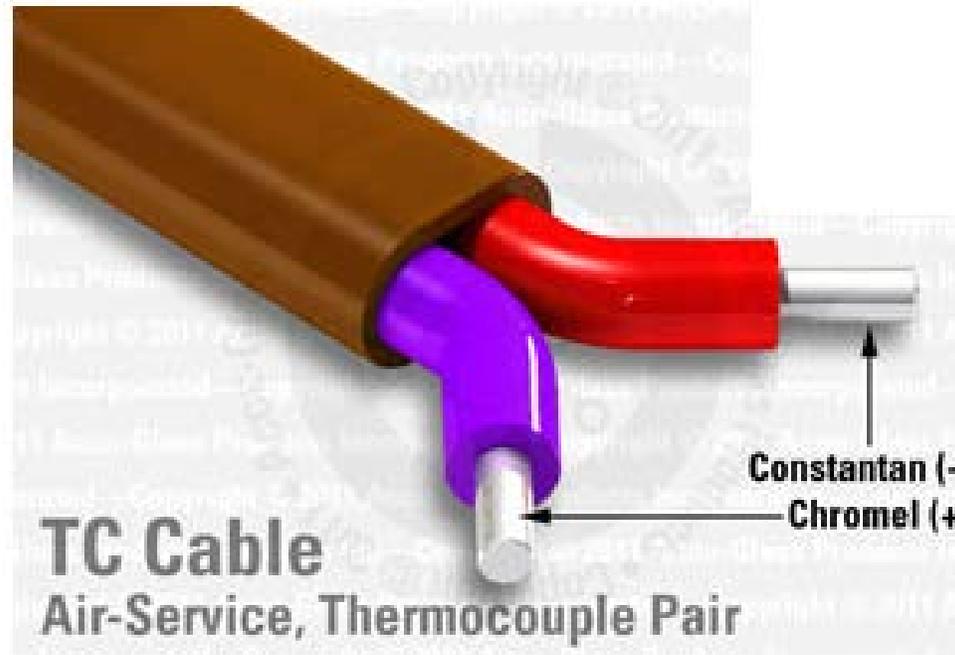


Temperature Measurements



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

Key Concepts

- 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

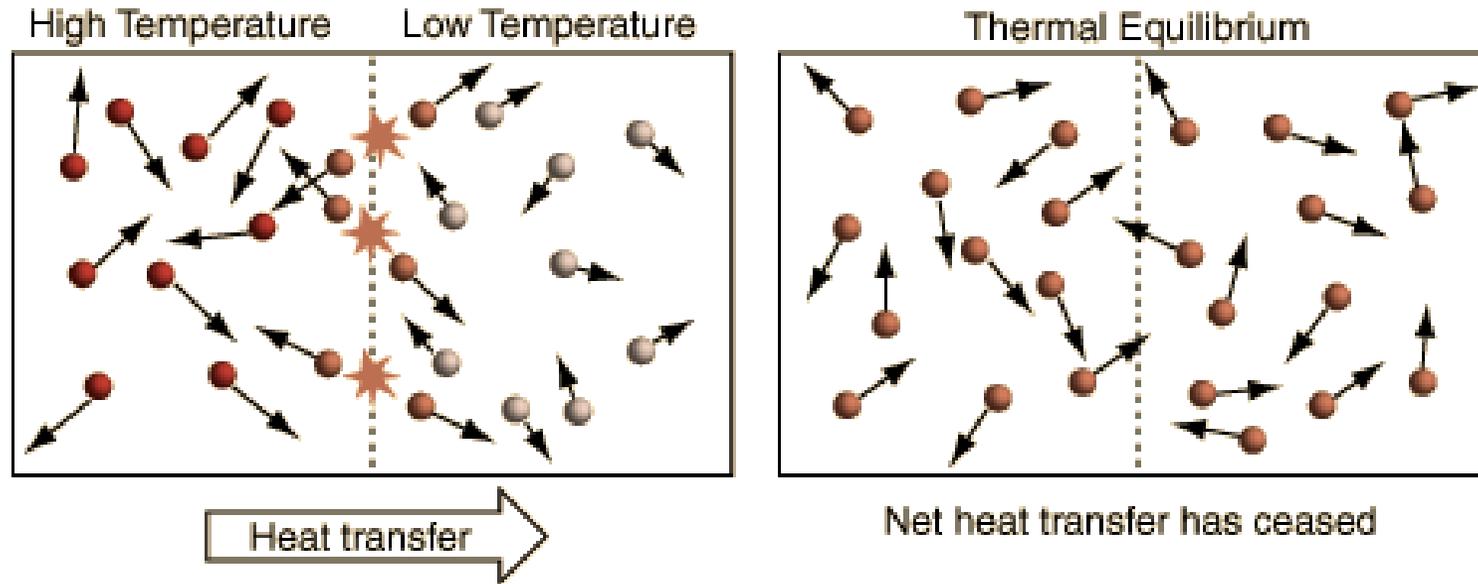
What is Temperature?



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

What is Temperature?

AN OVERLY SIMPLIFIED DESCRIPTION OF TEMPERATURE



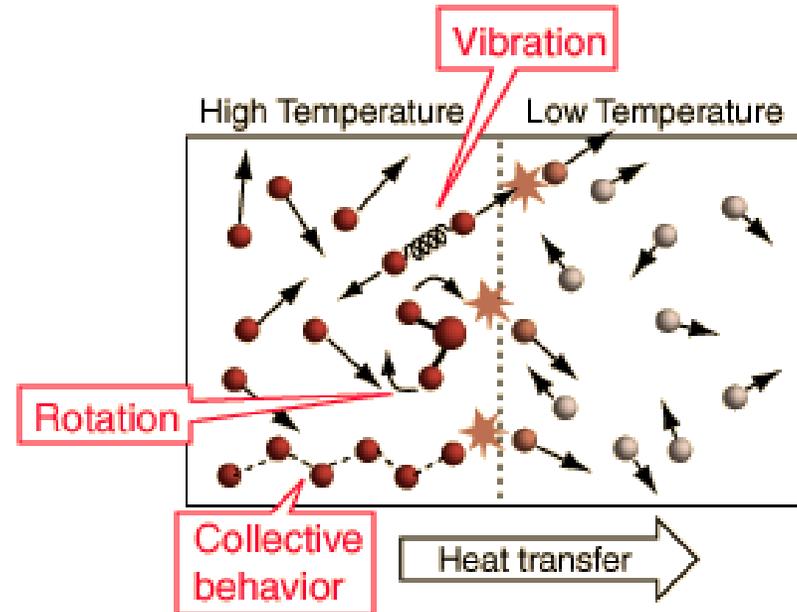
SOURCE: <http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/temper2.html#c1>

"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.)

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Measuring Temperature with Rockets

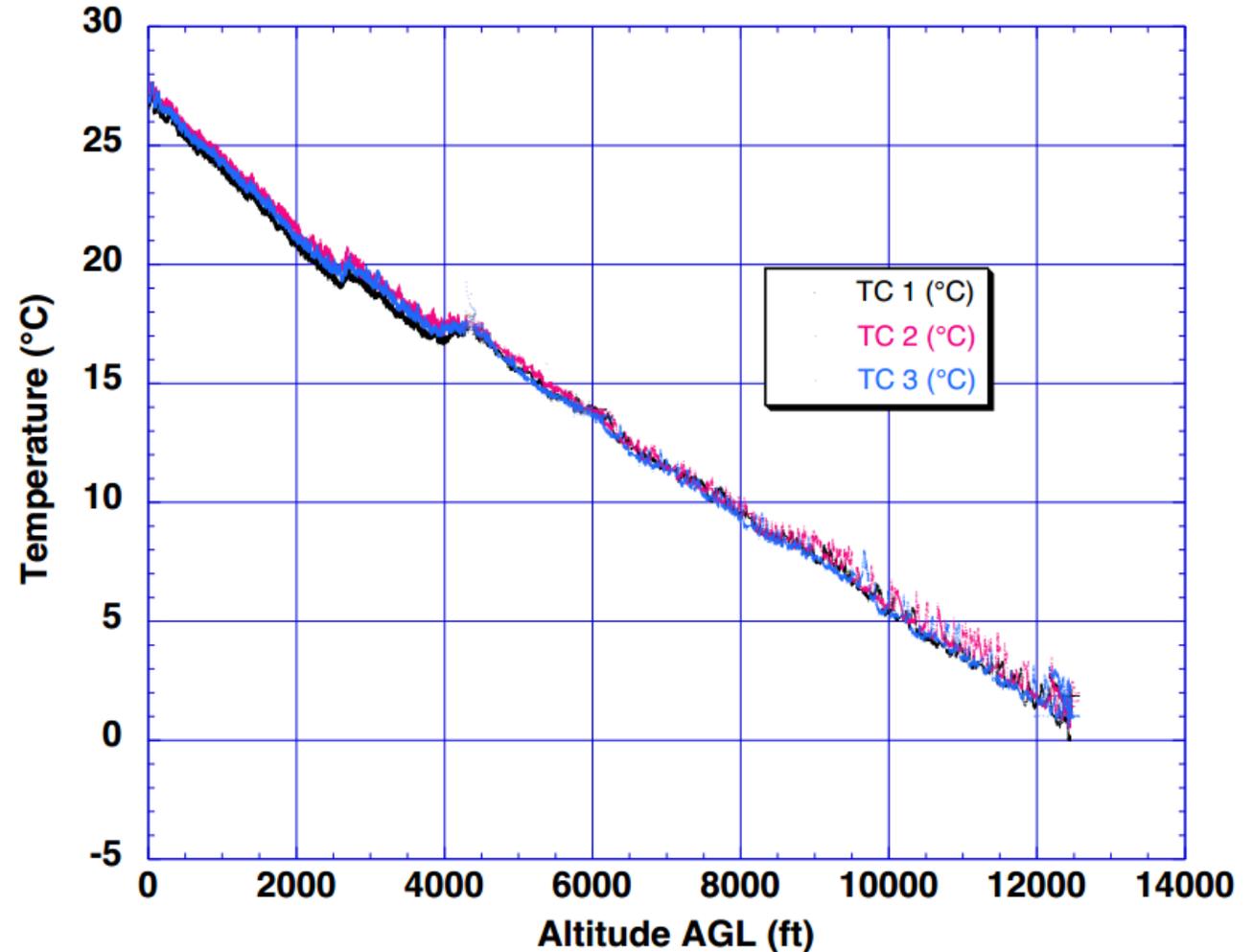


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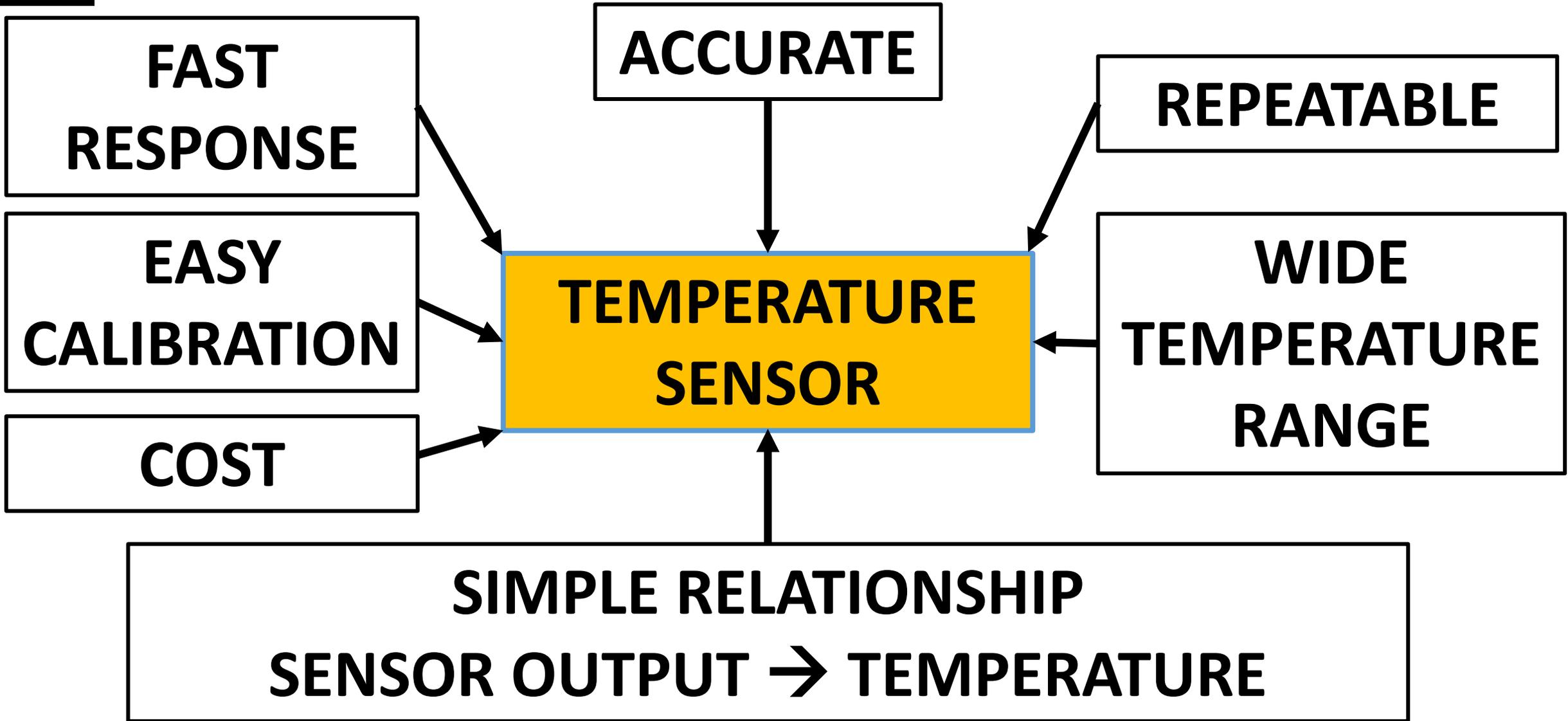


What are desirable characteristics of a temperature sensor?

**Lucerne Valley 11 AUG 2013
Plot of Temperature vs. Altitude**



Desirable Temperature Sensor Characteristics



Thermistor

Thermistor – a resistor whose resistance changes with temperature



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- Packaged in a thermally conductive glass bead or disk with two metal leads

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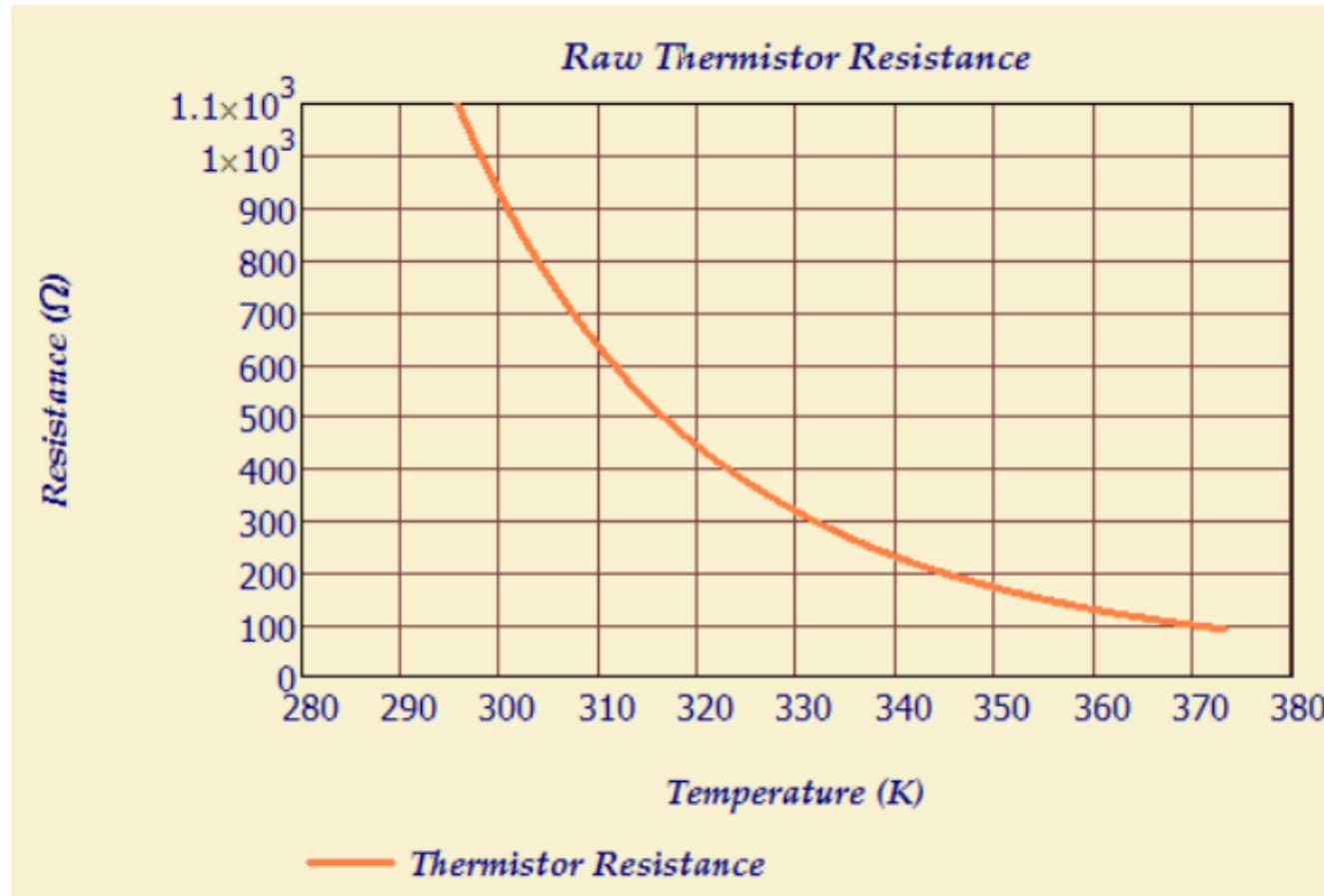
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 - What does this mean?
 - At room temperature, the resistance of the thermistor is 1 k Ω
 - What happens to resistance as we increase temperature?

