Physics AS Level Coursework

Experimenting with Thermocouples

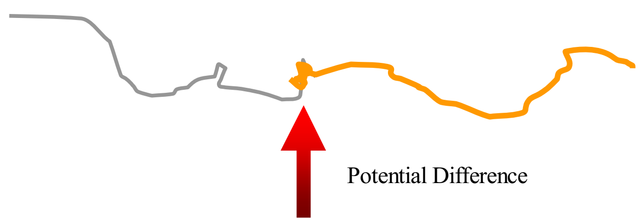
Introduction

For my sensor coursework, I have chosen to investigate the properties of thermocouples. A thermocouple is a sensor which detects a temperature difference, and produces a very small electrical output.

> "In 1822, an Estonian physician named Thomas Seebeck discovered (accidentally) that the junction between two metals generates a voltage which is a function of temperature. Thermocouples rely on this Seebeck effect. Although almost any two types of metal can be used to make a thermocouple, a number of standard types are used because they possess predictable output voltages and large temperature gradients."

Source: http://www.picotech.com/applications/thermocouple.html

Welding, or otherwise combining, two dissimilar metals can make a thermocouple. Varying the temperature of the junction where the two metals combine will produce a very small voltage and a very small current.



However, if one attempts to connect the thermocouple to a Voltmeter, another thermocouple junction is made. This is at the point of contact, where the ends of the thermocouples meet the contacts of the Voltmeter, and causes problems, as it can lead to errors in the result. To compensate for this, a technique known as cold junction compensation (CJC) is used. This entails adding an extra wire of the first material at the end of the thermocouple, so that the metal in contact with the voltmeter are both made from the same material, which cancels out the potential difference.

A result of the CJC is that there are two free junctions. One junction is kept at a constant temperature for the other junction to refer to. That is why this junction is commonly known as the "reference" junction. As most reference junctions are kept in an ice bath at a stable temperature of 0 ^{o}C, it is also known as the "cold junction", hence the term "cold junction compensation". Accordingly, the other junction that actually measures the temperature is commonly referred to as the "hot junction".

When there is a difference in temperature between the junctions, a very small voltage is produced and a very small current will flow.

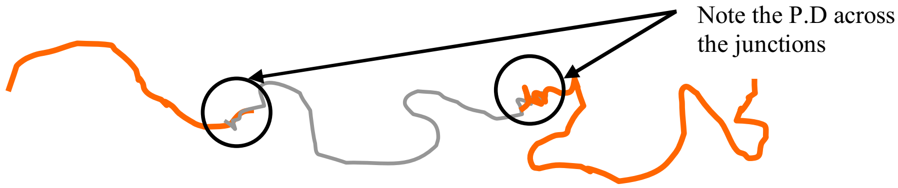


Figure 1 A Copper-Constantan thermocouple

I decided to analyse the relationship between the temperature difference across the junctions of a thermocouple, and the magnitude of the current produced. My aim is to find the formula linking current (in Amperes) to the temperature difference (in centigrade[1]). From this, I can determine the sensitivity of the thermocouple, measured in Amps/ ^{o}C. I can then compare this to thermocouples made from different materials. I can also analyse the resolution of the thermocouple i.e. the smallest temperature change that registers a change in current, and then relate this to practical uses in industry.

Not all metal combinations are ideal for making thermocouples, however, so I have taken steps to find out the most common metal combinations used in industry.

Table 1 http://www.engineeringtoolbox.com/32_496.html

Thermocouple	Temperatures ^{o}C	
	Continuous	Spot
Copper-Constantan (Type T)	400	500
Iron-Constantan (Type J)	850	1100
Chromel-Constantan	700	1000
Chromel-Alumel	1100	1300
Nicrosil-Nisil	1250	-
Tungsten-Molybdenum*	2600	2650

Due to limitations of the actual school resources, I will only use the Copper-Constantan and Iron-Constantan combinations. Tungsten-Molybdenum can only be used at temperatures over 1560 ^{o}C

The Galvanometer

I was advised (from my Physics tutor) that thermocouples produce an extremely small current. To detect such a current, I needed a specialised device known as a Moving-Coil Galvanometer, which was sensitive enough to detect such minute currents.

The Moving Coil Galvanometer is a very delicate piece of equipment, namely because it contains a Moving Coil. When handling this sensitive piece of equipment, it was vital to observe a few precautions. Firstly, when the Galvanometer was being

[1] Ideally I would measure the temperature in Kelvin, starting from absolute zero. Unfortunately, this is impossible to recreate in a school lab environment.

moved, I had to ensure it was set to "shorted". Secondly, it was important to be very careful the treatment of the equipment, as it was very sensitive to shaking, dropping and extreme vibrations.

