Unit 15

Thermoelectric Effect

This unit online, with its interactives:
science-playground.com/s/12f15

Twist two different wires together, warm one joint with a candle, and a current flows round them, with no battery anywhere. It is a tiny current, but it measures the heat inside a furnace, keeps a gas heater from leaking gas when its flame blows out, and has kept the Voyager spacecraft talking to Earth for nearly fifty years. Run it backwards, pushing a current through the joints, and one joint gets cold: a refrigerator with no moving parts.

This unit is about these **thermoelectric effects**, where heat and electric charge in metals affect each other.

Thomas Johann Seebeck was a German physicist who worked on heat, electricity, magnetism and the science of materials. In 1821, experimenting with circuits, he found that a loop made of two different metals, with its two joints at different temperatures, deflected a compass needle placed near it: a current was flowing, driven by the difference in temperature alone. Seebeck himself thought he had found a way to make **magnetism** directly from heat, and called it "thermomagnetism"; others soon showed that the needle turned because of an electric current. The **Seebeck effect** showed for the first time a direct link between heat and electricity. It is the basis of the **thermocouples** used everywhere today to measure temperature, and of thermoelectric power generation and cooling.



Figure 15.1 *Thomas Johann Seebeck (1770–1831).*
Photo: The original uploader was Jlorenz1@web.de at German Wikipedia . (Original text: Ölbild im Familienbesitz (1932)), Public domain

15.1 Introduction

Have you ever wondered whether heat could make electricity?

The **thermoelectric effect** is the appearance of an e.m.f. when there is a difference of temperature across a material, or across the junctions of two materials. The elec-

tricity from such an e.m.f. is called **thermoelectricity**. It comes from the way heat and electric charge interact inside a conductor, and it is the foundation of the field of thermoelectrics.

The thermoelectric effect was discovered by Seebeck in 1821. It offers ways of converting energy and controlling heat that matter in renewable energy and electronics, and it is used for measuring temperature, for thermoelectric power generation and for cooling.

There are three thermoelectric effects:

- the **Seebeck effect** (Section 15.2): a temperature difference makes an e.m.f.;
- the **Peltier effect** (Section 15.5): a current makes one junction hot and the other cold;
- the **Thomson effect** (Section 15.6): a current along a single wire whose ends are at different temperatures gives out or takes in heat along it.

15.2 Seebeck effect

What do you think might happen if two different metals are joined and one of their junctions is heated?

When two wires of different materials are joined to form a closed loop, and the two junctions are kept at **different temperatures**, a small e.m.f. is set up in the circuit, and a small current flows round it in a definite direction. This is the **Seebeck effect** (or the thermoelectric effect, in its narrow sense). The e.m.f. is called the **thermo e.m.f.**, and the current it drives the **thermoelectric current**.

The e.m.f. is small. For a copper–iron pair with one junction in ice and the other in boiling water, it is about a millivolt; a pair often used in industry, chromel and alumel (the “type K” thermocouple), gives about 41 μV for each degree of difference, about 4 mV at 100 °C. Small, but easy to measure accurately with a potentiometer or a modern electronic meter.

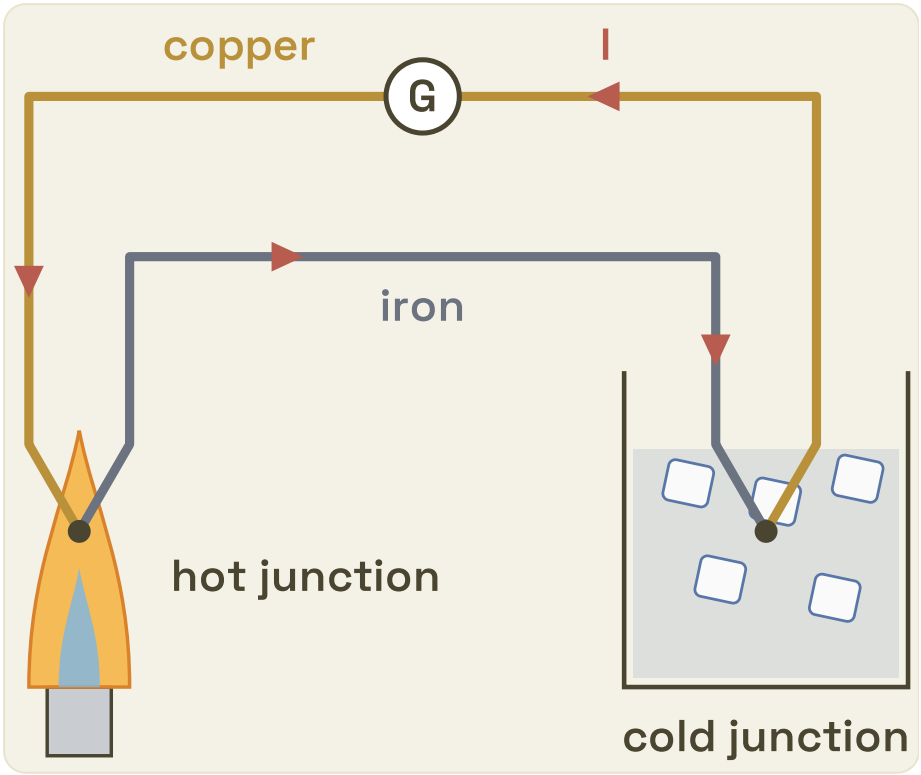


Figure 15.2 *A copper–iron thermocouple. One junction is heated in a flame (the hot junction) and the other is kept in ice (the cold junction). A galvanometer in the copper wire shows a current: it flows from copper to iron at the hot junction, and from iron to copper at the cold junction.*

Causes of the Seebeck effect

The usual textbook explanation: different metals have different numbers of free electrons per unit volume (different **electron densities**). When two metals are joined, free electrons diffuse from the metal with the higher electron density into the one with the lower, until the charge built up stops them. A potential difference, the **contact potential**, is set up at the junction.

