Nanomaker

Lab #9: Piezoelectricity and Thermoelectricity

Energy Harvesting

Piezoelectricity

Thermoelectricity

Energy Harvesting

Illustration of energy harvesting sources removed due to copyright restrictions.
Refer to: Fig. 1 in Kume, Hideyoshi. "From Low Power to No Power through Energy Havesting: Powering Up the Battery-Free World." *Nikkei Electronics Asia*, October 31, 2010.

Energy Harvesting

Source	Harvested Power
Vibration (efficiency: up to 50 %)	
Human	4 µW/cm^2
Industrial	100 µW/cm^2
Heat (efficiency: up to 10 %)	
human	30 µW/cm^2
industrial	1-10 mW/cm^2
Light (efficiency: up to 40 %)	
Indoor	10 µW/cm^2
outdoor	10 mW/cm^2
RF (efficiency: up to 50 %)	
GSM	0.1 µW/cm^2
WiFi	1 µW/cm^2

Energy Harvesting

Piezoelectricity

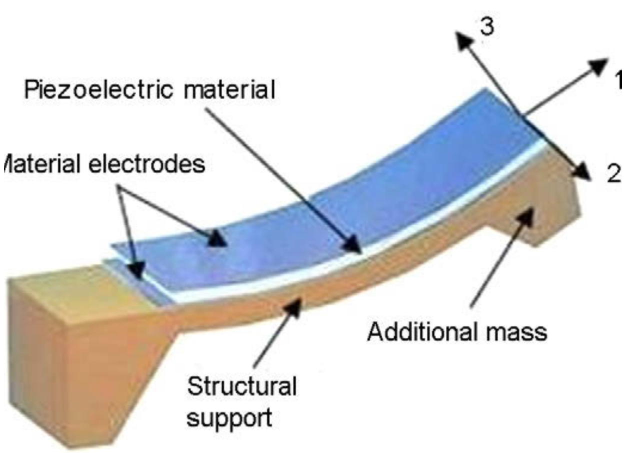
Thermoelectricity

Vibration Transduction Mechanisms

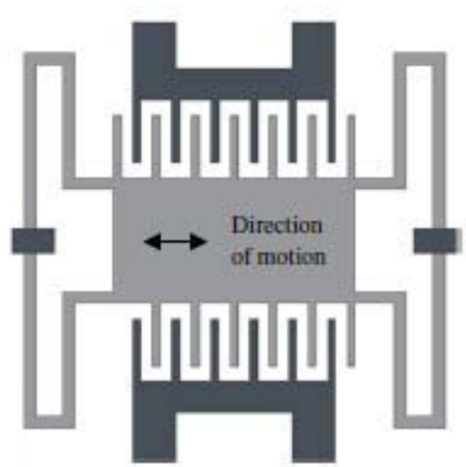
Piezoelectric
Strain in piezoelectric material causes a charge separation (voltage across capacitor)

Capacitive
Change in capacitance causes either voltage or charge increase

Electromagnetic
Relative motion of a magnetic mass causes current in a coil



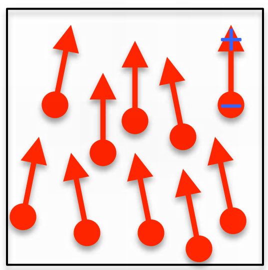
Renaud et al., Sensors and Actuators A, 145-146 (2008) 380



Roundy et al., Computer Communications 26 (2003) 1131

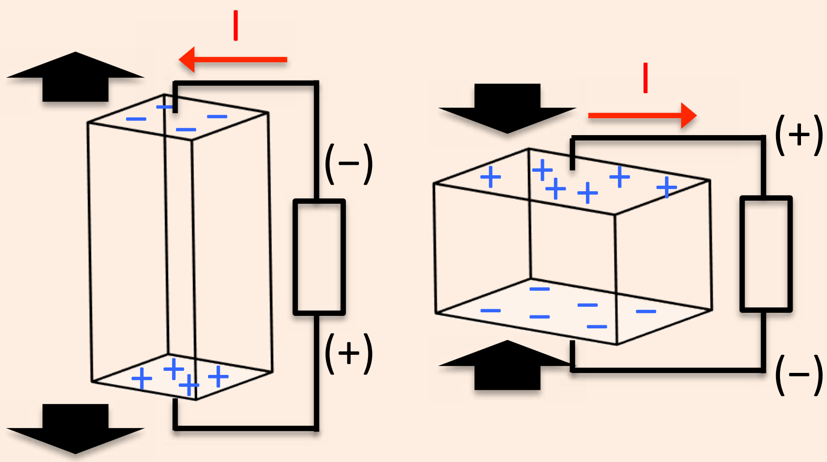
Image of electromagnetic transduction mechanism removed due to copyright restrictions.

