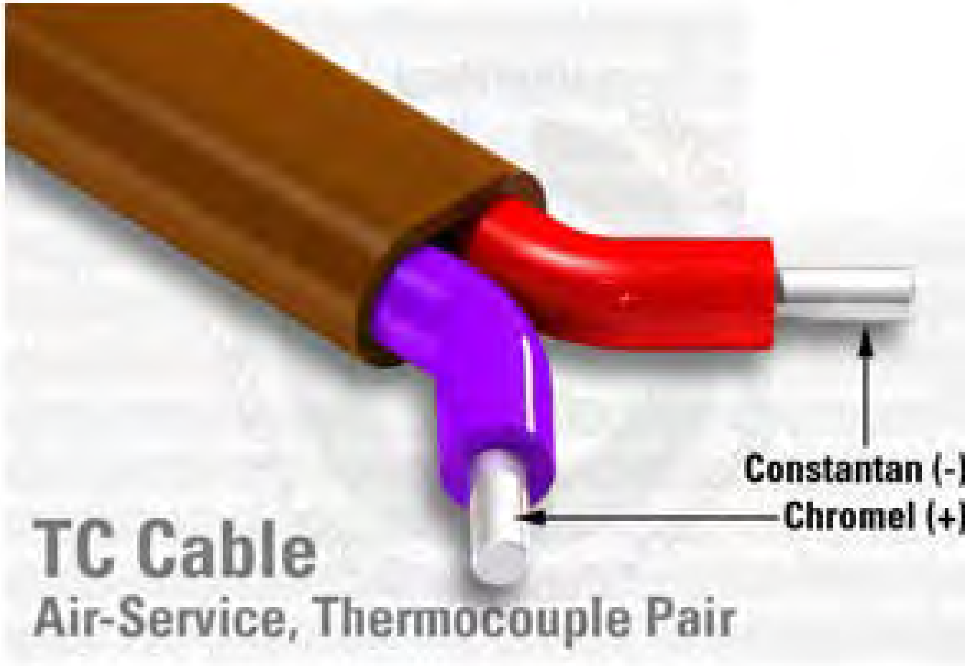
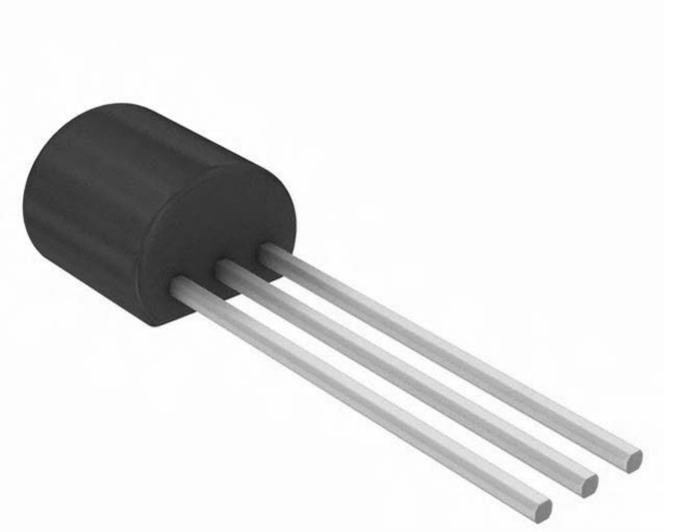
Temperature Measurements

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



SOURCE: http://www.accuglassproducts.com/product.php?productid=17523



SOURCE: http://elcodis.com/photos/19/51/195143/to-92-3_standardbody__to-226_straightlead.jpg

What You'll Be Learning About Today…

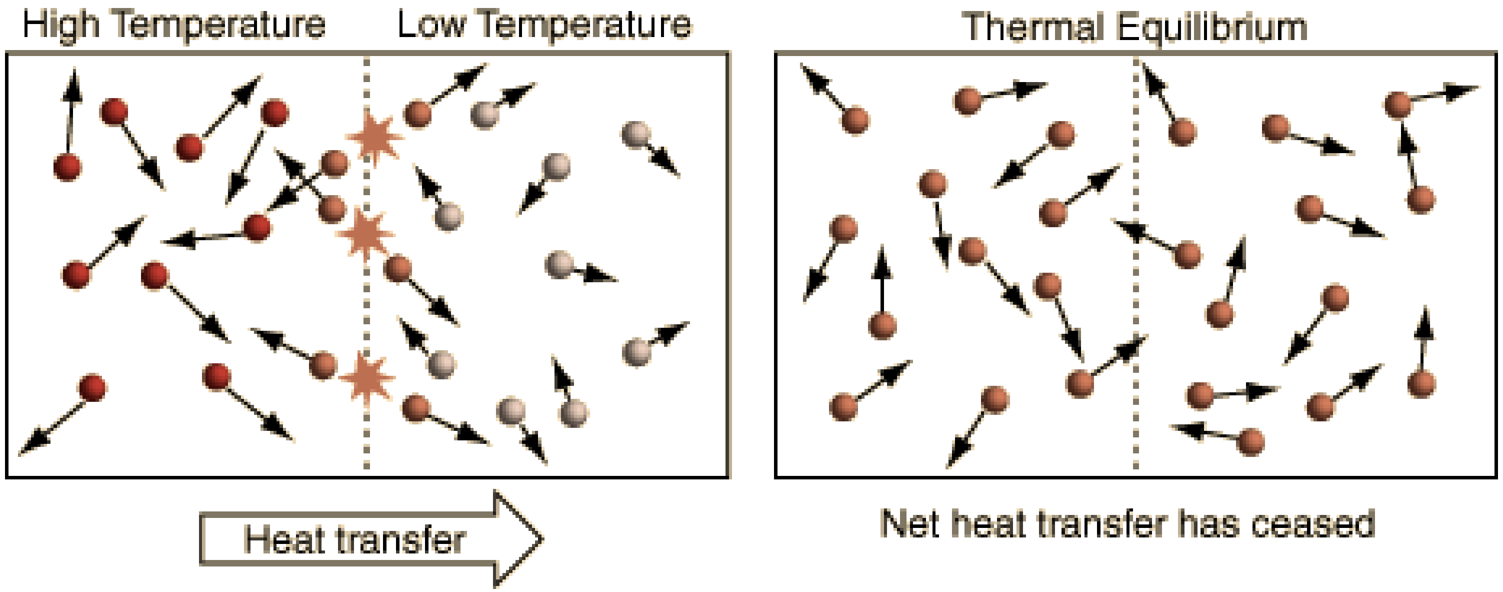
- Measuring Temperature
- Types of Temperature Sensors
  - Thermistor
  - Integrated Silicon Linear Sensor
  - Thermocouple
  - Resistive Temperature Detector (RTD)
- Choosing a Temperature Sensor
- Calibrating Temperature Sensors
- Thermal System Transient Response

What is Temperature?

SOURCE: http://www.clker.com/cliparts/6/5/b/f/11949864691020941855smiley114.svg.med.png

What is Temperature?

AN <u>OVERLY SIMPLIFIED</u> DESCRIPTION OF TEMPERATURE



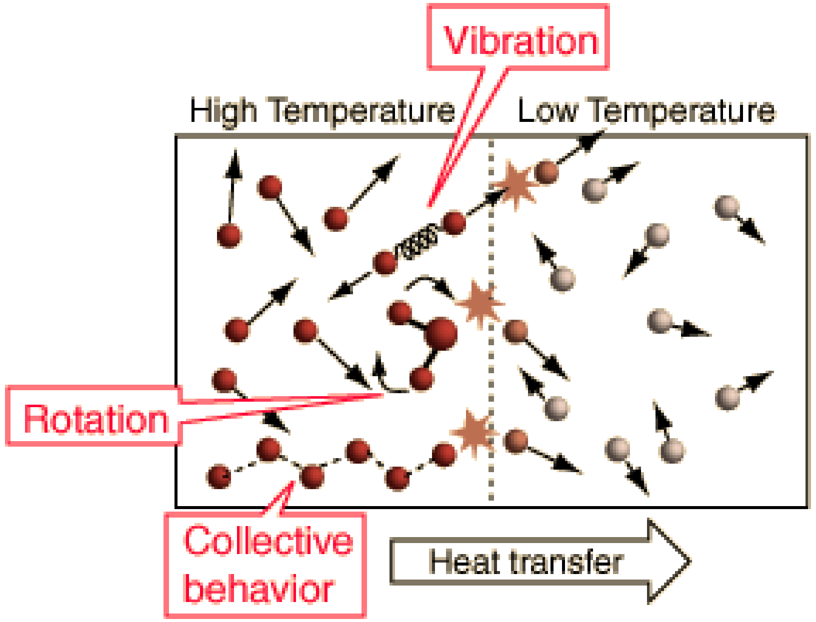
SOURCE: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/temper2.html#c1

"Temperature is a measure of the tendency of an object to spontaneously give up energy to its surroundings. When two objects are in thermal contact, the one that tends to spontaneously lose energy is at the higher temperature."

(Schroeder, Daniel V. An Introduction to Thermal Physics, 1st Edition (Ch, 1). Addison-Wesley.)

What is Temperature?

A SIMPLIFIED DESCRIPTION OF TEMPERATURE



SOURCE: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/temper2.html#c1

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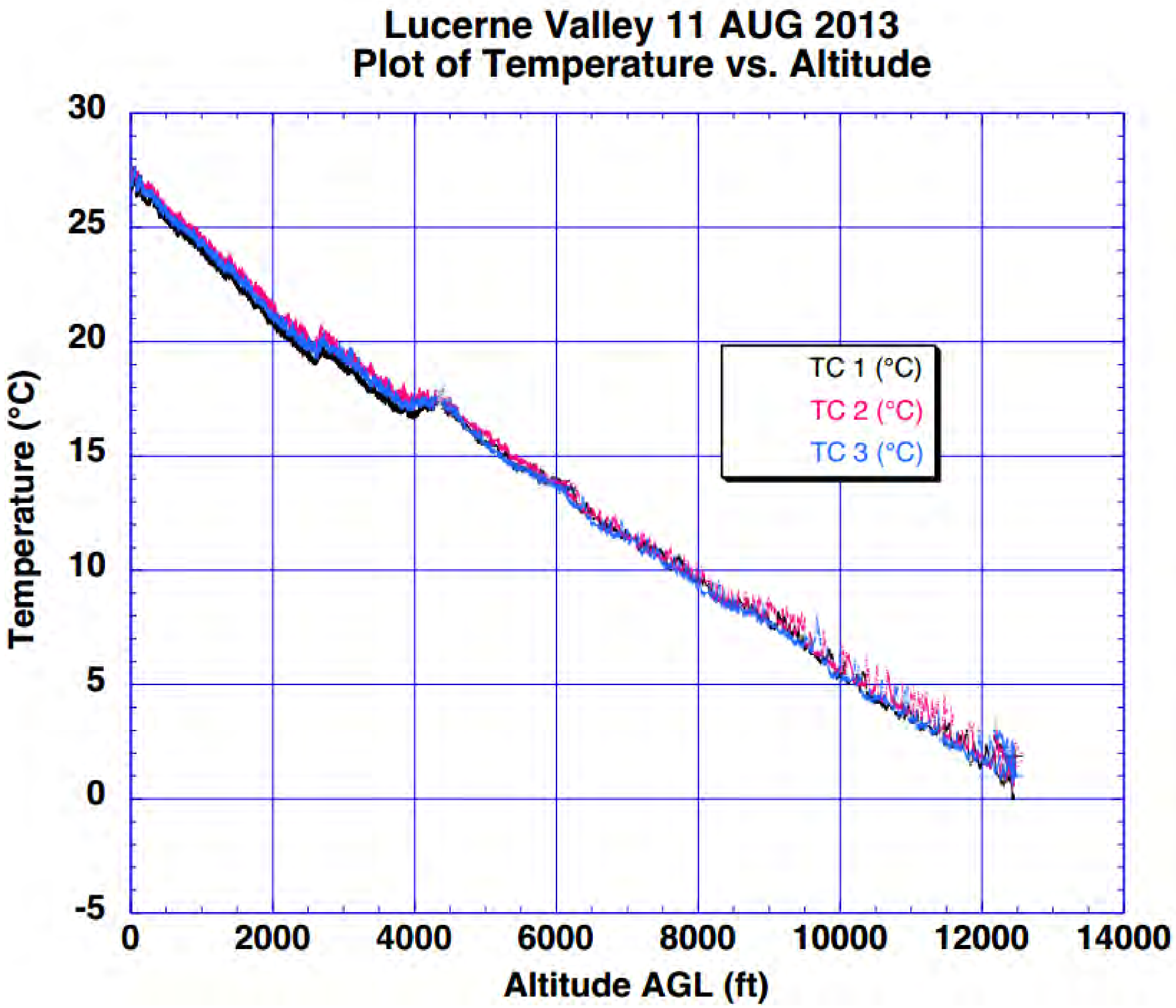
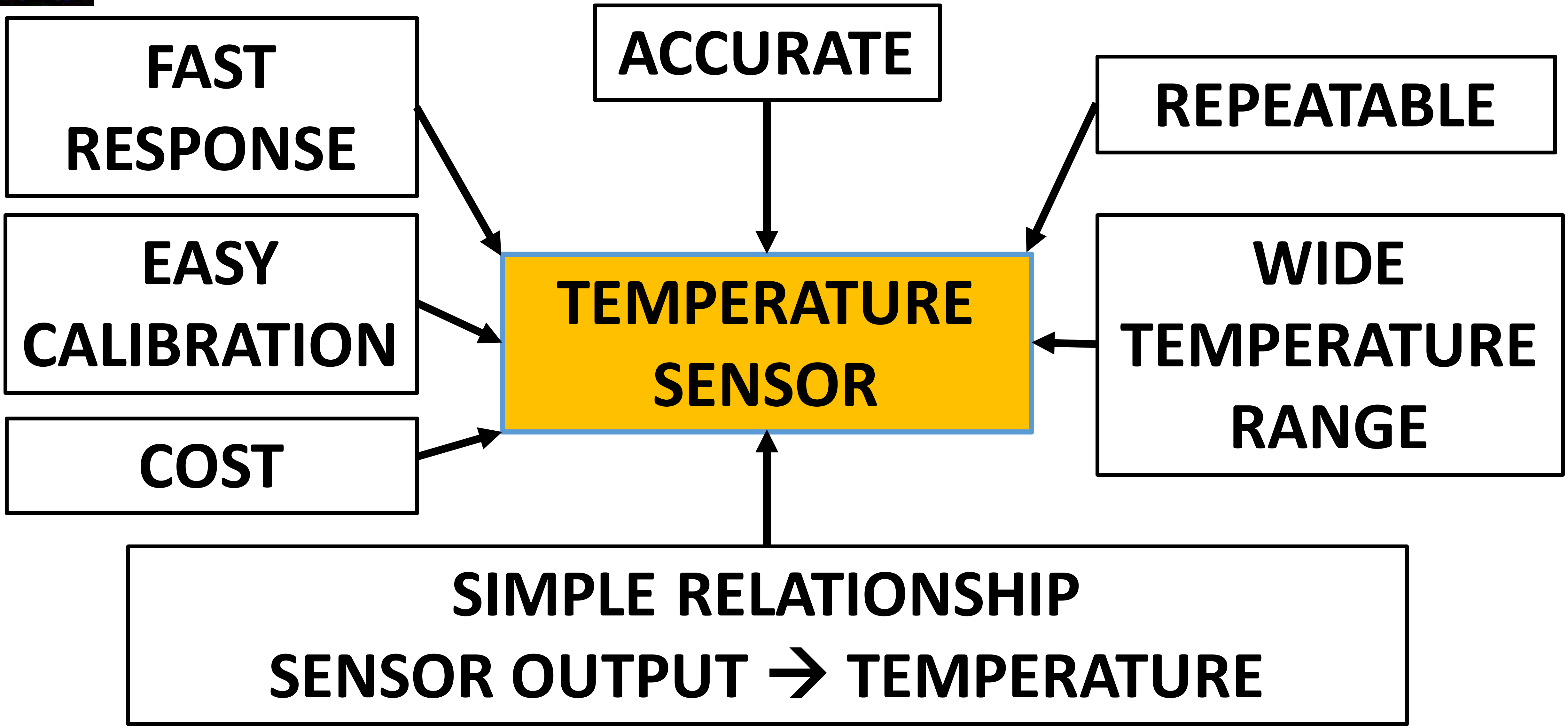
Measuring Temperature with Rockets



