Seebeck Voltages & Thermocouples

ASEN 2002 : Thermodynamics & Aerodynamics

Department of Aerospace Engineering Sciences

University of Colorado

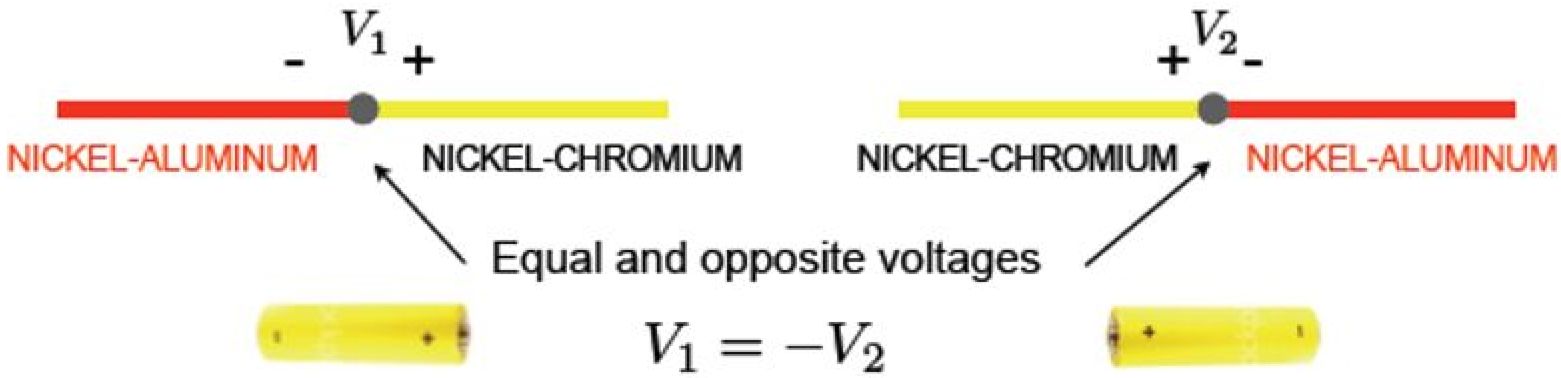
Seebeck Voltage

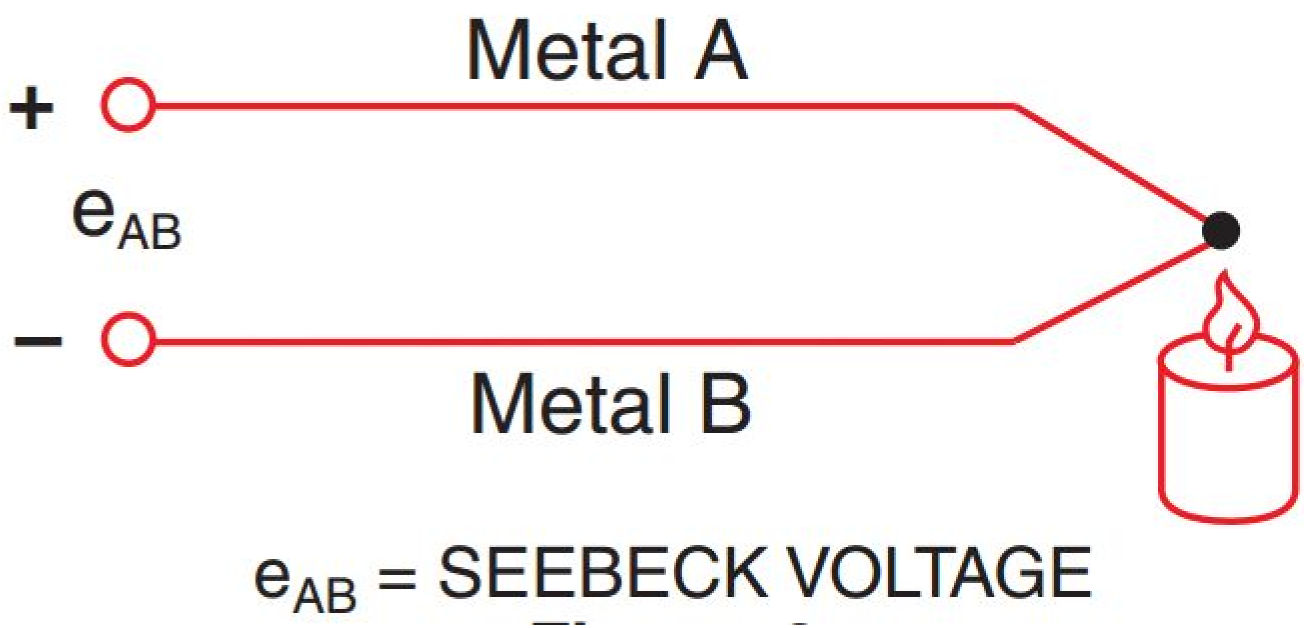
A temperature dependent voltage is formed at any junction between two metals. This is called a **Seebeck Voltage**, expressed as:

$$\underbrace{V}_{\text{Voltage generated}} = \underbrace{S}_{\text{Seebeck coefficient (different for different metals)}}\underbrace{T}_{\text{Temperature}}$$

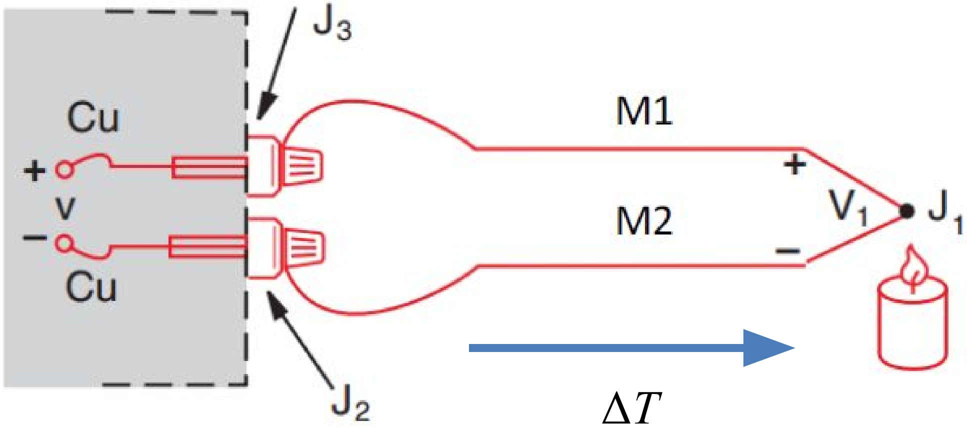
- Why does this happen?
  - Think about the properties of metals…

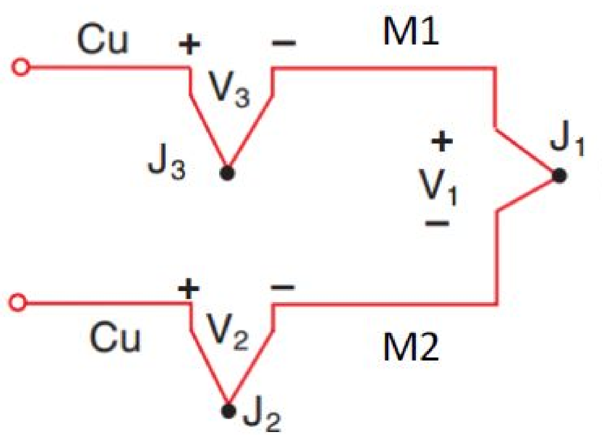
A thermocouple junction can be thought of like a battery, but instead of chemical processes causing the electromotive force to separate charge it is the temperature gradient across the junction of the two dissimilar metals.





