Xi'an Jiaotong-Liverpool University
西交利物浦大学

EEE220 Instrumentation and Control System

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Lecture 3

Outline

Sensors & Transducers

- **Temperature Sensors**
  - Bimetallic strips
  - Resistance temperature detectors (RTDs)
  - Thermistors
  - Thermocouples

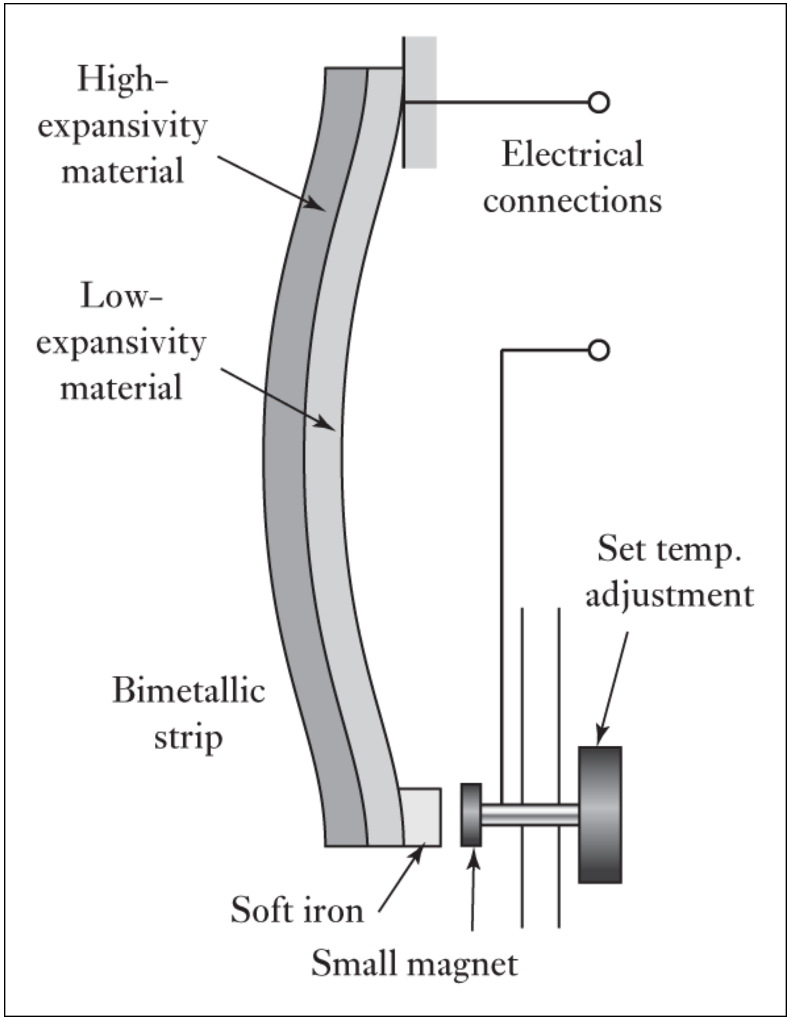
Temperature Transducers

Changes are commonly used to monitor temperature are expansion or contraction of solids, liquids or gases, the change in electrical resistance of conductors and semiconductors, and thermoelectric e.m.f. (electromotivative force).

The following are some of the commonly used temperature sensors:

- *Bimetallic strips*
- *Resistance temperature detectors (RTDs)*
- *Thermistors*
- *Thermocouples*

Bimetallic Strips



- The device consists of two different metal strips bounded together;
- The metals have different coefficients of expansion;
- When the temperature changes, the composite strip bends into a curved strip, with the higher coefficient metal on the outside of the curve;
- This deformation may be used as a temperature-controlled switch.

Resistance Temperature Detectors (RTDs)

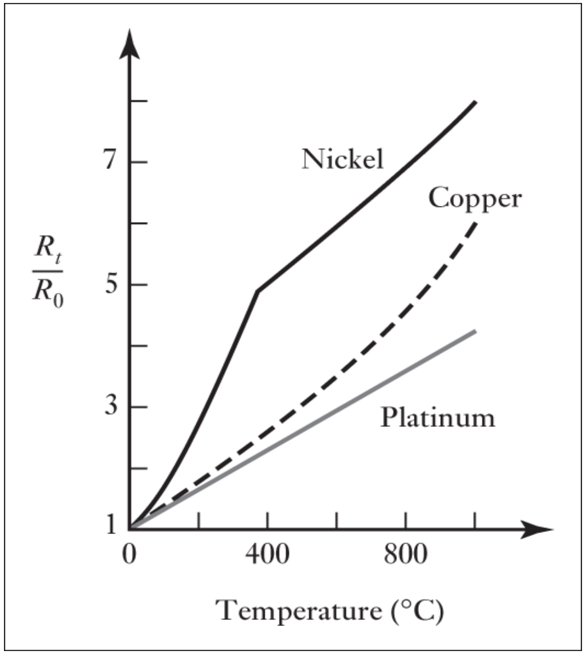
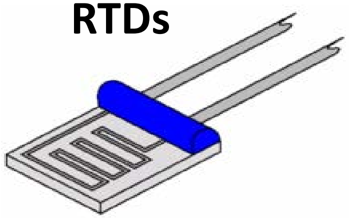
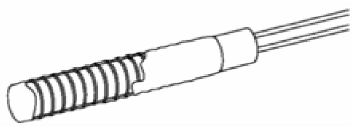


Fig. Variation of resistance with temperature for metals.

3 Forms of RTDs



Thin-film



Wire-wound

Coils of wires

- The resistance of most metals increases, over a limited temperature range, in a reasonably linear way with temperature.
- RTDs are highly stable and give reproducible response over long periods of time; they tend to have response time of the order of 0.5 to 5 s or more.
- For such a linear relationship,

$$R_t = R_0(1 + \alpha t)$$

where

- R_t is the resistance at a temperature $t(^oC)$,
- R_0 is the resistance at 0^oC,
- α is a constant for the metal termed the temperature coefficient of resistance.

RTDs (cont'd)