What are desirable characteristics of a temperature sensor?

Desirable Temperature Sensor Characteristics



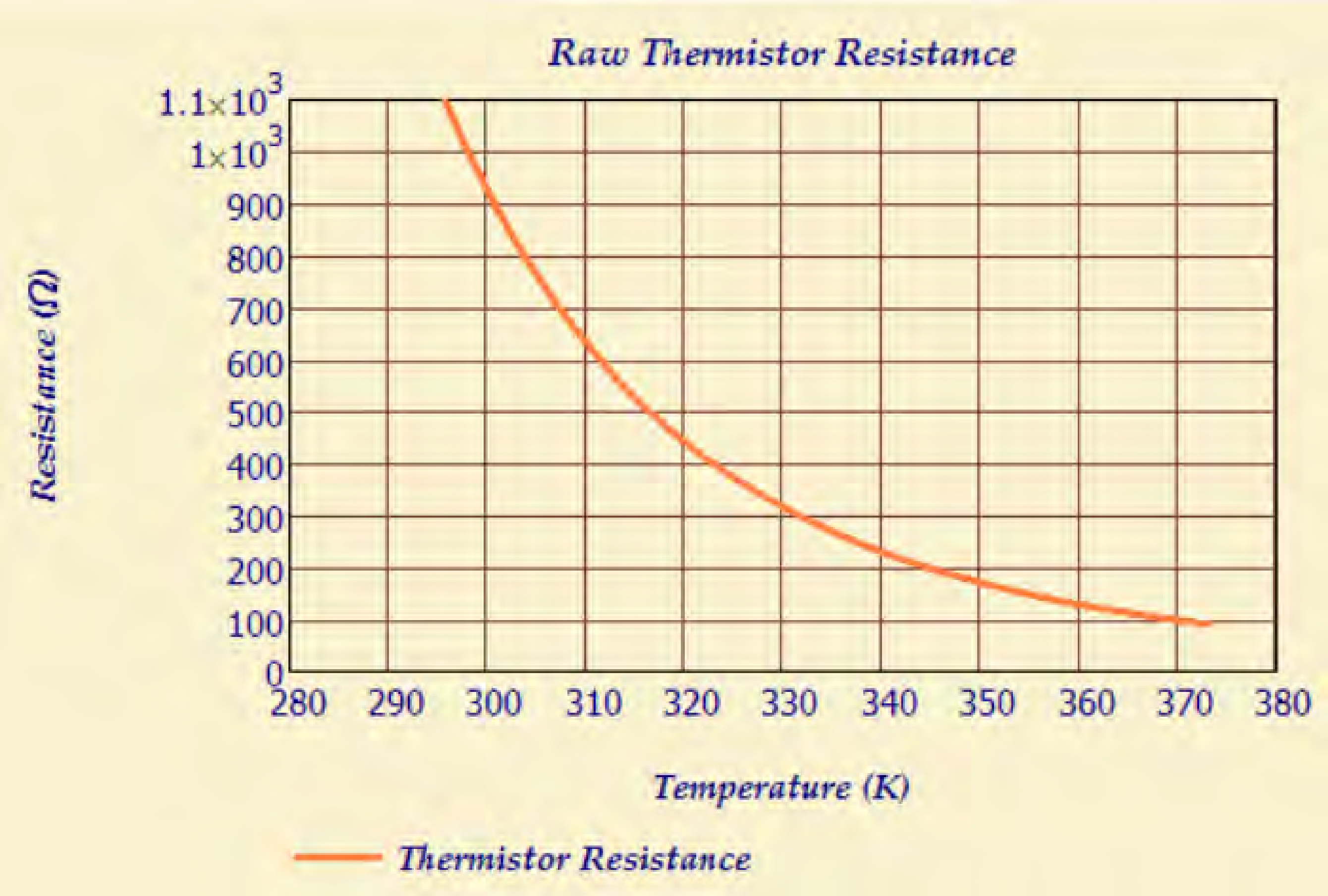
Thermistor

Thermistor – a resistor whose resistance changes with temperature

- Resistive element is generally a metal-oxide ceramic containing Mn, Co, Cu, or Ni
- Packaged in a thermally conductive glass bead or disk with two metal leads
- Suppose we have a “1 kΩ thermistor”
  - What does this mean?
  - At room temperature, the resistance of the thermistor is 1 kΩ
  - What happens to resistance as we increase temperature?

Negative Temperature Coefficient

- Most materials exhibit a **negative temperature coefficient (NTC)**
  - Resistance **drops** with temperature!



Converting Resistance to Temperature

- **The Steinhart-Hart Equation** relates temperature to resistance

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

- T is the temperature (in Kelvin)
- R is the resistance at T and R_{ref} is resistance at T_{ref}
- A_1, B_1, C_1, and D_1 are the Steinhart-Hart Coefficients
- **HOW COULD WE DETERMINE THESE COEFFICIENTS?**

SOURCE: http://p.globalsources.com/IMAGES/PDT/B1055847338/Thermistor.jpg

Converting Resistance to Temperature

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

PARAMETER FOR DETERMINING NOMINAL RESISTANCE VALUES

NUMBER	$B_{25/85}$ (K)	NAME	TOL. B VALUE %	A	B (K)	C (K^2)	D (K^3)	A_1	B_1 (K^{-1})	C_1 (K^{-2})	D_1 (K^{-3})
1	2880	Mat O. with Bn = 2880K	3	- 9.094	2251.74	229098	- 2.744820E+07	3.354016E-03	3.495020E-04	2.095959E-06	4.260615E-07
2	2990	Mat P. with Bn = 3990K	3	- 10.2296	2887.62	132336	- 2.502510E+07	3.354016E-03	3.415560E-04	4.955455E-06	4.364236E-07
3	3041	Mat Q. with Bn = 3041K	3	- 11.1334	3658.73	- 102895	5.166520E+05	3.354016E-03	3.349290E-04	3.683843E-06	7.050455E-07
4	3136	Mat R. with Bn = 3136K	3	- 12.4493	4702.74	- 402687	3.196830E+07	3.354016E-03	3.243880E-04	2.658012E-06	- 2.701560E-07
5	3390	Mat S. with Bn = 3390K	3	- 12.6814	4391.97	- 232807	1.509643E+07	3.354016E-03	2.993410E-04	2.135133E-06	- 5.672000E-09
6	3528 (1)	Mat I. with Bn = 3528K	0.5	- 12.0596	3687.667	- 7617.13	- 5.914730E+06	3.354016E-03	2.909670E-04	1.632136E-06	7.192200E-08
	3528 (2)			- 21.0704	11903.95	- 2504699	2.470338E+08	3.354016E-03	2.933908E-04	3.494314E-06	- 7.712690E-07
7	3560	Mat H. with Bn = 3560K	1.5	- 13.0723	4190.574	- 47158.4	- 1.199256E+07	3.354016E-03	2.884193E-04	4.118032E-06	1.786790E-07
8	3740	Mat B. with Bn = 3740K	2	- 13.8973	4557.725	- 98275	- 7.522357E+06	3.354016E-03	2.744032E-04	3.666944E-06	1.375492E-07
9	3977	Mat A. with Bn =3977K	0.75	- 14.6337	4791.842	- 115334	- 3.730535E+06	3.354016E-03	2.569850E-04	2.620131E-06	6.383091E-08
10	4090	Mat C. with Bn = 4090K	1.5	- 15.5322	5229.973	- 160451	- 5.414091E+06	3.354016E-03	2.519107E-04	3.510939E-06	1.105179E-07
11	4190	Mat D. with Bn = 4190K	1.5	- 16.0349	5459.339	- 191141	- 3.328322E+06	3.354016E-03	2.460382E-04	3.405377E-06	1.034240E-07
12	4370	Mat E. with Bn = 4370K	2.5	- 16.8717	5759.15	- 194267	- 6.869149E+06	3.354016E-03	2.367720E-04	3.585140E-06	1.255349E-07
13	4570	Mat F. with Bn = 4570K	1.5	- 17.6439	6022.726	- 203157	- 7.183526E+06	3.354016E-03	2.264097E-04	3.278184E-06	1.097628E-07

Notes

(1) Temperature < 25 °C

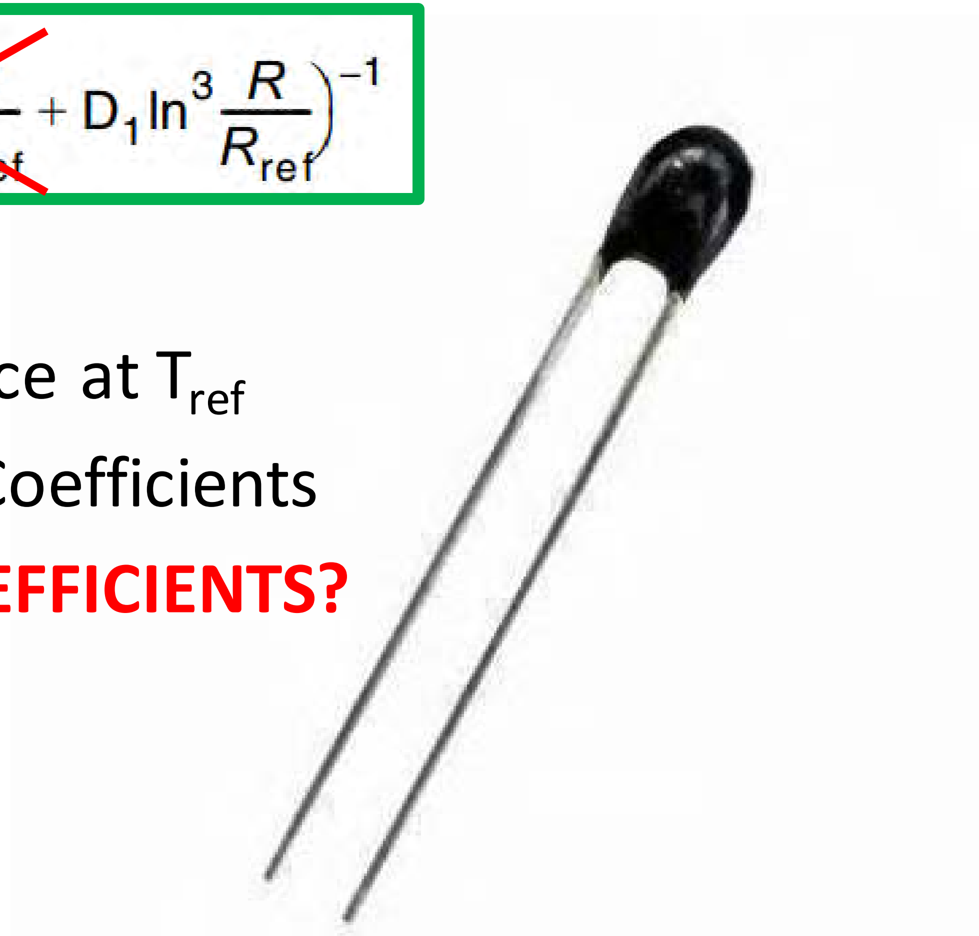
(2) Temperature ≥ 25 °C

Converting Resistance to Temperature

- **The Steinhart-Hart Equation** relates temperature to resistance

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

- T is the temperature (in Kelvin)
- R is the resistance at T and R_{ref} is resistance at T_{ref}
- A_1, B_1, C_1, and D_1 are the Steinhart-Hart Coefficients
- **HOW COULD WE DETERMINE THESE COEFFICIENTS?**
  - Take a look at the data sheet
  - Measure 3 resistances at 3 temperatures
    - Matrix Inversion (Linear Algebra)



SOURCE: http://p.globalsources.com/IMAGES/PDT/B1055847338/Thermistor.jpg

How is Resistance Measured?