Measurement Scheme

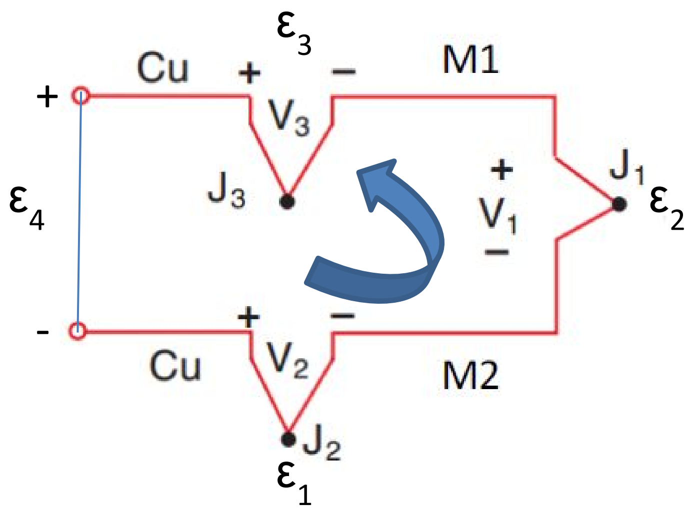




- Junctions 1, 2 and 3 are all producing an emf leading to a change in voltage across the junction with all temperatures are unknown. The types of metal at each junction and the direction of the temperature gradient determines the polarity

Apply Kirchoff's Law for Circuits

For the case with J1 of a higher temperature



- Loop Rule – the sum of the voltage changes around a closed path, or loop, in the circuit must add to zero

$$\sum \Delta V = 0$$

- For the chosen direction (let's pick counter clockwise starting from the lower terminal)
  - V=-ε , if direction of the loop crosses a battery from + to – (high to low potential)
  - V=+ε, if direction of the loop crosses a battery, from – to + (low to high potential)

$$\sum \Delta V = 0 \;\therefore\; \varepsilon_4 + \varepsilon_3 + {}_2 + {}_1 = 0$$

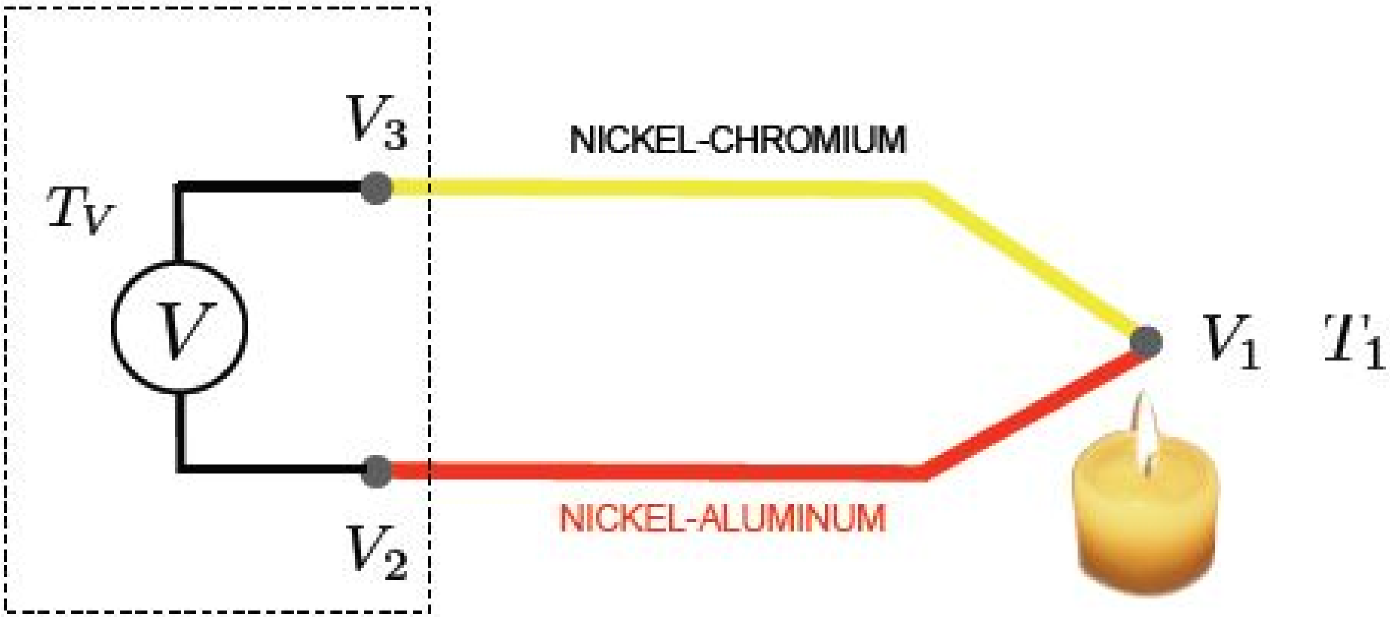
Applying Kirchoff's rule: $-\varepsilon_4 + \varepsilon_3 + \varepsilon_2 + (-\varepsilon_1) = 0$

