

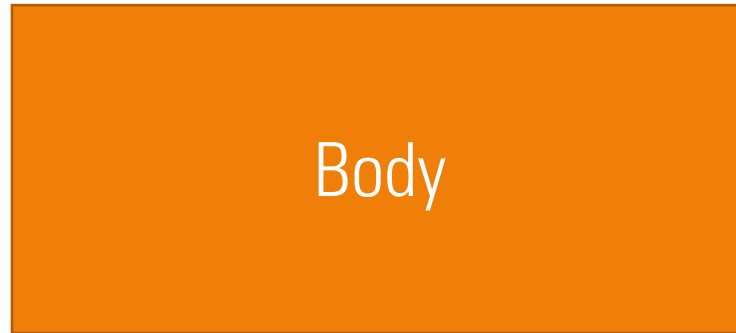
Transducers & Instrumentation

Module 06

Measuring Temperature

Temperature

- A macroscopic property of a body → It's a measure of the average kinetic energy of the molecules of an object.



- Thermometer – Produces a physical response to the temperature of a body through physical contact or EM radiation.

Temperature scales

- Three common scales:
 - Kelvin scale (K)
 - Celsius scale ($^{\circ}\text{C}$)
 - Fahrenheit scale ($^{\circ}\text{F}$)
- **Kelvin scale:** Based on the *triple point* of water, where all three states exist at a pressure of 4.58mmHg. This is defined at 273.16K.
 - 0 K is the absolute lowest temperature where all particles have zero kinetic energy
- **Celsius scale:** Based on the melting and boiling point of water at atmospheric pressure at sea level.
 - $1^{\circ}\text{C} = 1K$

Modes of heat transfer

Conduction

$$\dot{Q} = \frac{dQ}{dt} = -kA \frac{dT}{dx}$$

k : Thermal conductivity

Convection

Requires and intermediate fluid to take heat from the warmer body to the cooler body.

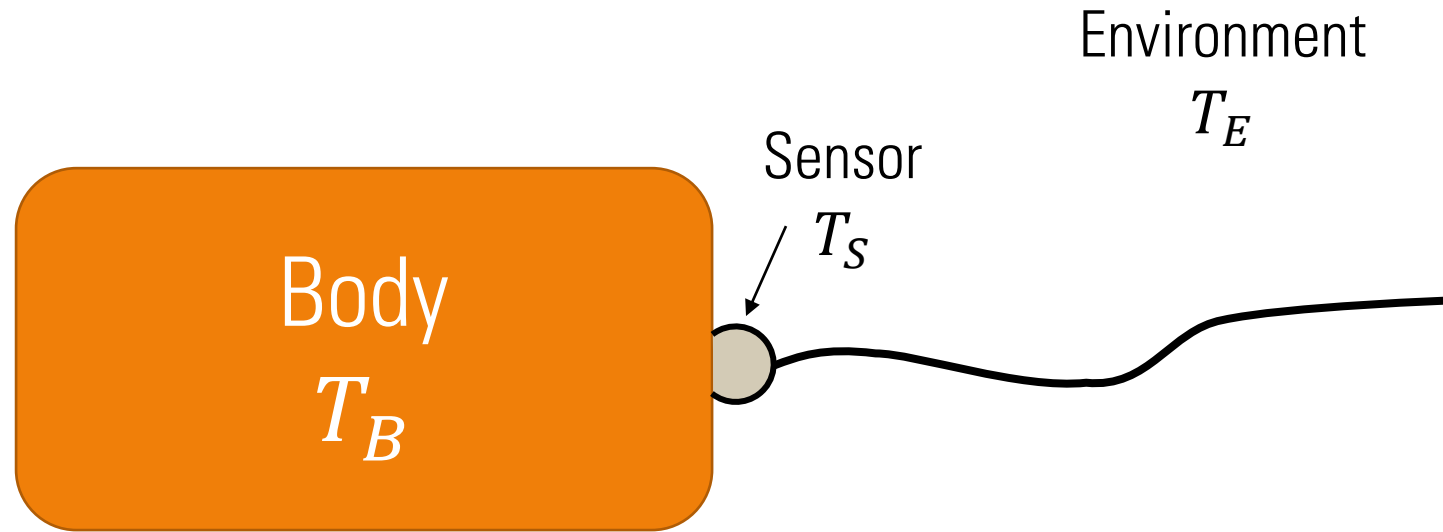
Radiation

Vibrating atoms and molecules generate electromagnetic radiation.