Negative Temperature Coefficient

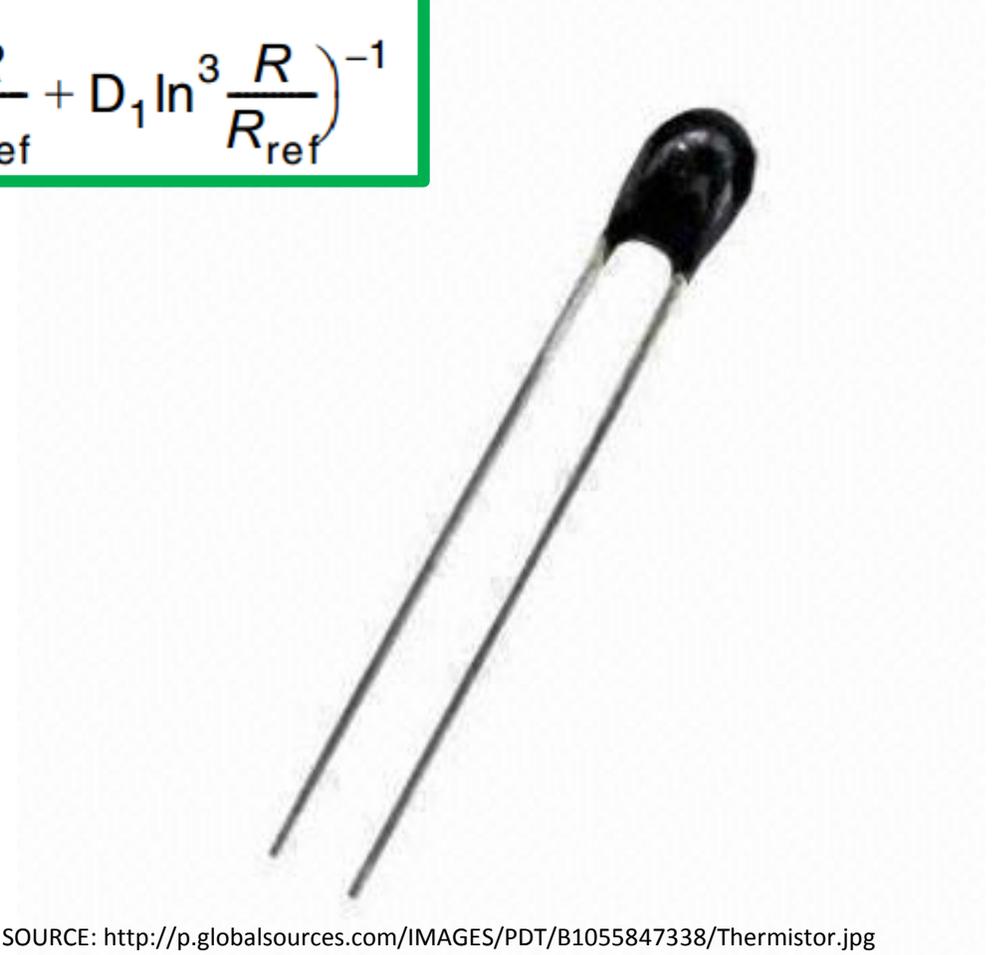
- Most materials exhibit a negative temperature coefficient (NTC)
 - Resistance drops with temperature!



Converting Resistance to Temperature

- The Steinhart-Hart Equation relates temperature to resistance

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



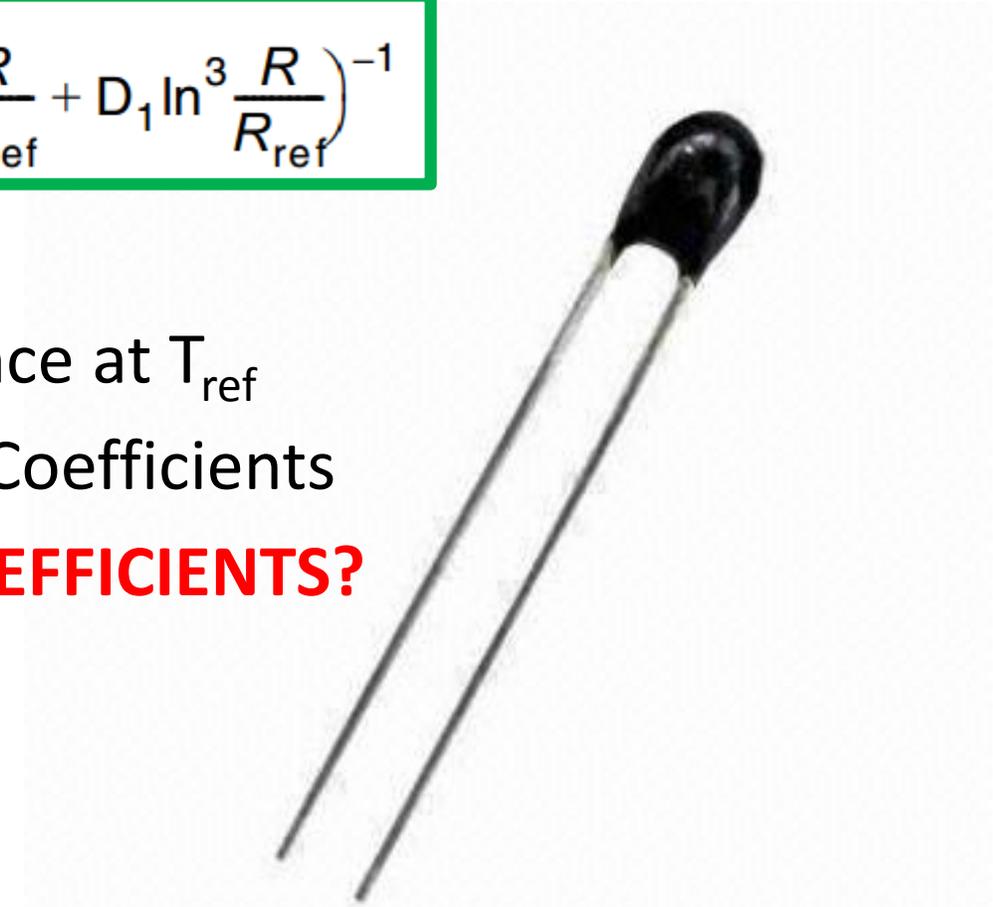
SOURCE: <http://p.globalsources.com/IMAGES/PDT/B1055847338/Thermistor.jpg>

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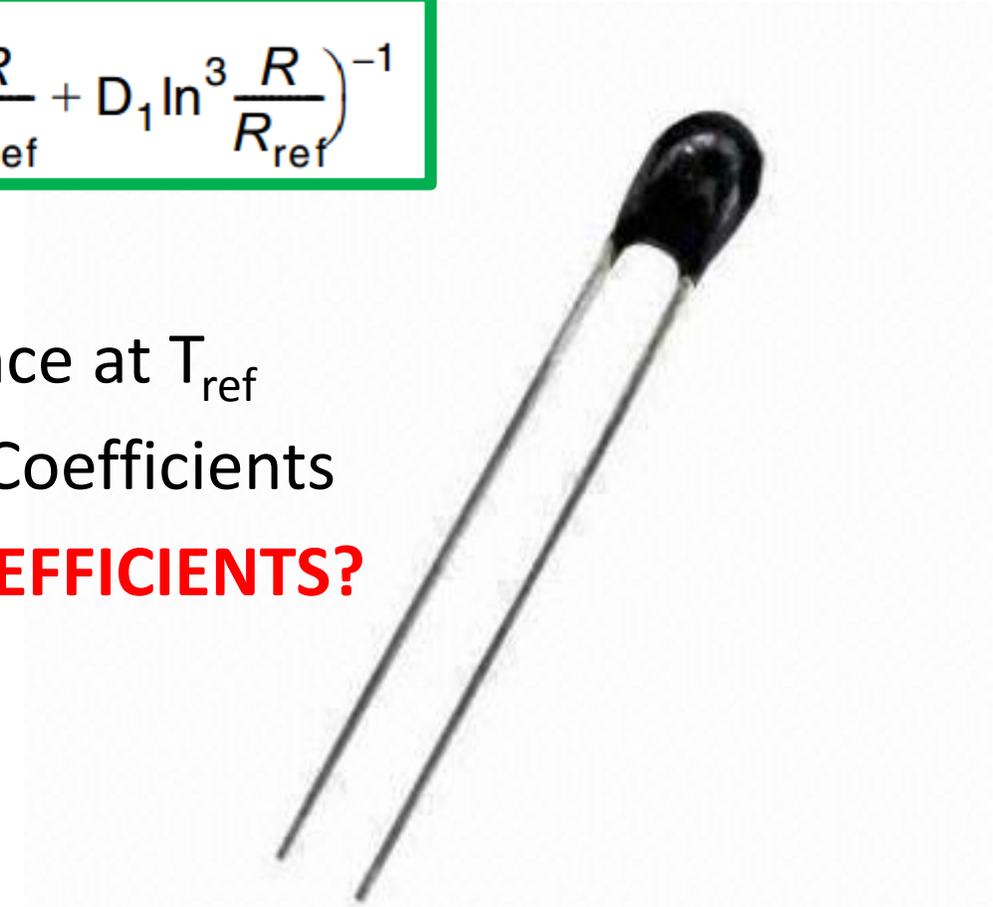
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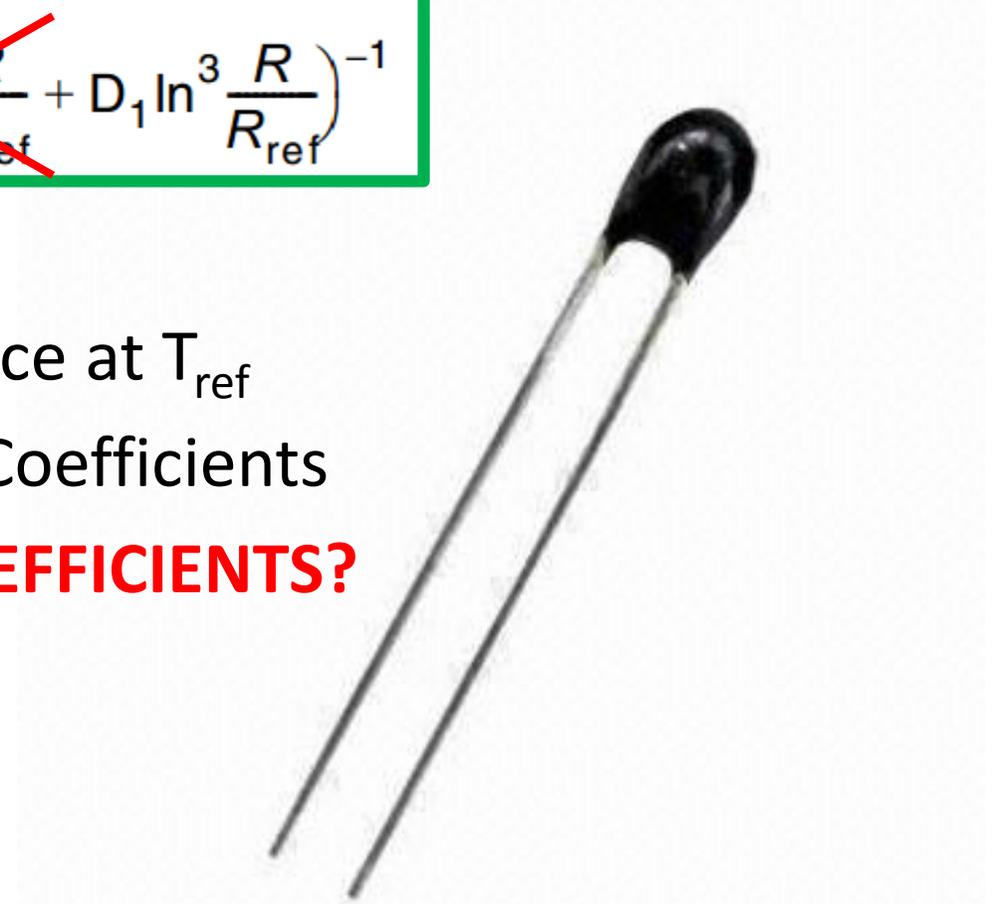
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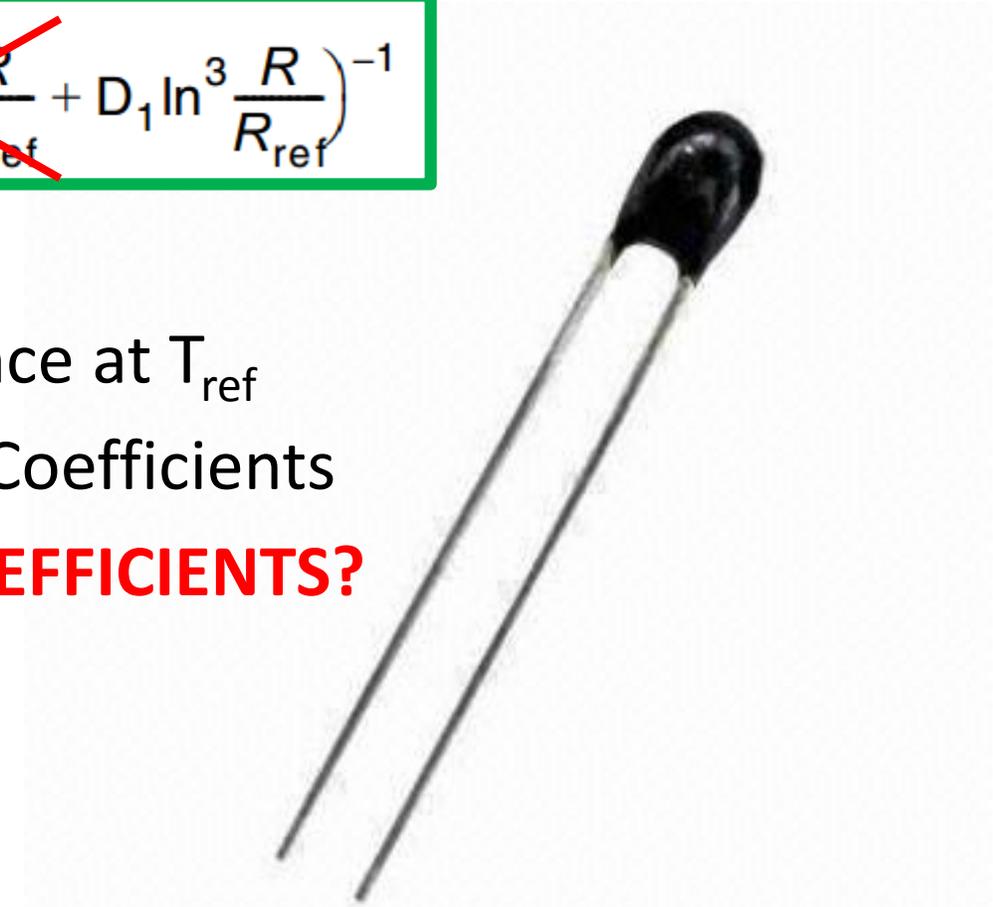
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 - Measure 3 resistances at 3 temperatures
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How is Resistance Measured?

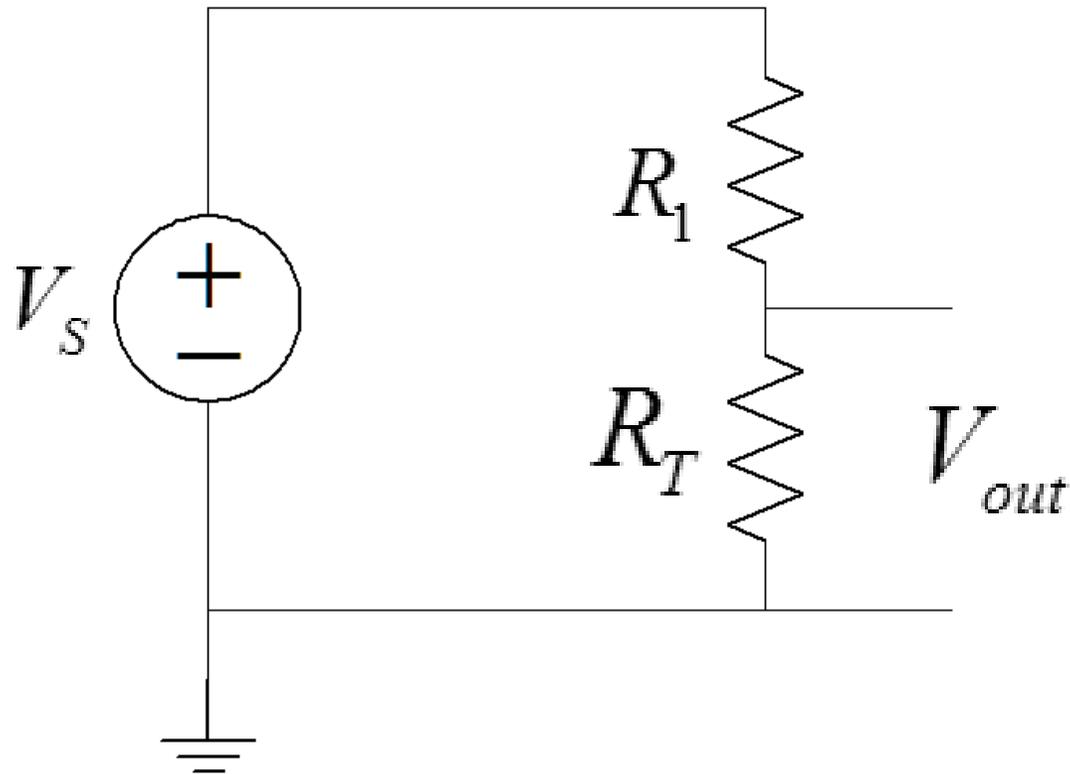
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Thermistor Resistance (R_T)

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



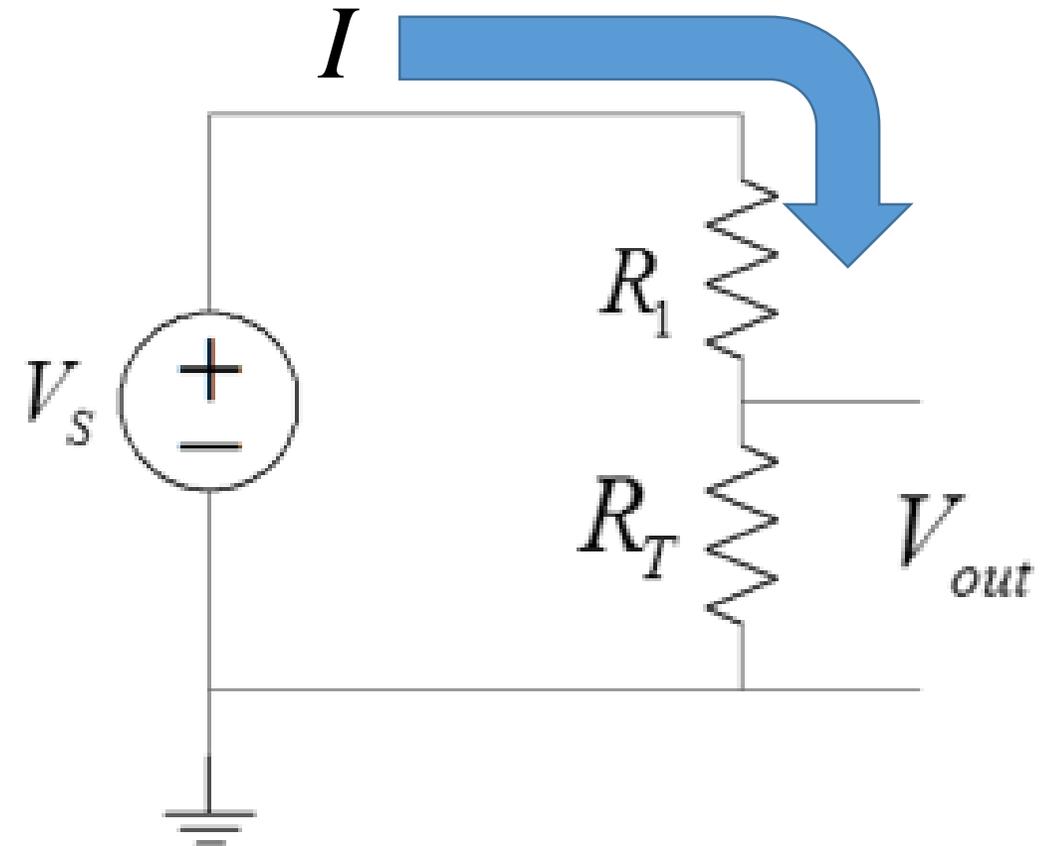
$$V_{out} = V_S \frac{R_T}{R_T + R_1}$$

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)

$$P = \delta \Delta T$$

Where P is in [W], ΔT is the rise in temperature in [$^{\circ}\text{C}$]

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

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$$\Delta T = 1.5 \text{ }^{\circ}\text{C}$$

- What effect does a ΔT of $1.5 \text{ }^{\circ}\text{C}$ have on your thermistor measurements?