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

SOURCE: http://cdn.teachersupplysource.com/images/D/024-ENC-M-1700.jpg

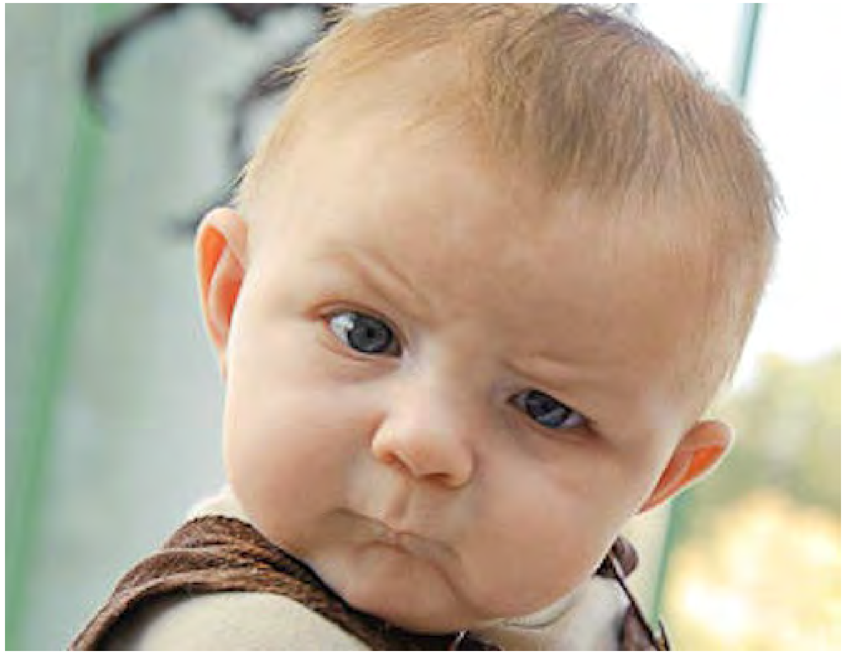
SOURCE: http://p.globalsources.com/IMAGES/PDT/B1055847338/Thermistor.jpg

SOURCE: http://images.studica.com/images/product/National-Instruments-students-ni-labview-mydaq/51NI%20myDAQ%20Device%2005041223.jpg

Thermistor Resistance (R_T)

- A thermistor produces a resistance (R_T), which could be converted to a voltage signal

HOW COULD WE DO THIS?



SOURCE: http://2.bp.blogspot.com/-Pwxc29B8fkU/VHDBayyJGmI/AAAAAAAAAOw/Po9R4z7WPYI/s1600/Baby-Making-Funny-Face.png

Thermistor Resistance (R_T)

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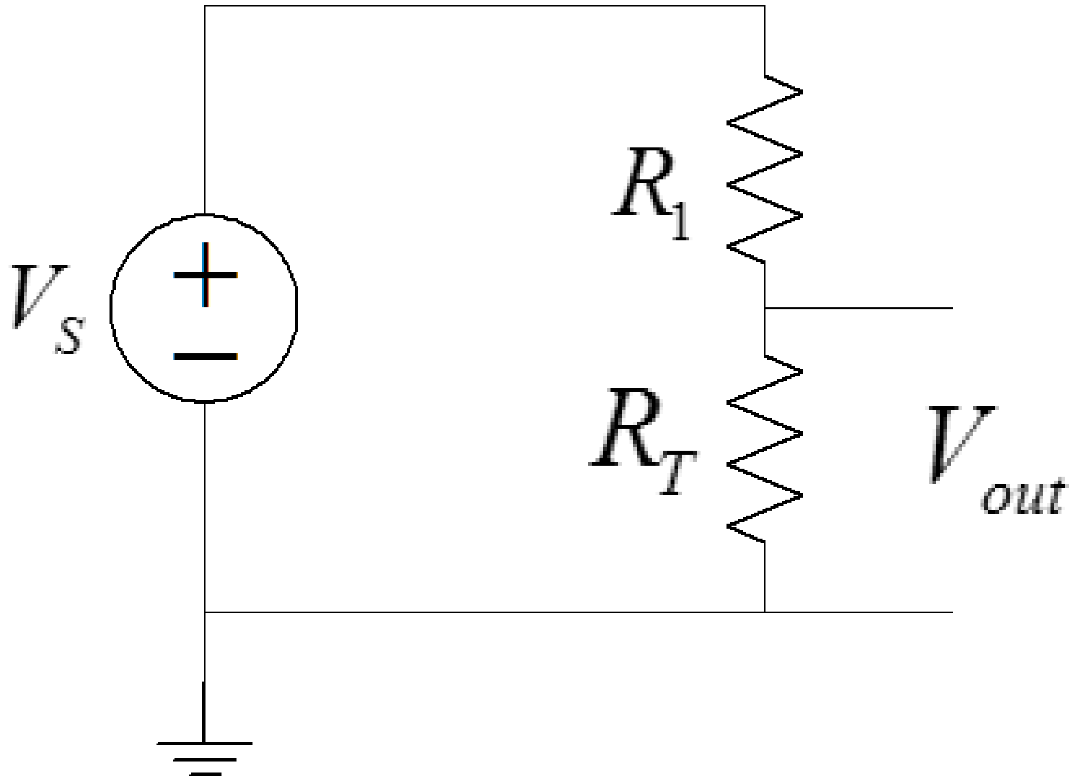


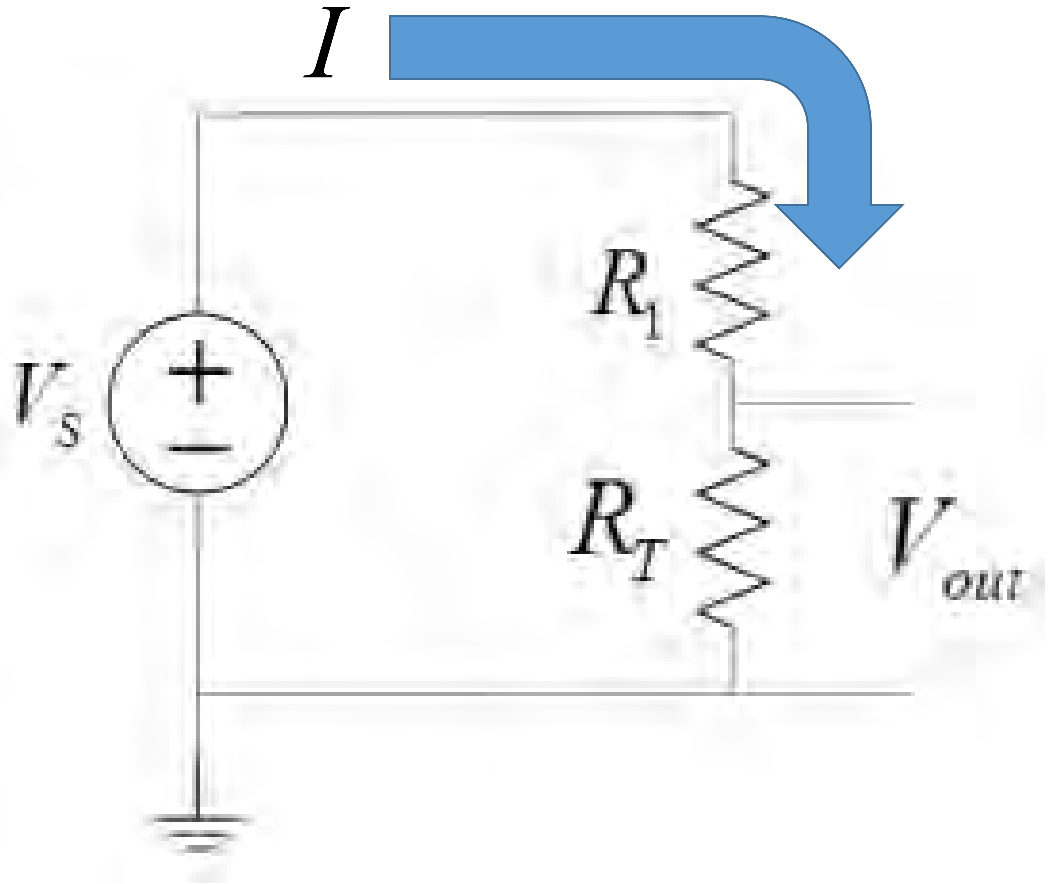
$$V_{out} = V_S \frac{R_T}{R_T + R_1}$$

Power Dissipation in Thermistors

- A current must pass through the thermistor to measure the voltage and calculate the resistance
- The current flowing through the thermistor generates heat because the thermistor dissipates electrical power

$$P = I^2 R_T$$

- The heat generated causes a temperature rise in the thermistor
- This is called **Self-Heating**
- **WHY IS SELF-HEATING BAD?**



Power Dissipation and Self-Heating

- Self-Heating can introduce an error into the measurement
- The increase in device temperature (ΔT) is related to the power dissipated (P) and the power dissipation factor (δ)

$$\boxed{P = \delta\, \Delta T}$$

Where P is in [W], ΔT is the rise in temperature in [^{o}C]

- Suppose $I = 5$ mA, $R_T = 4$ kΩ, and $\delta = 0.067$ W/^{o}C, what is ΔT?

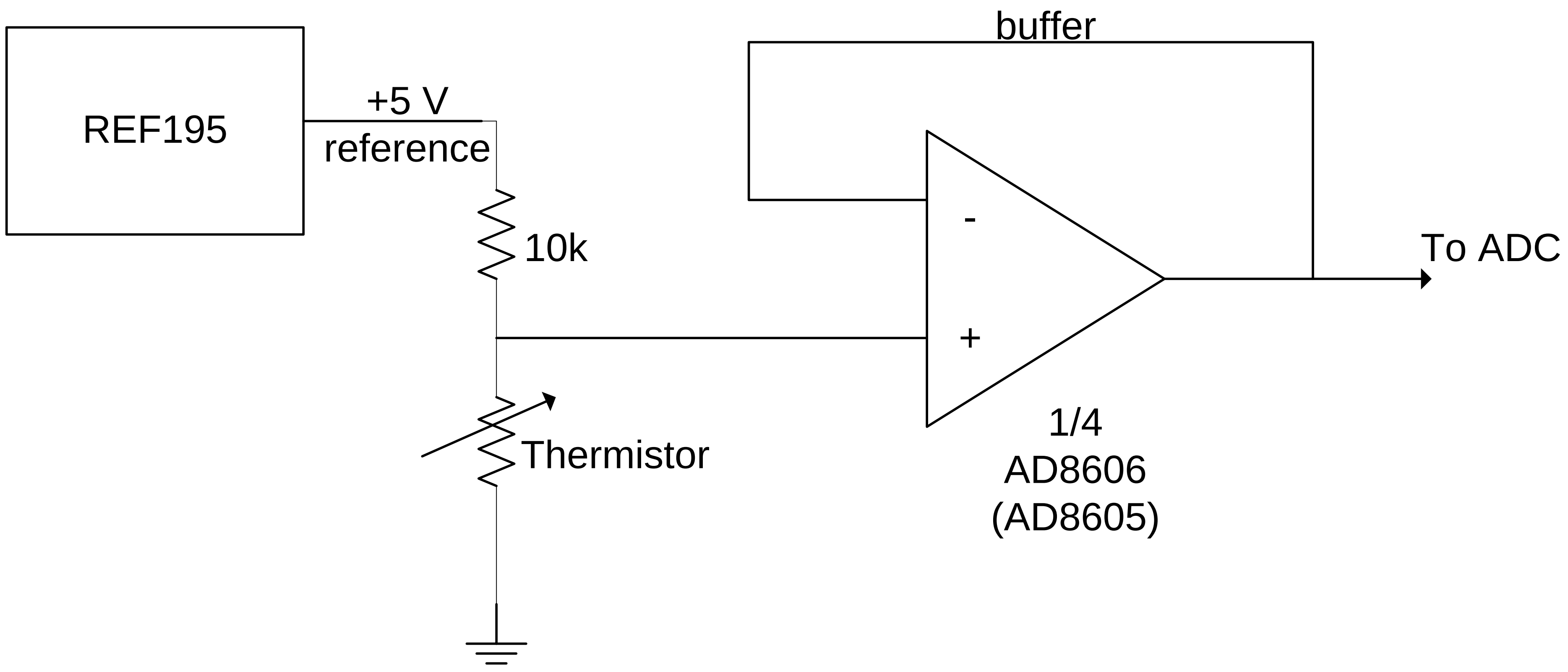
$$(0.005\ \text{A})^2(4000\ \Omega) = (0.067\ \text{W}/^o\text{C})\ \Delta T$$

$$\Delta T = 1.5\ ^oC$$

- What effect does a ΔT of 1.5 ^{o}C have on your thermistor measurements?
- How can we reduce the effects of self-heating?
  - Increase the resistance of the thermistor!