$$V_3 + V_2 - V_1 = V_4$$

V_4 represents the multimeter measured voltage
$V_{1,2,3}$ represents emf's for each junction of dissimilar metals. Must know the types of metals, their Seebeck coefficients, and the temperature at each junction. If same dissimilar metals and same temperature at junction 2 and 3 then their voltages cancel out.

$$V_2 = V_4$$

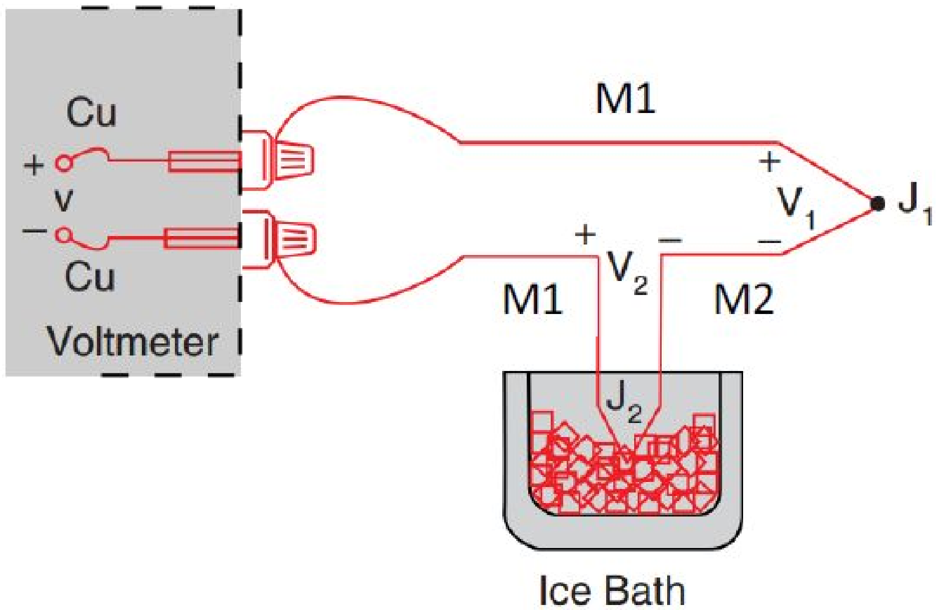
K-Type Thermocouple



Connections between the thermocouple and the voltmeter also count as thermocouple junctions!

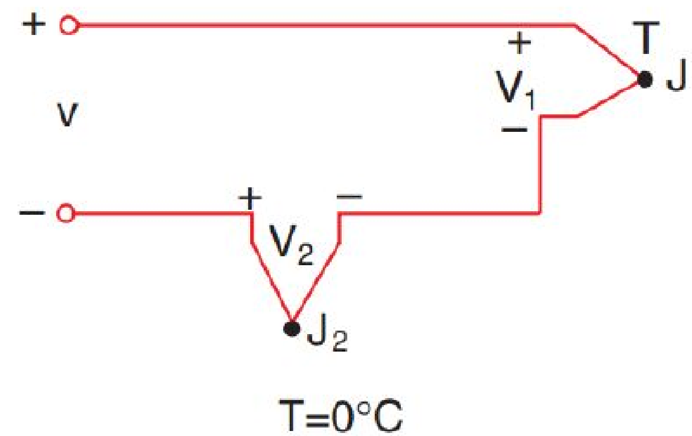
$$\begin{aligned}\Sigma V &= V_3 + V_2 + V_1 \\ &= \underline{S_3 T_V + S_2 T_V} + S_1 T_1\end{aligned}$$

Must account for two separate Seebeck coefficients!