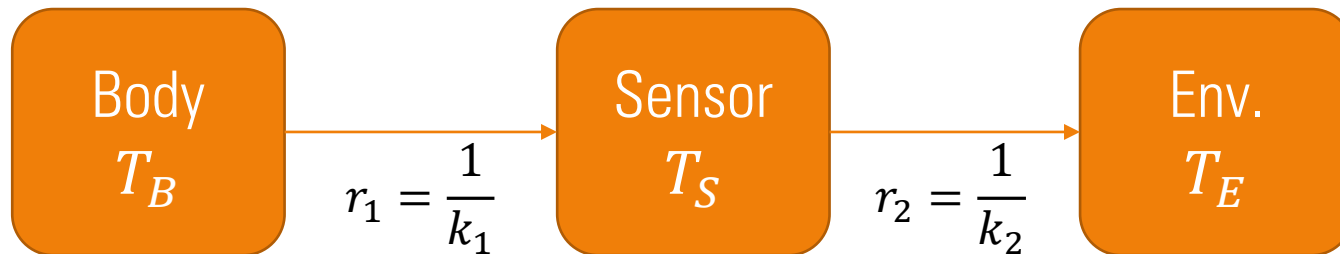
Temperature of the body determines the wavelength of the emitted radiation.

Total energy emitted will also depend on the emissivity.

Temperature measurement – Static case

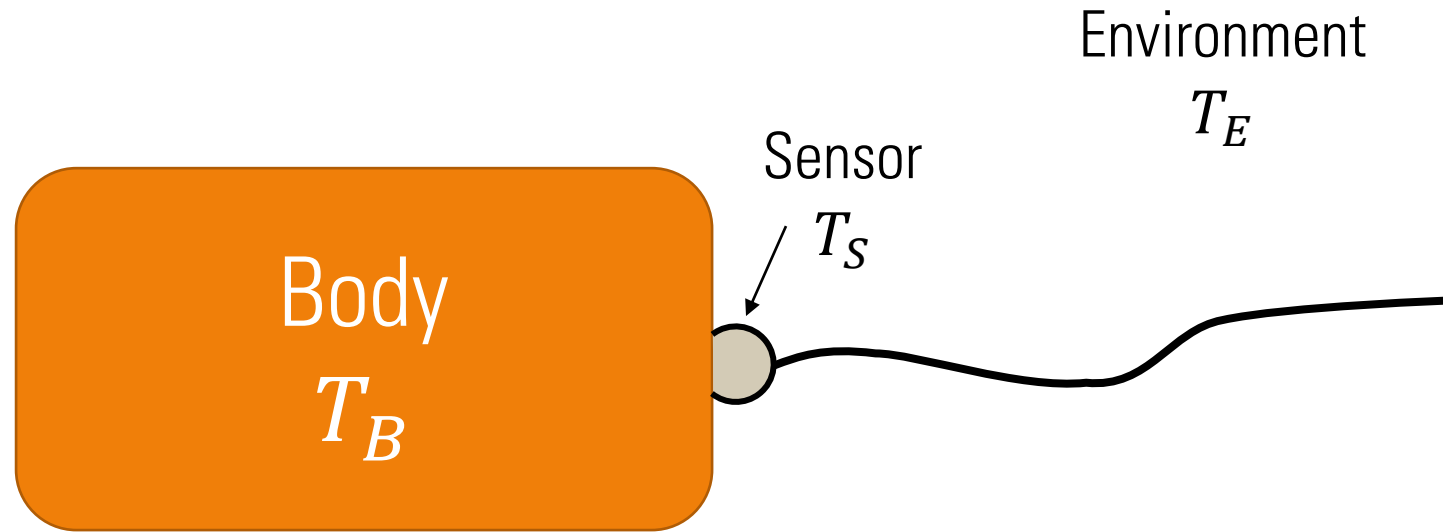


- Contact-based sensors.
- Requires flow of heat between the sensor and the body to measure T_B .
- Static measurement of temperature