When it came to using the Galvanometer, I had a choice of settings.

Setting	Description
Shorted	Used to keep Galvanometer safe when in transport/not in use.
1 x	Gives largest operating range, units in mA, lowest accuracy.
0.03 x	Gives a compromise between operating range and accuracy.
0.001 x	Gives smallest operating range, units in μA, most accurate.

As a quick preliminary to find out which setting would give an appropriate output for a thermocouple, I took a small sample of three Copper-Constantan thermocouples, attached the ends to the Galvanometer, and held onto one junction while letting the other junction remain free. Thus, one junction was at room temperature while the other was nearly at body temperature. I found that in all cases, 1x gave the most sensible output, as the readings remained within range but stable and accurate. With the other two settings, the output would go out of range, or fluctuate wildly.

Calibration of the Galvanometer

To produce an accurate relationship, the Galvanometer must be calibrated. Therefore, before the "hot" junction[2] is inserted into the boiling water, it will be inserted into the ice bath, along with the "cold junction"[3]. This will give a relative temperature difference of $0^{o}C$. When this is done, the Galvanometer will be "zero-set" i.e. manually calibrated so that the reading is 0 mA. Therefore, if there is no temperature difference, there will be no current, eliminating any constants in the equation.

As the Galvanometer is analogue, it may be difficult to accurately judge when the marker is on zero. To improve accuracy, it should be set as close as possible to zero on the lowest resolution. Then, increase the resolution, and set the marker as close as possible to zero again. Repeat as many times as possible, to increase accuracy.

Equipment needed for all Experiments

Moving Coil Galvanometer	As thermocouples produce such a small current, a standard ammeter would not be inadequate. A Moving-Coil Galvanometer is sensitive enough to measure the current accurately, and can be calibrated beforehand to get an accurate relationship between temperature difference of junctions and current produced. Ideally a digital Galvanometer would be used for improved accuracy.
Kettle	This is the safest method of heating up water, compared to using a Bunsen burner (open flame

[2] The junction which is in the area where the temperature has to be determined, i.e. the junction actually 'measuring' the temperature.
[3] Also known as the "reference junction", this junction remains at a fixed temperature, usually 0 ^{o}C.

	hazard). It is also cheaper than using a water bath, although unlike its more advanced counterpart, it cannot maintain a user-defined temperature.
Polystyrene beakers	These are safer to use than glass/Pyrex beakers, as polystyrene is a good insulator, reducing the chance of injury from handling the beakers, which contain hot substances. Being a good insulator also reduces the rate at which the ice will melt, so I can continue the experiment for longer. One polystyrene beaker will be used to contain the hot water for the "hot junction", while the other will contain the ice for the "cold junction".
Mercury Thermometer	The basic instrument for measuring the temperature of the water. Cheap but reliable and accurate, the thermometer must be read at eye level for accuracy. Can operate between 0 ^{o}C and 100 ^{o}C, well within my parameters for my experiment. Ideally a digital thermometer would be used for greater accuracy.
Crushed Ice	This has two purposes. Firstly, it is required to construct an ice bath for the "cold" reference junction. Secondly, it can be used as a coolant if the water is taking to long to cool by itself, a situation which can occur if the ambient room temperature is higher than average. Being crushed gives the ice a larger surface area, which allows a larger surface area of the thermocouple junction to remain in contact.
Water Supply	To construct a hot water bath. Water is cheap, readily available and a liquid, allowing the temperature to be distributed evenly throughout. Water is also safer to use than ethanol, which is flammable. Will be used as a variable source of heat for the "hot junction"