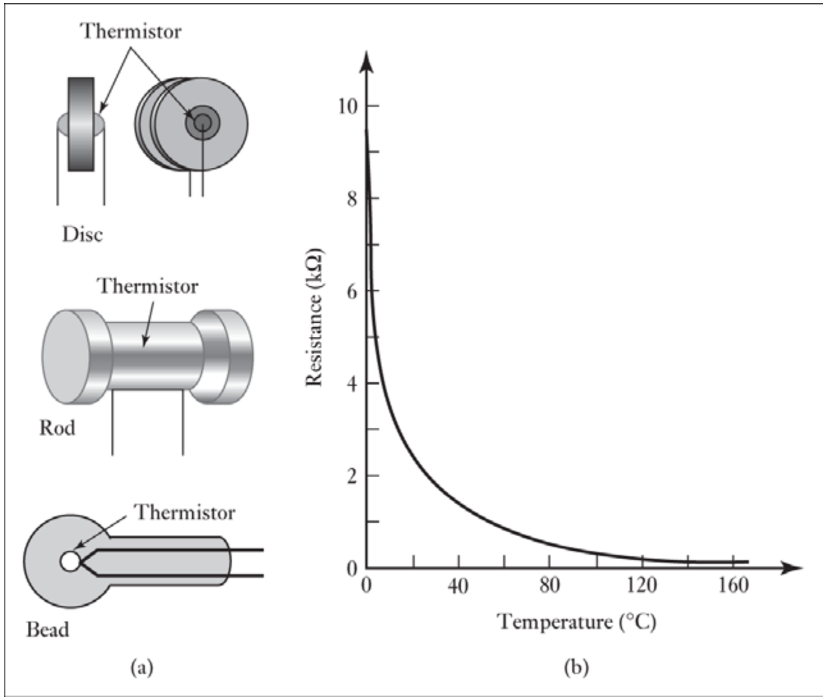
$$R_t = R_0(1 + \alpha t)$$

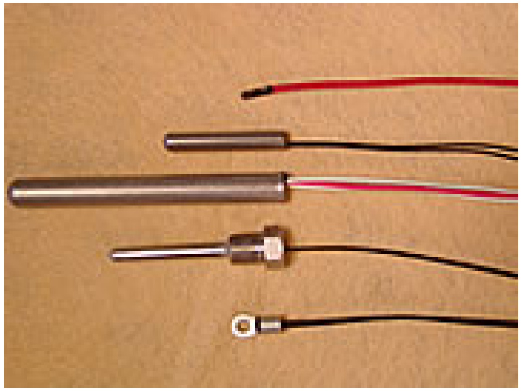
Material	resistivity (ohm. m)	α (per ^oC)
Copper	1.68×10^{-8}	0.0068
Nichrome (Ni,Fe,Cr alloy)	100×10^{-8}	0.0004
Platinum	10.6×10^{-8}	0.0039
Tungsten	5.6×10^{-8}	0.0045

Which material is more sensitive (with higher sensitivity)?

In practice, this linear equation is only approximately valid over a limited temperature range.

Thermistors





- Thermistors are small pieces of material made from mixtures of metal oxides, such as those of chromium, cobalt, iron, manganese and nickel. These oxides are semiconductors;
- The resistance of conventional metal-oxide thermistors decreases in a very nonlinear manner with an increase in temperature.
- The resistance-temperature relationship for a thermistor can be described by

$$R_t = Ke^{\beta/t}$$

where

- R_t is the resistance at a temperature $t(^oC)$,
- K and β are constants.

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Thermistors (cont'd)

Advantages:

- Rugged and can be very small, enabling temperatures to be monitored at virtually a point
- Responds very rapidly to changes in temperature
- Gives very large changes in resistance per degree changes in temperature

Main Disadvantage:

- Nonlinearity

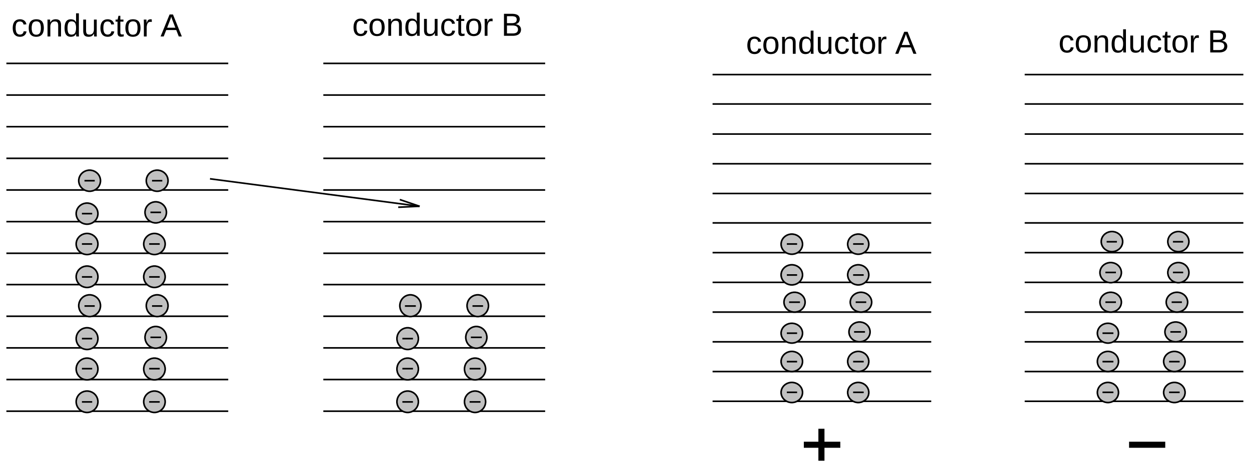
Typical Resistance/Temperature Dependence.

T ^{o}C	R_T ohms
0	350 000
25	100 000
50	34 000
100	6 000
150	1 600
200	550
250	240
300	110

Thermocouples

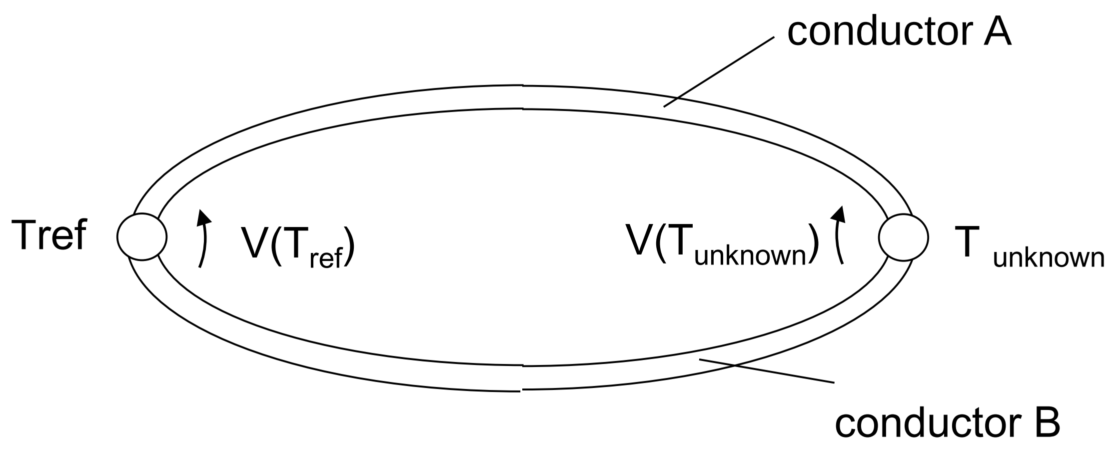
Physical principle:

If two different electrical conducting materials are brought into electrical contact then a contact potential (electromotive force, e.m.f.) will be created across the interface, and the e.m.f. produced depends on the metals used and the temperature of the junction.



It occurs because the electrons are 'stacked' in the available energy levels to different maximum energies in each material .

If both ends of conductors A and B are joined together, two inter-metallic contacts are formed.



