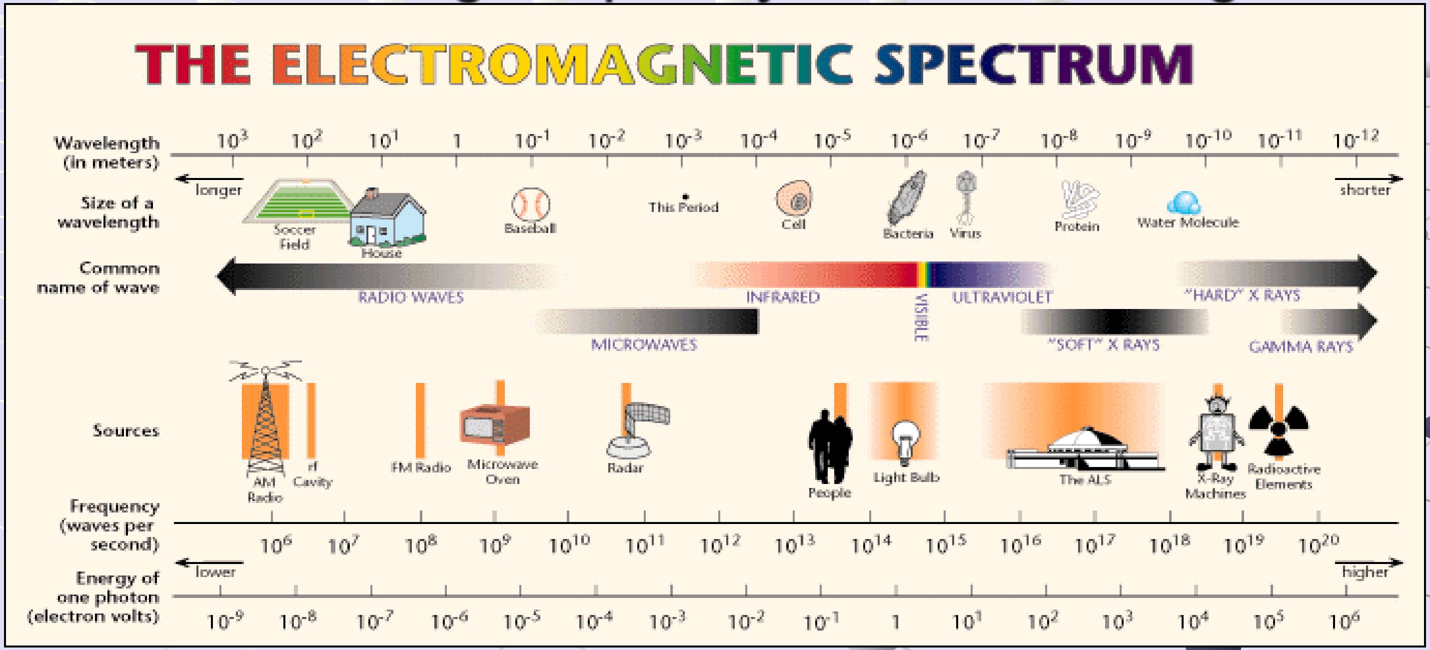
The Electromagnetic Spectrum

- The EM spectrum is the ENTIRE range of EM waves in order of increasing frequency and decreasing wavelength.



- As you go from left → right, the wavelengths get smaller and the frequencies get higher. This is an inverse relationship between wave size and frequency. (As one goes up, the other goes down.) This is because the speed of ALL EM waves is the speed of light (300,000 km/s).

Things to Remember

- The higher the frequency, the more energy the wave has.
- EM waves do not require media in which to travel or move.
- EM waves are considered to be transverse waves because they are made of vibrating electric and magnetic fields at right angles to each other, and to the direction the waves are traveling.
- Inverse relationship between wave size and frequency: as wavelengths get smaller, frequencies get higher.

The Waves (in order…)

Radio waves: Have the longest wavelengths and the lowest frequencies; wavelengths range from 1000s of meters to .001 m

- Used in: RADAR, cooking food, satellite transmissions

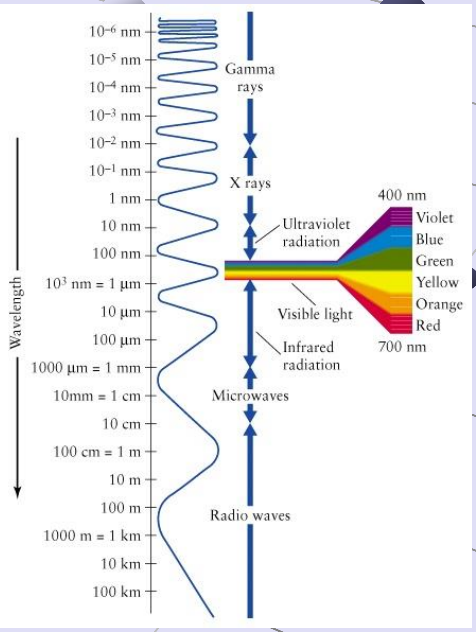


Infrared waves (heat): Have a shorter wavelength, from .001 m to 700 nm, and therefore, a higher frequency.

- Used for finding people in the dark and in TV remote control devices

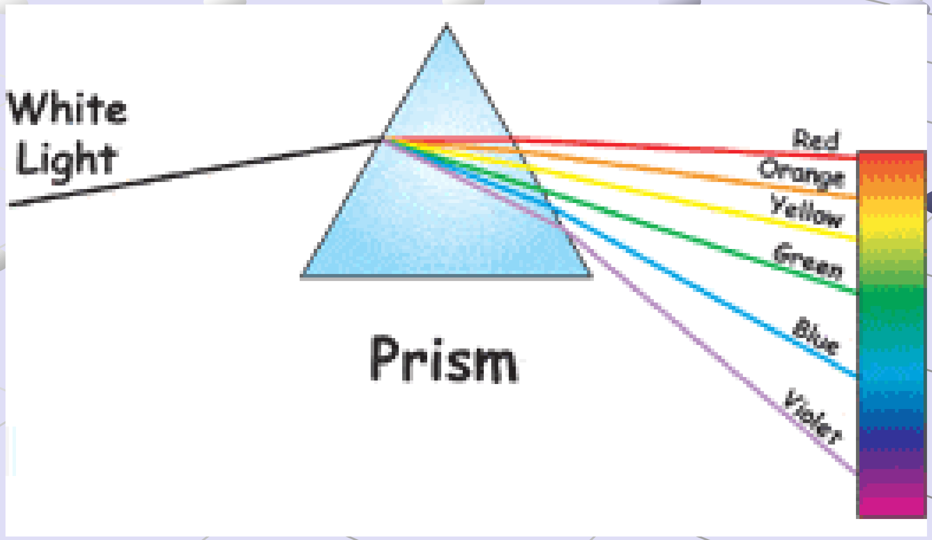
Visible light: Wavelengths range from 700 nm (red light) to 400 nm (violet light) with frequencies higher than infrared waves.

- These are the waves in the EM spectrum that humans can see.
- Visible light waves are a very small part of the EM spectrum!



Visible Light
Remembering the Order

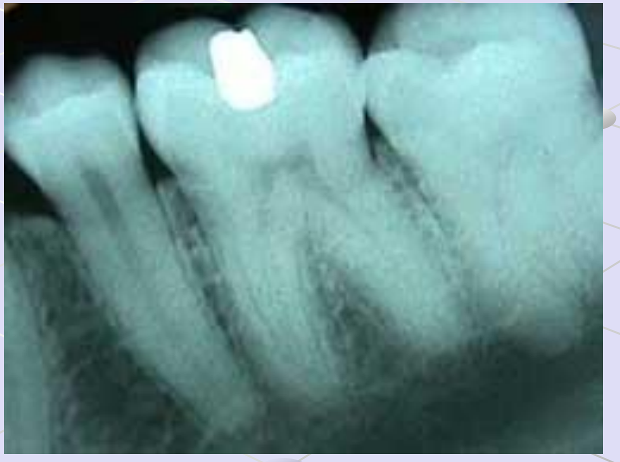
- ROY G. BV
  - red
  - orange
  - yellow
  - green
  - blue
  - violet



Ultraviolet Light: Wavelengths range from 400 nm to 50 nm; the frequency (and therefore the energy) is high enough with UV rays to penetrate living cells and cause them damage.

- Although we cannot see UV light, bees, bats, butterflies, some small rodents and birds can.
- UV on our skin produces vitamin D in our bodies. Too much UV can lead to sunburn and skin cancer. UV rays are easily blocked by clothing.
- Used for sterilization because they kill bacteria.

X-Rays: Wavelengths from 10 nm to .001 nm. These rays have enough energy to penetrate deep into tissues and cause damage to cells; are stopped by dense materials, such as bone.



- Used to look at solid structures, such as bones and bridges (for cracks), and for treatment of cancer.

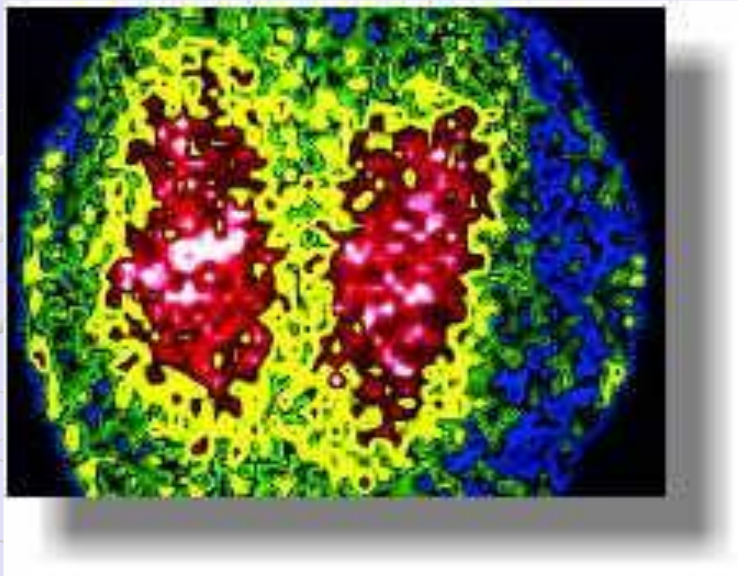
Gamma Rays: Carry the most energy and have the shortest wavelengths, less than one trillionth of a meter (10^{-12}).

- Gamma rays have enough energy to go through most materials easily; you would need a 3-4 ft thick concrete wall to stop them!

- Gamma rays are released by nuclear reactions in nuclear power plants, by nuclear bombs, and by naturally occurring elements on Earth.
- Sometimes used in the treatment of cancers.