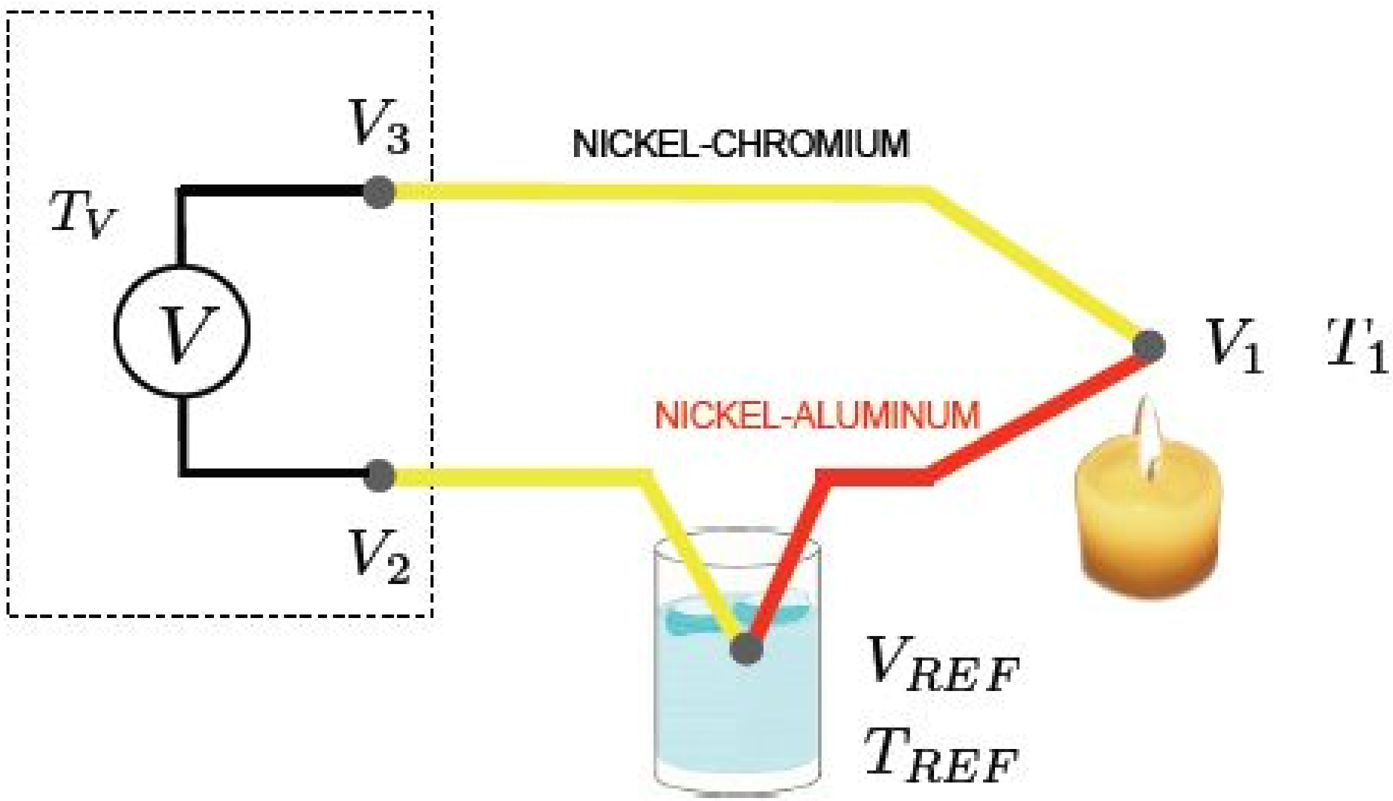


We use an ice bath or boiling water because their temperatures are *known*

The two Cu-M1 voltages cancel each other (opposite polarity), so we have two voltages with only one unknown temperature!