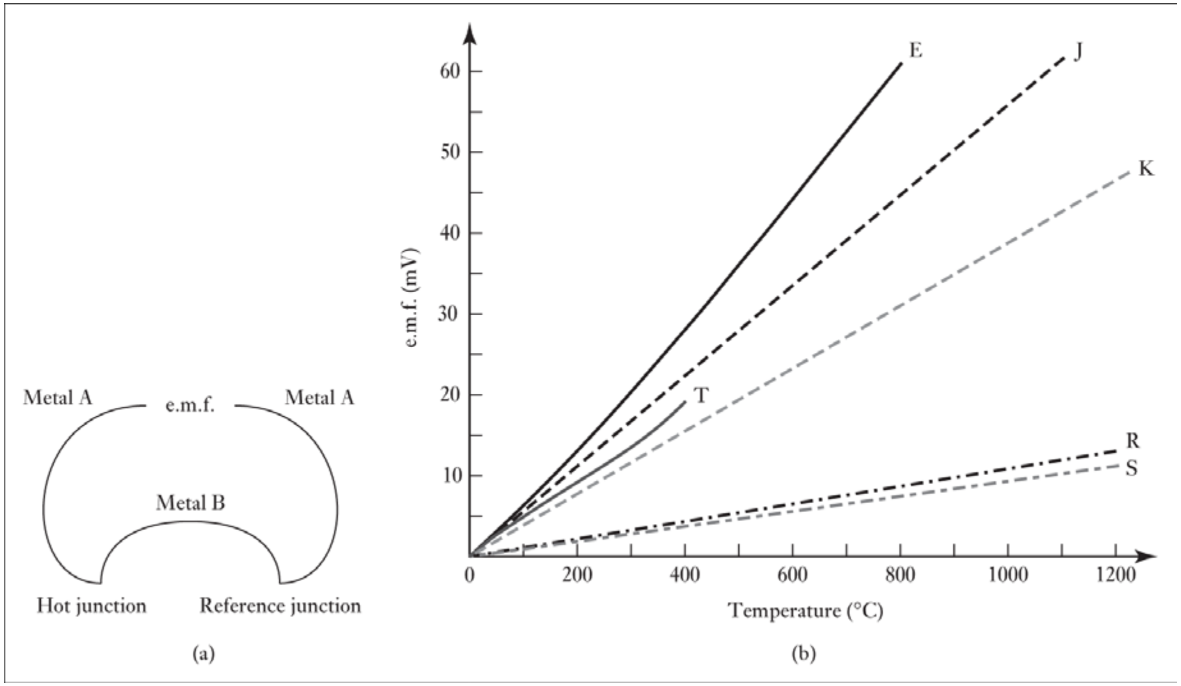
No net potential difference (net e.m.f. = 0) will be produced in the circuit provided both junctions are at the same temperature.

However, if one is at a different temperature than the other ($T_{ref} \neq T_{unknown}$), a potential difference will occur and can be measured.

Different Types of Thermocouples

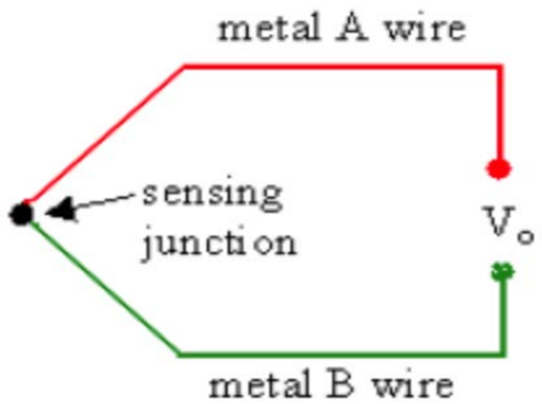
Ref.	Materials	Range (°C)	(μV/°C)
B	Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
E	Chromel/constantan	−200 to 1000	63
J	Iron/constantan	−200 to 900	53
K	Chromel/alumel	−200 to 1300	41
N	Nirosil/nisil	−200 to 1300	28
R	Platinum/platinum 13% rhodium	0 to 1400	6
S	Platinum/platinum 10% rhodium	0 to 1400	6
T	Copper/constantan	−200 to 400	43

- The value of e.m.f. produced depends on the two metal concerned and the temperature of both junctions.
- The left table shows the commonly used the thermocouples with temperature ranges and typical sensitivity.



International standards have been established for thermocouple materials. These are covered by BS4937: 1973 - 74 International Thermocouple Reference Tables.

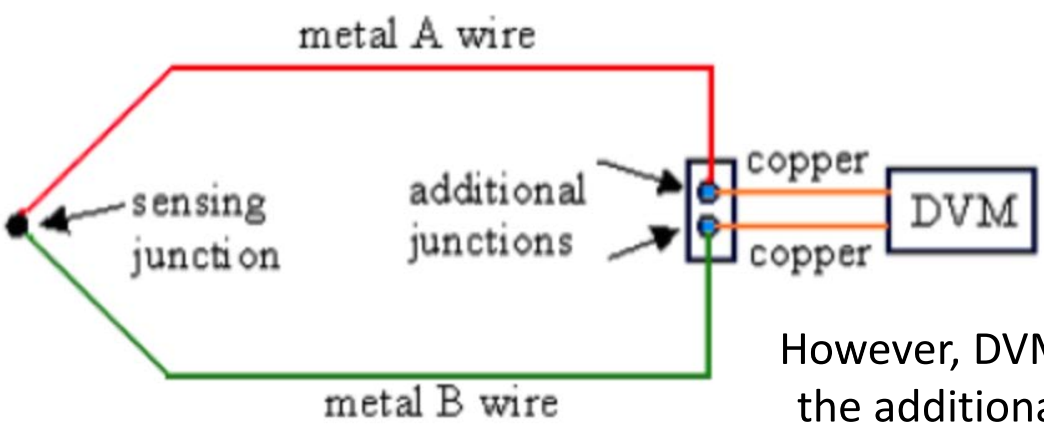
How to Measure the E.M.F.?



Why?

and How to solve the problem?

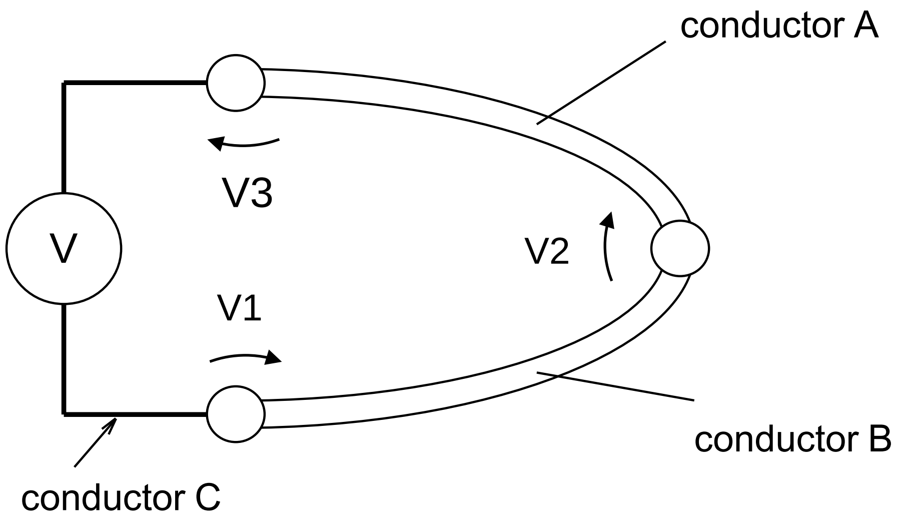
Voltage can be measured to infer the temperature.