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$$P = \delta \Delta T$$

Where P is in [W], ΔT is the rise in temperature in [$^{\circ}\text{C}$]

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

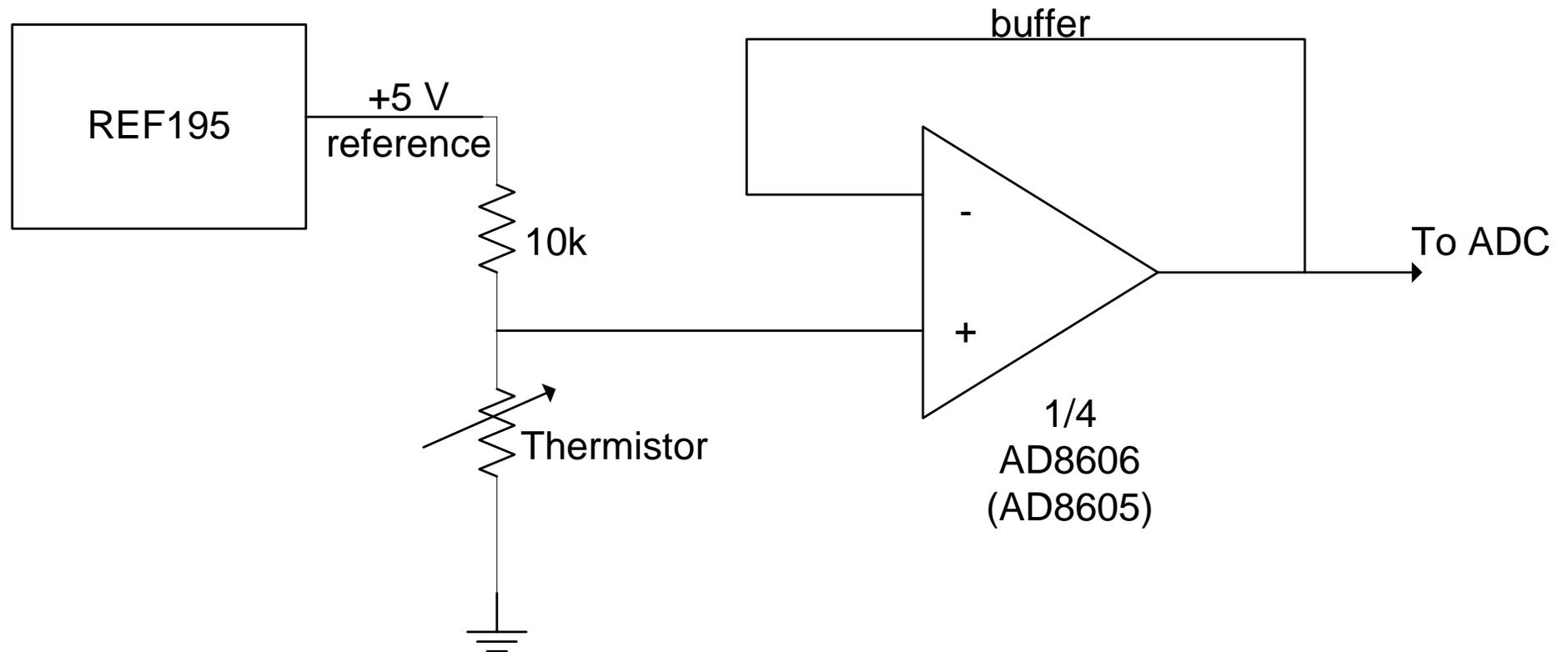
$$(0.005 \text{ A})^2(4000 \text{ }\Omega) = (0.067 \text{ W}/^{\circ}\text{C}) \Delta T$$

$$\Delta T = 1.5 \text{ }^{\circ}\text{C}$$

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

Thermistor Signal Conditioning Circuit

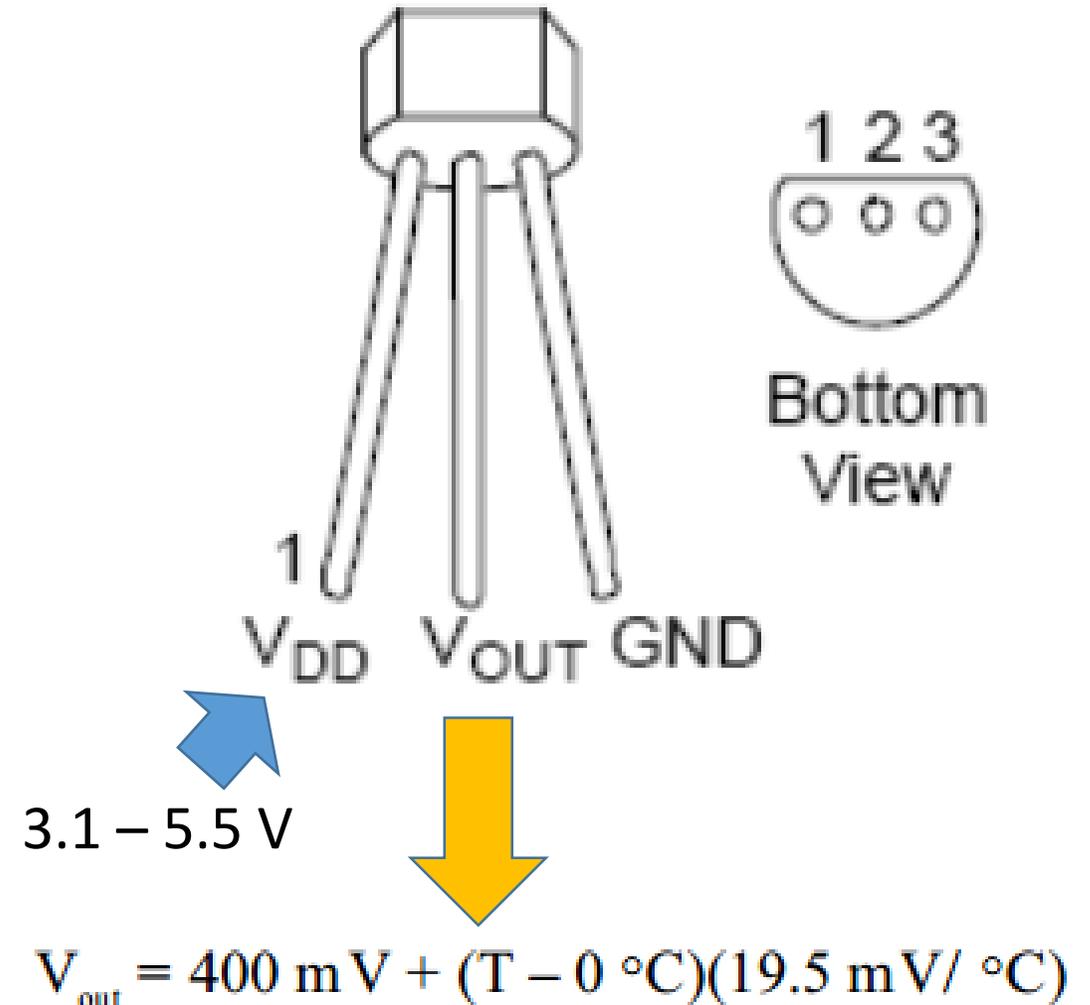
- A voltage divider and a unity gain buffer are required to measure temperature in the lab



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

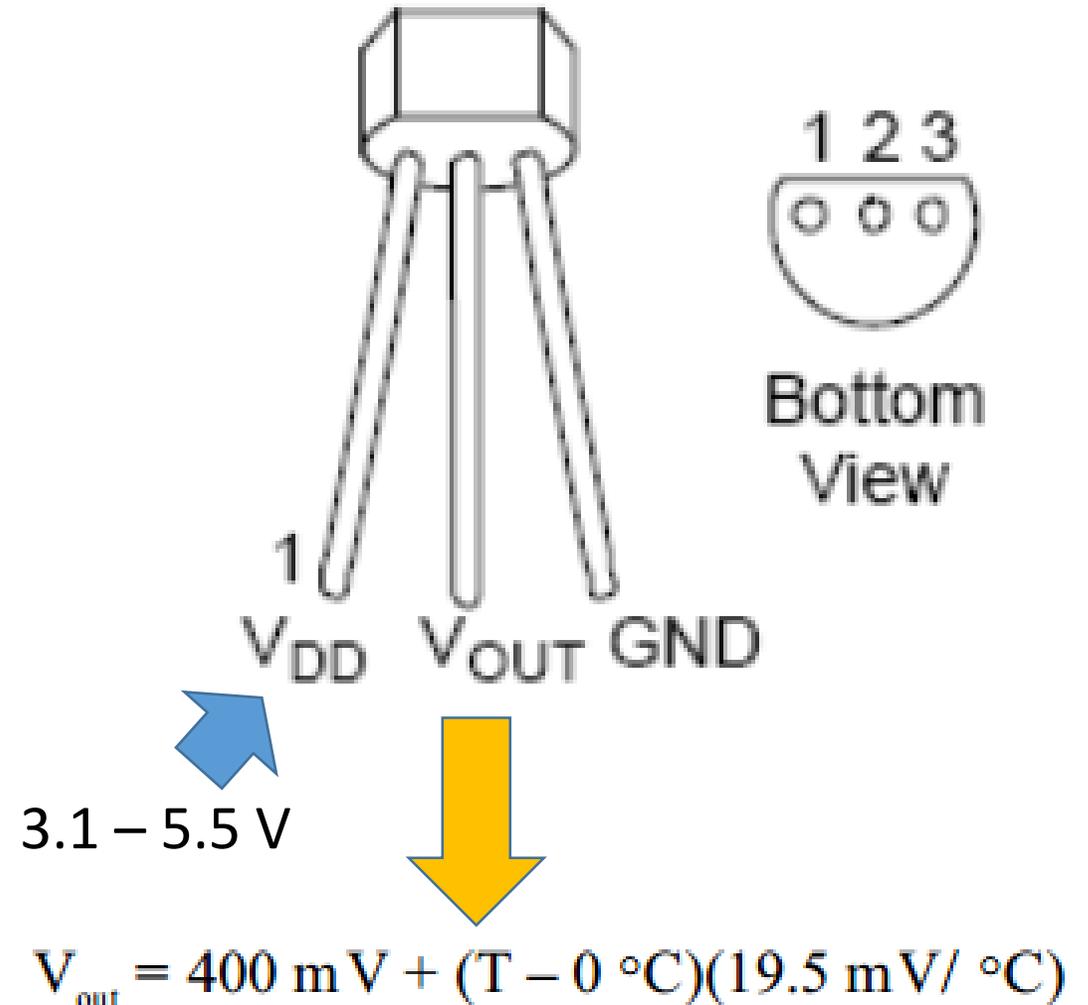
Microchip MCP9701A



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

Microchip MCP9701A

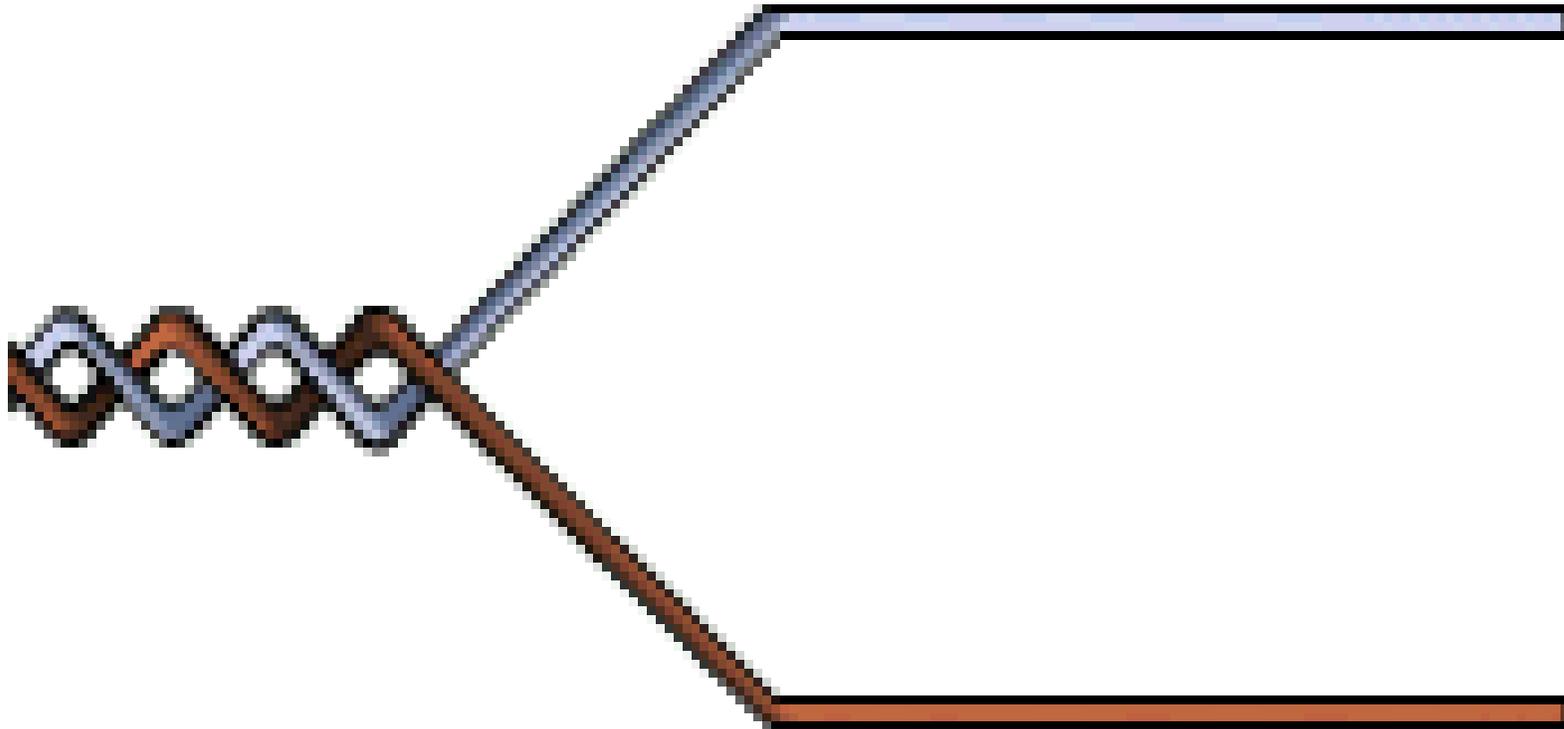


Summary Thus Far...

