Thermal subsystem

MAE 4160, 4161, 5160

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Today’s topics:

- What it is for
- Sources of heat
- Heat transfer physics
- Equilibrium temperatures
- Thermal management strategies and technologies

What is the thermal subsystem for?

- Control the temperature of the spacecraft and its components by:
    - Dissipating excess heat (typically passive radiators)
    - Cooling certain components (e.g. instrument focal planes)
    - Heating certain components (e.g. batteries, sometimes)
- Spacecraft must survive very hot/cold environments
- Spacecraft must survive extreme temperature changes in short amounts of time

Thermal requirements

Several components have operational/survival temperature ranges:

- Keep batteries between 10-20C
- Keep computers between 10-50C
- Keep humans alive and comfortable (e.g. crew cabin at 295K) → temperatures got as low as 43F during Apollo 13
- Keep liquid propellant from freezing/boiling
- Keep certain instruments cold
- Keep RTG heat source hot
- Avoid thermal cycling of components that can lead to thermal fatigue and structural damage

Component/ System	Operating Temperature (C)	Survival Temperature (C)
Electronics	0 to 50	-50 to 70
Humans	15 to 25	0 to 35
Batteries (NiCad)	10 to 20	0 to 50
IR detectors	-273 to -173	-273 to 35
Solid-state particle detectors	-60 to 0	-125 to 35
Momentum wheels	0 to 50	-20 to 70
Solar panels	-100 to +100 Efficiency decreases with Temperature	-150 to +150

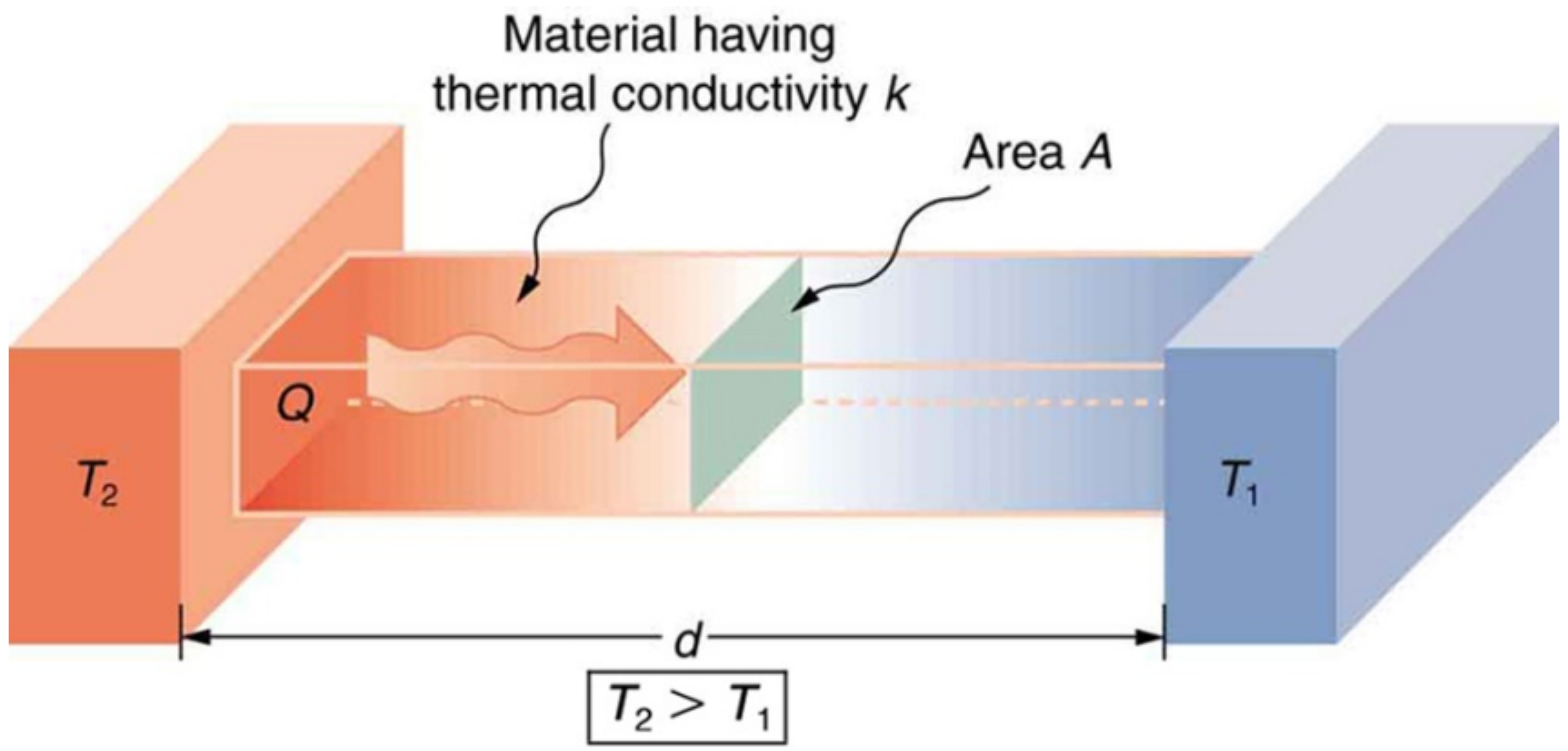
Sources of heat

- Internal energy dissipation
  - I^2R losses
  - Mechanical work (friction)
  - Combustion
- Sun
- Nearby planetary body (e.g. Earth)
- Cosmic background radiation (microwaves): ~2.73K

Heat transfer mechanisms

Water: $k = 0.606$
Aluminum: $k = 205$

Conduction



- Requires physical contact
- Heat flows from high T to low T according to Fourier's law:

$$\dot{Q} = \frac{\partial E}{\partial t} = k \cdot A \cdot \frac{\partial T}{\partial x}$$

where k is the thermal conductivity $\left[\frac{W}{m \cdot K}\right]$

heat transfer per unit time $[W]$	=	thermal conductivity $\left[\frac{W}{m \cdot K}\right]$	•	radiating surface area $[m^2]$	•	rate of change of temperature $\left[\frac{K}{m}\right]$

Heat transfer mechanisms

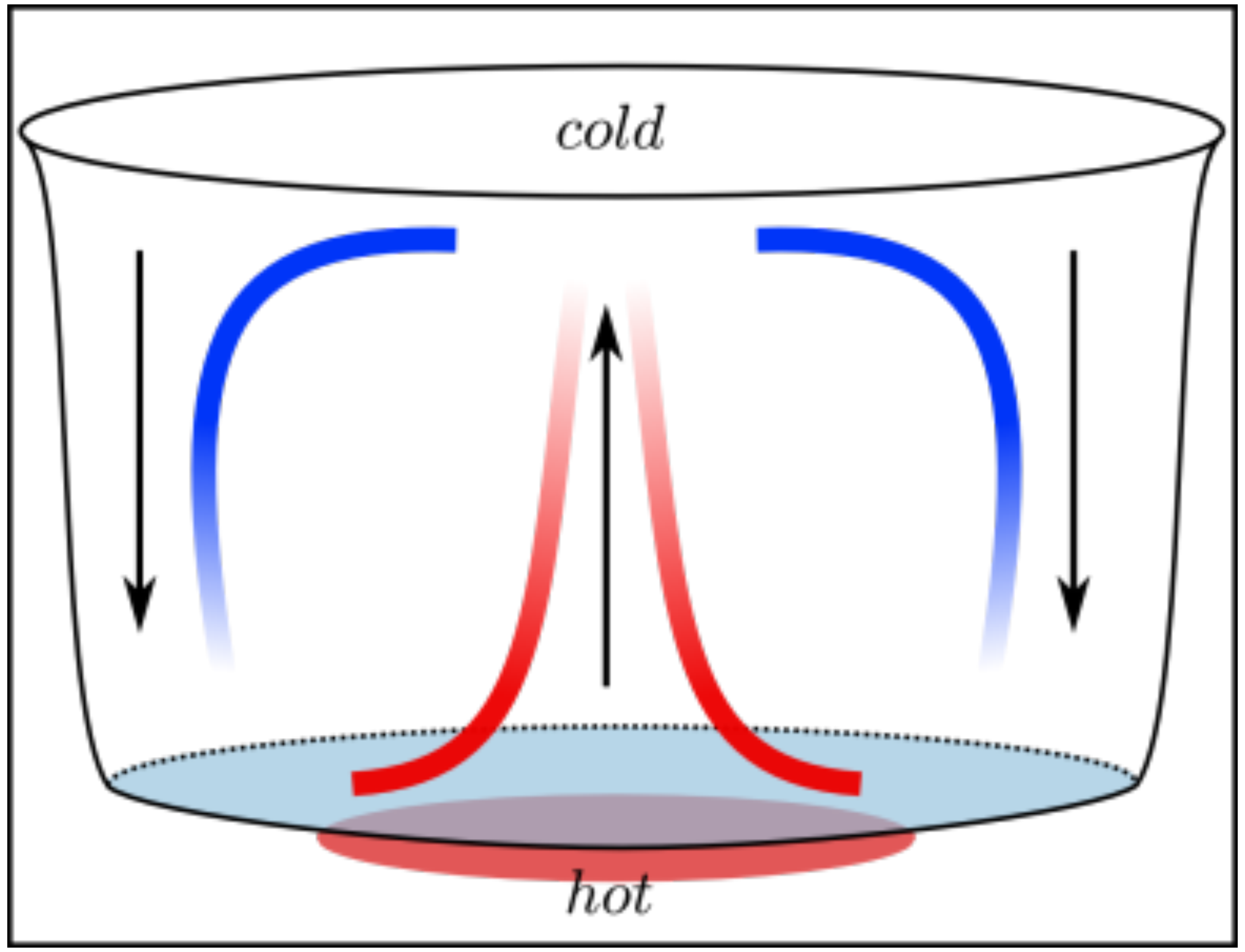
Convection

- "Heat rises" — requires gravity

$$\dot{Q} = \frac{\partial E}{\partial t} = h \cdot A \cdot \left(T - T_{fluid}\right)$$

where h is the heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

- Usually not a factor in space



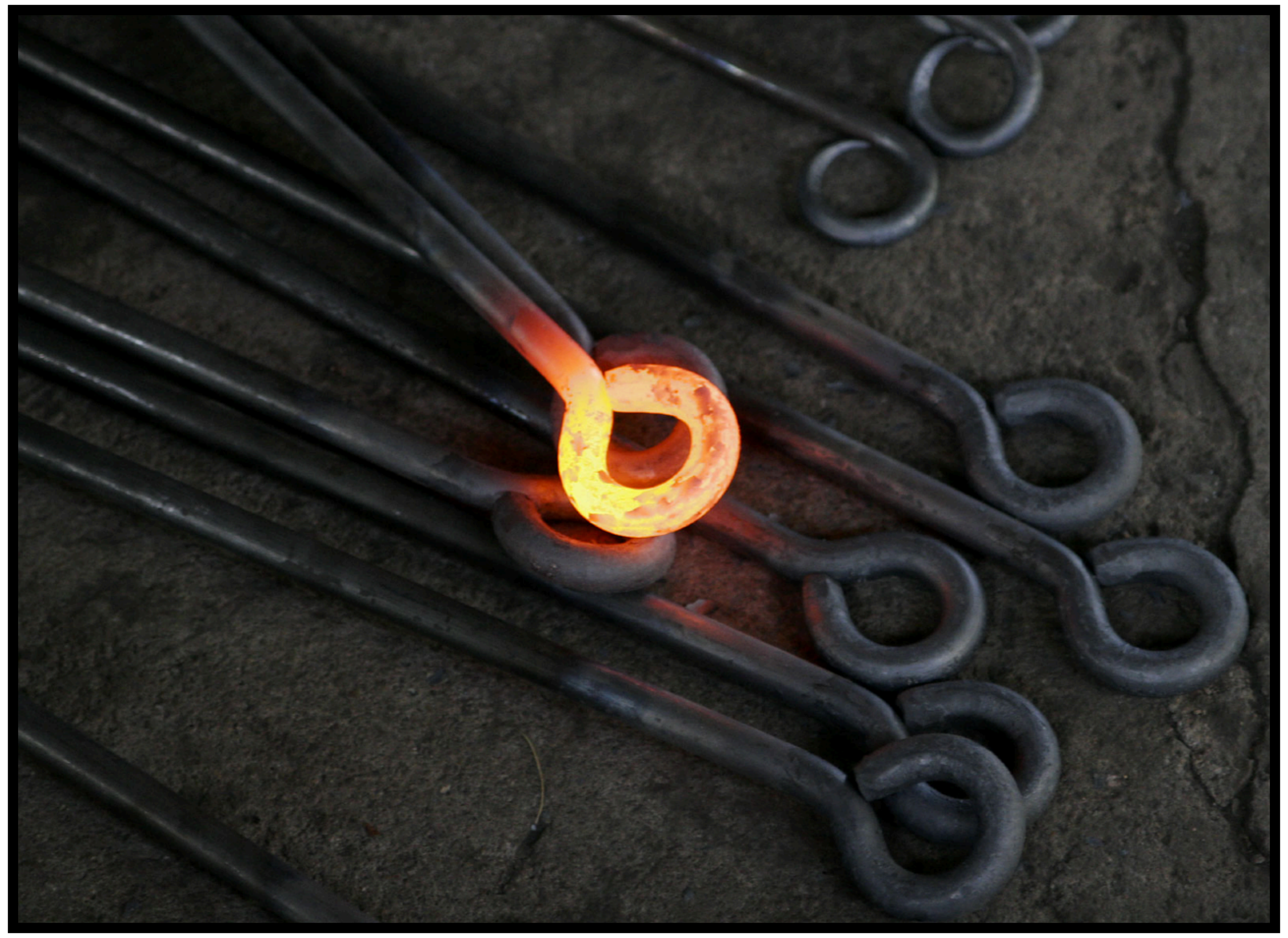
$$\underset{[W]}{\text{heat transfer per unit time}} = \underset{\left[\frac{W}{m^2 \cdot K}\right]}{\text{heat transfer coefficient}} \bullet \underset{[m^2]}{\text{radiating surface area}} \bullet \left(\underset{[K]}{\text{surface temperature}} - \underset{[K]}{\text{fluid temperature}}\right)$$