If both junctions are at the **same temperature**, the contact potentials at the two junctions are equal and opposite round the loop, and no current flows. If one junction is **heated**, the electrons there diffuse faster and the contact potential at that junction is greater. The two no longer cancel, and the difference is a net e.m.f. round the loop: the **thermo e.m.f.**

CAREFUL

Where the e.m.f. really comes from

The contact-potential picture is what most books give, and it explains why two different metals are needed and why a temperature difference is. But the e.m.f. isn't really made at the junctions. It is made **along the wires**, wherever there is a temperature gradient. In each wire, the electrons at the hot end move faster and spread towards the cold end more than the cold ones spread back, until a small voltage along the wire balances them. This **thermal diffusion** gives a voltage along each wire that depends on its metal. In a loop of one metal, the voltages along its two sides cancel exactly, however hot one junction is. In a loop of two metals they don't cancel, and the difference is the Seebeck e.m.f. The junctions only decide where one metal changes to the other. That is why a thermocouple can be made with joints of any shape, soldered, welded or twisted, and still give the same e.m.f.

Check 1

A loop is made of two copper wires, one junction heated in a flame and the other kept in ice. The galvanometer in the loop shows:

a no current, because both wires are of the same metal

b a current from the hot junction to the cold one

c a current that grows as the hot junction gets hotter

d a current only while the flame is being moved

15.3 Thermocouples

Have you ever wondered why a thermocouple needs two different metals?

A pair of wires of two different metals, joined to form a loop that produces thermoelectricity, is called a **thermocouple**. The size of its e.m.f., and the direction of its current, depend on **which two metals** are chosen (their places in the thermoelectric series, below) and on the **temperatures of the junctions**. If the heating and cooling of the junctions are swapped, the current flows the other way.

A very common thermocouple, copper–iron, and the direction of its current, is shown in Figure 15.2.

16.

a. Discuss the principle and construction of a thermocouple.

b. How is it used to measure temperature? How are thermocouples used for measuring temperature in industry? List their advantages and limitations.

c. A thermocouple has its neutral temperature at 270 °C. If the cold junction is at 30 °C, at what temperature will the e.m.f. become zero again (the temperature of inversion)?

17.

a. Discuss the materials used in common thermocouples, and explain why they are chosen.

b. Two metals A and B form a thermocouple. The e.m.f. is 2.8 mV when the hot junction is at 150 °C and the cold junction at 30 °C. Find the average Seebeck coefficient.

18.

a. Describe the working of a thermopile and its use in detecting radiation.

b. A thermocouple gives a reading of 5 mV when its hot junction is at 200 °C. Find the e.m.f. when the hot junction is at 150 °C, assuming a linear relation.

19.

a. Explain the construction and calibration of a thermocouple using standard reference junctions.

b. A thermocouple produces a thermoelectric e.m.f. of 4.5 mV when its hot junction is at 100 °C and its cold junction at 0 °C. Calculate the Seebeck coefficient.

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

Answer these questions

12.

a. What is the Seebeck effect?

b. Discuss the cause of thermo e.m.f. Explain its mechanism with the help of a diagram.

c. List the factors on which the thermo e.m.f. produced in a thermocouple depends.

d. In a copper–iron thermocouple, the e.m.f. is related to the temperature of the hot junction (with the cold junction at 0 °C) by $E = a\theta + b\theta^2$, with a = 14 μV/°C and b = −0.04 μV/°C². Find the neutral temperature and the temperature at which the thermo e.m.f. changes its sign.

The textbook gives b = 0.04 μV/°C², positive; with a positive b the e.m.f. would only keep rising, with no maximum and no change of sign, so the book's numbers don't work. Its answers, 175 °C and 350 °C, need b = −0.04 μV/°C², as here.

13.

a. What is thermoelectric e.m.f.?

b. Describe the origin of thermo e.m.f., and explain how it varies with the temperature of the hot junction.

c. The two junctions of a thermocouple are kept at 0 °C and θ °C. The thermo e.m.f. is given by $E = 10^{-5}\theta - 0.01 \times 10^{-5}\theta^2$ volts. Find the neutral temperature and the maximum value of the thermo e.m.f.

14.

a. Explain the Peltier effect. How is it different from the Seebeck effect?

b. How can you say that the Peltier effect is the converse of the Seebeck effect?

c. Compare and contrast the Seebeck and Peltier effects, with examples and applications.

d. The e.m.f. produced by a thermocouple is $E = aT + bT^2$, where a = 25 μV/°C and b = 0.01 μV/°C². Calculate the e.m.f. when T = 100 °C.