Gamma Rays

- This picture is a "scintigram" ➔
- It shows an asthmatic person's lungs.



- The patient was given a slightly radioactive gas to breath, and the picture was taken using a gamma camera to detect the radiation.
- The colors show the air flow in the lungs.

Basic Laws of Radiation

1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects. The amount of energy radiated is proportional to the temperature of the object raised to the fourth power.

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➡ This is the **Stefan Boltzmann Law**

$$F = \sigma T^4$$

F = flux of energy (W/m^2)
T = temperature (K)
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$ (a constant)

Scientific Notation

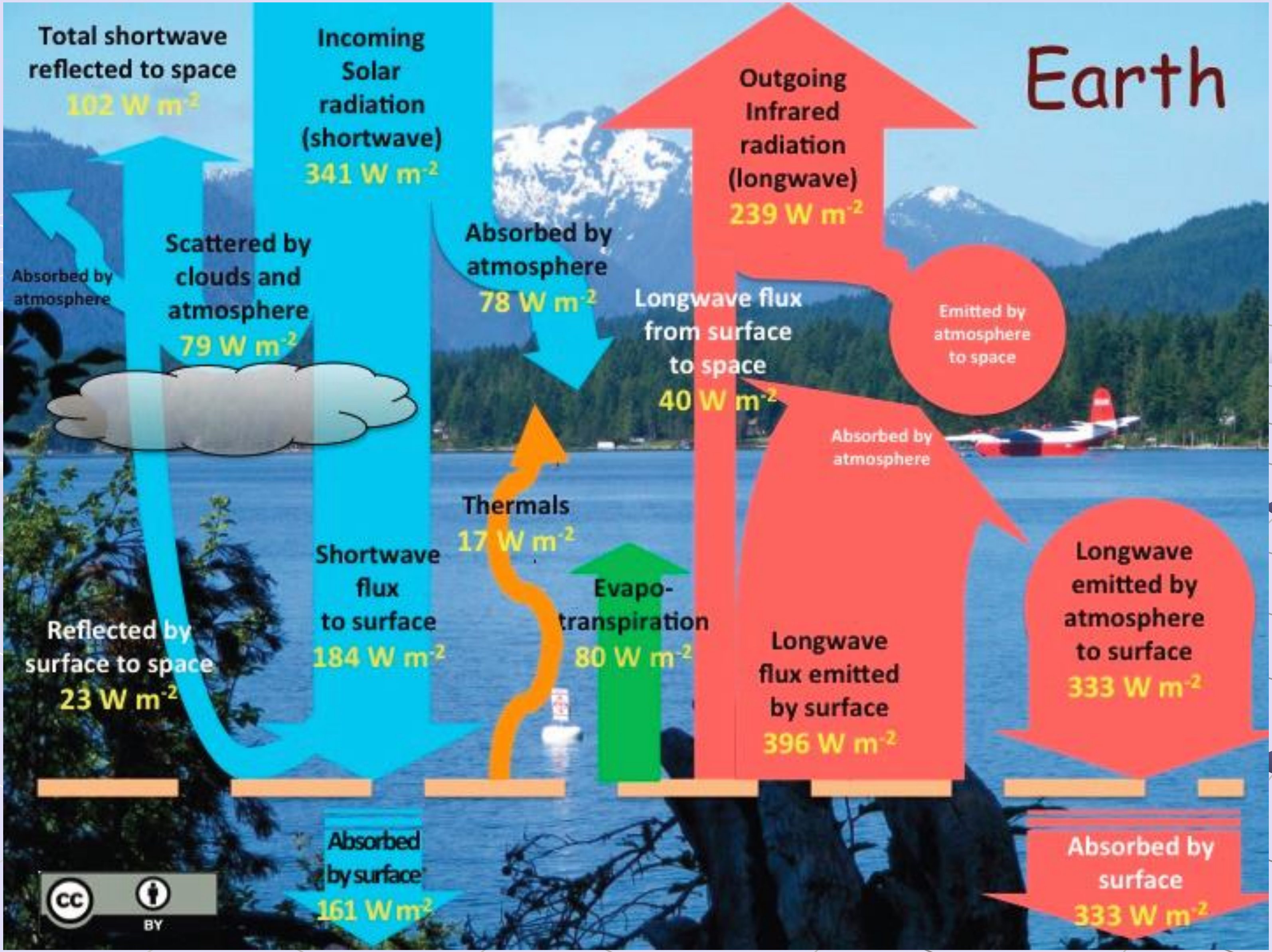
$10 = 10^1$

$100 = 10^2$

$1,000 = 10^3$

$1,000,000 = 10^6$

$1,000,000,000,000 = 10^{12}$


Earth
Total shortwave reflected to space
102 W m-2
Incoming Solar radiation (shortwave)
341 W m-2
Outgoing Infrared radiation (longwave)
239 W m-2
Absorbed by atmosphere
Scattered by clouds and atmosphere
79 W m-2
Absorbed by atmosphere
78 W m-2
Longwave flux from surface to space
40 W m-2
Emitted by atmosphere to space
Absorbed by atmosphere
Thermals
17 W m-2
Shortwave flux to surface
184 W m-2
Evapo-transpiration
80 W m-2
Longwave emitted by atmosphere to surface
333 W m-2
Reflected by surface to space
23 W m-2
Longwave flux emitted by surface
396 W m-2
Absorbed by surface
161 W m-2
Absorbed by surface
333 W m-2
BY

Basic Laws of Radiation

1) All objects emit radiant energy.

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3) The hotter the object, the shorter the wavelength (λ) of emitted energy.

Basic Laws of Radiation

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➡ This is Wien's Law

$$\lambda_{max} \cong \frac{\mathbf{3000\ \mu m}}{\mathbf{T(K)}}$$

- *Stefan-Boltzmann law*

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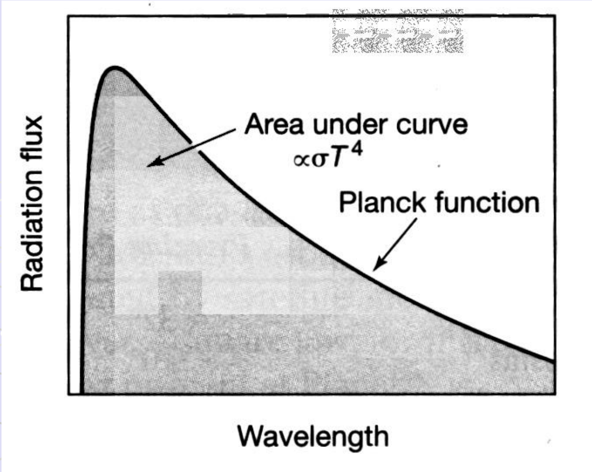
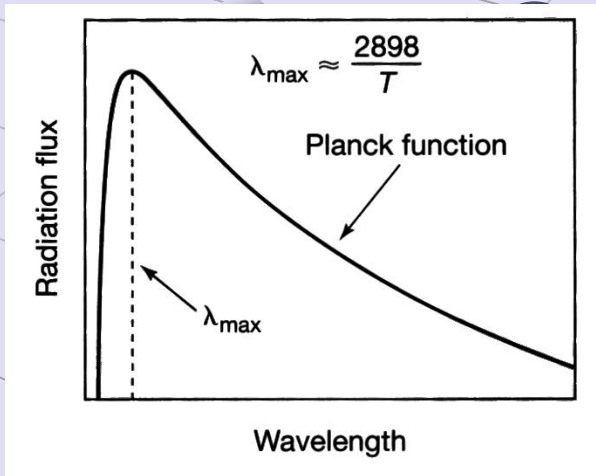
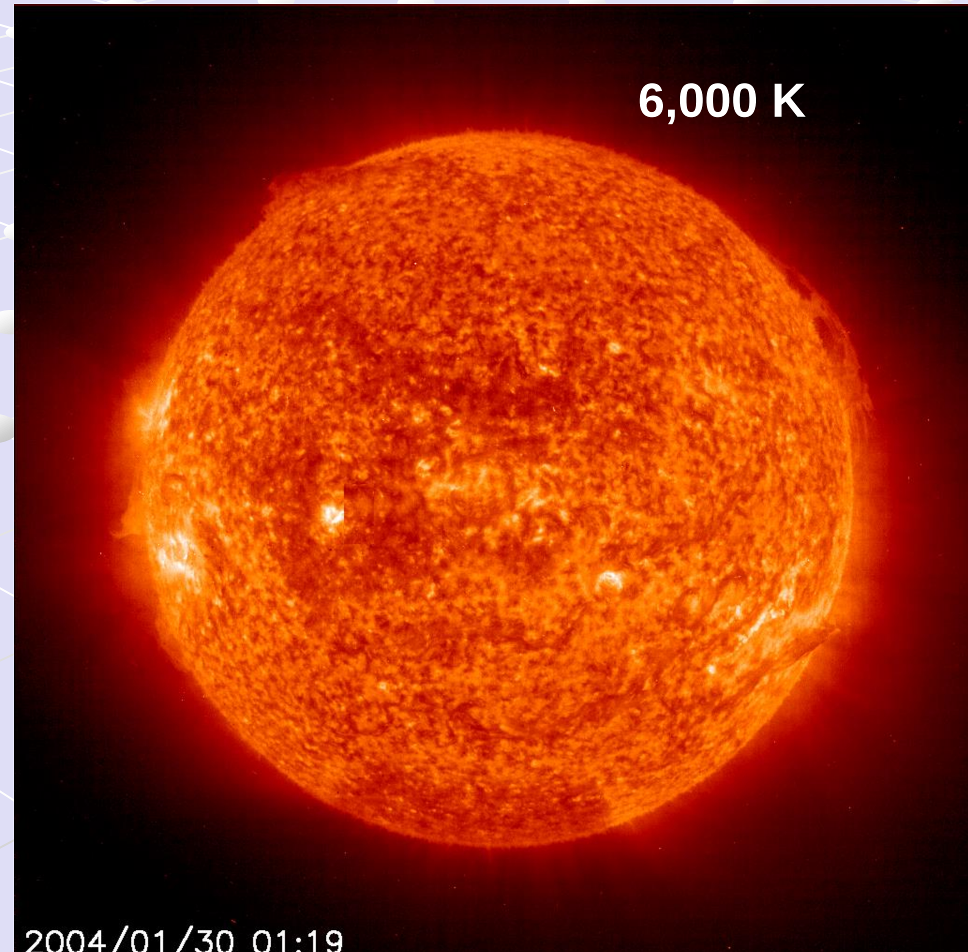