William and Yates, Sensors and Actuators A, 52 (1996) 8

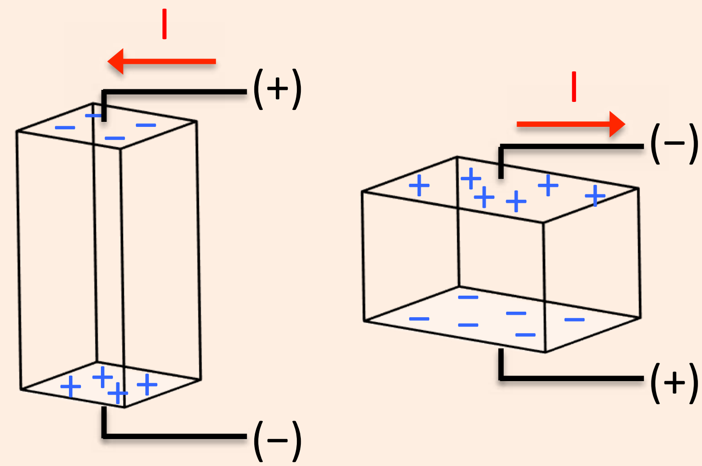


Piezoelectric Effect

Discovered in 1880 by Jacques and Pierre Curie during studies into the effect of pressure on the generation of electrical charge by crystals.

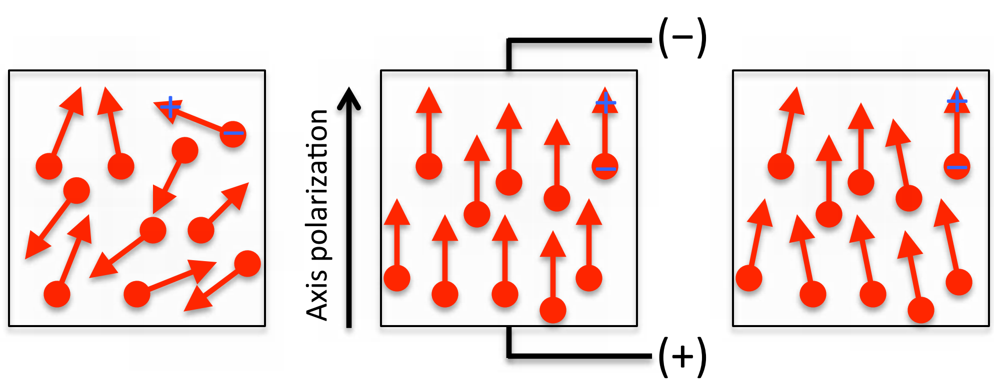


Direct piezoelectric effect

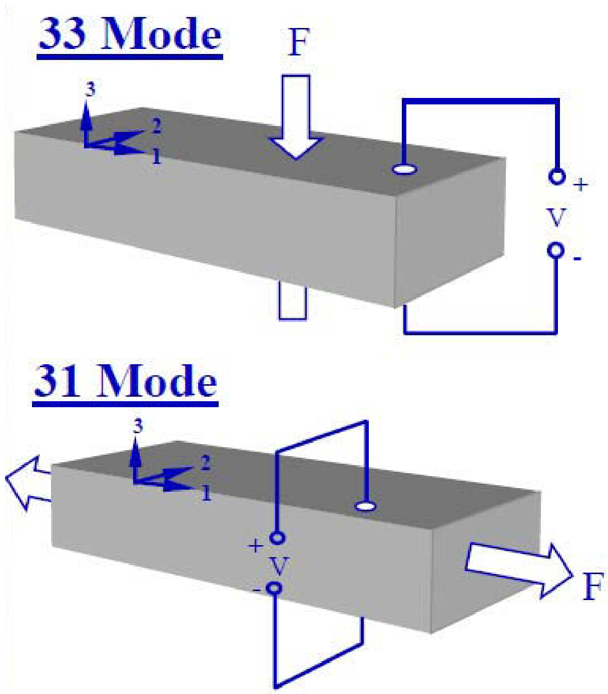


Converse piezoelectric effect

Polarizing (poling): Exposure to strong electric field at an elevated temperature



Piezoelectric Conversion



$$D = dT + \epsilon E$$

D = electric displacement [C/m^2]
d = piezoelectric coefficient [C/N]
T = stress [N/m^2]
ε = permittivity [F/m]
E = electric field [V/m]

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} {}_{11} & 0 & 0 \\ 0 & {}_{22} & 0 \\ 0 & 0 & {}_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Piezoelectric Materials

Rochelle Salt was the first material discovered to exhibit piezoelectricity

"baking soda" + "cream of tartar" = "piezoelectric crystals"

sodium bicarbonate [NaHCO3] **potassium bitartrate [KHC4H4O6]** **Potassium sodium tartrate [KNaC4H4O6·4H2O]**

- Crystals: Quartz (crystalline SiO2), Cane sugar, Rochelle salt
- Ceramics: Lead zirconate titanate (PZT), Barium titanate (BaTiO3)
- Polymers: Polyvinylidenfluoride (PVDF)

Applications

Actuator
(electrical to mechanical)

Piezoelectric buzzer

Nanopositioning

Piezo inkjet printer

Power source
(mechanical to electrical)

Grill lighter

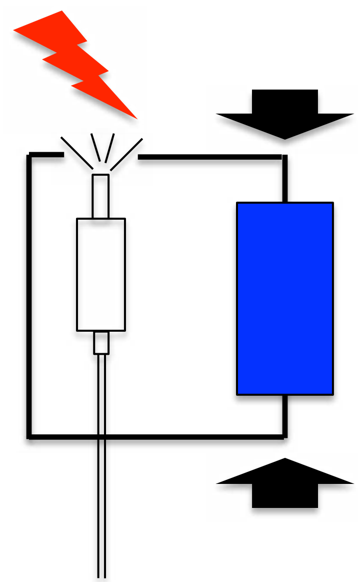
Energy harvesting

Paper-based
piezoresistive force sensor

Piezoelectric Lighter

1. Observe sparks
2. Connect to LED

This image is in the public domain.



