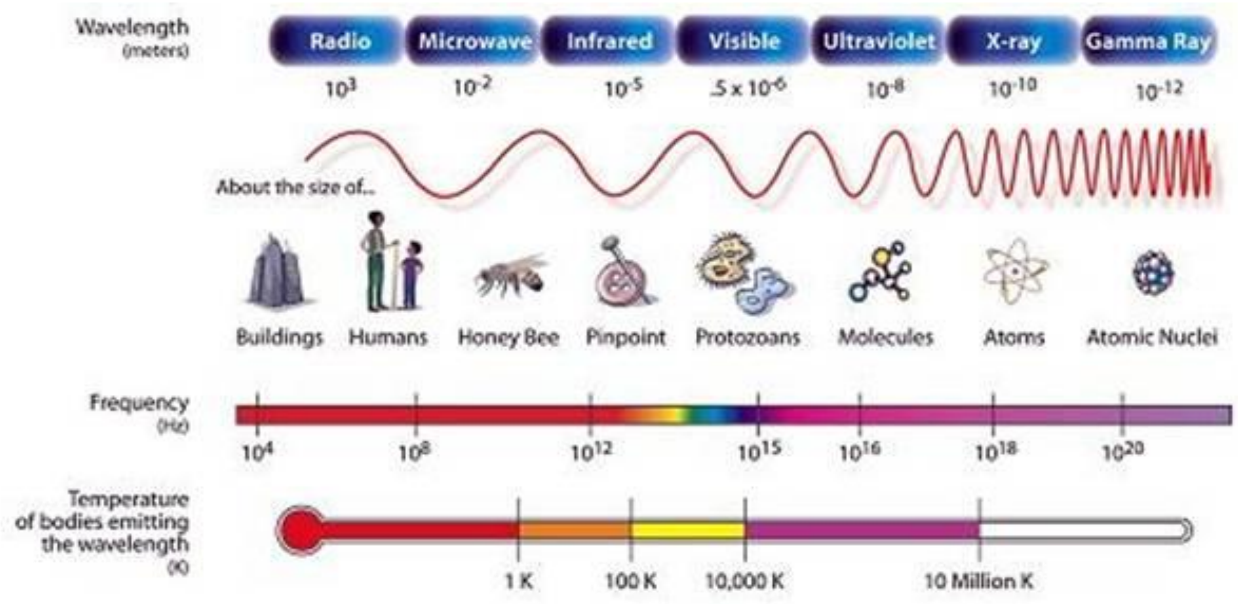
III. Radiation and the Greenhouse Effect

A. **The electromagnetic spectrum** consists of radiation we can see (visible light, the colors of the rainbow), radiation we can feel (the infrared), radiation we can exploit (microwaves for cooking and communication, radio and TV, and weather radar), and radiation we can largely do without, such as X-rays, gamma rays, and much of the ultraviolet.



B. Radiation travels as waves, and waves are characterized by wavelength, the distance between crest to crest of a wave or from trough to trough.
   1. The electromagnetic spectrum spans an enormous rage of wavelengths.
   2. Gamma and X-rays are about a wavelength of a billionth of a meter.
   3. Ultraviolet rays are about 10 millionths of a meter. That means you can put 4 million of them in an inch. It is about a tenth of a micron, introducing a very useful unit to use in radiation. (A micron is a millionth of a meter).
   4. Visible light is the range from 0.4-0.7 microns, or roughly 2/100,000 ths of an inch.
   5. We divide up the infrared part of the spectrum into 2 sections, the near infrared, about a micron, and the far infrared, closer to 10 microns, about 4/10,000 ths of an inch.
   6. Beyond that, we have microwaves, 1000 microns, or 0.04 inches.
   7. TV and FM radio use wavelengths of about a meter, or 40 inches.
   8. Finally, AM radio has a wavelength of about 100 meters, or the distance of a football field.
      [Our focus in this course is ultraviolet, visible, and the near and far infrared.]
   9. {For visible light, remember "ROYGBIV". Those are the colors of visible light, arranged from long wavelength to short}.

