Thermocouples

by Kenneth A. Kuhn
Feb. 24, 2013

A thermocouple consists of two dissimilar conductors joined at one end and produces a voltage across the open ends in proportion to the difference in temperature between the joined end and the open end. A thermocouple does not measure absolute temperature. It only measures temperature difference. Thermocouples can accurately measure temperatures from cryogenic to over 1,000 C.

The Seebeck Effect

Although it is impossible to directly measure, when one end of a conductor is at a different temperature than the opposite end there is a non-uniform distribution of free charges (electrons in many cases but could be positive ions instead). The non-uniform distribution is known as the Seebeck effect. That non-uniformity results in a voltage gradient across the length of the conductor as shown in Figure 1.

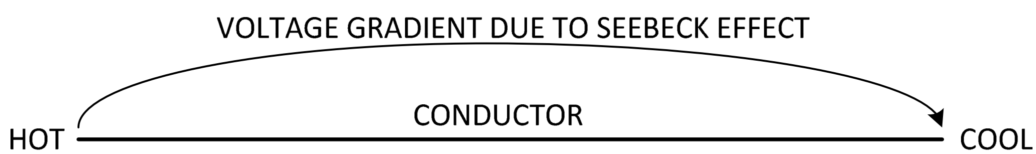

Figure 1: End to end thermal emf

The magnitude and polarity of the effect is called the Seebeck coefficient. If free electrons tend to cluster towards the hot end then the cool end is more positive and the Seebeck coefficient is positive. In some materials the free electrons cluster towards the cool end and the Seebeck coefficient is negative.

That voltage can be calculated by multiplying the temperature difference by the Seebeck coefficient for the conductor. As an example, the Seebeck coefficient for copper is around 1.8 uV/C. If the hot end of the conductor were at 100 C and the cool end were at 25 C then the voltage across the wire would be (100 – 25)*1.8uV = 135 uV. The Seebeck coefficient varies a bit with temperature so this calculation is only approximate but illustrates the point.

It might be thought that if another conductor were connected to the distal end of the conductor that the voltage difference could be measured. That always fails because the second conductor will also have the identical voltage across it and the net voltage will be zero as shown in Figure 2.

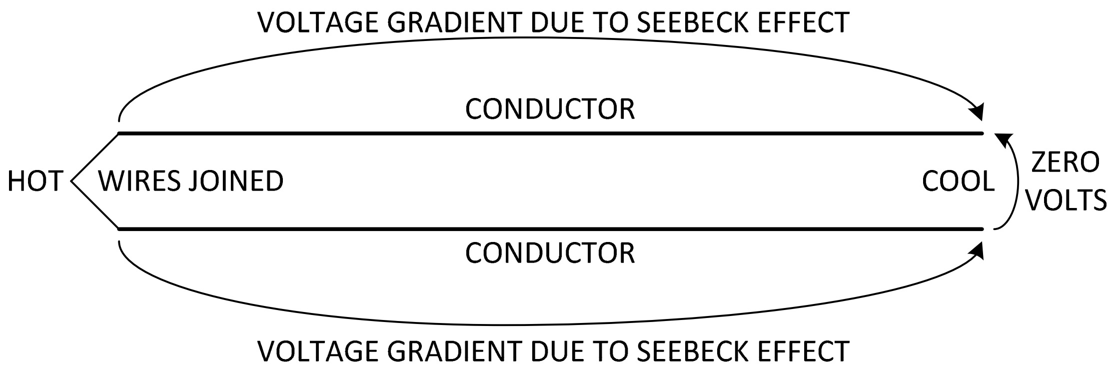

Figure 2: Attempting to measure voltage gradient using two wires fails

If instead we use conductors made of different materials and with different Seebeck coefficients then there will be a net voltage to measure as a result of the temperature difference. This is how a thermocouple works as shown in Figure 3.