Thermistor Signal Conditioning Circuit

- A voltage divider and a unity gain buffer will be used to measure temperature in the lab



Summary Thus Far…

	Thermistor
Temperature Range	–100 to 450°C
Sensitivity	several Ω / Ω / ˚C
Accuracy	±0.1°C
Linearity	Requires at least 3rd order polynomial or equivalent look up table.
Ruggedness	The thermistor element is housed in a variety of ways, however, the most stable, hermetic Thermistors are enclosed in glass. Generally thermistors are more difficult to handle, but not affected by shock or vibration.
Responsiveness in stirred oil	1 to 5 Secs
Excitation	Voltage Source
Form of Output	Resistance
Typical Size	0.1 x 0.1 in.
Price	> $10

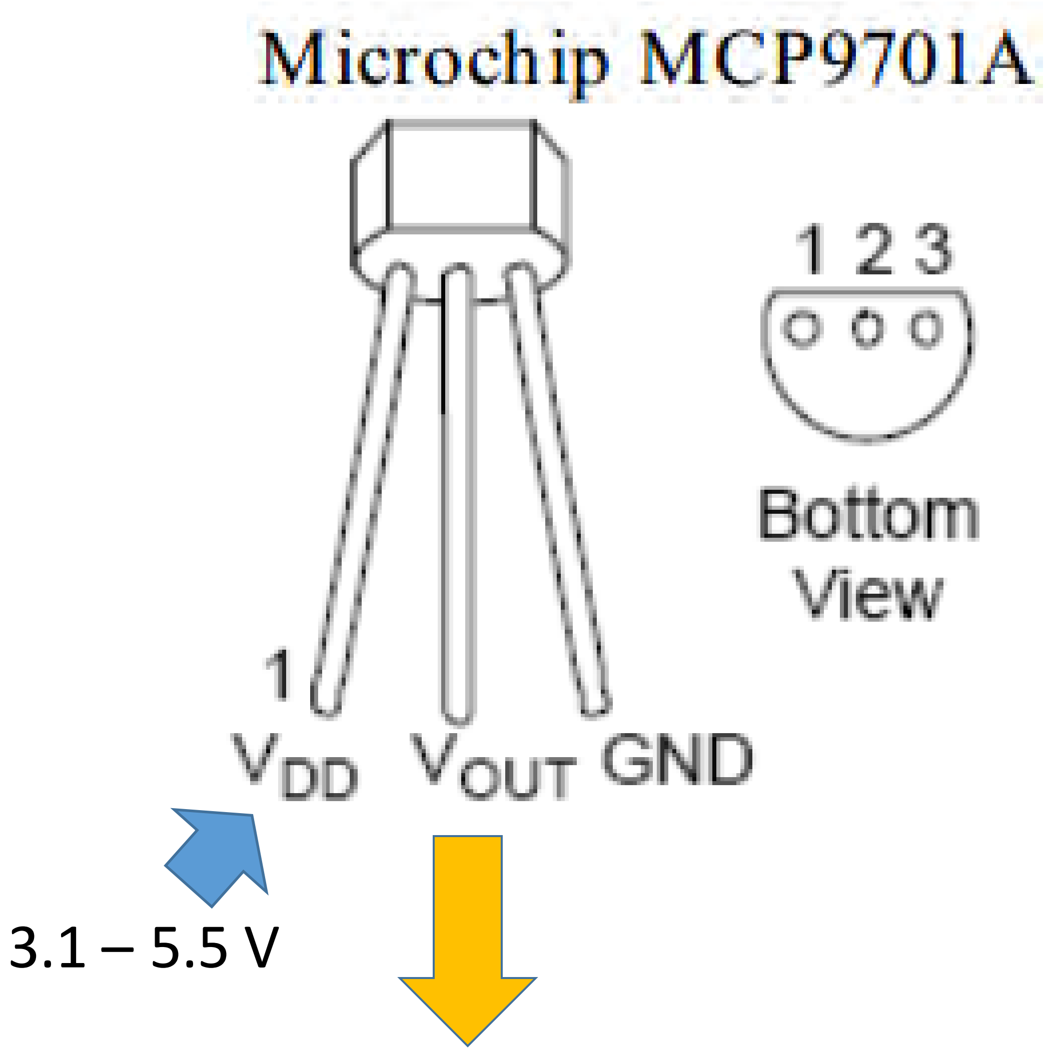
Integrated Silicon Linear Sensors

SOURCE: https://labjack.com/sites/default/files/LM34CAZ_1.png

Integrated Silicon Linear Sensors

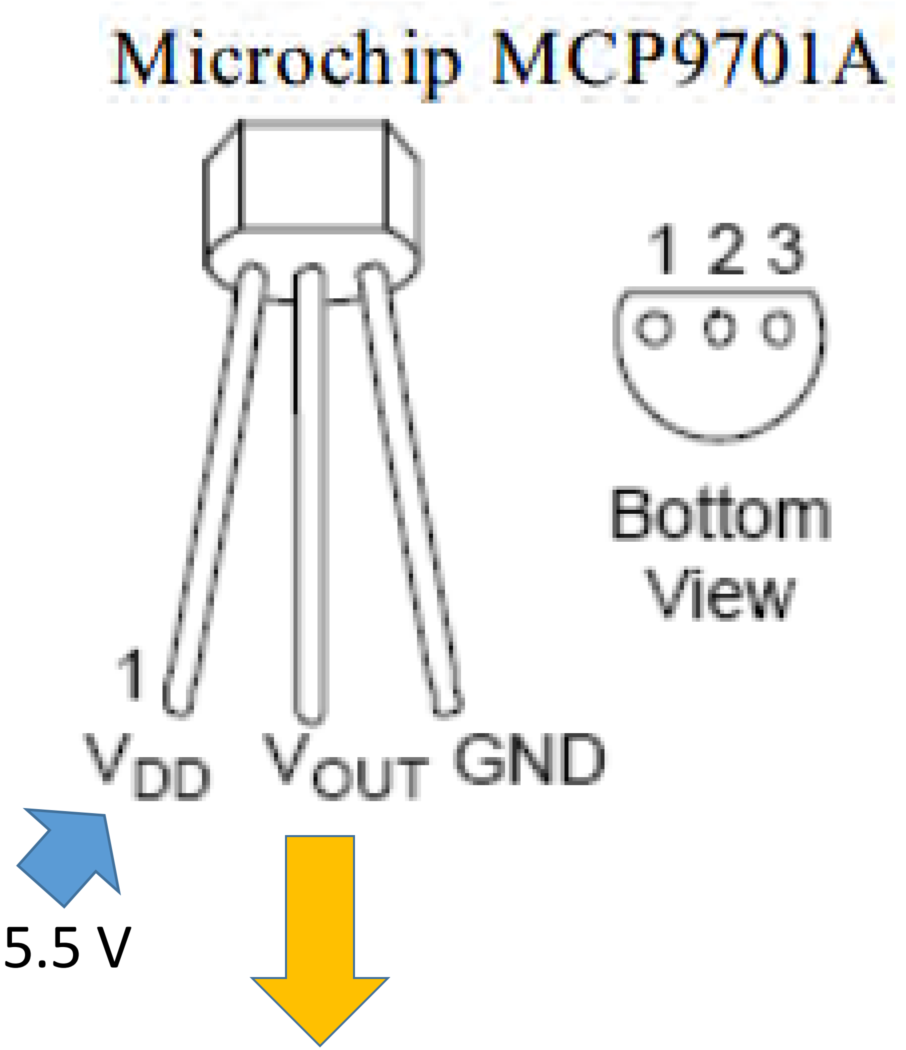
- An **integrated silicon linear sensor** is a three-terminal device
  - Power and ground inputs
  - Relatively simple to use and cheap
  - Circuitry inside does linearization and signal conditioning
  - Produces an output voltage linearly dependent on temperature

$$\boxed{V_{OUT} = T_C \bullet T_A + V_{0°C}}$$



Integrated Silicon Linear Sensors

- An **integrated silicon linear sensor** is a three-terminal device
  - Power and ground inputs
  - Relatively simple to use and cheap
  - Circuitry inside does linearization and signal conditioning
  - Produces an output voltage linearly dependent on temperature
  - When compared to other temperature measurement devices, these sensors are **LESS** accurate, operate over a **NARROWER** temperature range, and are **LESS** responsive



3.1 – 5.5 V

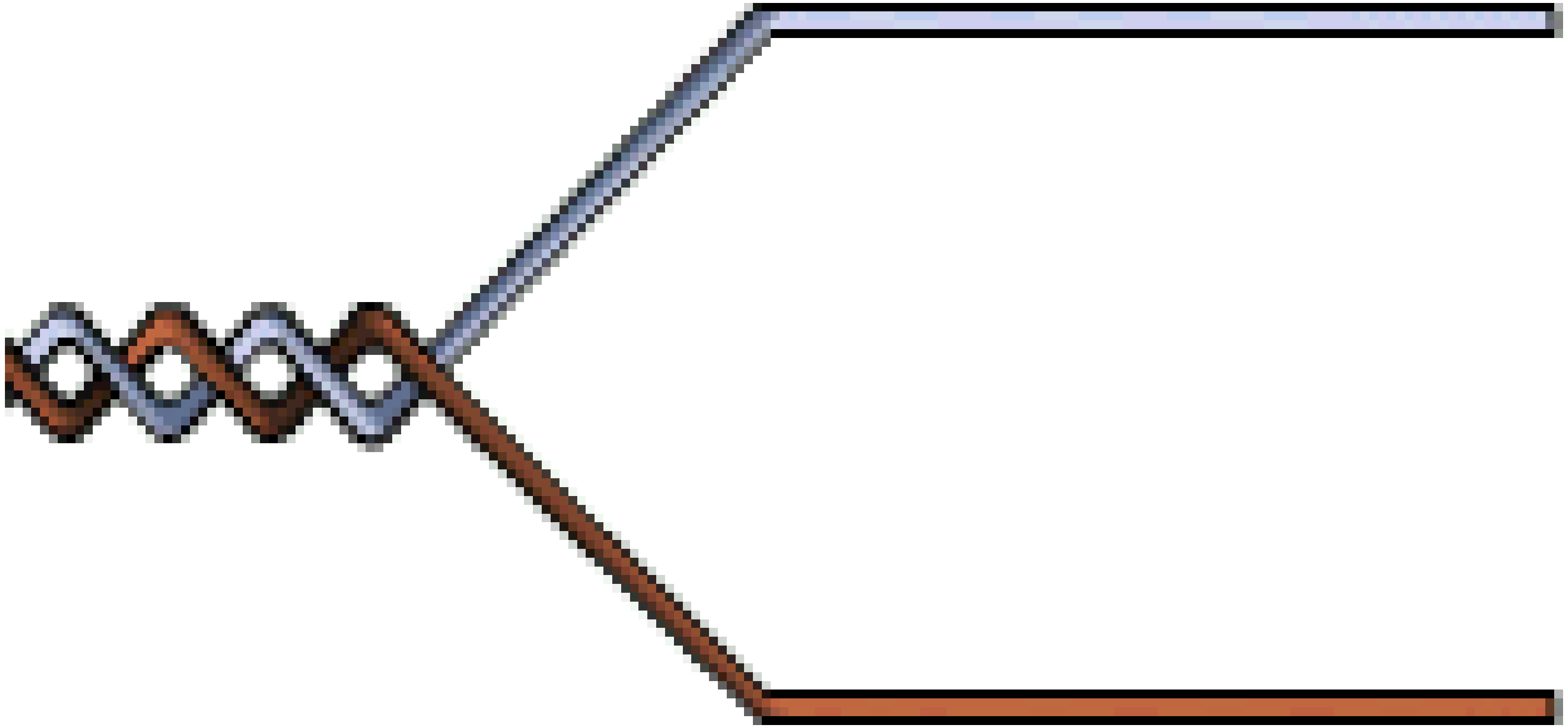
HARVEY MUDD COLLEGE

Summary Thus Far...