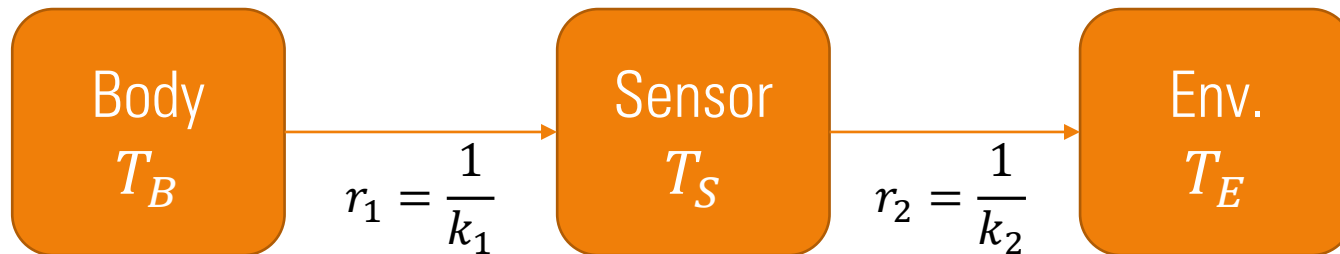
$$T_S = \left(\frac{r_2}{r_1 + r_2} \right) T_S + \left(\frac{r_1}{r_1 + r_2} \right) T_E$$

Temperature measurement – Dynamic case



- Dynamic measurement of temperature.
- Assuming infinite capacity for the body, and infinite resistance for r_2 .

$$T_S(t) = T_B - (T_B - T_S(0))e^{-t/\tau}$$



Resistance temperature detectors (RTD)

- Resistance of materials change with temperature.
- Variation of resistance of metals can be approximated through the following relationship:

$$R_{T_1} = R_{T_0} [1 + \alpha_0 (T_1 - T_0)]$$

- α_0 is the temperature coefficient of resistivity of the material.
- Most metals have 0.3-0.5% change in resistance per degree Celsius.
- Platinum is often preferred due to its wide linear resistance-temperature relationship.

Resistance Temperature Detector (RTD)

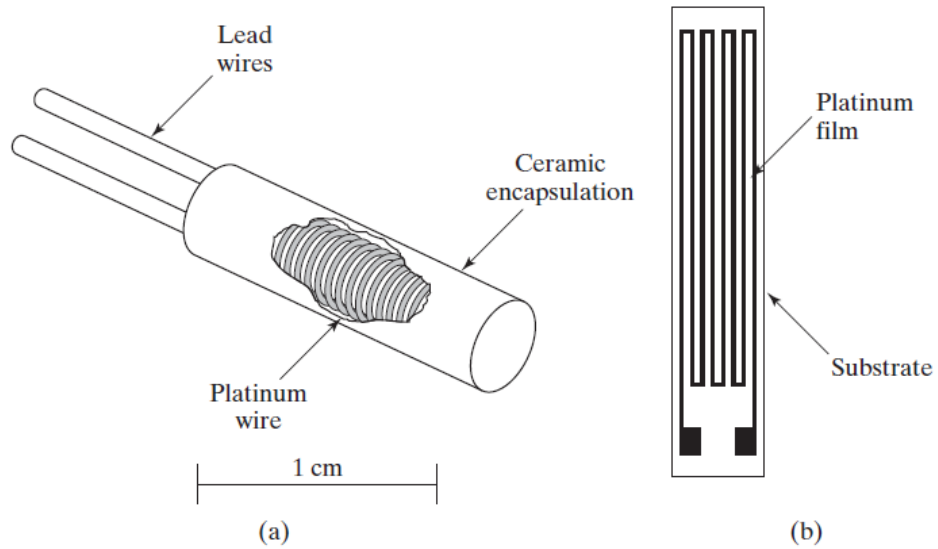


FIGURE 9.20
Resistance temperature detectors: (a) platinum wire; (b) thin film.

Source: Wheeler, Anthony J., et al. *Introduction to engineering experimentation*. Vol. 480. Pearson, 2010.

