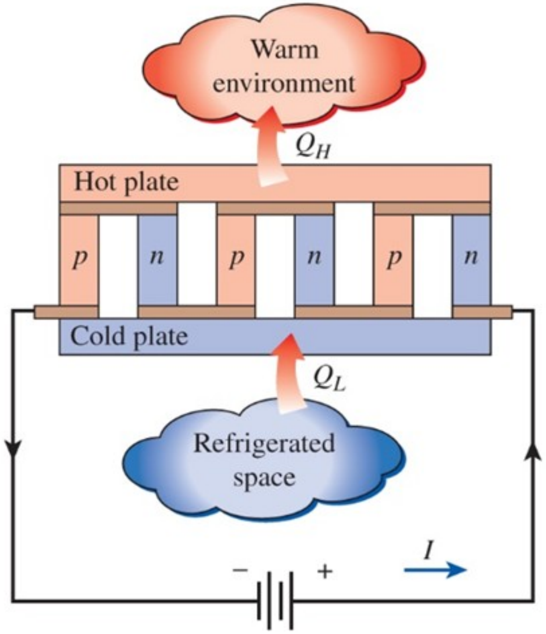
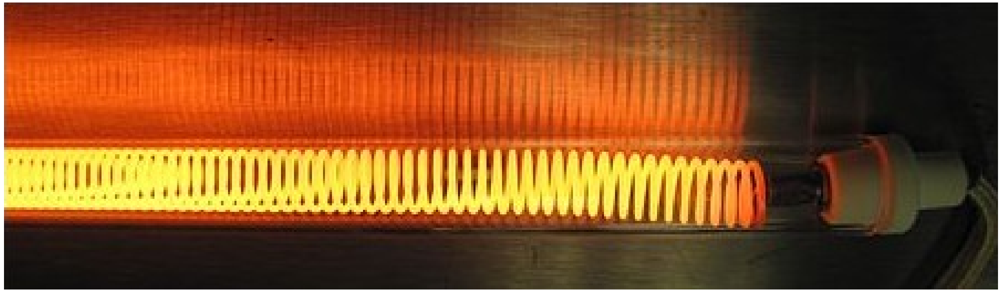
Thermoelectric Effects





Joule Heating

- Consider any material that has a voltage potential difference across it (e.g. a wire)

- If we do an energy balance on the system, we can see that a change internal energy is caused by the decrease in voltage potential as electrons move from low to high voltage
  - Remember conventional current goes from high to low, but electrons flow in the opposite direction

$$\Delta U = N\left(V^- - V^+\right)$$

- Since $V^+ > V^-$, there is always a lost of energy.

Joule Heating

- If we substitute this equation into the rate form of 1st Law

$$q=\frac{\Delta U}{\Delta t}=\frac{N}{\Delta t}\Delta V$$

- Or more commonly as

$$q=-IV=\frac{-V^2}{R}=-I^2 R$$

- The negative sign denotes that heat is leaving.
- This shows that the drop in electrical potential energy ΔV as current I passes through a material due to a voltage difference will create heat Q.
- This phenomena is called Joule (or ohmic or resistance) heating.

Joule Heating

- What factors affect heat generation?
  - We can see that high voltage difference and/or high currents can produce large amounts of heat.
  - The resistance of the material will affect voltage/current, thus the heat.
    - If high voltage, low resistance is best.
- Recall that the resistance of a material depends on it geometry and material properties.
  - So, thermal properties of the material will also have an effect on heat dissipation.

$$R = \frac{\rho L}{A} = \frac{L}{\sigma A}$$

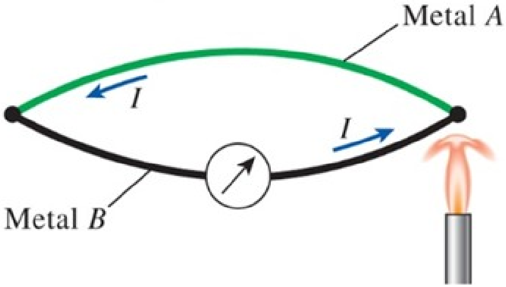
where ρ is the resistivity of the material (Ωm), L is the length of the material, and A is the cross sectional area of the material. σ is know as conductivity and has units of $1/\Omega m$.