			Thermistor	Integrated Silicon
Temperature Range			–100 to 450°C	-55 to 150°C
Sensitivity			several Ω / Ω / ˚C	Based on technology that is -2mV/°C sensitive
Accuracy			±0.1°C	±1°C
Linearity			Requires at least 3rd order polynomial or equivalent look up table.	At best within ±1°C. No linearization required.
Ruggedness			The thermistor element is housed in a variety of ways, however, the most stable, hermetic Thermistors are enclosed in glass. Generally thermistors are more difficult to handle, but not affected by shock or vibration.	As rugged as any IC housed in a plastic package such as dual-in-line or surface outline ICs.
Responsiveness in stirred oil			1 to 5 Secs	4 to 60 Secs
Excitation			Voltage Source	Typically Supply Voltage
Form of Output			Resistance	Voltage, Current, or Digital
Typical Size			0.1 x 0.1 in.	From TO-18 Transistors to Plastic DIP
Price			> $10	$1 to $10

Thermocouple

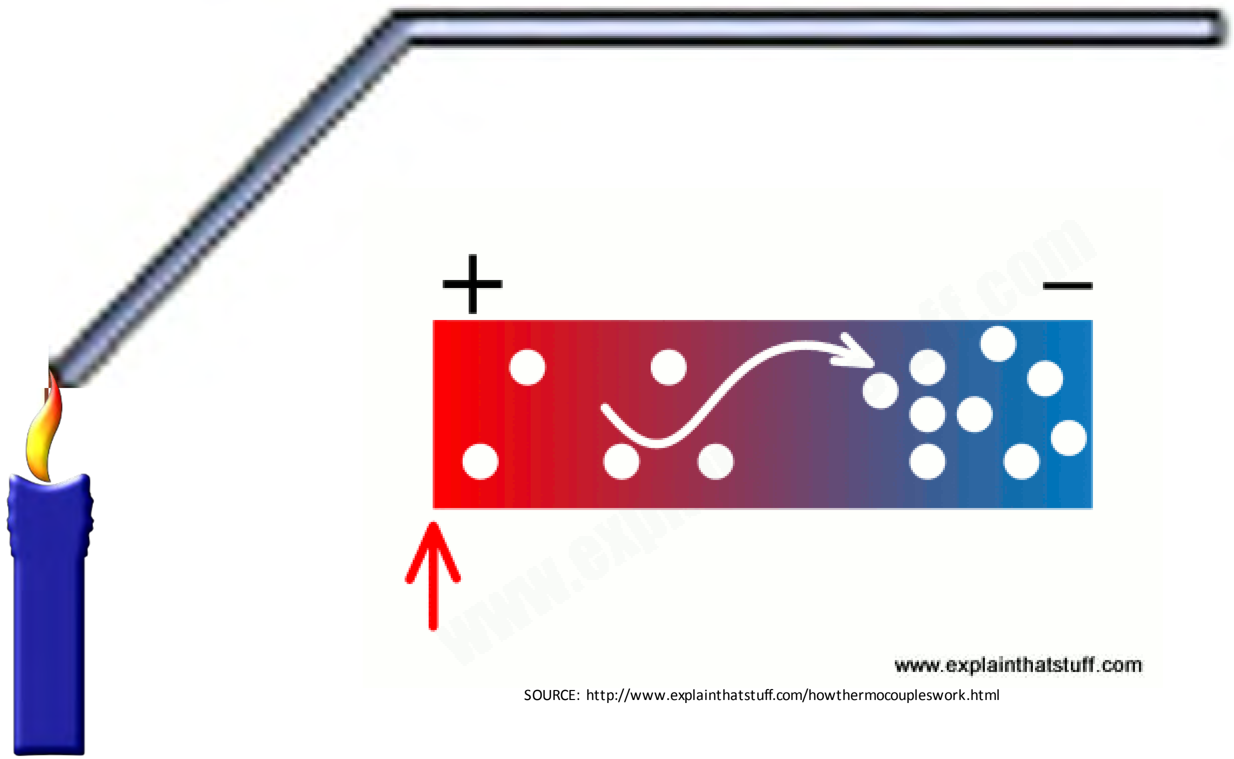
- **Thermocouple** – a two-terminal element consisting of two dissimilar metal wires joined at the end



SOURCE: http://upload.wikimedia.org/wikipedia/en/e/ed/Thermocouple_(work_diagram)_LMB.png

The Seebeck Effect

- **Seebeck Effect** – A conductor generates a voltage when it is subjected to a temperature gradient

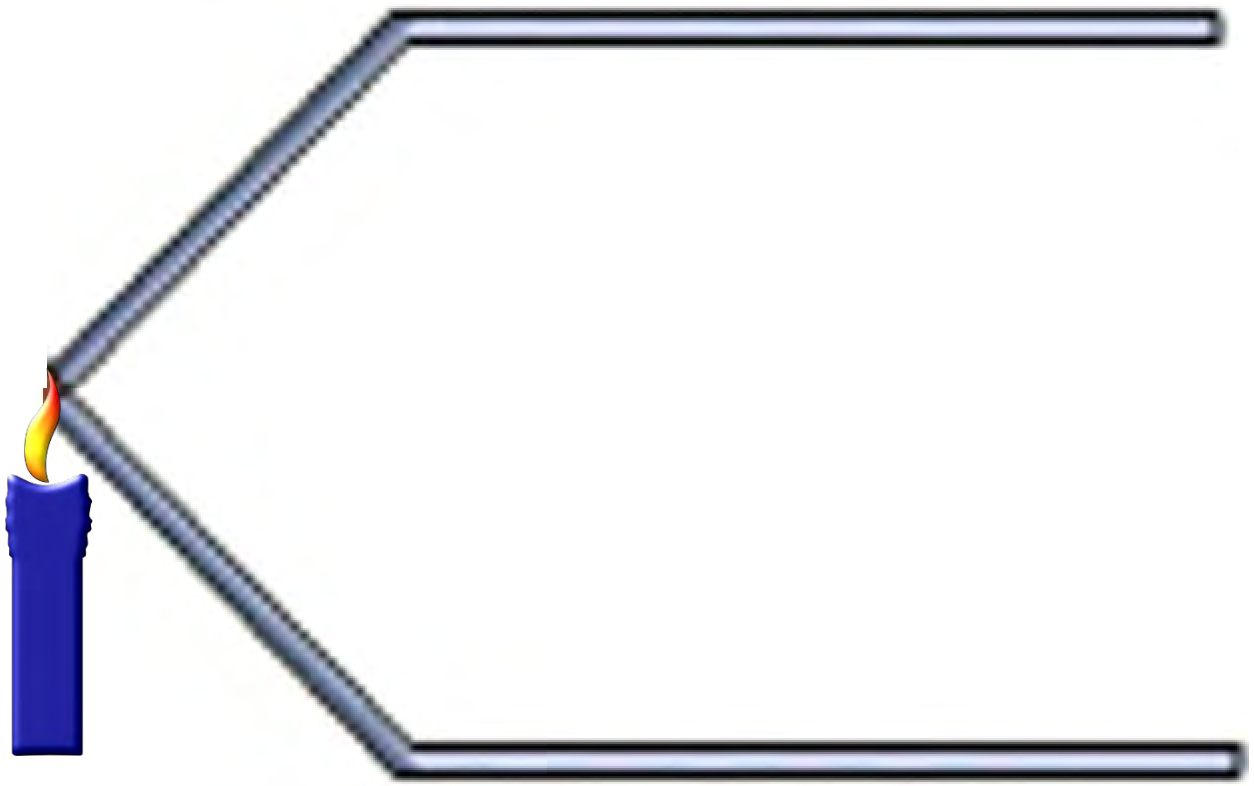


SOURCE: http://www.explainthatstuff.com/howthermocoupleswork.html

The Seebeck Effect

- **Seebeck Effect** – A conductor generates a voltage when it is subjected to a temperature gradient
  - Measuring this voltage requires the use of a second conductor material

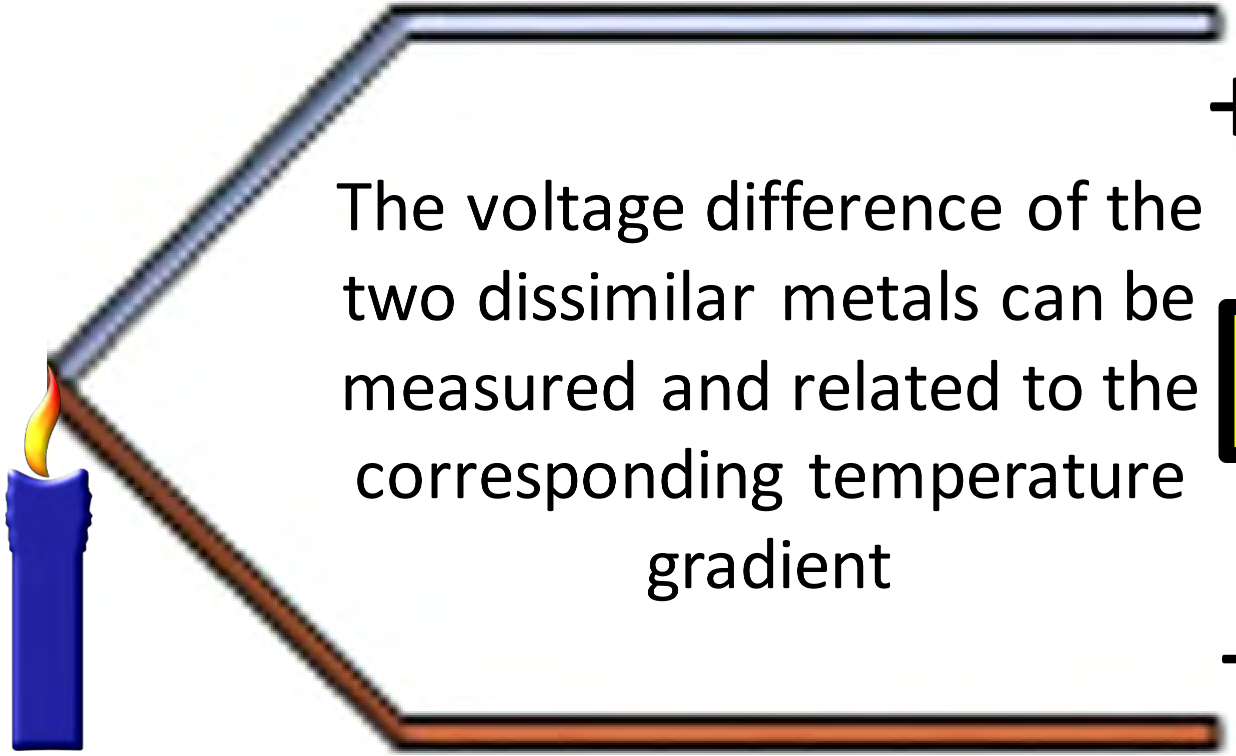
Will I observe a difference in voltage at the ends of two wires composed of the same material?



The Seebeck Effect

- **Seebeck Effect** – A conductor generates a voltage when it is subjected to a temperature gradient
  - Measuring this voltage requires the use of a second conductor material
  - The other material needs to be composed of a different material

The relationship between temperature difference and voltage varies with materials



The voltage difference of the two dissimilar metals can be measured and related to the corresponding temperature gradient

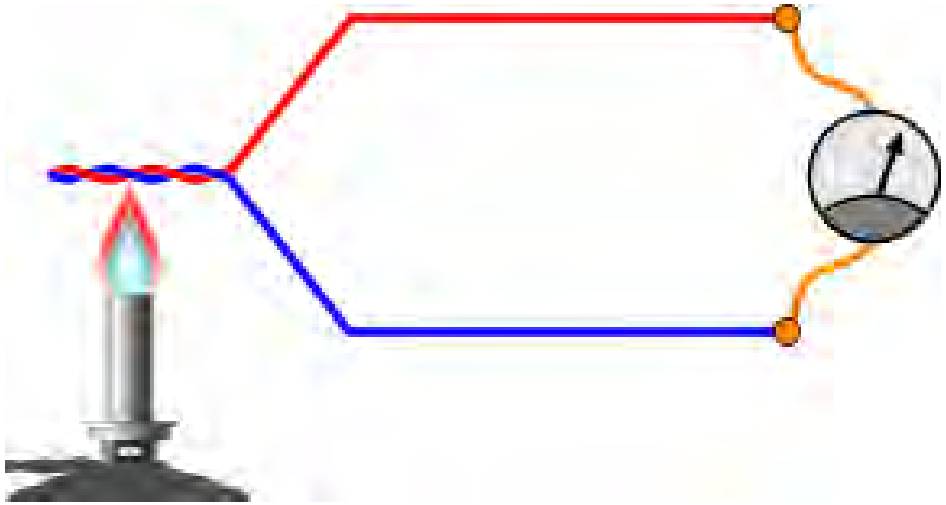
\+ Nickel-Chromium Alloy

$$\boxed{V_S = S\Delta T}$$

\- Copper-Nickel Alloy

Measuring Temperature

- To measure temperature using a thermocouple, you can't just connect the thermocouple to a measurement system (e.g. voltmeter)
- The voltage measured by your system is proportional to the temperature difference between the primary junction (hot junction) and the junction where the voltage is being measured (Ref junction)



SOURCE: http://www.pcbheaven.com/wikipages/images/thermocouples_1271330366.png

Measuring Temperature

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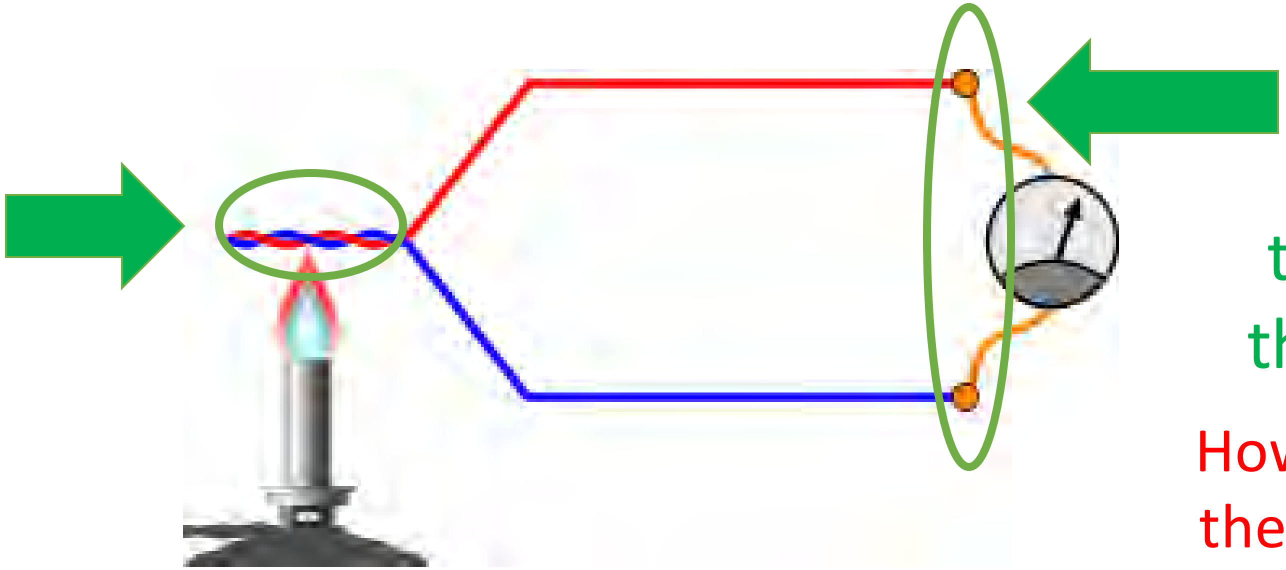
To determine the absolute temperature at the hot junction…