	Thermistor	Integrated Silicon
Temperature Range	-100 to 450°C	-55 to 150°C
Sensitivity	several $\Omega / \Omega / ^\circ\text{C}$	Based on technology that is -2mV/°C sensitive
Accuracy	$\pm 0.1^\circ\text{C}$	$\pm 1^\circ\text{C}$
Linearity	Requires at least 3rd order polynomial or equivalent look up table.	At best within $\pm 1^\circ\text{C}$. 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

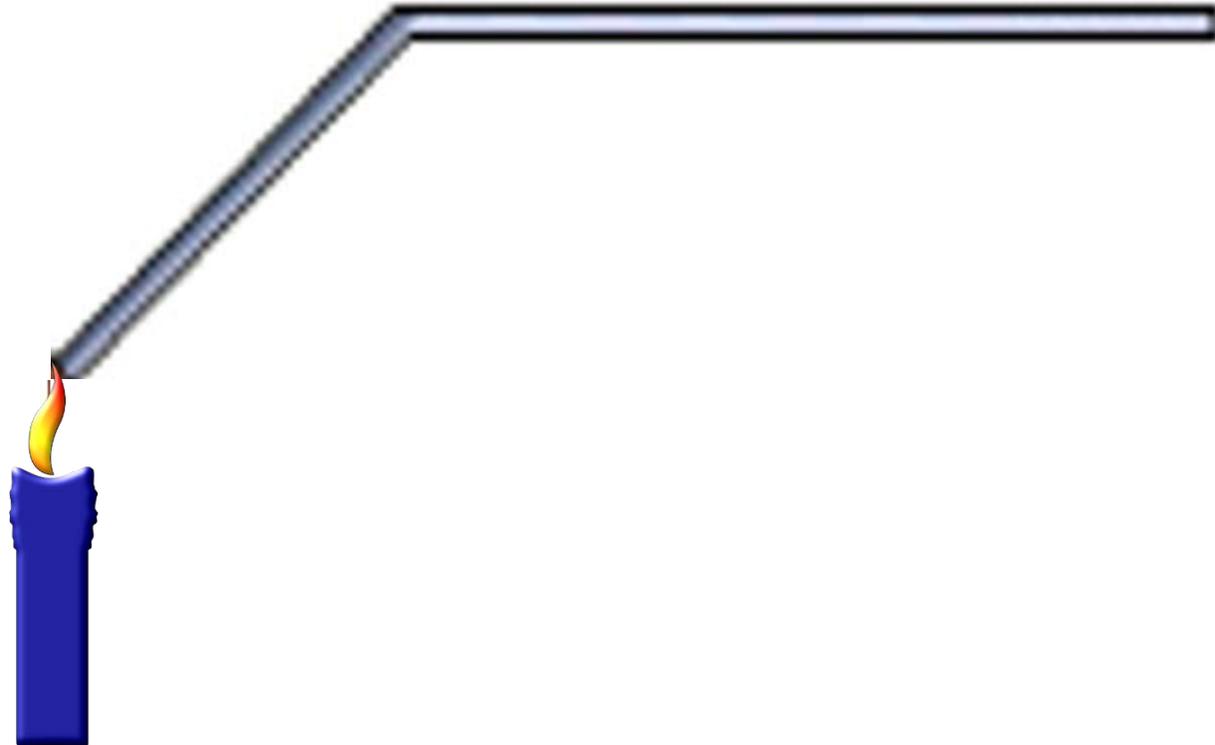
- Thermocouple – a two-terminal element consisting of two dissimilar metal wires joined at the end



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



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

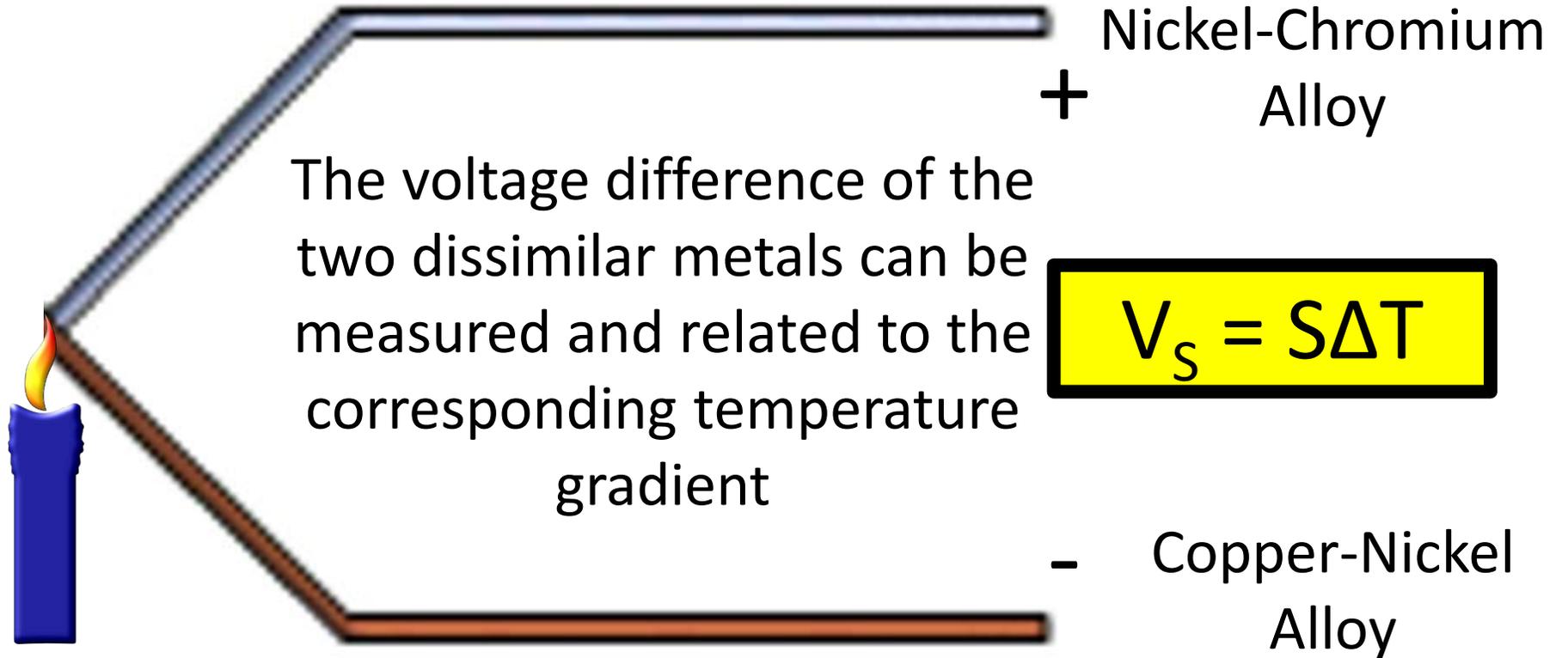
The relationship between temperature difference and voltage varies with materials



The Seebeck Effect

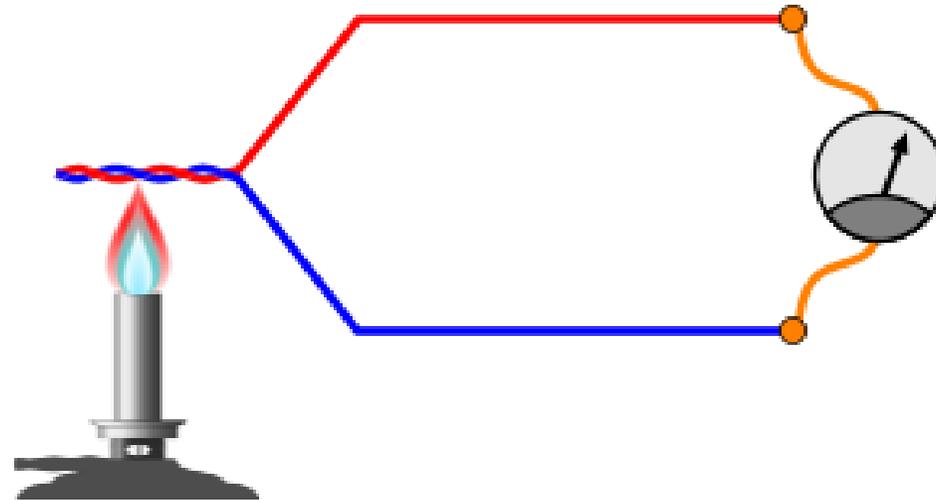
- Seebeck Effect – A conductor generates a voltage when it is subjected to a temperature gradient
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The relationship between temperature difference and voltage varies with materials



Measuring Temperature

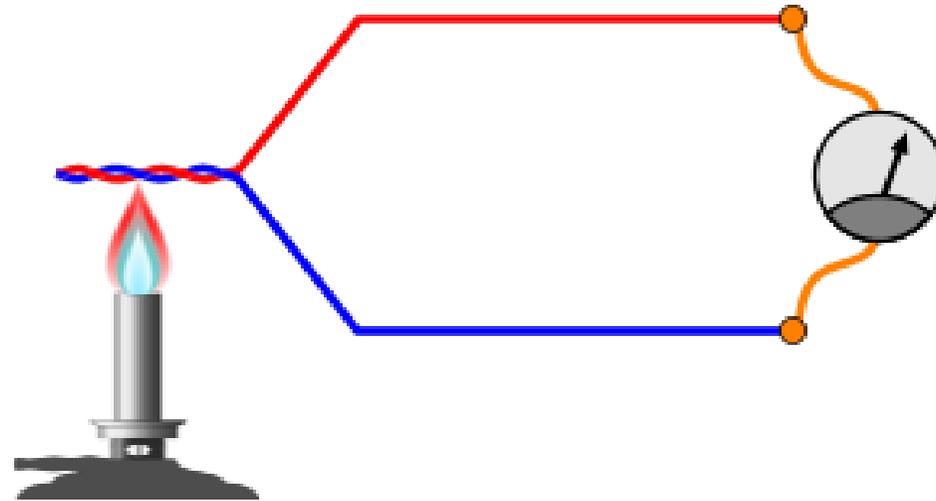
- To measure temperature using a thermocouple, you can't just connect the thermocouple to a measurement system (e.g. voltmeter)



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

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)

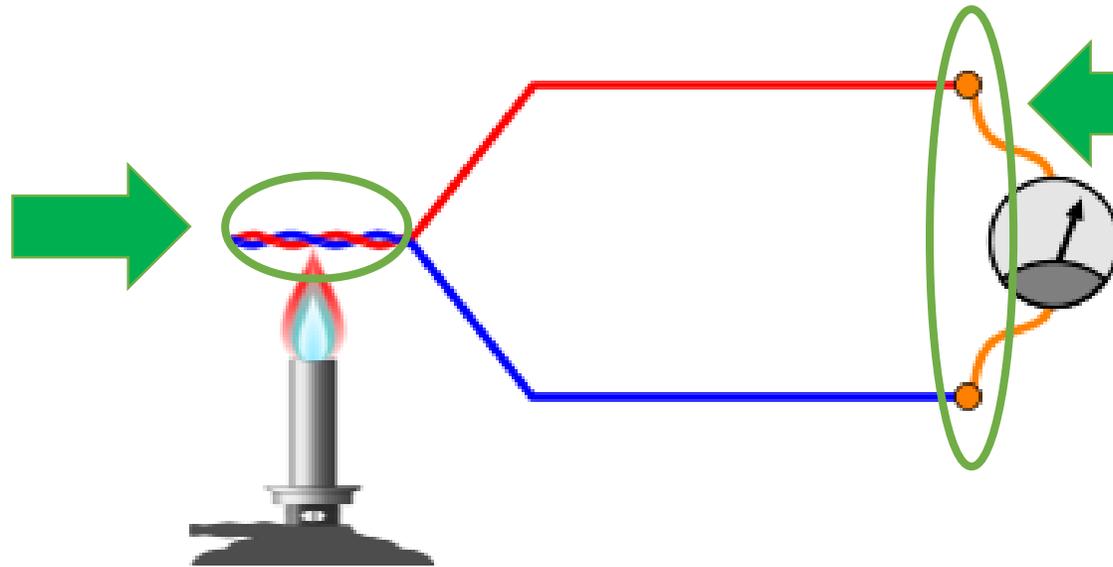


SOURCE: http://www.pcbheaven.com/wikipages/images/thermocouples_1271330366.png

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To determine the absolute temperature at the hot junction...



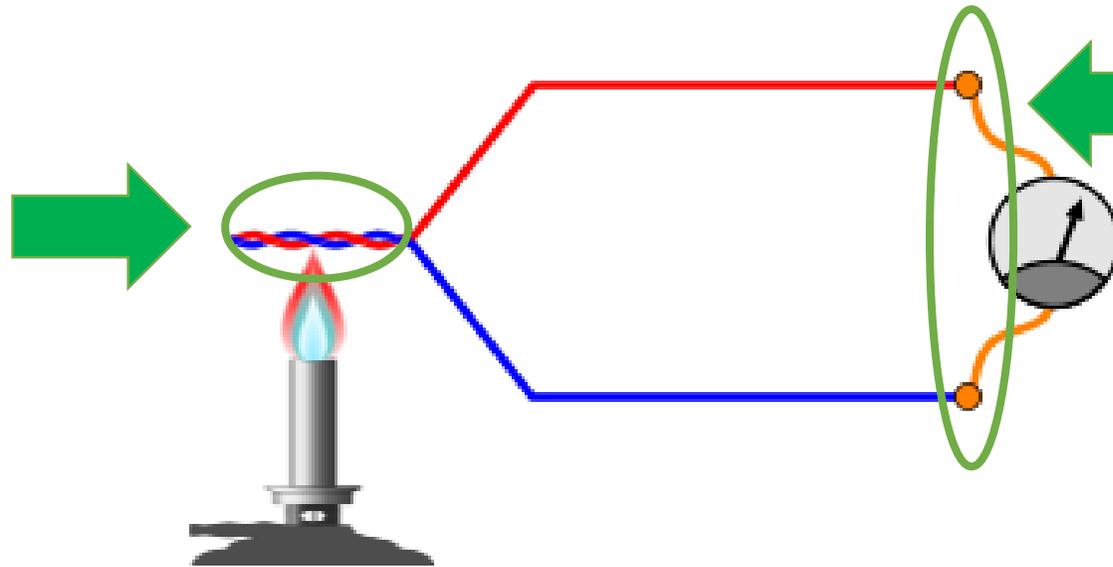
You need to know the temperature at the Ref junction!

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...



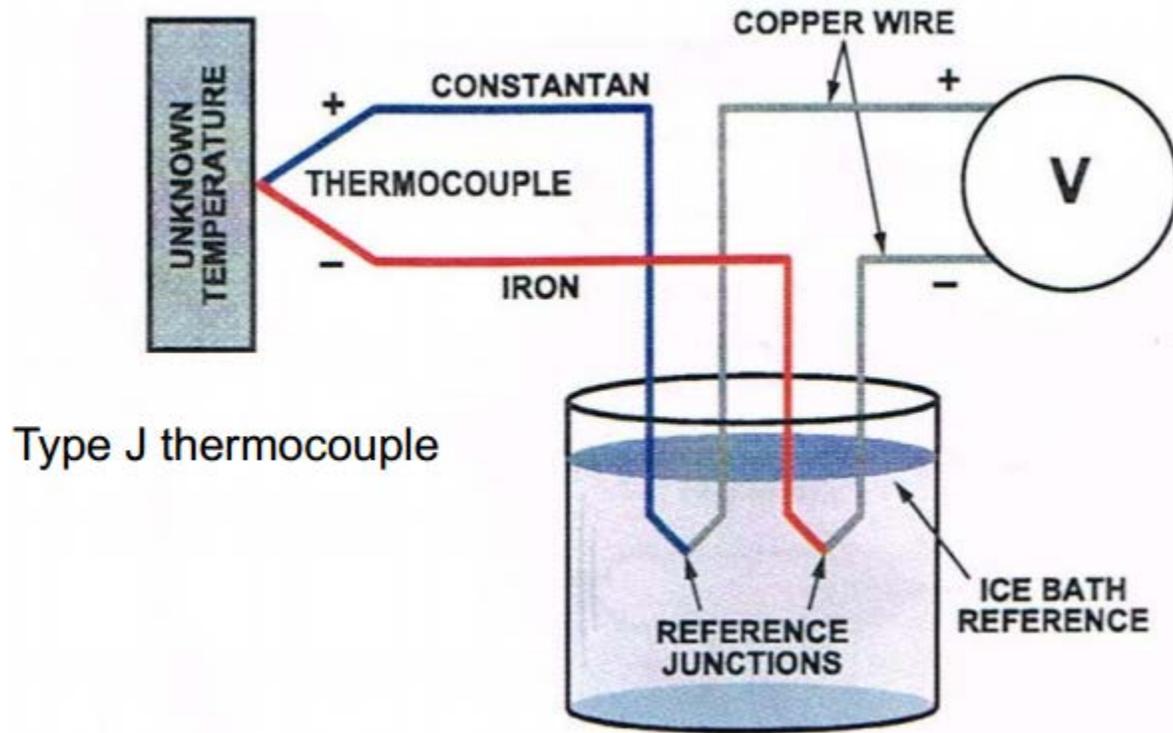
You need to know the temperature at the Ref junction!

How can we determine the temperature at the reference junction?

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

Ice Bath Method (Forcing a Temperature)

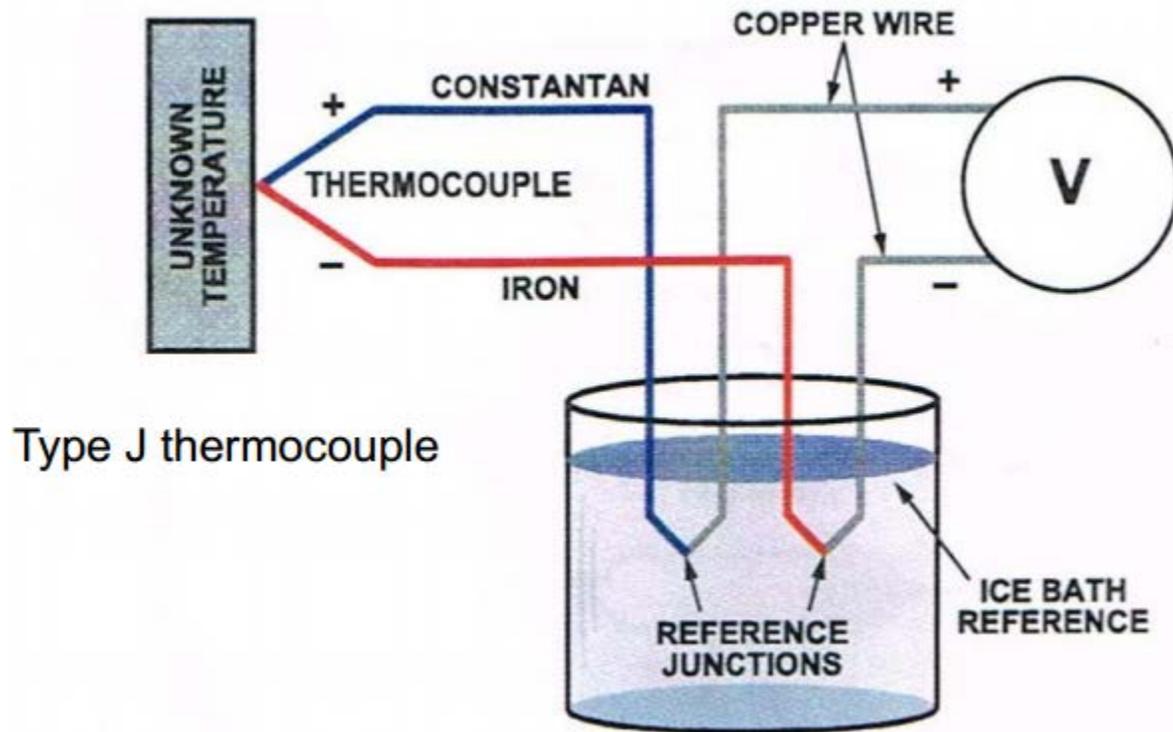
- Thermocouples measure the voltage difference between two points
- To know the absolute temperature at the hot junction, one must know the temperature at the Ref junction