Heat transfer mechanisms

Radiation

- Through electromagnetic fields
- Dominates heat transfer in space

$$\dot{Q} = \sigma \epsilon A T^4$$

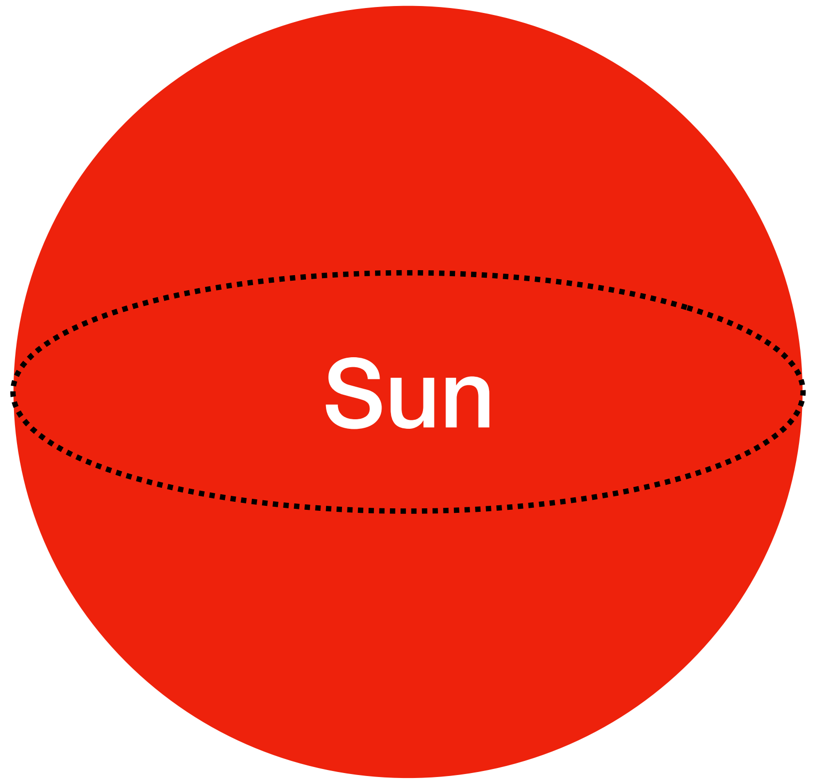


heat transfer per unit time $[W]$ = **Stefan-Boltzmann constant** $5.67 \times 10^{-8} \frac{W}{m^2 K^4}$ • **emissivity** • **radiating surface area** $[m^2]$ • $\left(\textbf{temperature}\ [K]\right)^4$

Equilibrium temperature

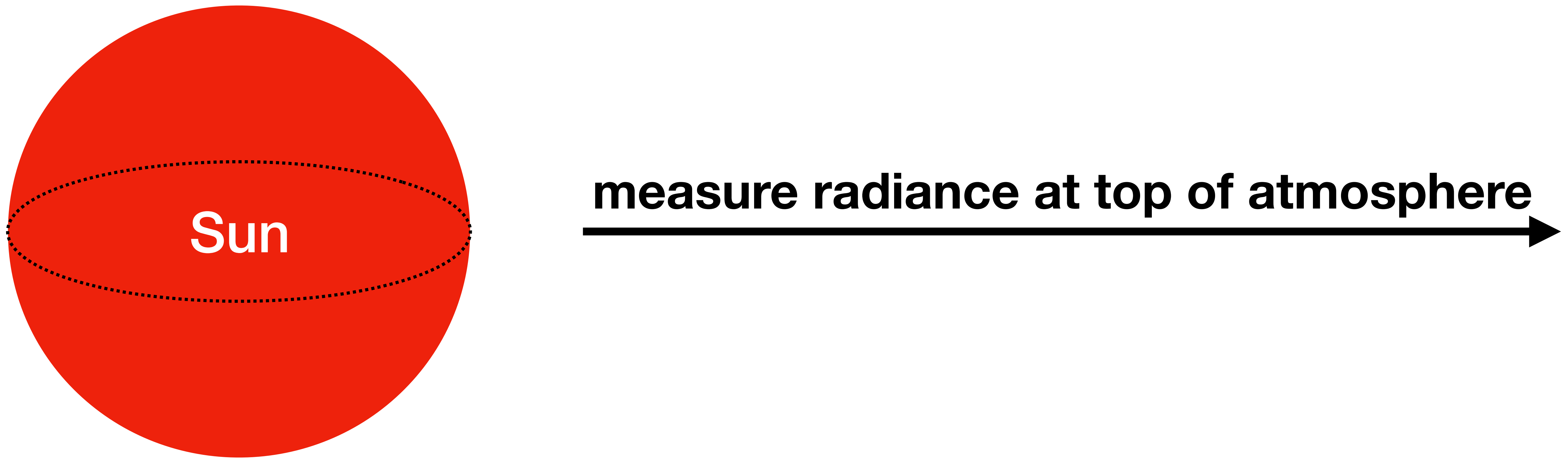
Heat power **in** = heat power **out**

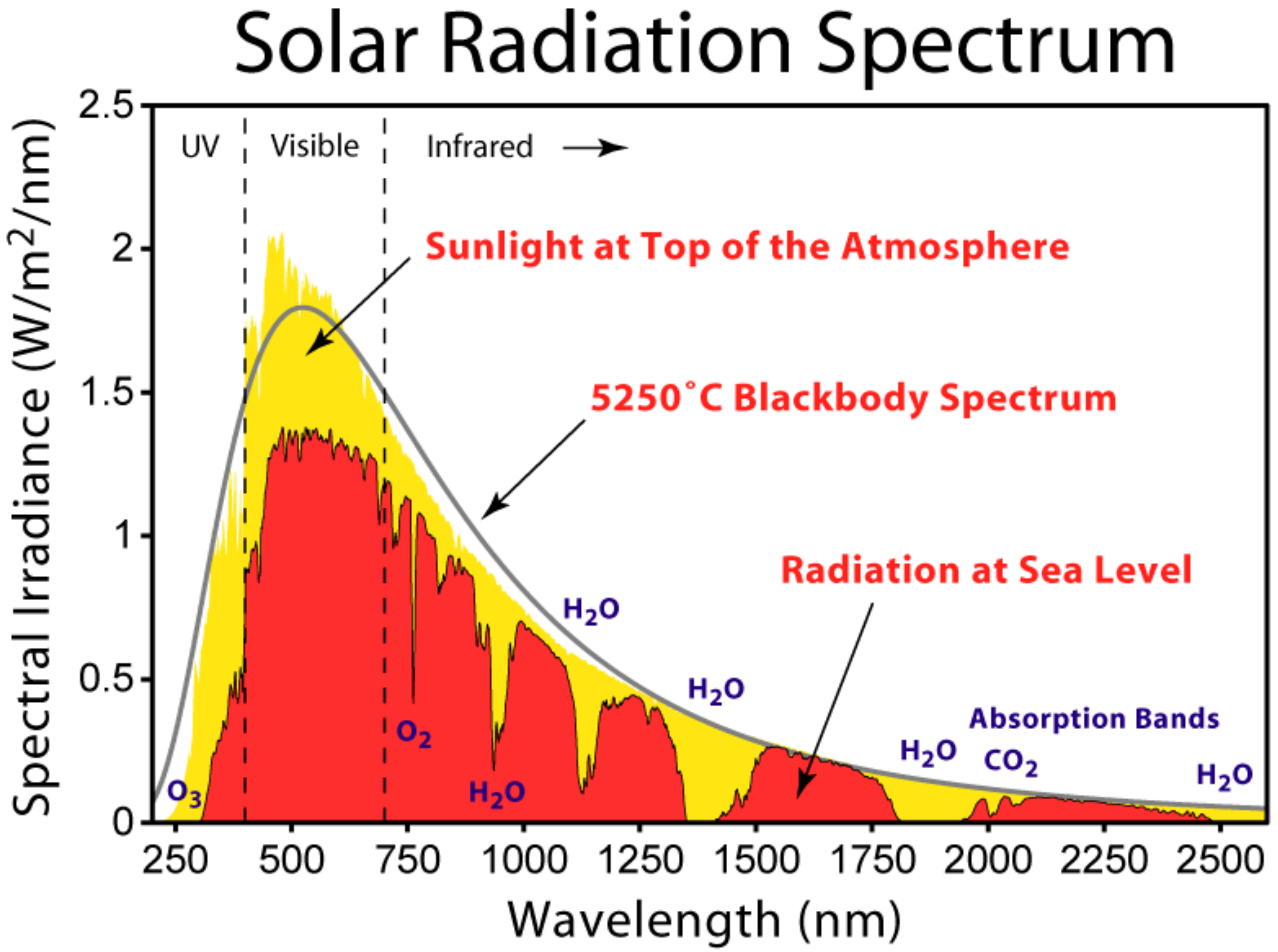
Some of the power **in** comes from the Sun.



Equilibrium temperature

What is the radiation spectrum at the top of atmosphere?

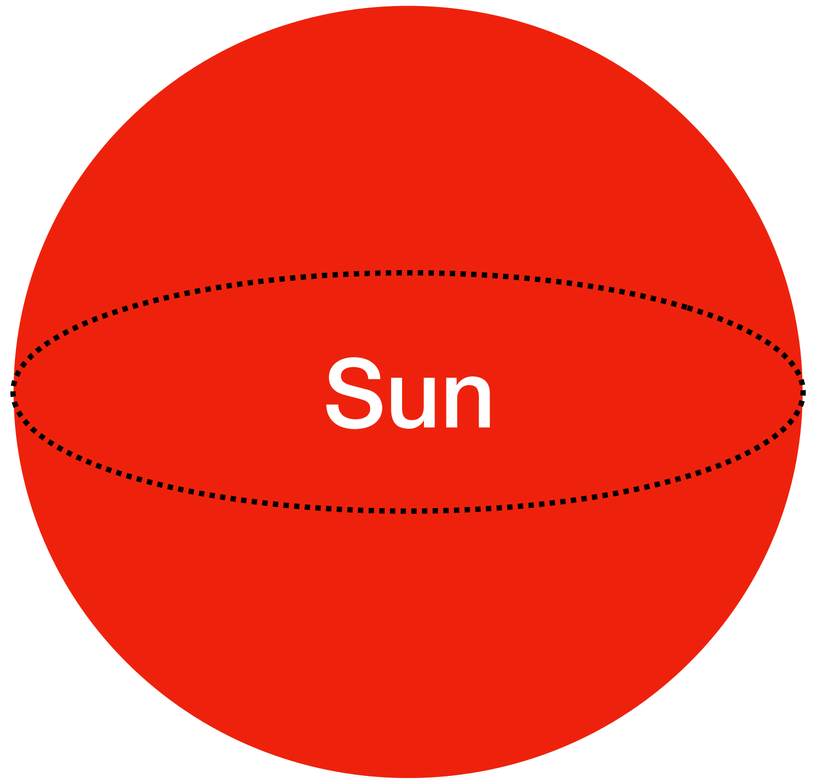




The Sun can be modeled as a **blackbody** with a peak wavelength of emission at $\lambda_{max} = 0.5015 \mu m$

Equilibrium temperature

How hot is the Sun?