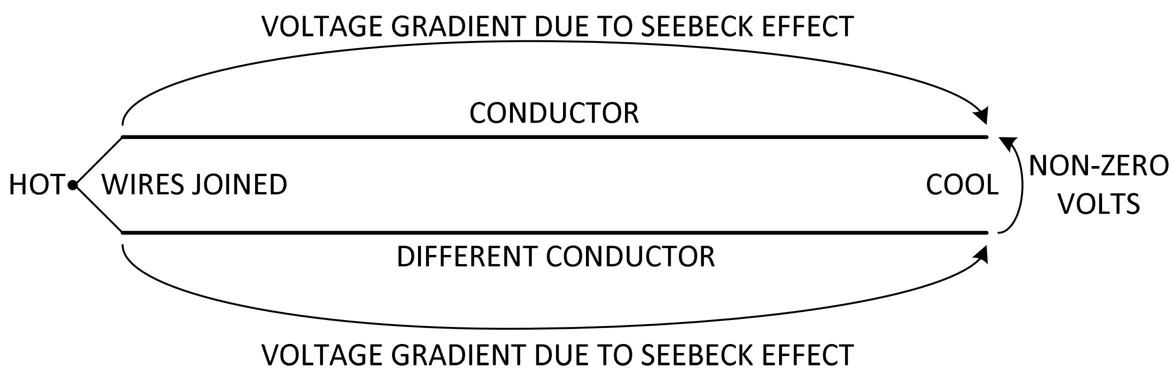

Figure 3: Net thermal voltage due to conductors with different Seebeck coefficients

Figure 4 shows a typical thermocouple. The two wires are joined by spot welding. As an example the upper conductor is iron with a Seebeck coefficient of 18 uV/C and the lower conductor is constantan with a Seebeck coefficient of -33 uV/C – this is a type J thermocouple as discussed in the next section. The net thermal voltage will be 18 – -33 = 51 uV/C – a value known as the thermocouple constant.

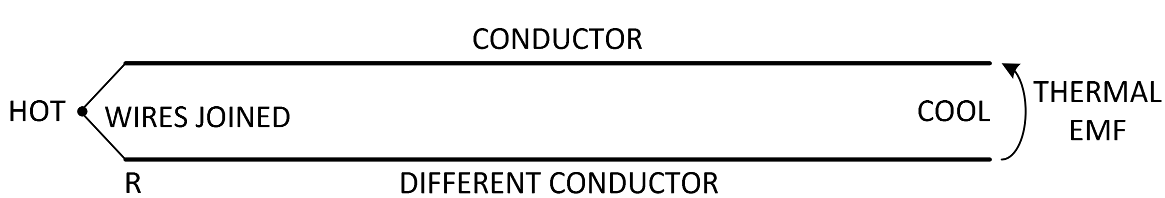

Figure 4: Basic thermocouple comprised of two different conductors

The Seebeck coefficients vary a bit with temperature so the thermocouple constant is also temperature dependent. That temperature dependency means that the thermocouple response is not linear over a wide range but is often sufficiently linear over a medium range. Linearization can be performed electronically or in a computer if necessary.

A common myth concerning thermocouples is that the voltage is directly across the junction. That is false as the voltage at that location is always exactly zero unless there is a temperature gradient across the junction – not the typical situation. The thermocouple voltage is a result of the temperature difference across the length of the two conductors. However, it turns out that all our math works perfectly and our descriptive language is much simpler if we think of the voltage as being across the junction. Even though our usage is totally wrong compared to the actual physics we still obtain the correct result. The discussion and calculation examples will utilize this.

Thermocouple types

Thermocouples are specified by letter type designation. The insulation on the wires is color coded and the most common standard used in the United States is ANSI which always uses red for the negative lead – be sure you grasp that or you will connect thermocouples backwards. The other lead identifies the type. The first metal listed is the positive lead. Some common types are shown below. Type K is the preferred type for general purpose use. Other types such as B, C, M, N, R, and S have special features that make them useful at either cryogenic temperatures or very high temperatures. The thermocouple constant (uV/C) shown is typically but varies with temperature.

Type	Colors	Constant	Metals
J	White-red	51uV/C	Iron-Constantan
K	Yellow-red	40uV/c	Chromel-Alumel
T	Blue-red	43uV/C	Chromel-Constantan
E	Violet-red	68uV/C	Copper-Constantan

Thermocouple algebra

It is impossible to have only a single thermocouple in a system. There are always at least two or more – the real thermocouple of interest plus what are known as parasitic thermocouples formed when we make connections to the thermocouple of interest. We don’t want those thermocouples but they will exist when we connect dissimilar conductors.