However, DVM (digital voltemeter) output = 0 given the additional junctions in the same temperature.

Thermocouple: Measuring Arrangement

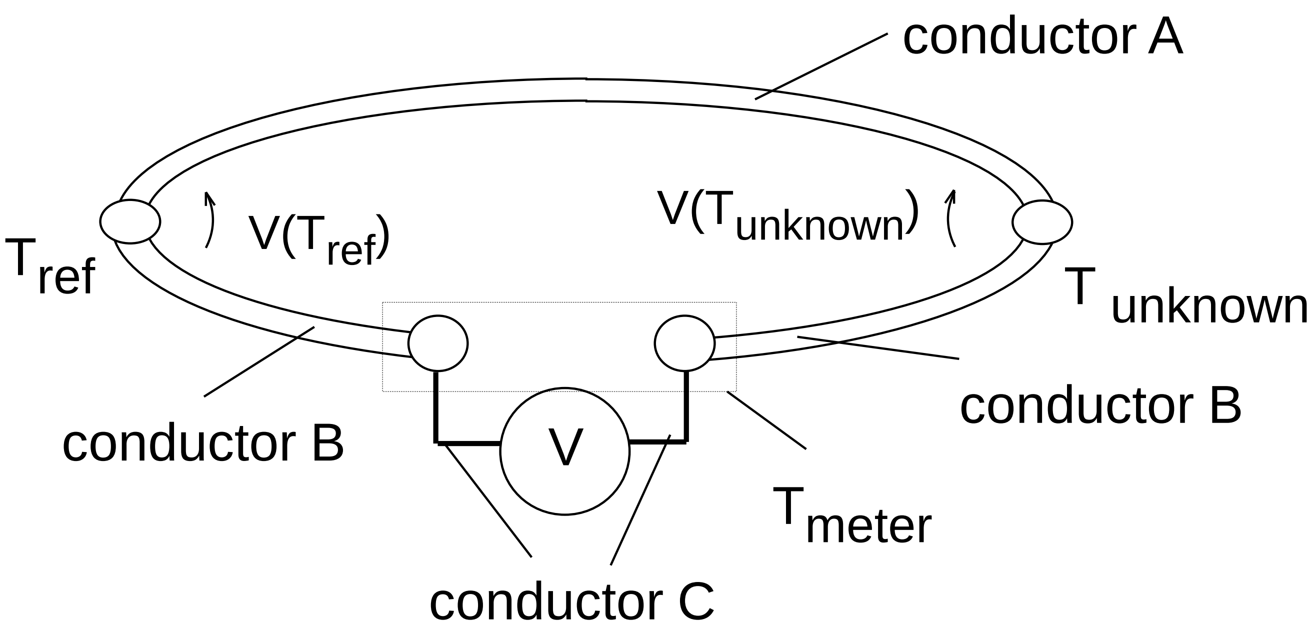
The contact potential cannot be directly measured with a voltmeter, because compensating contact potentials(V1, V3) are created where the voltmeter is connected.



We find that $V1 + V2 + V3 = 0$

Arrangement 1

Thermocouple voltage measurement – arrangement 1

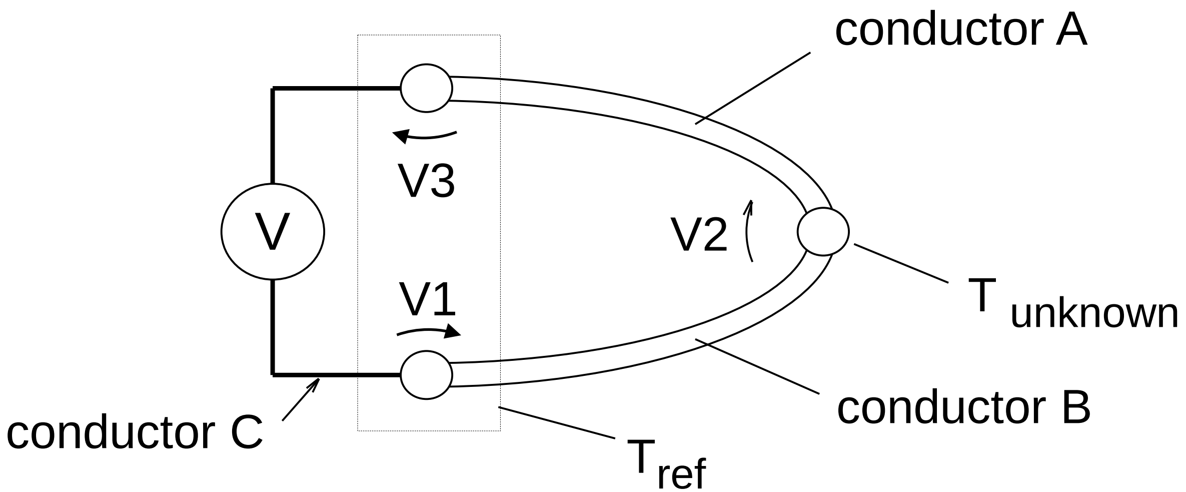


- provided both junctions of the conduct C (wires of voltmeter) are at the same temperature (T_{meter}).

Arrangement 2

Thermocouple voltage measurement – arrangement 2

In practice the following, more convenient, circuit may be used:

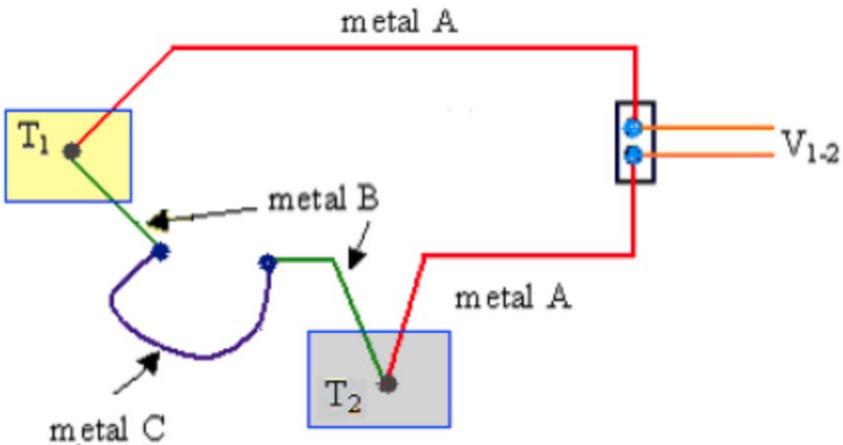


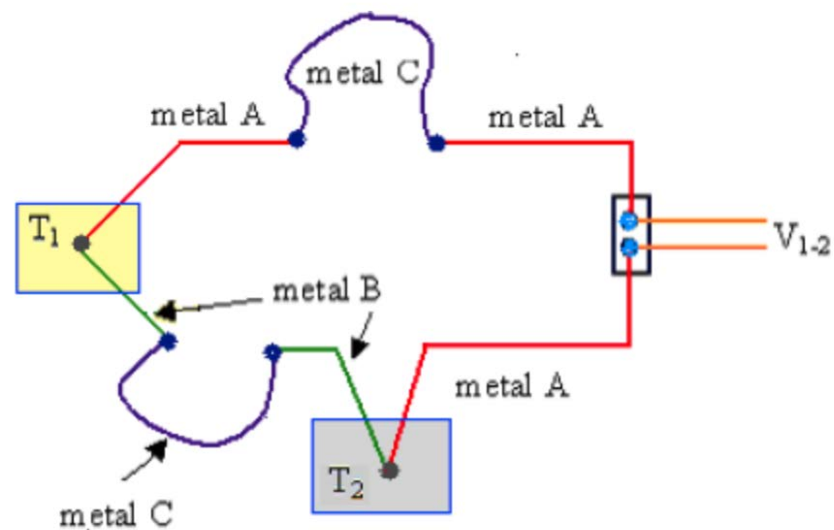
- provided by adding the meter are kept at the same, known temperature (T_{ref}) and the voltmeter reading is corrected/compensated.