C. Four fundamental points concerning radiation:

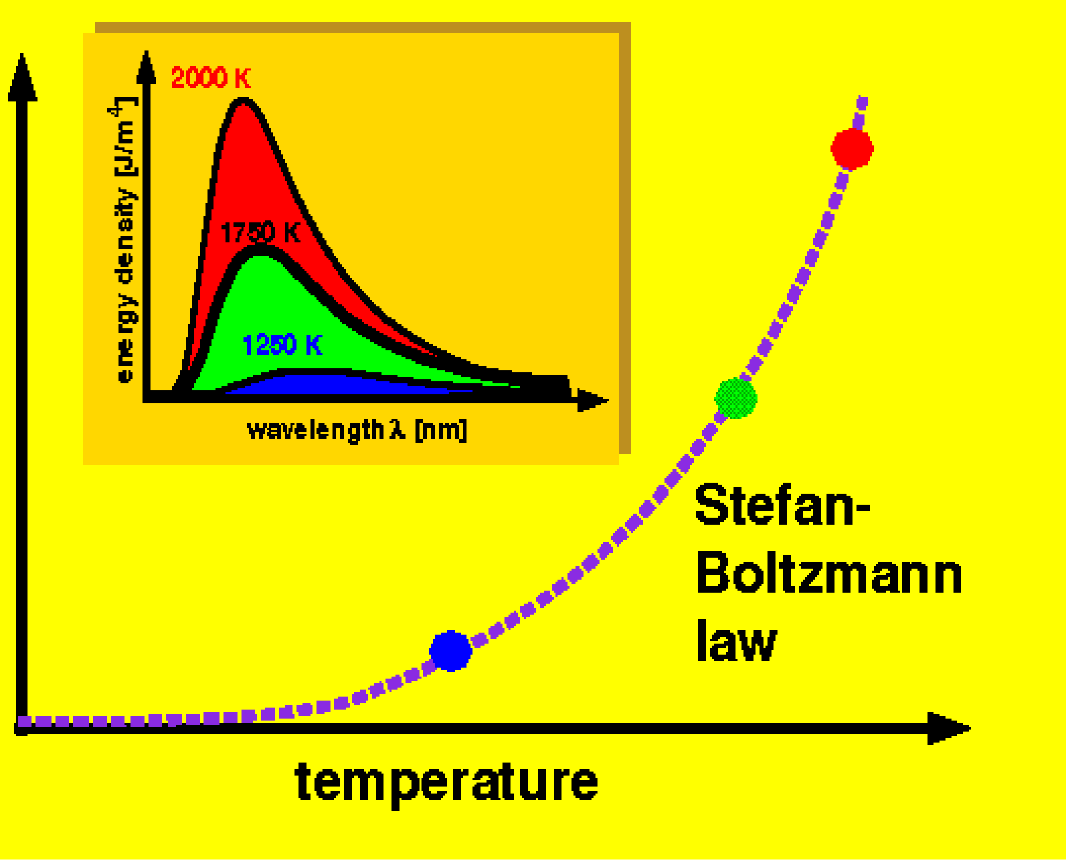
1. All objects emit radiation.
    a. True for all objects with a temperature greater than absolute zero.
    b. That narrows it down to everything---the Sun, the air, the ground and your hair.
    c. Absolute zero is -459°F, -273°C, and zero on the Kelvin absolute temperature scale.
    d. It is suffice to say that objects emit radiation because they have a temperature.
2. The radiative energy emitted very strongly depends on temperature.
    a. The energy is proportional to the fourth power of temperature. We call this the "Stefan-Boltzmann law".

