Thermal Imaging

…An Introduction

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Overview

- What is temperature?
- Measuring temperature
- Transferring energy as heat
- Blackbody radiation
- Thermal IR detection
- Available Technologies
- Next time

What is Temperature?

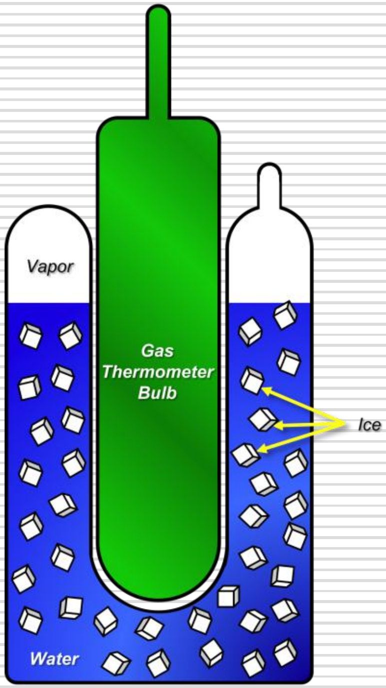
- Zeroth Law of Thermodynamics
  - □□"It is a matter of experience that when two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with one another." [Moran 2000].
  - Allows us to make temperature measurements.
    - Every object has a property called temperature
    - When two or more objects are in thermal equilibrium, they have the same temperature

Measuring Temperature

- The temperature scale can be derived starting with Boyle's Law and a fixed volume of an ideal gas (He) at two measured temperatures.

$$\frac{P_1V_1}{P_2V_2} = \frac{nR\cdot(T_1 - T_0)}{nR\cdot(T_2 - T_0)} \qquad \frac{P_1}{P_2} = \frac{T_1 - T_0}{T_2 - T_0} \qquad \frac{1}{1.366099} = \frac{0 - T_0}{100 - T_0} \Rightarrow T_0 = -273.15 \ ^{\circ}C$$

- A triple-point scale (right) is used to establish a precise, known temperature to calibrate temperature measuring devices.
- This natural phenomenon provides validation for the equations above.
- Other natural phenomena are used for other calibrations depending on the measuring device and temperature ranges [Sostmann 1990 and 1995].



Transferring Energy as Heat

- Thermal energy is transferred through the mechanisms of conduction, convection and/or radiation.
- Conduction

$$\dot{Q}_L = -\kappa A \frac{dT}{dL}$$

- Convection

$$\dot{Q}_c = hA \cdot (T_{body} - T_{fluid})$$

- Skin-heat transfer models use elements of conduction and convection to derive blood perfusion models/data.
  - Body conducts heat from the core
  - Body convects heat at the skin surface
  - Body is cooled from evaporation due to sweat