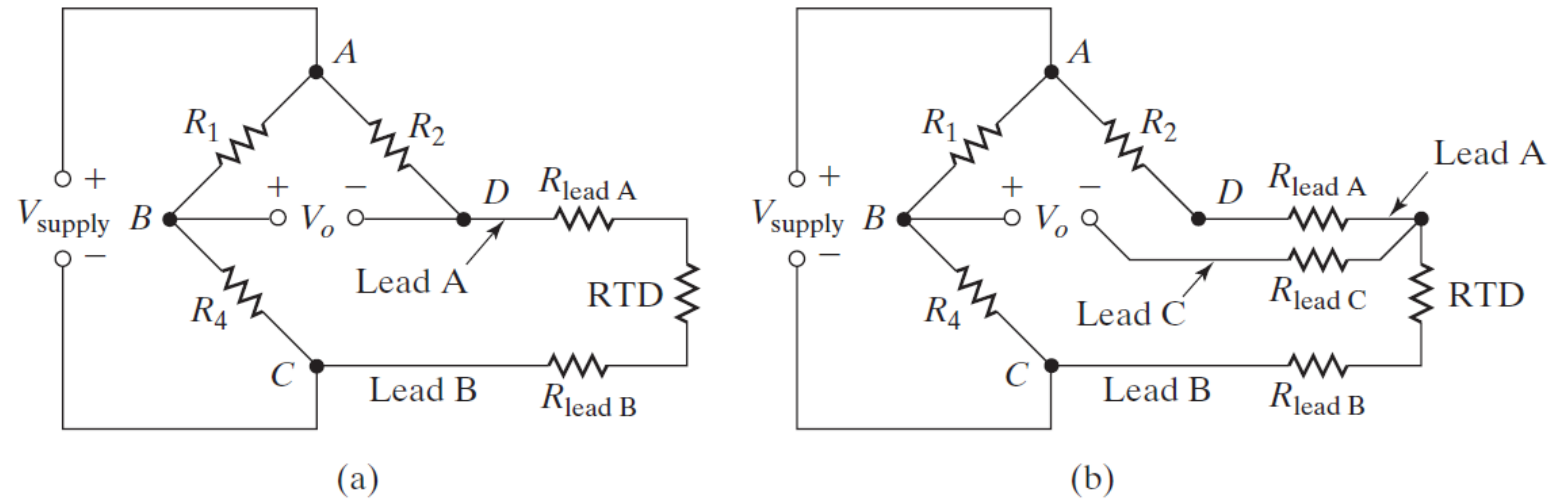


FIGURE 9.21
Wheatstone bridge circuits for RTD: (a) two-wire; (b) three-wire.

Thermistors

- Made from ceramics, composed of a mixture of metal oxides.
- Shaped into different forms depending on the application.
- Temperature coefficient is negative, and its absolute value is larger.

$$R_{T_1} = R_{T_0} \cdot e^{\beta(1/T_1 - 1/T_0)}$$

- Temperature coefficients are around 4-6% change in resistance per degree Celsius.
- Non-linear temperature-resistance relationship.
- Typical resistance values are a few hundred ohms to a megaohm.
- Care must be taken to minimize errors due to self-heating.

Thermistor

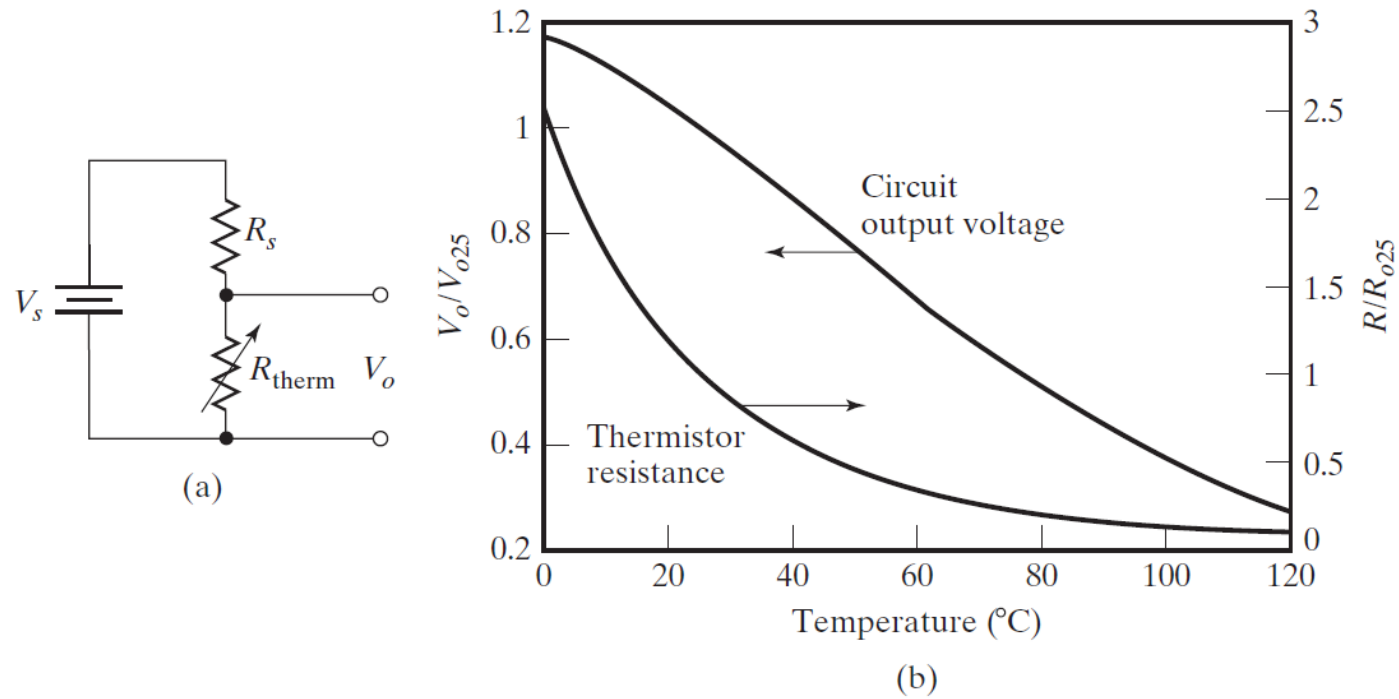
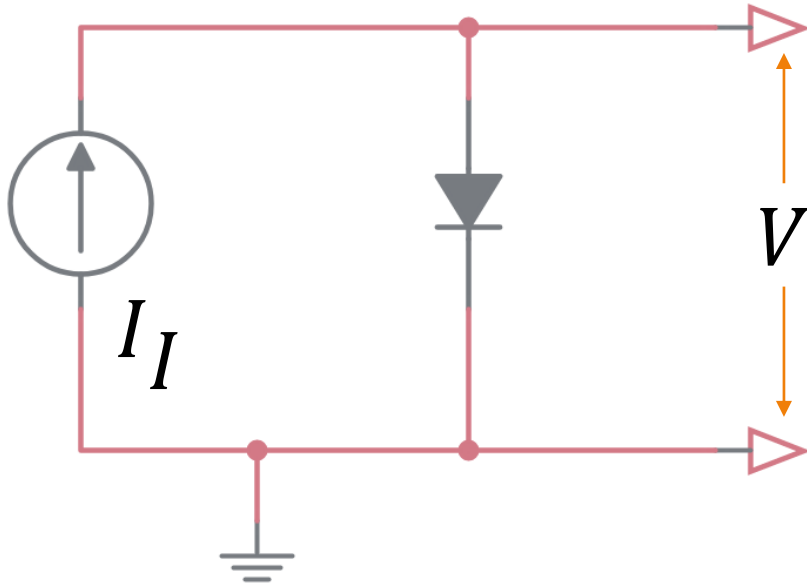