Thermocouple Pair



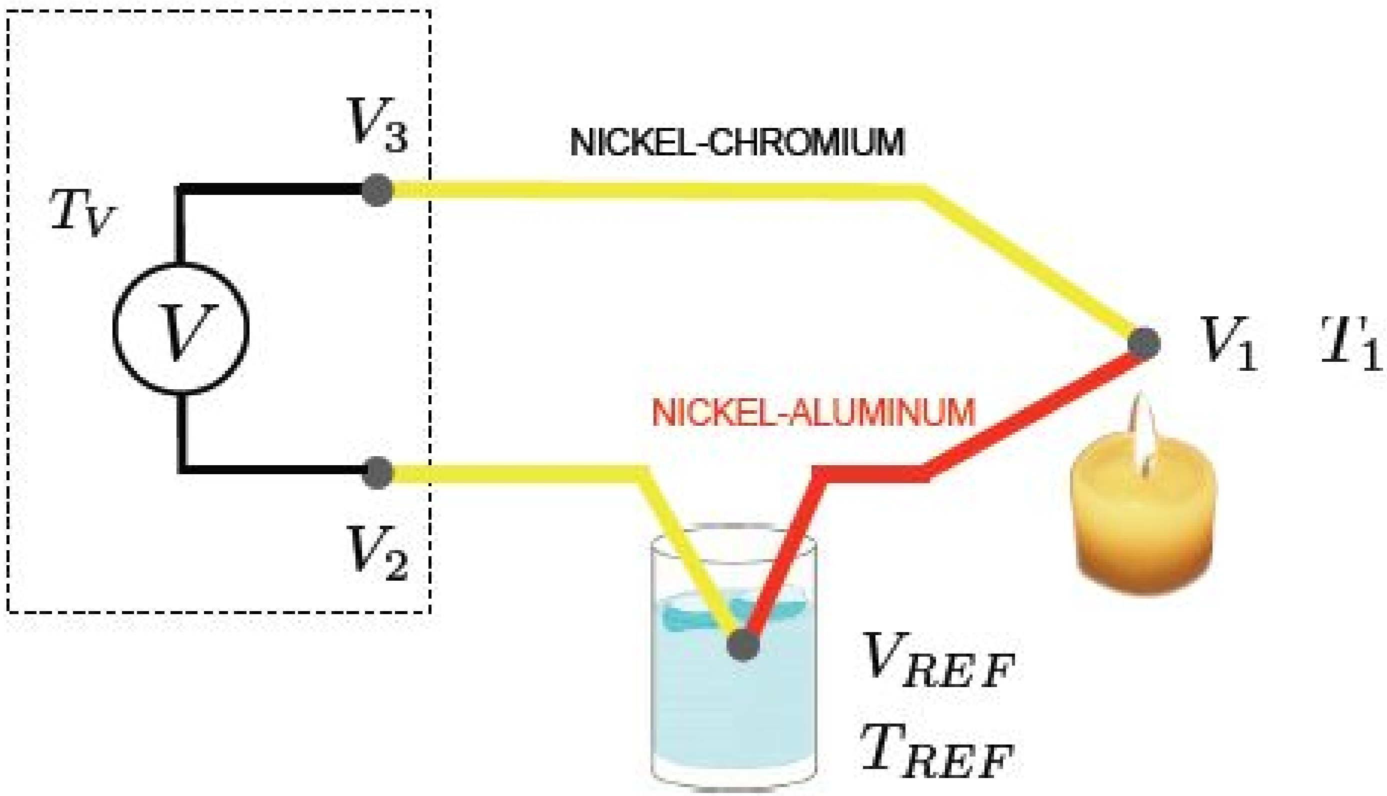
V_2 and *V_3* now equal and opposite, canceling out.

V_1 and *V_{REF}* have opposite polarity, but same Seebeck coefficient.

$$\Sigma V = \cancel{V_3 + V_2} + V_1 - V_{REF} = \boxed{S(T_1 - T_{REF})}$$

Only have to account for one Seebeck coefficient

Thermocouple Pair



You can compute Vref from the known temperature using the relations on the following slide.