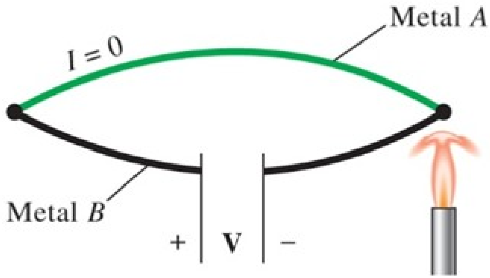
Example 1

A hair dryer is designed to output $2000\ W$ of heat by using $90\ V$ source. If the heating coil is composed of nichrome (nickel-iron-chromium alloy) with a resistivity of $1.10\times10^{-6}\Omega m$ and a diameter of $0.4\ mm$, how long must the nichrome wire be?

Thermoelectric Power Generator

- Recall the purpose of a heat engine → Convert heat into work
- Consider two different metals joined at both ends to create a closed circuit.
- If there is a temperature difference between the two junctions, then a current flows through the circuit.
- If we break the circuit, current cannot flow, but a voltage difference is generated.



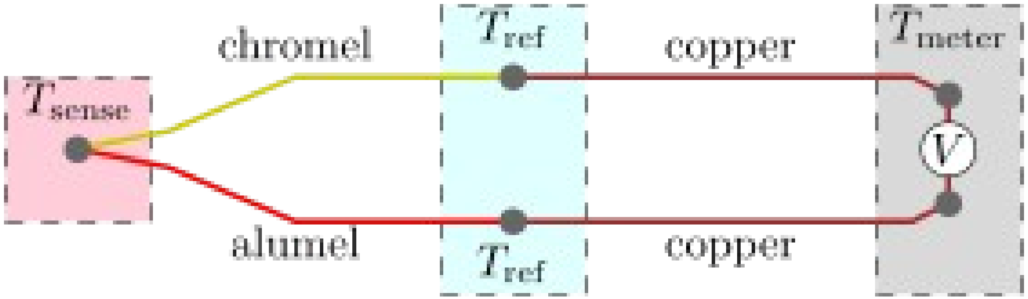


Seebeck Effect

- The Seebeck effect describes the voltage potential generation due to a temperature difference across two junctions of two conjoined different metals.
  - Named after Thomas Seebeck for his discovery in 1821.
- There are two major applications of the Seebeck effect
  - Temperature measurement
  - Power generation
- A thermoelectric device is any device that operates using a thermoelectric circuit which incorporates thermal and electrical effects.