$$E^* = \sigma T^4$$

where σ (sigma) = $5.67 \times 10^{-8}\ \mathrm{Wm^{-2}\,K^{-4}}$

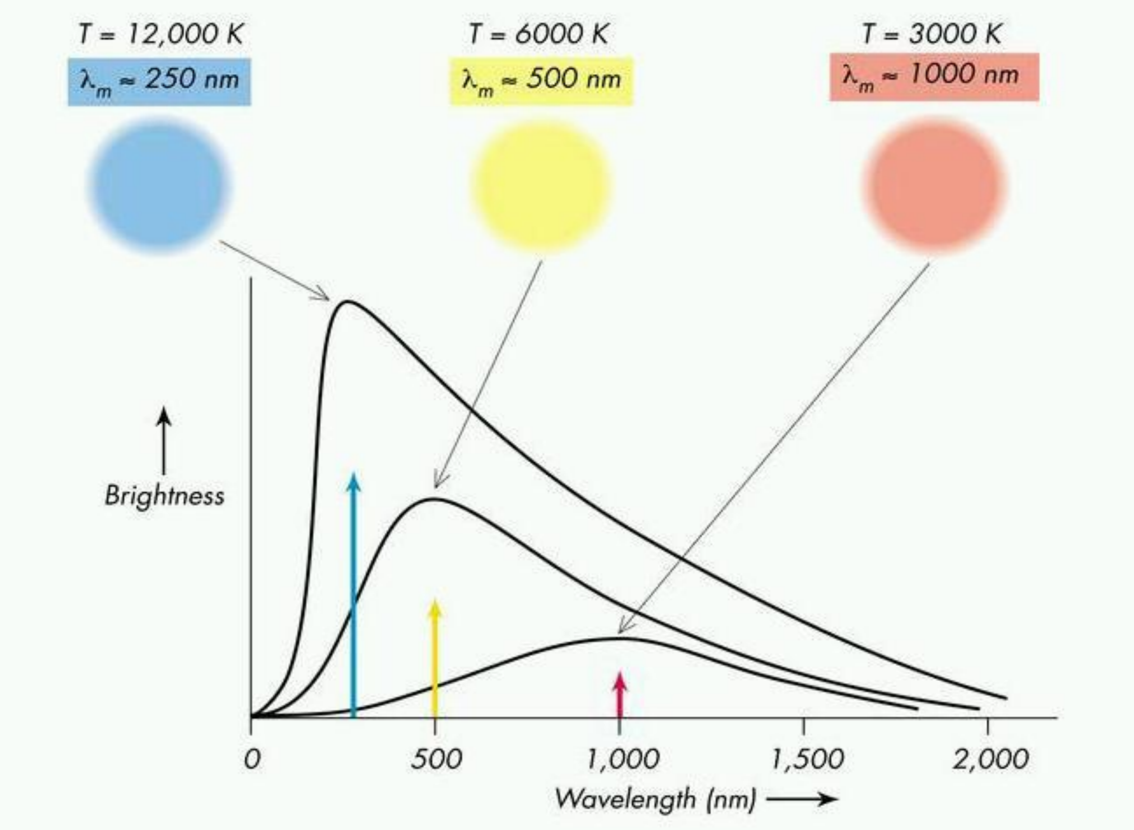
and T is the temperature in Kelvin

    b. If we measure the temperature in Kelvin, we see that if we take an object's temperature and we double it, the radiation energy output increases by a factor of 16 because 16 is 2 raised to the fourth power.
    c. Picture a warm summer day. The warm ground is maybe 80°F. That's 300 Kelvin. The temperature of the Sun's outer surface is 6000 Kelvin, or near-abouts. That's 20 times hotter. That means the Sun produces 160,000 times more radiation than the warm ground does.



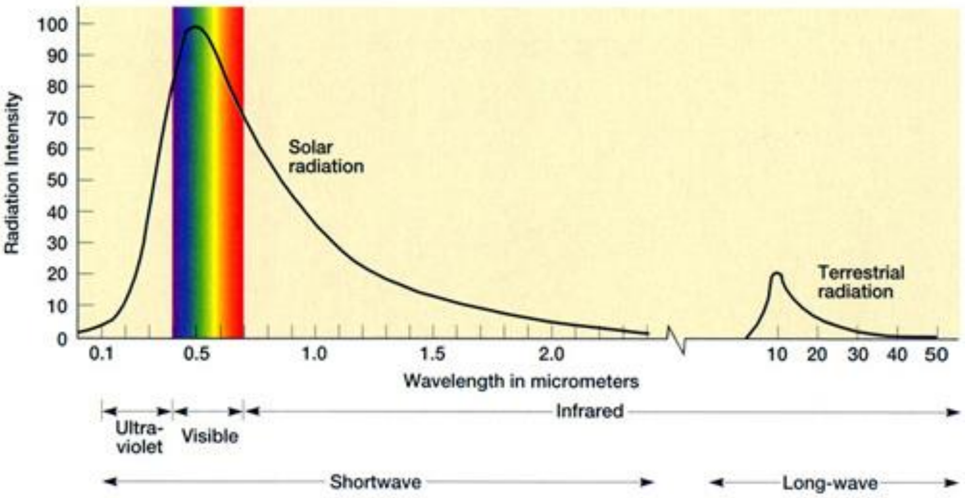
3. All objects radiate energy at all wavelengths of the electromagnetic spectrum.
    a. The Sun, the air, the ground, your hair emit gamma and X-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.
    b. Beach sand might be hot at noon, but it certainly doesn't give off visible light, and we sure hope it's not producing much deadly gamma ray radiation either.
4. Objects radiate much more energy at some wavelengths than others.
    a. The Sun produces gamma ray and radio waves, but most of its output is in the visible light between 0.4 and 0.7 microns and nearby wavelengths.
    b. Beach sand radiates virtually all of its radiation in the far infrared. Emission of visible light, and microwaves, are finite, but undetectably small.
    c. So we've seen that the amount of radiation produced depends on temperature, but also the kind of radiation produced also depends on temperature.