15.

a. Define neutral temperature and temperature of inversion of a thermocouple. How are they determined?

b. On what does the temperature of inversion depend?

c. The junctions of a nickel–copper thermocouple are kept at 0 °C and 100 °C. Find the Seebeck e.m.f. produced, using $E = \alpha\theta + \frac{1}{2}\beta\theta^2$, with α = 16.3×10^{-6} V/°C and β = -0.042×10^{-6} V/°C² for this couple.

Thermoelectric series

A **thermoelectric series** is a list of metals in order, arranged so that the order tells which way the current flows in a thermocouple made of any two of them, and roughly how big its e.m.f. is. It helps in choosing a suitable pair of metals for a thermocouple. The metals in the series are:

Antimony (Sb), Iron (Fe), Zinc (Zn), Silver (Ag), Gold (Au), Tin (Sn), Lead (Pb), Copper (Cu), Platinum (Pt), Cobalt (Co), Nickel (Ni), Bismuth (Bi)

The series is drawn up from the Seebeck effect itself, by measuring each pair. When any two metals of the series form a thermocouple:

- the current flows **through the cold junction** from the metal that comes **earlier** in the series to the one that comes **later** (and so through the hot junction from the later to the earlier);
- the **farther apart** the two metals are in the series, the **larger** the e.m.f. (for small temperature differences). Antimony and bismuth, at the two ends, make the strongest pair in the list.

Two rules help remember the direction:

- **"Hot coffee"**, **Hot Cu–Fe**: at the **hot** junction, the current flows from **Cu** to **Fe**.
- **"ABC"**, **A**ntimony to **B**ismuth at the **C**old junction: at the cold junction, the current flows from Sb to Bi.

Both agree with the series: iron comes before copper, so at the cold junction the current goes from iron to copper, and at the hot junction from copper to iron.

> DID YOU KNOW?
>
> **Which metals are used, and why**
>
> Real thermocouples use alloys chosen for a large, steady e.m.f. that changes nearly in proportion to the temperature, and for wires that survive heat. **Type K** (chromel–alumel, two nickel alloys) is the everyday one, from −200 °C to about 1250 °C; **type J** (iron–constantan) for up to about 750 °C; **type T** (copper–constantan) for low temperatures; and **types R and S** (platinum against platinum–rhodium) for furnaces up to about 1600 °C, where they barely change with use. The tables that turn each type's e.m.f. into a temperature are international standards.

WORKED EXAMPLE

Example 15.1: the cause of thermo e.m.f.

What is the cause of thermo e.m.f.?

Answer

Different metals have different numbers of free electrons per unit volume (electron density), and how they behave depends on temperature. When two metals with different electron densities are joined, free electrons diffuse from the metal of higher electron density to the metal of lower, setting up a contact potential at each junction. If the two junctions are at the same temperature, the two contact potentials are equal and opposite round the loop. If one junction is hotter, its electrons diffuse faster and its contact potential is larger, so the two don't cancel: the difference is the thermo e.m.f., and it drives a current round the loop. A larger temperature difference gives a larger e.m.f. (More exactly, the e.m.f. arises from the electrons' diffusion from hot to cold along each wire, which is different in the two metals.)

WORKED EXAMPLE

Example 15.2: what the e.m.f. depends on

What are the factors on which the thermo e.m.f. produced in a thermocouple depends?

Answer

The thermo e.m.f. depends on:

i. the **nature of the two metals** forming the thermocouple (their electron densities; their places in the thermoelectric series);

ii. the **difference of temperature** between the two junctions (and, since the e.m.f. isn't exactly proportional to it, on the actual temperatures).

It doesn't depend on the length or thickness of the wires, or on how the junctions are made.

15.4 Variation of thermo e.m.f. with temperature

To study how the thermo e.m.f. changes with temperature, an **iron–copper** thermocouple can be used as in Figure 15.3. One junction is kept at a constant low temperature θc, in a mixture of ice and water. The other is put in an **oil bath** (oil, not water,

Check 8

6. A Peltier device is used for cooling an electronic circuit. What happens when the direction of current is reversed?

a The cooling effect remains unchanged.
b The cooling and heating junctions switch roles.
c The entire device stops working.
d The thermoelectric e.m.f. becomes zero.

Check 9

7. The efficiency of a thermoelectric generator depends on:

a the material used and the temperature difference between junctions.
b only the material used.
c only the temperature difference.
d the external electric field applied.

Check 10

9. A thermocouple generates an e.m.f. of 5 mV when the temperature difference between its junctions is 100 °C. What will be the e.m.f. when the temperature difference increases to 500 °C, assuming a linear relationship?

a 10 mV
b 20 mV
c 25 mV
d 50 mV

Check 11

10. A Peltier module has a coefficient of performance (COP) of 0.5. If the input power is 10 W, what is the rate at which heat is absorbed at the cold junction?

a 2 W
b 5 W
c 10 W
d 20 W

Check 12

11. A copper–constantan thermocouple develops a thermoelectric e.m.f. of 1 mV for a temperature difference of 10 °C. If the hot junction is at 300 °C and the cold junction at 20 °C, calculate the expected e.m.f. (taking it as proportional to the difference).

a 20 mV
b 25 mV
c 28 mV
d 30 mV

Check 4

2. In a thermocouple, the thermoelectric e.m.f. is generated due to:

a the difference in electrical resistance of the metals.
b the difference in temperature between two junctions of dissimilar metals.
c the application of an external magnetic field.
d the flow of current from high potential to low potential.