Transferring Energy as Heat

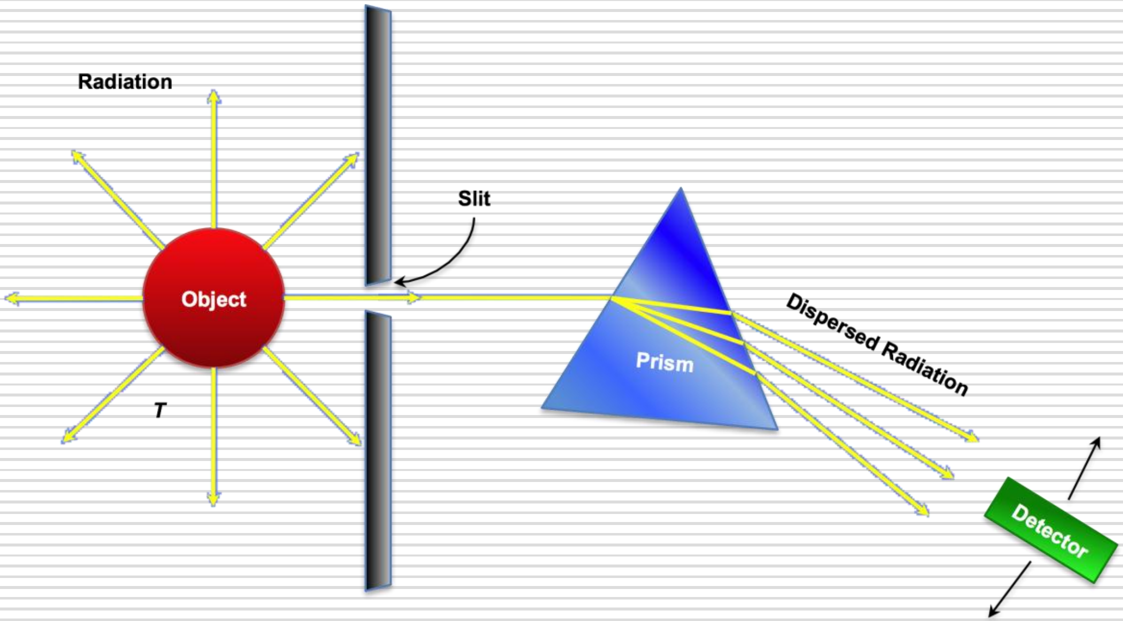
- Thermal Radiation
  - Blackbodies radiate thermal energy.
    - Only dependent on object’s temperature, no other characteristic [Tippler 2003].
  - Thermal radiation needs no transfer medium (i.e. thermal energy can radiate in a vacuum) [NDT 2008].

$$\dot{Q}_e = \varepsilon \sigma A T_{body}^4$$

- When thinking about thermal radiation, remember, we are talking about light, not temperature.

Blackbody Radiation

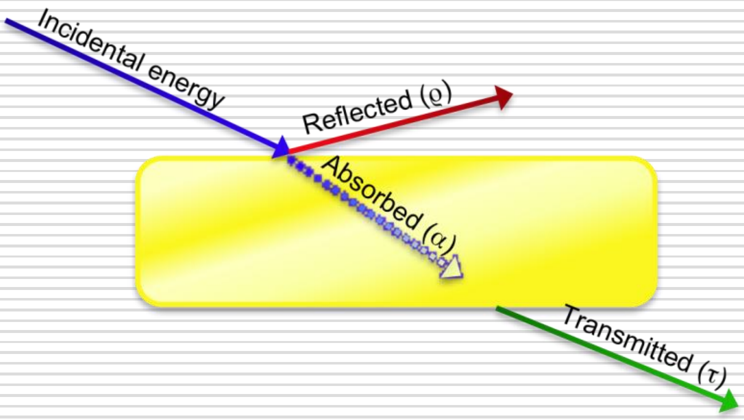
- "A body that absorbs *all* radiation incident on it is called an *ideal blackbody*." [Tipler 2003]



- *Schematic diagram for determining the spectral distribution for a given object at a temperature T.* In this figure, the object at temperature *T* emits radiation, which passes through the slit and is dispersed via the prism according to its wavelength to the wavelength-sensitive detector.

Material Properties

- All real sources reflect, transmit, and absorb radiant energy at different wavelengths (λ) and temperatures (T).
- This expressed mathematically as: $\rho+\alpha+\tau=1$
  - ρ: reflectivity
  - τ: transmissivity
  - α: absorptivity
- Emissivity is given as the ratio of the heat flux radiated by the object to the heat flux of the black body [Wong 2004].
  - Ideal blackbodies have 100% emissivity/absorptivity.
  - Reflectivity and transmissivity are more involved calculations [Wong 2004].