D. Planck's law tells us how much of each kind of radiation an object produces.
1. The "Planck curve" for an object of roughly 6000 K, about the temperature of the Sun's outer surface.
    a. The horizontal axis is wavelength in microns from short to long. The vertical axis is a measure of the relative output of radiation at that wavelength. {The total radiative energy is the area beneath this curve}



    b. Subdividing this curve into 4 principal types of radiation, ultraviolet, visible, near infrared, and far infrared, we see the peak for the Sun is in the visible portion of the spectrum, and in fact, the peak is near to the colors green and yellow. Our Sun is a yellowish star, and it's color reflects it's temperature. Further, we see that almost half of the solar radiation is in the visible band from 0.4-0.7 microns. So 44% of the Sun's output is visible light. Another 37% in the near infrared, 11% underneath the long tail of IR and beyond, and only 7% is ultraviolet and shorter, but this means that more than half of the Sun's energy is actually invisible to our eye.

c. Let's look at the Planck curve for a cooler object, an object that is cooler by a whole 500 Kelvin. We see a couple of things.
   i) The area beneath the curve is a lot smaller. This illustrates the Stefan-Boltzmann effect.
   ii) There's less radiation at every wavelength, and it may be hard to see, but the peak of the curve has been shifted to the right.
   iii) It's still in the visible, but it's been nudged a little bit towards the color red, which are the longer wavelengths of visible light.

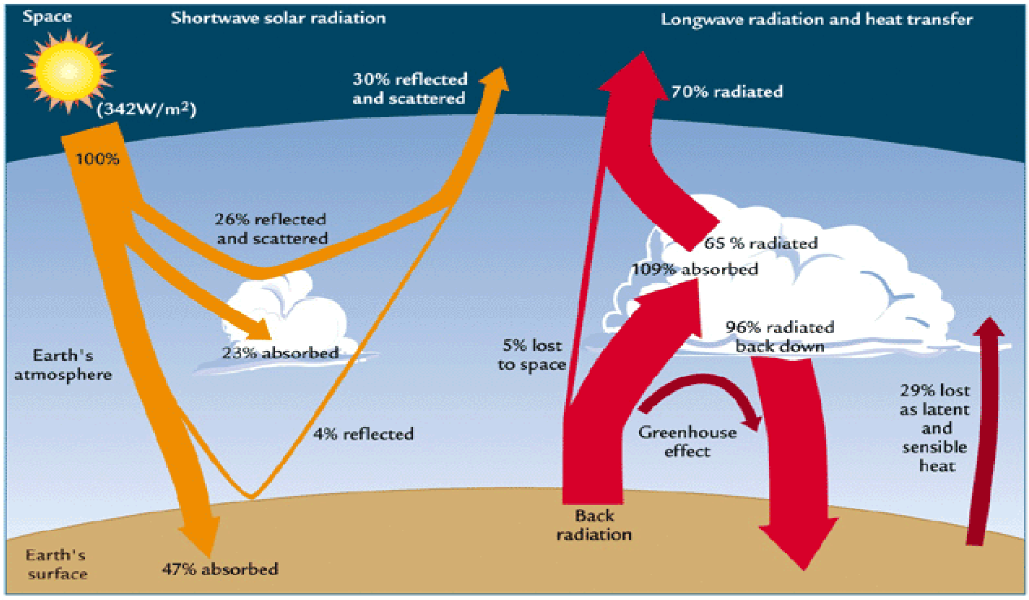


d. For progressively colder objects, the peak shift to longer wavelengths is now very obvious. **Wien's law tells us that wavelengths of maximum emission is inversely proportional to temperature.**
   i) We still have a curve that looks like a Planck curve, but the curve is a lot shallower because the temperature is lower, so there's less energy being produced, and the curve's peak is shifting to longer and longer wavelengths as the temperature gets lower.
   ii) Note that in the world of color temperature blue is hot and red is cool.
   iii) The typical Earth surface produces negligible amounts of radiation at visible and ultraviolet wavelengths, and that's why we can't see at night.

e. Observing the Planck curves for the Sun and the Earth, we notice that the hotter Sun has a curve with an equal height than the earth. Why?
   i) Solar radiation is spread throughout space. The Sun may produce 160,000X more radiation than the Earth does but its spread out far and wide.
   ii) We need a radiation budget to be balanced in thermal equilibrium. We need **in** to-equal **out**, so over a long period of time----not so long as to incorporate climate change, but long enough to smear out the effects of