Thermocouple algebra involves adding up the effects of the thermocouple of interest plus all parasitic thermocouples in a system to determine the net thermal voltage. We assign a unique number to each different conductor type as shown in Figure 5. In that example the violet (1) and red (2) conductors are of an actual thermocouple of interest. The green (3) is taken to be the copper wires used to connect the thermocouple to the processing electronics. Note that a pair of parasitic thermocouples is formed at the connection of the copper wires to the thermocouple wires. That is always the case and it is important that those two thermocouples be at the same temperature as shown. A temperature difference will cause the measured voltage to be in error and it will be impossible to determine the true temperature of the measurement thermocouple.

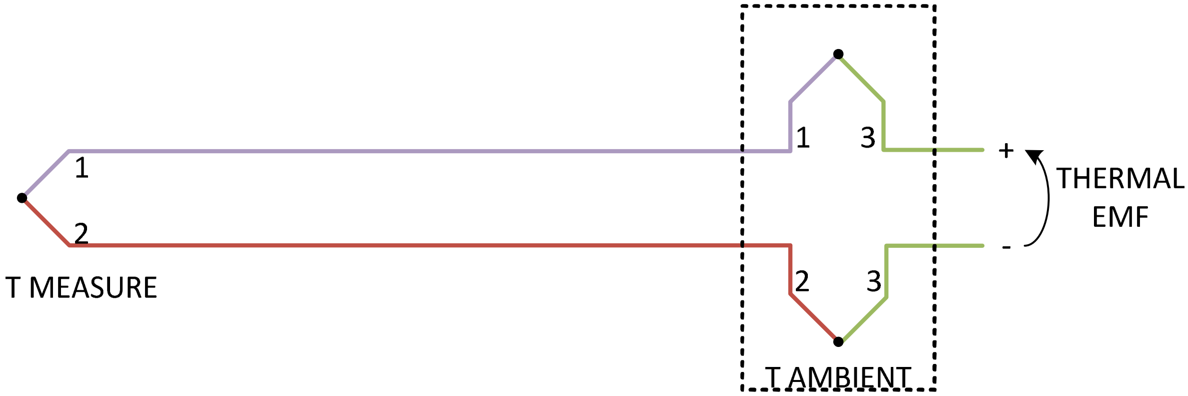

Figure 5: Thermocouple example

To perform thermocouple algebra we conveniently utilize the myth about thermocouple voltages being across the junction as discussed previously. We also utilize a technically wrong assumption that that voltage is related to absolute temperature. Using myths and wrong assumptions then how can we possibly calculate the correct result? This is one of those rare cases where it all works out. It is not magic. The result will be proportional to the actual temperature difference which is a true fact. Absolute temperatures become true relative in the final result.

The concept is to write the equation for each mythical thermocouple voltage across each junction responding to the absolute temperature at that point – $T*K_{AB}$ where K_{AB} is the thermocouple constant for the combination of metals 'A' and 'B'. Then we sum the voltages around the loop to obtain the net thermal emf voltage, V. We will use T_M for the temperature measurement thermocouple and T_A for the temperature of the two ambient thermocouples.

$V = T_A*K_{23} + T_M*K_{12} + T_A*K_{31}$ Summing voltages around the loop (Figure 5)

$V = T_M*K_{12} + T_A*(K_{23} + K_{31})$ Combining terms and putting T_M first

Since K_{12} is an actual thermocouple then we know what that factor is from the data sheet. However, we rarely know what K_{23} and K_{31} are as those two thermocouples are formed by our connections. It would seem that we can't continue because we are stuck with two unknowns. However, with a little thought the unknown thermocouple constants can be transformed into the known constant as shown in Figure 6.

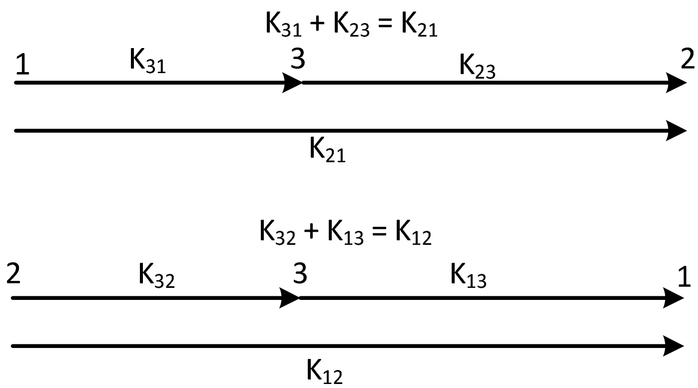

Figure 6: Transforming parasitic thermocouple constants into known constant

That process works only if both of the connection thermocouples are at the same temperature. That is why we make effort to insure that those two junctions are isothermal – at the same temperature. Now we can continue with the algebra.

