The University of Jordan
School of Engineering
Electrical Engineering Department

EE 449
Instrumentation and Control Lab

EXPERIMENT 10
BASICS OF THERMOCOUPLE

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BASICS OF THERMOCOUPLE

OBJECTIVES

1. To understand the basic principles behind thermocouple operations and know their types.
2. To understand the relationship between the measured temperature and the output voltage for some popular thermocouple types.
3. To measure the time constant of the thermocouple response when measuring temperature.

DISCUSSION

There are several types of temperature sensor in use these days. Popular ones include: glass thermometers (or liquid-in-glass thermometers), thermistors, resistance temperature detectors (RTD), and thermocouples. There are other types as well. Each type offers a unique set of advantages for specific applications.

Glass thermometers

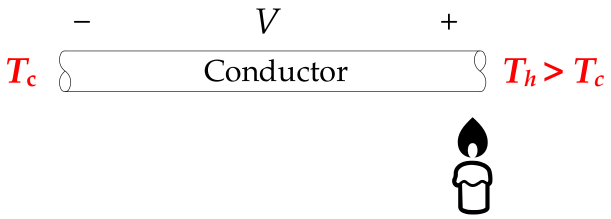
Thermistors

Resistance temperature detectors (RTD)

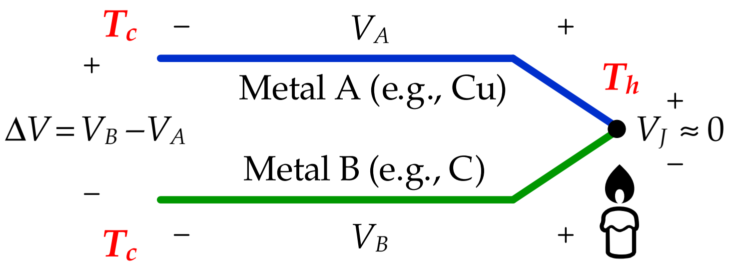
Thermocouples

Thermocouples are widely used in several industrial and scientific applications due to their durability, relatively low price, versatility, wide temperature range, and long-term stability.

The underlying principle behind the operation of a thermocouple is known as the *Seebeck effect* (or thermoelectric electromotive force). The Seebeck effect describes how a temperature gradient across a conductor (metal wire) can produce a voltage gradient (i.e., voltage difference or, equivalently, electromotive force (emf)) across the length of the wire. The amount of resulting voltage gradient is dependent on the temperature difference and the material from which the wire is made. An example is shown below where the voltage difference V has developed across the conductor due to one of its ends being at a higher temperature T_h compared to the other cold end, which is at temperature T_c.



A thermocouple is built using two dissimilar metals (wires) soldered or welded together at one end to form an electrical junction (see figure below). For example, in a J type thermocouple, one wire is iron, and the other is made of a copper-nickel alloy (constantan). The junction is called the *measurement junction* or the *hot junction*. When this junction temperature, T_h, is different than the temperature of the other ends of the wires (which can be at room temperature $T_c = T_{room}$, for example), a voltage gradient develops across each conductor, dependent on that temperature difference and the material from which the wire is made. Since the conductors are made of different materials, the voltage V_A (across wire A) will be different than voltage V_B (across wire B). This results in an open-circuit voltage difference between the two ends of the conductors, equal to $\Delta V = V_B - V_A$. If we maintain the same cold temperature T_c for the free ends of the wires, this voltage is proportional to the temperature difference $\Delta T = T_h - T_c$, and is typically in the millivolt range.



A common misconception among engineers is that the Seebeck voltage results at the junction of the two dissimilar metals, and that voltage increases when heating the junction. This is not the case. The junction voltage itself V_J is almost zero volts[1]. However, the Seebeck voltage develops across the wires due to the temperature gradient, and depends on the temperature difference $\Delta T = T_h - T_c$, not just T_h of the hot junction. For example, if wire A is made of copper, then the resulting voltage V_A (across wire A) is small for a certain temperature difference ΔT, while if wire B is made of constantan, then the resulting voltage V_B is high for the same temperature difference ΔT, resulting in a measurable voltage difference $\Delta V = V_B - V_A$ that is related to ΔT.

Remember that the hot junction provides an electrical connection between the dissimilar metals and is placed where the temperature needs to be measured. However, virtually no voltage develops right at the junction.