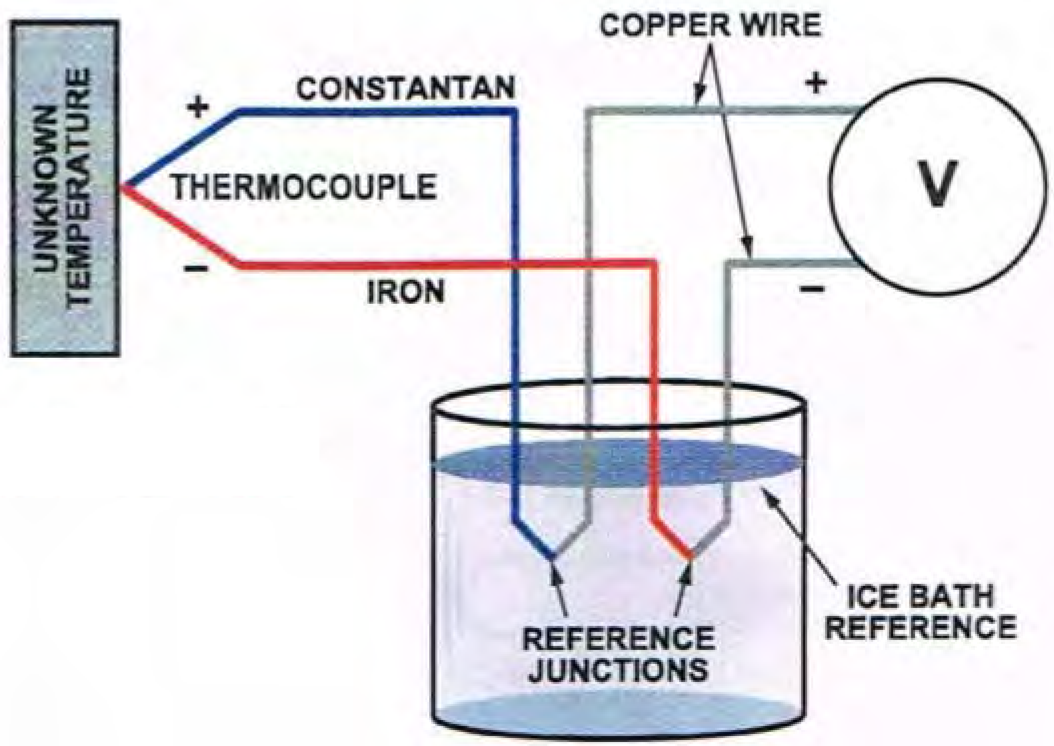
SOURCE: http://www.pcbheaven.com/wikipages/images/thermocouples_1271330366.png

You need to know the temperature at the Ref junction!

How can we determine the temperature at the reference junction?

Ice Bath Method (Forcing a Temperature)

- Thermocouples measure the voltage difference between two points
- To know the absolute temperature at the hot junction, one must know the temperature at the Ref junction



- NIST thermocouple reference tables are generated with $T_{ref} = 0\ ^oC$

$$V_{meas} = V(T_{hot}) - V(T_{ref})$$

$$V(T_{hot}) = V_{meas} + V(T_{ref})$$

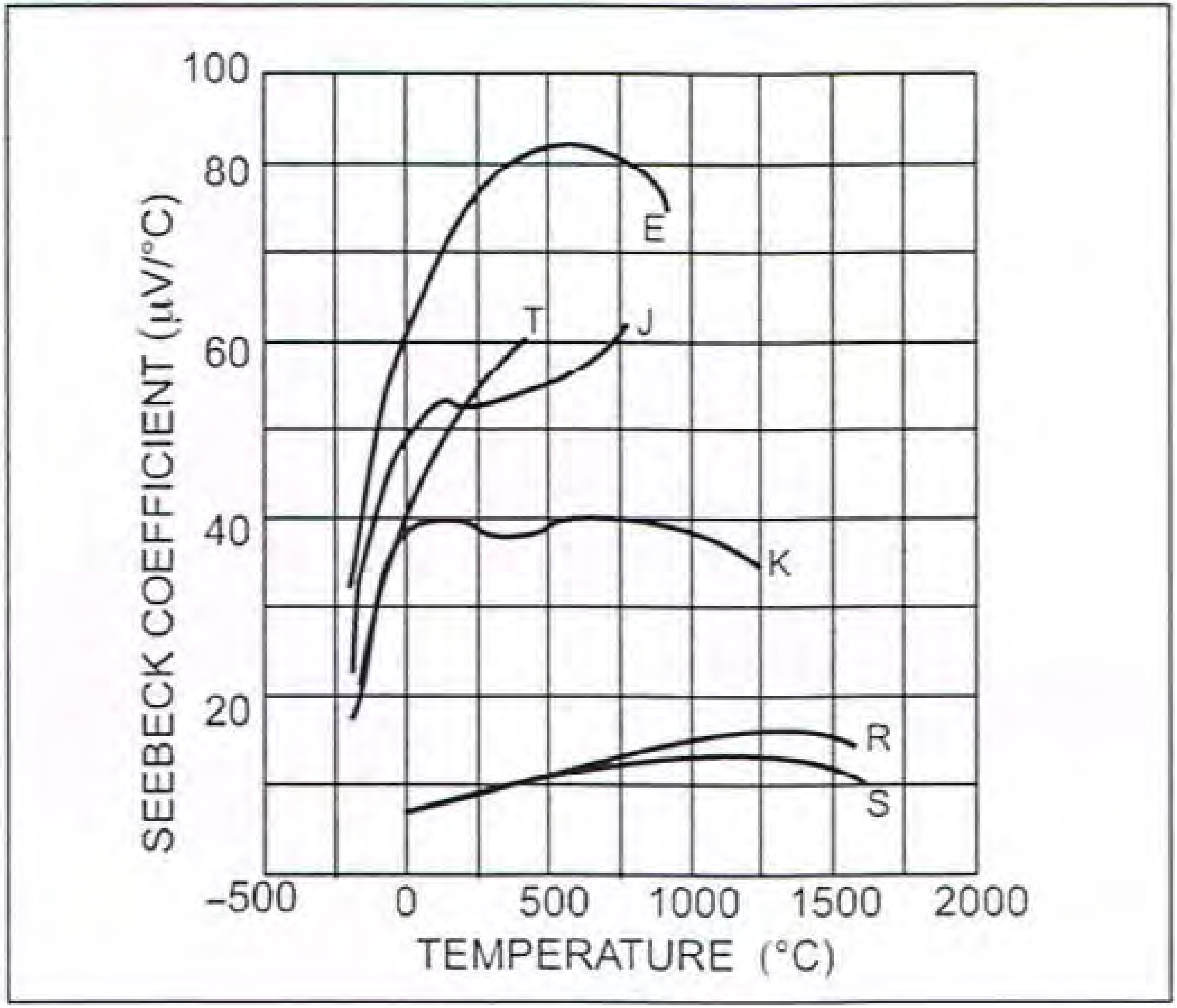
If we know the voltage-temperature relationship of our thermocouple, we could determine the temperature at the hot junction

IS IT REALLY THAT EASY?

Nonlinearity in the Seebeck Coefficient

$$V_S = S\Delta T$$

- Thermocouple output voltages are highly nonlinear
- The Seebeck coefficient can vary by a factor of 3 or more over the operating temperature range of the thermocouples



Temperature Conversion Equation

$$T = a_0 + a_1 V + a_2 V^2 + \ldots + a_n V^n$$

	TYPE E	TYPE J	TYPE K	TYPE R	TYPE S	TYPE T
	Nickel-10% Chromium(+) Versus Constantan(-)	Iron(+) Versus Constantan(-)	Nickel-10% Chromium(+) Versus Nickel-5%(-) (Aluminum Silicon)	Platinum-13% Rhodium(+) Versus Platinum(-)	Platinum-10% Rhodium(+) Versus Platinum(-)	Copper(+) Versus Constantan(-)
	-100˚C to 1000˚C ± 0.5˚C 9th order	0˚C to 760˚C ± 0.1˚C 5th order	0˚C to 1370˚C ± 0.7˚C 8th order	0˚C to 1000˚C ± 0.5˚C 8th order	0˚C to 1750˚C ± 1˚C 9th order	-160˚C to 400˚C ±0.5˚C 7th order
a_0	0.104967248	-0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2	-282639. 0850	-218614.5353	67233.4248	-48840341.37	-31568363.94	-767345.8295
a_3	12695339.5	11569199.78	2210340.682	1.90002E + 10	8990730663	78025595.81
a_4	-448703084.6	-264917531.4	-860963914.9	-4.82704E + 12	-1.63565E + 12	-9247486589
a_5	1.10866E + 10	2018441314	4.83506E + 10	7.62091E + 14	1.88027E + 14	6.97688E + 11
a_6	-1. 76807E + 11		-1. 18452E + 12	-7.20026E + 16	-1.37241E + 16	-2.66192E + 13
a_7	1.71842E + 12		1.38690E + 13	3.71496E + 18	6.17501E + 17	3.94078E + 14
a_8	-9.19278E + 12		-6.33708E + 13	-8.03104E + 19	-1.56105E + 19	
a_9	2.06132E + 13				1.69535E + 20	

Look-Up Table for a Type T Thermocouple

Voltage difference of the hot and cold junctions: V_{meas} = 3.409 mV

What is the temperature of the hot junction if the cold junction is at 22 ^{o}C?

ITS-90 Table for Type T thermocouple

Thermoelectric voltage in mV

°C	0	1	2	3	4	5	6				
-10	-0.383	-0.345	-0.307	-0.269	-0.231	-0.193	-0.154				
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234				
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234				
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629				
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814
90	3.814	3.860	3.907	3.953	3.999	4.046	4.092	4.138	4.185	4.232	4.279
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228

$$V_{meas} = V(T_{hot}) - V(T_{ref})$$

$$V(T_{hot}) = V_{meas} + V(T_{ref})$$

At 22 ^{o}C, the reference junction voltage is 0.870 mV

The hot junction voltage is therefore 3.409 mV + 0.870 mV = 4.279 mV

The temperature at the hot junction is therefore 100 ^{o}C

HARVEY MUDD COLLEGE

APPLYING WHAT WE'VE LEARNED

Voltage difference of the hot and cold junctions: V_{meas} = 4.472 mV

What is the temperature of the hot junction if the cold junction is at –5 °C?