Check 5

3. Why does the thermoelectric e.m.f. vary non-linearly with temperature in a thermocouple?

a Because the resistance of metals varies with temperature.
b Due to the dependence of electron energy distribution on temperature.
c Because the temperature difference between junctions remains constant.
d Due to the direct proportionality between e.m.f. and temperature.

Check 6

4. What is the main function of a thermocouple?

a To generate a magnetic field.
b To convert electrical energy into mechanical energy.
c To measure temperature using thermoelectric e.m.f.
d To store electrical energy.

Check 7

5. An iron–constantan thermocouple is used in an industrial furnace. If the hot junction is at 800 °C and the cold junction at room temperature (25 °C), what behavior of the e.m.f. is expected?

a The e.m.f. remains constant irrespective of temperature change.
b The e.m.f. increases with temperature difference.
c The e.m.f. decreases with temperature difference.
d The e.m.f. oscillates randomly.

so it can be heated well above 100 °C) with a thermometer, and heated. A sensitive galvanometer (or a potentiometer) measures the e.m.f.

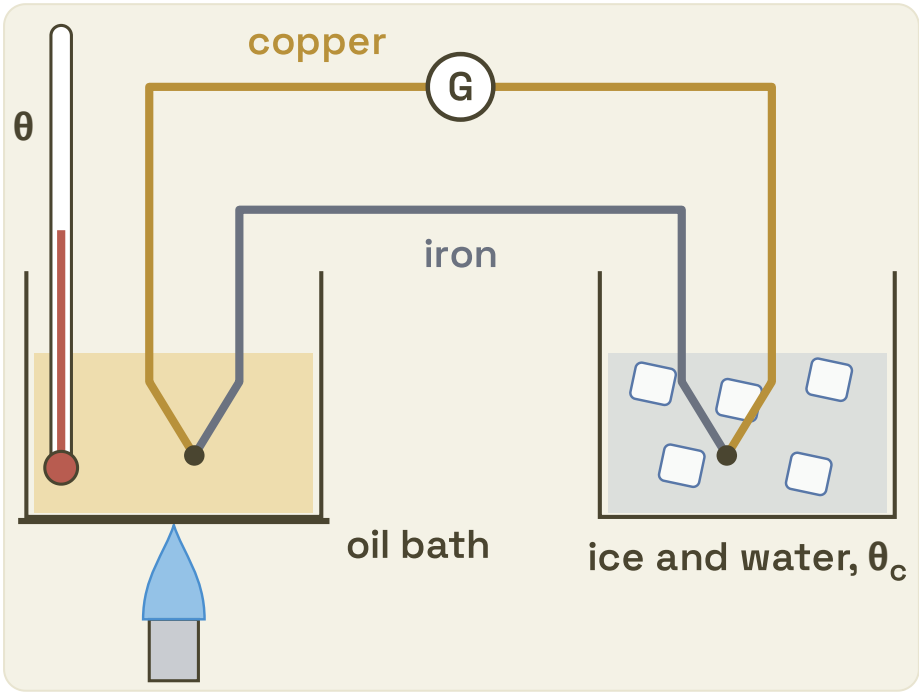


Figure 15.3 *Measuring a thermocouple's e.m.f. against temperature. The copper–iron thermocouple's cold junction is in ice and water at θc, and its hot junction, beside a thermometer, in an oil bath over a burner. A galvanometer in the copper wire shows the current.*

When both junctions are at the same temperature θc, there is no e.m.f., and the galvanometer shows no deflection. As the oil is heated, keeping the cold junction at θc, the galvanometer shows the thermo e.m.f. **increasing**, becoming a **maximum**, then **decreasing** to zero, and finally **reversing** its direction (Figure 15.4).

- The temperature of the hot junction at which the thermo e.m.f. is a **maximum** is called the **neutral temperature**, θn. For an iron–copper thermocouple, the neutral temperature is about **270 °C**. It depends only on the two metals, **not** on the temperature of the cold junction.
- The temperature of the hot junction at which the thermo e.m.f. becomes **zero and then reverses** is called the **temperature of inversion**, θi. It depends on the two metals **and** on the temperature of the cold junction.