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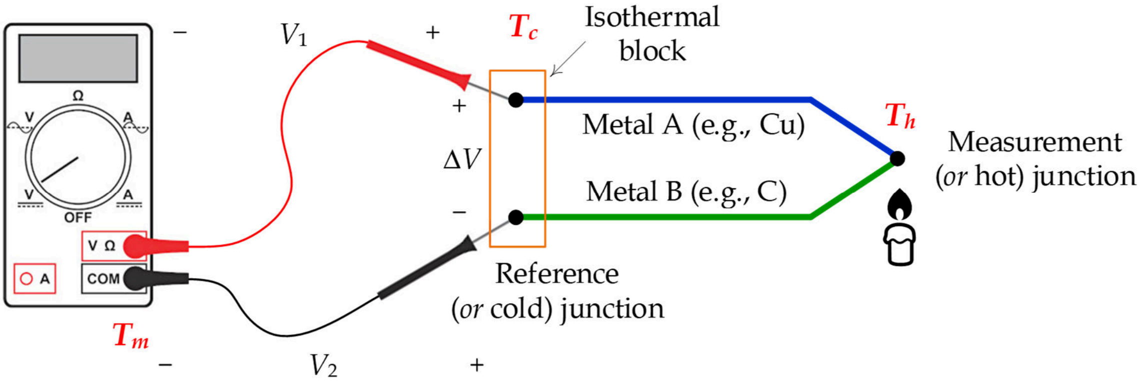
[1] Junction voltage should not be confused with the small electrical contact resistance that exists for all wires connected together (i.e., all electrical junctions). A small voltage drop develops across this resistance only if a current flows through it. This is different and independent from the Seebeck voltage.

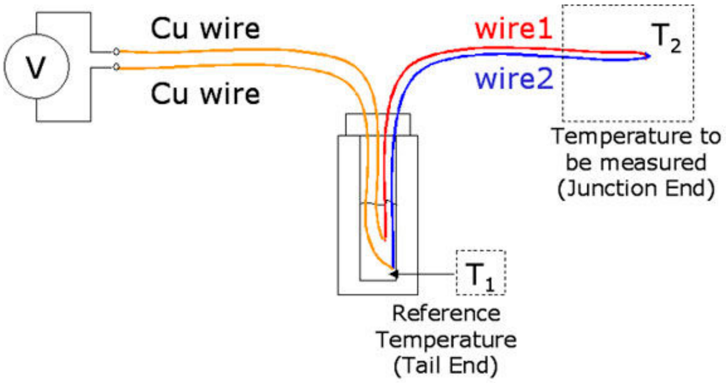
To ensure we get the same T_c at the free ends of both wires, an isothermal block (which is made of a heat conducting material, that is also an electrical insulator) is commonly used to keep the free ends of the thermocouple at the same temperature. This is typically called the *reference junction* (or the *cold junction*), even though it is not an actual electrical junction (i.e., it is not a short circuit).

Maintaining the same cold temperature T_c at both ends of the two wires of the thermocouple is important for proper measurement of the resulting voltage difference ΔV using a voltmeter. This is illustrated in the figure below. Notice that the voltemter has two test leads that need to be connected to the thermocouple, and those leads made of copper (a conductor). If there is a temprature differnece between the reference junction temprature T_c and the meter temprature T_m, Seebeck voltages V_1 and V_2 will develop across the test leads themselves (due to the temprature difference $T_c - T_m$). However, since we made sure that the termprature of both ends of the thermocouple are at the same temprature T_c, while the meter is at temprature T_m, and since both test leads are made of the same copper material, then $V_1 = V_2$, and they cancel each other at the voltmeter, since the reading the voltmeter displays is:

$$V_m = -V_1 + \Delta V + V_2 = \Delta V$$



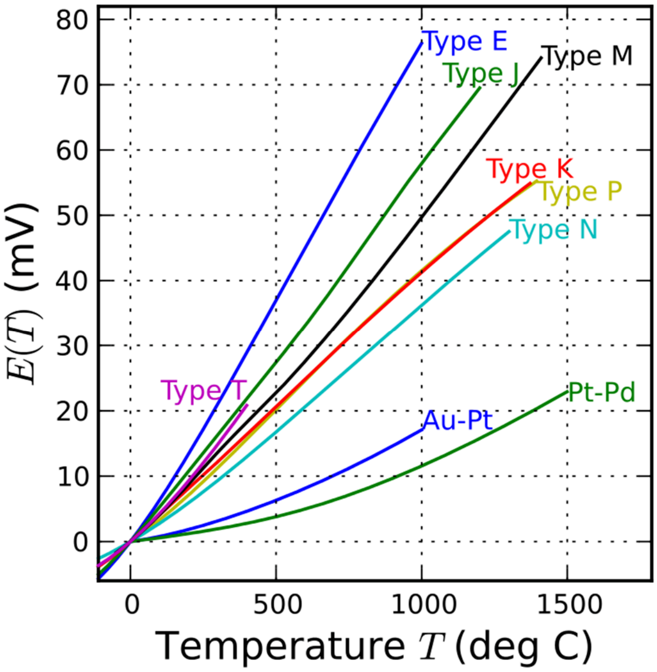
Note that a thermocouple measures the temperature difference between the measurement and reference junctions, not the absolute temperature at the hot junction. The open-circuit voltage at the reference junction is proportional to the *temperature difference* between the two junctions. That is why sometimes the reference junctions is placed at a well-known temperature (for example in an ice path at 0 °C) in order to calibrate the thermocouple (see figure below). Sometimes an extra junction is also introduced and placed inside the ice path. You can read about this calibration process by searching the web if you are interested.