Type J thermocouple

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



Type J thermocouple

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

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

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

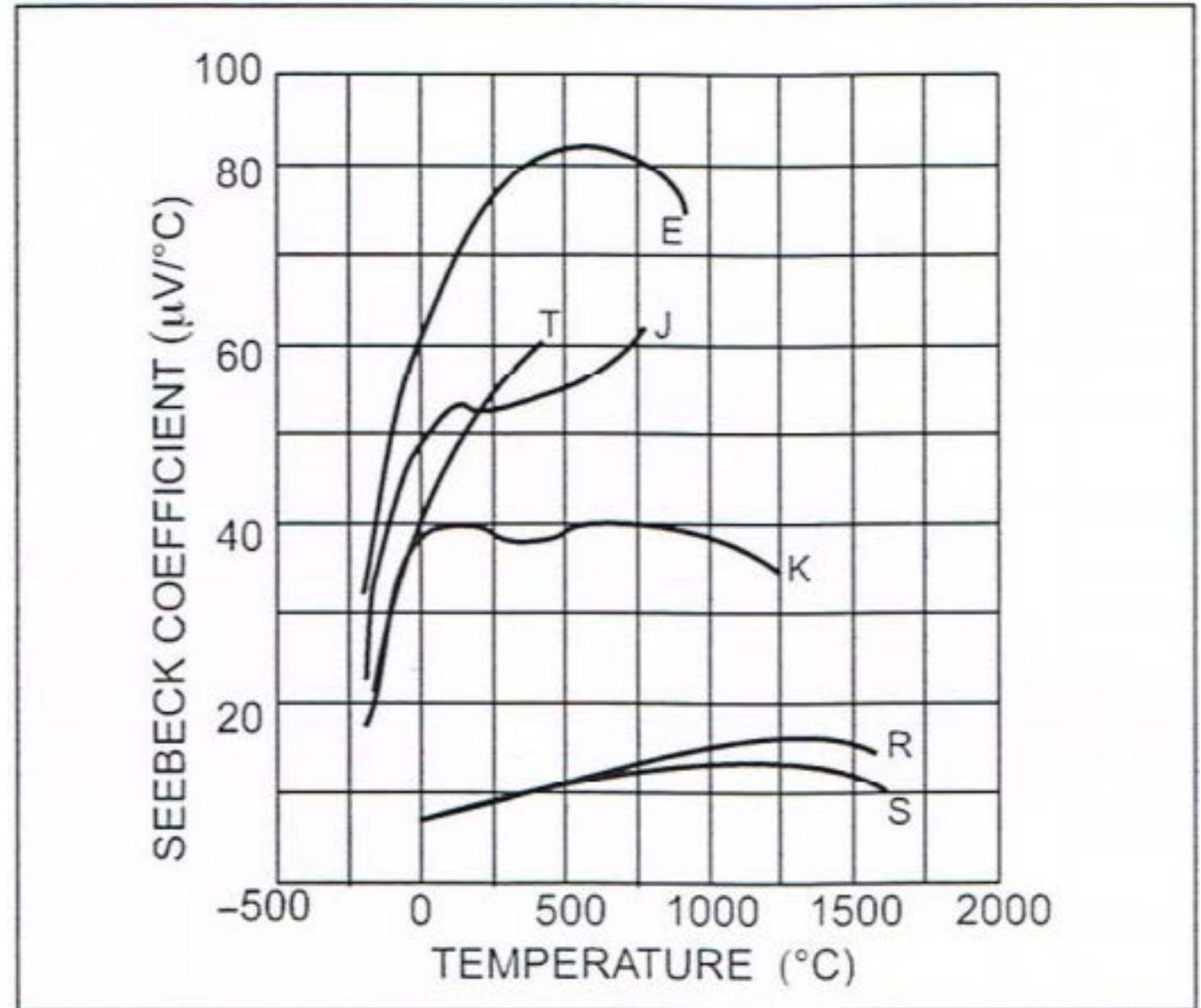
If we know the voltage-temperature relationship of our thermocouple, we could determine the temperature at the hot junction

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

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

	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	0°C to 760°C ± 0.1°C	0°C to 1370°C ± 0.7°C	0°C to 1000°C ± 0.5°C	0°C to 1750°C ± 1°C	-160°C to 400°C ± 0.5°C
	9th order	5th order	8th order	8th order	9th order	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: $V_D = 3.409 \text{ mV}$

What is the temperature of the hot junction if the cold junction is at $22 \text{ }^\circ\text{C}$?

ITS-90 Table for Type T thermocouple

$^\circ\text{C}$	0	1	2	3	4	5	6	7	8	9	10
	Thermoelectric voltage in mV										
-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
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

Look-Up Table for a Type T Thermocouple

Voltage difference of the hot and cold junctions: $V_D = 3.409 \text{ mV}$

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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

At $22 \text{ }^\circ\text{C}$, the reference junction voltage is 0.870 mV

The hot junction voltage is therefore $3.409 \text{ mV} + 0.870 \text{ mV} = 4.279 \text{ mV}$

The temperature at the hot junction is therefore $100 \text{ }^\circ\text{C}$

APPLYING WHAT WE'VE LEARNED

Voltage difference of the hot and cold junctions: $V_D = 4.472 \text{ mV}$

What is the temperature of the hot junction if the cold junction is at $-5 \text{ }^\circ\text{C}$?

ITS-90 Table for Type T thermocouple

$^\circ\text{C}$	0	1	2	3	4	5	6	7	8	9	10
	Thermoelectric voltage in mV										
-10	-0.383	-0.345	-0.307	-0.269	-0.231	-0.193	-0.154	-0.116	-0.077	-0.039	0.000
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110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228

APPLYING WHAT WE'VE LEARNED

Voltage difference of the hot and cold junctions: $V_D = 4.472 \text{ mV}$

What is the temperature of the hot junction if the cold junction is at $-5 \text{ }^\circ\text{C}$?

ITS-90 Table for Type T thermocouple

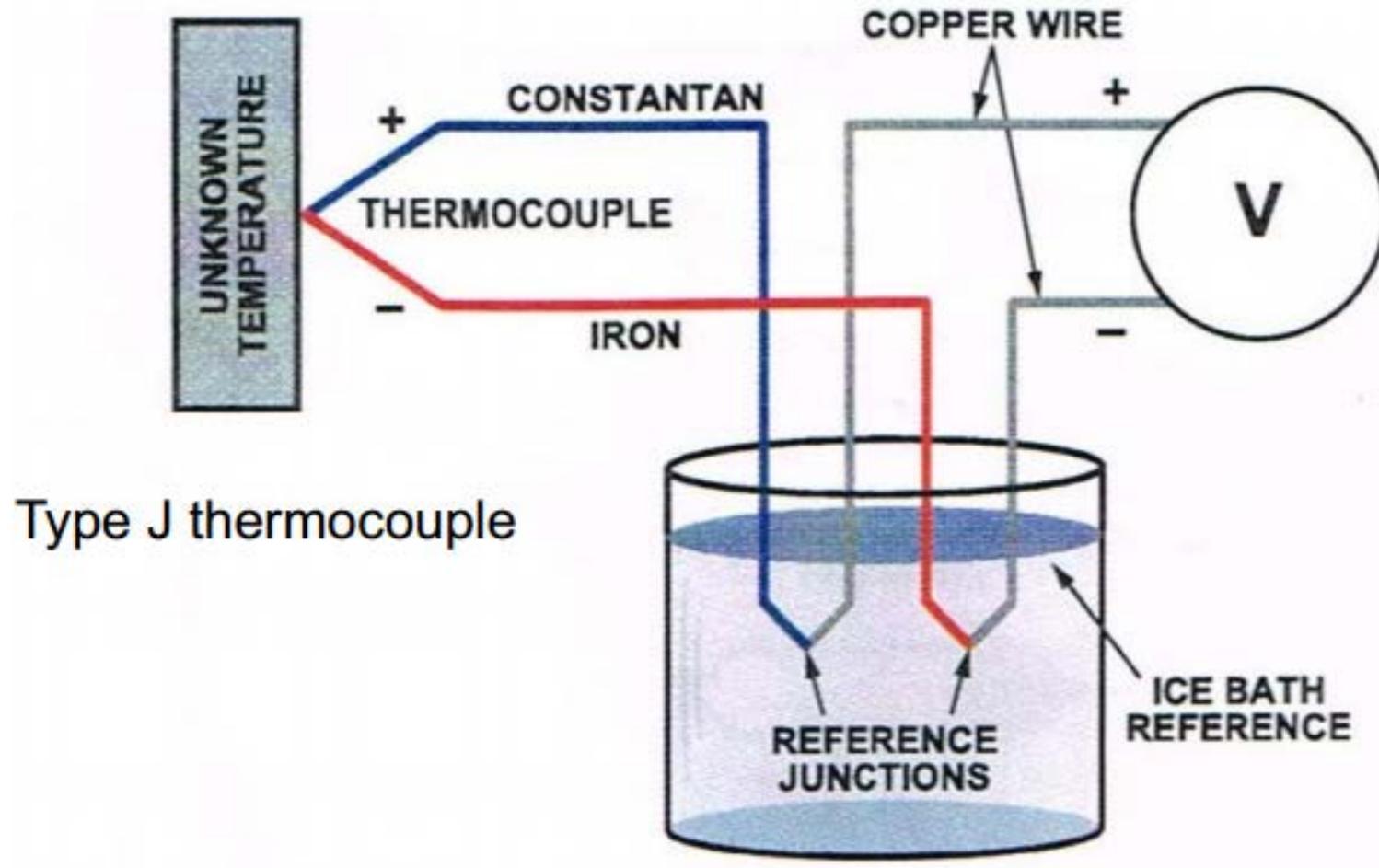
$^\circ\text{C}$	0	1	2	3	4	5	6	7	8	9	10
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110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228

At $-5 \text{ }^\circ\text{C}$, the cold junction voltage is -0.193 mV

The hot junction voltage is therefore $4.472 \text{ mV} - 0.193 \text{ mV} = 4.279 \text{ mV}$

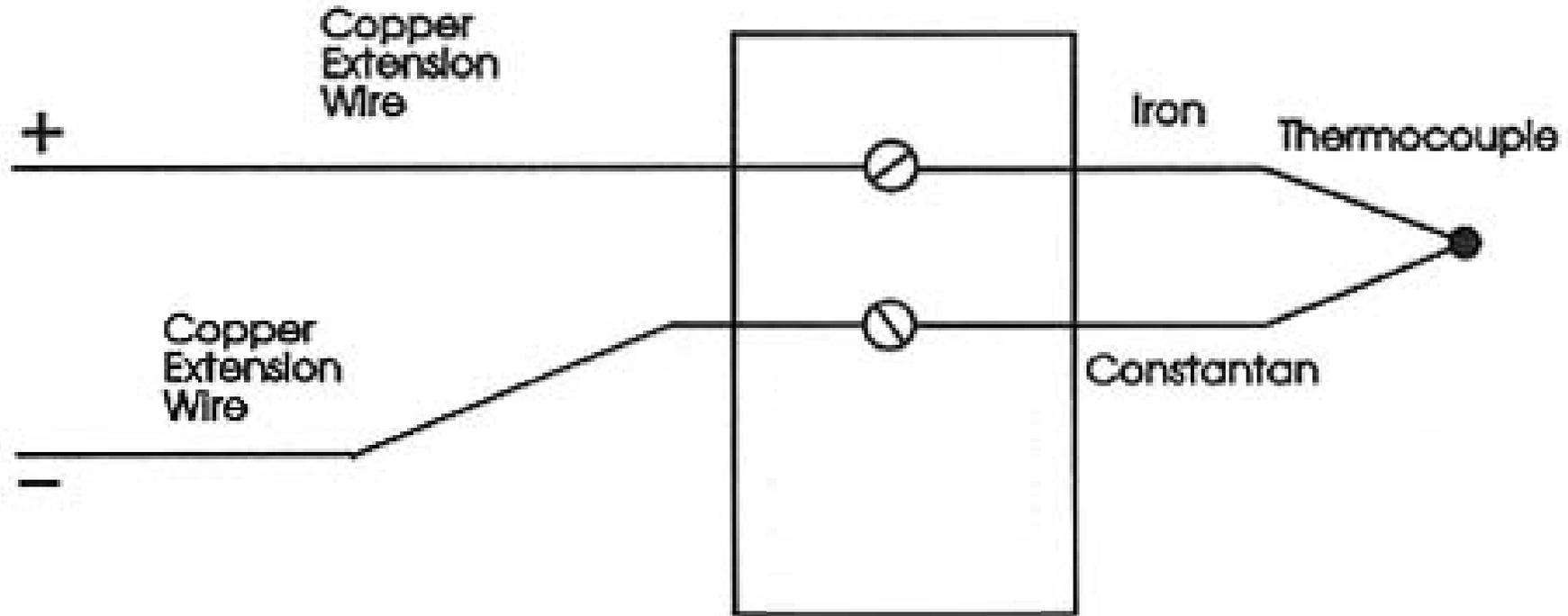
The temperature at the hot junction is therefore $100 \text{ }^\circ\text{C}$

Is This Really Practical For a Rocket?



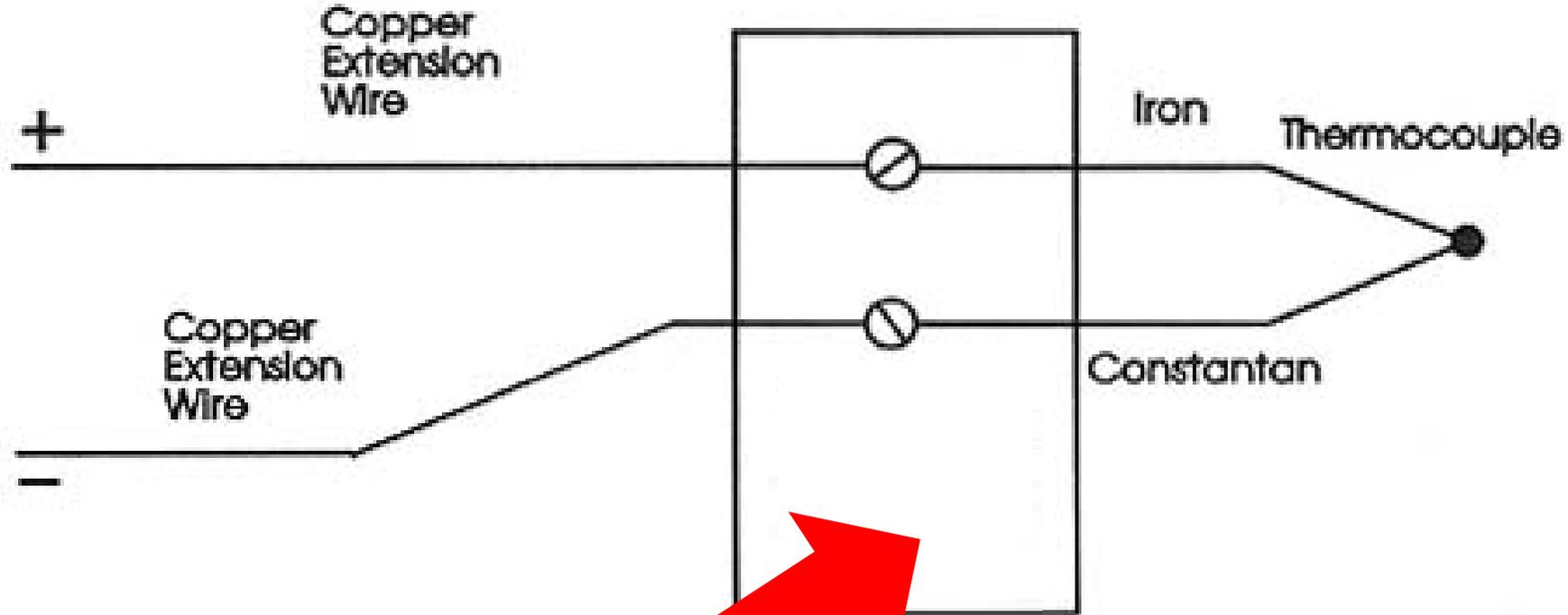
What is another method of determining the temperature at the reference junction?

Cold Junction Compensation



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

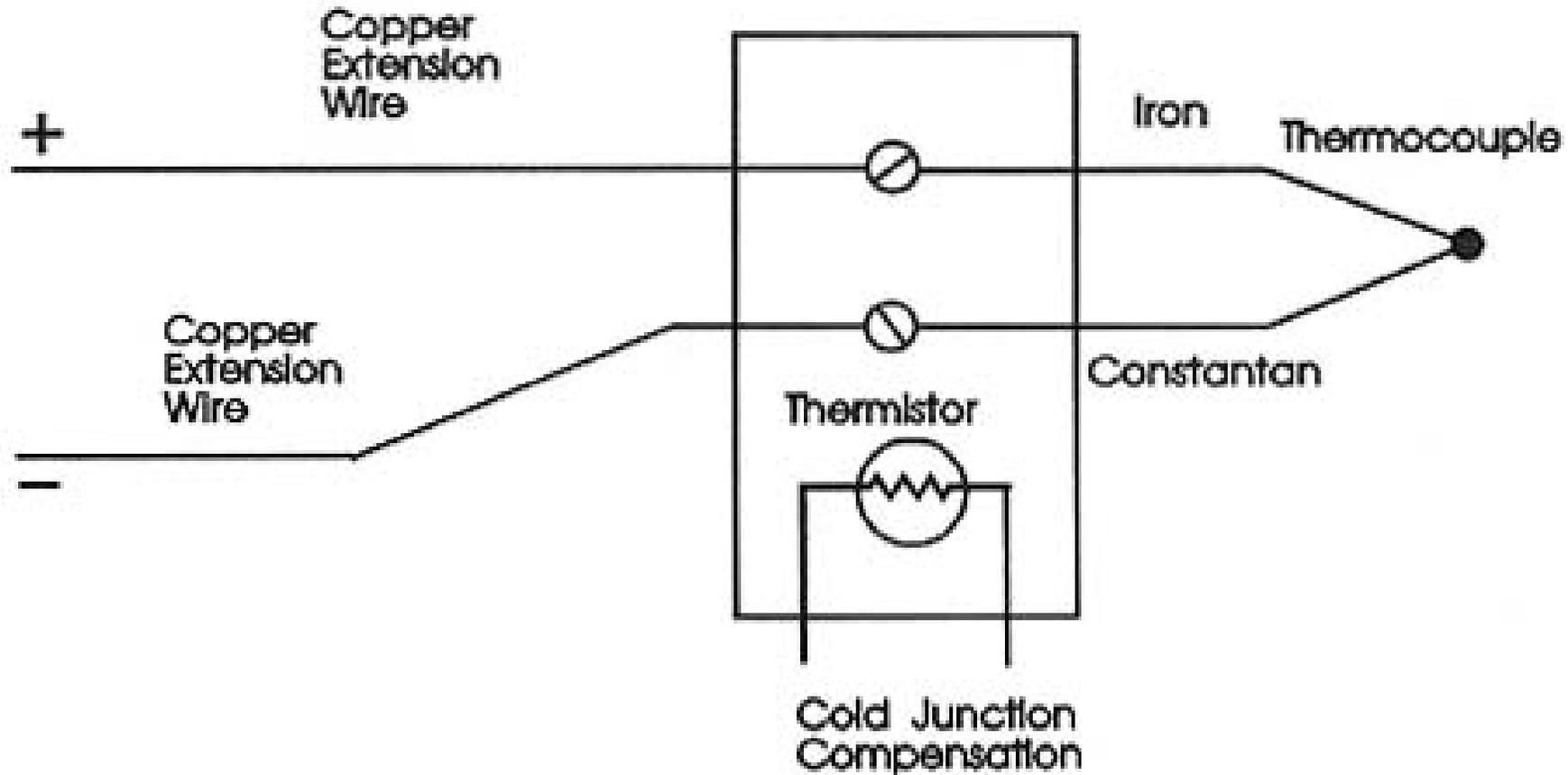
Cold Junction Compensation



How could I determine the temperature of the block?