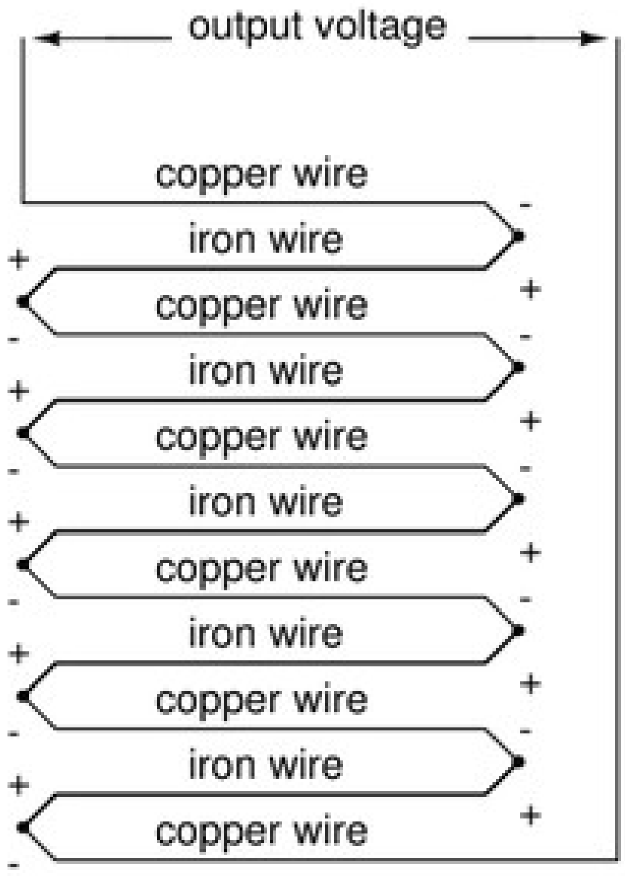
Seebeck Effect: Temperature Measurement

- If the circuit is broken, a voltage difference that is proportional to the temperature difference may be measured.
- If the voltage difference is measured, the temperature difference may be determined.
- This is the working principles behind thermocouples.
- There are many different types of thermocouples.
  - K-type (chromel-alumel) are the most common with a sensitivity of $41\ \mu V/°C$.



Seebeck Effect: Temperature Measurement

- A single thermocouple generates a small amount of voltage per degree change in temperature.
- What if very small temperature differences (e.g. mK) are to be measured?
- Many thermocouples may be placed together to produce a thermopile.
- Commonly used in applications where heats of reactions are being measured.



Seebeck Coefficient

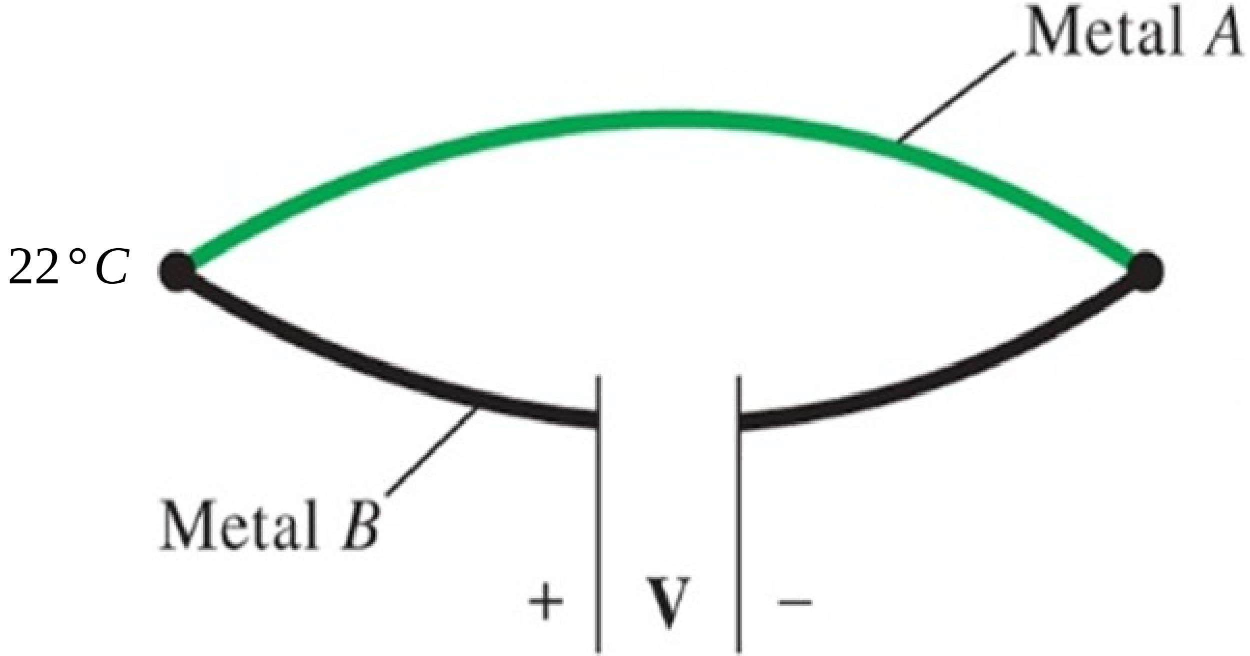
- Thermocouples made from different metals will have different sensitivities.
- The Seebeck coefficient is the material property that represents the induced voltage in response to a temperature difference across the material.
- When we combine two different materials, we can identify the expected voltage difference or temperature difference.