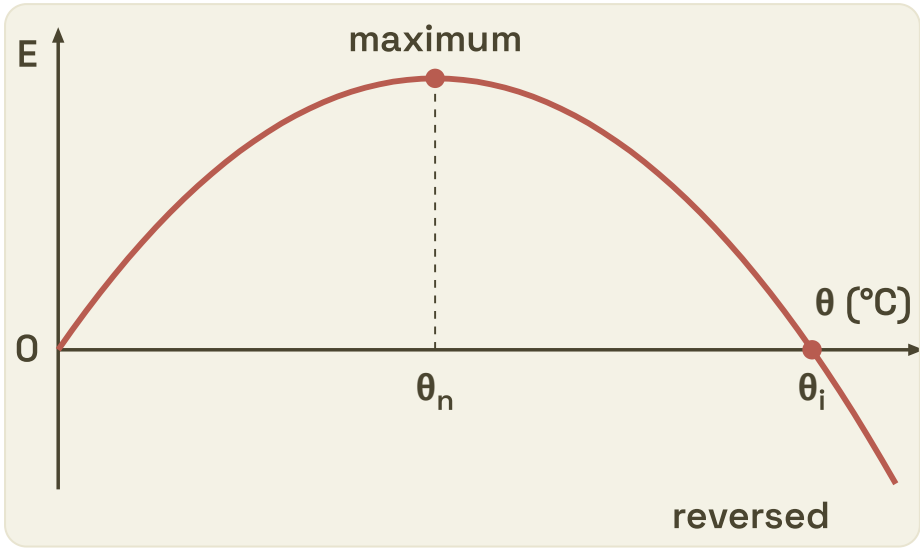


Figure 15.4 *Thermo e.m.f. against the hot junction's temperature θ, with the cold junction at θc = 0 °C. The e.m.f. rises to a maximum at the neutral temperature θn, falls to zero at the temperature of inversion θi = 2θn, and then changes sign. The curve is a parabola, symmetric about θn.*

The e.m.f. as a formula

The graph of thermo e.m.f. against temperature is a **parabola**. With the cold junction at 0 °C and the hot junction at θ (in °C), it is expressed as

$$E = \alpha\theta + \frac{1}{2}\beta\theta^2 \quad \dots (15.1)$$

where α and β are **thermoelectric coefficients**, constants for a given pair of metals. For iron–copper, α is positive and β negative; a negative β makes the parabola turn over.

Knowing α and β, θn and θi can be found.

Step 1. Neutral temperature. E is a maximum where its slope is zero:

$$\frac{dE}{d\theta} = \alpha + \beta\theta = 0 \qquad \Rightarrow \qquad \theta_n = -\frac{\alpha}{\beta} \quad \dots (15.2)$$

Step 2. Temperature of inversion. E is zero where

$$\alpha\theta + \frac{1}{2}\beta\theta^2 = \theta\left(\alpha + \frac{1}{2}\beta\theta\right) = 0$$

The root θ = 0 is the cold junction's own temperature; the other is

$$\theta_i = -\frac{2\alpha}{\beta} = 2\theta_n \quad \dots (15.3)$$

IN SHORT

- **Seebeck effect:** in a loop of two different metals with its junctions at different temperatures, a **thermo e.m.f.** is set up and a current flows. It depends on the two metals and the temperature difference.
- **Thermoelectric series:** Sb, Fe, Zn, Ag, Au, Sn, Pb, Cu, Pt, Co, Ni, Bi. Current flows from the earlier metal to the later through the cold junction ("ABC": Sb to Bi at the cold junction; "hot coffee": Cu to Fe at the hot junction).
- **Thermo e.m.f. against temperature:** a parabola, $E = \alpha\theta + \frac{1}{2}\beta\theta^2$. **Neutral temperature** (maximum e.m.f.): $\theta_n = -\alpha/\beta$, independent of the cold junction. **Temperature of inversion** (e.m.f. zero, then reversed): $\theta_i = -2\alpha/\beta - \theta_c$; $\theta_n = (\theta_c + \theta_i)/2$. With $E = a\theta + b\theta^2$: $\theta_n = -a/2b$.
- **Peltier effect:** a current through a thermocouple heats one junction and cools the other; reversing the current swaps them. Reverse of the Seebeck effect; used in thermoelectric coolers.
- **Thomson effect:** a current along one conductor with a temperature gradient gives out or absorbs heat, depending on its direction.
- **Thermopile:** many Sb–Bi thermocouples in series, one set of junctions blackened, to detect and measure heat radiation.

Exercise

Choose the correct option

Check 3

1. Which of the following statements correctly defines the Seebeck effect?

a The conversion of heat energy into electrical energy due to a temperature difference.

b The emission of electrons from a heated metal surface.

c The production of heat due to the passage of electric current.

d The generation of a magnetic field in a coil due to current flow.

vanometer deflect. The **higher the intensity** of the radiation, the more the blackened junctions are warmed, and the **larger the deflection**.

Antimony and bismuth are used because they are at the two ends of the thermoelectric series, and so give the largest e.m.f. for each degree of difference.

DID YOU KNOW?

The thermometer you point at a forehead

The non-contact infrared thermometers used at the doors of schools and hospitals, and in kitchens, are built round a tiny **thermopile**: hundreds of microscopic thermocouples on a silicon chip, their hot junctions on a thin blackened membrane. Infrared radiation from the forehead, focused by a lens, warms the membrane by a fraction of a degree, and the thermopile's e.m.f. gives the temperature in about a second.

Electricity from heat

Turned to generating, the Seebeck effect makes **thermoelectric generators**, with no moving parts. The **Voyager** spacecraft, launched in 1977 and now beyond the planets, are powered by heat from decaying plutonium-238, turned into electricity by silicon–germanium thermocouples; so is the **Curiosity** rover on Mars. On Earth, small thermoelectric modules on wood stoves can charge a phone or a light where there is no grid. They are not efficient, a few percent to about 8 % of the heat becomes electricity, but they are silent, reliable and last for decades.