Voltage-Temperature Relations

I. The Seebeck coefficient is nonlinear in temperature
   1. Thus the voltage temperature relationships must be approximated

   2. Example from National Instruments Tutorial on D2L
      A. Temperature to voltage (NI Table 2)

$$V(T) = c_0 + c_1 T + c_2 T^2 + \ldots + c_9 T^9 + 118.5976 e^{(-1.183432E-4)(T-126.9686)^2}$$

      B. Voltage to temperature (±0.05°C) (NI Table 1)

$$T(\mathrm{V}_{obj}) = a_0 + a_1 \mathrm{V}_{obj} + a_2 \mathrm{V}_{obj}^2 + \ldots + a_9 \mathrm{V}_{obj}^9$$

   3. Polynomial coefficients for these equations can be found from lookup tables

Error Summary

I. Consider systematic biases and statistical uncertainties in voltages –> ASEN2012

1. **Reference Temperatures**
   - A. For ice bath, T_{ref} = 0.0ºC and assume error in T_{ref} is negligible. Compute the voltage contribution for this temperature using the temperature-to-voltage relationship for K-type thermocouple
   - B. Tref for boiling water – how should we calculate it? (you decide and document in report)
     - A. Calculate based on atmospheric pressure (84.3 kPa)
     - B. Get temperature from earlier measurement using ice bath
   - C. Calculate error in temperature estimate of reference bath – either by uncertainty in pressure or uncertainty in measurement

2. **Reference Voltages and error**
   - A. Ice bath Vref computed from ice bath Tref using NI Table 1
   - B. Ice bath Vref uncertainty assumed negligible
   - C. Boiling water Vref from boiling water Tref using NI Table 1
   - D. Boiling water Vref uncertainty determined by adding and subtracting an uncertainty to the Tref value and compute the higher and lower voltage values using the NI Table 1

Error Summary

I. Consider systematic biases and statistical uncertainties in voltages –> ASEN2012

3. **Object Voltage Estimate**
   A. Account for reference voltage

$$V_{object} = V_{measured} + V_{ref}$$

   B. Calculate the expected voltmeter error using the formula provided in the 34461A multimeter handout and relate that to the error observed in reading the voltage from the display.
   C. Use the measurement with both thermocouples in the ice bath to estimate a systematic uncertainty present in the experiment (ideally this result should approach the uncertainty of the multimeter). If this value exceeds the multimeter uncertainty, it will represent a voltage bias introduced by the experiment and may need to be removed for a more accurate result
   D. Account for any systematic biases identified in ice bath / ice bath measurements

4. **Object Voltage Error (standard deviation)**

$$V_{object} = V_{measured} + V_{ref} + V_{systematicbias}$$

   A. Estimate uncertainty in measured voltage by observing the digital display and assigning the object's voltage uncertainty to the least significant digit on the display (a range value for the first right-most digit value that is flipping, for example maybe you observe a +- 10 μV flipping).
   B. Assuming each voltage estimate (measured, reference, and systematic bias) has an error and assuming they are all independent, random errors then the total error for the object voltage is a combination of errors from each voltage value, "summed in quadrature"
   C. Decide on what errors to include in your assessment (may need to revisit as you may not recognize errors until evaluating your final temperature results).

$$\delta V_{object} = \sqrt{\sigma^2_{Vmeasured} + \sigma^2_{vref} + \sigma^2_{systembias}}$$

II. Body Voltage Estimates

5. **Mean Voltage**
   A. When computing body temperature from 10 measurements, compute the mean value assuming the errors from the "n" measurements are all similar

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

6. **Error of the Mean**
   A. Compute the error of the mean by computing the sample Standard Deviation and divide by square root of n

$$\sigma_{\overline{x}} = \frac{\sigma_{sd}}{\sqrt{n}}$$

III. Temperature Retrieval

7. **Temperatures and Errors**

A. Determine temperature from voltage estimate using NI Table 1

B. Determine error in temperature by adding and subtracting the object's voltage error to the value of the object's voltage,