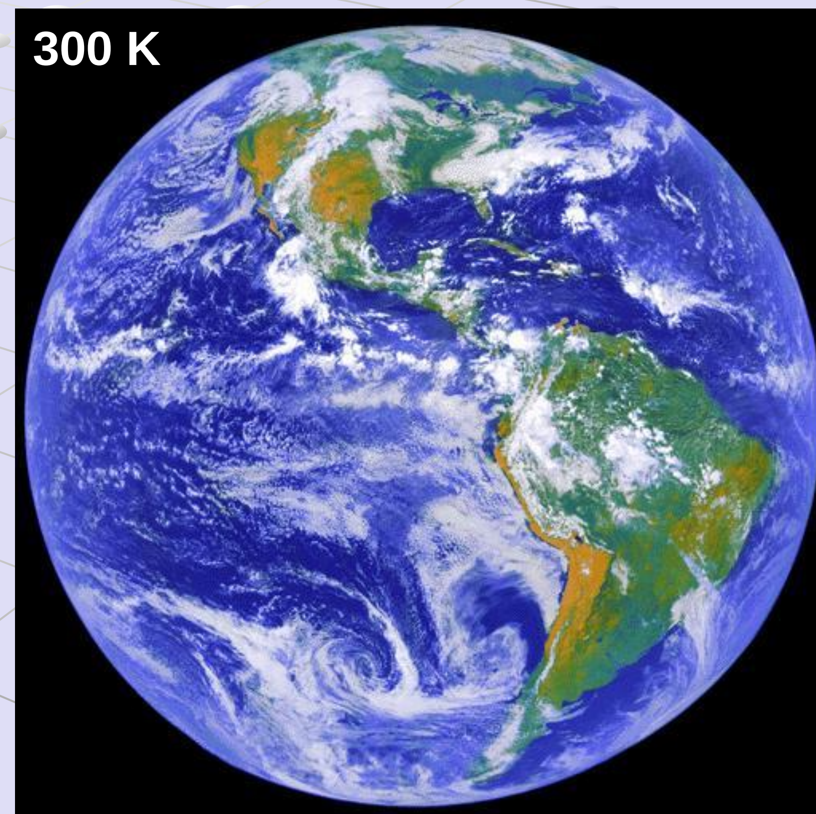
- *Wien's law*

$\lambda_{max} \cong 3000\ \mu m$
$T(K)$



We can use these equations to calculate properties of energy radiating from the Sun and the Earth.



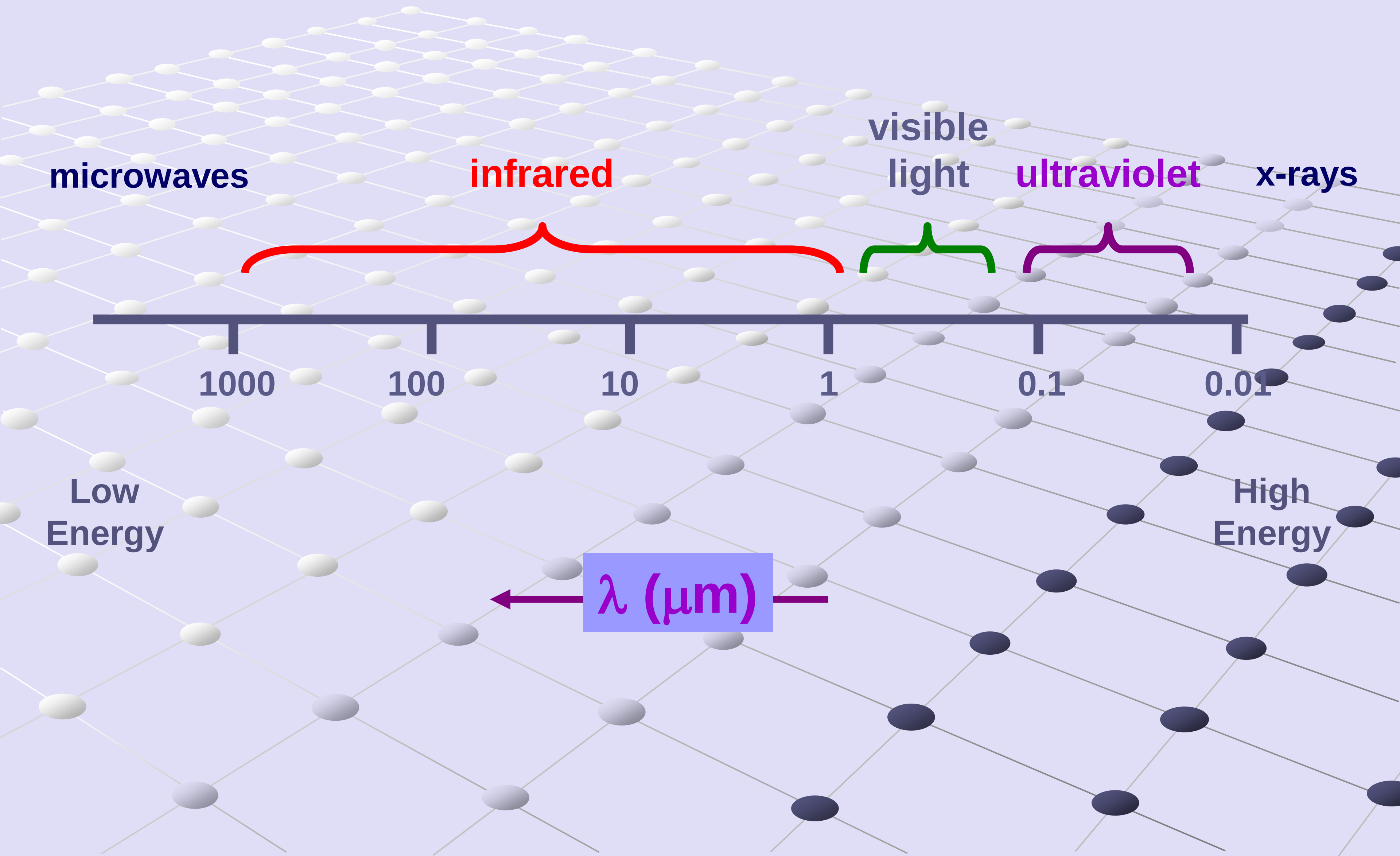


	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000			
Earth	300			

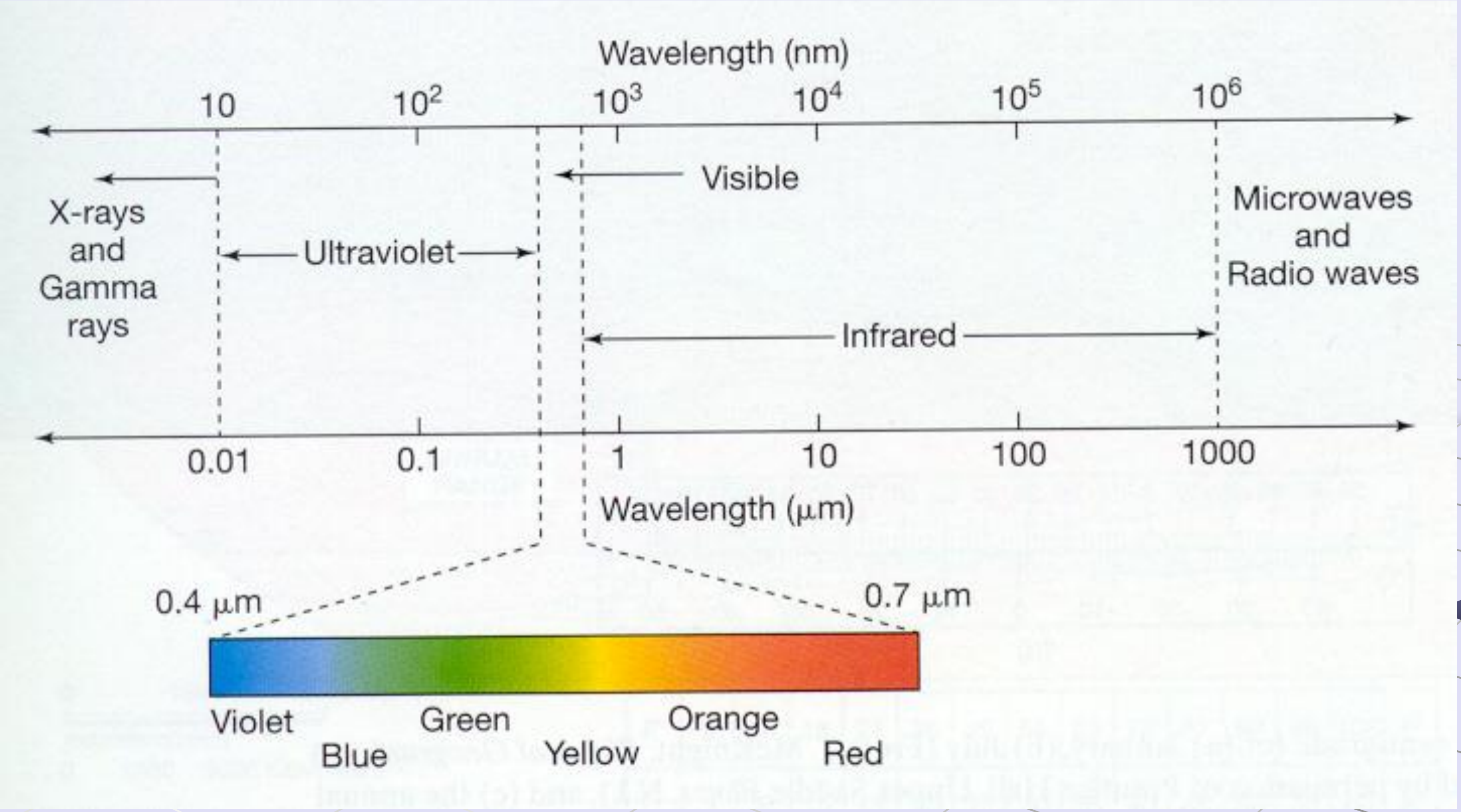
	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5		
Earth	300	10		

Wien's law: $$\lambda_{max} \cong \frac{3000\ \mu m}{T(K)}$$

Electromagnetic Spectrum



	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	Visible (yellow?)	
Earth	300	10	infrared	



- Blue light from the Sun is removed from the beam by Rayleigh scattering, so the Sun appears yellow when viewed from Earth's surface even though its radiation peaks in the green