Determining the Resolution of a Thermocouple

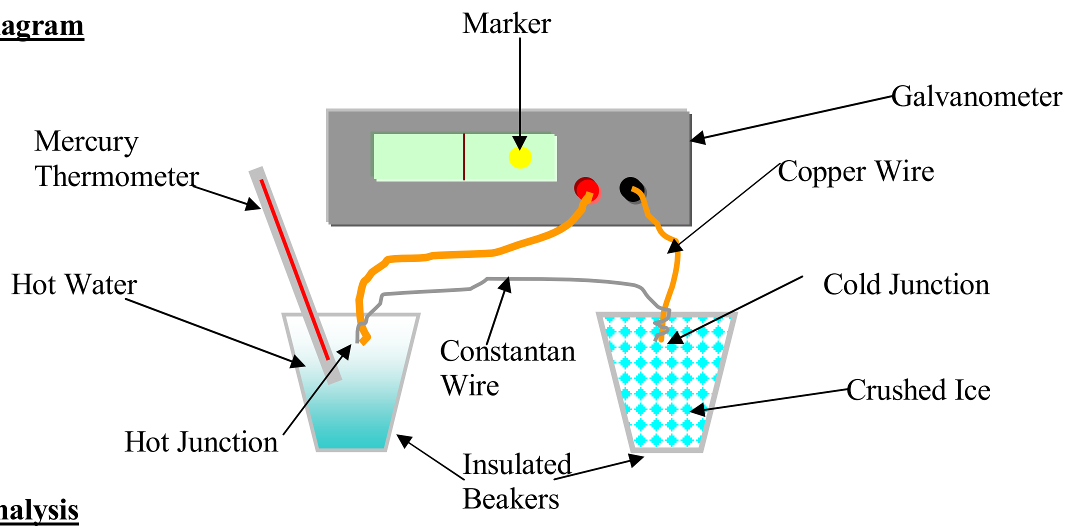
Firstly, I attempted to determine the resolution of the Copper-Constantan thermocouple with a moving coil Galvanometer. The resolution is the smallest change in the substance being tested that can be detected and produce an output from the sensor. For a thermocouple, the resolution was the smallest temperature change that will produce a change in the reading from the Galvanometer.

Method

- Clear work area, set out equipment, ensure Galvanometer is set to "x 1" and plugged into the mains.
- Attach the Copper-Constantan thermocouple to the Galvanometer, calibrate using method described above
- Boil water using kettle, once boiling, pour into insulated beaker and immerse the hot junction, taking care not to insert more than just the junction.

- Fill next insulated beaker with crushed ice (or use beaker filled with ice from calibration), then insert cold junction, again taking care not to insert more than just the junction.
- Insert thermometer into hot water. Wait until temperature drops to 50 °C, or else the water will cool too quickly to gain accurate results.
- Record the current flowing at 50 °C, 40 °C, 35 °C, 32 °C, 30 °C, 29 °C and 28.5 °C. This gives you a set of results for a change of 10 °C, 5 °C, 3 °C, 2 °C, 1 °C and 0.5 °C.
- Work out the change in current by taking the first result, and subtracting the next result, e.g. to work out the current change for 10 °C, take the current flowing at 50 °C and subtract the current flowing at 40 °C.
- Repeat experiment using a different Copper-Constantan thermocouple to average out errors.

Diagram



Analysis

From my results (see Appendix A), I have established that the resolution is 1 °C. This is due to the fact that a change of temperature smaller than 1 °C produces no change in the reading on the Galvanometer.

Evaluation

If I had used a digital Galvanometer, the resolution could possibly be increased, as it is easier to read off a number than judge where a marker is positioned. For example, on the analogue Galvanometer, I could only judge to the nearest 0.1mA, whereas with a digital Galvanometer it would be possible to get a reading to the nearest 0.01mA. This means that a change of 1 °C may not register a change on the analogue Galvanometer, but could register a change on the digital version, which means the resolution of the thermocouple is limited by the resolution of the Galvanometer.

With a digital Galvanometer, I could have detected a change in current for every 0.5 °C. To further determine resolution, I would also need to upgrade my equipment by procuring a digital thermometer, as it is difficult to judge temperature changes less than 0.5 °C on a standard thermometer. With a high-quality digital thermometer, it would be possible to take current readings at 28.25 °C, 28.125 °C etc. Therefore I could improve the experiment determining the resolution of a thermocouple by using a digital thermometer and digital Galvanometer.

Observations on Response Time

When I had finished conducting the experiment to determine the resolution of a thermocouple, I decided to make a quick investigation of the thermocouple response time. From observing the first experiment, I found that the response time of the thermocouple seemed to be almost instant, for if the temperature decreased by a tiny amount, the current would decrease by a tiny amount.

To investigate the response time of the thermocouple, I refilled the beaker with boiling water, immersed the hot junction in it and observed the reading on the Galvanometer. As previously, as the temperature decreased, the reading decreased at the same rate. I then put some crushed ice in the boiling water. This caused the water to cool far more rapidly. I noticed that this time, the Galvanometer was fluctuating considerably, and only stabilised when the ice had completely melted, thus restoring the cooling rate of the water to normal.