FIGURE 9.24

Linearization circuit for thermistor.

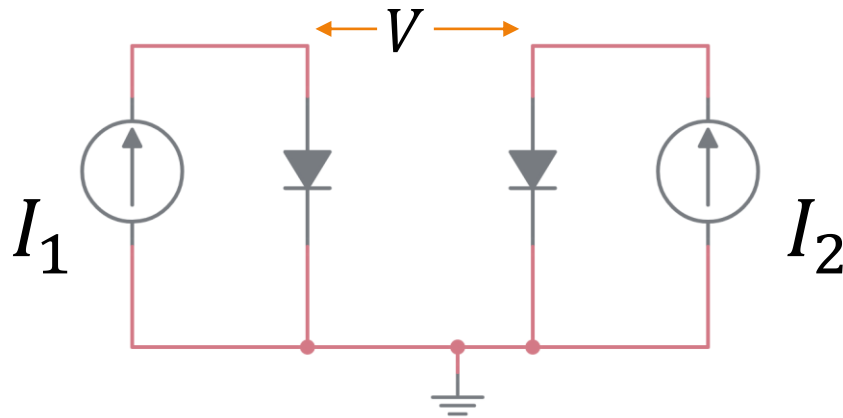
Source: Wheeler, Anthony J., et al. *Introduction to engineering experimentation*. Vol. 480. Pearson, 2010.

p-n Junction Temperature Sensor



$$I = I_0 e^{\left(\frac{qV - E_g}{kT}\right)}$$

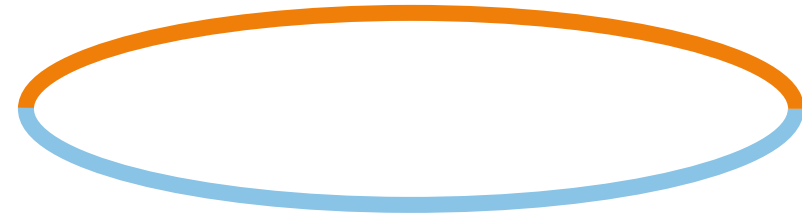
When the current I is kept constant, the voltage across the diode will be a function of the temperature