$$\varepsilon_\lambda = \frac{q_\lambda(T)}{q_{\lambda b}(T)}$$

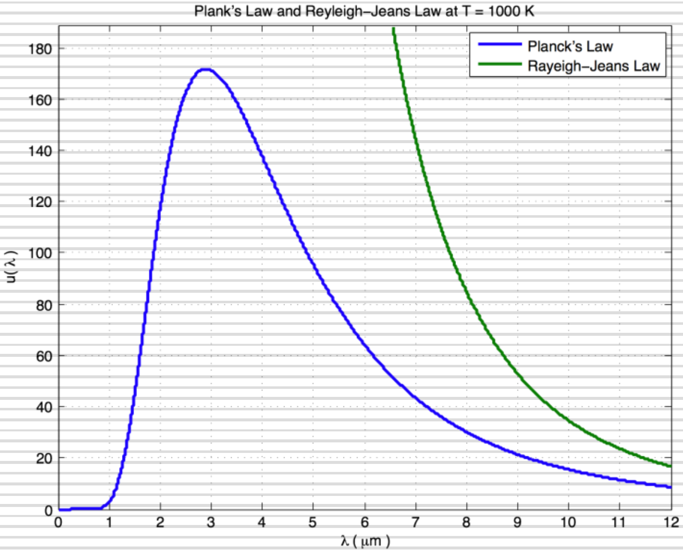
Blackbody Radiation

- The power spectral distribution is the product of the density of states with the average energy.
- Rayleigh-Jeans (ultraviolet-catastrpohe)

$$f(E) = Ae^{-E/kT}$$

$$\bar{E} = \int_0^\infty E \cdot f(E)dE = \int_0^\infty E \cdot Ae^{-E/kT}dE = kT$$

$$u(\lambda) = kTg(\lambda) = 8\pi kT\lambda^{-4}$$



- Planck's law□

$$E_n = n\varepsilon = nhf \quad n = 0, 1, 2, \ldots$$

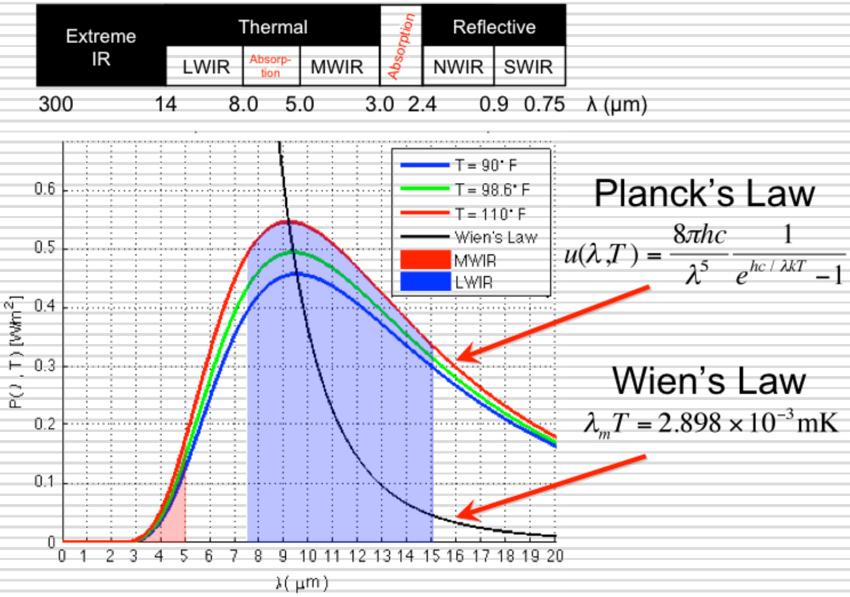
$$f_n = Ae^{-E_n/kT} = Ae^{-n\varepsilon/kT}, \quad where \sum_{n=0}^{\infty} f_n = 1$$

$$\bar{E} = \sum_{n=0}^{\infty} E_n f_n = A\sum_{n=0}^{\infty} E_n e^{-E_n/kT} = \frac{\varepsilon}{e^{\varepsilon/kT} - 1} = \frac{hf}{e^{hf/kT} - 1} = \frac{hc/\lambda}{e^{hc/\lambda kT} - 1}$$