Determining the Sensitivity a Thermocouple

To gather suitable results, I varied the temperature difference between the junctions (independent variable), whilst measuring the current flowing through the wire (dependent variable). To vary the temperature difference, I placed the "cold" junction in an ice bath to keep it at a constant temperature of 0 ^{o}C.

N.B *The ice bath can be re-used from the calibration of the Galvanometer*.

I then immersed the "hot" junction in boiling water. As the water temperature decreased, the temperature difference decreased from 100 ^{o}C down to room temperature. As cooling began immediately, I began observations at 80 ^{o}C; due the to the fact that the cooling rate decreases as the temperature difference between the hot water and the air decreases, I decided to end observations at 40 ^{o}C. It was difficult to gain results from temperatures lower than 40 ^{o}C as ice was needed to cool the liquid further. I recorded the reading from the Galvanometer every 5 ^{o}C to give me a wide range of results.

Method

- Clear work area, set out equipment, ensure Galvanometer is set to "x 1" and plugged into the mains.
- Attach the Copper-Constantan thermocouple to the Galvanometer, calibrate using method described above
- Boil water using kettle, once boiling, pour into insulated beaker and immerse the hot junction, taking care not to insert more than just the junction.
- Fill next insulated beaker with crushed ice (or use beaker filled with ice from calibration), then insert cold junction, again taking care not to insert more than just the junction.
- Insert thermometer into hot water. Wait until temperature drops to 80 ^{o}C, or else the water will cool too quickly to gain accurate results.

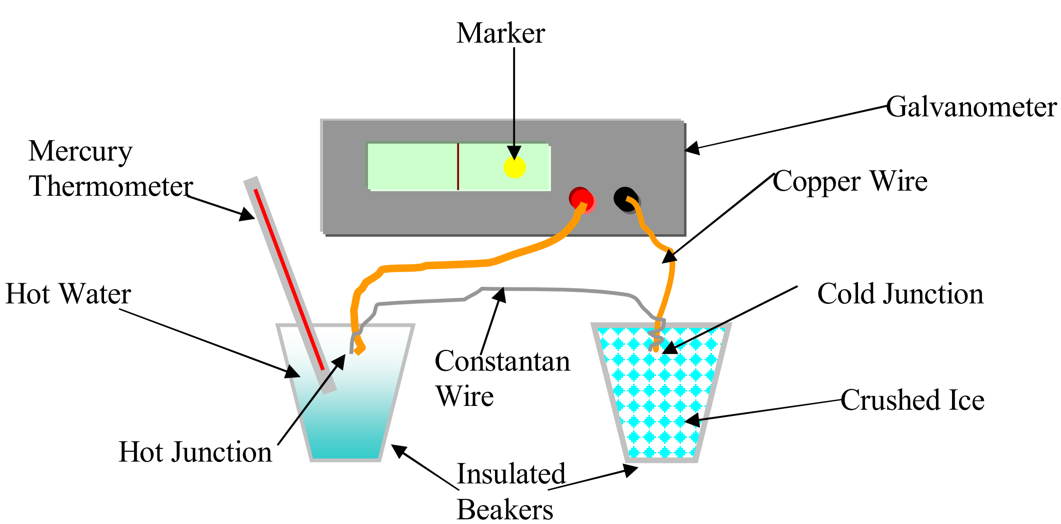
- Record the current flowing at 80 °C, 75 °C, 70 °C etc for every 5 °C, stopping at 40 °C.
- Repeat experiment using a different Copper-Constantan thermocouple to average out errors.

Important features to note are:

- Lead Resistance. To minimise thermal shunting and improve response times, thermocouples are made of thin wire (in the case of platinum types cost is also a consideration). This can cause the thermocouple to have a high resistance, which can make it sensitive to noise and can also cause errors due to the input impedance of the measuring instrument.
- *Decalibration* is the process of unintentionally altering the makeup of thermocouple wire. The usual cause is the diffusion of atmospheric particles into the metal at the extremes of operating temperature. To minimize this problem, I used enamelled copper wire. This has a protective coating on the outside, so the copper does not oxidise with oxygen in the air. Only the junctions are exposed.
- Noise. The output from a thermocouple is a small signal, so it is prone to electrical noise pick up. To reduce the effect of external 'noise' in my experiment, I ensured I was working well away from any other electronic equipment, such as motors, radios etc.
- Thermal Shunting. All thermocouples have some mass. Heating this mass takes energy, and affected the temperature I was trying to measure. When I was measuring the temperature the boiling water, there were two potential problems. The first is that heat energy will travel up the thermocouple wire and dissipate to the atmosphere so reducing the temperature of the water around the wire. A similar problem could have occurred if the thermocouple was not sufficiently immersed in the liquid; due to the cooler ambient air temperature on the wires, the thermocouple junction would have been a different temperature to the liquid itself.