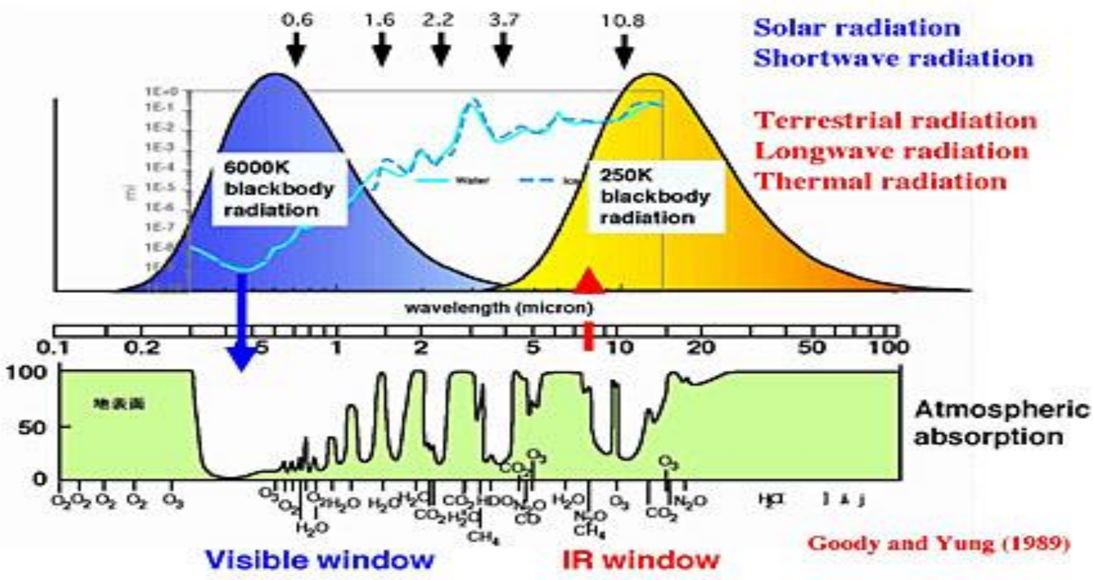
seasons and days and sea breezes and things like that---our radiation budget is balanced, and the energy that we receive from the Sun and the energy that we lose to the cold of space are equal.

f. Also, the Planck curves never overlap. This lack of overlap leads to an interesting and powerful consequence: the greenhouse effect.
    i) I'm going to call solar radiation "shortwave radiation" because it basically occupies the shorter wavelengths of the electromagnetic spectrum, and my synonym for the Earth's radiation will be long-wave radiation.
    ii) The division between the two is at about 3 microns, but if you look at the curves, you see there's relatively little radiation there, so we don't need to be very precise with our demarcation.



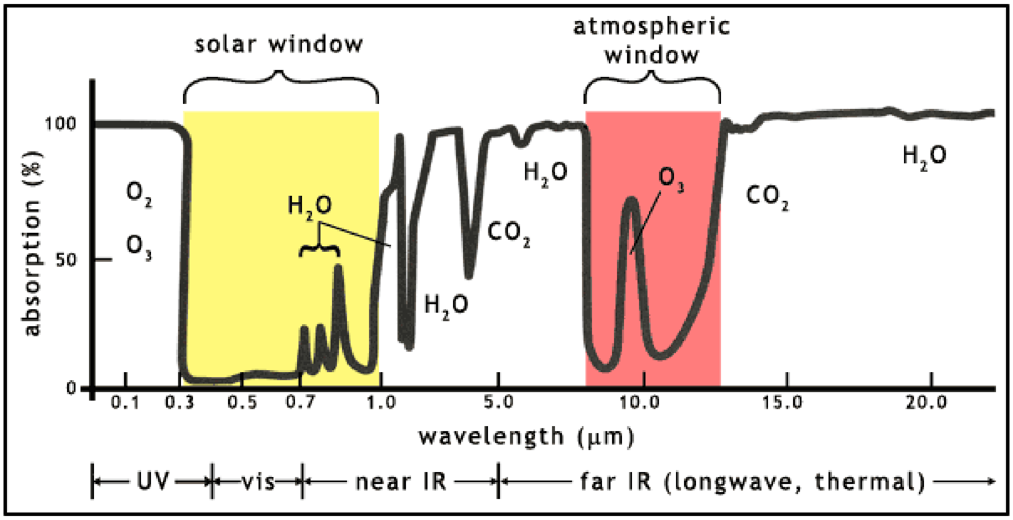
E. What is the fate of radiation, whether it's shortwave from the Sun or long-wave from the Earth? {Three possibilities}
1. It can be reflected back to its origin.
    a. Red objects reflect red frequency wavelengths. A white object reflects all colors equally. A black object absorbs all colors of visible light.
2. It can be scattered in all directions.
3. It can be absorbed.
    a. It can be absorbed by the ground, by air, by particles in the air, such as cloud droplets and soot.
    b. The only way radiation can change the temperature of an object is through absorption.
    c. Objects, by which I mean atoms and molecules, absorb wavelengths for which they have a particular affinity. Objects that absorb everything, that have an affinity for everything, are called "blackbodies". The Earth's surface, dirt, is very nearly a blackbody, and we treat it as such.

d. In contrast, and a very important contrast, atmospheric gases ten to be very selective absorbers.
   i) Nitrogen, 78% of the Earth dry atmospheric mass, absorbs almost nothing.
   ii) Ozone, O_3, absorbs a lot of ultraviolet, some far infrared, and a wee bit more.