$$u(\lambda) = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

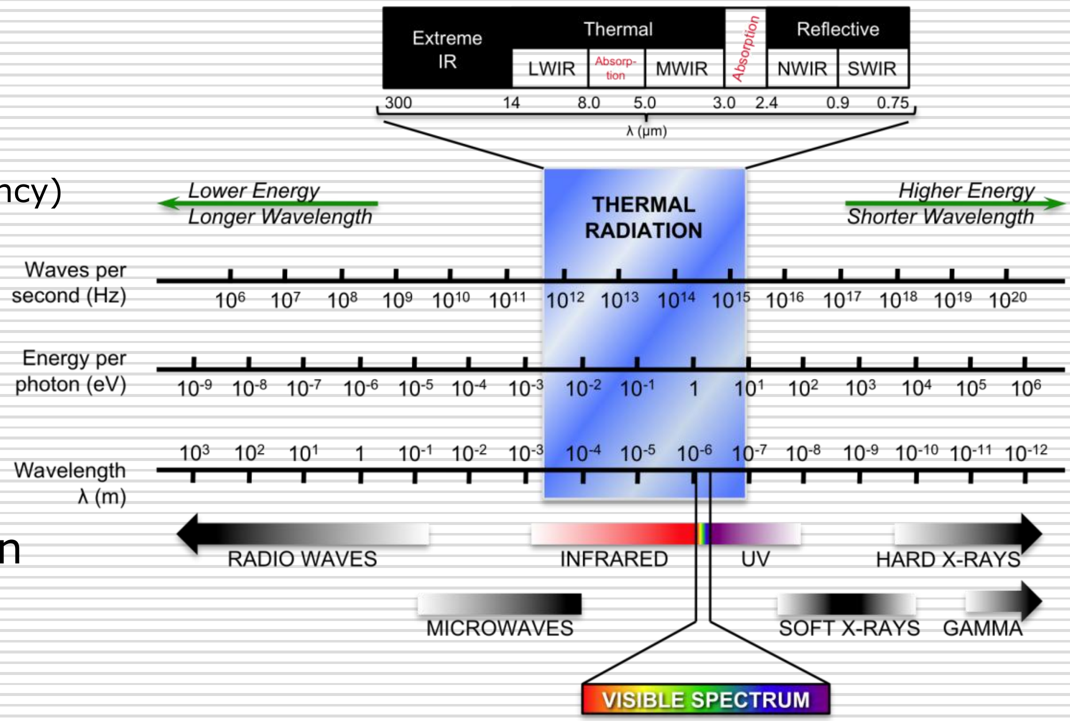
Blackbody Radiation

- Planck's law is important because it accurately predicts the power of thermal radiation emitted at a given wavelength from an object's temperature.
  - Experiments are designed around the properties of the objects being evaluated.
- The three three curves correspond to the standard operating temperature range for humans. The shaded areas correspond to thermal IR bands.



Thermal IR Detection

- Planck's theory ($E = hf$) is graphically illustrated to the right.
  - Higher energy light has shorter wavelengths (i.e. higher frequency)
- The Thermal IR spectrum covers the wavelengths from 780 nm to 1000 μm
  - Near infrared (780-2500 nm)
  - Mid-infrared (2.5-50 μm)
  - Far infrared (50-1000μm)
- We use Mid-IR, subdivided in the table above



Thermal IR Detection

- Certain atmospheric components such as CO_2, O_2, and H_2O attenuate certain IR bands to the point where those bands cannot be used.
- The 2.4-3.0 μm and 5-7.5 μm bands are attenuated in this manner.
- The image created by Robert Rohde of Global Warming Art on the right shows the usable spectrum.
  Source: www.globalwarmingart.com/wiki/Image:Atmospheric_Transmission_png