ITS-90 Table for Type T thermocouple

Thermoelectric voltage in mV

°C	0	1	2	3	4	5	6	7	8	9	10
-10	-0.383	-0.345	-0.307	-0.269	-0.231	-0.193	-0.154	-0.116	-0.077	-0.039	0.000
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.790
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814
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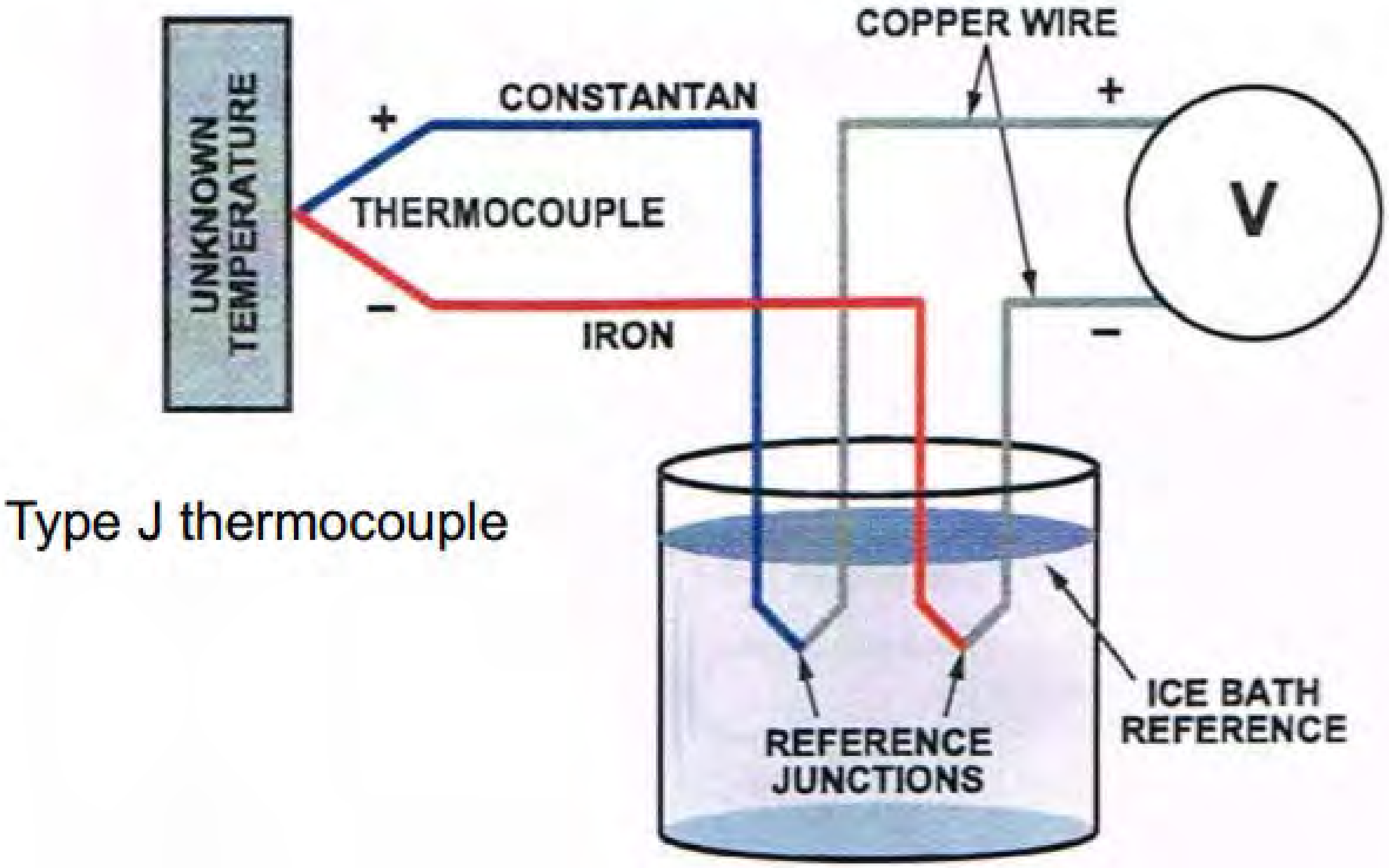
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228

At -5 °C, the cold junction voltage is –0.193 mV

The hot junction voltage is therefore 4.472 mV – 0.193 mV = 4.279 mV

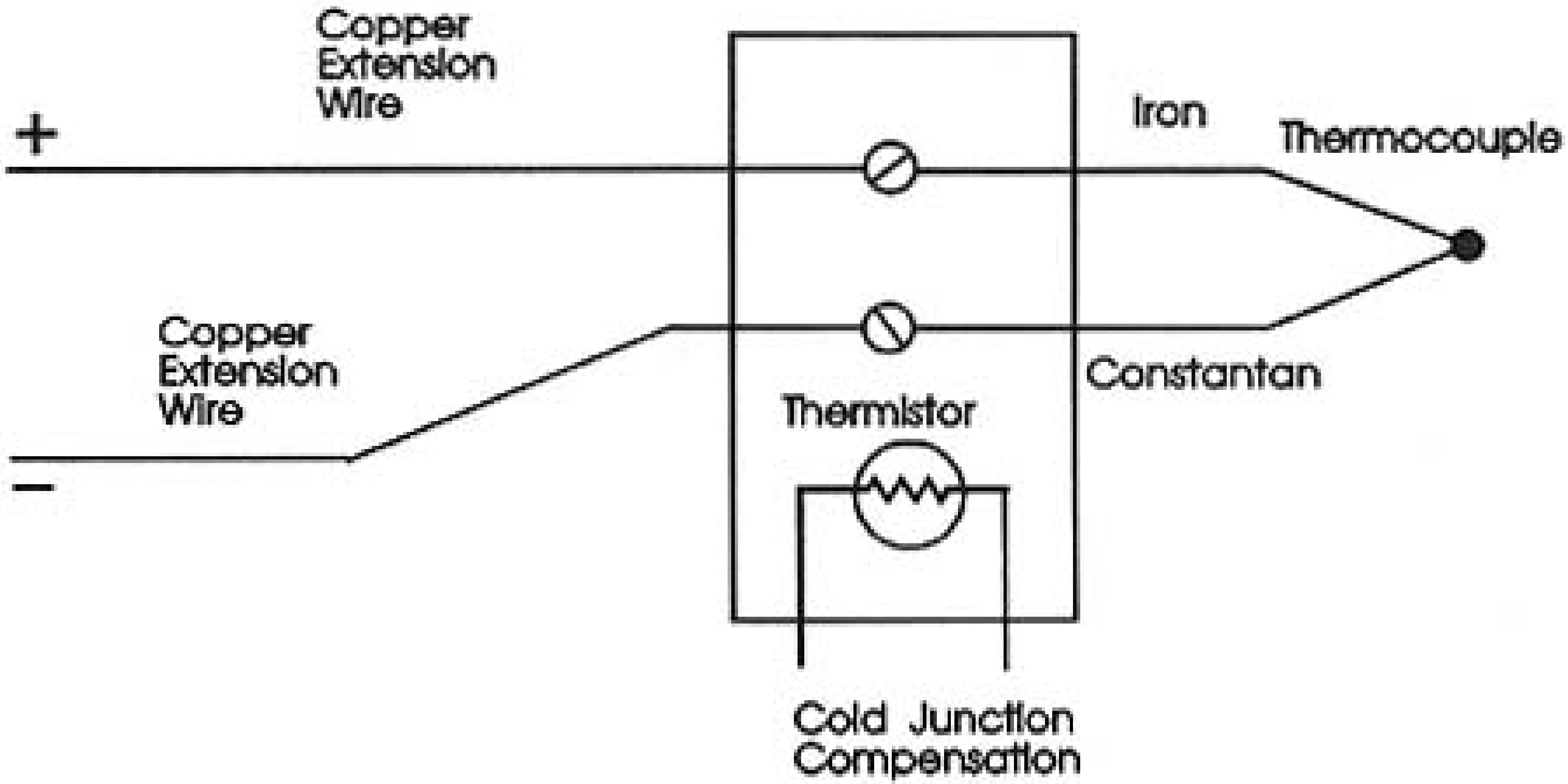
The temperature at the hot junction is therefore 100 °C

Is This Really Practical For a Rocket?



What is another method of determining the temperature at the reference junction?

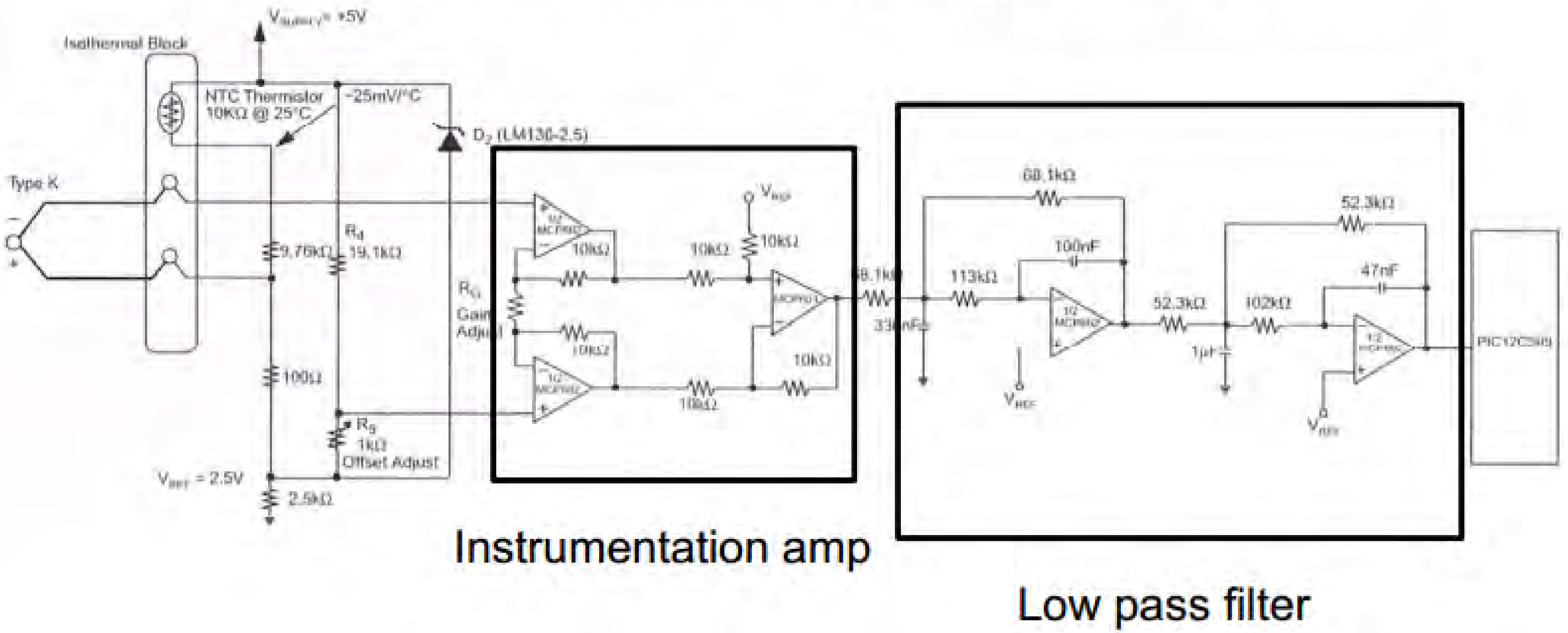
Cold Junction Compensation



SOURCE: http://www.industrial-electronics.com/DAQ/images/10_13.jpg

Acquiring Data

Thermocouples are very noise prone & usually need filtering



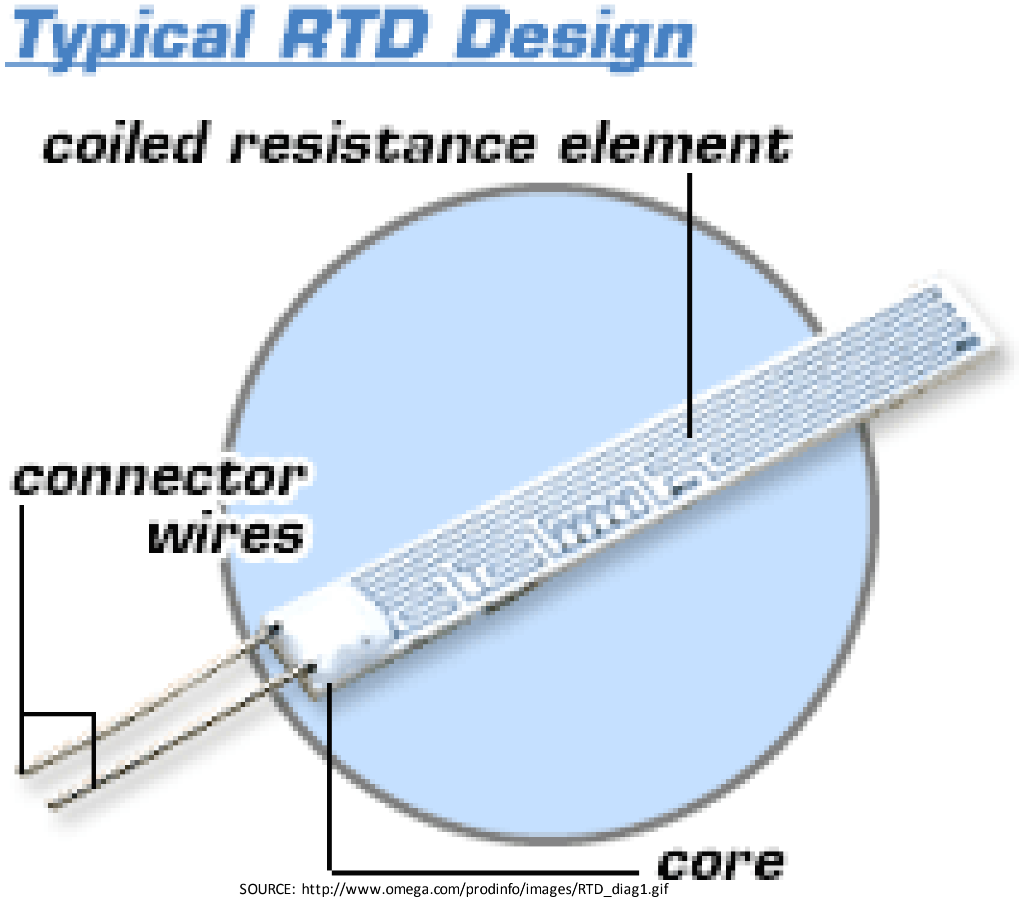
Temperature Measurement Devices in Lab

	Thermocouple	Thermistor	Integrated Silicon
Temperature Range	–270 to 1800°C	–100 to 450°C	-55 to 150°C
Sensitivity	10s of µV / ˚C	several Ω / Ω / ˚C	Based on technology that is -2mV/°C sensitive
Accuracy	±0.5°C	±0.1°C	±1°C
Linearity	Requires at least a 4th order polynomial or equivalent look up table.	Requires at least 3rd order polynomial or equivalent look up table.	At best within ±1°C. No linearization required.
Ruggedness	The larger gage wires of the thermocouple make this sensor more rugged. Additionally, the insulation materi-als that are used enhance the thermo-couple's sturdiness.	The thermistor element is housed in a variety of ways, however, the most stable, hermetic Ther-mistors are enclosed in glass. Generally ther-mistors are more difficult to handle, but not affected by shock or vibration.	As rugged as any IC housed in a plastic pack-age such as dual-in-line or surface outline ICs.
Responsiveness in stirred oil	less than 1 Sec	1 to 5 Secs	4 to 60 Secs
Excitation	None Required	Voltage Source	Typically Supply Voltage
Form of Output	Voltage	Resistance	Voltage, Current, or Digital
Typical Size	Bead diameter = 5 x wire diameter	0.1 x 0.1 in.	From TO-18 Transistors to Plastic DIP
Price	\$1 to \$50	> \$10	\$1 to \$10