Mechanical shock is converted to electricity

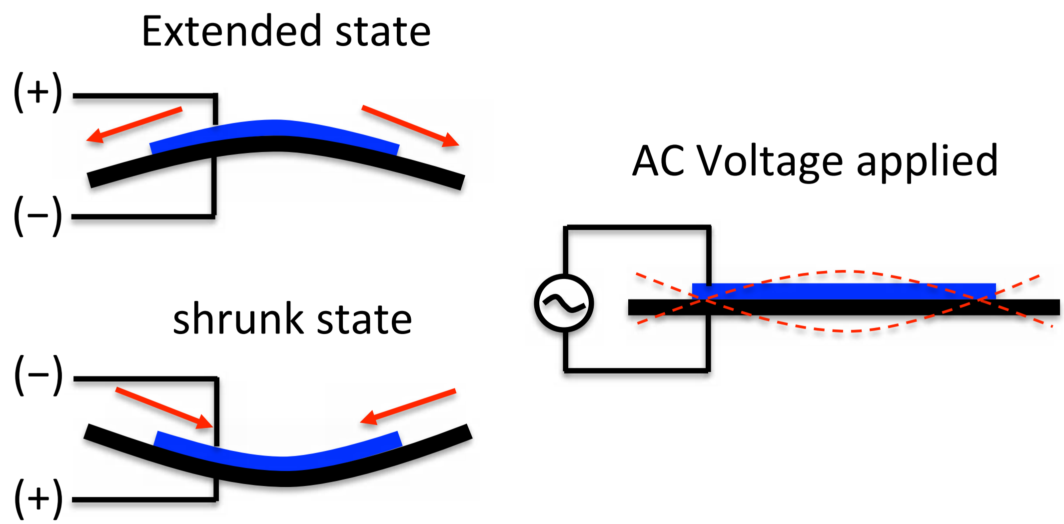
Breakdown voltage in air???

A small, spring-powered hammer rise off the surface of the piezo crystal strikes the crystal as the gas is turned on. The impact creates a large voltage across the crystal, and therefore a spark between the wires, which ignites the gas.

Piezoelectric Buzzer

1. Observe movements
2. Connect to LED
3. Connect to Function Gen.
4. Connect to Tone Gen.

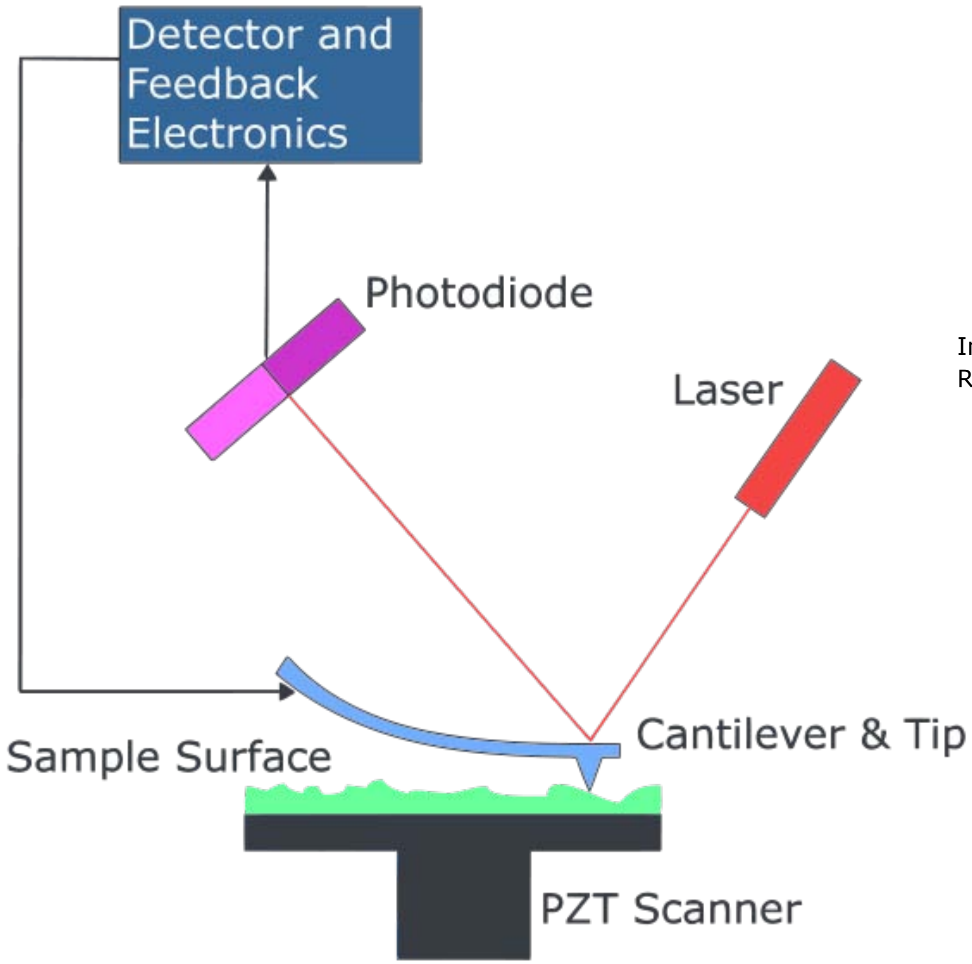
Photograph of piezoelectric elements of a contact microphone removed due to copyright restrictions.
Refer to: Photograph on Wikimedia Commons.