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

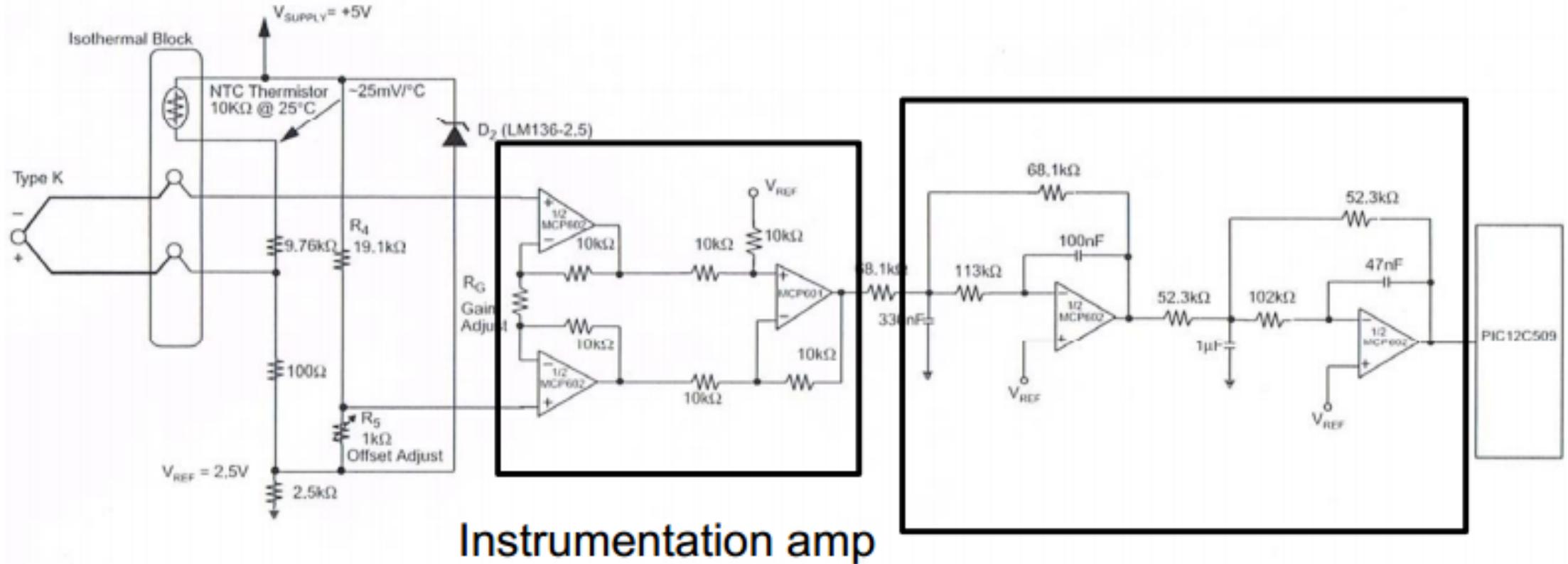
Cold Junction Compensation



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

Acquiring Data

Thermocouples are very noise prone & usually need filtering



Instrumentation amp

Low pass filter

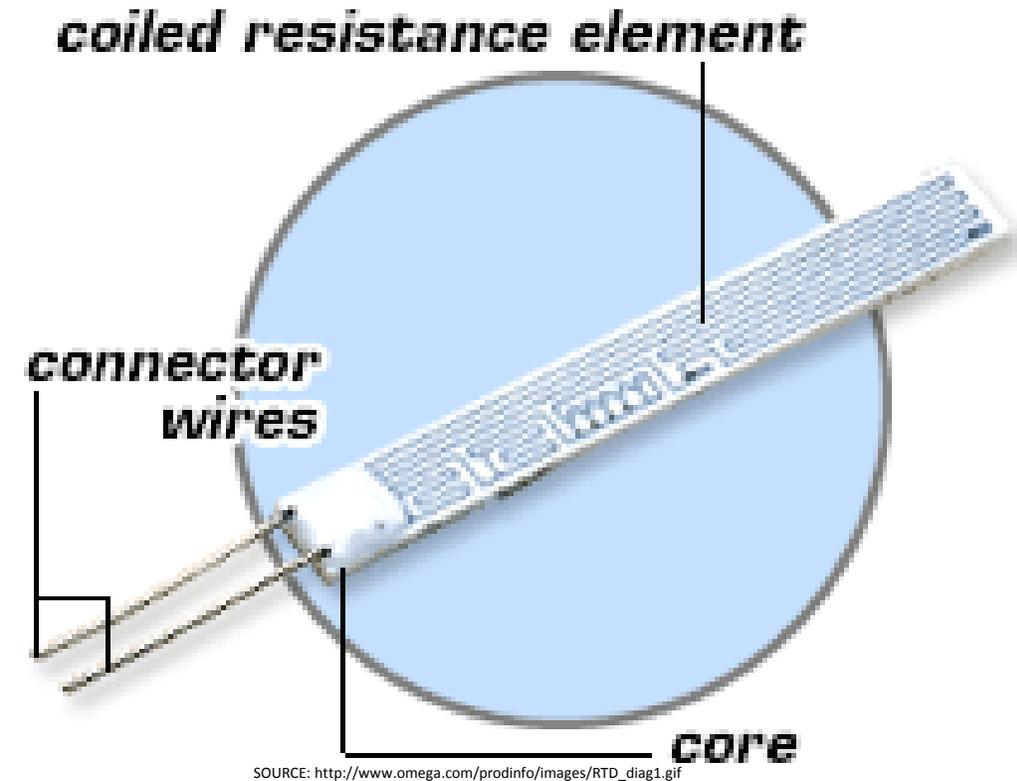
Temperature Measurement Devices in Lab

	Thermocouple		Thermistor	Integrated Silicon
Temperature Range	-270 to 1800°C		-100 to 450°C	-55 to 150°C
Sensitivity	10s of $\mu\text{V} / ^\circ\text{C}$		several $\Omega / \Omega / ^\circ\text{C}$	Based on technology that is $-2\text{mV}/^\circ\text{C}$ sensitive
Accuracy	$\pm 0.5^\circ\text{C}$		$\pm 0.1^\circ\text{C}$	$\pm 1^\circ\text{C}$
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 $\pm 1^\circ\text{C}$. No linearization required.
Ruggedness	The larger gage wires of the thermocouple make this sensor more rugged. Additionally, the insulation materials that are used enhance the thermocouple's sturdiness.		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	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 $T_0 = 0^\circ\text{C}$
 $R_0 = 100 \Omega$, $\alpha = 0.03385 \Omega / \Omega ^\circ\text{C}$
- At 10°C , $R = 100(1+0.3385)(10) = 103.85 \Omega$
- They are best operated using a small constant current source
- Accuracy of $0.01 ^\circ\text{C}$
- **EXPENSIVE!**

Typical RTD Design



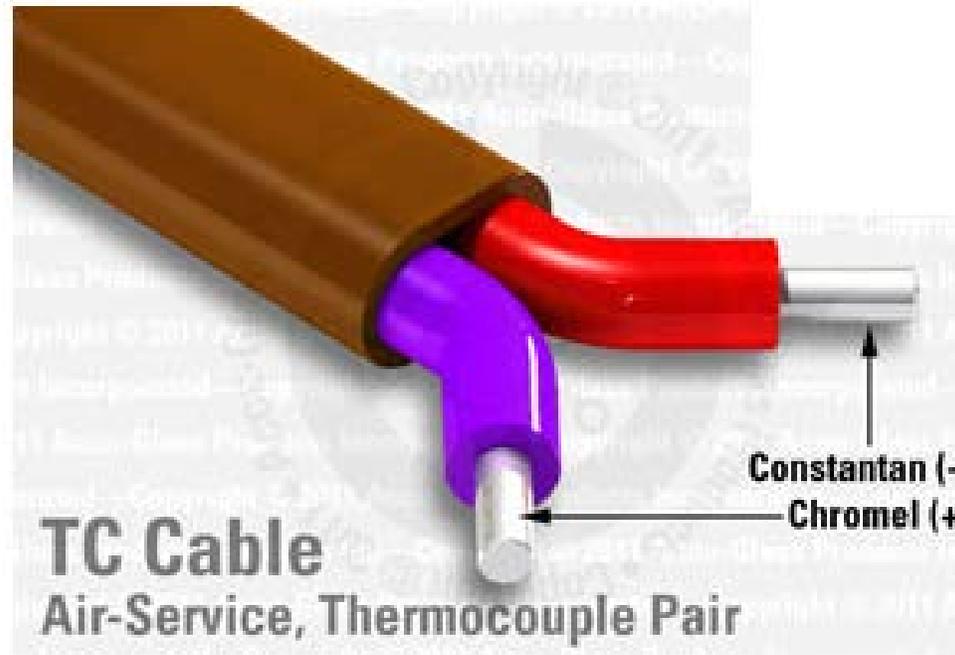
Temperature Measurement Devices

	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 $\mu\text{V} / ^\circ\text{C}$	0.00385 $\Omega / \Omega / ^\circ\text{C}$ (Platinum)	several $\Omega / \Omega / ^\circ\text{C}$	Based on technology that is -2mV/°C sensitive
Accuracy	$\pm 0.5^\circ\text{C}$	$\pm 0.01^\circ\text{C}$	$\pm 0.1^\circ\text{C}$	$\pm 1^\circ\text{C}$
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 $\pm 1^\circ\text{C}$. No linearization required.
Ruggedness	The larger gage wires of the thermocouple make this sensor more rugged. Additionally, the insulation materials that are used enhance the thermocouple's sturdiness.	RTDs are susceptible to damage as a result of vibration. This is due to the fact that they typically 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 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	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>



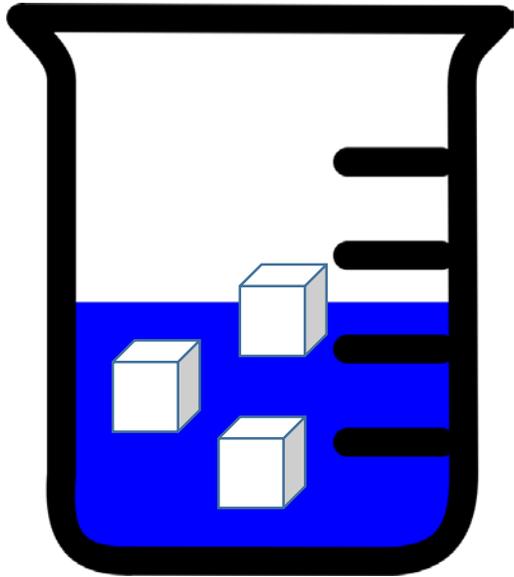
SOURCE: http://elcodis.com/photos/19/51/195143/to-92-3_standardbody__to-226_straightlead.jpg

Calibration

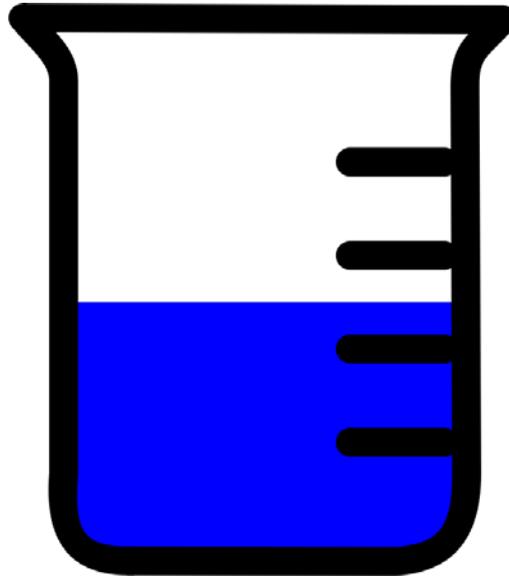
- How could we calibrate a temperature sensor?

Calibration

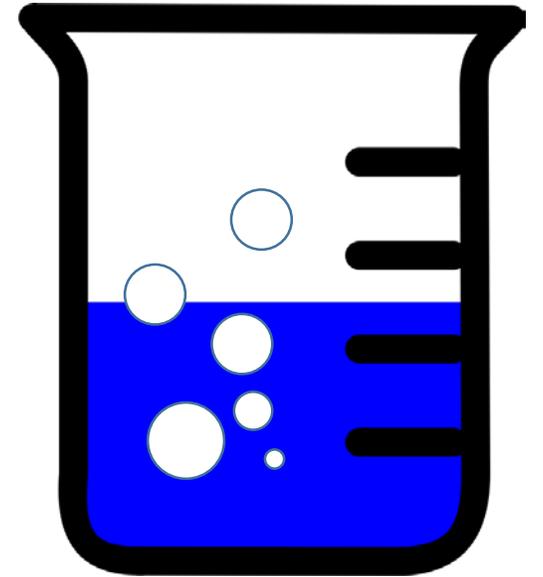
- How could we calibrate a temperature sensor?



0 °C



25 °C



100 °C

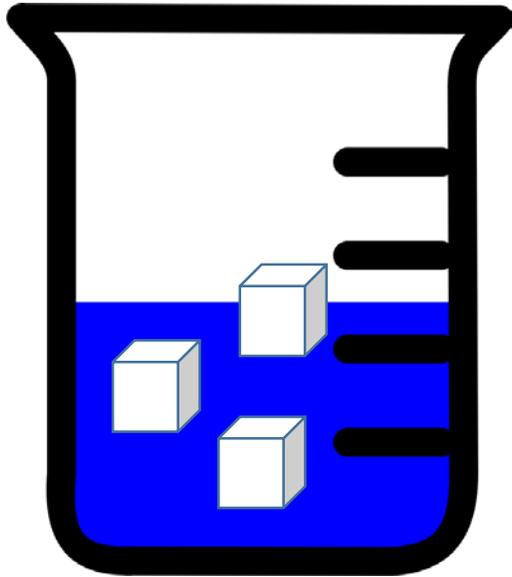
Calibration

- How could we calibrate a temperature sensor?

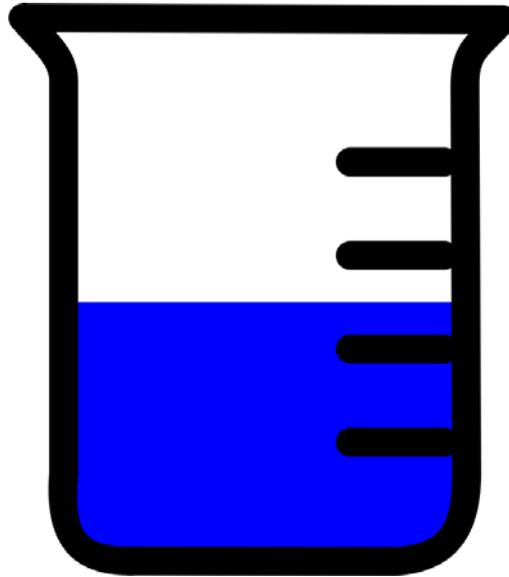


USB Reference
Thermometer

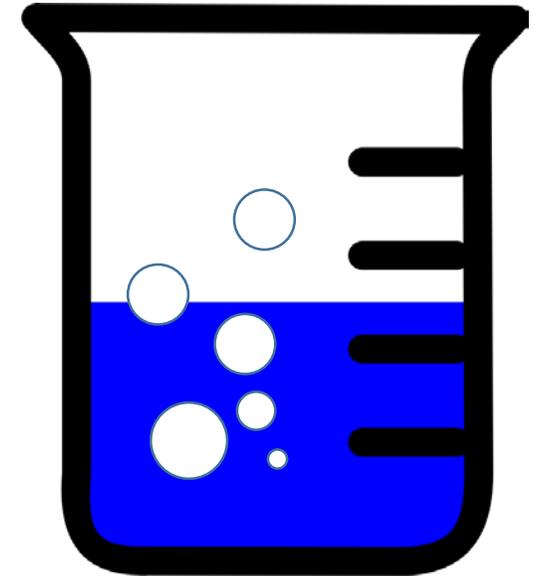
SOURCE: http://www.thermoworks.com/products/calibration/usb_reference.html



0 °C



25 °C



100 °C

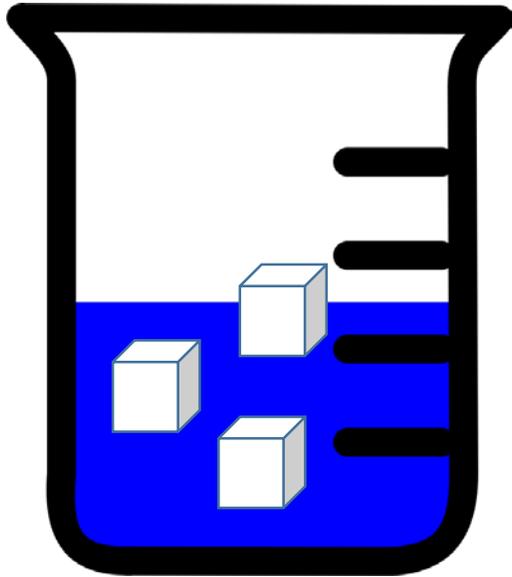
Calibration

- How could we calibrate a temperature sensor?