How hot is the Sun? Use **Wien's Law:**

$$\lambda_{max} = \frac{2898[\mu m \cdot T]}{T}$$

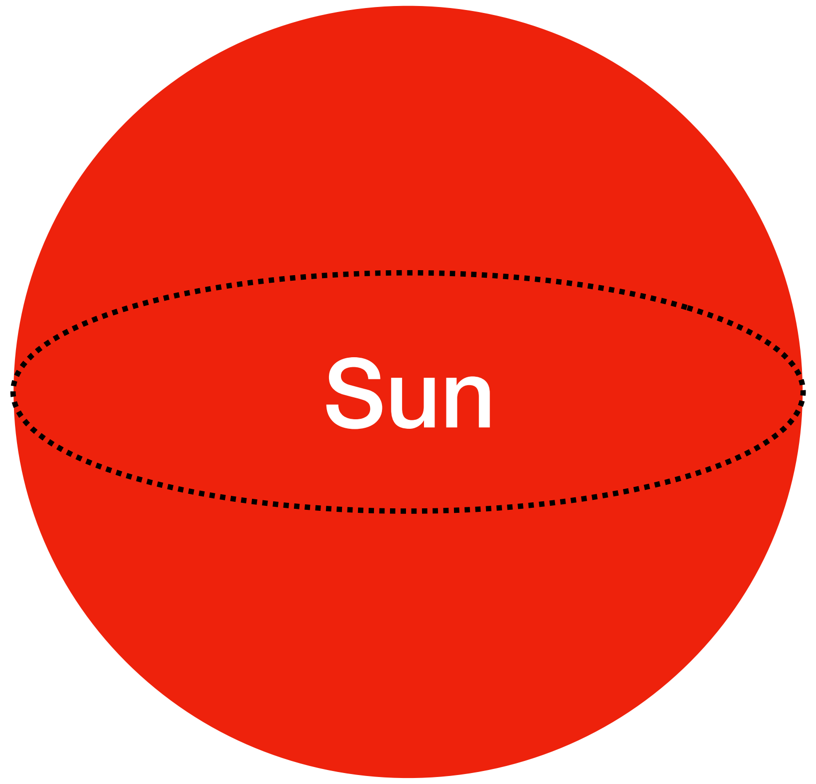
Solve for T**:**

$$T = \frac{2898}{\lambda_{max}} = \frac{2898}{0.5015} = 5778K$$

The Sun can be modeled as a **blackbody** with a peak wavelength of emission at $\lambda_{max} = 0.5015\mu m$

Equilibrium temperature

How much power per unit area does the Sun emit?



Use **Stephan-Boltzmann Law:**

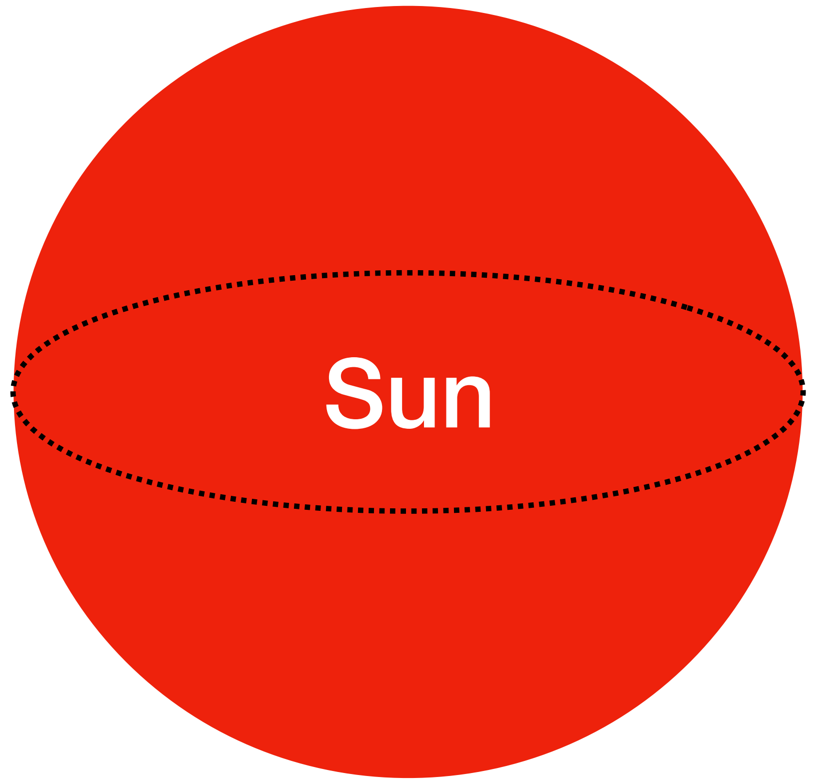
$$F = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8} \left[\dfrac{W}{m^2 K^4}\right]$ and F has units of $\dfrac{W}{m^2}$.

$$F = \left(5.67 \times 10^{-8}\right)\left(5778\right)^4$$
$$= 6.31 \times 10^7 \frac{W}{m^2}$$

Equilibrium temperature

How much total energy per unit time (Luminosity) does the Sun emit?



Multiply the power per unit area by the surface area:

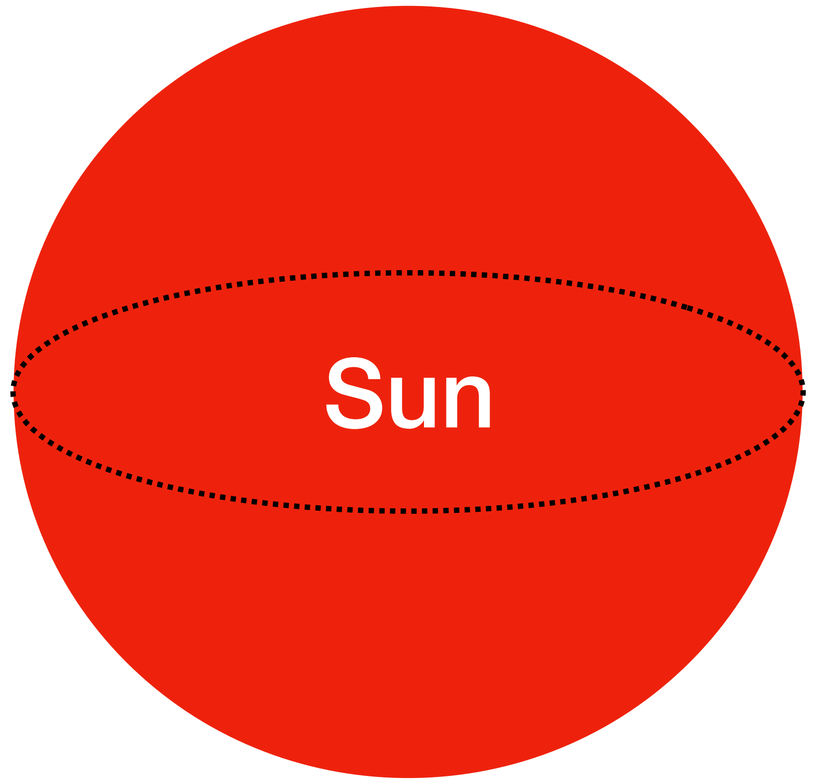
$$L = 4\pi R^2 \sigma T^4$$

We know that the Sun has a radius of the Sun is 6.97×10^8 meters. So, the luminosity is:

$$L = 4\pi \left(6.97 \times 10^8\right)^2 \left(6.31 \times 10^7\right)$$
$$= 3.85 \times 10^{26} W$$

Equilibrium temperature

How much energy per unit time at a particular distance from the Sun (1AU)?



Recall that this total energy gets distributed on the surface of a sphere with radius equal to the distance to the Sun. For some distance d_S, the received power P_d :

$$P_d = \frac{L}{4\pi d_S^2}$$

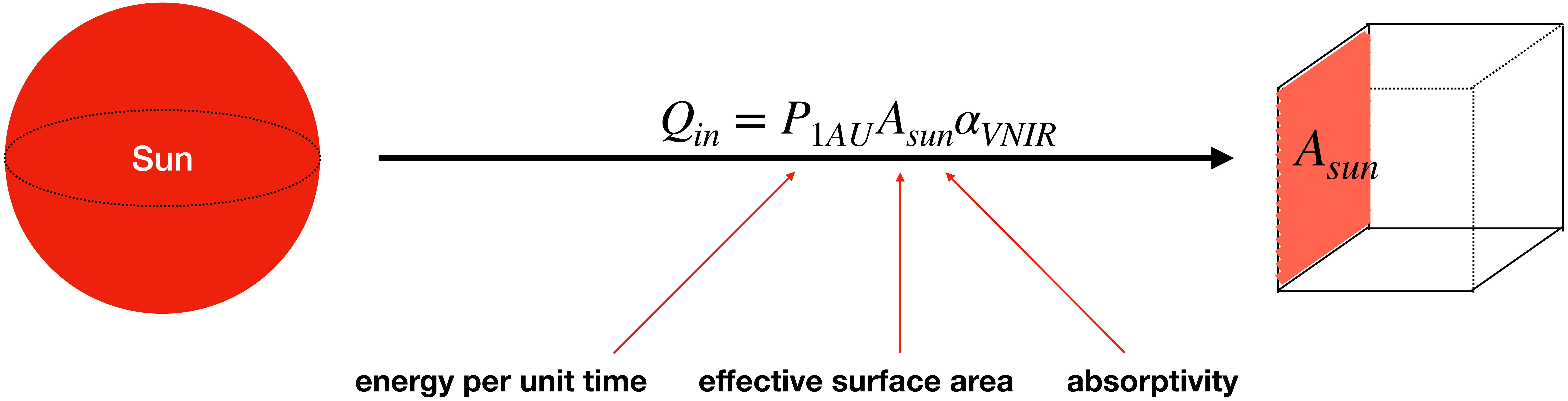
In the particular case that $d = 1AU = 1.49 \times 10^{11}$ m:

$$P_{1AU} = \frac{3.85 \times 10^{26}}{4\pi \left(1.49 \times 10^{11}\right)^2}$$

$$= 1370 \frac{W}{m^2} = S_0$$

Equilibrium temperature

That energy is **absorbed** by the part of the spacecraft which is **perpendicular to the Sun.**



Equilibrium temperature

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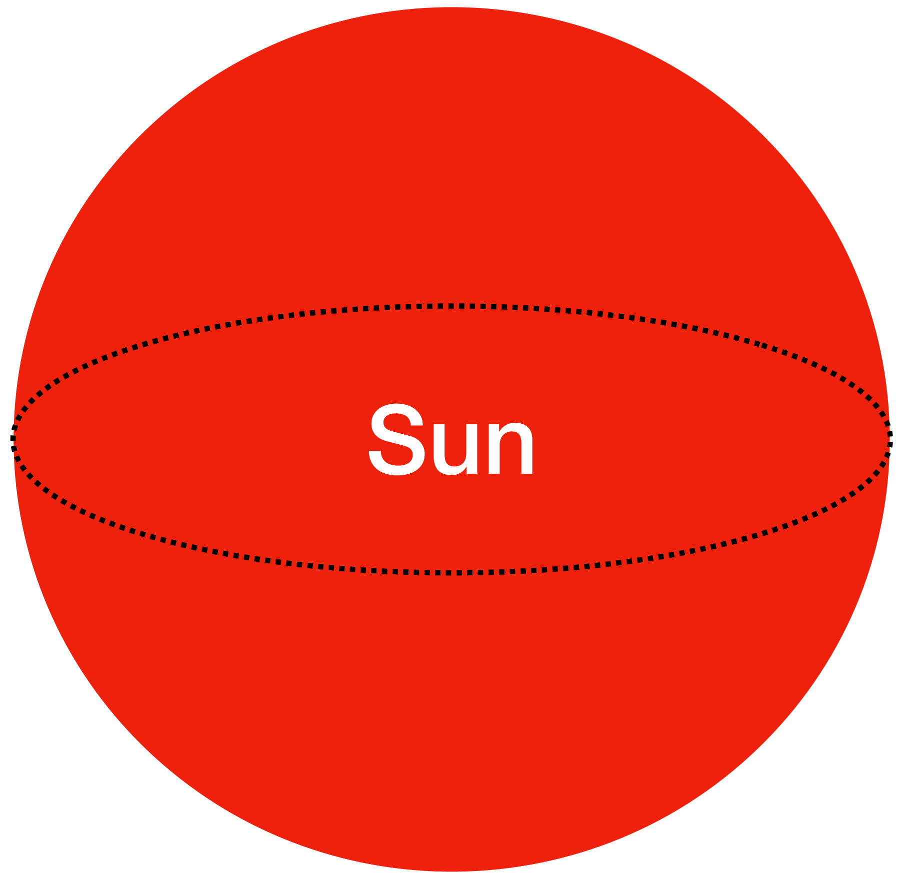
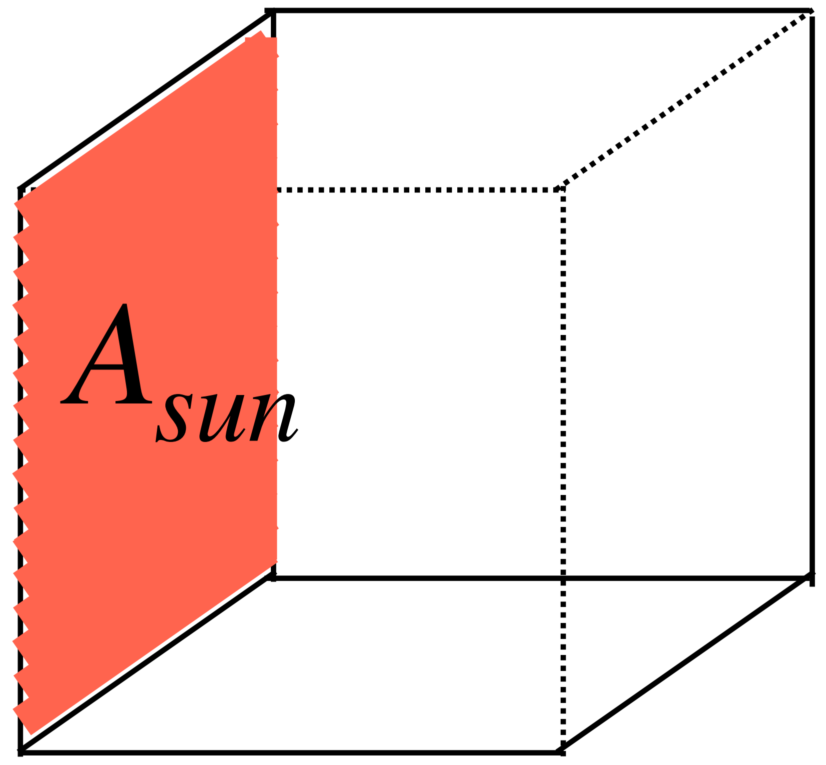