Rules of Thermocouples

Rule 1: Law of intermediate metals

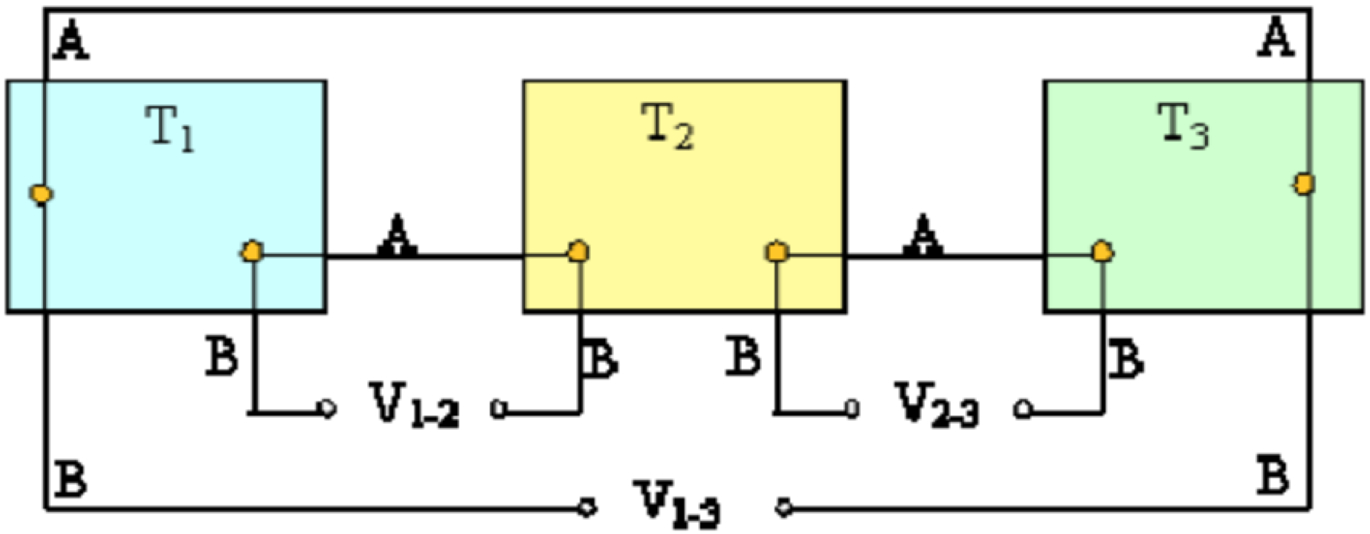
A third (intermediate) metal wire can be inserted in series with one of the wires without changing the output voltage, provided both junctions of the third metal are at the same temperature.





Rule 2: Law of intermediate temperatures

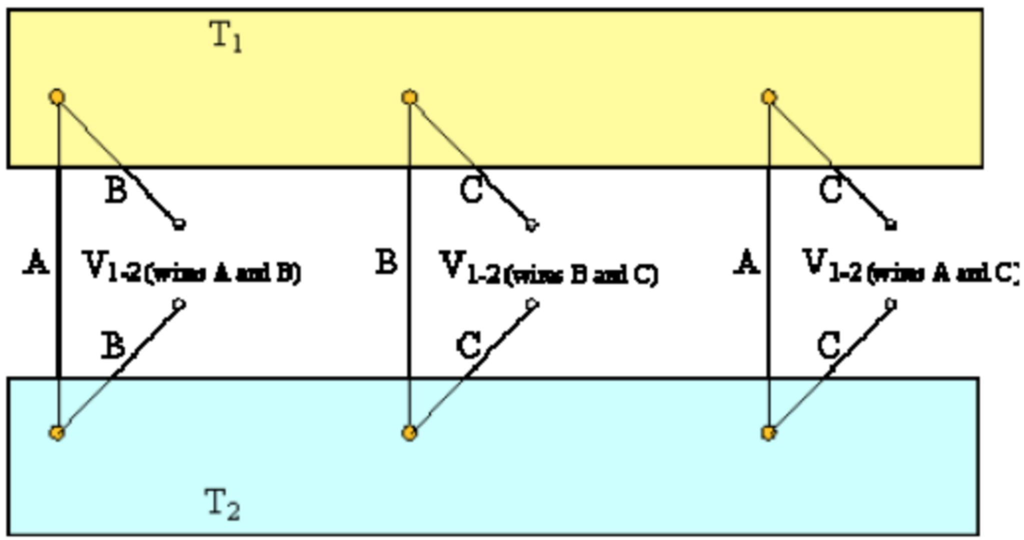
If a thermocouple has an output voltage of V_{12} when its junctions are at temperatures T_1 and T_2 and an output voltage of V_{23} when its junctions are at T_2 and T_3, then its output voltage will be $V_{12} + V_{23}$ when its junctions are at T_1 and T_3.



$$V_{1-3} = V_{1-2} + V_{2-3}$$

Rule 3: Law of additive voltages

For a given set of 3 thermocouple wires, A, B and C, all measuring the same temperature difference T_1-T_2, the voltage measured by wires A and C must equal the sum of the voltage measured by wires A and B and the voltage measured by wires B and C.