A piezoelectric diaphragm consists of a piezoelectric ceramic plate which has electrodes on both sides and a metal plate.

When AC voltage is applied across electrodes, the bending is repeated, producing sound waves in the air.

Atomic Force Microscope



Van der Waals Force

Graph of net intermolecular force intensity removed due to copyright restrictions.
Refer to: Fig. 10 from Barr, Ewan J. "Modelling Atomic Force Micrscopy (Using An Euler-Bernoulli Beam Equation)."

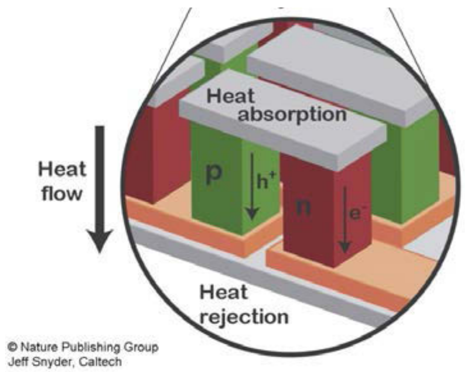
A small probe (nm) is brought close to or in contact with a surface

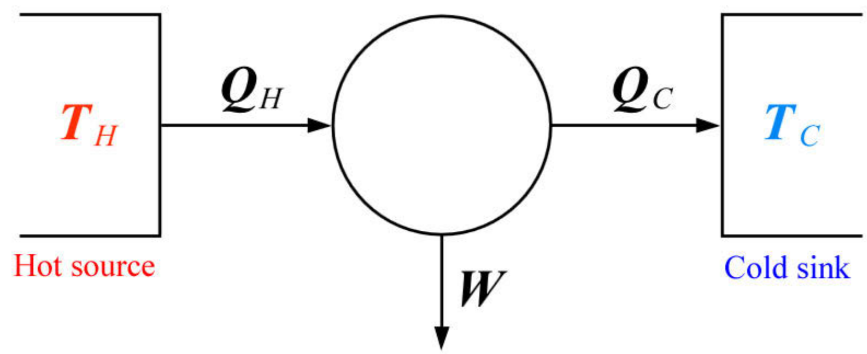
Energy Harvesting
Piezoelectricity
Thermoelectricity

Heat Transduction Mechanisms

<u>Thermoelectric</u>
Direct conversion of temperature differences to electric voltage (Seebeck) and vice versa (Peltier)

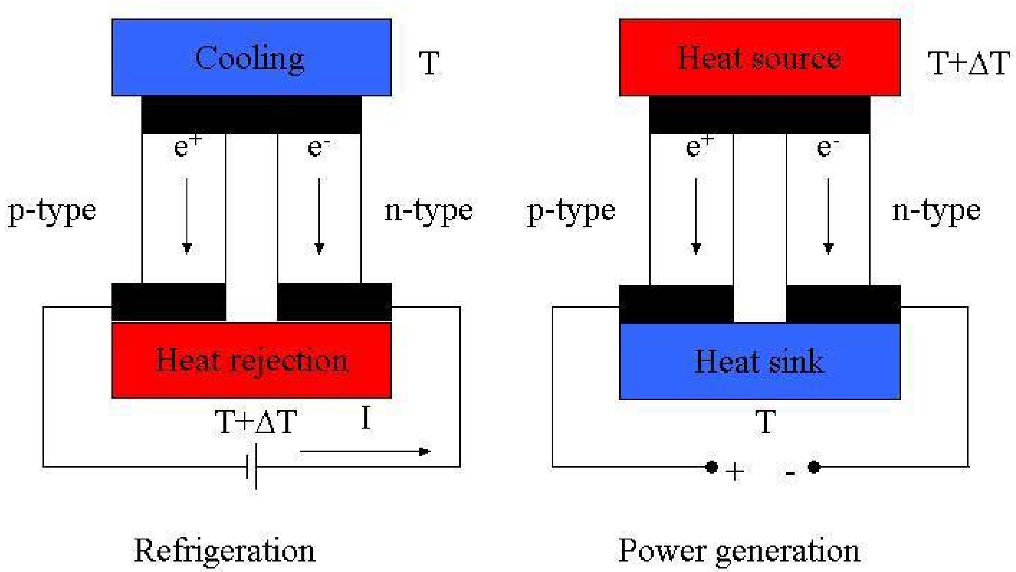
<u>Heat Engine</u>
System that performs the conversion of heat or thermal energy to mechanical work





Thermoelectric Effect

Thomas Johann Seebeck was a physicist who in 1921 discovered the thermoelectric effect.