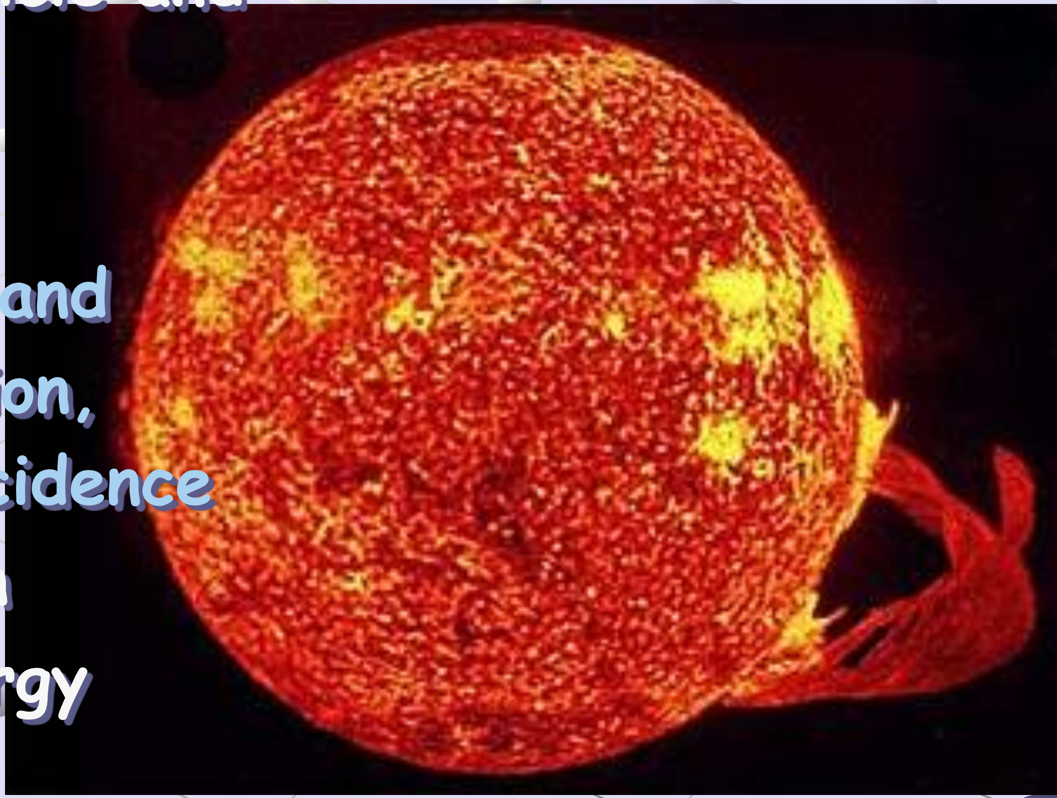
	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	Visible **(green)**	
Earth	300	10	infrared	

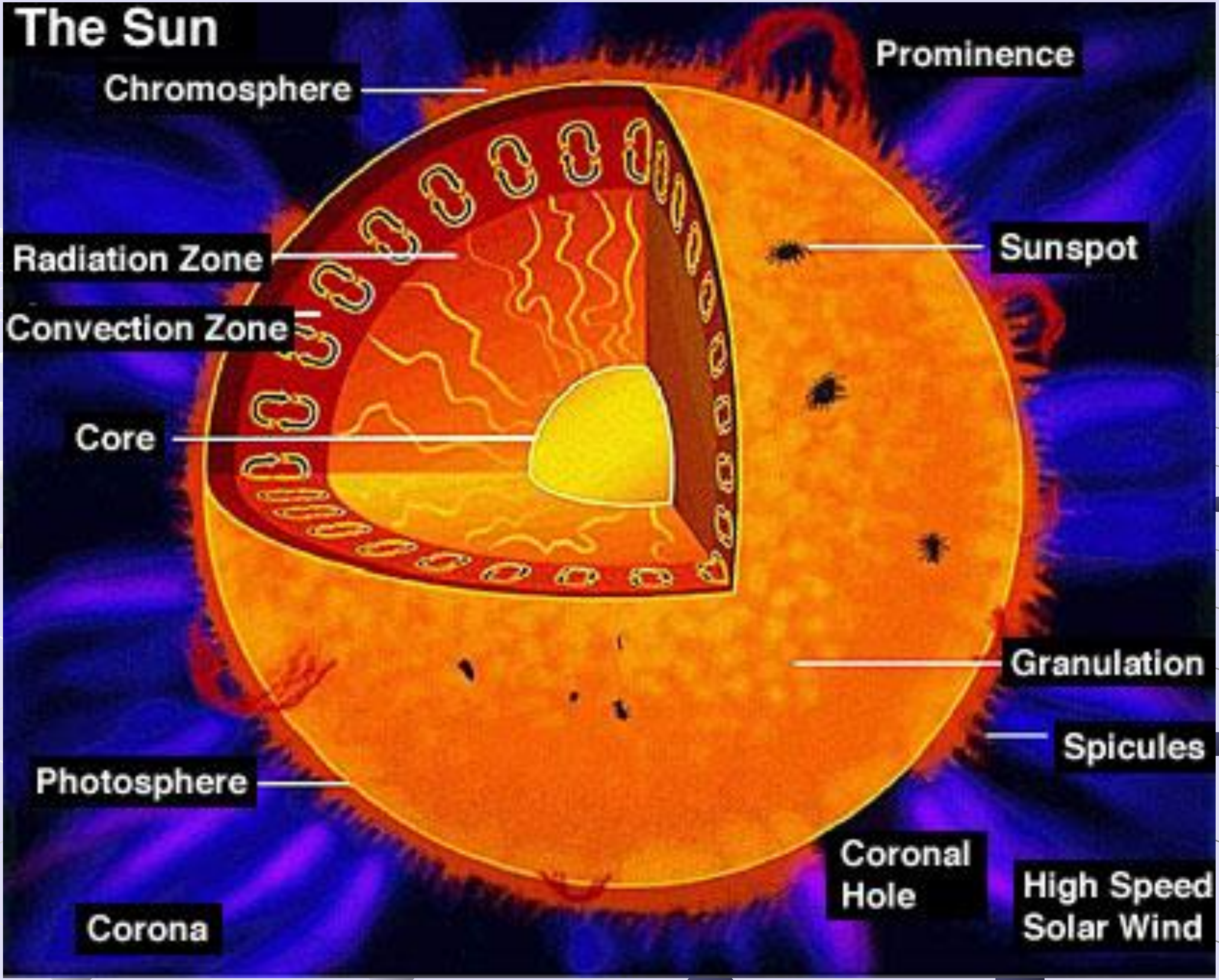
	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	Visible (green)	7×10^7
Earth	300	10	infrared	460

Stefan-Boltzmann law: **$F = \sigma T^4$**

Solar Radiation: The driving factor

- **Radiation (Electromagnetic energy) released, absorbed & reflected by all things**
- travels as both a particle and a wave
- is affected by
  - gravity, magnetism, and atmosphere composition, distance, angle of incidence
- provides Earth with an external source of energy




The Sun
Chromosphere
Prominence
Radiation Zone
Sunspot
Convection Zone
Core
Granulation
Spicules
Photosphere
Coronal
Hole
High Speed
Solar Wind
Corona

Chromosphere

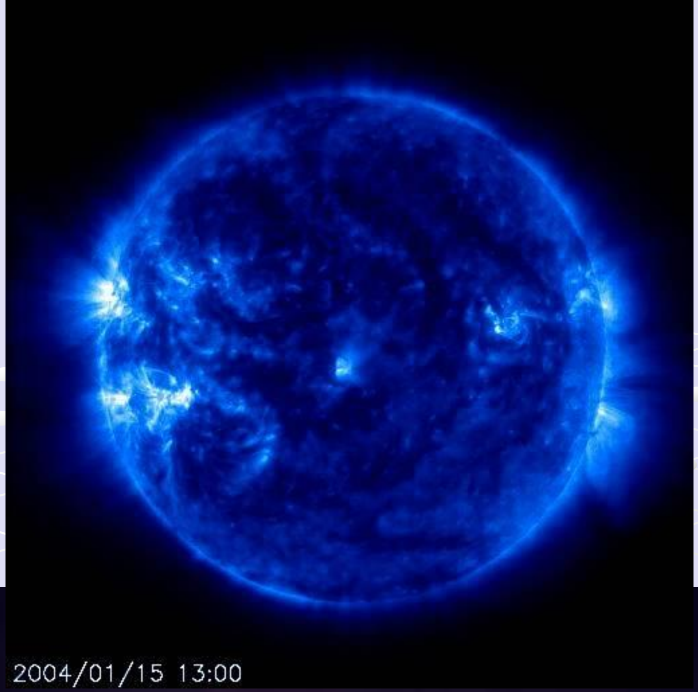
A wide (up to 1,000,000 km) but variable zone of burning gases above the photosphere

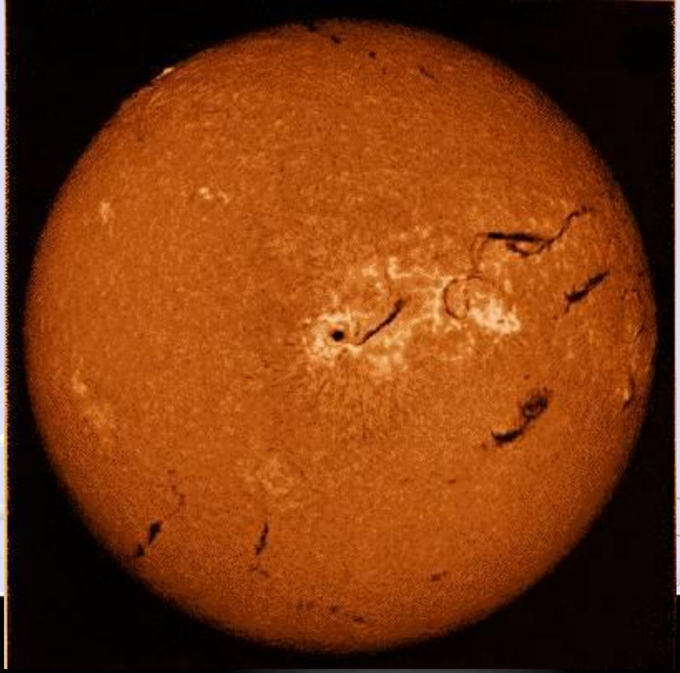
The gases in this zone move at high velocities and travel outward from the sun as the solar wind