Thermocouples are available in various types, each suited for specific temperature ranges, chemical environments, and industry requirements. Each type is identified by a letter designation—such as Types K, J, T, E, R, S, B, N, etc—and exhibits distinct characteristics including accuracy, temperature range, signal stability, oxidation resistance, and durability.

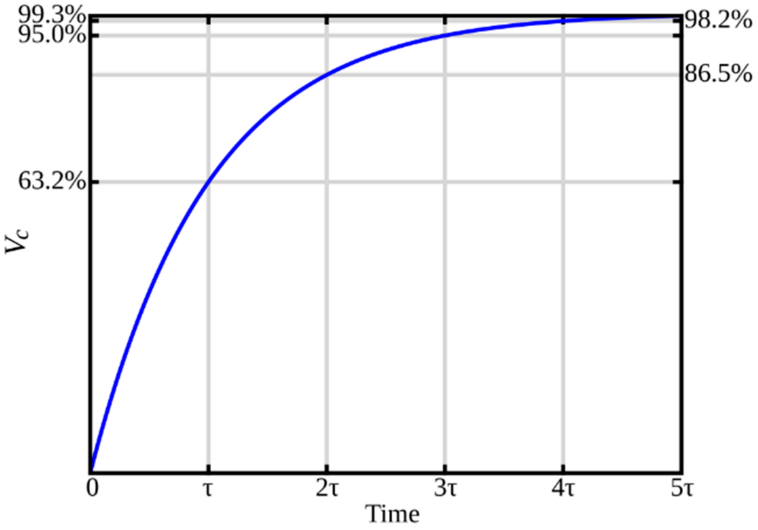
Type	Materials	Details
K	Nickel-Chromium (Chromel) & Nickel-Aluminum (Alumel)	Temperature range spans -200°C to 1260°C. Reliable in general purpose and industrial temperature measurement. Widely used due to cost-effectiveness, corrosion resistance in oxidizing atmospheres, and good signal stability.
J	Iron & Copper-Nickel (Constantan)	Suitable for a variety of atmospheres—oxidizing, vacuum, inert, and reducing. Temperature span (0°C to 760°C) and affordability made them popular in plastics processes, process heating, and temperature control systems.
T	Copper & Copper-Nickel (Constantan)	Excellent for low-temperature and cryogenic applications. Their range (-200°C to 370°C) allows precise control in refrigeration, biomedical, and chemical storage environments.
E	Nickel-Chromium (Chromel) & Copper-Nickel (Constantan)	Wide temperature range (-200°C to 870°C) and strong EMF versus temperature characteristics. Excellent for sub-zero and cryogenic temperature readings, as well as mid-range industrial heating.
R	Platinum (13% Rhodium) & Platinum	Temperature range of -50°C to 1450°C. Resilient. Exceptional accuracy and higher rhodium content makes them favorite for harsh process environments, such as sulfur recovery, glass manufacturing, and pharmaceutical sterilization.
S	Platinum (10% Rhodium) & Platinum	Employed in high-temperature environments within medical device sterilization, and pharmaceutical industries, as well as in precision laboratory research. Maximum temperature of 1450°C and high measurement stability over time.
B	Platinum (30% Rhodium) & Platinum (6% Rhodium)	Used in demanding high-temperature applications, offering high temperature tolerance. Stable and accurate up to 1700°C.
N	Nickel-Chromium-Silicon (Nicrosil) & Nickel-Silicon-Magnesium (Nisil)	Offers stability and longevity throughout their wide operating temperature range of 0°C to 1260°C. Their resistance to oxidation, green rot, and hysteresis makes them popular in chemical processing, refining, and petrochemical industry.

The figure below shows the relationship between the output voltage versus junction temperature (difference) for various types of thermocouples. You can see that the curves are not perfectly linear, but some can be approximated as such, especially for a small region of their wide temperature range.