$$S_{B-A}=S_B-S_A=\frac{-\Delta V}{\Delta T}$$

- Since, the Seebeck coefficient is a relative value, material values are compared to a reference material (i.e. platinum, $S_{pt}=0\ \mu V/K$).
- The voltage direction points in the opposite direction of the temperature.

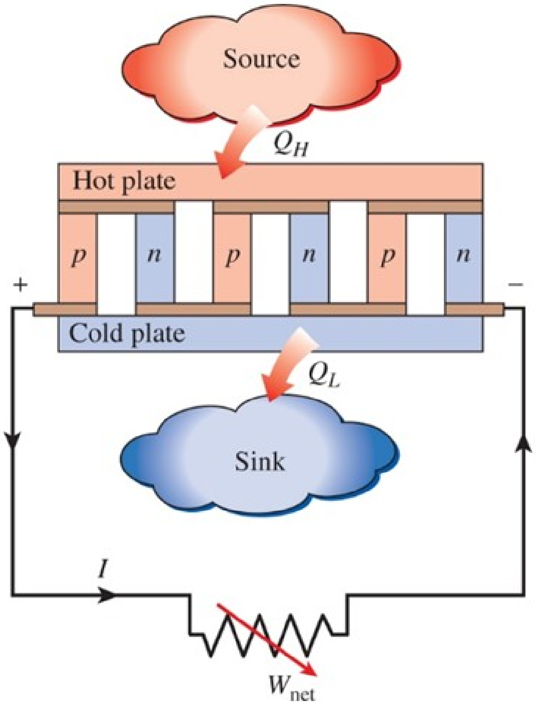
Example 2

A bismuth-antimony thermocouple reads a voltage difference of $0.1\ mV$. The Seebeck coefficients of bismuth and antimony are $-72\ \mu V/K$ and $47\ \mu V/K$, respectively. If the temperature of the reference junction is known to be $22°C$, what is the temperature of the measuring junction?



Thermoelectric Generator

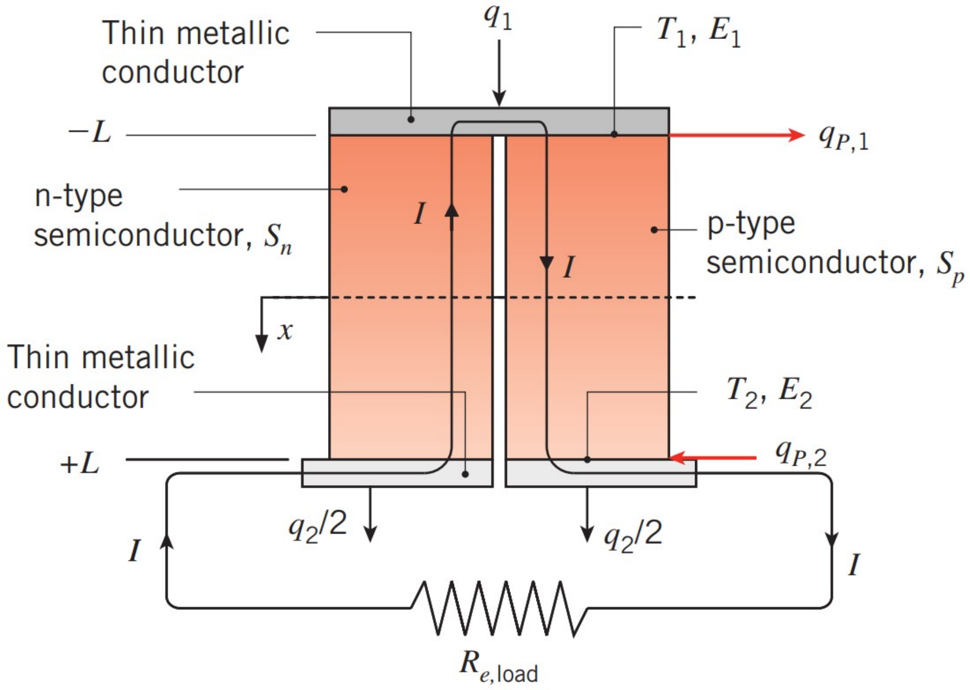
- A thermoelectric generator absorbs heat from a high temperature source and rejects heat to a low temperature sink; the difference is the produced electrical work.
- Behaves like a heat engine with electrons serving as the "working fluid".
- Like a heat engine, the efficiency of the device is limited by the temperature of the source and sink.
- Used in various applications
  - Low power applications
  - Limited fuel source applications (e.g. space exploration)
  - Waste heat recovery