Also the zone within which sun spots and solar flares occur

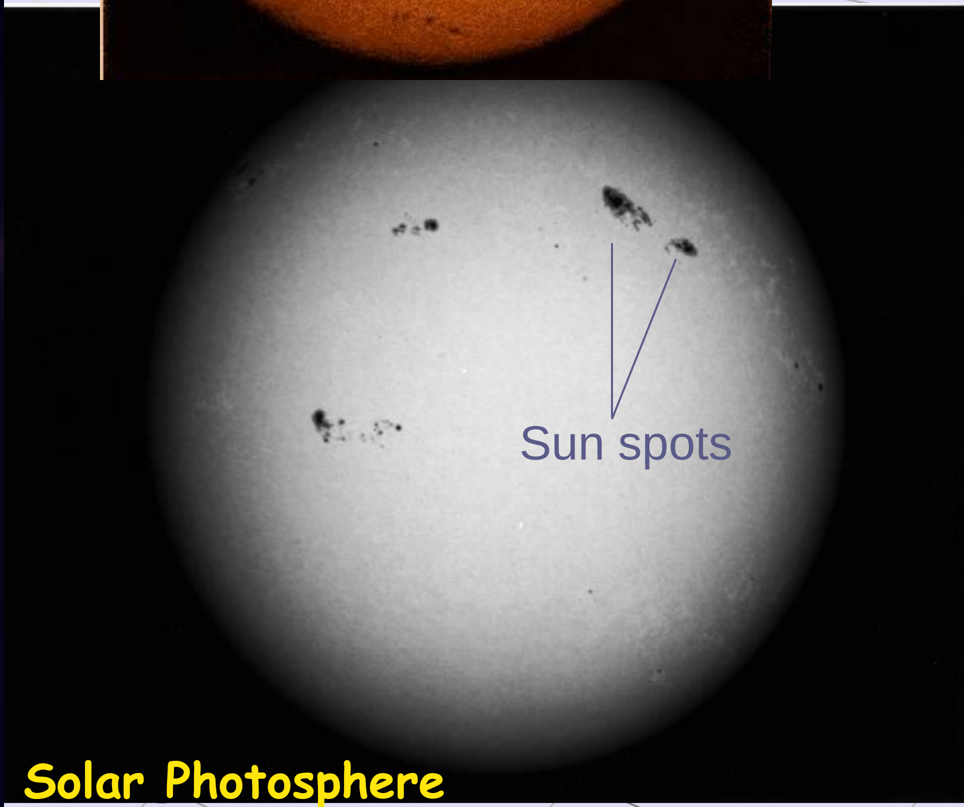
Sun spots are cooler regions on the sun’s surface zones of intense magnetic disturbance

Flares are explosive eruptions of atomic particles and radiation that extend outward for millions of miles and can influence stuff 100’s of millions of miles away





Solar Corona



Solar Photosphere

What happens to solar radiation? It decreases with distance traveled outward

Inverse square law

$F_{rec} = F\,(1/d^2)$

where F = radiation from Sun

F_{rec} = Radiation received

and d = distance from source

d is in astronomical unit (AU) or distance from Sun to Earth = 1

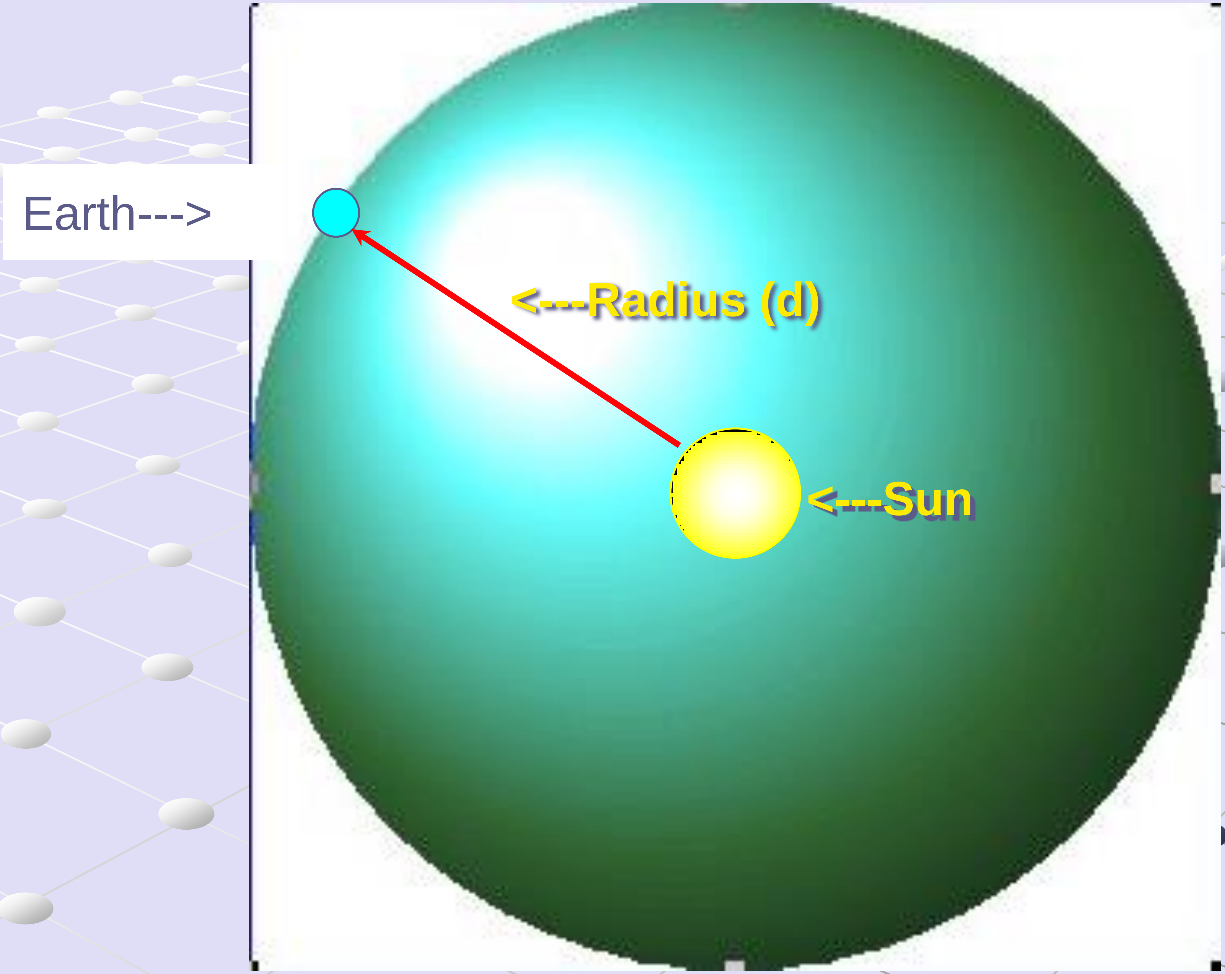
Our distance from the sun controls how much solar energy we get from the Sun

F_{rec} is very small 1/2,000,000,000 of the total energy produced by the Sun

Several things can happen to that incoming energy

Reflection, Refraction, Scattering, Absorption

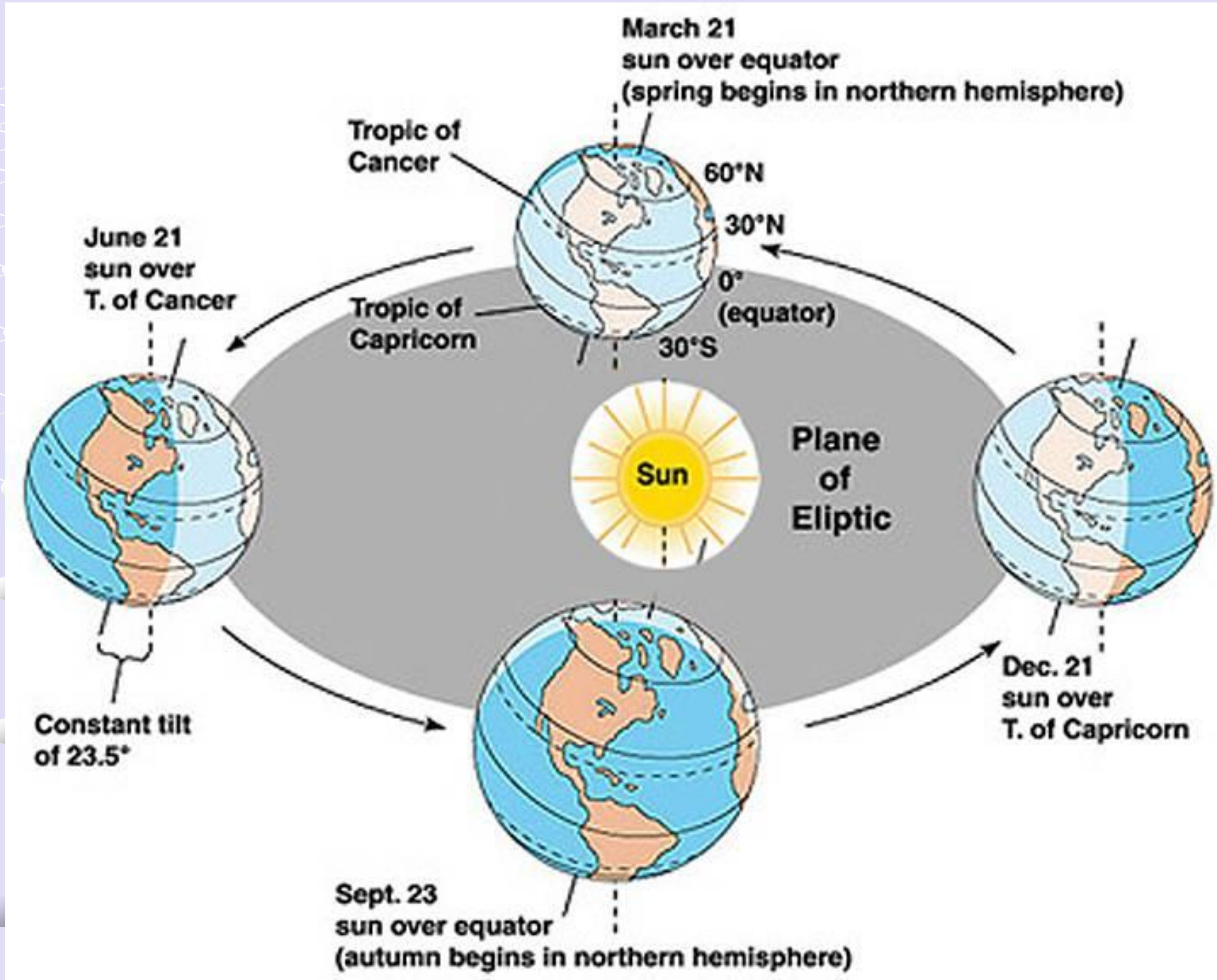
How much energy does the Earth receive?