Source: http://www.picotech.com/applications/thermocouple.html

Diagram



Once enough measurements have been taken, the experiment should be repeated with another T type thermocouple to get an average value, thus eliminating errors.
The experiment can then be repeated with different materials for the thermocouple wires.

I repeated the experiment using a thermocouple I had made myself. To do this, I cut two 10cm lengths of enamelled copper, making sure to strip roughly 2cms at each end for electrical contact. I then cut a 10 cm length of iron wire, which had been previously cleaned to remove corrosion etc, and twisted the ends of the copper wires together with the ends of the iron wire.

When I tested this version on the Galvanometer, I could not obtain an output, when I let one junction remain free in the air while tightly gripping the other junction. I increased the sensitivity to 0.03x, and saw a very small change. It was only when I set the Galvanometer to 0.001x that I managed to get a satisfactory output. From this, I determined that my thermocouple did not have as great an output as the ready-made school thermocouples. As the results seemed to be in a completely different order of magnitude than normal, I thought it would be inappropriate to use my results to compare Iron-Copper thermocouples to Constantan-Copper thermocouples. The results of the Iron-Copper thermocouple can be found in Appendix A.

I believe the reason why my thermocouple produced such a small current is due to the fact that my junctions were poorly made. As the two wires were simply twisted together, the actual contact between the two metals could have been quite sparse. The school thermocouples were welded together using capacitive discharge, which means that the actual area of the dissimilar metals - which were in contact - was much greater.

If the area of contact between the metals were greater, then more electrons would be able to 'move' over from one metal to the other, creating a larger potential difference. This would then cause a larger current to flow.

Analysis

From the results of this experiment (see Appendix A), one thing immediately becomes obvious. Although all the thermocouples are made of the same material, the current produced at a specific temperature varies from thermocouple to thermocouple. However, the gradients of the different thermocouples are slightly different themselves, which confirms that they were calibrated correctly.

There are number of reasons why the thermocouples did not all give roughly the same current at any specific temperature:

- The thermocouple junctions were not all the same size. The size of the junction determines how much contact there is between the two different metals, thus the potential difference and current.
- I was not told when the thermocouples were made. The age of the thermocouple is a factor, as the electro-chemical properties change with it. This would affect the gradient of the graph.

- The materials of which thermocouple wires are made of are not inert and the thermoelectric current developed along the length of the thermocouple wire may be influenced by corrosion etc.

Looking at the graph for the Copper-Constantan thermocouple (see Appendix A), it is clear that there is a linear relationship between temperature and current, as there is a straight line of best fit. As I have calibrated the Galvanometer so when the temperature difference is 0 ^{o}C, the current produced is 0mA. This means the line will go through the origin, allowing us to project my line of best fit backwards, so I can estimate the current produced for lower temperatures than 40 ^{o}C. As the line goes through the origin I can now state that:

The current produced by a thermocouple is directly proportional to the temperature difference across the junctions.

Using the gradient of the line of best fit, I can determine an equation to work out the current produced at a certain temperature, for the Copper-Constantan thermocouple:

C = 0.0764 T, where **C** is the current in milliamps (mA) and T is the temperature at the hot junction in degrees Celsius (^{o}C). However, I need to adapt the formula to work in SI Units. This means current will be measured in Amperes (A) and temperature in degrees Kelvin (^{o}K). Thus:

C = 0.0000764 x (T – 273.15), where **C** is the current in Amps and T is the temperature at the hot junction in Kelvin.

However, there will be occasions where the cold junction will not be at 0 ^{o}C, so the temperature difference would not be the temperature at the hot junction alone. Instead, it would be the temperature at the hot junction **minus** the temperature at the cold junction. A minor change is needed:

C = 0.0000764 x ([T_H – T_C] – 273.15) where **T_H** is the temperature of the hot junction and **T_C** is the temperature of the cold junction.

The co-efficient of the formula is very useful, as it also determines the sensitivity of the Thermocouple in Amps/ ^{o}C. The greater the co-efficient, the more sensitive the thermocouple is, as it would take a smaller change in temperature to register the same change.