$$V = V_1 - V_2 = \left(\frac{kT}{q}\right) \ln \left(\frac{I_1}{I_2}\right)$$

Thermocouple

- Seebeck Effect



Thermocouple

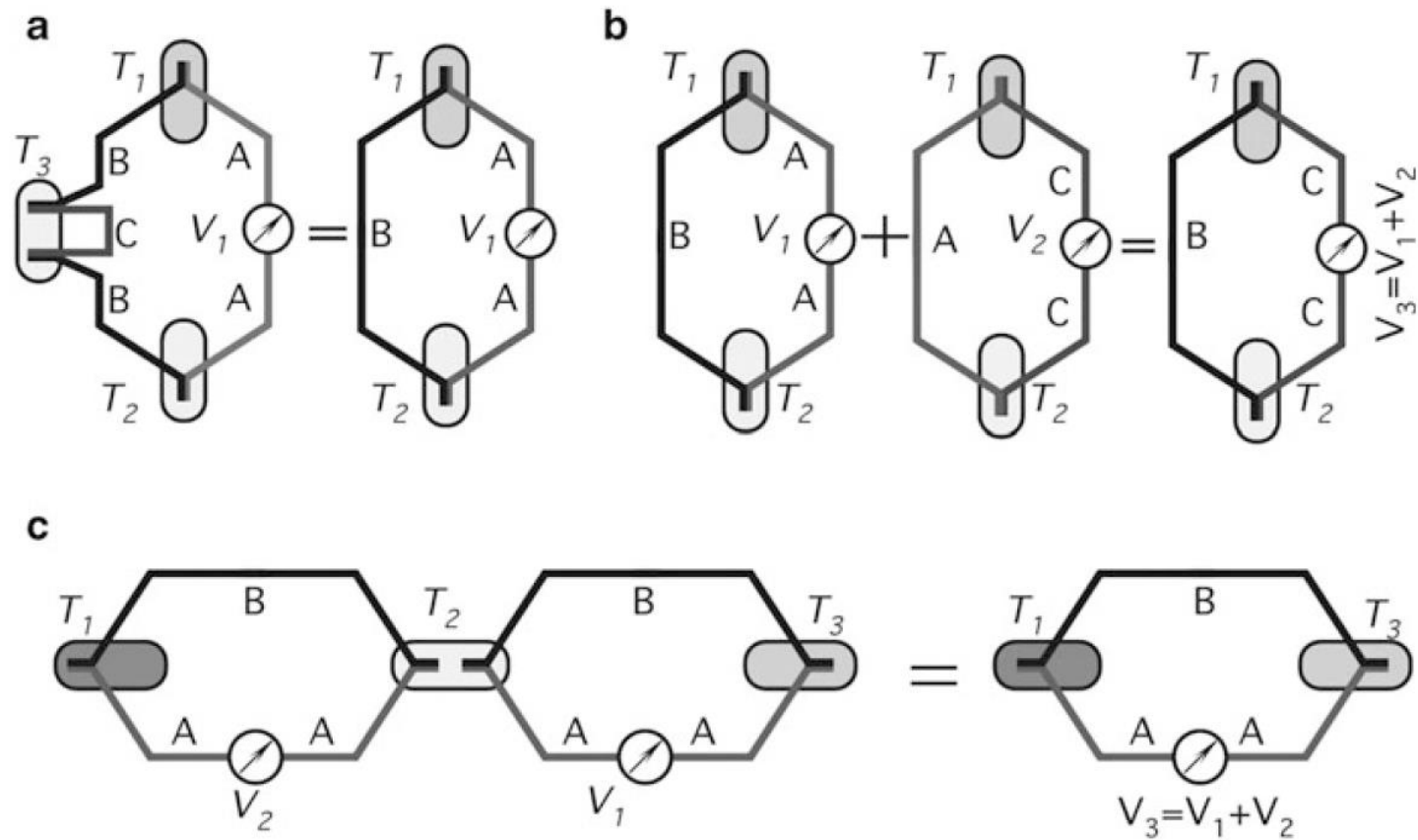


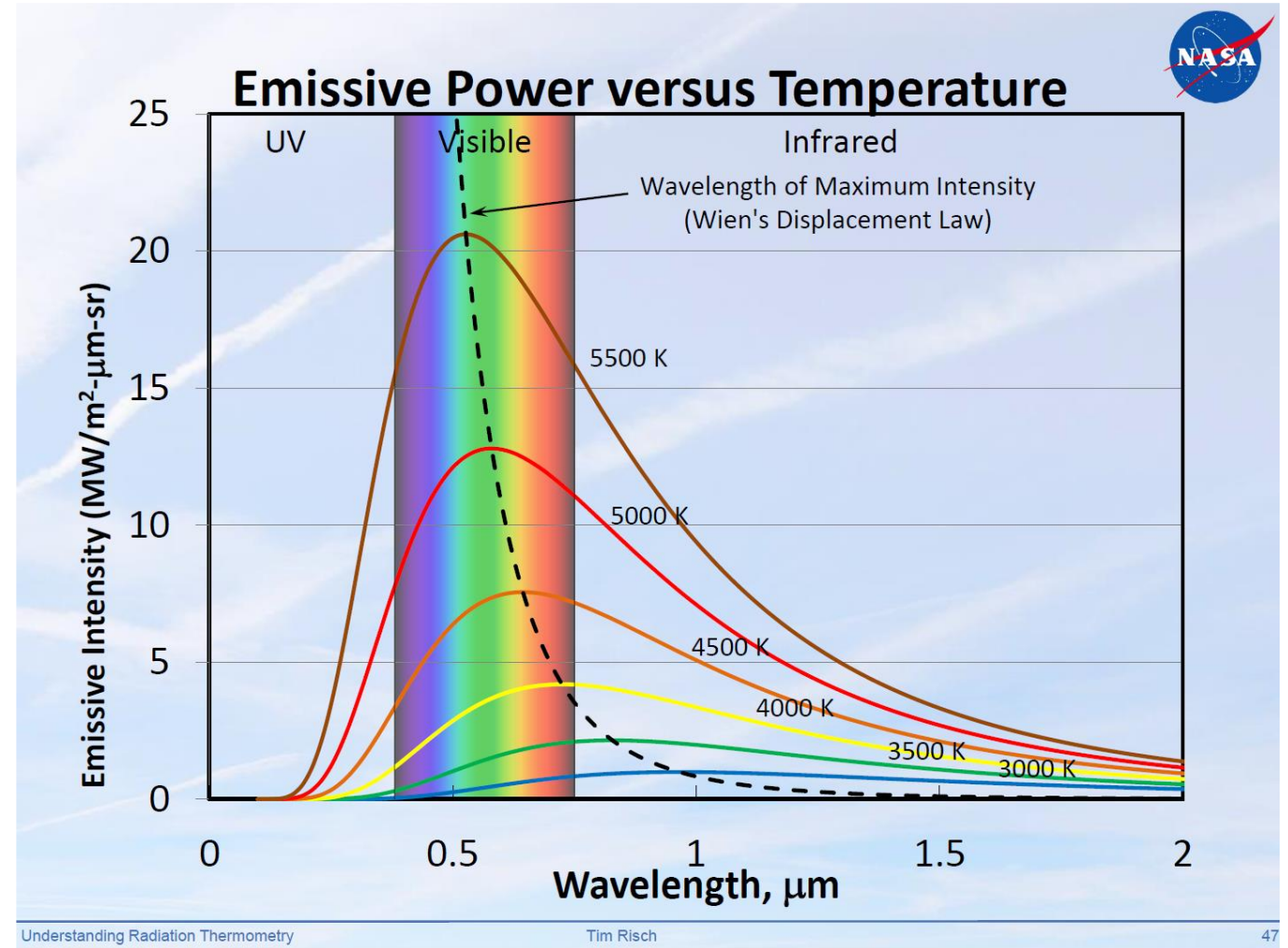
Fig. 17.27 Illustrations for the thermoelectric laws

Radiation thermometry

- All bodies with temperature above 0 Kelvin will emit electromagnetic radiation.
- The spectrum density of black body radiation is given by Planck's law:

$$L_{\lambda}(\lambda, T) = \frac{hc}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

$W/m^2 \cdot sr \cdot \mu m$



Radiation thermometry

- Wein's displacement law:

$$\lambda_{max}T = 2897.77\mu m \cdot K$$

- Stefan-Boltzmann law: Total thermal radiation power.

$$\int_0^{\infty} L_{\lambda}(\lambda, T) d\lambda = \frac{\sigma T^4}{\pi} = L_b$$