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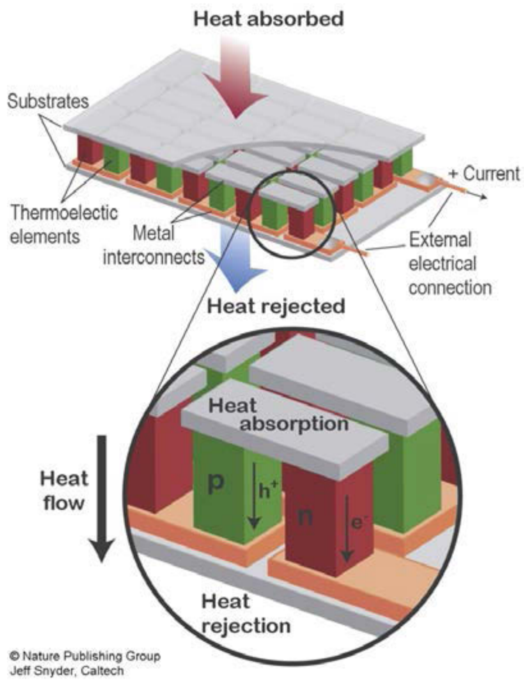
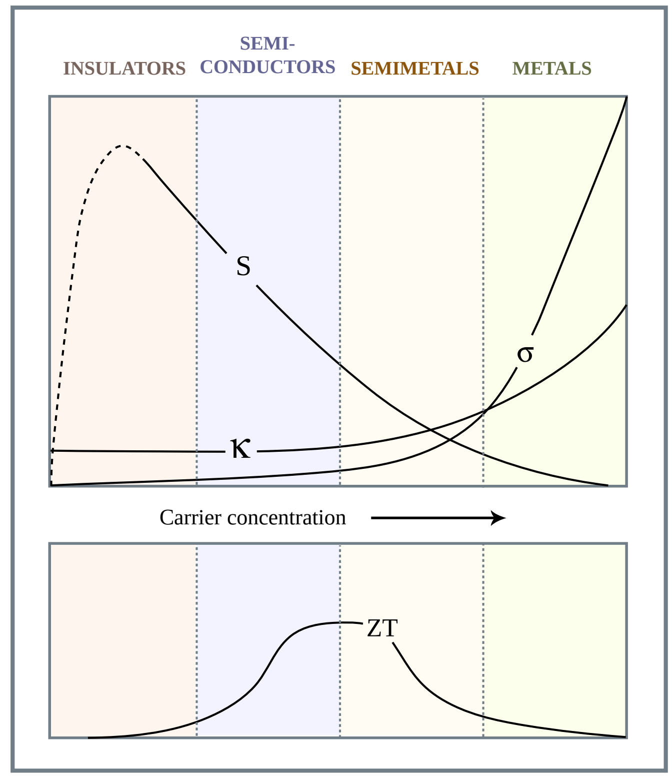
- Direct conversion of temperature differences to electric voltage (Seebeck) and vice versa (Peltier)
- Module contains n and p-type doped semiconductor connected electrically in series and thermally in parallel
- Charge carriers diffuse due to temperature difference and motion of charge carriers results in an electrical current

Figure of Merit





Seebeck coefficient

Electrical conductivity

$$ZT = \frac{S^2 \sigma}{\kappa} T$$

thermal conductivity

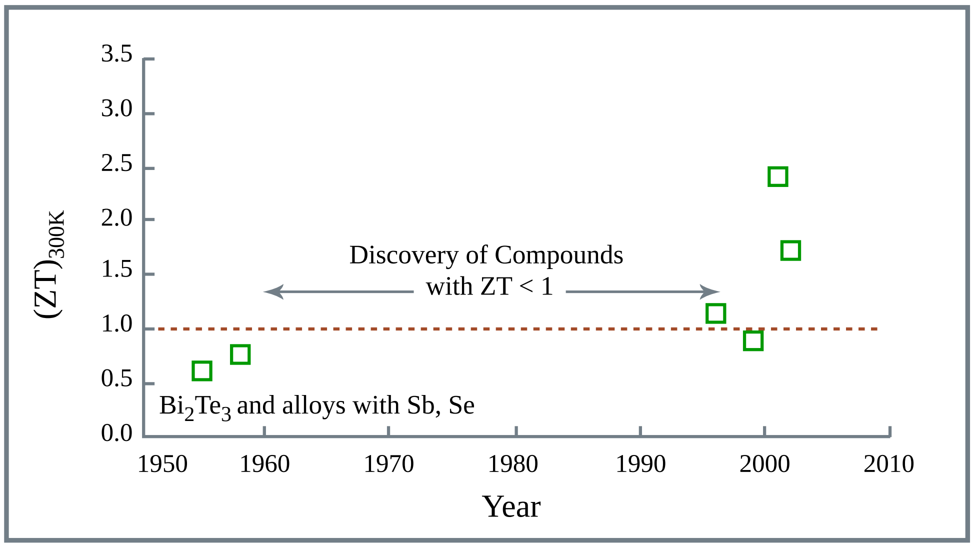
Terminal S, σ, and k that we measure are <u>average</u> values.