For my self-made Iron-Copper thermocouple, the results were slightly disappointing. Although I had to increase the resolution of the Galvanometer, it appeared I was collected a linear set of results similar to the ones obtained from the Copper-Constantan thermocouples. However, looking at the graph (Appendix B), it is apparent that I did not calibrate the Galvanometer correctly, as although the results form another similar linear relationship, the line of best fit does not go through zero. Instead, I am left with a constant, which should have been eliminated during calibration. The error during calibration could have been due to the temperature in the ice bath being a few degrees above zero or due to fluctuations with the Galvanometer readings.

For the self made Iron-Copper thermocouple, the equation to work out current from temperature is:

$$\mathbf{C = [\ 0.0000000607 \times (T - 273.15)\ ] - 1.5}$$

Where **C** is the current in Amps and T is the temperature in Kelvin.

By deduction, as both these formulas are linear, if the temperature difference between the junctions was negative (i.e -100 °C and 0 °C) then we would expect to see a negative current i.e. a current flowing in the opposite direction. This effect could also be achieved by simply swapping the junctions around.

SYSTEMATIC ERROR Calibration

Evaluation

To improve both experiments, two things could be altered. Firstly, using a digi tal thermometer would greatly increase accuracy, as judgements made on a standard thermometer may be inaccurate, which will lead to recording results at the wrong time. For example, if the temperature of the water was actually 28 °C, but I thought it was 30 °C, then I would be recording the result far too late, which may cause an 'anomaly' in the results.

The second way to improve accuracy is by using a digital Galvanometer. The analogue Galvanometer allows readings to be taken to the nearest 0.01A. A digital Galvanometer can increase that accuracy, allowing the thermocouple to have a greater resolution, as the Galvanometer can register a smaller current change.

The Galvanometer itself performed very well, as throughout my experiment the reading did not fluctuate at all for the Copper-Constantan thermocouple.
When I tested my Iron-Copper Thermocouple, the Galvanometer did fluctuate slightly at first, at which point I sought advice from my Physics Tutor. I was informed that the fluctuations were caused by bad connections between the thermocouple and the Galvanometer. As I was using enamelled copper, I thought it would be wise to scrape of some more of the enamelling around the parts of the wire in contact with the Galvanometer. This fixed the problem, and there were no more fluctuations.

There were some elements of the experiment that were beyond my control. Firstly, to ensure a fair test, the lengths of the wires used to construct the thermocouple should be the same for all the thermocouples tested, as different wire lengths would have different resistances, which would affect the current measured.

Secondly, the thermocouple junction sizes should also be the same, as a larger junction size would produce a larger potential difference, as there are more electrons available to move in between the metals. A larger potential difference would result in a larger current.

Applications Within Industry

Thermocouples are already used widely in industry. This is due to a variety of factors, including the cheap cost (excluding Platinum-Rhodium thermocouples), the robustness of the sensor (made from metal wires) and the simplicity (temperature difference will produce a voltage and current through the wires.

A practical example for use of a thermocouple is in an old style boiler. When the pilot light (essentially a flame) is turned on, it heats up one junction of the thermocouple. This produces a small current, which is used as feedback to keep the pilot light alight.

From my experiments, I can see that there are some drawbacks, however. In Copper-Constantan thermocouples, the smallest temperature change that can be sensed is 1 ^{o}C. In some precision measuring applications in industry, this may simply be not accurate enough for the task at hand, such as monitoring a sick person's body temperature in a hospital, for example, as this would deal in looking at changes in temperature in 0.1 ^{o}C.

Also, it appears that a rapidly changing temperature would cause problems.

Bibliography

http://www.picotech.com/applications/thermocouple.html - A company specialising in the manufacture, research and development of a wide range of thermocouples.

http://www.madsci.org/posts/archives/oct99/939333814.Ph.r.html - An excellent overview of thermocouple theory on the atomic level.

http://www.its.org - The International Thermoelectric Society, a vast resource of information on all thermoelectric effects, which included thermocouple theory.

http://www.engineeringtoolbox.com/32_496.html - A general, all purpose website outlining various types of thermocouples, uses and operating ranges.

Advanced Level Practical Physics: Fourth Edition by M. Nelkon and J.M Ogborn – A source of ideas for experiments involving thermocouples.

Heinmann Advanced Science: Physics by Patrick Fullick – General listing of common sensors along with advantages and disadvantages of thermocouples.

Physics Tutor for advice on experiments and technical support.