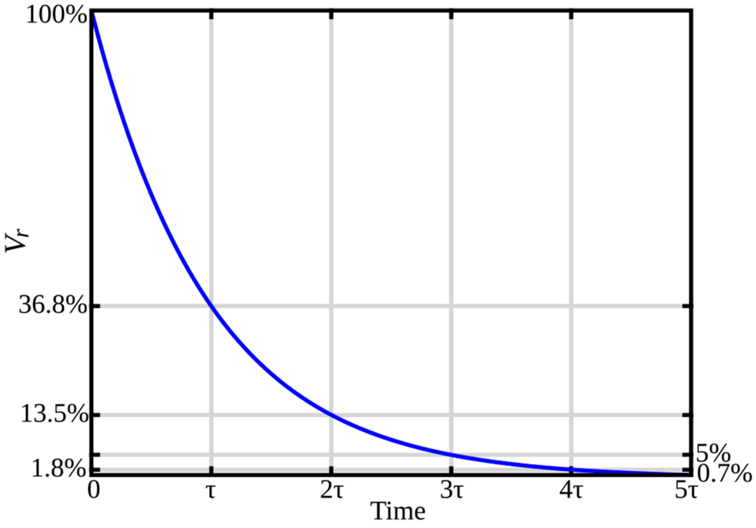
Just like any other electrical system, a thermocouple does not respond instantaneously to a unit-step change in junction temperature difference. Rather, the output voltage of the thermocouple requires some time to settle. If we approximate the behavior of the thermocouple to a first-order system, you will notice an increasing or decaying exponential behavior of the output voltage. For example, if you suddenly move the thermocouple's measurement junction from a cold environment to a hot environment, the voltage will rise exponentially as shown below, requiring one time constant, τ, to reach 63.2% of the final steady-state value V_s. This behavior can be expressed mathematically using the formula:

$$v(t) = V_s\left(1 - e^{-t/\tau}\right)$$



On the other hand, if you suddenly move the thermocouple's measurement junction from a hot environment to a cold environment, the voltage will drop exponentially as shown below, requiring one time constant, τ, to reach 36.8% of the starting value V_0. This behavior can be expressed mathematically using the equation:

$$v(t) = V_0\, e^{-t/\tau}$$



PROCEDURE A: VOLTAGE VERSUS TEMPERATURE CURVE

1. Connect the provided K type thermocouple terminals to the first digital mutlimeter. Set the mutlimeter to measure voltage, and select the 200 mV range. This is now called Voltmeter K.

2. Record the voltage reading when the K type thermocouple is reading your current ambient (room) temperature.

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3. Connect the provided J type thermocouple terminals to the second digital mutlimeter. Set the mutlimeter to measure voltage, and select the 200 mV range. This is now Voltmeter J.

4. Record the voltage reading when the J type thermocouple is reading your current ambient (room) temperature.

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5. Prepare a mug of cold water from the tap.

6. Pour some tap water in the provided kettle and boil the water. Make sure it is boiling before you switch the kettle OFF. Now pour that water into another mug. Be careful as boiling water can scald your skin.

7. Place the provided glass thermometer, along with the K type thermocouple, and the J type thermocouple all in the same hot water mug so they measure about the same temperature, and let the water cool down naturally.

8. As the water temperature starts dropping, keep monitoring the glass thermometer and the voltmeters' readings. Every time the temperature drops one °C in the range from 80°C to 30°C, take a reading of the glass thermometer and both Voltmeter K and Voltmeter J, and record the values in the following table. One student can monitor the glass thermometer, one can record Voltmeter K readings, and another student can record Voltmeter J readings. This team effort will speed things up and result in more accurate readings.

IMPORTANT: Be careful. **Avoid direct contact** with the hot steam, especially against your face and eyes.

9. If you notice that the change in temperature is very slow as you reach closer to room temperature, you can speed things up further by pouring some of the cold water from the cold-water mug into the hot-water mug. Wait for 5 seconds for the temperature to settle and take the reading.

Glass thermometer reading	K type thermocouple voltage reading (mV)	J type thermocouple voltage reading (mV)
80 °C		
79 °C		
78 °C		
77 °C		
76 °C		
75 °C		
74 °C		
73 °C		
72 °C		
71 °C		
70 °C		
69 °C		
68 °C		
67 °C		
66 °C		
65 °C		
64 °C		
63 °C		
62 °C		
61 °C		
60 °C		
59 °C		
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46 °C		
45 °C		
44 °C		
43 °C		
42 °C		
41 °C		
40 °C		
39 °C		
38 °C		
37 °C		
36 °C		
35 °C		
34 °C		
33 °C		
32 °C		
31 °C		
30 °C		

10. Plot (**by hand**) the voltage values for both the K type thermocouple and J type thermocouple (on the same graph using different colors) versus the glass thermometer temperature readings. Use a scatter diagram for each.