…vary with nanoparticle size, shape, and density,

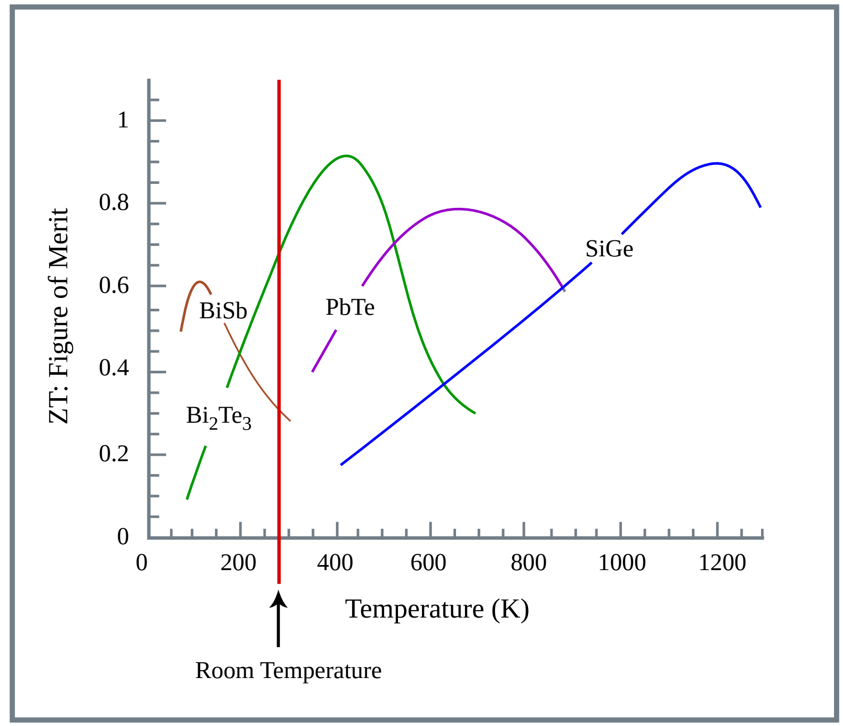
…vary with superlattice period, flatness, grain size,

…vary with alloy composition.

Figure of Merit



ZT was less than 1 for a long time



ZT changes with temperature

Heat Sources

Industrial Processes
Can be constant source of heat and require high temperature technologies

Solar Thermal
Weather, latitude and seasonal variability can extend operation

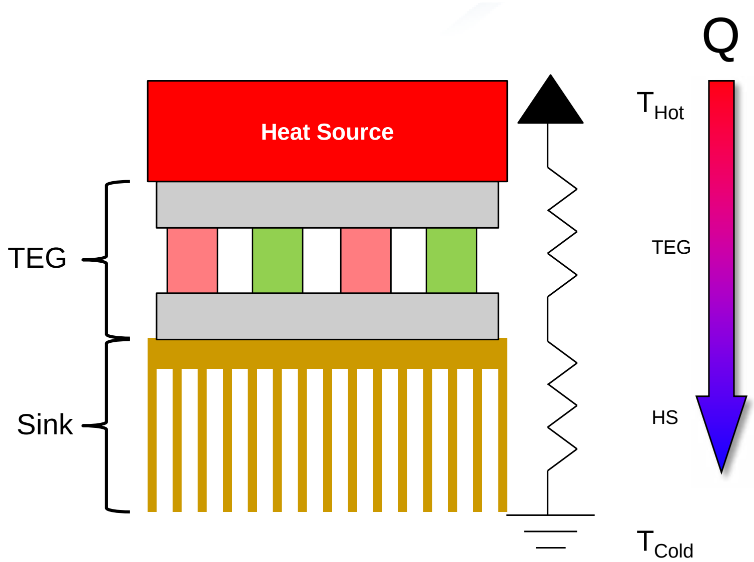
Automotive
Requires high temperature technologies and/or air flow

Living Space (HVAC)
Requires systems that harvest at low temperature differentials

Aviation
Altitude and speed dependent, weight is important

Human Body
Requires systems that harvest at low temperature differentials

Thermoelectricity Generator



Devices convert heat directly into electrical energy. The typical efficiencies are around 5-10%. And the most common material is bismuth telluride (Bi_2Te_3) semiconductor p-n junctions with thicknesses in the millimeter range.