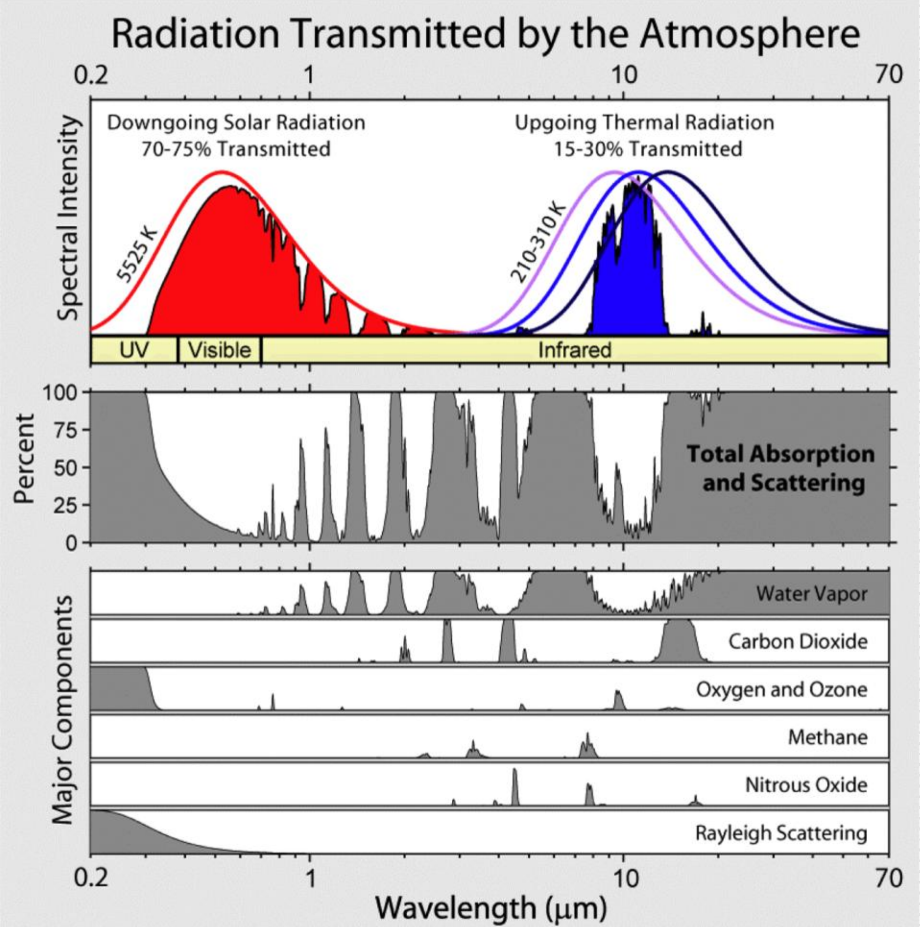
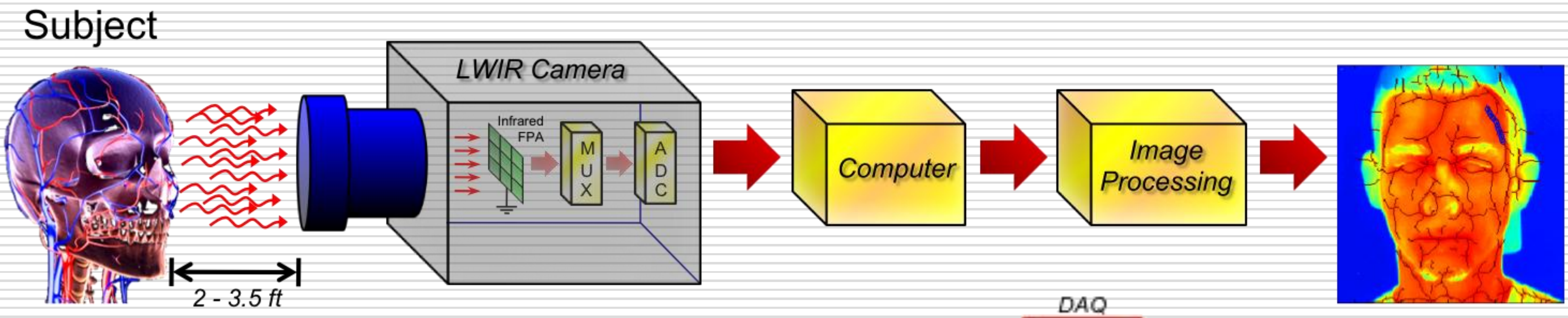
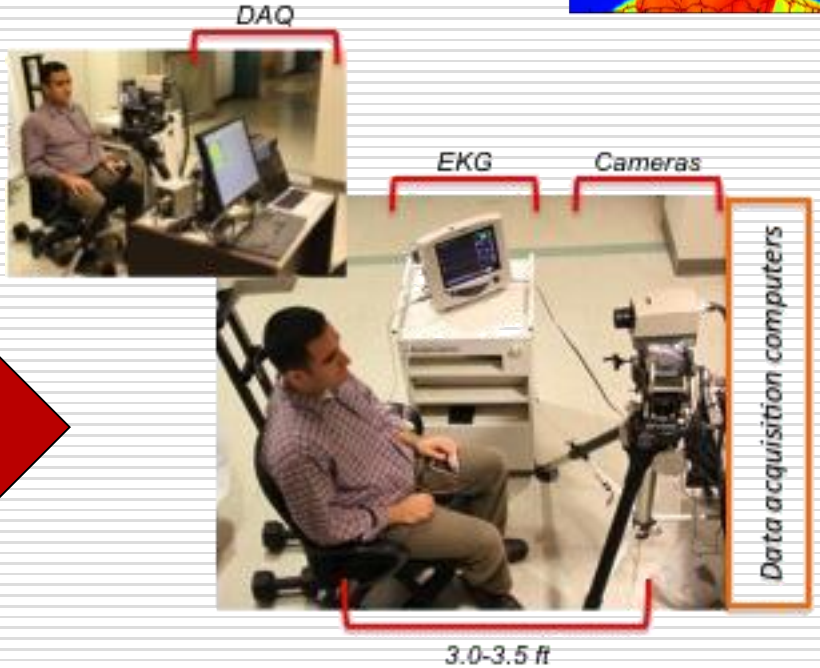


