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The Greenhouse Effect

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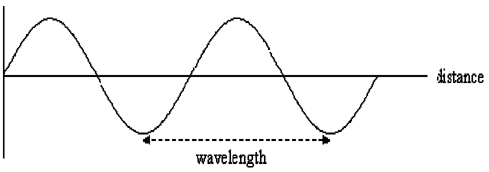
THE GREENHOUSE EFFECT

To understand the ***greenhouse effect*** you first need to know a bit about ***solar radiation*** – what it is, where it comes from and what happens when it reaches Earth.

Solar radiation is more than just light – it also contains some ***ultra-violet*** (uv: you'll have heard that uv-A is what gives you a suntan, while too much uv-B and uv-C can cause burning and skin cancers) and a lot of ***infra-red*** (ir).

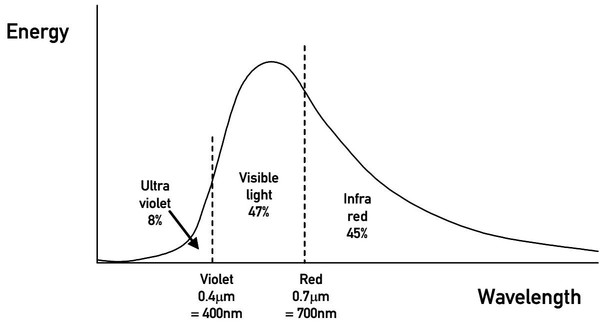
Light, uv and ir are all ***electromagnetic waves*** – waves consisting of oscillating electric and magnetic fields – that's pretty complicated, and it needs some serious physics in order to explain electromagnetic waves properly.

The important feature for now is that waves have a characteristic ***wavelength*** – the distance between two adjacent peaks (or troughs) in the waveform.



The wavelengths in solar radiation are very, very small: 1 micron (written 1μm for short, and equal to 1/1000 of a millimeter) and shorter.

As we go from infra-red, through the colours of visible light (red – orange- yellow – green – blue – indigo – violet) to ultra-violet, the wavelengths get progressively shorter. We can describe solar radiation as a ***spectrum*** of electromagnetic waves.



The range from 400 to 700nm is called the visible spectrum – the colours you see in a rainbow, or reflected from the tiny grooves in a CD. The raindrops or the groove pattern on the CD separate light waves according to their wavelengths, or colours.

Electromagnetic waves don't cease to exist beyond ultra-violet and infra-red – they're not present in significant amounts in the solar radiation, but they can be generated in other ways.

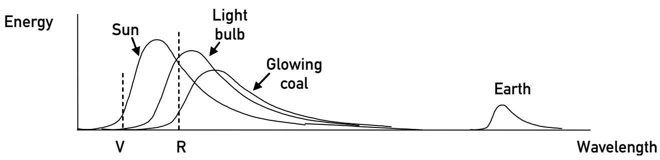
You're already familiar with electromagnetic waves that have wavelengths longer than infra-red waves: they are called microwaves and radio waves.
You've also heard about electromagnetic waves with wavelengths shorter than ultra-violet rays: they are called X-rays and gamma rays.

Although our eyes are sensitive only to the wavelengths between 400 and 700nm, in most respects other than wavelength, these other sorts of electromagnetic waves are just the same as light waves. In particular, in empty space they travel at the speed of light, c = 300,000,000 m/s.

Next we need to find out why the Sun emits this spectrum of electromagnetic waves.

The surface of the Sun is at a temperature of about 6000^0C. All bodies at this temperature emit a spectrum of radiation like the Sun's.

Perhaps the most familiar example of this is an ordinary light bulb. The filament inside a light bulb is not quite as hot as the Sun, but as you know, it emits whitish light. Put your hand close and you'll also feel heat – this is because it also emits a lot of infra-red radiation. The light bulb is emitting a spectrum like the Sun's, but with more infra-red and less light.



A glowing ember of coal or the bar of an electric fire provide another example – they are cooler again, maybe 600^0C, and emit only a little light – at the red end of the visible spectrum, but they emit lots of infra-red, which we feel as heat.

All bodies above absolute zero of temperature emit a spectrum of electromagnetic radiation. The shape of the spectrum is always similar, but the peak of the spectrum is at longer and longer wavelengths the cooler the body. This is called ***thermal radiation.***

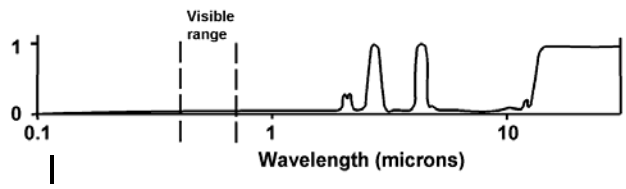
Even the Earth itself emits thermal radiation. Earth's average surface temperature is about 13^0C, and this means that the peak is at about 10μm, or 1/100 mm: still very short, but way outside the visible range – near the upper end of infra-red.

The fact that the radiation emitted by Earth is at different wavelengths from the solar radiation is important in explaining the greenhouse effect. Another important factor is that the rate at which energy is radiated is much higher the hotter the body: one square metre of the Sun's surface emits energy 200,000 times faster than one square metre on Earth's surface.

So, there are two ways in which the thermal radiation emitted by a surface depends on its temperature:

- As the temperature rises, the rate at which energy is radiated increases rapidly: hot bodies emit energy a lot faster than cooler ones
- As the temperature rises, the peak of the spectrum moves to shorter wavelengths: cool bodies emit long wavelength infra-red, hot bodies glow red, really hot bodies emit white light

Greenhouse gases are atmospheric gases whose molecules absorb electromagnetic radiation strongly at the long infra-red wavelengths present in Earth's thermal radiation. (Molecules are generally very choosy about the wavelengths of radiation they like to absorb – other wavelengths they spit straight back out.)