Imagine a sphere with a radius (d) the distance from the Earth to the center of the Sun = 1 AU

Position affects radiation too

- Far away= less radiation
- Tilted away= less radiation in North
- Titled toward= more radiation in North



Milankovitch Orbital variations

Eccentricity - change of Earth's orbit around the Sun from a Circle to an Ellipse. Timeframe: 100,000 years

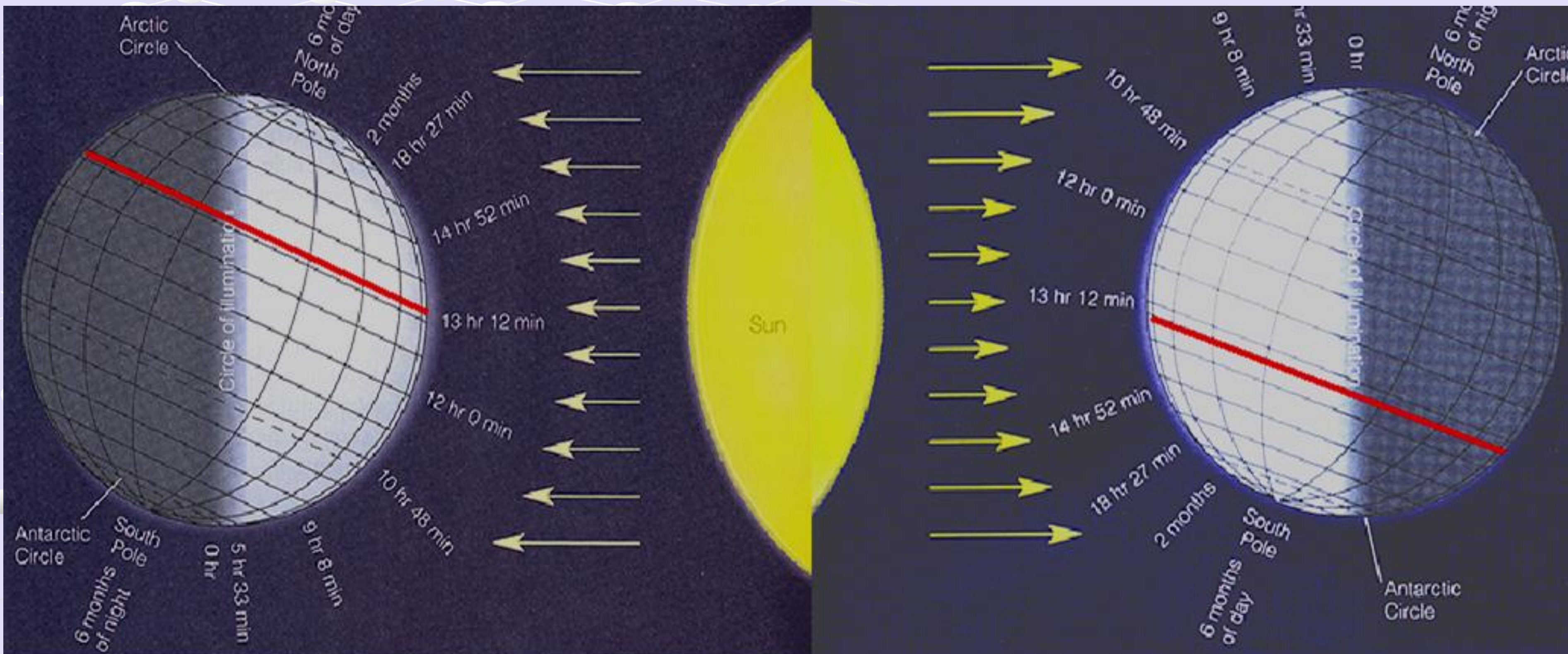
Obliquity- Change in the tilt of the Earth's axis of daily rotation. Timeframe: 41,000 yrs

Precession- the wobble of earths tilt or the change in the timing of the tilt of the Earth that forces the northern hemisphere toward the sun- at perihelion vs aphelion 22,000 - to 26,000 years

These work with other systems in the earth to set the pace of climate change

- Sun's energy at 90° at Tropic of Cancer
- Sun overhead at noon

- Sun's energy at 90° at Tropic of Capricorn
- Sun overhead at noon



Summer Solstice

> ~June 21

Winter Solstice

~December 21

*

Albedo

$$\text{Albedo} = \frac{\text{reflected radiation}}{\text{incident radiation}}$$

- A measure of the amount of reflected radiation
- Some things reflect radiation better than others
  - "dry" or "cold" Snow & Ice = high albedo
  - water = moderate for visible, low for infrared
  - plants= moderate for visible
- Land absorbs and releases radiative energy quicker than water

Typical albedos of various surfaces to incoming solar radiation	
Type of surface	Percent reflected energy (Albedo)
Fresh Snow	75 - 95%
Old Snow	30 - 40%
Water	
0°	99%
10°	35%
30°	6%
90°	2%
Clouds	
Cumulus	70 - 90%
Stratus	60 - 84%
Cirrus	44 - 50%
Forest	5 - 20%
Grass	10 - 20%
Sand	35 - 45%
Plowed soil	5 - 25%
Crops	3 - 15%
Concrete	17 - 27%
Earth as a Planet	30%

Reflection
- energy is bounced away without being absorbed or transformed

Scattering
- energy is diffused or scattered into different wavelengths
- related to composition and thickness of atmosphere

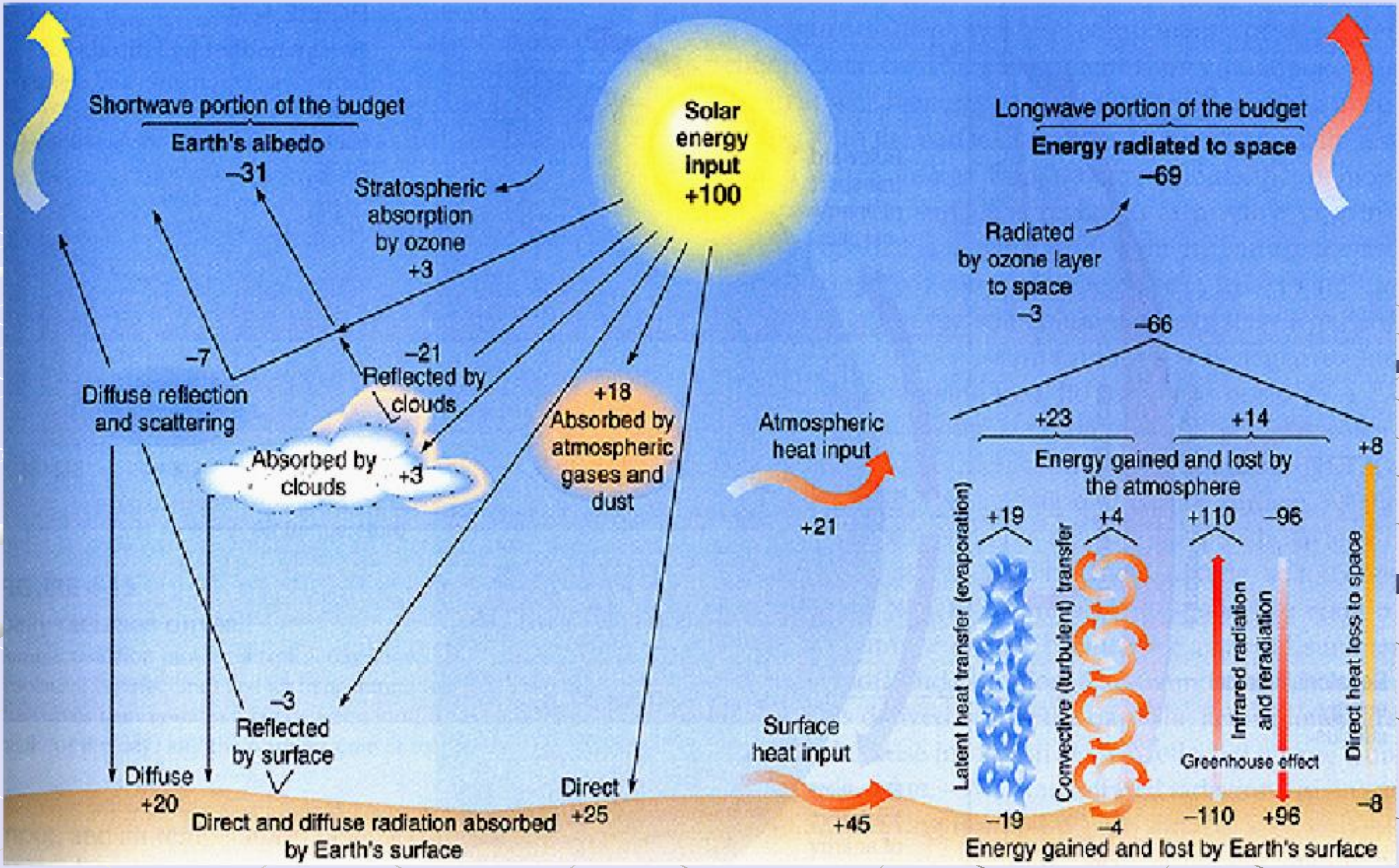
Absorption
- some gases and aerosols capture (absorb) energy
- energy is typically re-released as longer wavelength radiative energy

Transmissivity
- The amount of radiation that actually gets through to the surface

Greenhouse effect

- Seen as a bad thing by the public because of biased (both the left *and* the right) or poorly produced media coverage
- Greenhouse effect is absolutely essential to Earth's habitability
- Without some means to absorb, block, scatter or transform energy, the Earth would be barren.
- Atmosphere does all four things
- Most important among these is absorption of longwave (Earth-reemitted or transformed) radiation
- Various gases capture this energy which warms the Earth's atmosphere

Distribution of energy



An energy energy budget example

Latent Heat

When a solid melts or a liquid boils, energy must be added but the temperature remains constant! (This can be explained by considering that it takes energy to break the bonds holding the material together.)

The amount of energy it takes to melt or boil a certain amount of material is called a **latent heat**.

Heat Transfer

There are four ways of moving heat:

- **Evaporation** :(using latent heat - we’ve already looked at this)
- **Convection** :(moving heat with a material)
- **Conduction:** (moving heat through a material)
- **Radiation** :We’ll develop equations for conduction and radiation and talk about convection.