$V = T_M{*}K_{12} + T_A{*}K_{21}$	Merging ambient thermocouples
$V = T_M{*}K_{12} - T_A{*}K_{12}$	Changing sign to make a single K_{12}
$V = (T_M - T_A){*}K_{12}$	Final result

Note that the final result is proportional to the temperature difference between the measurement point and the ambient temperature. That is true to the physics of thermocouples. As an example, say T_M is at 100 C and T_A is at 25 C and we are using a type K thermocouple with a constant of 40 uV/C. The thermal emf voltage will be (100 – 25)*40uV = 3.0 mV. If T_M were 10 C then the thermal emf voltage would be (10 – 25)* 40 uV = -0.6 mV.

Eliminating T_A

Our interest is the temperature of the measurement point, T_M. We need some way to eliminate T_A from the net result. One method used many years ago prior to modern electronics is shown in Figure 7. The concept is to connect a second thermocouple in series opposing to the measurement thermocouple and locate that second thermocouple in an ice water (pure) bath which by the laws of physics holds a steady temperature of 0 C. The parasitic ambient thermocouples are the same type and in series opposing so they cancel provided they are isothermal. No thermocouple is formed at the connection of the two (red) thermocouple wires because each wire is the same material.

Thermocouples

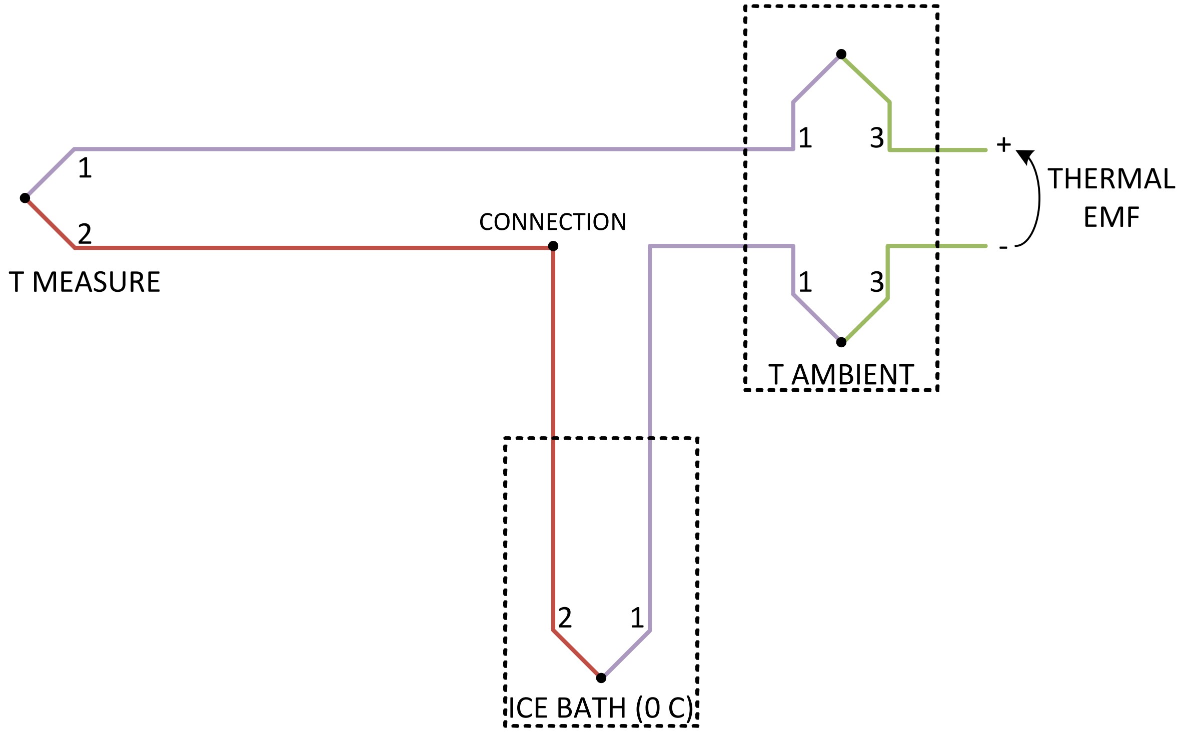

Figure 7: Using an ice bath to eliminate T_A

The thermal emf voltage, V, is found as follows. Note that the ambient thermocouples cancel.