11. Use MATLAB or Excel to calculate the best line fit for each of the two curves above, draw that fit on the above diagram, and write down the mathematical expressions below.

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12. Did you get a graph similar to the one shown in page 6, or a different one. Explain your findings.

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PROCEDURE B: MEASURING THE TIME CONSTANT

1. Keep the K type and J type thermocouples connected to their respective voltmeters. You need to perform this procedure for the K type thermocouple first, then repeat it for the J type thermocouple.

2. Prepare a mug of cold water from the tap.

3. Pour some tap water in the provided kettle and boil the water. Make sure it is boiling before you switch the kettle OFF. Now pour that water into another mug. Be careful as boiling water can scald your skin.

4. Let the water cool down for about **5 minutes** and do not place anything in the hot-water mug just yet.

IMPORTANT: Be careful. **Avoid direct contact** with the hot steam, especially against your face and eyes.

5. Place the K type thermocouple in the cold-water mug. Wait for the voltage to settle. Record the steady-state voltage value you read from Voltmeter K.

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6. Use a stop watch for the following step to get accurate times. If one is not provided to you, use the one on your phone.

7. Quickly (but *carefully*) move the K type thermocouple from the cold-water mug immediately to the hot-water mug and keep it there. Simultaneously start the stop watch. Now record the voltage values you see on Voltmeter K every 2 seconds in the table below. One student can monitor the stop watch, another one can move the thermocouple and a third student can record Voltmeter K readings. Alternatively, you can use your phone camera to record a video of Voltmeter K readings for about half a minute after moving the thermocouple to the hot-water mug. Then you can re-watch the video to record the values in the following table every 2 second increments.

Time (seconds)	K type thermocouple voltage reading (mV)
0 sec	
2 sec	
4 sec	
6 sec	
8 sec	
10 sec	
12 sec	
14 sec	
16 sec	
18 sec	
20 sec	
22 sec	
24 sec	
26 sec	
28 sec	
30 sec	

8. Plot (**by hand**) the voltage values for the K type thermocouple versus time (in seconds).

9. Identify the time constant, τ, for the thermocouple on the above graph, and write its value below.

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10. Repeat the same procedure for the J type thermocouple by placing it in the cold-water mug, let the voltage settle, and then moving it suddenly to the hot-water mug. You can switch off Voltmeter K now to avoid mistakes in reading the voltage. Fill the table below from Voltmeter J readings.

Time (seconds)	J type thermocouple voltage reading (mV)
0 sec	
2 sec	
4 sec	
6 sec	
8 sec	
10 sec	
12 sec	
14 sec	
16 sec	
18 sec	
20 sec	
22 sec	
24 sec	
26 sec	
28 sec	
30 sec	

11. Plot (**by hand**) the voltage values for the J type thermocouple versus time (in seconds).

12. Identify the time constant, τ, for the thermocouple on the above graph, and write its value below.

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Q. Explain below the advantages and disadvantages of placing the cold junction in iced water (see figure below) compared to just using an isothermal block for the cold junction.

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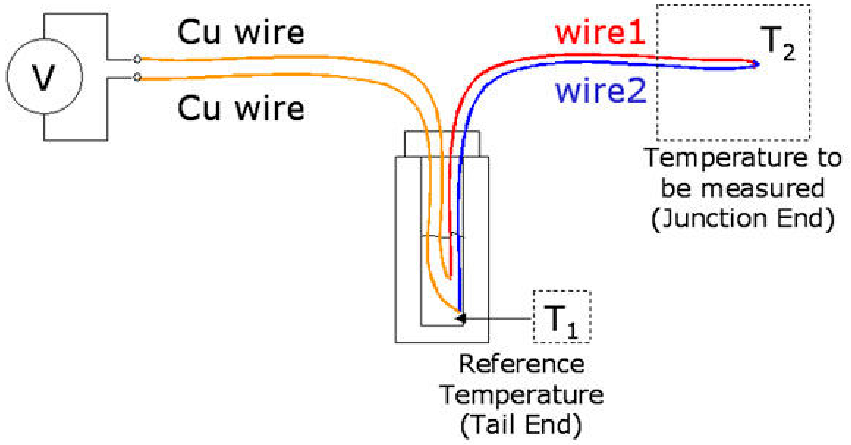

** **End** **