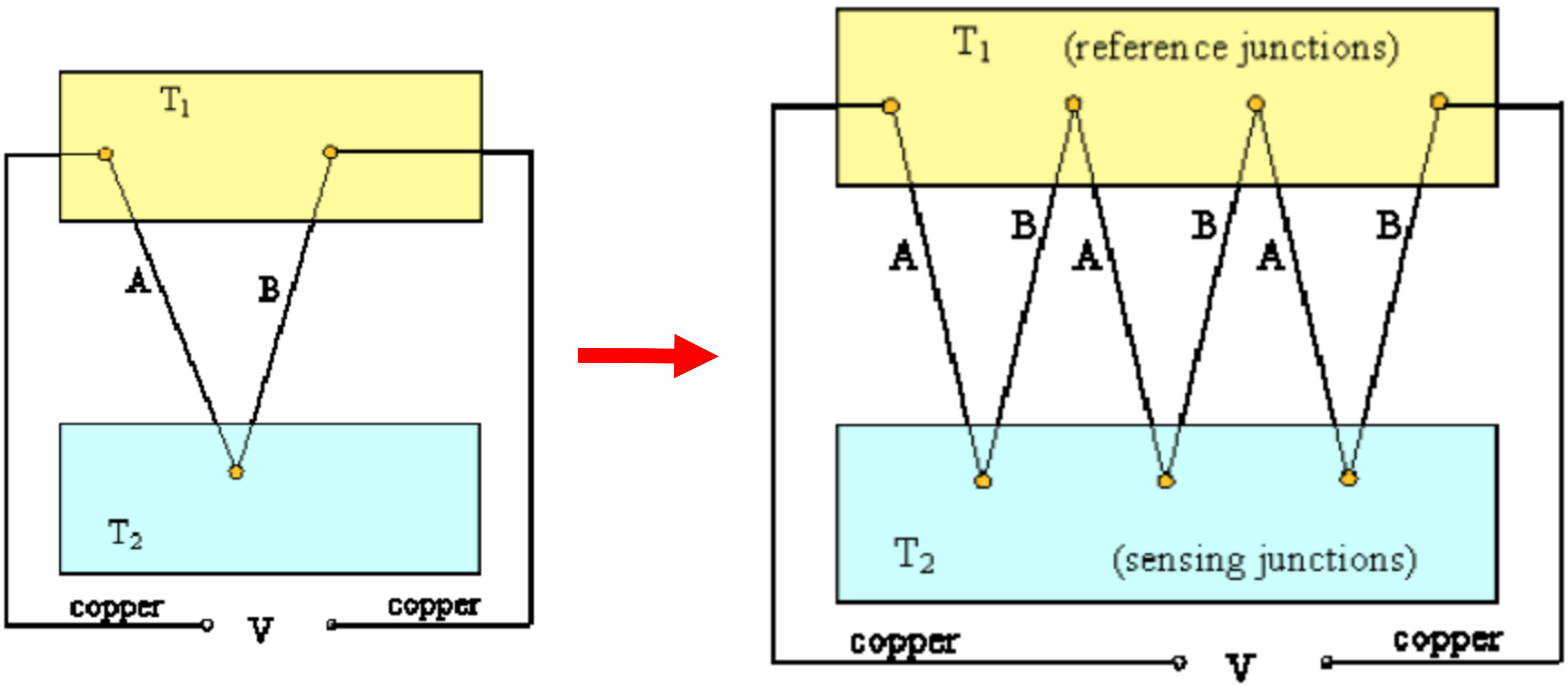


$$V_{1-2(with\ A,C)} = V_{1-2(with\ A,B)} + V_{1-2(with\ B,C)}$$

Thermopile

A **thermopile** is defined as several thermocouples connected in series.

- The advantage of a thermopile is increased sensitivity
- With enough sensing junctions, a thermopile can actually generate a useful voltage. For example, thermopiles are often used to control shut-off valves in furnaces.



Thermocouple Calibration Table

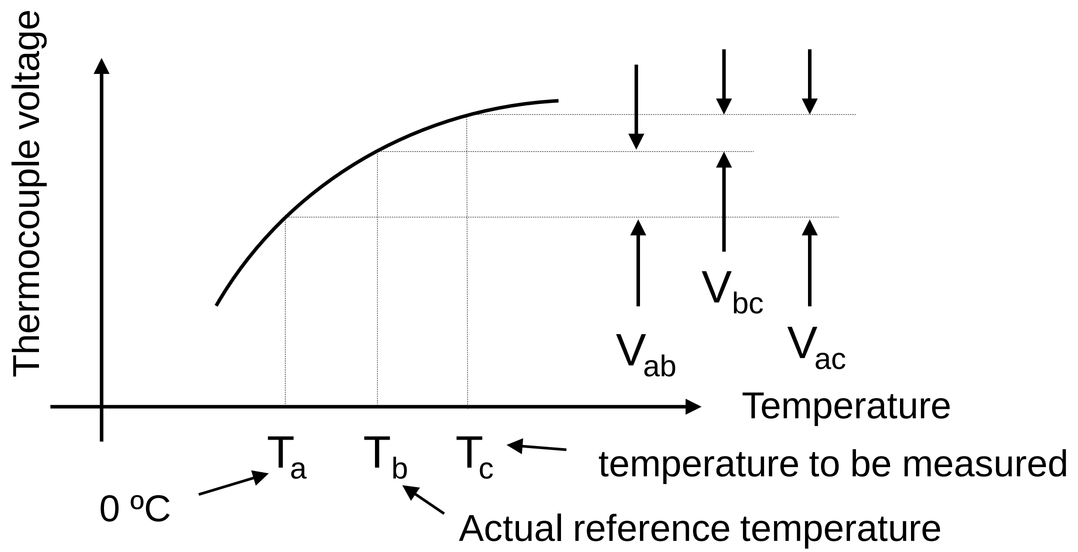
In a practical calibration, one junction would be kept at a known reference temperature, T_{ref}, (usually 0°C) and the other held at a unknown temperature $T_{unknown}$ and the voltage measured is then used to derive $T_{unknown}$.

Nickel-chromium/copper-nickel (Type E) thermocouple with reference temperature 0 ^{o}C. E.m.f (in mV).

T (^{o}C)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
20	1.19	1.25	1.31	1.37	1.43	1.49	1.56	1.62	1.68	1.74
30	1.80	1.86	1.92	1.98	2.04	2.10	2.17	2.23	2.29	2.35
40	2.41	2.48	2.54	2.60	2.66	2.72	2.79	2.85	2.90	2.98
50	3.05	3.11	3.17	3.23	3.30	3.36	3.43	3.49	3.55	3.61
60	3.68	3.74	3.81	3.87	3.94	4.00	4.07	4.13	4.20	4.27
70	4.34	4.40	4.47	4.53	4.60	4.66	4.73	4.79	4.86	4.92
80	4.99	5.05	5.12	5.19	5.26	5.32	5.39	5.45	5.52	5.59
90	5.66	5.72	5.79	5.85	5.92	5.98	6.05	6.12	6.19	6.25
100	6.32	6.39	6.46	6.52	6.59	6.66	6.73	6.80	6.80	6.94
110	7.01	7.07	7.14	7.21	7.28	7.35	7.42	7.48	7.55	7.62
120	7.69	7.76	7.83	7.90	7.97	8.04	8.11	8.18	8.25	8.32

Thermocouple: Correction/Compensation Method

Correction for thermocouples with reference temperature not at 0°C



Let T_a = 0°C , T_b = actual reference junction temperature and T_c = the temperature to be measured ($T_{unknown}$)