$V = T_A{*}K_{13} + 0{*}K_{21} + T_M{*}K_{12} + T_A{*}K_{31} = T_M{*}K_{12}$

A disadvantage of Figure 7 is that it takes two thermocouples. A modified method is shown in Figure 8 that only requires a single thermocouple. Any issue with imperfect isothermal ambient connections is also eliminated.

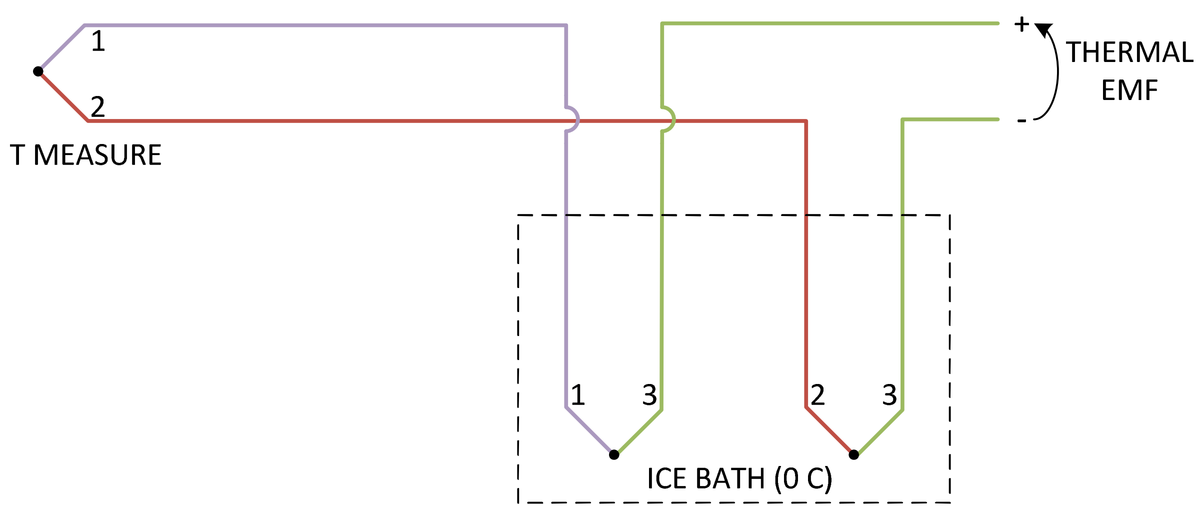

Figure 8: Ice bath concept using a single thermocouple

The thermal emf voltage, V, is found as follows. With both connection thermocouples at 0 C there is no ambient term to consider.

$V = 0*K_{23} + T_M*K_{12} + 0*K_{31} = T_M*K_{12}$

Electronic processing of thermocouples

An ice bath is inconvenient for most applications. It would be nice to perform the correction by electronic means. Also, it would be nice to scale the voltage up to a convenient value such as 10 mV/C. Figure 9 shows a simple circuit for accomplishing both functions. For a type K thermocouple with a constant of 40 uV/C the gain resistor, R, for the instrumentation amplifier would be calculated for a gain of 250 so that the output voltage of the amplifier has the desired 10 mV/C. The 100K resistor to ground provides a path for the required input bias current of the amplifier. Without that resistor the inputs to the amplifier are floating and the amplifier can't operate properly.

The ambient compensator consists of a temperature sensor, often a solid-state device, and processing electronics so that it reports ambient temperature with a 10 mV/C factor. Then a 25 C ambient would produce 0.25 volts. Many instrumentation amplifiers have a summing input so that an external voltage can add or subtract from the amplified difference signal. Using a previous example of T_M being 100 C and T_A being 25 C then the input voltage to the instrumentation amplifier is (100 – 25)* 40 uV = 3.0 mV. When amplified by the gain of 250 the output voltage would be 0.75 volts. The ambient sensor and processing puts out 25 * 0.01 = 0.25 volts to the summing input of the amplifier resulting in 0.75 + 0.25 = 1.00 volts output which corresponds to a T_M of 100 C.