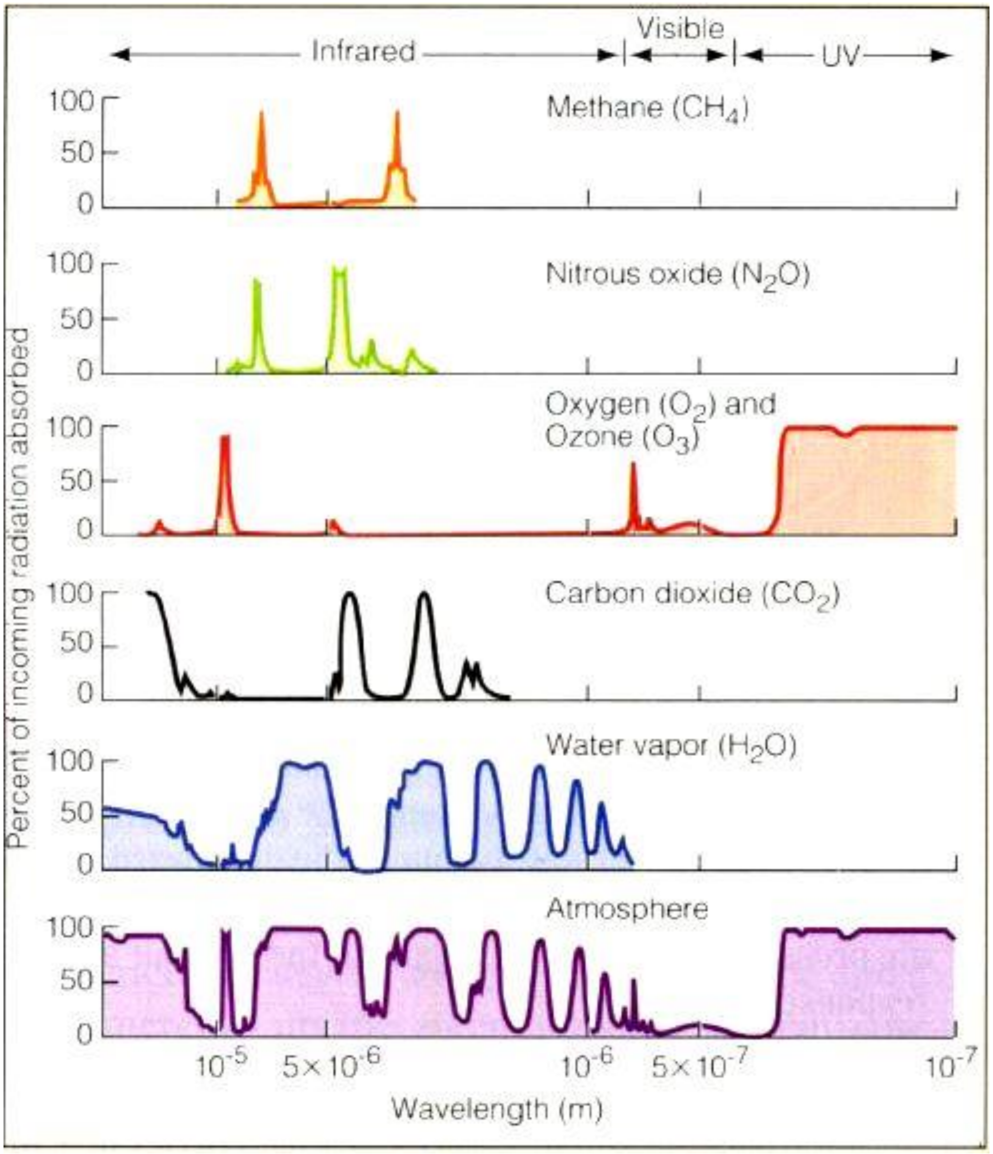


Goody and Yung (1989)

F. The flip side of absorption is emission. Objects that absorb must also emit.
   1. Absorption depends on affinity. Emission is determined by temperature. Absorption depends on affinity, and emission depends on temperature.