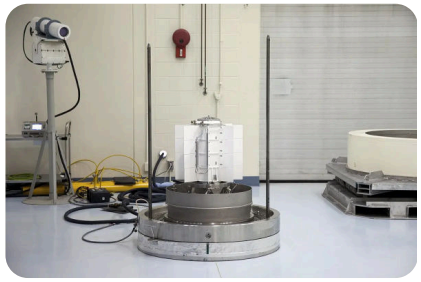


Figure 15.9 *The thermoelectric generator that powers the Curiosity rover on Mars. Heat from plutonium-238 inside warms one set of thermocouple junctions; the fins keep the other set cool.*

Photo: Kim Shiflett, Public domain

Step 3. A cold junction not at 0 °C. With the cold junction at θc, the e.m.f. is the difference between the two junctions' values, $E = \alpha(\theta - \theta_c) + \tfrac{1}{2}\beta(\theta^2 - \theta_c^2)$. Its slope, α + βθ, is the same as before, so the **neutral temperature doesn't change**. It is zero where $\alpha + \tfrac{1}{2}\beta(\theta + \theta_c) = 0$ (dividing by θ − θc), that is at $\theta_i = -\dfrac{2\alpha}{\beta} - \theta_c = 2\theta_n - \theta_c$.

So

$$\theta_i - \theta_n = \theta_n - \theta_c \qquad \text{or} \qquad \boxed{\theta_n = \frac{\theta_c + \theta_i}{2}} \qquad \ldots (15.4)$$

The neutral temperature lies **halfway** between the cold junction's temperature and the temperature of inversion. The parabola is symmetric about θn: raising θc moves θi down by the same amount.

CAREFUL

Two ways of writing the same parabola

Some books write the e.m.f. as $E = a\theta + b\theta^2$, with b in place of ½β. Then $\dfrac{dE}{d\theta} = a + 2b\theta$, so $\theta_n = -\dfrac{a}{2b}$ and $\theta_i = -\dfrac{a}{b}$. Check which form a question uses before putting numbers into a formula: the same pair of metals has b = ½β.

WORKED EXAMPLE

Example 15.3: finding the neutral temperature

In a thermocouple, the temperature of the cold junction is −10 °C and the temperature of inversion is 510 °C. What is the neutral temperature?

Answer

θc = −10 °C, θi = 510 °C.

$$\theta_n = \frac{\theta_c + \theta_i}{2} = \frac{-10 + 510}{2} = \frac{500}{2} = \mathbf{250\ ^\circ C}$$

(Take care with the sign: the cold junction is 10 degrees **below** zero.)

WORKED EXAMPLE

Example 15.4: from the coefficients

The thermo e.m.f. and the temperature θ of the hot junction satisfy $E = a\theta + b\theta^2$, where $a = 4.1 \times 10^{-5}$ V/°C and $b = -4.1 \times 10^{-8}$ V/°C². If the cold junction is at 0 °C, find the neutral temperature.

Answer

$$\frac{dE}{d\theta} = a + 2b\theta$$

At the neutral temperature the e.m.f. is a maximum, so $\frac{dE}{d\theta} = 0$:

$$a + 2b\theta_n = 0 \quad \Rightarrow \quad \theta_n = \frac{a}{-2b} = \frac{4.1 \times 10^{-5}}{-2 \times (-4.1 \times 10^{-8})} = \mathbf{500\ ^\circ C}$$

WORKED EXAMPLE

Example 15.5: the largest e.m.f.

One junction of a thermocouple is at 0 °C and the other at θ °C. The thermo e.m.f. (in volts) is $E = 20 \times 10^{-6}\theta - 0.02 \times 10^{-6}\theta^2$. Find the neutral temperature and the maximum value of the e.m.f.

Answer

$$\frac{dE}{d\theta} = 20 \times 10^{-6} - 2 \times 0.02 \times 10^{-6}\,\theta = 2 \times 10^{-5} - 4 \times 10^{-8}\,\theta$$

At the neutral temperature the e.m.f. is a maximum, so $\frac{dE}{d\theta} = 0$:

$$2 \times 10^{-5} = 4 \times 10^{-8}\,\theta_n \quad \Rightarrow \quad \theta_n = \frac{2 \times 10^{-5}}{4 \times 10^{-8}} = \mathbf{500\ ^\circ C}$$

The maximum e.m.f.:

$E_m = 20 \times 10^{-6} \times 500 - 0.02 \times 10^{-6} \times 500^2 = 0.010 - 0.005 = 0.005\ \text{V} = \mathbf{5}$

15.7 Thermopile

A **thermopile** is a device for **detecting and measuring heat radiation**, such as the intensity of radiation from the Sun. It can also measure the high temperatures of furnaces. It works on the **Seebeck effect**.