Applications

(Peltier)

Seat Cooling/ Heating

Wine Cooler

Laser Cooling

(Seebeck)

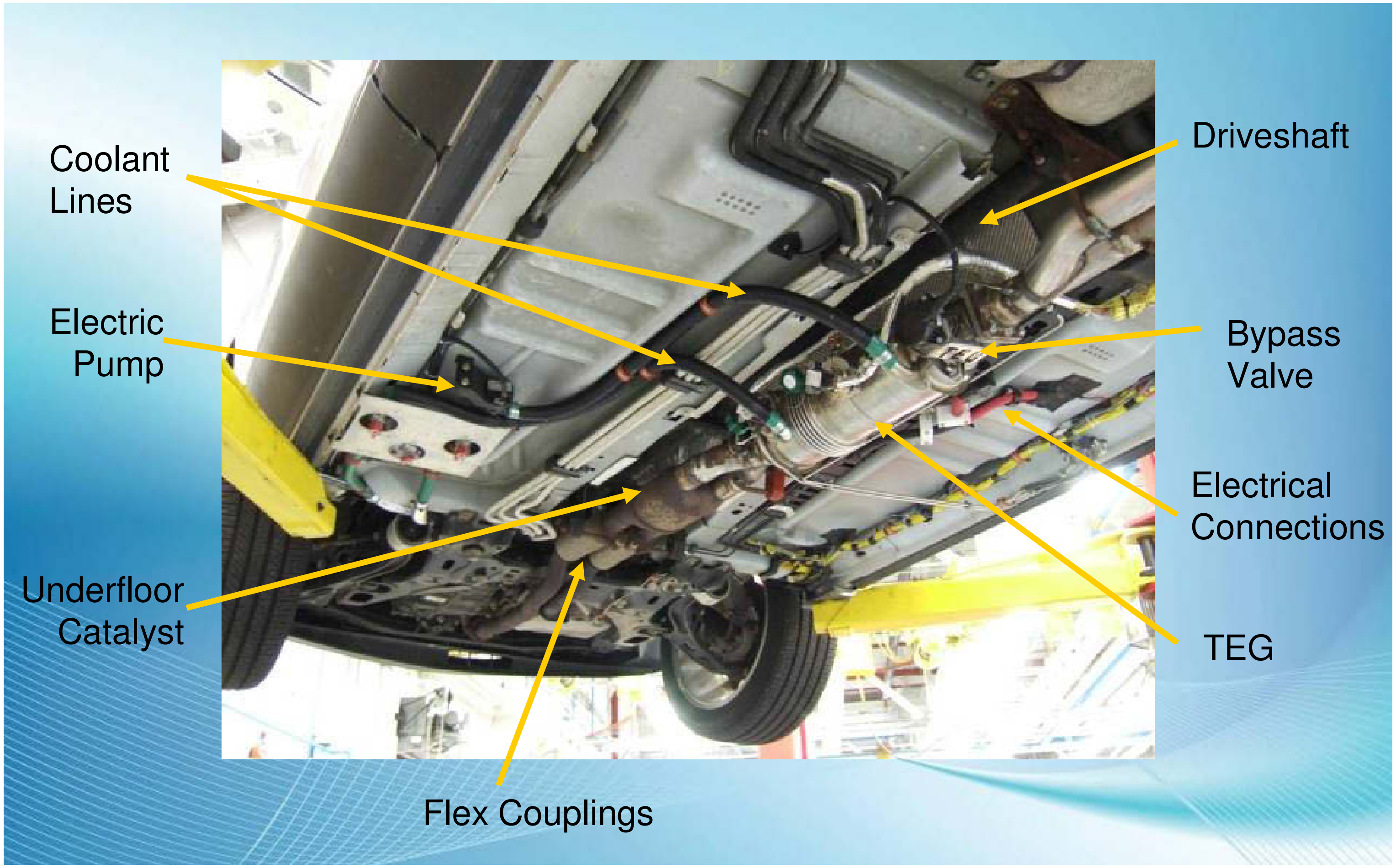
Watch

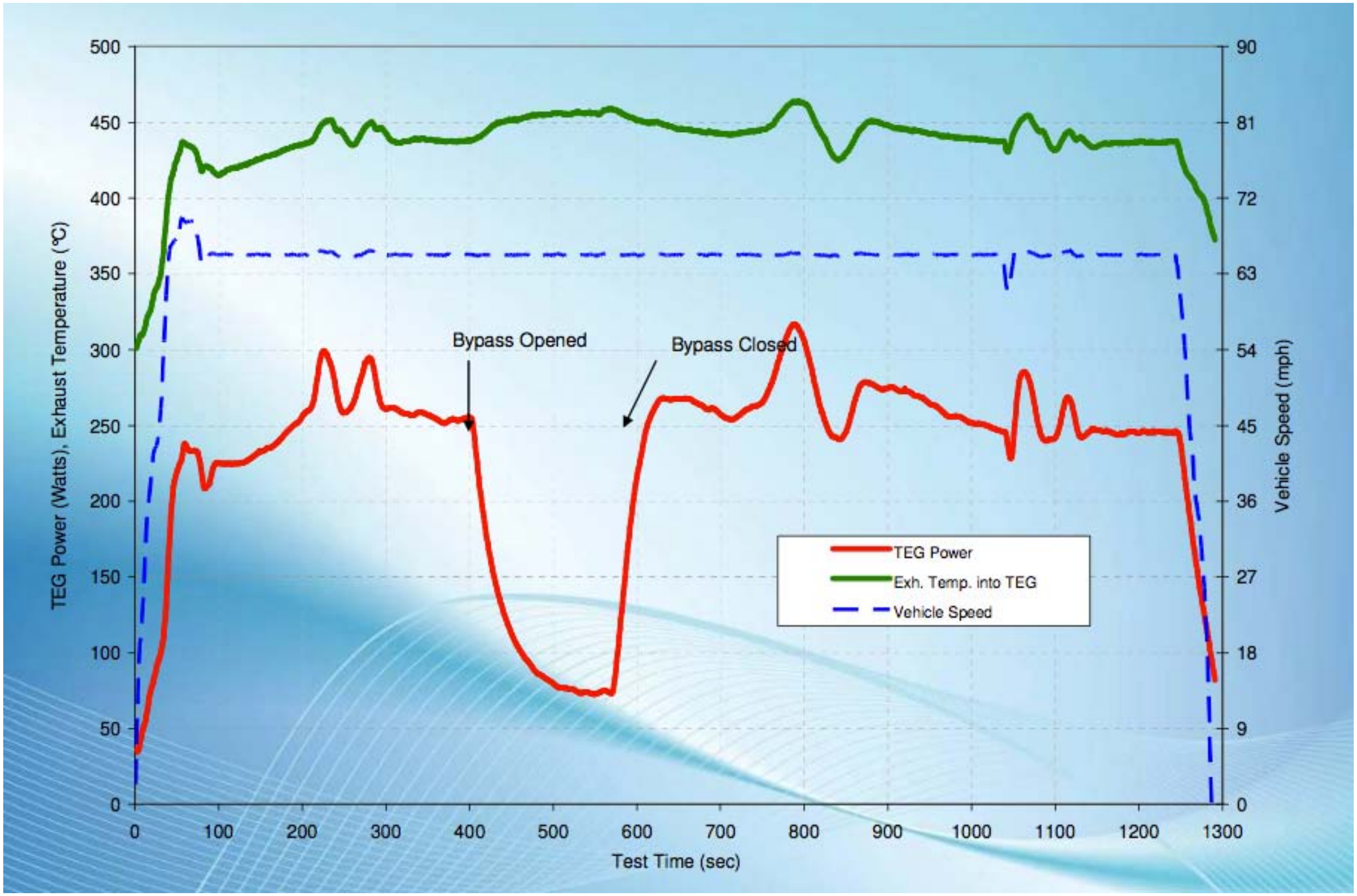
Exhaust Pipe

Water Pipe

Pulse Oximeter

How much energy can you generate from waste heat in engines?





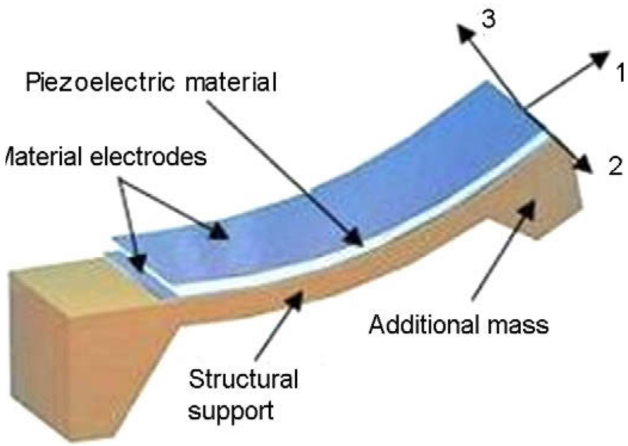
How much energy can you generate from waste heat in engines? Answer: 300 W

Thermoelectric Cooler

1. Take it apart
2. Measure resistance of TE module