a. Ozone emits in the far infrared, owing to its relatively cool temperature, but it absorbs ultraviolet coming in from the Sun. UV in, far-infrared out.
b. Atmospheric absorption diagram: The horizontal axis is the wavelength in microns and the vertical axis is the fraction of radiation that is absorbed by the atmosphere. If the line is very high up on the curve, then that represents very large absorption affinity.
c. Look at the shortest wavelengths of sunlight, the ultraviolet radiation wavelength less than 0.4 microns. The simplified absorption for this portion of the spectrum shows that absorption is generally very high. That absorption is accomplished by oxygen and ozone in the stratosphere. That's why the stratosphere exists and why it is relatively warm. However, notice the absorption curve dips downward before we reach the far end of the ultraviolet. The very longest wavelengths of ultraviolet do reach the ground.



d. In the visible light portion, we see there is very little absorption in the atmosphere, so very little absorption affinity. If you look closely, there actually is a little bit, and it's in the longer wavelengths of visible light, the colors orange and red.

e. Left is mainly near infrared, and some far infrared as well, and we see we're back to significant absorption. This is absorbed primarily by water vapor.

f. Let's compare what's being absorbed by the atmosphere and what the Sun is producing. They seem opposite.

  i) The atmosphere absorbs best what the Sun make the least of-----half of the Sun's radiation is almost totally ignored. Much of that can pass right through air as if it weren't even there, and it reaches the ground, which will absorb anything, and that warms the Earth.

  ii) Now we're dealing with radiation emitted by the cool earth as a result of absorbing all that nice visible light. These are longer wavelengths, the far infrared.

g. Our absorption spectrum: absorption of incoming solar radiation----limited, but important. Much of that radiation survives to be absorbed by the ground. That radiation is then reradiated upwards at longer wavelengths, owing to the cooler temperatures of the Earth. A lot of that radiation, though, is absorbed on the way out especially by water vapor and carbon dioxide. Our primary greenhouse gases are very selective absorber, and that is that is the greenhouse effect.

h. Actually, some of the outgoing radiation escapes to space, but some is absorbed by greenhouse gases. The greenhouse gases themselves radiated in all directions, including down, down towards the ground, where it is absorbed by our blackbody friend, the ground. As a result, it warms up more.

i. If you absorb, you must emit, so the ground emits radiation again. Some of this escapes to space. Some is absorbed by our greenhouse gases yet again.

j. We're moving towards equilibrium, where in equals out, but the temperature of that equilibrium is a lot higher than if none of this extra greenhouse action had taken place.

k. The presence of greenhouse gases has made the Earth much warmer than it otherwise would have been. Earth's average temperature, averaged equator to pole, winter to summer, land to sea is about 60°F.

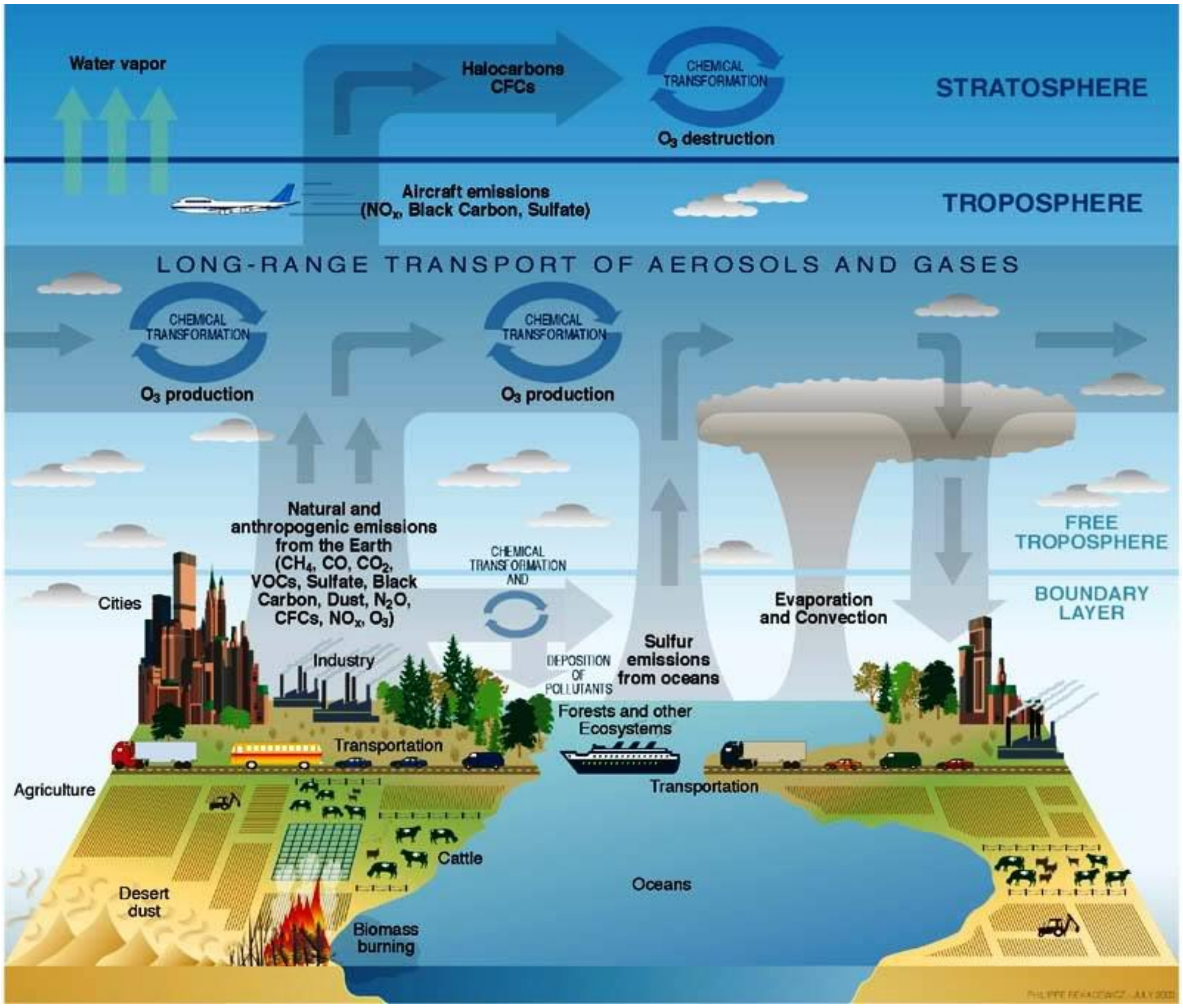
  i) Without the greenhouse effect, that average temperature would by 60°F lower. The average would be zero. The Earth's surface would likely be frozen everywhere, including the tropics.