- For a real body,

$$L_r = \epsilon L_b = \epsilon \frac{\sigma T^4}{\pi}$$

Radiation thermometry

- Measurement system

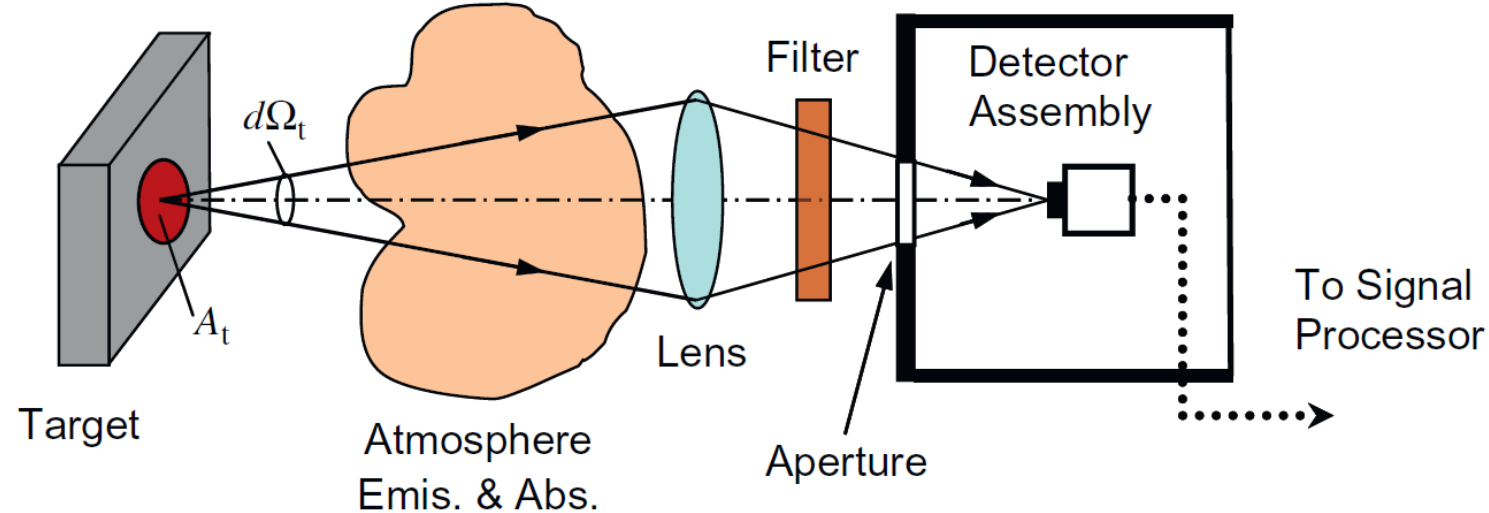


Figure 1 Schematic diagram of radiometric temperature measurement.

$$L_{\lambda}(\lambda) = \tau_{env} [\varepsilon_{\lambda} L_{b,\lambda}(\lambda, T_b) + L_{ref,\lambda}(\lambda)] + L_{em,\lambda}(\lambda, T_{env})$$

Radiation thermometry methods

- “True” surface temperature: T
- Equivalent black body temperature. T_b
- **Wideband measurement:** If L_r is the measured power, then the estimated temperature of the body is given by,

$$T = \frac{1}{\epsilon^{1/4}} \cdot T_b \Rightarrow \frac{\delta T}{T} = -\frac{1}{4} \frac{\delta \epsilon}{\epsilon}$$

Radiation thermometry methods

- Single wavelength measurement:

$$L_{\lambda}(\lambda, T) = \epsilon \frac{hc}{\lambda^5 (e^{hc/\lambda kT} - 1)} = \frac{hc}{\lambda^5 (e^{hc/\lambda kT_b} - 1)}$$

$$\frac{1}{T} = \frac{1}{T_b} + \frac{\lambda k}{hc} \ln(\epsilon)$$

Radiation thermometry methods

- Dual wavelength measurement:

$$L_{\lambda_1}(\lambda_1, T) = \epsilon_{\lambda_1} \frac{hc}{\lambda_1^5 (e^{hc/\lambda_1 kT} - 1)} = \frac{hc}{\lambda_1^5 (e^{hc/\lambda_1 kT_{b,\lambda_1}} - 1)}$$

$$L_{\lambda_2}(\lambda_2, T) = \epsilon_{\lambda_2} \frac{hc}{\lambda_2^5 (e^{hc/\lambda_2 kT} - 1)} = \frac{hc}{\lambda_2^5 (e^{hc/\lambda_2 kT_{b,\lambda_2}} - 1)}$$

$$\frac{1}{T} = \frac{1}{\tilde{T}} + \Lambda \frac{k}{hc} \ln \left(\frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_2}} \right)$$

$$\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} \quad \tilde{T} = \frac{\Lambda}{\lambda_1 T_{b,\lambda_1}} + \frac{\Lambda}{\lambda_1 T_{b,\lambda_2}}$$

Radiation thermometry methods

- **Multiwavelength measurement:**
 - A functional form is assumed for emissivity as a function of wavelength.
 - Measurement at N different wavelengths can be used to estimate emissivity function and the unknown temperature.