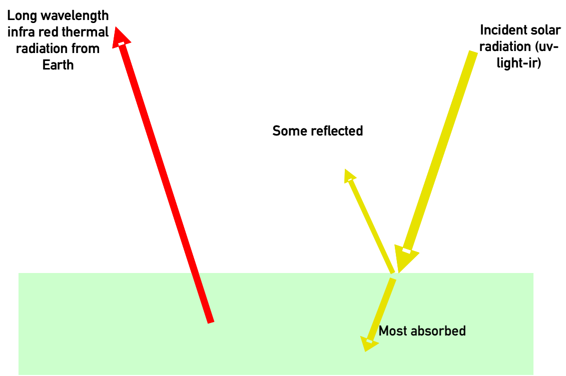


Absorption spectrum of carbon dioxide, showing that CO_2 is transparent to solar radiation, but absorbs strongly beyond 12 microns i.e. in the range of Earth's long wavelength, thermal radiation.

Water vapour, methane and certain other gases have similar absorption spectra, with peaks in the long wavelength infra-red region.

So, at last we can begin to explain the ***Greenhouse Effect:*** how increasing the concentration of greenhouse gases n the atmosphere can force the surface temperature of the planet to rise.

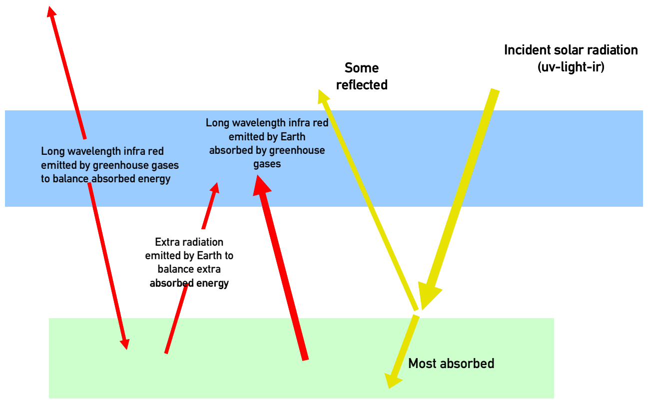
First imagine a planet with no greenhouse gases: Scenario 1. Solar radiation energy is incident on the dayside of the planet. When the planet is in equilibrium i.e. at a steady temperature, the rate of absorption of solar energy is balanced by the rate of emission of thermal radiation from the planet. This necessity to balance the absorbed solar energy with emitted thermal radiation determines the temperature of the surface of the planet: if Earth absorbed all the solar radiation incident on it and there was no atmospheric interaction with either the incident or emitted radiation, other than to spread the heat evenly around the globe, then Earth's surface would work out to be a uniform 8^{0}C. However, the incident solar radiation is not all absorbed: if you look at a picture of Earth taken from space, you'll soon see that the polar ice caps, oceans and clouds reflect a sizeable fraction of the sunlight – about 30%, so in fact less than 70% is absorbed. When this is accounted for, the temperature prediction drops to a chilly minus 16^{0}C.



Scenario 1: No greenhouse effect. The absorbed solar radiation is balanced by the emitted thermal radiation. The temperature of Earth's surface is related to the rate of thermal radiation

This sounds more like an ice age than a global warming problem: clearly we need to look at the role of the greenhouse gases. Carbon dioxide makes up only about 300 ppm (parts per million) or 0.03% of the atmosphere, methane even less: 1.5ppm or 0.00015%. Water vapour is by far the most abundant greenhouse gas, accounting for between 1% and 4%, depending on climate and temperature.

Let's imagine a situation with greenhouse gases. Let's suppose they are completely transparent to the solar radiation: so the solar energy absorbed by the earth is exactly the same as before: but now let's suppose that the greenhouse gases absorb all of the long wavelength infra-red thermal radiation emitted by Earth. Like the Earth, the atmosphere cannot simply go on and on absorbing energy: it also reemits energy, as its own thermal radiation, according to its temperature. However, when the atmosphere emits thermal radiation it directs equal amounts out into space and back down towards Earth's surface. The Earth must absorb this extra energy it receives from the atmosphere: in doing so its temperature rises, and at the same time the rate of thermal radiation from Earth's surface increases: until a new equilibrium is reached, in which the total rates of absorption and radiation are again in balance. If we were to follow through the calculations for this "perfect greenhouse" scenario, we would arrive at a surface temperature of 32.5^{0}C.



Scenario 2: The perfect greenhouse effect. The atmosphere contains greenhouse gases that allow the solar radiation to pass through unaffected, but which absorb all of the long wavelength thermal radiation emitted by Earth. The gh gas molecules reemit, also at long wavelengths, both out into space and back towards Earth. Since Earth must absorb this extra radiation, it must radiate more to re-establish a balance, and its temperature rises.

Both these calculations assume a uniform temperature over the whole Earth, which is obviously a huge simplification. However, the average observed surface temperature of about 13^0C, shows that we lie somewhere between the two extremes. Life on Earth is dependent on a well-tuned greenhouse effect, to keep the planet at just the right average temperature. However, increasing the effectiveness of the greenhouse any further, by increasing the concentration of greenhouse gases, will force the temperature up. Predicting the actual temperature rise for a given increase in greenhouse gas concentrations is a very complicated calculation: many variables come into the equations. However, the environmental consequences of even a 1 or 2 degree temperature rise would be very significant to the lives of many many people around the world.