Image Formation Process



Equipment

- N$_2$-cooled Indigo Phoenix QWIP LWIR Camera System
  - Spatial resolution of 320x256
- Real Time Imaging Electronics System
  - 8.000ms integration time
- Talon Ultra 5.2 image acquisition SW
  - 512 video frames at 30 fps
- Advisor Vital Signs Monitor
  - 5-lead chest-attached ECG
- Data Translation DT9816 16-bit ADC



Special Considerations

- Thermal images require no ambient light
- Thermal images are by definition, Lambertian surfaces
- Unlike a traditional CCD camera, thermal IR FPAs will heat up in a non-uniform manner
  - This leads to the distinction between cooled and uncooled cameras.
  - This can be corrected in pre-processing → NUC Table

Thermal IR Detection

- Thermal detectors – Absorbed thermal energy raises the temperature of the detector, changing a temperature-dependent parameter and is measured.
- Types
  - Heat sensitive coatings
    - Waxes, greases, paints
    - Cheap, but not good quantitative data
  - Thermoelectric devices
    - Thermocouples, thermopiles, thermistors, bolometers
    - Produce electrical responses based on the sensor’s change in temperature and are used for localized measurements

Thermal IR Detection

- Quantum detectors – detect photons directly from IR radiation and are far more sensitive.
  - Photons in a range of wavelengths are absorbed by the detector, creating free electron-hole pairs, detected as electrical current.
  - SNR low, so detectors are cooled to 77K or 4K with high pressure gasses
  - Some systems have temperature resolution small as 0.07 °C.
  - The CVIP lab uses a N_2-cooled QWIP camera
- Types
  - Photoconductive
    - Based on the photogeneration of charge carriers (electrons, holes, or pairs), which increases the material's (InSb, QWIP, MCT, PbS & PbSe) conductivity.
  - Photovoltaic
    - Use internal pn-junctions or Schottky barriers with a built-in E-field to separate photo-generated electron-hole pairs. (InSb, MCT, PtSi, silicon Schottky barriers).