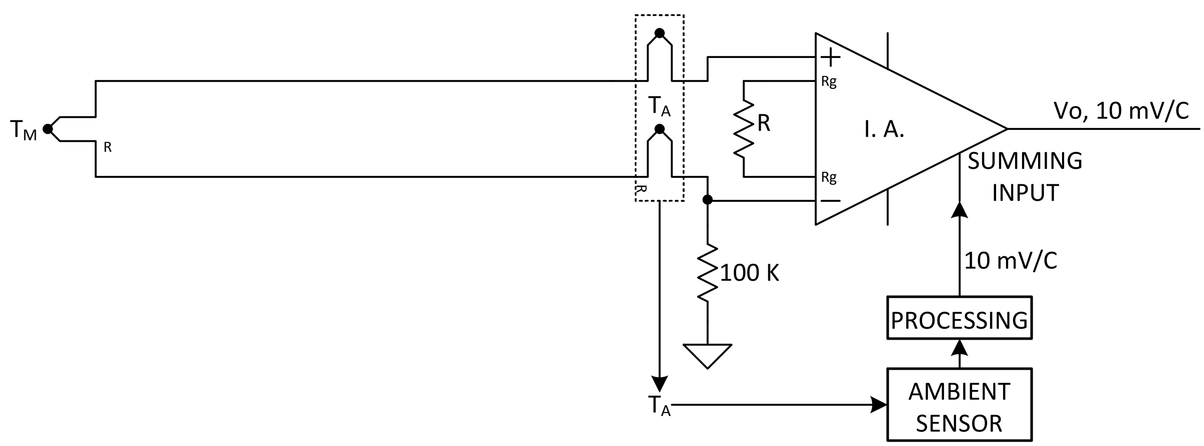

Figure 9: Electronic processing of thermocouple

A more complete circuit would include filters to prevent any interference picked up on the thermocouple cable from corrupting operation of the instrumentation amplifier. Also, there would be circuitry to detect an open or perhaps shorted thermocouple cable for an indication that the output voltage representing the apparent temperature of T_M is not valid.

The functionality shown in Figure 9 is available as a complete monolithic integrated circuit from Analog Devices – the AD594 for type J thermocouples and the AD595 for type K thermocouples.

Thermocouple connections

There are a variety of ways that thermocouples can be connected wrong which will result in measurement errors. The following rules for using thermocouples should be followed as precisely as possible.

1. The thermocouple should be electrically isolated from any metallic structures or circuits. Failure to do this will likely result in what is known as a ground loop where current paths exist to the thermocouple that will seriously corrupt the measurement. Sometimes safety personnel mandate that the thermocouple and other electronics be electrically connected to metallic structures. All you can do in such a case is obey for you cannot win any argument. Your solution will be more sophistication in the thermocouple processing or conditioning to be immune from ground loop issues.

2. Although thermocouple wire is expensive, it must run continuously from the thermocouple to the ambient connection near the processing electronics. If ordinary copper wire is connected to the thermocouple at some distant point from the processing electronics then ambient compensation will be in error – possibly a significant error.

3. If thermocouple wire must pass through connectors then it is important that the two pins are situated so that there is no thermal gradient across them – i.e. be thermally balanced. If that is achieved then the thermal voltages from the parasitic thermocouples formed at the connector will cancel.

4. There must be no current in the thermocouple wires as that will cause voltage drops that will corrupt the measurement.

5. Long runs of thermocouple wire can be expected to pick up significant common-mode interference signals. The thermocouple processing electronics must be designed to reject any interference.

The student should work the following examples to aid understanding.

Figure 10 is an example of failing to use thermocouple wire for the entire run. Since T_X is an unknown temperature there is no way to compensate for it. The ambient temperature at V does not factor into the measurement.