$$Q_{in} = P_{1AU} A_{sun} \alpha_{VNIR}$$

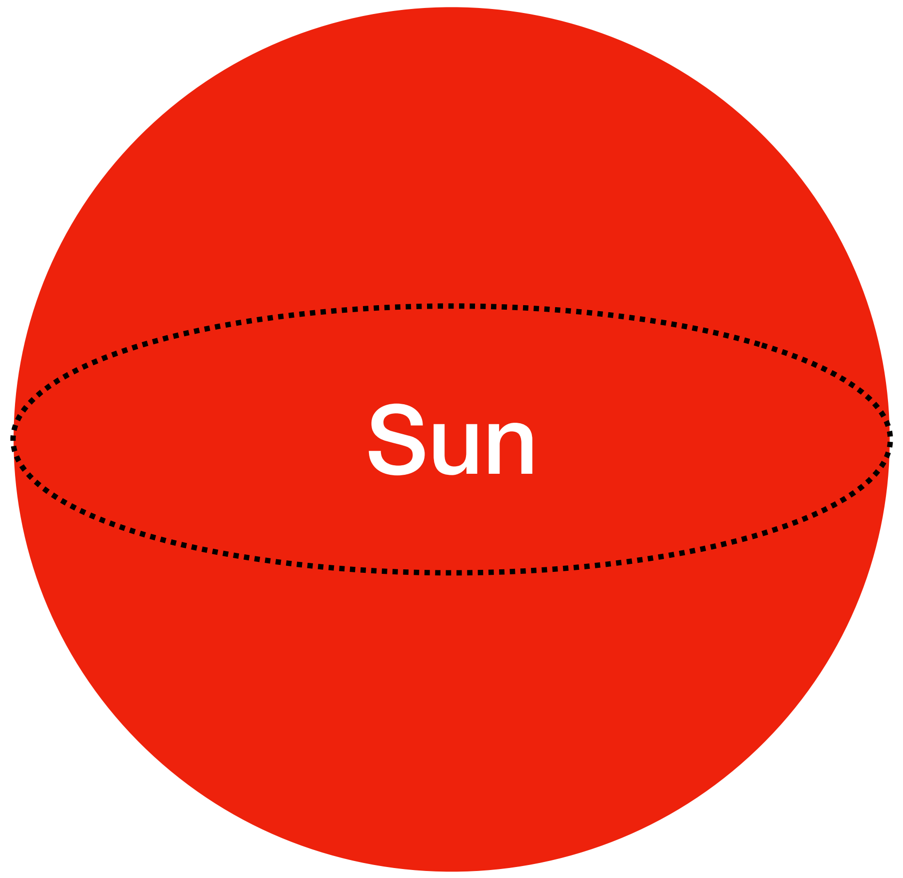


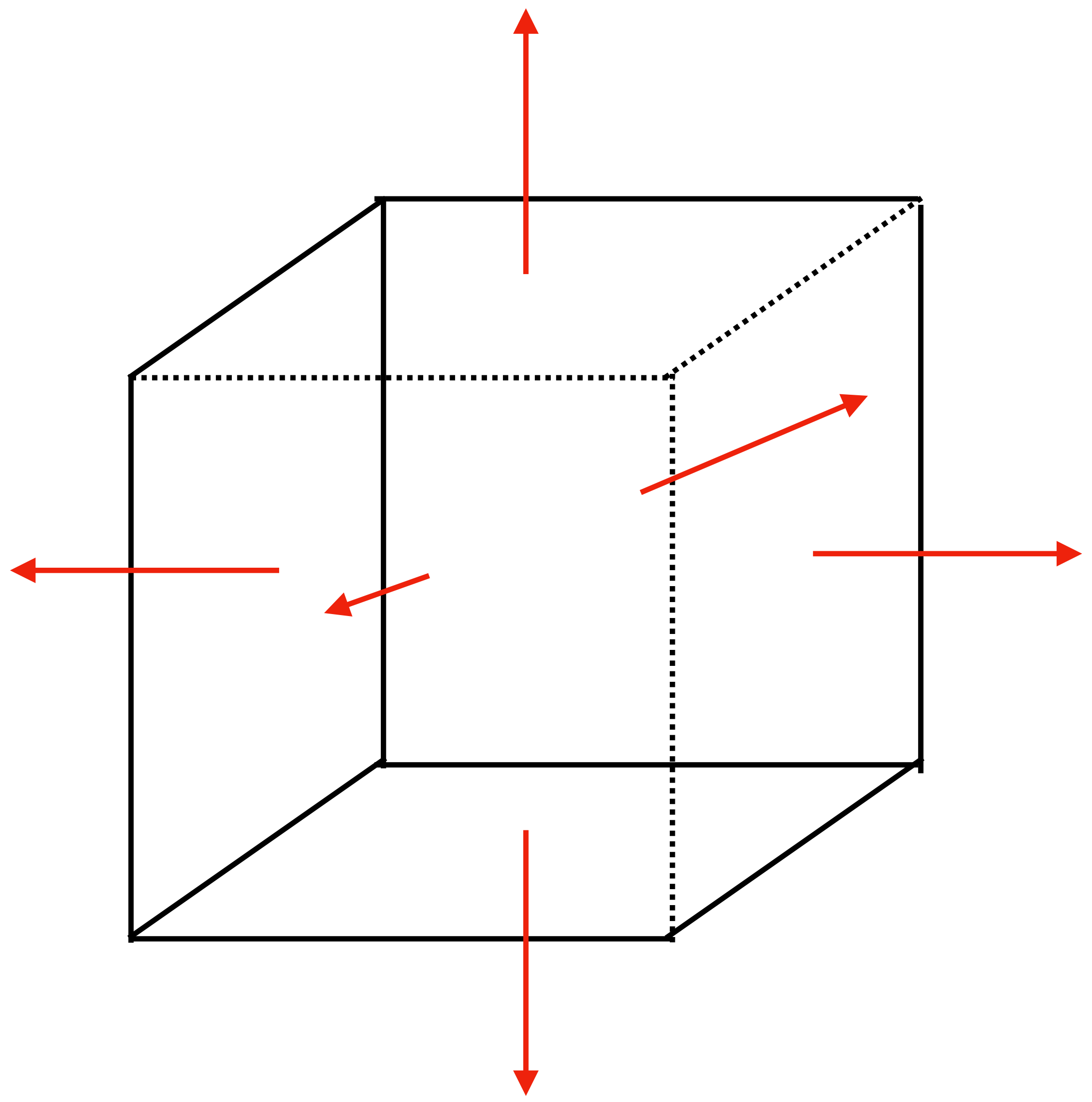
energy per unit time **effective surface area** **absorptivity**

What if the spacecraft were a flat plate at an angle to the Sun θ?

Equilibrium temperature

That energy is **radiated** by the part of the spacecraft which **faces space.**





$$Q_{out} = A_{cold}\epsilon_{TIR}\sigma T^4$$

radiating surface area **emissivity** **const.** **temp.**

Equilibrium temperature

Equilibrium is achieved when the outgoing energy equals the incoming energy.

$$Q_{out} = A_{cold}\epsilon_{TIR}\sigma T^4 = Q_{in} = P_{1AU}A_{sun}\alpha_{VNIR}$$

$$\downarrow$$

$$\boxed{T^4 = \frac{P_{1AU}}{\sigma} \cdot \frac{\alpha_{VNIR}}{\epsilon_{TIR}} \cdot \frac{A_{sun}}{A_{cold}}}$$

Equilibrium temperature

Suppose a black $\left(\dfrac{\alpha}{\epsilon} \approx 1\right)$ cubical spacecraft in Earth orbit. What is the equilibrium temperature?

$$T^4 = \frac{P_{1AU}}{\sigma} \cdot \frac{\alpha_{VNIR}}{\epsilon_{TIR}} \cdot \frac{A_p}{A_r}$$
$$= \frac{1370}{5.67 \times 10^{-8}} \cdot 1 \cdot \frac{1}{6}$$
$$\longrightarrow T \approx 252K = -21C$$

energy for spacecraft thermal control. Thes

Table 22-10. Temperatures for Various Geometries of Absorbing to Radiating Area ($\alpha = \varepsilon = 1$).

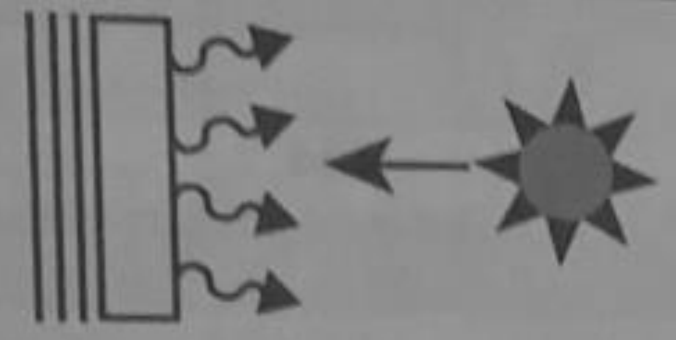
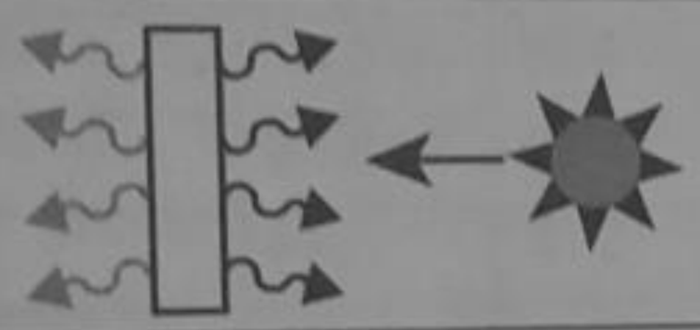
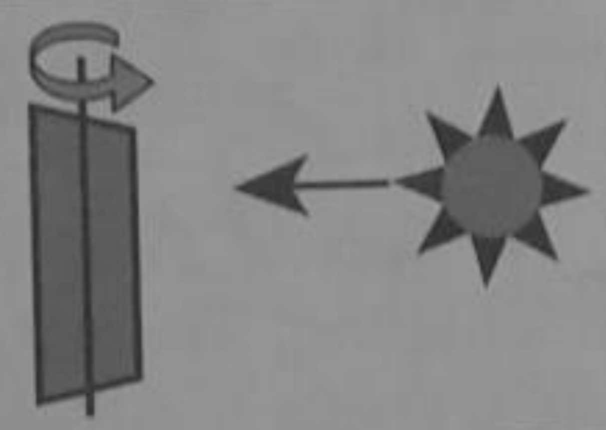
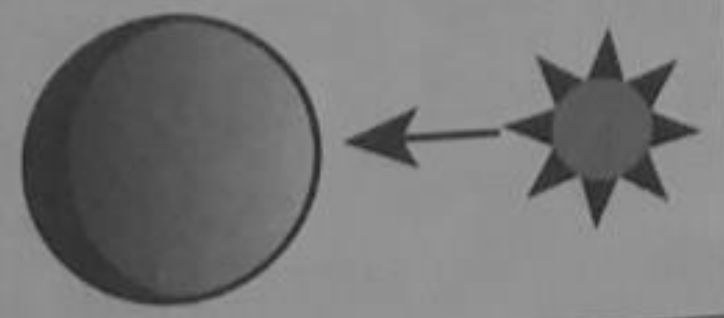
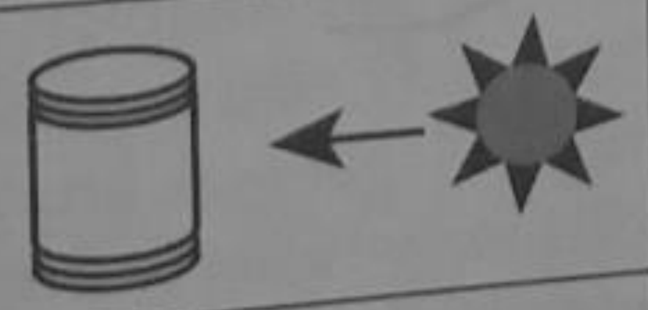
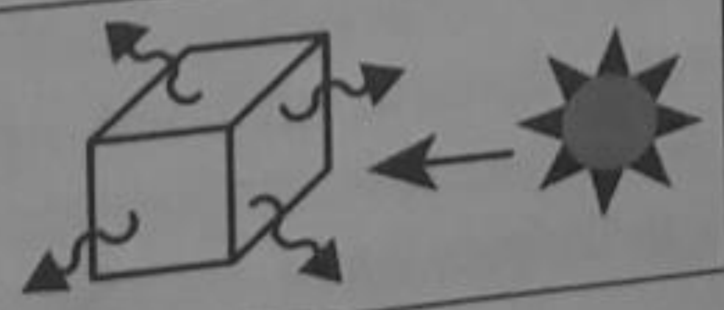
Geometry	Figure	Absorbing Area	Radiating Area	Area Ratio	Resulting Temp. °C Sun (1,366 W/m^2) ($\alpha = \varepsilon = 1$)
Plate Facing Sun with Insulated Back		1	1	1	121
Plate Facing Sun with Radiating Back		1	2	1/2	58
Plate Rotating in Sun both Sides Active		$2/\pi$	2	$1/\pi$	23
Sphere		πr^2	$4\pi r^2$	4	6
Cylinder Normal to Sun-Insulated Ends		$D \times H$	$\pi \times D \times H$	$1/\pi$	23
Cube (Isothermal) One Side Facing Sun		1	6	1/6	–21

