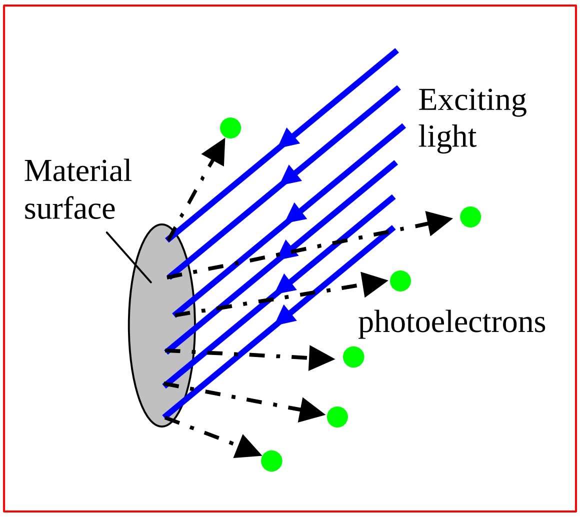
Photonics

This course has included substantial sections about the propagation of light. It is appropriate to end with a short section on what happens to light when it stops. It is then that the intrinsically quantum nature of light becomes conspicuous. Light delivers its energy in discrete packets – **photons**, the original *quanta*. A substantial amount of the cutting edge of modern optics is about photons and to reflect this modern emphasis the word *photonics* has come into use to describe this field. The word is strongly favoured by the optics industry, not least because it gives a modern ring to what are not always new or conceptually modern devices.

You may remember that it was Max Planck who first thought of the concept of light energy being absorbed and radiated in discrete packets, the quanta, in his quest to understand and explain why observed blackbody radiation had an energy spectrum different from that predicted by the conventional physics of the day. Planck associated the packets of energy with the material that was absorbing or emitting. It was a bold step but it might have remained a conjecture for very many years had it not been for Einstein. Einstein made the further hypothesis that light itself was composed of nothing but quanta, which came to be called photons. He did so in the context of trying to understand the law that governed the spectrum of electromagnetic radiation emitted by bodies at different temperatures and he backed this up with an explanation of how the photoelectric effect worked. This explanation was cited in 1921 as the most important reason he was awarded the Nobel Prize for Physics. One of the remarkable facts about Einstein's work on light quanta and the photoelectric effect is that he predicted in 1905 how the effect worked, long before there were good measurements. The detailed experimental work was undertaken by Robert Millikan, around 1915, and it vindicated Einstein's understanding that we'll give in the next section. The photoelectric effect is one of the basic phenomena that reveal the behaviour of photons. It is also an immensely useful effect for device technology. What is the photoelectric effect?

Photoelectric effect

The photoelectric effect is the emission of electrons from a material when it is bombarded by light or, more generally, electromagnetic radiation. Nowadays, the word is also used for the creation by light of free, mobile, electrons within a semiconductor.



Photoelectrons released from a surface by light are so weak in energy that they don't travel any appreciable distance unless they are generated in a good vacuum. We shan't be concerned about any practical details of measuring them, except to say that devices that exploit released photoelectrons are made inside vacuum tubes.

There are two crucial and puzzling properties associated with this effect, which were explored at length by Millikan and later workers. They are:

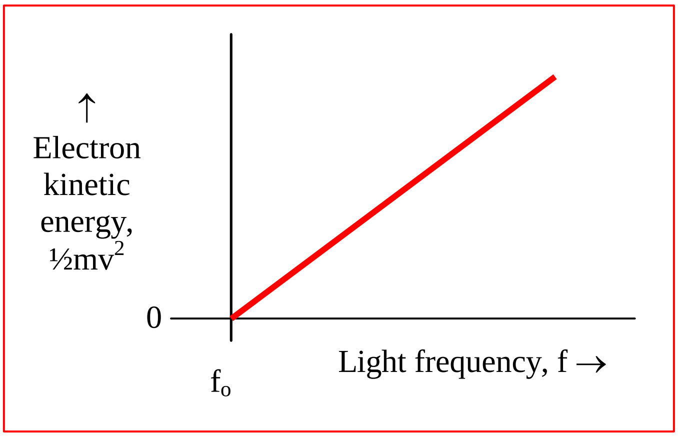
1 Light below a certain frequency, which depends on the material investigated,

will not produce any emitted electrons, no matter how strong the irradiance is. Thus, for example, a very weak green, blue or purple light can easily produce enough electrons to form a measurable current, whereas a most intense red light may produce nothing at all.

2 The kinetic energy of the electrons produced increases linearly as the light frequency exceeds the threshold needed to produce them, and is quite independent of the irradiance of the light. Thus, for example, a very weak purple light produces more energetic photoelectrons than a most intense bright green light.

Puzzling, isn't it?

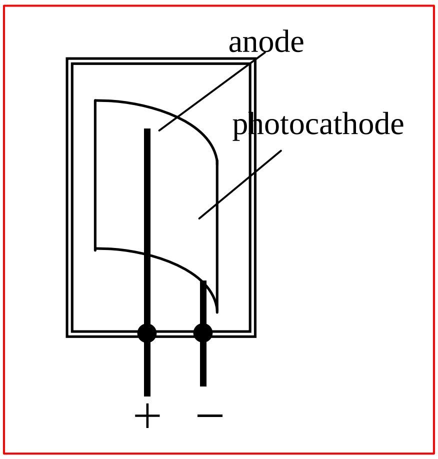
A typical graph of what happens appears like this. It looks innocent enough, a straight line through the origin of electron kinetic energy. Why did it need the 26 year old Einstein to perceive what was going on? Because the solution looks simple in hindsight but involved what was then a radical change of viewpoint. Einstein proposed that Planck's packets of energy with E = h*f* weren't just a convenient 'fix' for an awkward law of radiated energy but were a fundamental constituent of nature – that, in effect, light travelled as photons and interacted with matter in a truly quantum way. This was many years before Bohr, Schrödinger and Heisenberg developed what we now know as quantum theory.