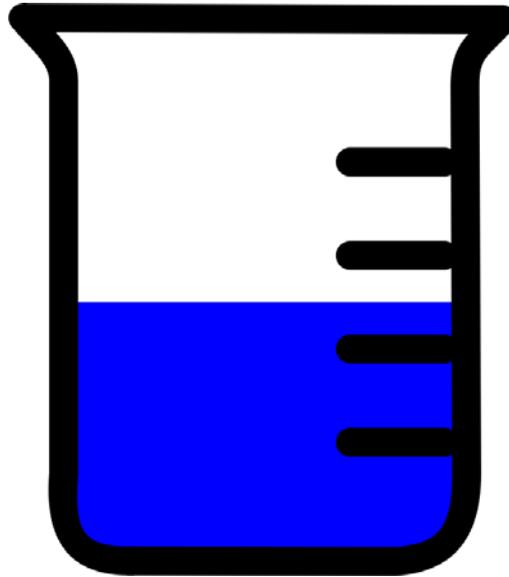


Each probe includes an individual NIST-Traceable calibration certificate with test data at 0, 25, 70, and 100°C.

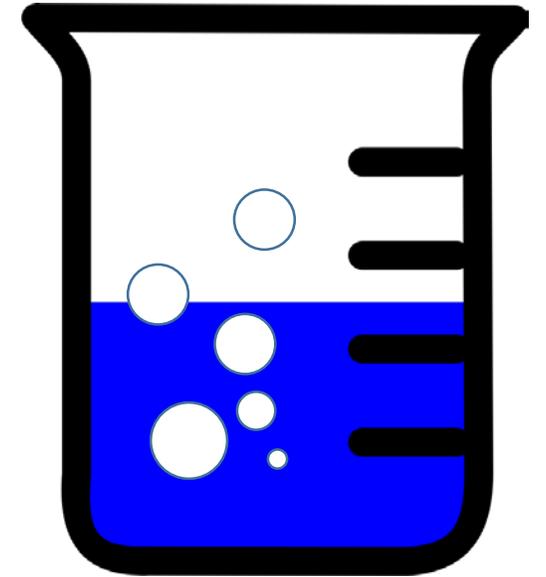
SOURCE: http://www.thermoworks.com/products/calibration/usb_reference.html



0 °C



25 °C



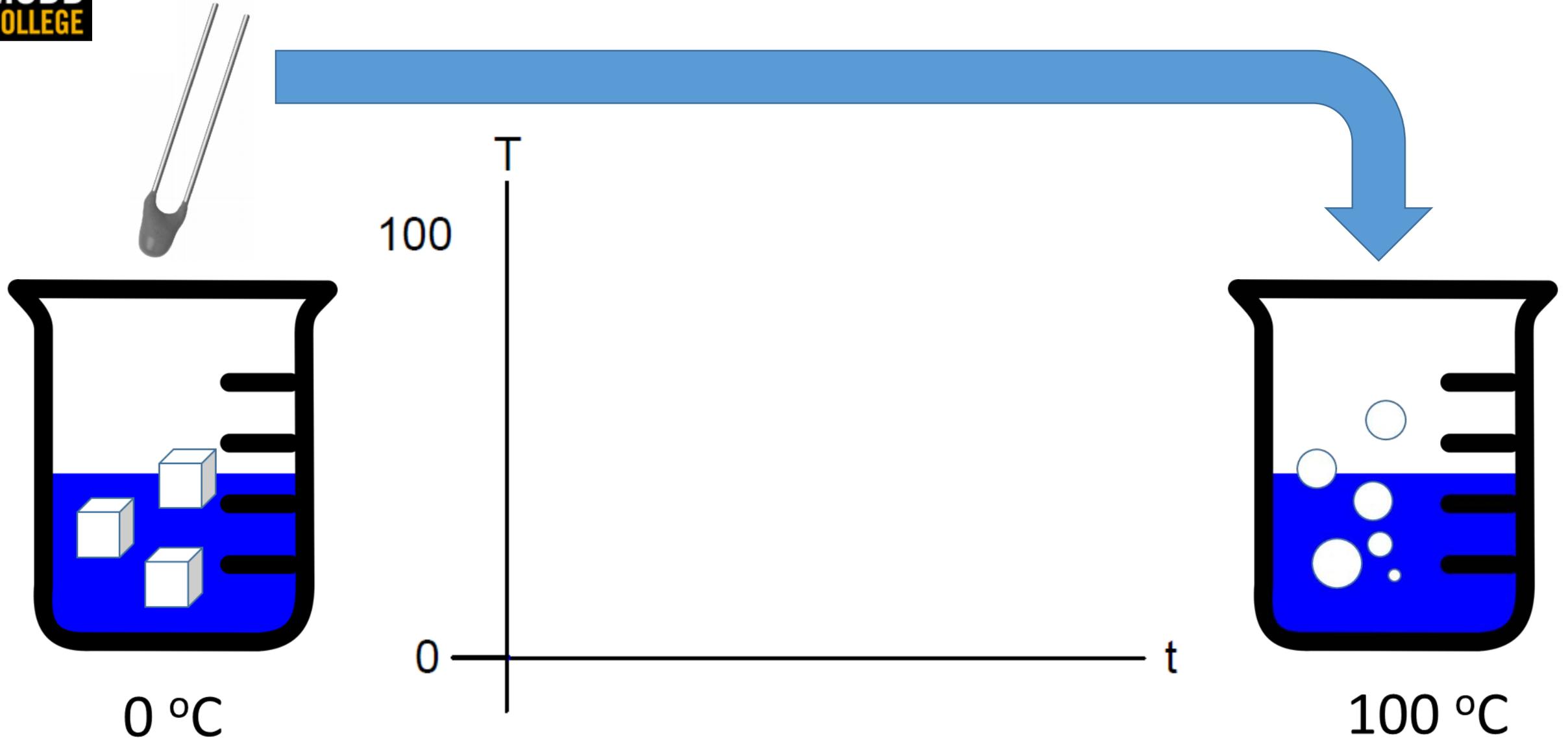
100 °C

Tracking the Rate of Temperature Change

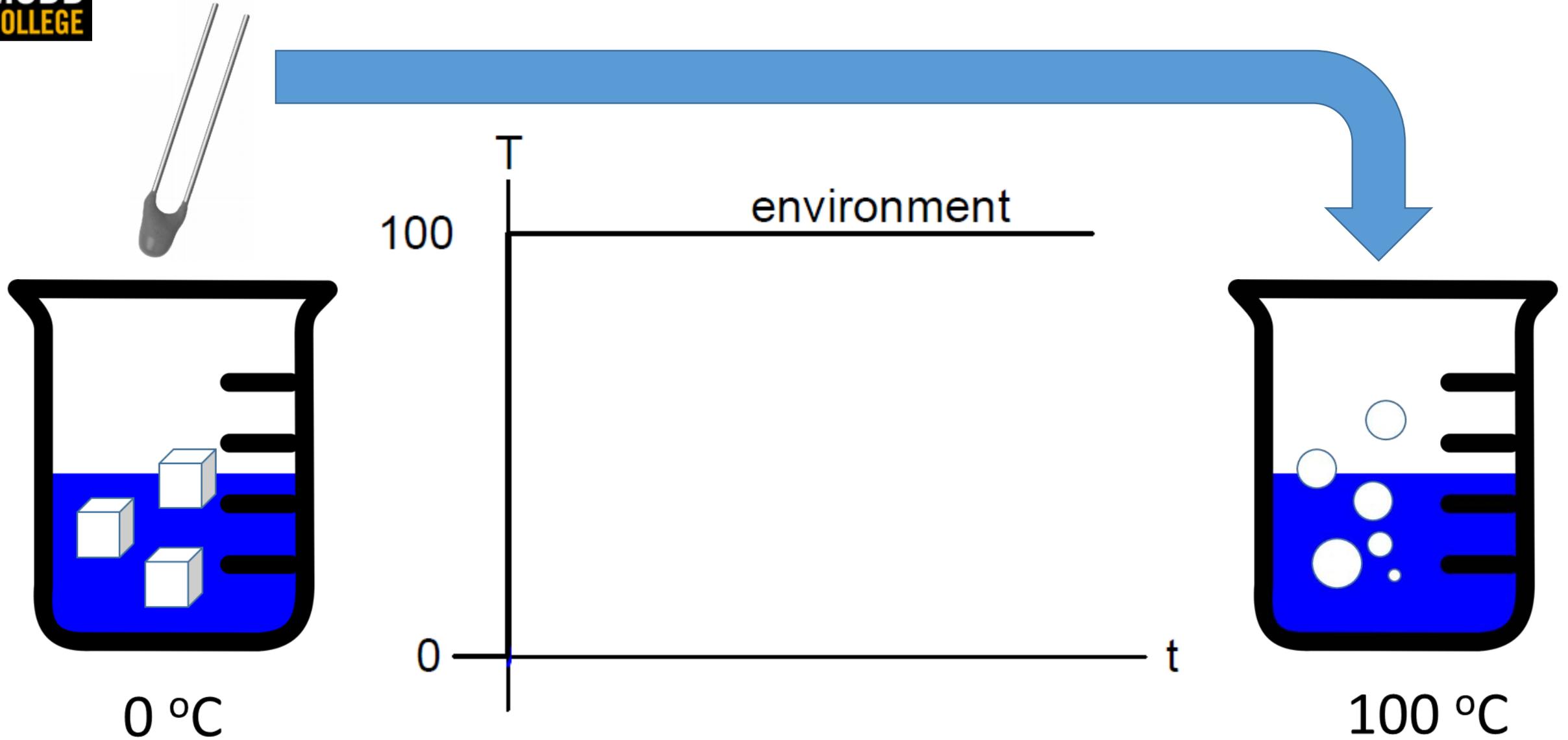
- If a slow sensor is placed into a rocket that is launched to a high altitude, the sensor may not be able to track the rate of temperature change
- A critical property of a temperature-measurement device is how quickly it responds to a change in external temperature



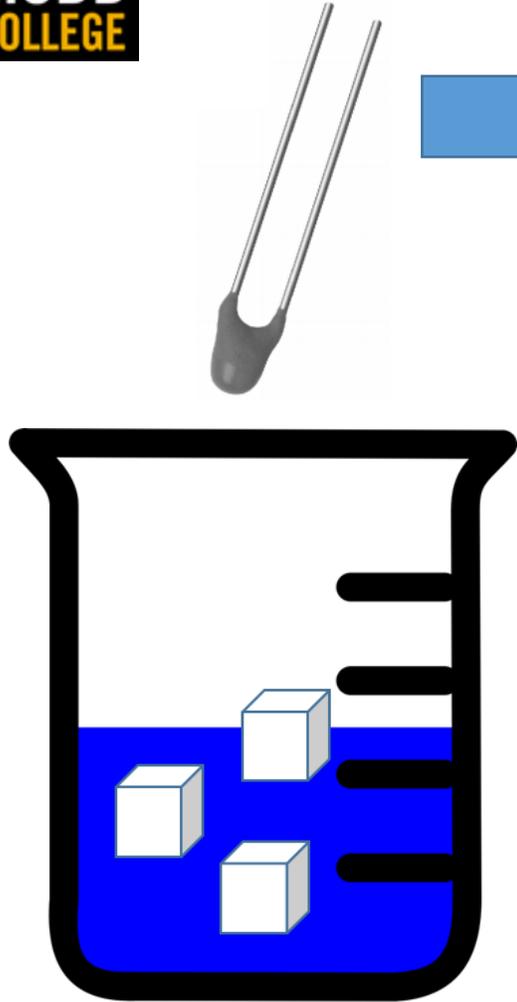
Thermal System Step Response



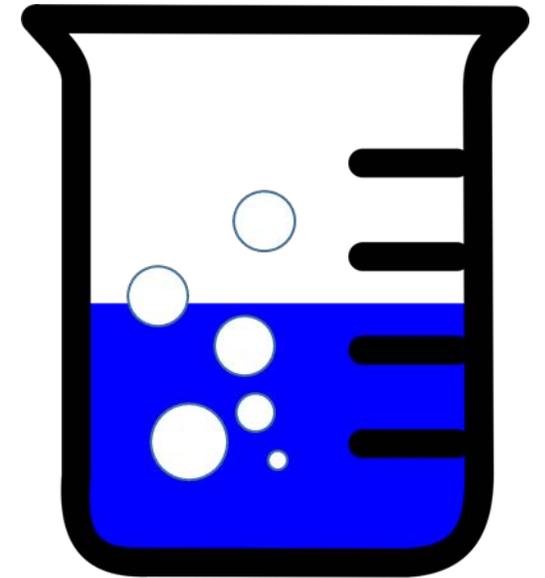
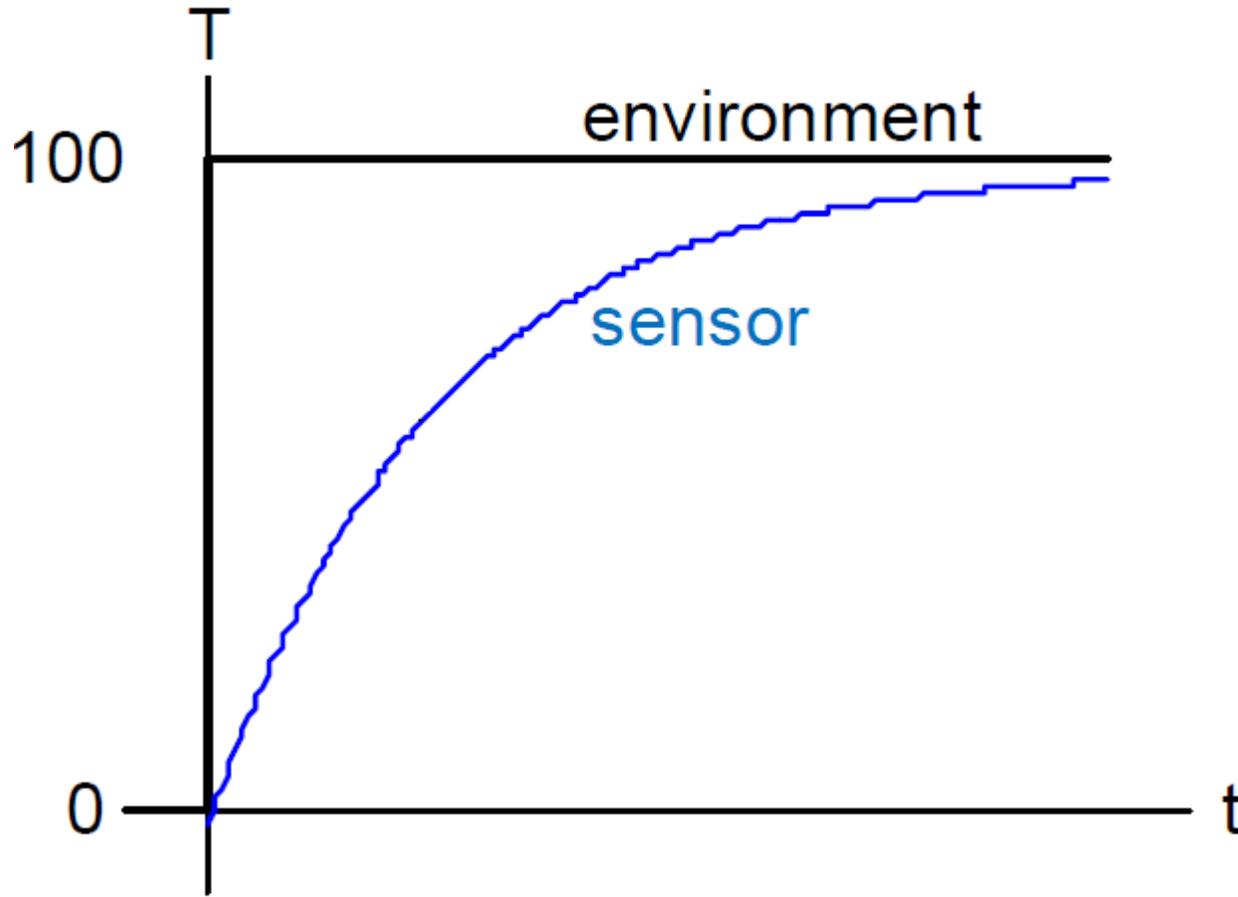
Thermal System Step Response