Table 22-10, Fig. 22-16, Eq. 2

Equilibrium temperature

Equilibrium is achieved when the outgoing energy equals the incoming energy.

$$Q_{out} = A_{cold}\epsilon_{TIR}\sigma T^4 = Q_{in} = P_{1AU}A_{sun}\alpha_{VNIR}$$

$$\downarrow$$

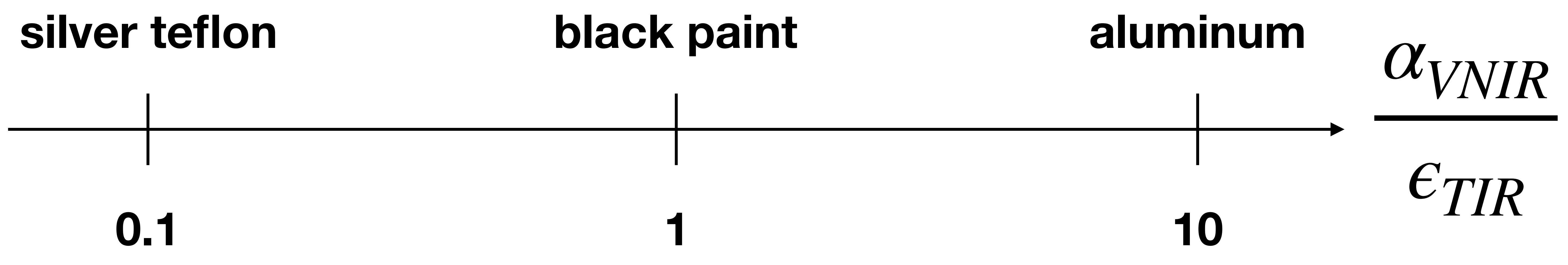
$$\boxed{T^4 = \frac{P_{1AU}}{\sigma} \cdot \frac{\alpha_{VNIR}}{\epsilon_{TIR}} \cdot \frac{A_{sun}}{A_{cold}}}$$

choice of materials

Emissivity and absorptivity of materials

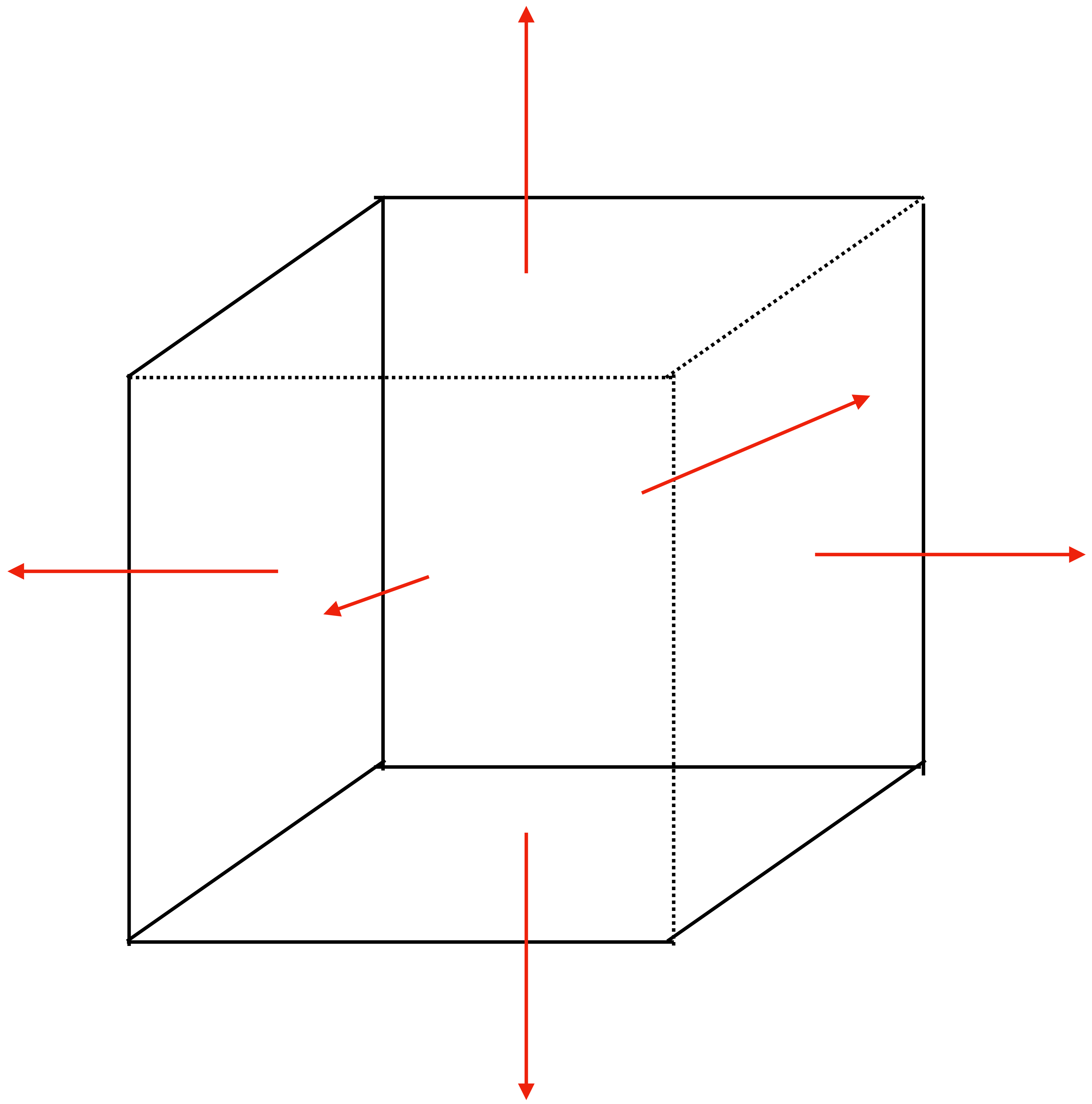
Material	α_{VNIR}	ϵ_{TIR}	Ratio
Aluminum	0.09	0.03	3.00
White paint	0.20	0.92	0.22
Black paint	0.92	0.89	1.03
Silver Teflon	0.08	0.8	0.10
Aluminized Kapton	0.38	0.67	0.56

- Use silver teflon to minimize solar absorption but maximize emissions (e.g. for telescope mirrors)
- Use black paint to maximize energy transfer, both absorption and emission
- Use metals to minimize both absorption and emission (instrument sun shield)
- Combine these surfaces to get almost any ratio that you want



A brief aside: how fast to things cool down in space?

Cooling/heating rate



$$Q_{out} = A_{cold}\epsilon_{TIR}\sigma T^4$$

Recall that specific heat capacity $C_p \left[\dfrac{J}{kg \cdot K}\right]$

is the energy needed to change the temperature of a material per unit temperature and unit mass

$$dQ = mC_p dT$$

combine these two equations . . .

$$\frac{dQ}{dt} = mC_p \cdot \frac{dT}{dt} = \epsilon\sigma T^4 A$$

integrating . . .

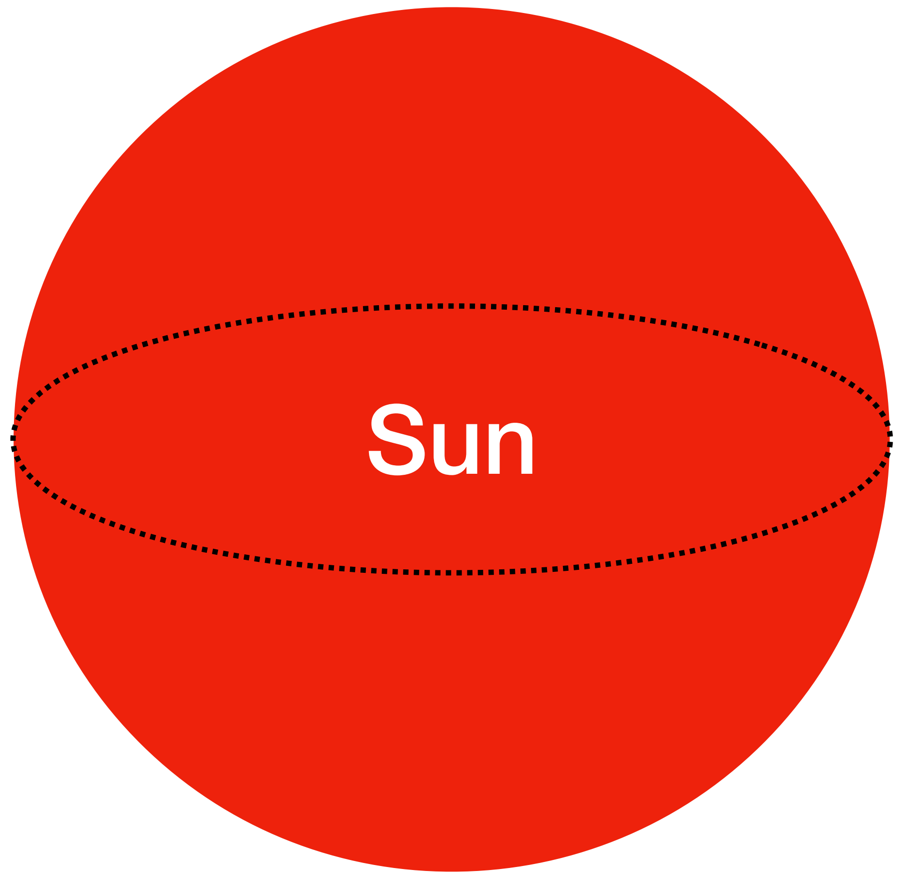
$$\frac{\left(T_f^{-3} - T_i^{-3}\right)}{3} = \frac{\epsilon\sigma A}{mC_p}\Delta t$$

But there are other sources of heat! Including thermal emissions from Earth, Earth albedo, and internal heat generation.

But there are other sources of heat! Including **thermal emissions from Earth**, Earth albedo, and internal heat generation.

Equilibrium temperature

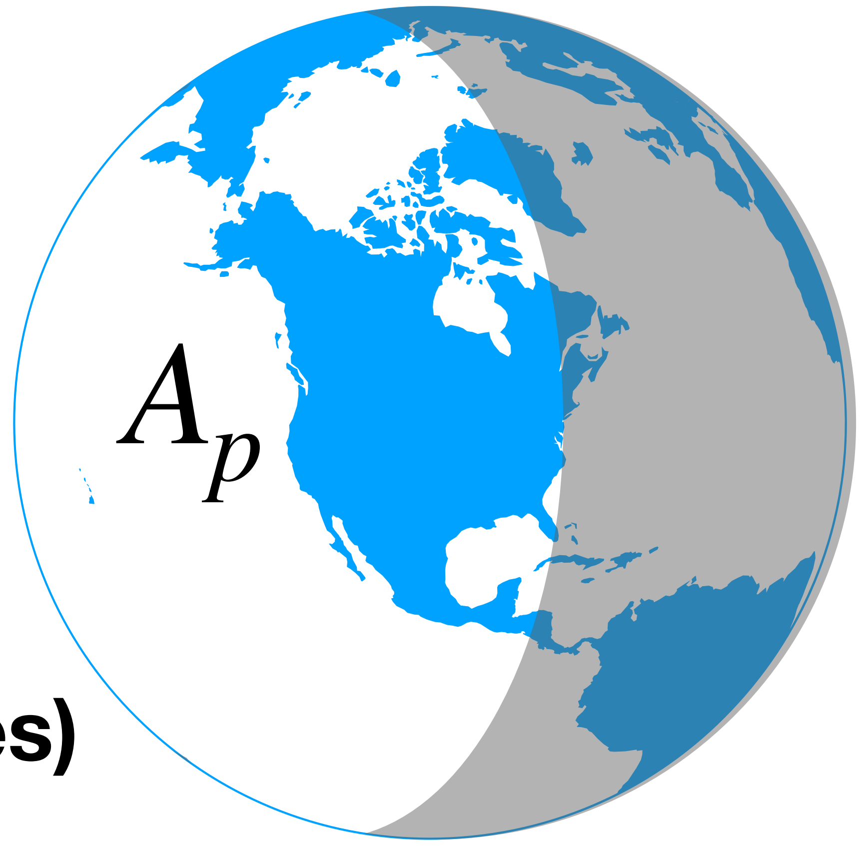
That energy is **absorbed** by the part of the **planet** which is **perpendicular to the Sun.**