Resistive Temperature Detector (RTD)

- Two terminal device
- Usually made out of platinum
- Positive temperature coefficient
- Tends to be linear
- $R = R_0(1+\alpha)(T-T_0)$ where $T_0 = 0^oC$

  $R_0 = 100\ \Omega$, $\alpha = 0.03385\ \Omega/\ \Omega\ ^oC$
- At 10^oC, $R = 100(1+0.385)(10) = 103.85\ \Omega$
- They are best operated using a small constant current source
- Accuracy of $0.01\ ^oC$
- **EXPENSIVE!**



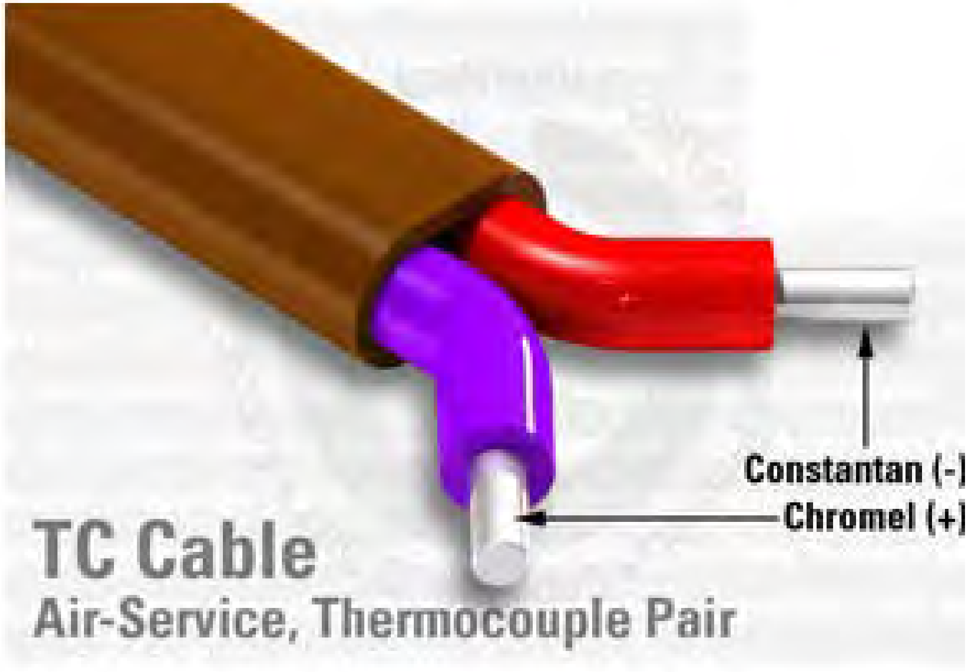
SOURCE: http://www.omega.com/prodinfo/images/RTD_diag1.gif

Temperature Measurement Devices

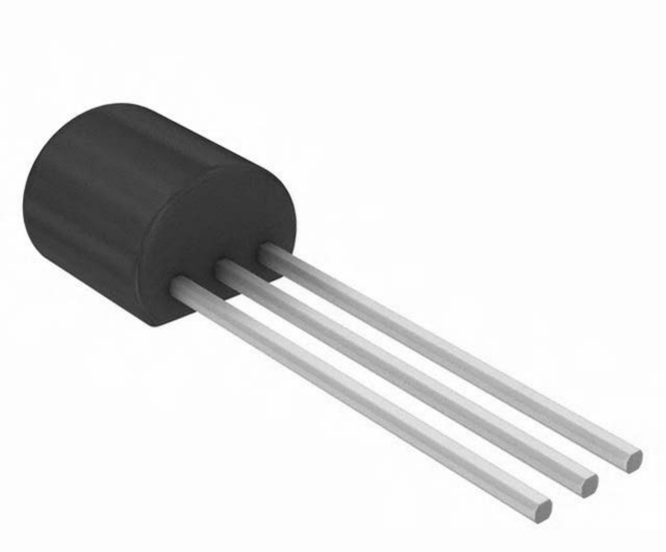
	Thermocouple	RTD	Thermistor	Integrated Silicon
Temperature Range	–270 to 1800°C	–250 to 900 °C	–100 to 450°C	-55 to 150°C
Sensitivity	10s of µV / ˚C	0.00385 Ω / Ω / ˚C (Platinum)	several Ω / Ω / ˚C	Based on technology that is -2mV/°C sensitive
Accuracy	±0.5°C	±0.01°C	±0.1°C	±1°C
Linearity	Requires at least a 4th order polynomial or equivalent look up table.	Requires at least a 2nd order polynomial or equivalent look up table.	Requires at least 3rd order polynomial or equivalent look up table.	At best within ±1°C. No linearization required.
Ruggedness	The larger gage wires of the thermocouple make this sensor more rugged. Additionally, the insulation materi-als that are used enhance the thermo-couple's sturdiness.	RTDs are susceptible to damage as a result of vibration. This is due to the fact that they typ-ically have 26 to 30 AWG leads which are prone to breakage.	The thermistor element is housed in a variety of ways, however, the most stable, hermetic Ther-mistors are enclosed in glass. Generally ther-mistors are more difficult to handle, but not affected by shock or vibration.	As rugged as any IC housed in a plastic pack-age such as dual-in-line or surface outline ICs.
Responsiveness in stirred oil	less than 1 Sec	1 to 10 Secs	1 to 5 Secs	4 to 60 Secs
Excitation	None Required	Current Source	Voltage Source	Typically Supply Voltage
Form of Output	Voltage	Resistance	Resistance	Voltage, Current, or Digital
Typical Size	Bead diameter = 5 x wire diameter	0.25 x 0.25 in.	0.1 x 0.1 in.	From TO-18 Transistors to Plastic DIP
Price	$1 to $50	$25 to $1000	> $10	$1 to $10

How Do I Know If These Are Working?

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



SOURCE: http://www.accuglassproducts.com/product.php?productid=17523



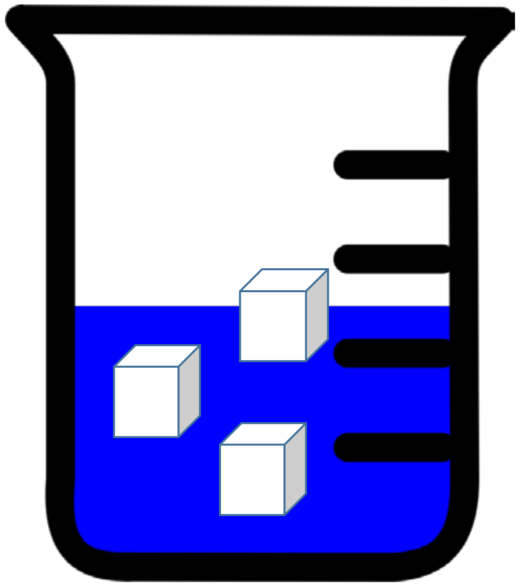
SOURCE: http://elcodis.com/photos/19/51/195143/to-92-3_standardbody__to-226_straightlead.jpg

Calibration

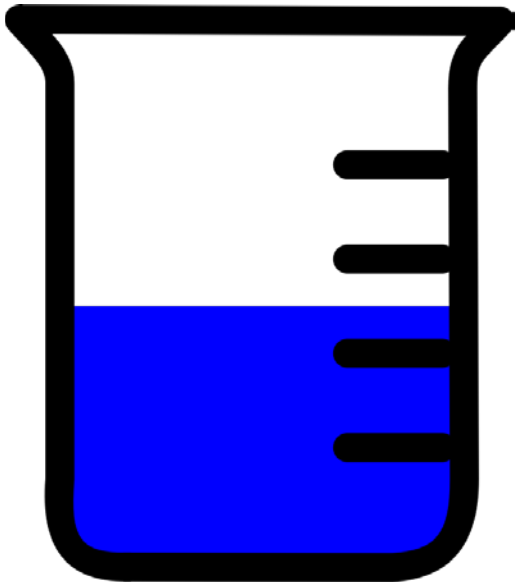
- How could we calibrate a temperature sensor?

Each probe includes an individual NIST-Traceable calibration certificate with test data at 0, 25, 70, and 100°C.

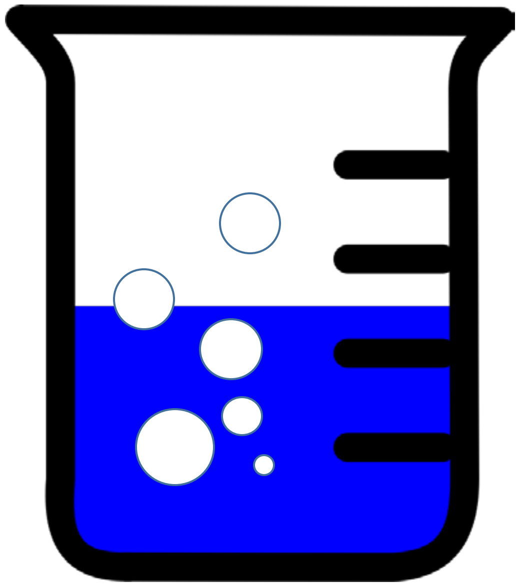
SOURCE: http://www.thermoworks.com/products/calibration/usb_reference.html



0 ºC



25 ºC



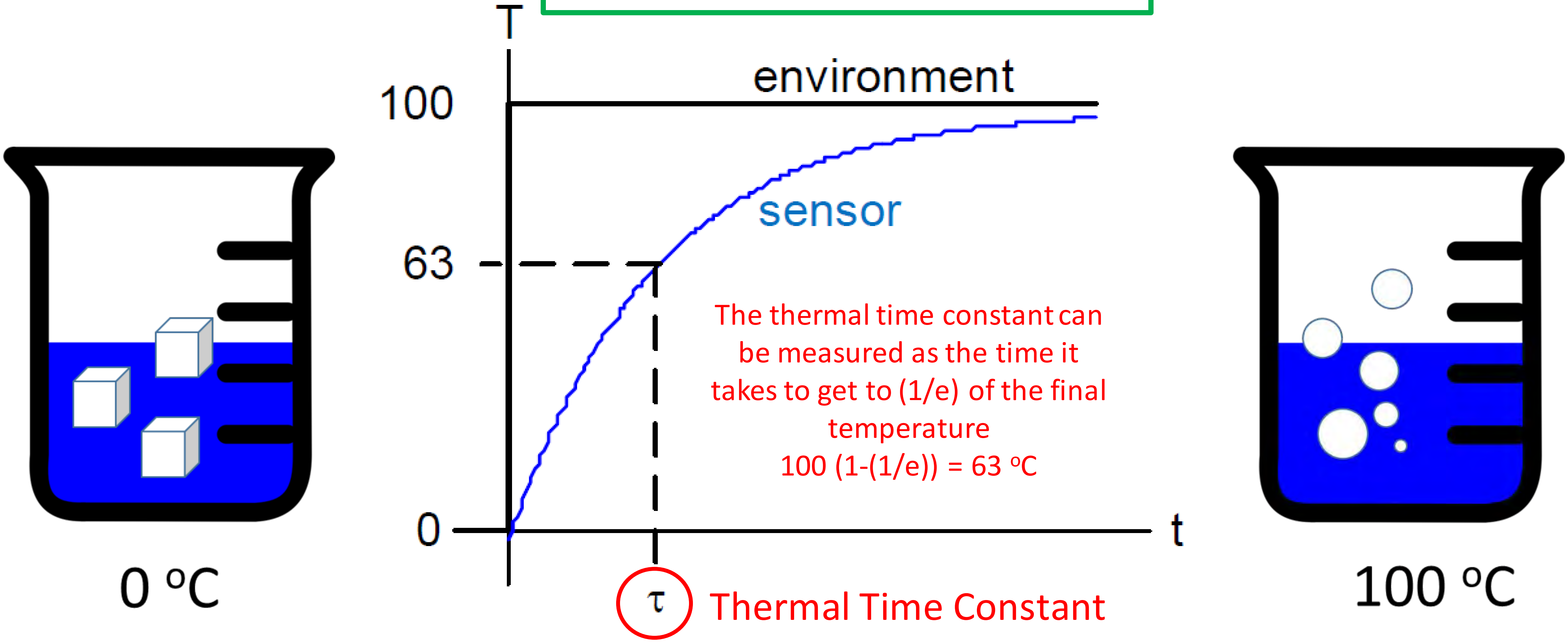
100 ºC

Tracking the Rate of Temperature Change

- If a slow sensor is placed into a rocket that is launched to a high altitude, the sensor may not be able to track the rate of temperature change
- A critical property of a temperature-measurement device is how quickly it responds to a change in external temperature

Thermal System Step Response

$$T_{sensor}(t) = T_2 + [T_1 - T_2]e^{-\frac{t}{\tau}}$$



SUMMARY

- Measuring Temperature
- Types of Temperature Sensors
  - Thermistor
  - Integrated Silicon Linear Sensor
  - Thermocouple
  - Resistive Temperature Detector (RTD)
- Choosing a Temperature Sensor
- Calibrating Temperature Sensors
- Thermal System Transient Response