Thermal System Step Response

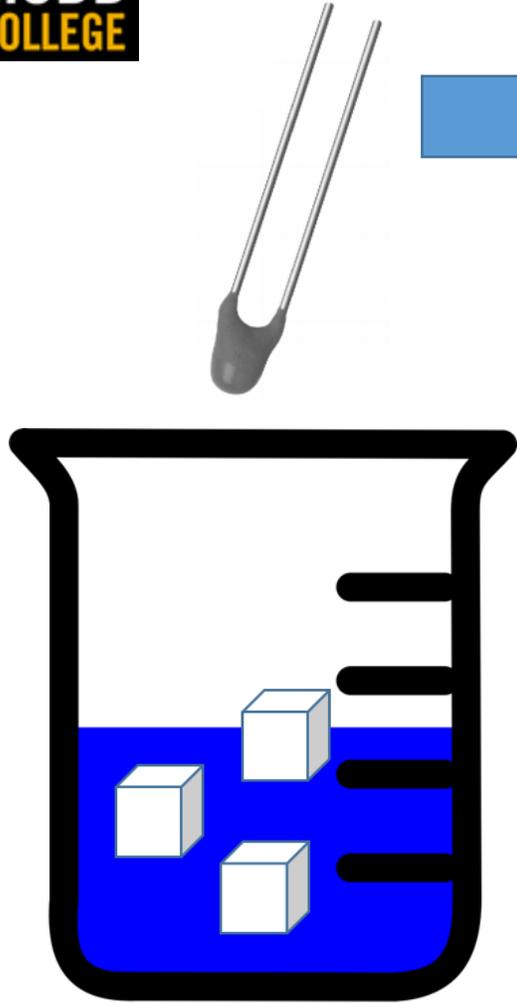


0 °C

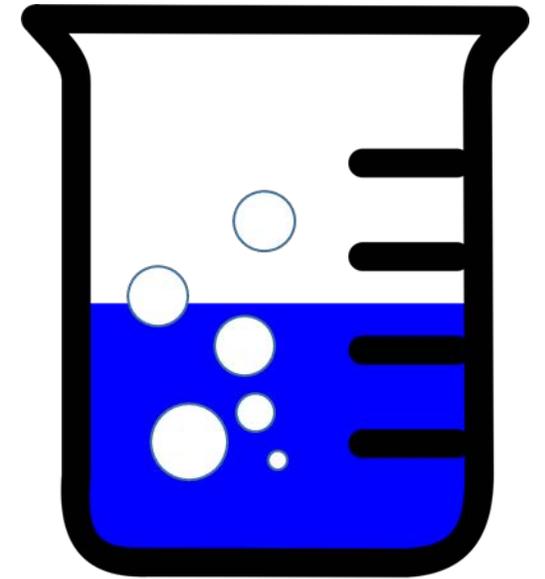
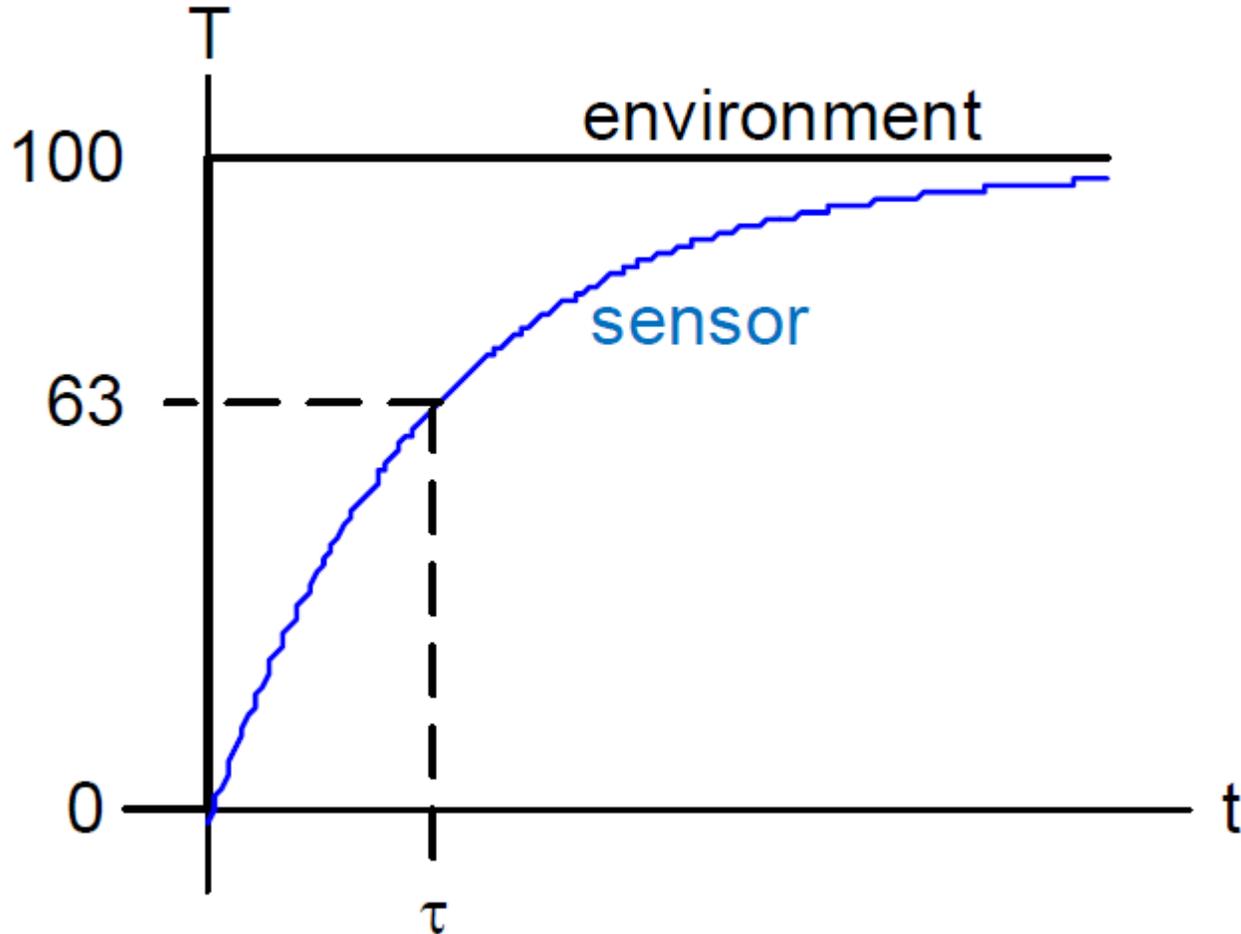
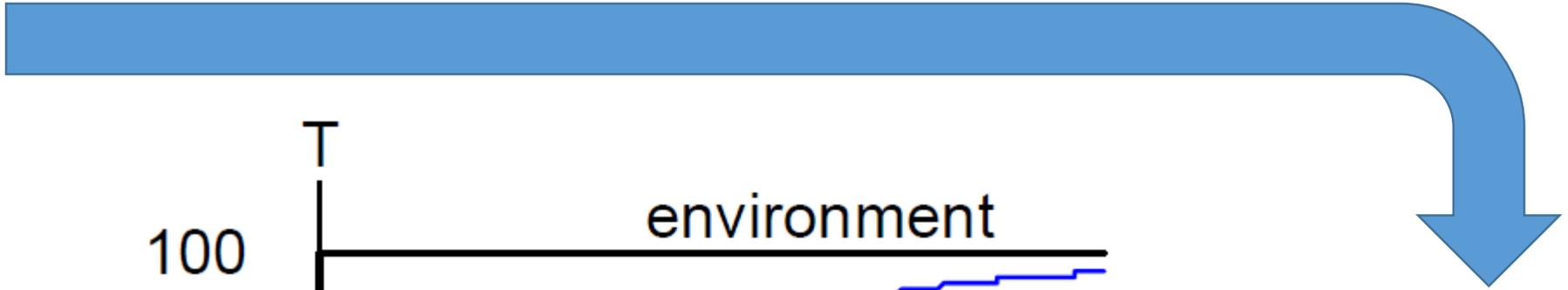


100 °C

Thermal System Step Response

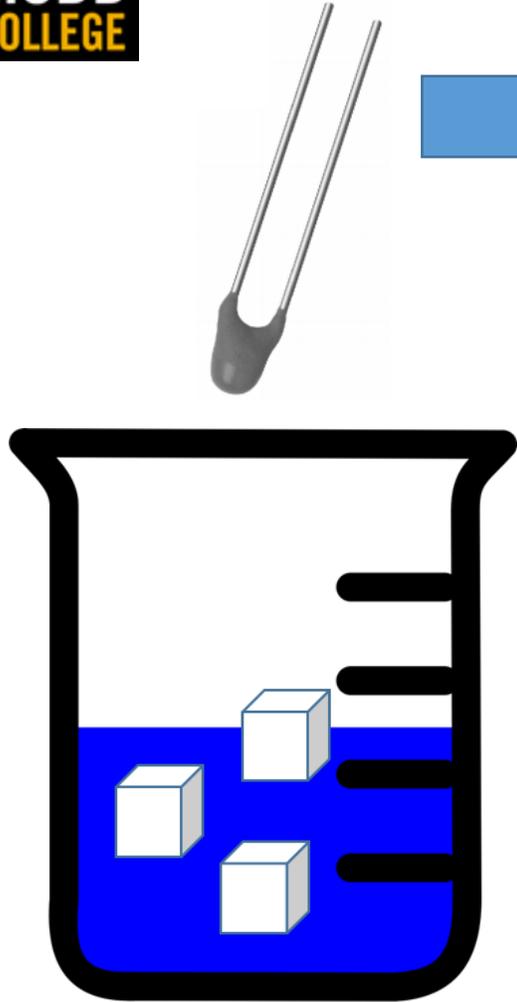


0 °C

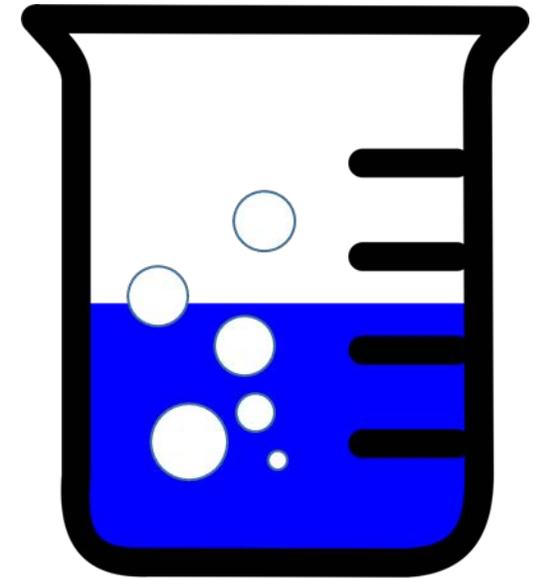
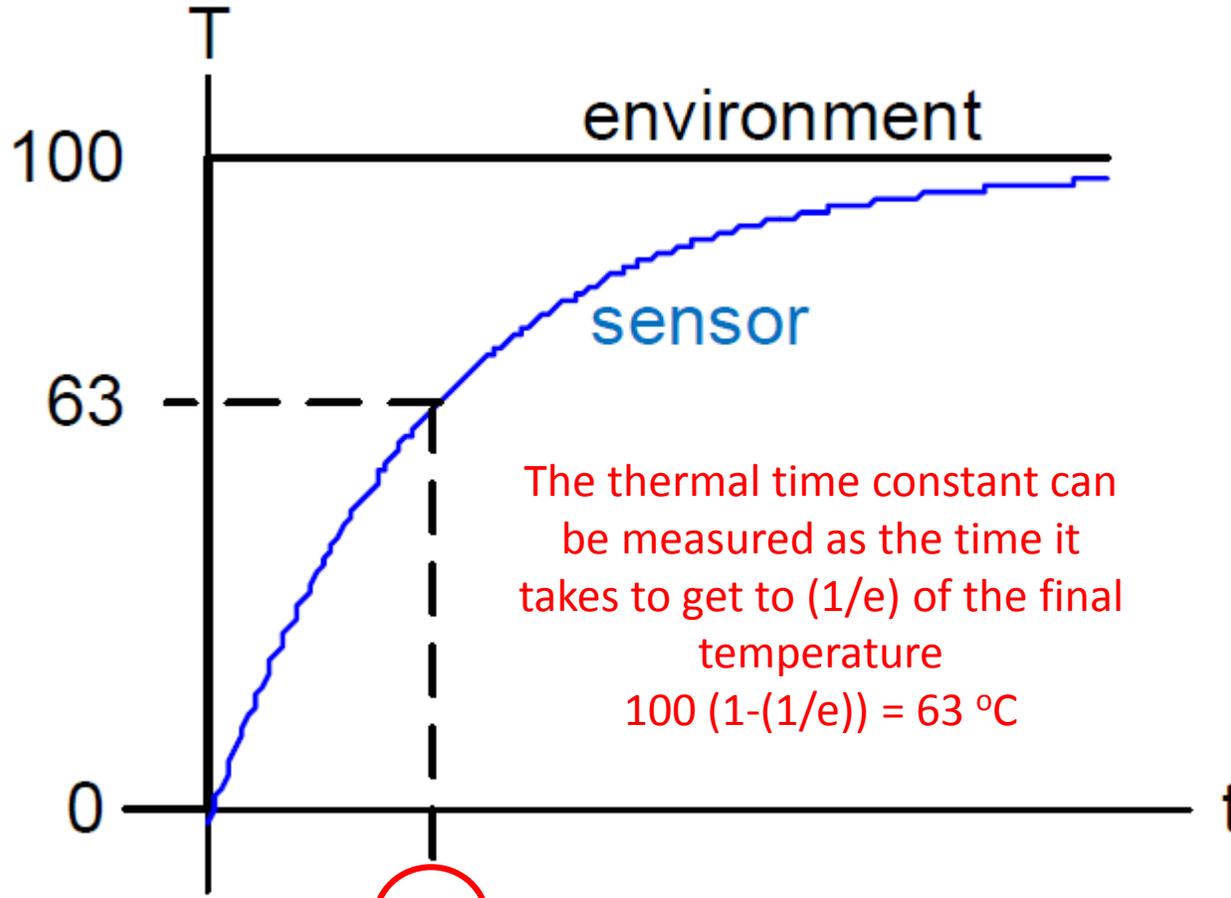


100 °C

Thermal System Step Response



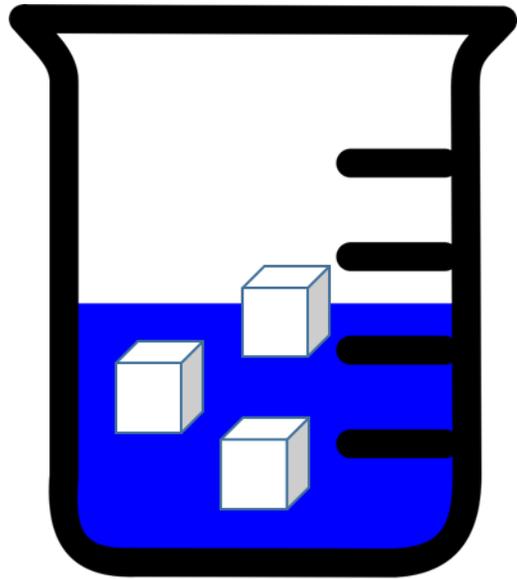
0 °C



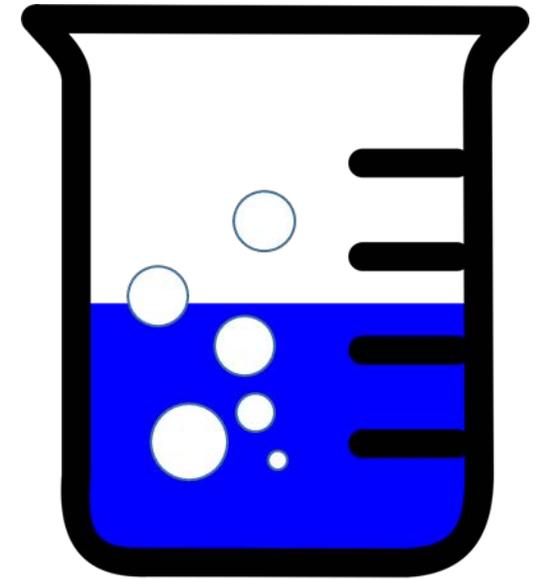
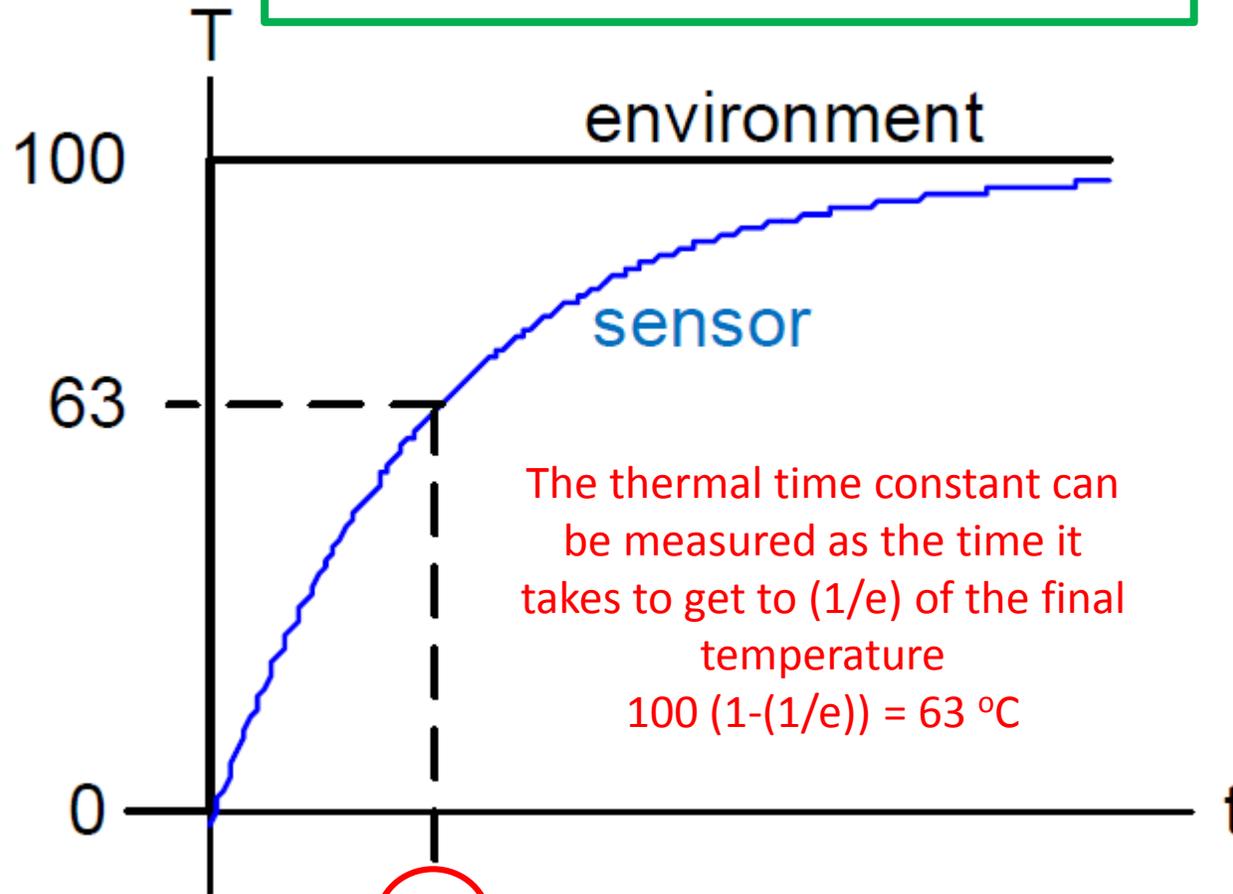
100 °C

Thermal System Step Response

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



0 °C



100 °C

Thermal System Step Response

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

<http://www.eng.hmc.edu/NewE80/PDFs/TemperatureMeasurementLecNotes.pdf>

<http://www.colorado.edu/MCEN/Measlab/background1storder.pdf>

$$\frac{T_{\text{sensor}}}{T_{\text{env}}}(j\omega) = \frac{1}{1 + j\omega\tau}$$

<http://www.eng.hmc.edu/NewE80/PDFs/TemperatureMeasurementLecNotes.pdf>

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

References

- Previous E80 Lectures and Lecture Notes
 - <http://www.eng.hmc.edu/NewE80/TemperatureLec.html>
- Thermocouples White Paper
 - <http://www.ohio.edu/people/bayless/seniorlab/thermocouple.pdf> (downloaded 02/04/2015)
- University of Cambridge Thermoelectric Materials for Thermocouples
 - <http://www.msm.cam.ac.uk/utc/thermocouple/pages/ThermocouplesOperatingPrinciples.html> (viewed 02/04/2015)
- National Instruments Temperature Measurements with Thermocouples: How-To Guide
 - http://www.technologyreview.com/sites/default/files/legacy/temperature_measurements_with_thermocouples.pdf (downloaded 02/04/2015)
- Vishay NTCLE100E3104JB0 Data Sheet
 - <http://www.eng.hmc.edu/NewE80/PDFs/VishayThermDataSheet.pdf> (downloaded on 02/04/2015)