disk facing Sun

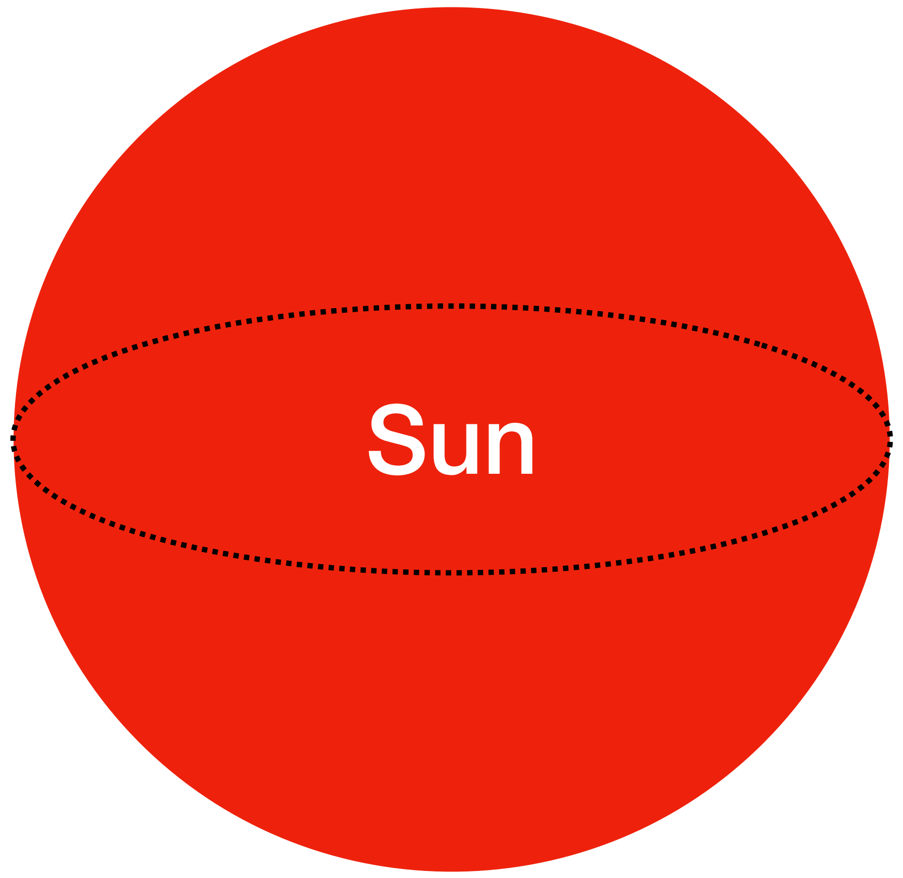
$$Q_{in} = P_{1AU} A_{sun} \alpha_{VNIR} = P_{1AU} \cdot \pi R_E^2 \cdot (1 - R)$$

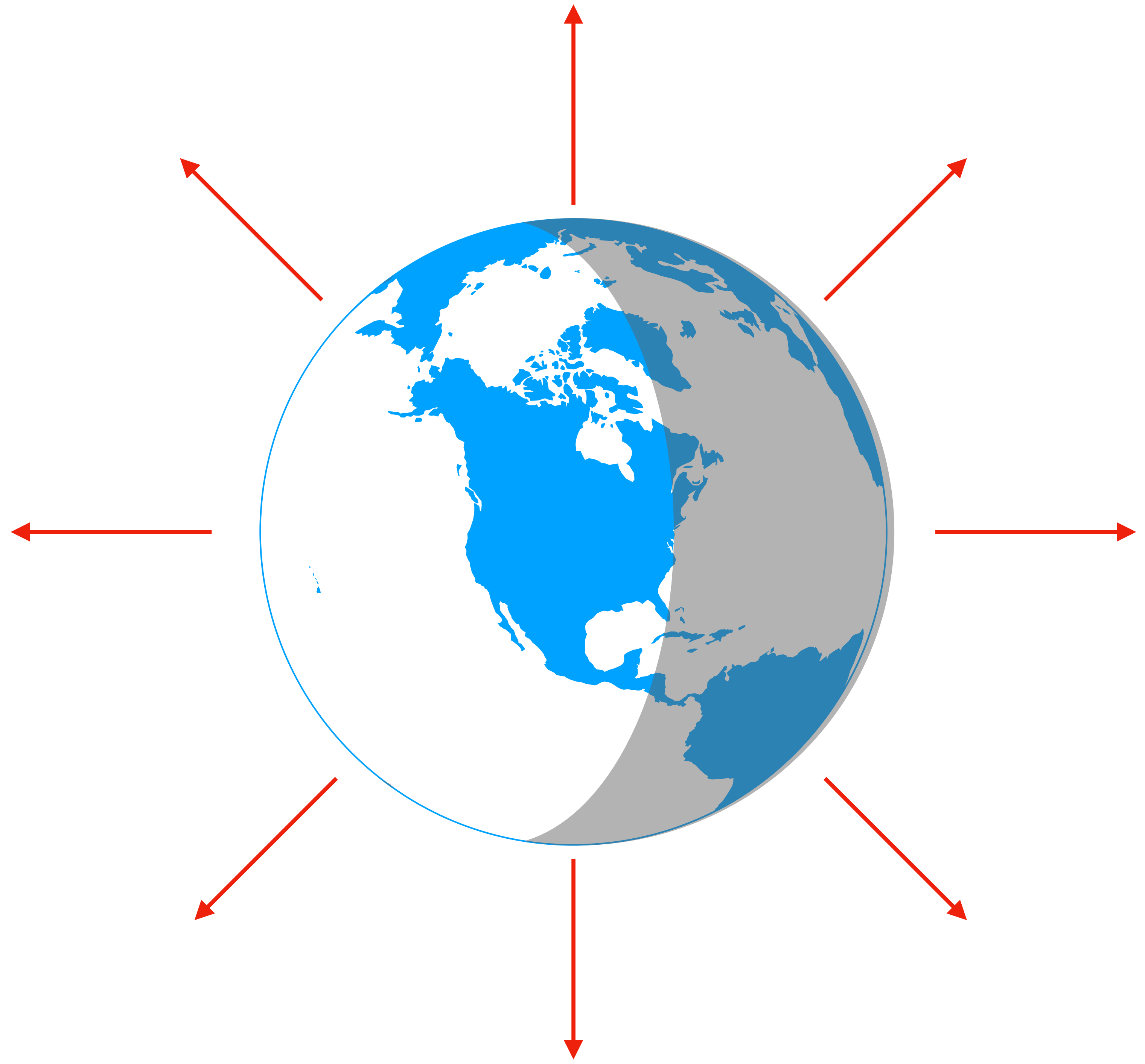
albedo ≈ 0.3 **(varies)**



Equilibrium temperature

Energy is **radiated** from the **entire surface area** of the planet.





$$Q_{out} = A_r \epsilon_{Earth} \sigma T^4 = 4\pi R_E^2 \epsilon_{Earth} \sigma T^4$$

Equilibrium temperature

What is the equilibrium temperature of **Earth**? ($\epsilon_{Earth} \approx 1$)

$$Q_{out} = 4\pi R_E^2 \sigma T^4 = Q_{in} = P_{1AU} \cdot \pi R_E^2 \cdot (1 - A)$$

$$0.7\pi R_E^2 P_{1AU} = 4\pi R_E^2 \sigma T^4$$

$$0.7 P_{1AU} = 4\sigma T^4$$

$$T = \left(\frac{0.7 P_{1AU}}{4\sigma}\right)^{\frac{1}{4}}$$

$$T = \left(\frac{0.7 \times 1370}{4 \times 5.67 \times 10^{-8}}\right)^{\frac{1}{4}}$$

$$= 255K = -18C$$

Why isn't the Earth this cold?

By the way, what wavelength is that?

Use **Wien's Law** again

$$\lambda_{max} = \frac{2898}{T} = \frac{2898}{255} = 11.36\mu m = 11{,}360nm$$

Earth is an infrared emitter.

Equilibrium temperature

What is the equilibrium temperature of **Earth**?

$$Q_{out} = 4\pi R_E^2 \sigma T^4 = Q_{in} = P_{1AU} \cdot \pi R_E^2 \cdot (1 - A)$$

$$0.7\pi R_E^2 P_{1AU} = 4\pi R_E^2 \sigma T^4$$

$$0.7 P_{1AU} = 4\sigma T^4$$

$$T = \left(\frac{0.7 P_{1AU}}{4\sigma}\right)^{\frac{1}{4}}$$

$$T = \left(\frac{0.7 \times 1370}{4 \times 5.67 \times 10^{-8}}\right)^{\frac{1}{4}}$$

$$= 255K = -18C$$

Equilibrium temperature

How much power per unit area does the Earth emit?

Use **Stephan-Boltzmann Law:**

$$F = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8} \left[\frac{W}{m^2 K^4}\right]$ and F has units of $\frac{W}{m^2}$.

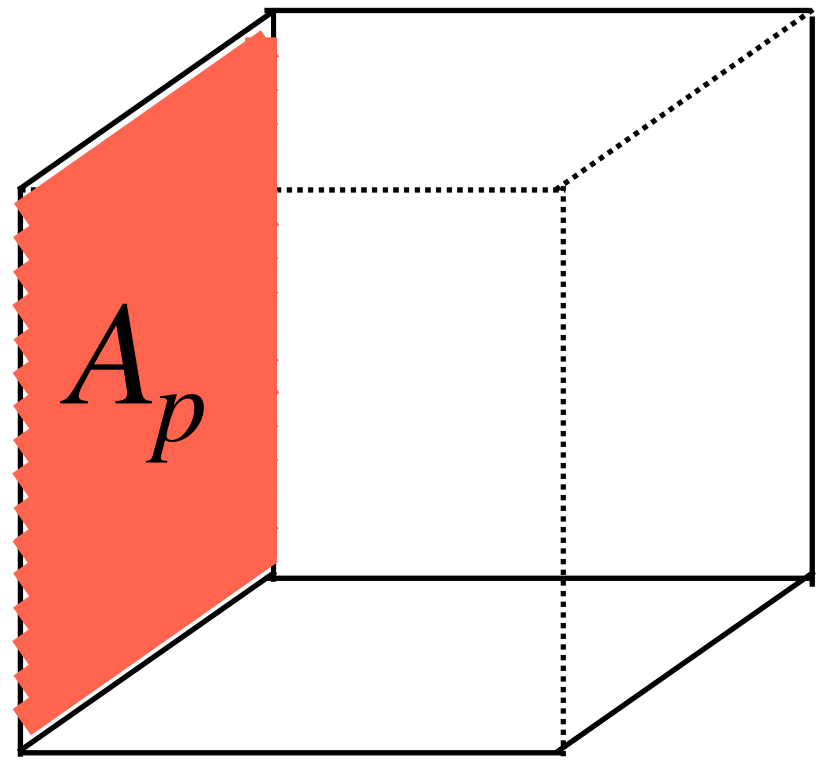
$$F = \left(5.67 \times 10^{-8}\right) \left(255\right)^4$$

$$= 240 \frac{W}{m^2}$$

Equilibrium temperature

How much of this power is absorbed by the spacecraft?

$$Q_{in} = P_{Earth} F A_{earth} \alpha_{TIR}$$



geometric factor taking into account detach due to difference in solid angle at h.

Approximately, $F \approx \left(\frac{R_E}{R_E + h} \right)^2$

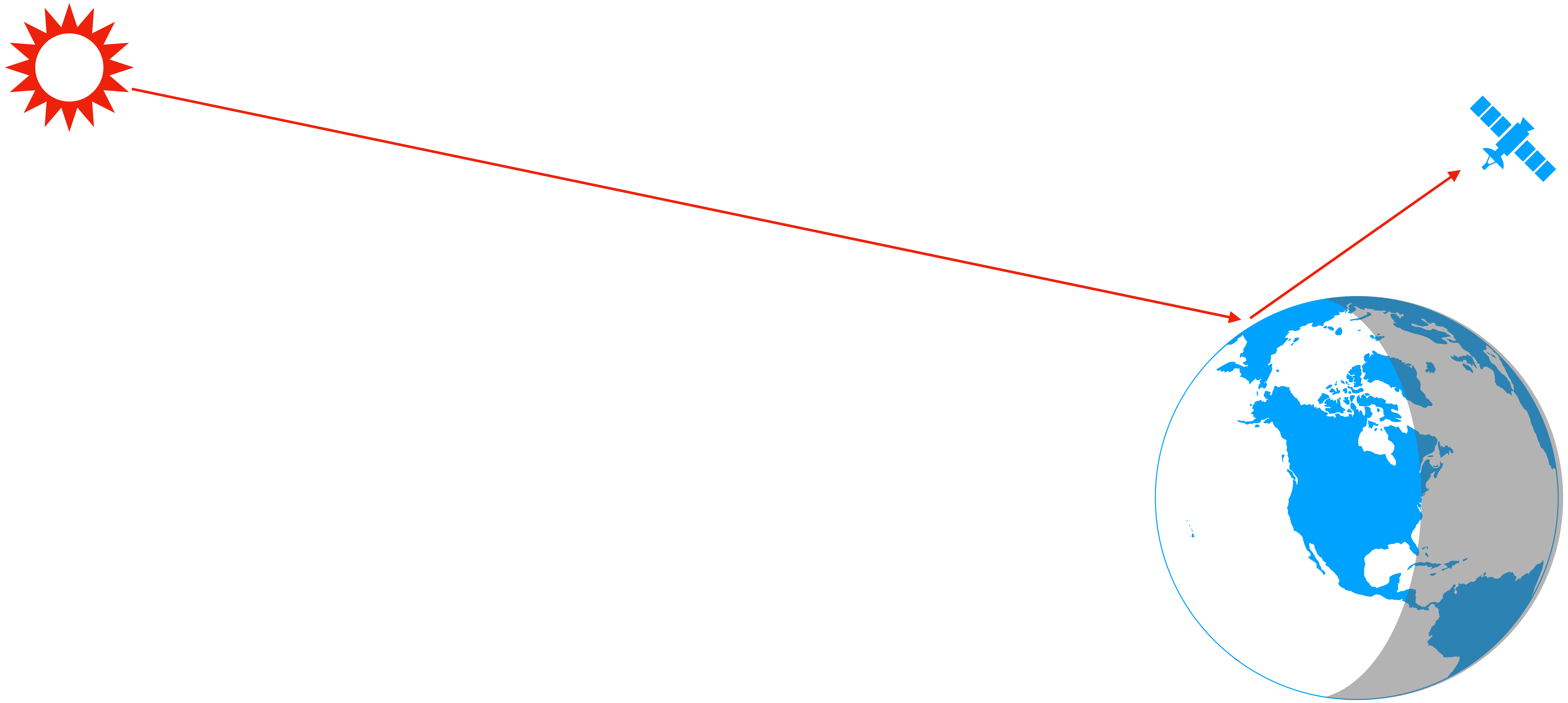
Table 22-11. Orbit Average Incident Radiant Fluxes on Surfaces of an Earth-Oriented Cube for Various Circular Orbits. β is the angle of the Sun out of the orbit plane. See Fig. 22-17 for orientation.