Thermoelectric Generator

- A simple thermoelectric circuit is shown to the right.
- Consists of two "pellets" of p- and n-type semiconductors.
- The heat absorbed is given by

$$q_p = I(S_p - S_n)T = I S_{p-n} T$$



Thermoelectric Generator

- A thermoelectric module is shown to the right.
- Consists of an array of p- and n-type pellet pairs.
- The heat rate at the top surface is given by

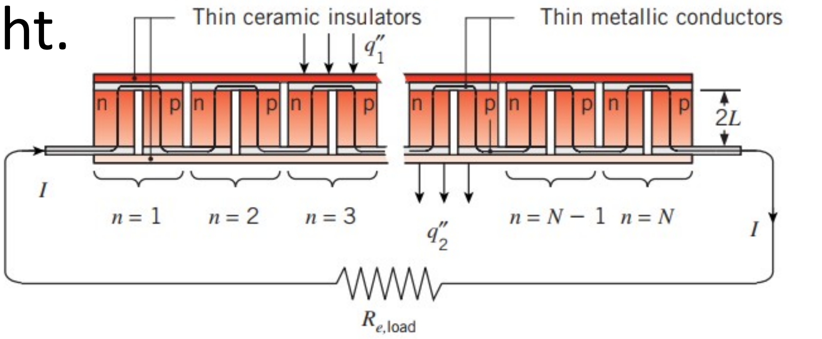
$$q_1 = \frac{1}{R_{t,cond,mod}}(T_1 - T_2) + I\,S_{p-n,eff}\,T_1 - I^2 R_{e,eff}$$

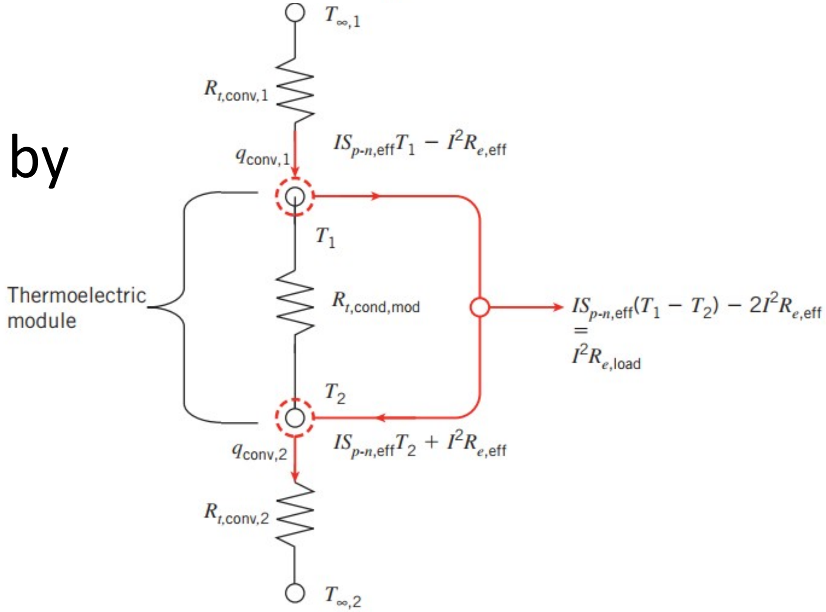
- The heat rate at the bottom surface is given by