  ii) The reason the Earth is not a big snowball in space is because of greenhouse gases, carbon dioxide, ozone, methane, nitrous oxide, and especially water vapor, the most important greenhouse gas of all. They are our thermostat.

G. Summary:

1. The electromagnetic spectrum encompasses a gigantic variety of waves and wavelengths. Ultraviolet, visible and infrared.

2. Objects emit radiation based on their temperature. The cooler the object, the longer the wavelengths of radiation that are produced.
3. Objects absorb radiation base on their affinity. Some objects absorb everything. We call them “blackbodies”. Others are very finicky and selective absorbers.
4. Most air constituents do not absorb much of the short wavelength radiation the Sun produces.
5. A significant and important exception is ozone, which absorbs ultraviolet radiation in the stratosphere, and also molecular oxygen participates in that as well.
6. The cooler Earth produces longer wavelengths, preferred by finicky gases like water vapor, carbon dioxide, and other minor constituents. This differential absorption represents the greenhouse effect.
7. The very same gases that largely ignored short wavelength radiation on the way down absorb at least some of Earth’s long-wave radiation welling upwards.
8. Since objects that absorb must also emit, and emit in all directions, some of that intercepted energy is returned to the surface. This make the Earth’s surface warmer than it would have been without the greenhouse effect.



H. Questions:

1. What does color tell us about temperature and when?

2. Why can't we see at night?

3. Why isn't the Earth's surface a frozen lump of ice?

4. The Sun, as seen from space, is a yellow-white star. Of course, the Sun generates all colors of light, but yellow predominates. As the Sun ages and cools, will it's light become more reddish or more bluish? Why?

5. Consider a conventional incandescent light bulb with clear glass that is connected to a source of electricity controlled via a dimmer switch. Turn on the light and slowly rotate the switch, allowing more current to pass through the circuit. At first, the bulb's filament glows a deep red, then a bright orange, then an even brighter yellow before glowing very bright white. Explain this color-shifting phenomenon.

6. Compared to Mercury, Venus is located almost twice as far from the Sun and receives only a fraction of the solar radiation. Yet it's surface temperatures are hotter than Mercury's. Why?

7. What is the difference between Planck's Law and Wien's Law?

8. How is the atmosphere heated? Explain.

9. What color of the electromagnetic spectrum is absorbed by the ozone layer? Explain.

10. What color of the electromagnetic spectrum is absorbed by water vapor in the atmosphere? Explain.

11. What color of the electromagnetic spectrum is absorbed by Earth? Explain.

12. What color of the electromagnetic spectrum is emitted by the Earth? Explain.

13. According to Wien's law, how is wavelength of light related to temperature?

14. What has a longer wavelength, ultraviolet or infrared?

15. What has a longer wavelength, Blue or red light?

16. Explain how the earth's atmosphere acts as a blanket? What is the analogy?