Cold Case—W/m²												
500 km	$\beta = 0$			$\beta = 45$			$\beta = 70$			$\beta = 90$		
Surface Orientation	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***
Zenith	418.2			295.8			143.1			1.3		
Nadir	30.4	79.1	186.8	44.7	66.3	186.8	143.1	42.7	186.7	1.3	15.2	186.5
Sun	0.8	24.5	58.3	630.7	23.7	58.1	123.76	19.0	58.1	1317.0	16.5	58.0
Anti Sun	0.8	24.5	58.2		17.5	58.2		8.3	58.2			58.0
± Ram	287.3	24.6	58.0	226.0	20.6	57.9	143.1	13.3	57.9	1.3	5.3	57.9
700 km	$\beta = 0$			$\beta = 45$			$\beta = 70$			$\beta = 90$		
Surface Orientation	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***
Zenith	418.2			295.8			143.1			1.3		
Nadir	41.3	74.6	176.4	62.0	62.6	176.4	143.1	40.9	176.3	1.3	18.8	176.2
Sun	0.8	21.3	50.8	661.0	21.4	50.6	1237.6	18.1	50.6	1317.0	18.2	50.6
Anti Sun	0.8	21.3	50.7		14.6	50.7		6.3	50.7			50.5
± Ram	299.7	21.4	50.5	238.4	18.0	50.5	143.1	11.8	50.5	1.3	5.8	50.5
Hot Case—W/m²												
500 km	$\beta = 0$			$\beta = 45$			$\beta = 70$			$\beta = 90$		
Surface Orientation	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***
Zenith	450.6			318.7			154.2			1.4		
Nadir	32.7	123.9	224.6	48.2	98.9	224.7	154.2	59.6	224.6	1.4	19.7	224.4
Sun	0.9	38.4	70.1	679.5	35.4	69.9	1333.4	26.5	69.9	1419.0	21.4	69.8
Anti Sun	0.9	38.5	70.0		26.1	70.0		11.5	70.0			69.8
± Ram	309.5	38.6	69.7	243.5	30.8	69.7	154.2	18.6	69.7	1.4	6.8	69.7
700 km	$\beta = 0$			$\beta = 45$			$\beta = 70$			$\beta = 90$		
Surface Orientation	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***	***Solar***	***Albedo***	***Earth IR***
Zenith	450.6			318.7			154.2			1.4		
Nadir	44.5	116.9	212.2	66.8	93.5	212.2	154.2	57.0	212.1	1.4	24.4	211.9
Sun	0.9	33.3	61.1	712.2	31.9	60.9	1333.4	25.2	60.9	1419.0	23.6	60.8
Anti Sun	0.9	33.4	60.9		21.7	61.0		8.7	61.0			60.8
± Ram	322.9	33.5	60.7	256.9	26.8	60.7	154.2	16.4	60.7	1.4	7.5	60.7

But there are other sources of heat! Including thermal emissions from Earth, **Earth albedo**, and internal heat generation.

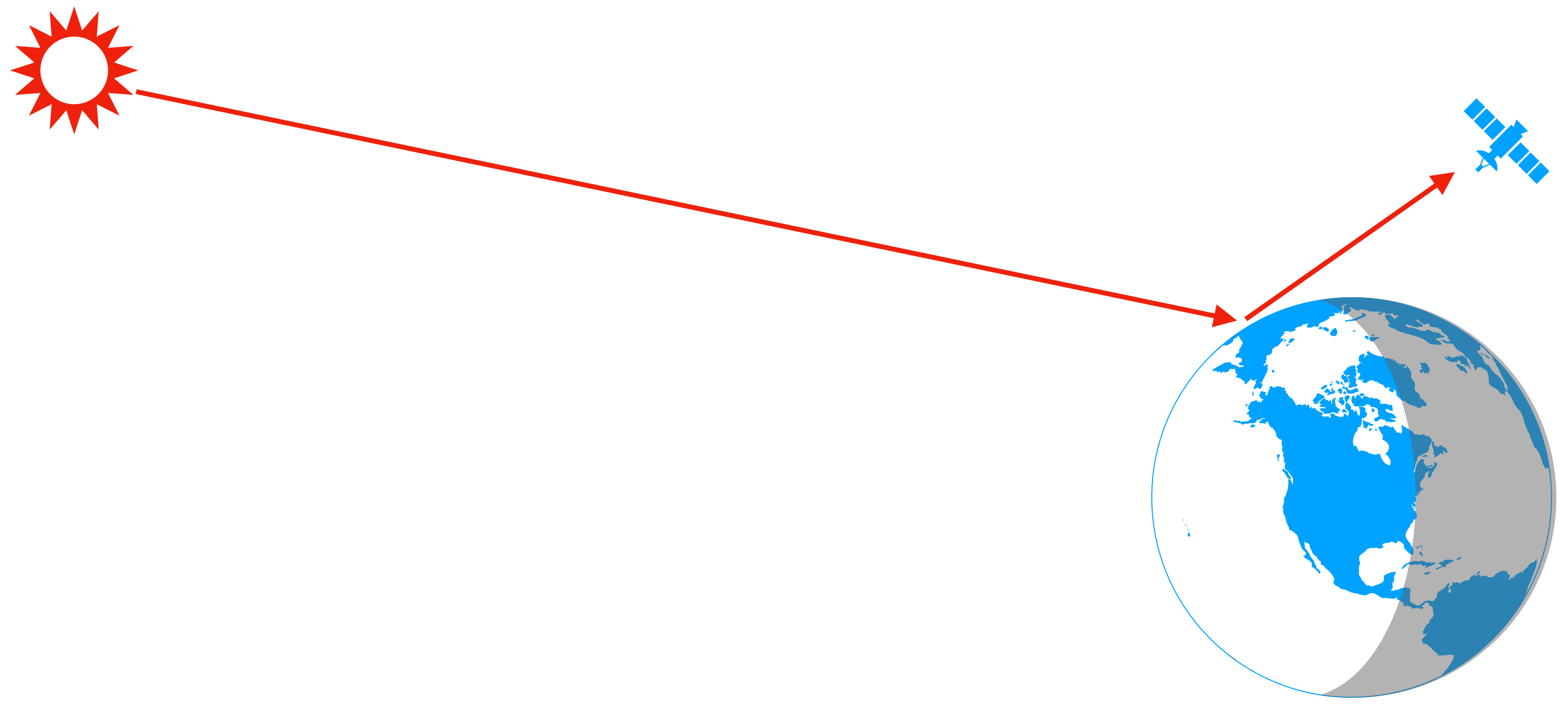
Equilibrium temperature

Some of the energy from the Sun is reflected off the Earth.



Equilibrium temperature

Some of the energy from the Sun is reflected off the Earth.



$$\dot{Q} = P_{1AU}\alpha_{VNIR} \cdot R \cdot A_{Earth}$$

where R is the albedo (fraction of solar irradiance reflected off Earth surface)

- Function of orbit and spacecraft attitude
- Values of Earth albedo oscillate significantly between 0.2-0.7

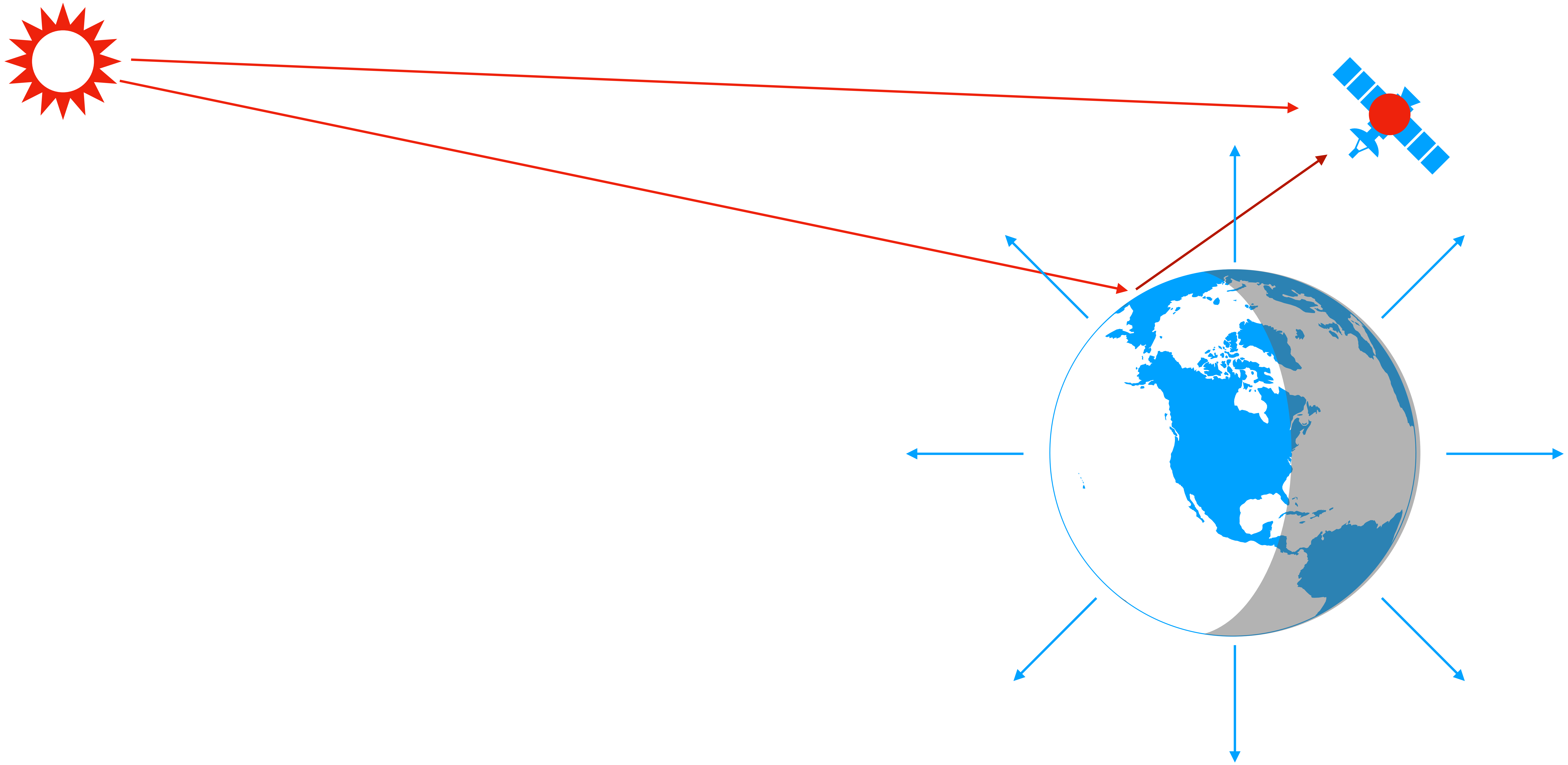
- A_{Earth} is the area projected to Earth

But there are other sources of heat! Including thermal emissions from Earth, Earth albedo, and **internal heat generation**.