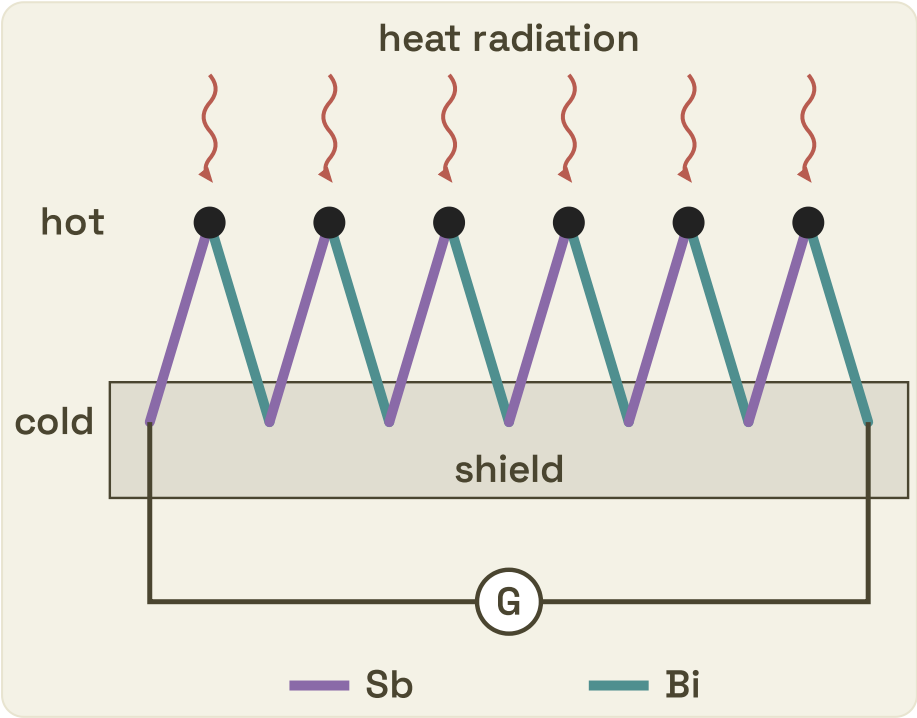


Figure 15.8 *A thermopile: antimony–bismuth thermocouples joined in series in a zigzag. The junctions on one side are blackened and face the radiation; those on the other side are shielded and stay cool. A galvanometer joined to the two ends measures the total e.m.f.*

Construction. A thermopile is made of a number of **antimony–bismuth thermocouples** joined in **series**, packed together in the form of a pile (Figure 15.8). One set of junctions is coated with **lamp black** (soot), which absorbs heat radiation well, and faces the radiation; the other set is shielded and kept at a steady, lower temperature. A sensitive galvanometer is connected across the ends of the series.

Working. When heat radiation falls on the blackened junctions, it is absorbed and their temperature rises. The difference of temperature between the two sets of junctions makes a thermo e.m.f. in **each** thermocouple, and since they are in series, these add up: n thermocouples give n times the e.m.f. of one. The total e.m.f. makes the gal-

DID YOU KNOW?

Freezing water with a current

In 1838, four years after Peltier's discovery, **Heinrich Lenz** (of Lenz's law) put a drop of water on a junction of bismuth and antimony, the two ends of the thermoelectric series, and passed a current through it. The water **froze**. Reversing the current, he melted the ice again. Real Peltier coolers use semiconductors, because their thermoelectric effects are hundreds of times larger than metals'.

15.6 Thomson effect

The third thermoelectric effect was predicted in 1851 by **William Thomson** (later **Lord Kelvin**), who worked out, from the laws of thermodynamics, that the Seebeck and Peltier effects could only be consistent if there were a third effect, and then found it by experiment.

When a current flows along a **single conductor** whose two ends are at **different temperatures**, heat is **given out or absorbed** along the conductor, depending on the direction of the current. This is the **Thomson effect**. Like the Peltier effect, it is reversible: reversing the current turns heating into cooling. Which way depends on the metal:

- In **copper** (and silver, zinc, antimony), a current flowing from the hot end to the cold end gives out heat, and a current from the cold end to the hot end absorbs it. The Thomson effect is said to be **positive**.
- In **iron** (and cobalt, nickel, platinum, bismuth), it is the other way round: a current from the hot end to the cold end absorbs heat, and from the cold end to the hot end gives it out. The Thomson effect is **negative**.
- In **lead** it is so small that lead is used as the reference metal when thermo e.m.f.s are measured.

The Thomson effect is why the thermo e.m.f. isn't simply proportional to the difference of temperature: it is what makes the curve of Figure 15.4 bend. Thomson's relations, linking all three effects, are part of thermodynamics; you will meet them in university physics.

WORKED EXAMPLE

Example 15.6: cooling the cold junction

If the temperature of the cold junction of a thermocouple is lowered, what happens to its neutral temperature?

Answer

Nothing. The neutral temperature is the hot junction's temperature at which the e.m.f. is a maximum, where $dE/d\theta = \alpha + \beta\theta = 0$. This depends only on α and β, that is on the two metals, and not on the cold junction's temperature. (The temperature of inversion does change: $\theta_i = 2\theta_n - \theta_c$ rises as θc is lowered.)



Figure 15.5 *A thermocouple probe. The two wires are joined at the tip inside the steel sheath; the plug connects them to a meter that keeps track of the cold junction's temperature.*
Photo: User:Harke, CC BY-SA 3.0

DID YOU KNOW?