Thermocouples

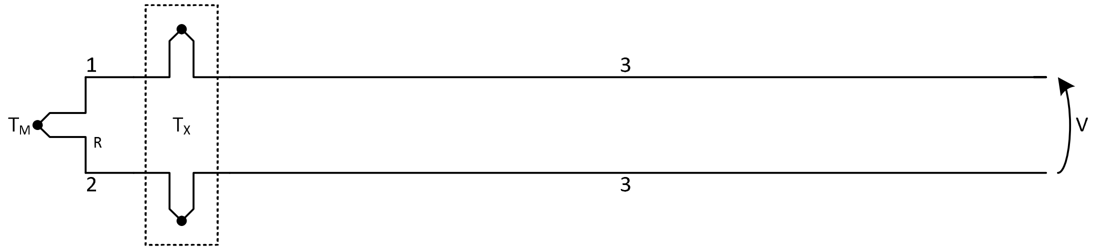

Figure 10: Failure to use thermocouple wire all the way. T_X is unknown.
$V = (T_M – T_X)* K_{12}$

Figure 11 shows a common situation where there must be a connector in the thermocouple connection path. Although a total of four thermocouples are formed the effect of all of them cancels provided they are all isothermal. This is an example of the correct method.

Figure 11: Thermocouple wire going through a connector
Metal 4 is unknown but because all junctions are isothermal,
$V = (T_M – T_A)*K_{12}$

Figure 12 shows a long run of a thermocouple signal with a portion of the run implemented with ordinary copper wire. There is no way to correct for the measurement errors caused by temperatures T_X and T_Y. Refer to Figure 6 for clarity on combining terms.

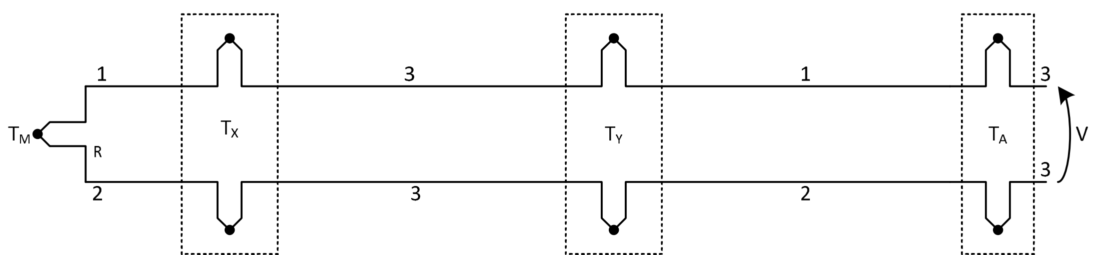

Figure 12: Copper extension wire is used for a portion of the run
Very bad practice resulting in significant measurement error
$V = (T_M – T_X + T_Y – T_A)*K_{12}$

Figure 13 shows a very bad practice of the two connection thermocouples being at different and also unknown temperatures. This causes uncorrectable measurement error. The ambient temperature at V does not figure in the measurement.

Thermocouples

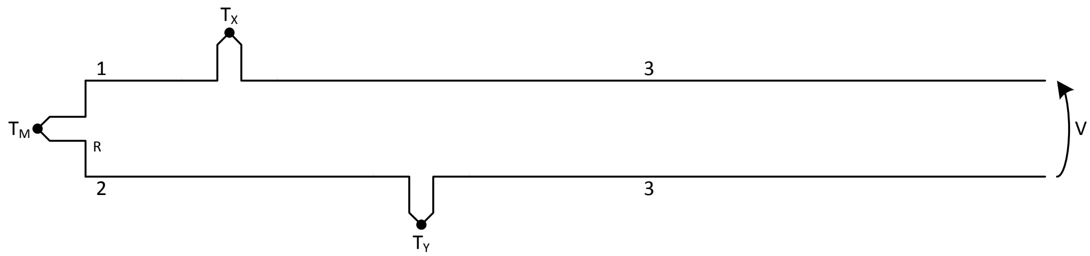

Figure 13: Extremely bad practice – connection thermocouples at different temperatures
In the following, T_X, T_Y, K_{23}, and K_{31} are all unknown
$V = T_M{*}K_{12} + T_Y{*}K_{23} + T_X{*}K_{31}$

There is more information at the following sites:

http://www.kasap.usask.ca/samples/Thermoelectric-Seebeck.pdf

http://www.electronics-cooling.com/2006/11/the-seebeck-coefficient/

http://www.efunda.com/designstandards/sensors/thermocouples/thmcple_theory.cfm

http://en.wikipedia.org/wiki/Thermocouple