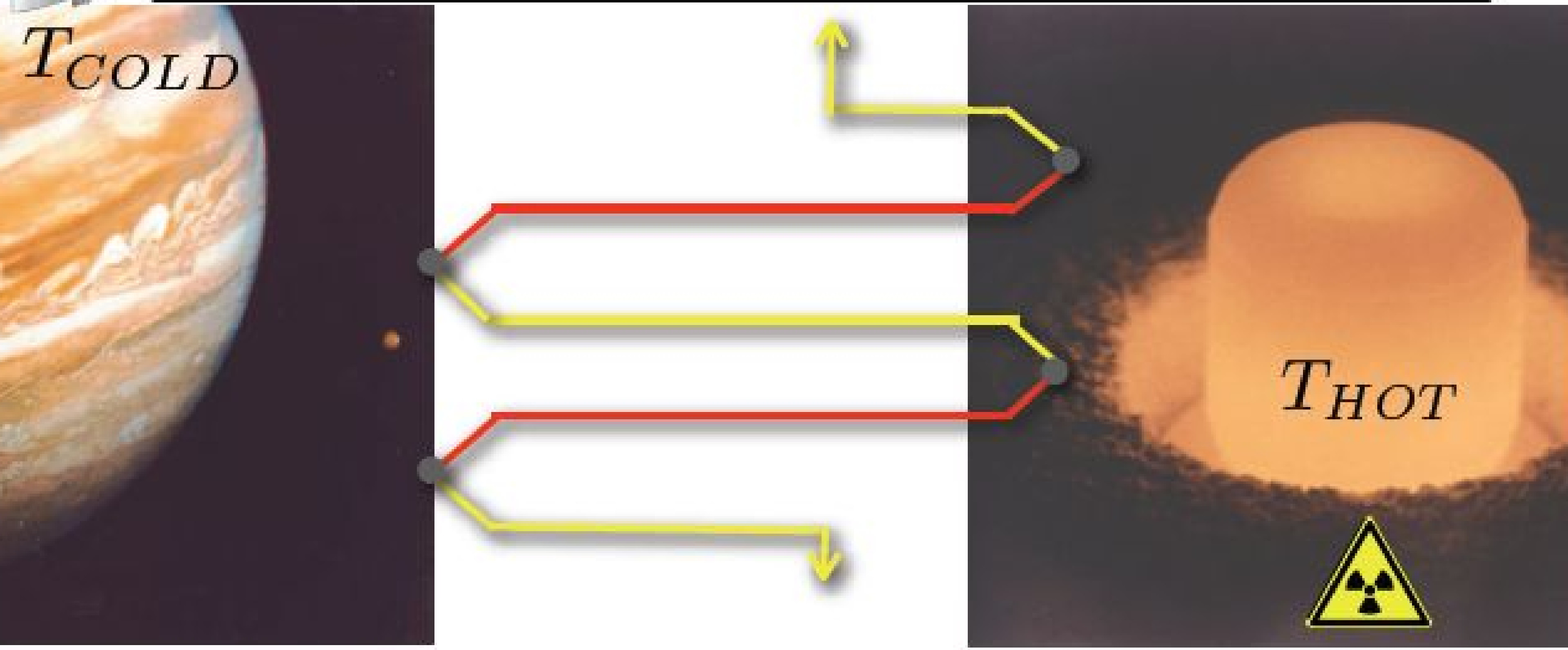
$$V^{+}_{object} = V_{object} + \delta V_{object} \qquad V^{-}_{object} = V_{object} - \delta V_{object}$$

and plug these values into the voltage-to-temperature relationship to get your temperature range

8. **Repeat for all Required Measurements**

9. **How precise is your thermocouple and methods used in determining temperature of an object?**

Thermopile



Total voltage is:

$$\Sigma V = 2S(T_{HOT} - T_{COLD})$$

Or, for *n* pairs:

$$\Sigma V = nS(T_{HOT} - T_{COLD})$$

Thus, a temperature gradient can be used to generate electricity!