The thermocouple that stops gas leaks

Many gas heaters and gas ovens, and some LPG stoves, have a **flame failure device**: a thermocouple whose tip sits in the pilot flame. Its few millivolts drive a current through a small electromagnet that holds the gas valve open. If the flame blows out, the thermocouple cools within seconds, the current stops, the magnet lets go, and a spring shuts off the gas. No battery, no electronics: the flame powers its own safety valve.

15.5 Peltier effect

When an electric current is passed through a thermocouple, heat is **given out** at one junction and **absorbed** at the other, depending on the direction of the current (Figure 15.6). This is the **Peltier effect**, found by the French watchmaker turned physicist

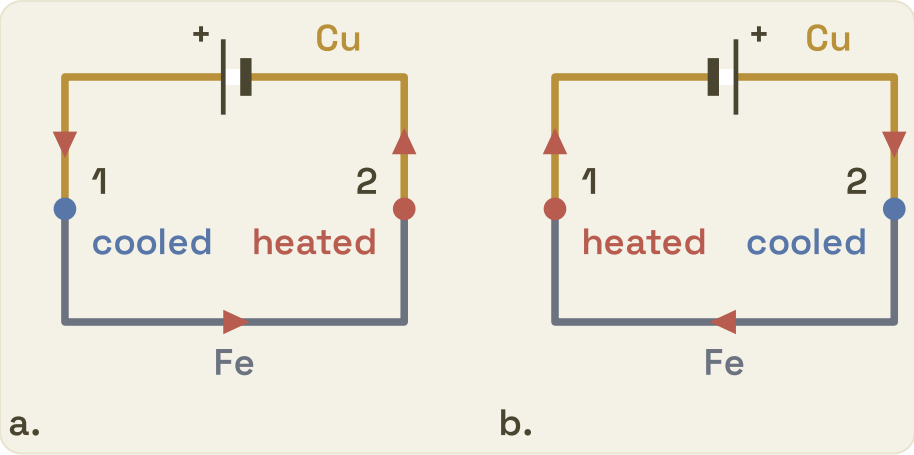


Figure 15.6 *The Peltier effect in a copper–iron couple joined to a cell. a. With the current flowing from copper to iron at junction 1, junction 1 is cooled and junction 2 heated. b. With the current reversed, junction 1 is heated and junction 2 cooled.*

Jean Charles Peltier in 1834. It is the **reverse of the Seebeck effect**: there a temperature difference makes a current; here a current makes a temperature difference.

The Peltier effect is **reversible**: when the direction of the current is reversed, the junction that was absorbing heat gives it out and the other absorbs it. This makes it quite different from Joule heating (I^2Rt), which heats a wire whichever way the current flows and is proportional to the square of the current; the Peltier heat is proportional to the current itself, and changes sign with it.

For a copper–iron couple, heat is **absorbed** (the junction cools) at the junction where the current flows from **copper into iron**, and **given out** (the junction warms) where it flows from **iron into copper**. This fits the Seebeck effect: in a copper–iron thermocouple the Seebeck current flows from copper to iron at the **hot** junction, and a current flowing that way through a junction **takes in heat** there. The thermocouple's own current always tends to cool its hot junction and warm its cold one, as it should: it is turning heat into electrical energy.

Causes of the Peltier effect

When two different metals are joined, a contact potential is set up at the junction. In the copper–iron couple, iron is at the **higher potential**. When a current is driven round the couple:

- at the junction where the current flows from the higher-potential metal to the lower (**iron to copper**), the charges lose energy, which is **given out** as heat: the junction becomes **hot**;
- at the junction where the current flows from the lower-potential metal to the higher (**copper to iron**), the charges must gain energy, which they **absorb** as heat from the junction: the junction becomes **cool**.

In Figure 15.6a, the current flows from copper to iron at junction 1 (cooled) and from iron to copper at junction 2 (heated); in b, the other way round.

Check 2

In a Peltier cooler, the direction of the current is reversed. Then:

a the cooling continues as before

b the cold side becomes hot and the hot side cold

c both sides become hot

d the device stops working

Uses of the Peltier effect

Peltier devices (**thermoelectric coolers**) are used for refrigeration and cooling: small car and picnic fridges, cooling the sensors of cameras and scientific instruments, keeping lasers and medical samples at a steady temperature, and water dispensers that give cold water. Reversing the current turns the same device into a **heater**. They have no moving parts and no refrigerant gas, so they are silent and last long, but they use more electricity than a compressor fridge for the same cooling.

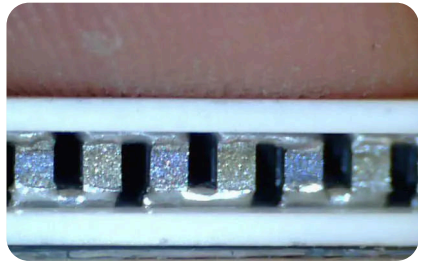


Figure 15.7 *Inside a Peltier module: many small blocks of semiconductor (bismuth telluride), joined in series by copper strips between two ceramic plates. One plate gets cold and the other hot.*

Photo: Michael Bemmerl, CC BY 3.0 de