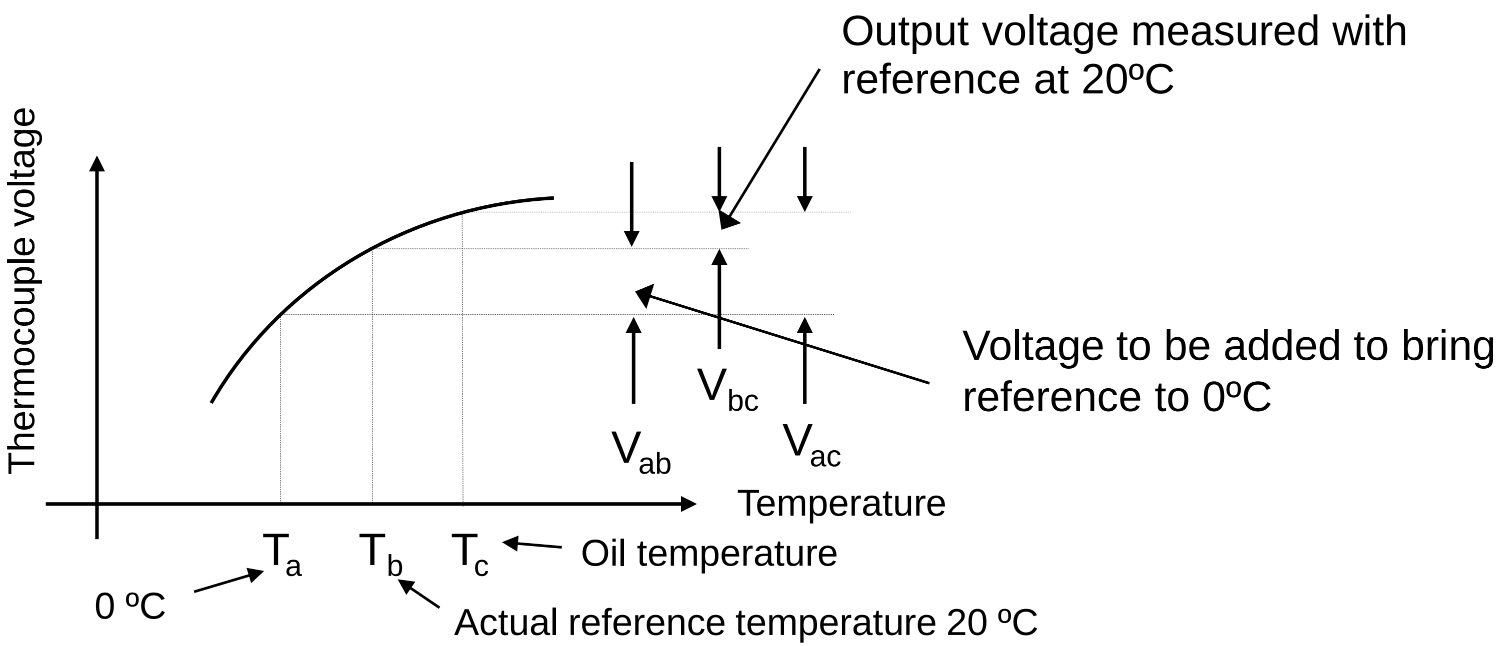
1) Look up V_{ab} from the Table

2) Add it to the measured voltage V_{bc} to give V_{ac}

3) Use V_{ac} to obtain the unknown temperature from the Table

Example 3.1

A type E thermocouple was used to measure the oil temperature of an engine. Its reference junction was at an ambient temperature of 20ºC. If an output voltage of 2.65mV was recorded, what was the temperature of the oil?



Solutions:

From the calibration table for type E thermocouple, the voltage produced with one junction at 0^{o}C and the other at 20^{o}C is 1.19mV.

The observed output voltage was 2.65mV. The total output voltage that would have been produced had the reference junction been placed at 0^{o}C is therefore:

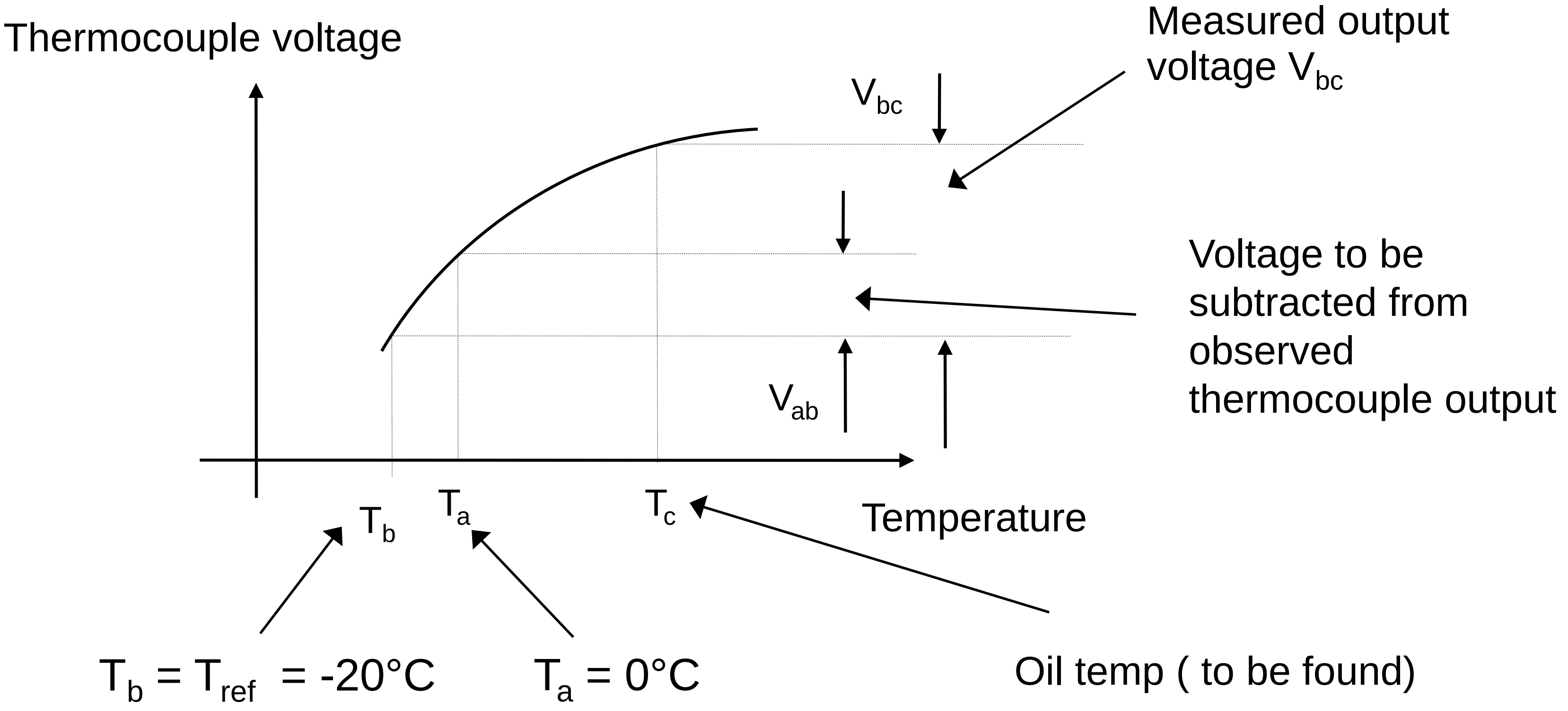
$$V_{ac} = V_{ab} + V_{bc} = 1.19 + 2.65 = 3.84\ mV.$$

This corresponds to an oil temperature of 62.5^{o}C.

Nickel-chromium/copper-nickel (Type E) thermocouple with reference temperature 0 deg.C. Emf (in mV).