Sources of heat

$$\dot{Q}_{Sun} + \dot{Q}_{alb} + \dot{Q}_{Earth} + \dot{Q}_{int} = \dot{Q}_{out}$$

$$P_{1AU}\alpha_{VNIR}\left(A_{Sun} + RA_{Earth}\right) + \alpha_{TIR}\epsilon_{Earth}F\sigma T^4_{Earth}A_{Earth} + \dot{Q}_{int} = \epsilon_{sc}\sigma T^4_{sc}A_{cold}$$

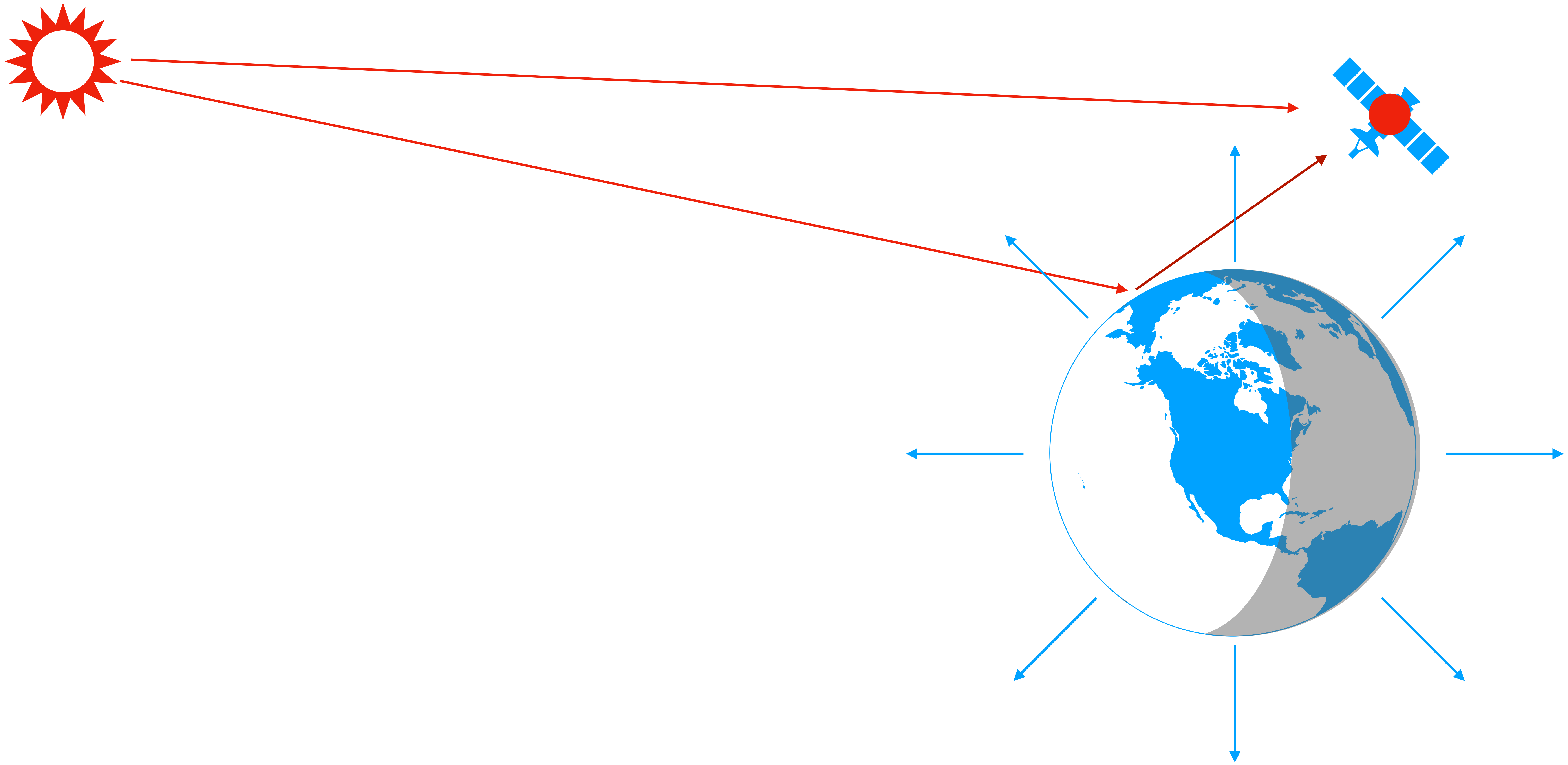


Sources of heat

$$\dot{Q}_{Sun} + \dot{Q}_{alb} + \dot{Q}_{Earth} + \dot{Q}_{int} = \dot{Q}_{out}$$

$$P_{1AU}\alpha_{VNIR}\left(A_{Sun} + RA_{Earth}\right) + \alpha_{TIR}\epsilon_{Earth}F\sigma T_{Earth}^4 A_{Earth} + \dot{Q}_{int} = \epsilon_{sc}\sigma T_{sc}^4 A_{cold}$$

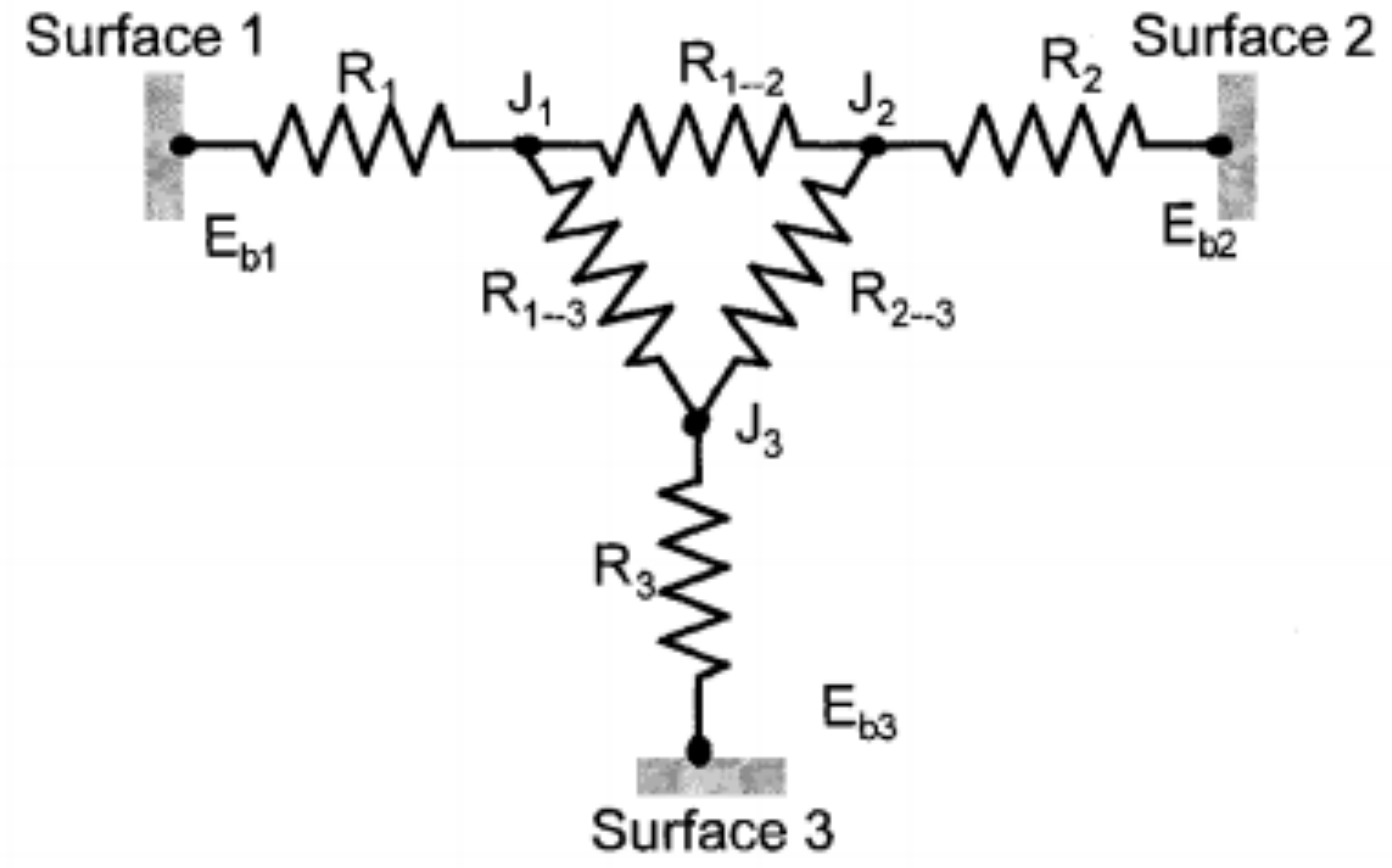
what are we free to change?



This treats the spacecraft as a single node. In practice, multi-node thermal models are required.

Multi-node thermal models

- Computing the temperature of the spacecraft as a single node is not adequate → multiple nodes are needed
- Can be modeled as a network of nodes connected in series/parallel
- Interfaces have different properties (e.g. heat conductance)
- Couplings between conduction and radiation are solved numerically



Thermal control technologies

Passive technologies

- Coatings
- Insulations

Active heating/cooling

Materials and coatings

- Use paints, mirrors, silvered plastics . . .
- Play with $\dfrac{\alpha_{VNIR}}{\epsilon_{TIR}}$

Multi-layer insulation (MLI)

- Used to isolate the spacecraft from the thermal environment
- Multiple layers of aluminized Kapton with a thin net of material between them
- Without air, primary coupling is radiation, not conduction
- High reflectivity, low emissivity → very little transfer between layers

Electric heaters

- Essentially resistors that produce heat through Joule effect
- Controlled by thermostats

Radiators

- Heat exchanger on outer surface to radiate excess heat into cold space

Louvers

- Shield radiator surfaces to moderate heat flow to space

Cold plates

- To cool down electronics
- May use fluids for convective heat transfer

Doublers

- Passive aluminum plates that increase heat exchange surface ares

Heat pipes

- Transport heat from source to sink using evaporation and condensation of a fluid

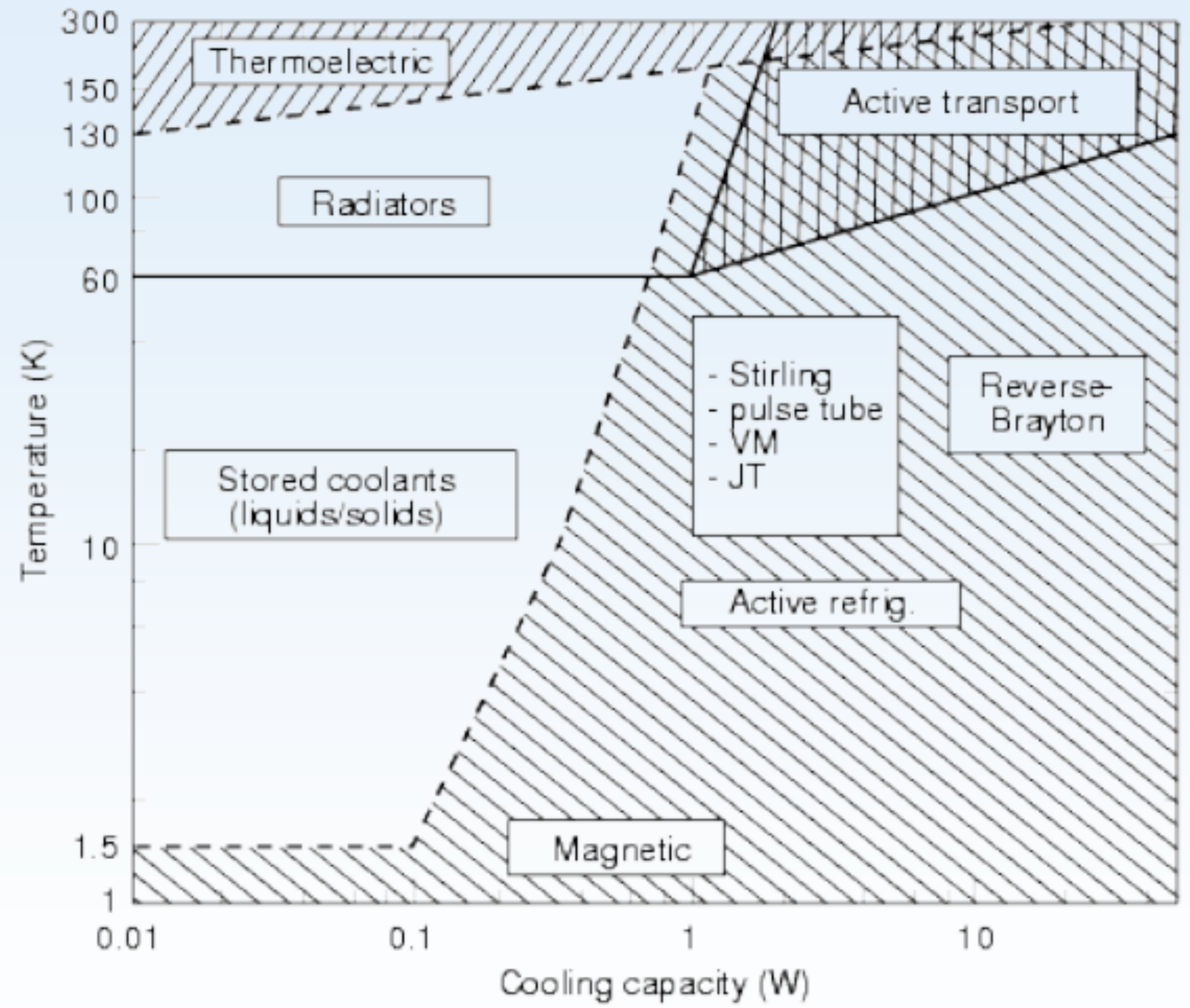
Thermoelectric coolers

- Electrical current induces cooling of junction of 2 different materials

Cryocoolers

- Use thermodynamic (e.g. Stirling) cycle (careful with vibrations!)
- Or just cryogenic fluids

Technologies to provide the cooling for Cryo applications



Overview of which technologies are usually employed in each temperature/heat-load regime.