Heat Transfer: **Convection**

- Heat Transfer by Convection is when you heat some material and then move that material containing the heat.
- The amount of heat energy moved depends on the heat in the material (heat capacity times amount of material times the temperature difference) and how much material you move per time.
- The blood and hot air furnaces use this method.

Heat Transfer: **Conduction**

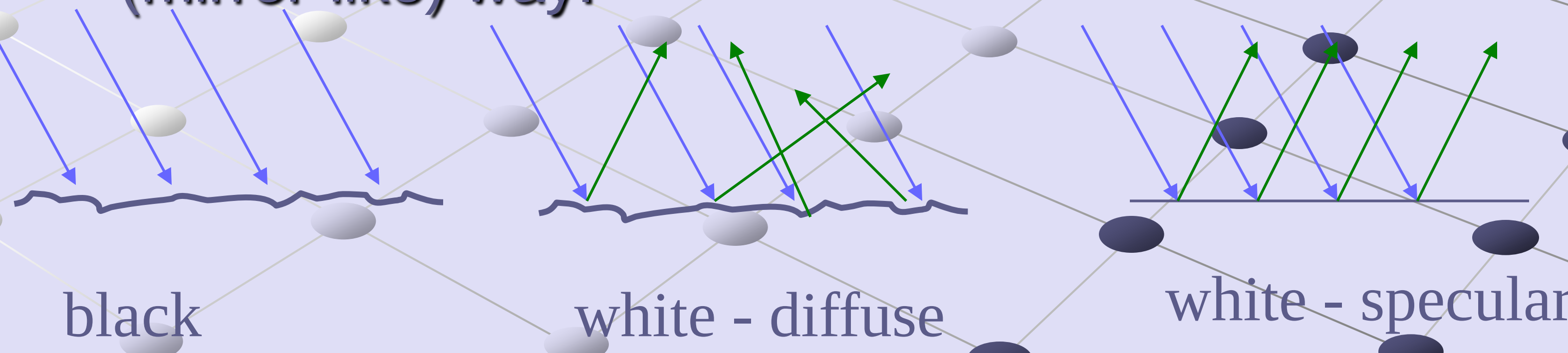
- Heat will flow through a solid material from the hot end to the cold end. What is flowing? No matter is flowing!
- We can think of energy as flowing in this case! We measure the flow of energy as power: 1 Watt = 1 Joule/sec .

Radiation: Reflected Light versus Emitted Light

Some objects, like the moon, can be seen by the light they reflect (from the sun). Other objects can be seen by the light that they create, like the sun. How do we tell the difference, and how do we analyze the light created (emitted)? First, consider this:

A BLACK object absorbs all the light incident on it.

A WHITE object **reflects** all the light **incident** on it, usually in a diffuse way rather than in a specular (mirror-like) way.



The First Law of Thermodynamics

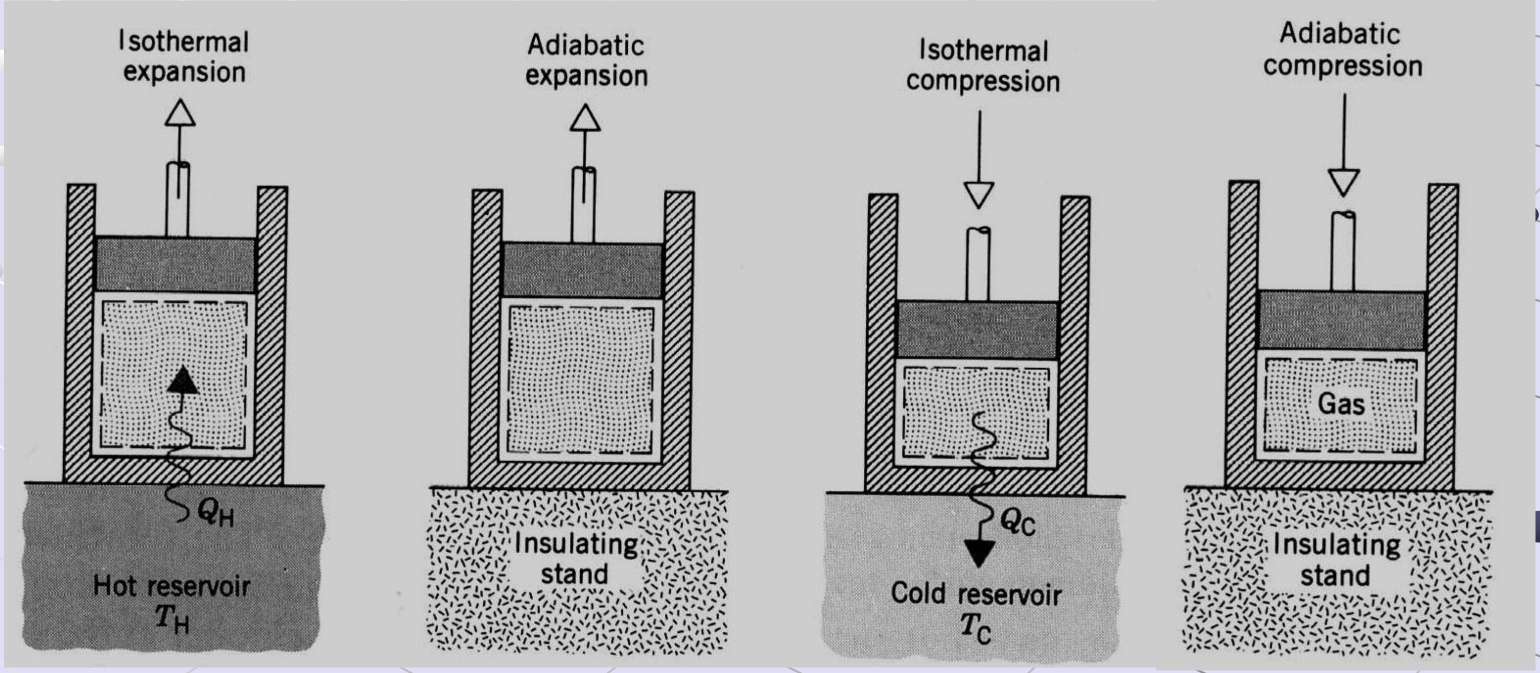
- The first law of thermodynamics, also known as Law of Conservation of Energy, states that energy can neither be created nor destroyed; energy can only be transferred or changed from one form to another. For example, turning on a light would seem to produce energy; however, it is electrical energy that is converted.
- A way of expressing the first law of thermodynamics is that any change in the internal energy (ΔE) of a system is given by the sum of the heat (q) that flows across its boundaries and the work (w) done on the system by the surroundings:
- Delta E = q + w
- This law says that there are two kinds of processes, heat and work, that can lead to a change in the internal energy of a system. Since both heat and work can be measured and quantified, this is the same as saying that any change in the energy of a system must result in a corresponding change in the energy of the surroundings outside the system. In other words, energy cannot be created or destroyed. If heat flows into a system or the surroundings do work on it, the internal energy increases and the sign of q and w are positive. Conversely, heat flow out of the system or work done by the system (on the surroundings) will be at the expense of the internal energy, and q and w will therefore be negative.

- **The Second Law of Thermodynamics**
- The second law of thermodynamics says that the entropy of any isolated system always increases. Isolated systems spontaneously evolve towards thermal equilibrium—the state of maximum entropy of the system. More simply put: the entropy of the universe (the ultimate isolated system) only increases and never decreases.
- A simple way to think of the second law of thermodynamics is that a room, if not cleaned and tidied, will invariably become more messy and disorderly with time – regardless of how careful one is to keep it clean. When the room is cleaned, its entropy decreases, but the effort to clean it has resulted in an increase in entropy outside the room that exceeds the entropy lost.

- **The Third Law of Thermodynamics**
- The third law of thermodynamics states that the entropy of a system approaches a constant value as the temperature approaches absolute zero. The entropy of a system at absolute zero is typically zero, and in all cases is determined only by the number of different ground states it has. Specifically, the entropy of a pure crystalline substance (perfect order) at absolute zero temperature is zero. This statement holds true if the perfect crystal has only one state with minimum energy.

The Carnot Cycle

- Idealized thermodynamic cycle consisting of **four** reversible processes (working fluid can be any substance):
- The four steps for a ***Carnot Heat Engine*** are:
  - ➢ Reversible isothermal expansion (1-2, T_H= constant)
  - ➢ Reversible adiabatic expansion (2-3, Q = 0, $T_H \rightarrow T_L$)
  - ➢ Reversible isothermal compression (3-4, T_L=constant)
  - ➢ Reversible adiabatic compression (4-1, Q=0, $T_L \rightarrow T_H$)



1-2 2-3 3-4 4-1

The Carnot Cycle (cont'd)

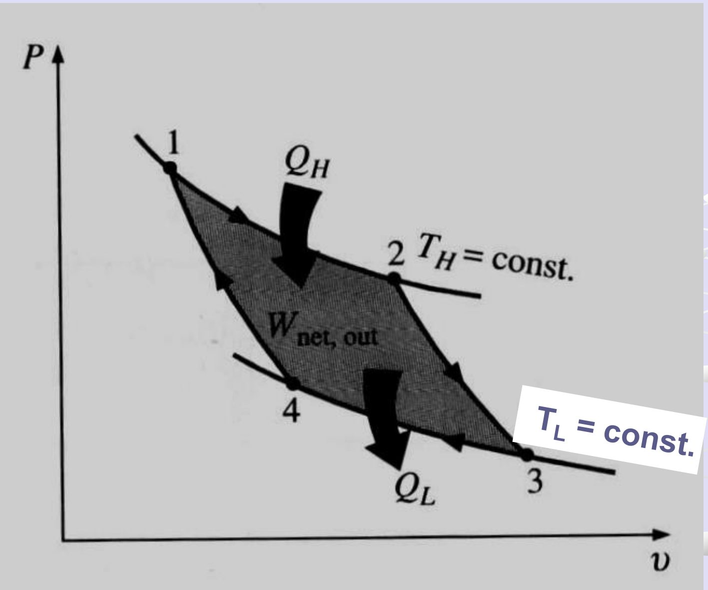
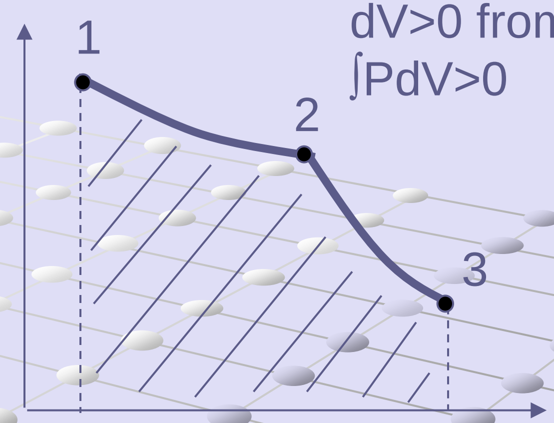


FIGURE 5-44

P-v diagram of the Carnot cycle.