Thermal Camera Jargon

The items listed below are typically seen in thermal camera specifications

- Spatial Resolution – same as with regular cameras
- MRTD – minimum resolvable temperature difference (i.e. thermal resolution)
  - Smaller = better
- D* (D-star) – detectivity (SNR @ 1W input)
  - Larger = better
- NUC – Non-uniformity correction/calibration
- NEDT – Noise equivalent temperature difference
  - Calculated at the measured temp. diff. between the image ref and ambient target
  - Smaller = better

Generations of Technology

- 1^{st} Generation
  - Principally for military and civilian IR use
  - Scans a scene one line at a time
  - No multiplexing function on FPA
- 2^{nd} Generation
  - Full-framing systems
  - Configured as 2D array of photodiodes connected with indium bumps to a readout IC (Sensor Chip Assembly, or SCA)
- 3^{rd} Generation
  - Vague in description
  - Defined to maintain the current technological advantage help by US/allied forces
  - Systems often include these characteristics
    - High performance, high resolution cooled imagers with two- or three-color bands
    - Medium- to high-performance un-cooled imagers
    - Very low cost, expendable un-cooled imager
- NASA currently has a high-sensitivity 64 Mpixel array created with a mosaic of, 4, 4Kx4K FPAs

Next time…

- Skin-heat transfer models and measuring the propagation of blood-heat through the circulatory system

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THANK YOU!

Measuring Temperature

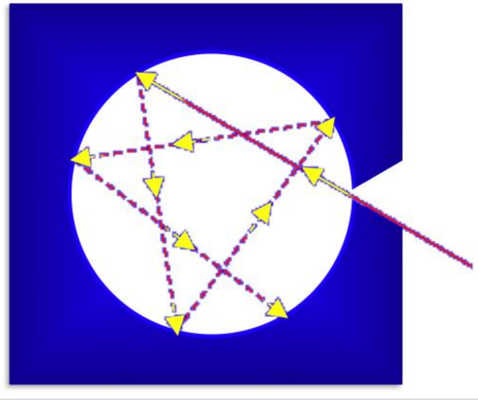
- Second Law of Thermodynamics (Clausius statement)
  - "It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler body to a hotter body."
- Second Carnot Corollary
  - "All reversible power cycles operating between the same two thermal reservoirs have the same thermal efficiency."

$$\eta = \frac{W_{cycle}}{Q_H} = 1 - \frac{Q_C}{Q_H} \qquad T = T_H \left(\frac{Q_C}{Q_H} \right)_{\substack{\text{rev}\\\text{cycle}}} = T_3 \left(\frac{Q}{Q_3} \right)_{\substack{\text{rev}\\\text{cycle}}} = 273.16 \left(\frac{Q}{Q_3} \right)_{\substack{\text{rev}\\\text{cycle}}}$$

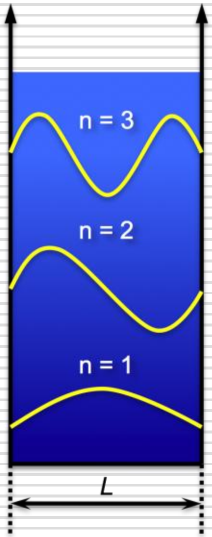
- The Kelvin scale has a zero of 0K. Why?
  - Energy rejected from the cycle by heat transfer Q_C cannot be negative, so T must not be negative, else efficiency would be outside the real domain [0,1].
- Reference [Moran 2000]☐.

Blackbody Radiation

- An practical ideal blackbody is modeled on the right with a small hole that leads into a (3D) cavity of arbitrary shape.
  - Most of the energy from the radiation will likely be completely absorbed before exiting the cavity.
  - Recall that absorptivity = emissivity for blackbodies [Robitaille 2008].



- To find the spectral distribution, one must first find the density of states for the cavity per unit volume and per unit wavelength starting with Schrödinger's time-independent equation modeling the infinite square well on the right [Zeghbroek 2007].



$$\frac{-\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2}+V(x)\psi(x)=E\psi(x)$$

$$\downarrow$$

$$\psi(x)=A\sin(kx)+B\cos(kx) \rightarrow g(\lambda)=\frac{hc}{\lambda^2}\cdot\frac{8\pi(hc)^2}{(hc)^3\lambda^2}=8\pi\lambda^{-4}$$