$$q_2 = \frac{1}{R_{t,cond,mod}}(T_1 - T_2) + I\,S_{p-n,eff}\,T_2 - I^2 R_{e,eff}$$

- The total module electric power is given by

$$P_N = q_1 - q_2 = I\,S_{p-n,eff}(T_1 - T_2) - 2I^2 R_{e,eff}$$





Example 3

The Mars Curiosity Rover uses a radioisotope thermoelectric generator (RTG) which uses the heat from nuclear decay to generate electricity. Curiosity uses $4.8\ kg$ of plutonium-238 dioxide which has a power density of $0.54\ W/g$. The average temperature of the heat source is $550\ °C$ and the average temperature of the external sink is $230\ °C$. What is the maximum rate of power production for this thermoelectric generator?

Curiosity actually produces $110\ W$ of electrical power and outputs $2\ kW$ of heat waste. What is the actual thermal efficiency of the RTG?

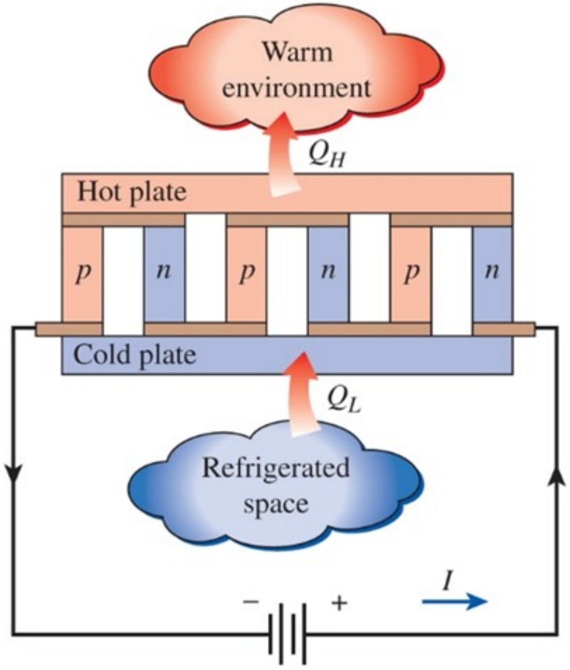
Fun Fact: ^{238}Pu has a half-life of 97.7 years; which means the power output will decrease by 0.787% per year.

Peltier Effect

- Consider the thermoelectric generator that produces electrical work in the presence of a temperature difference.
- What if we powered the device by means of an external voltage?
  - We could drive the heat transfer in the opposite direction (like a refrigerator or heat pump).
- Thermoelectric refrigerators are driven by the Peltier effect.
  - Named after Jean Charles Athanase Peltier for his discovery in 1834.
- Compared to vapor-compression refrigeration cycles, Peltier coolers are smaller, quieter, simpler, and more reliable, but they have low COPs.

Peltier Cooler

- Looking inside of a Peltier cooler, numerous 2 column pairs are found.
- One column is n-type (heavily doped with extra electrons) and the other is p-type (doped to create extra vacancies).
- These alternating columns are arranged in series.
- When a current passes through, it draws heat away from the cold side and rejects heat to the warm side.



Inside of Peltier cooler
Top plate removed
Some columns were damaged during removal
University of Utah

Example 4

A Peltier cooler uses $50\ W$ of power to absorb $500\ W$ of heat from a cold temperature source. If the external warm temperature is $85\ °F$, what is the coldest temperature the source could be?