T (deg.C)	0	1	2	3	4	5	6	7	8	9
20	1.19	1.25	1.31	1.37	1.43	1.49	1.56	1.62	1.68	1.74
30	1.80	1.86	1.92	1.98	2.04	2.10	2.17	2.23	2.29	2.35
40	2.41	2.48	2.54	2.60	2.66	2.72	2.79	2.85	2.90	2.98
50	3.05	3.11	3.17	3.23	3.30	3.36	3.43	3.49	3.55	3.61
60	3.68	3.74	3.81	3.87	3.94	4.00	4.07	4.13	4.20	4.27
70	4.34	4.40	4.47	4.53	4.60	4.66	4.73	4.79	4.86	4.92
80	4.99	5.05	5.12	5.19	5.26	5.32	5.39	5.45	5.52	5.59

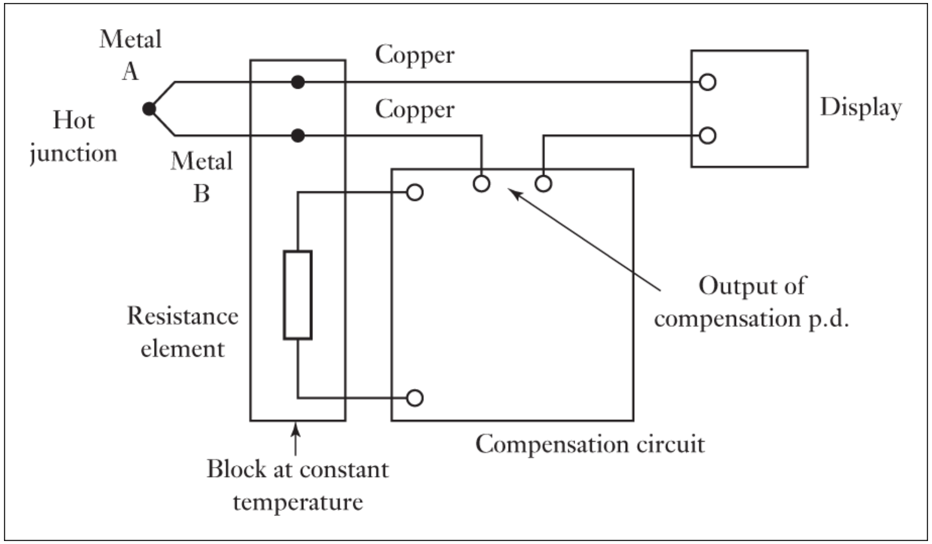
Note – if the reference temperature had been below 0ºC, then the correction voltage would have been subtracted.



Cold Junction Compensation

To maintain one junction of a thermocouple at 0°C, i.e. have it immersed in a mixture of ice and water, is often not convenient.

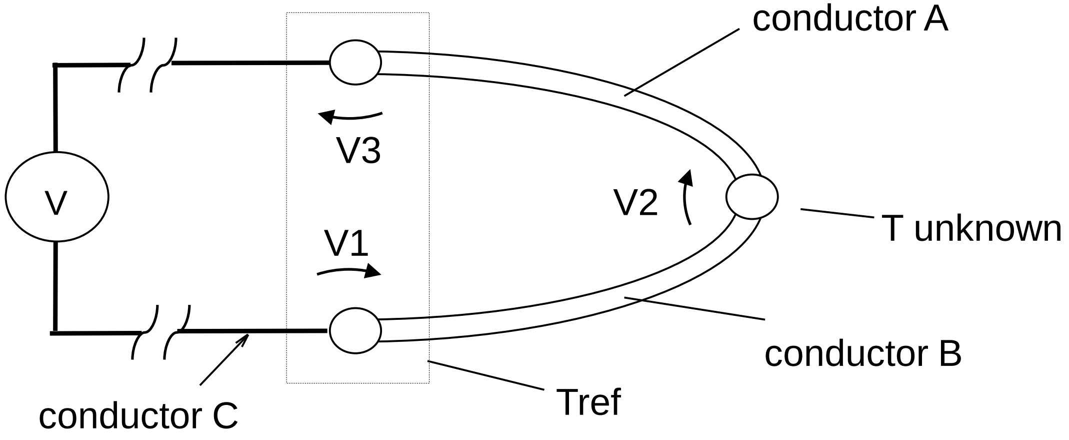
A compensation circuit can, however, be used to provide an e.m.f. which varies with the temperature of the cold junction (reference temperature). This is called 'cold-junction compensator'.



In such a way, the thermocouple will always generates a combined e.m.f. which is the same as when the cold junction is held at 0°C.

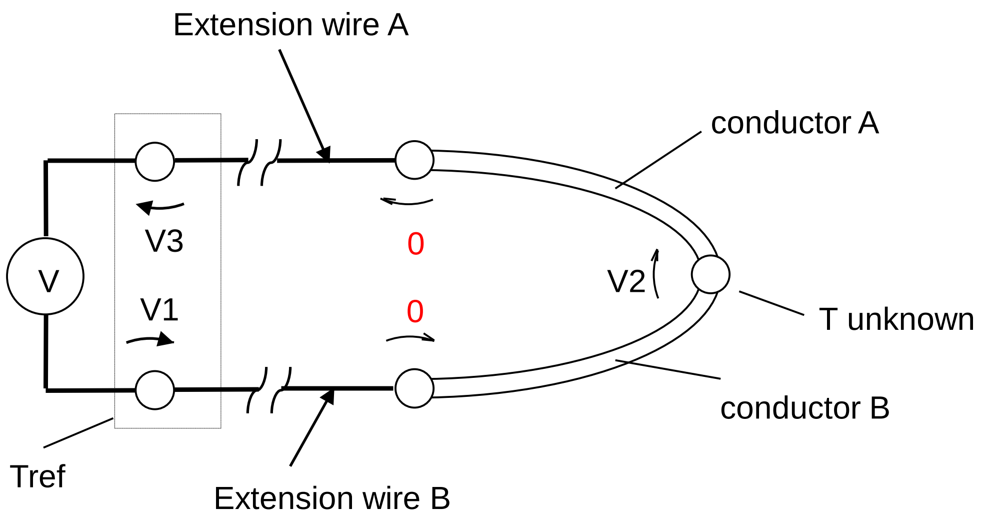
Thermocouple: Extension Wires

The measuring instrument or display is often required to be remote from the location of the unknown temperature being measured, the use of ordinary copper wires to connect the thermocouple would mean that those junctions become the new reference junction and its temperature would need to be known and the two junctions should be kept at the same temperature.



One solution is to use very long lengths of thermocouple wire.

This is very expensive!!



A lower cost alternative is to use extension wires of an appropriate composition such that no contact potentials are created at the junction with the actual thermocouple wires, but can be manufactured less expensively.

This can be done because the extension wires only have to match to the thermocouple wires over a much smaller range of temperatures (corresponding to the temperature of the junctions between the thermocouple and extension wires)

Quiz

Quiz 3.1

A thermocouple is used to measure temperature between 0 and 200^{o}C. The e.m.f. at 0^{o}C is 0 mV, at 100^{o}C it is 4.277 mV, and at 200^{o}C it is 9.286 mV. What will be the nonlinearity error at 100^{o}C? Please express it in %FSD. (Hint: use end-point nonlinearity)

Quiz 3.2

A type E thermocouple is used to measure temperature of some car engine. The reference junction is placed at 35^{o}C, the output voltage is 5.62 mV. What is the temperature of this car engine? (Please refer to the calibration table in previous slides)

Thank You !