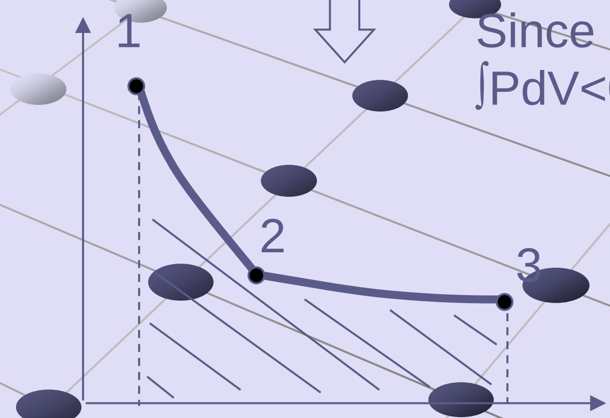
Work done ***by the gas*** = ∫ PdV, i.e. area under the process curve 1-2-3.



dV>0 from 1-2-3
∫PdV>0

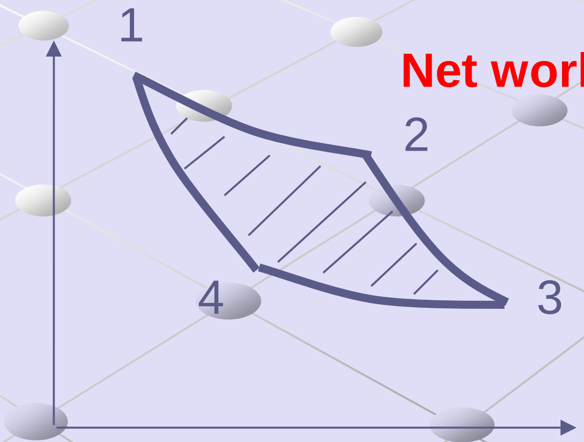
Work ***done on gas*** = ∫PdV, area under the process curve 3-4-1

subtract



Since dV<0
∫PdV<0

Net work



The Carnot Principles/Corollaries

1. The efficiency of an irreversible, i.e. a real, heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs. $\eta_{th,\ irrev} < \eta_{th,\ rev}$

2. The efficiencies of all reversible heat engines operating between the same two thermal reservoirs are the same. $(\eta_{th,\ rev})_A = (\eta_{th,\ rev})_B$

- Both of the above statements can be demonstrated using the second law (K-P statement and C-statement). **Therefore, the Carnot heat engine defines the maximum efficiency any practical heat engine can (hope to) achieve**. (see YAC: 5.8, for proof)

- Thermal efficiency $\eta_{th} = W_{net}/Q_H = 1-(Q_L/Q_H) = f(T_L, T_H)$
  - In the next slide we will show that $\eta_{th} = 1-(Q_L/Q_H) = 1-(T_L/T_H)$.
  - This relationship is often called the ***Carnot efficiency*** since it is usually defined in terms of a Carnot Heat Engine .

Carnot Efficiency

Consider an ideal gas undergoing a Carnot cycle between two temperatures T_H and T_L.

- 1 to 2, isothermal expansion, $\Delta U_{12} = 0$

$Q_H = Q_{12} = W_{12} = \int PdV = mRT_H \ln(V_2/V_1)$ **(1)**

- 2 to 3, adiabatic expansion, $Q_{23} = 0$

$(T_L/T_H) = (V_2/V_3)^{k-1}$ **(2)**

- 3 to 4, isothermal compression, $\Delta U_{34} = 0$

$Q_L = Q_{34} = W_{34} = -\, mRT_L \ln(V_4/V_3)$ **(3)**

- 4 to 1, adiabatic compression, $Q_{41} = 0$

$(T_L/T_H) = (V_1/V_4)^{k-1}$ **(4)**

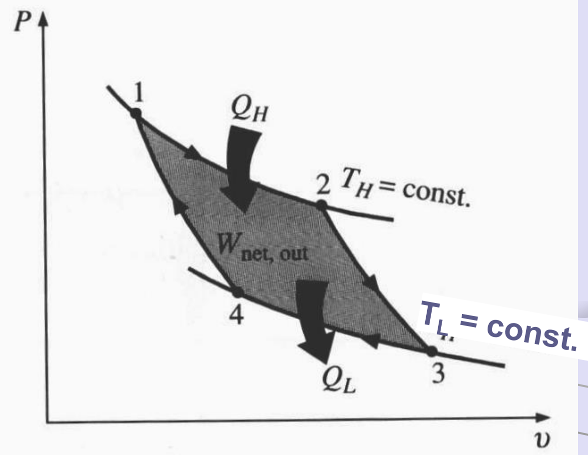


FIGURE 5-44
P-v diagram of the Carnot cycle.

From **(2)** & **(4)**: $(V_2/V_3) = (V_1/V_4) \Rightarrow (V_2/V_1) = (V_3/V_4)$
Since $\ln(V_2/V_1) = -\ln(V_4/V_3)$; substituting for $\ln(V_4/V_3)$ in **(1)**
$\Rightarrow (Q_L/Q_H) = (T_L/T_H)$
Hence: $\eta_{th} = 1-(Q_L/Q_H) = 1-(T_L/T_H)$

It has been proven that $\eta_{th} = 1-(Q_L/Q_H) = 1-(T_L/T_H)$ for all Carnot engines since the Carnot efficiency is independent of the working substance.

Example: A typical steam power plant operates between T_H=800 K (boiler) and T_L=300 K(cooling tower). For this plant, the maximum achievable efficiency is 62.5%.

Factors which affect Carnot Efficiency

Example: Consider a Carnot heat engine operating between a high-temperature source at 900 K and rejecting heat to a low-temperature reservoir at 300 K. (a) Determine the thermal efficiency of the engine; (b) Show how the thermal efficiency changes as the temperature of the high-temperature source is decreased; (b) Determine the change in thermal efficiency as the temperature of the low-temperature sink is decreased

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{900} = 0.667 = 66.7\%$$

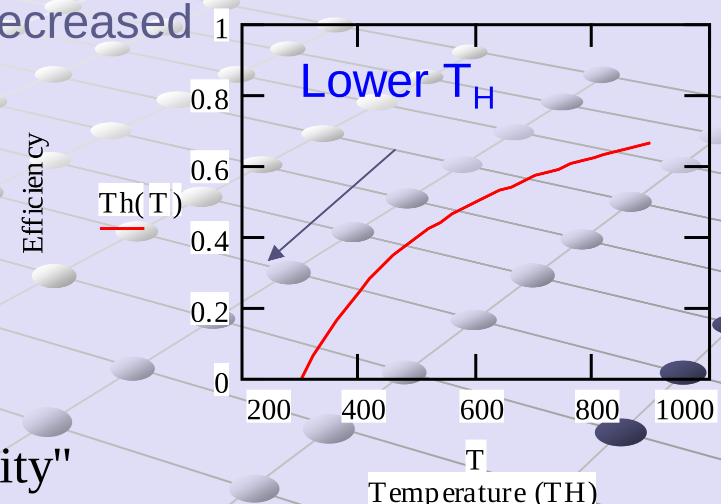
Fixed $\mathrm{T_L} = 300(K)$ and lowering $\mathrm{T_H}$

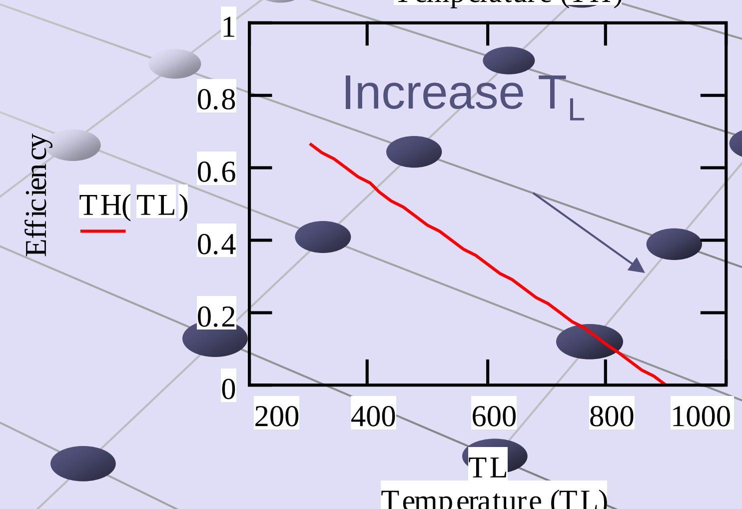
$$\eta_{th}(T_H) = 1 - \frac{300}{T_H}$$

The higher the temperature, the higher the "quality" of the energy: More work can be done

Fixed $\mathrm{T_H} = 900(K)$ and increasing $\mathrm{T_L}$

$$\eta_{th}(T_H) = 1 - \frac{T_L}{900}$$





Carnot Efficiency & Quality of Energy

- The previous example illustrates that higher the temperature of the low-temperature sink, more difficult it becomes for a heat engine to reject/transfer heat into it.
  - This results in a lower thermal efficiency
  - One reason why low-temperature reservoirs such as rivers, lakes and atmosphere are popular for heat rejection from power plants.

- Similarly, the thermal efficiency of an engine, e.g a gas turbine engine, can be increased by increasing the temperature of the combustion chamber.
  - This may sometimes conflict with other design requirements. Example: turbine blades can not withstand high temperature (and pressure) gases, which can leads to early fatigue. A Solution: better materials and/or innovative cooling design.

Quality of Energy cont'd

•This illustrates that the ***quality*** of energy is an important factor in determining the efficiencies of systems. E.g. for the same amount (***quantity***) of total energy, it is easier – more efficient – to produce work from a high temperature reservoir than a low temperature reservoir. Consequently, extracting energy from low-temperature reservoirs such as rivers and lakes is not very efficient. E.g. solar pond/lake have typical efficiencies of around 5%

•Also, work is in general more valuable – of a higher ***quality*** - relative to heat, since work can convert to heat almost with almost 100% efficiency but not the other way around. Energy becomes less useful when it is transferred to and stored in a low-temperature reservoir.