3. Measure Seebeck coefficient of TE module



Conclusions



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$$D = dT + \epsilon E$$

$\boldsymbol{D}$ = electric displacement [C/m^2]
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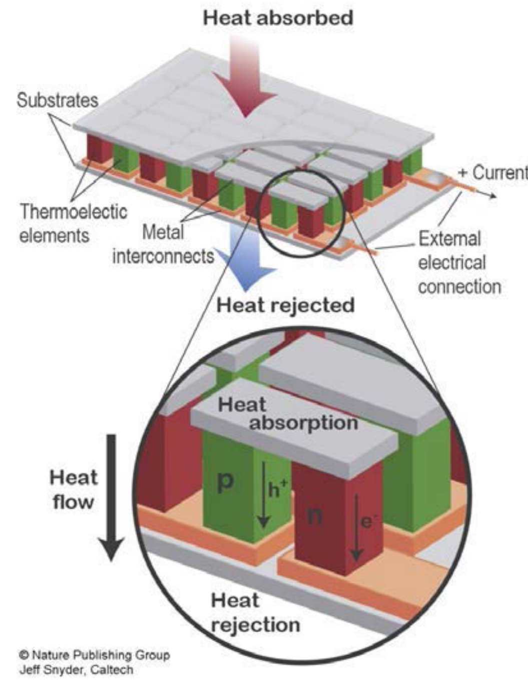

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Seebeck coefficient

Electrical conductivity

$$ZT = \frac{S^2 \sigma}{\kappa} T$$

thermal conductivity

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