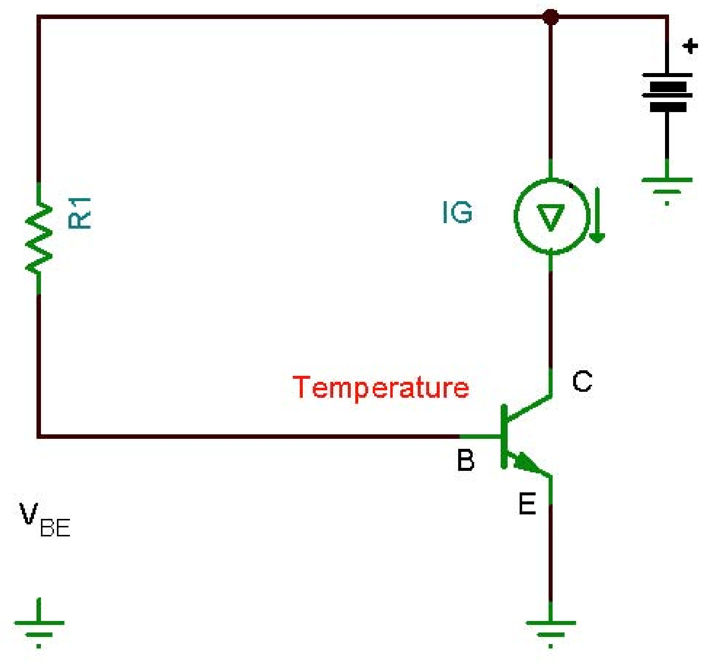
Part IV: Si sensors

(semiconductor details for reference if ever needed)

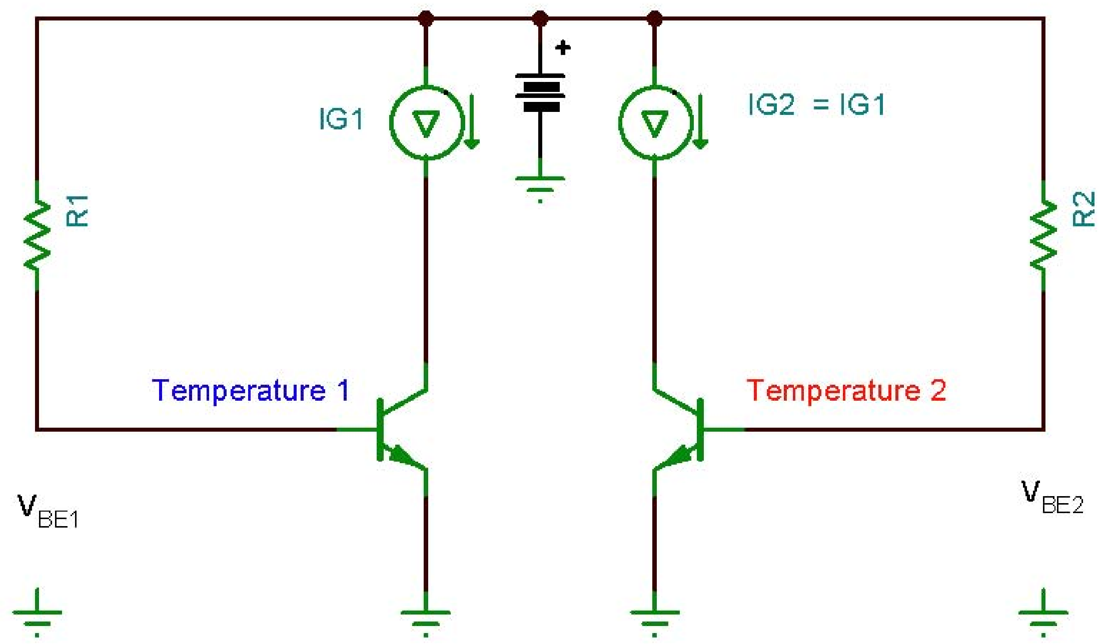
- The silicon bipolar transistor bandgap V_{BE} temperature sensor is an extremely common form of temperature sensor used in electronic equipment:



The V_{BE} as a function of T

- $V_{BE} = V_{GO}\,(1 – T/T_0) + V_{BEO}\,(T/T_O) + (nkT/q)\, ln(T_0/T) + (kT/q)\, ln(I_C/I_{C0})$
  - where
  - T = temperature in °K
  - T_0 = reference temperature; often 300°K
  - V_{G0} = bandgap voltage at absolute zero
  - V_{BE0} = bandgap voltage at temperature T_0 and current I_{C0}
  - k = Boltzmann's constant
  - q = charge on an electron
  - n = a device-dependent constant
- Change in V_{BE} with Temperature ≈ --2mV/°C

Matching transistors at different temperatures



Difference in V_{BE} = -2mV/^{o}C

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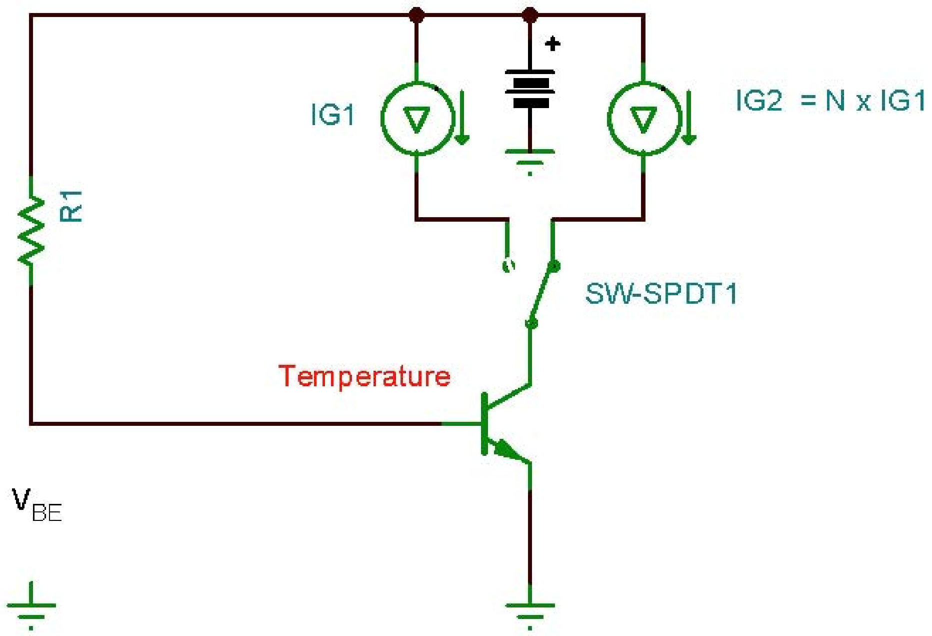
Determining the Voltage change wrt Temperature

- By comparing the bandgap voltages of the same transistor at two different currents, I_{G1} and I_{G2} and where $I_{G2} = N\, I_{G1}$, many of the variables in the V_{BE} equation can be eliminated, resulting in

$$\Delta V_{BE} = (kT/q)\, \mathit{ln}\, (I_{G2}/I_{G1})$$
$$= (kT/q)\, \mathit{ln}\, (N)$$

Usually this small voltage is multiplied by internal amplifiers

Switch the same transistor between two different currents.



Rats and Mice
(not covered in this lecture)

- Noncontact IR single sensors.
- Noncontact IR imaging cameras.

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So......References

- Previous years' E80 lectures on Temperature by Professors S. Harris and Q. Yang
- Wikipedia
- Microchip Application Notes AN679, AN684, AN685, AN687, AN871, AN893
- Texas Instruments SBAA180
- Baker, Bonnie, "Designing with temperature sensors, part one: sensor types," *EDN*, Sept 22, 2011, pg 22.
- 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.