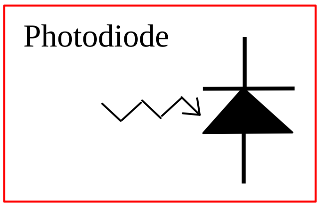
As an equation, Einstein wrote the photoelectric relationship as:

$$\frac{1}{2}mv^2 = hf - \Phi \quad ,$$

where ½mv² is the kinetic energy of an emitted electron. Einstein's prediction was that the slope of the graph would always be Planck's constant *h*. Φ is called the *work function* of the surface and represents how difficult it is to liberate electrons. Einstein's equation is a statement of conservation of energy, with Φ reducing the available energy of the light photons, namely Planck's value *hf*, *f* being the light frequency here.



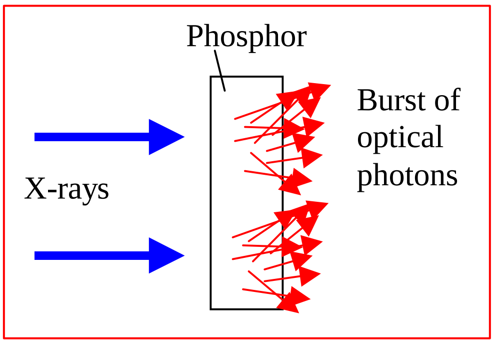
Many experiments have demonstrated that Einstein was right. You can measure Planck's constant *h*, which is one of the fundamental constants of physics, from the behaviour of the photoelectric effect. Photocells are made in a huge variety of shapes and sizes but the 'classic' design is a simple glass envelope to let in the light and keep out the atmosphere. Within the envelope is a large *photocathode* to generate the electrons and a positive anode wire to attract the negative electrons and create a photocurrent. Many modern photocells have no glass envelope but are based on semiconductor technology. The emitted electrons never escape from the semiconductor in which they are generated and so no vacuum is necessary. The most common type is the photodiode, which has a clear window at the end of its capsule to let in the light.

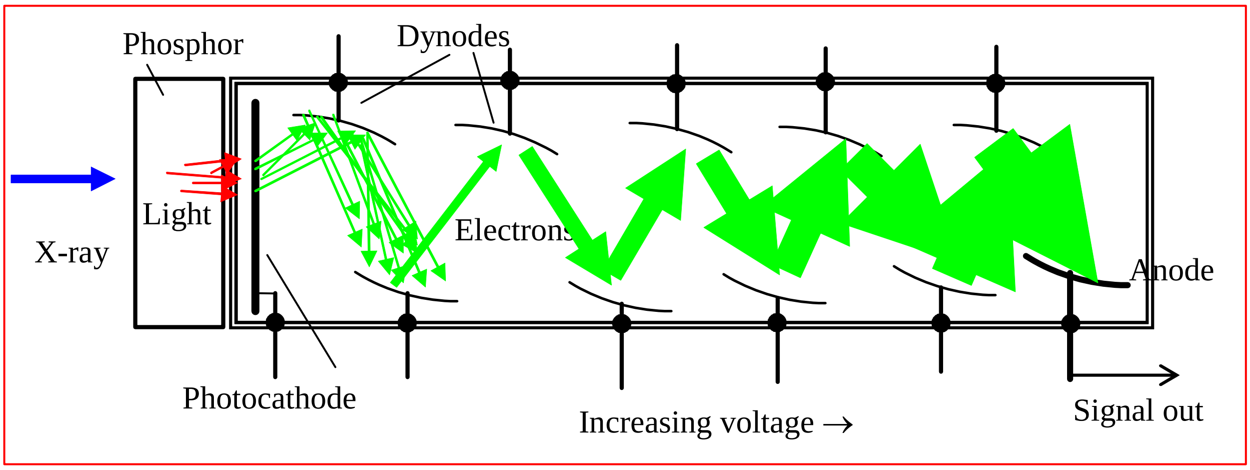


The photomultiplier

The photomultiplier doesn't so much multiply light but multiplies the electrical output of a photodetector. It is used in circumstances where low light levels need to be detected. One particularly widespread use of photomultipliers is their use in sensitive radiation detectors, to detect X-rays from man-made sources or γ-rays produced by radioactivity. This radiation detection is used a lot in areas of applied science like X-ray crystallography, medical imaging or geological rock analysis. The detection is a two-stage process: the radiation produces light and the light is detected by a photomultiplier. Finally, of course, the resulting electrical signal is then processed in a way appropriate to the application.

First, look at the conversion of radiation energy to light. This is done by a phosphor. Earlier in the course it was mentioned that an X-ray photon may have an energy 10,000 times that of an optical photon. A γ-ray photon may have an energy 10^6 greater than an optical photon. When one of these photons is absorbed in a material, it does so by a cascade mechanism during which a large number of lower energy photons are created and destroyed along the path. This happens very quickly, typically in 10^{-7} to 10^{-10} seconds. The net result is that a significant amount of the initial energy is converted into a burst of optical photons, if the lowest set of energy levels is right for this to happen. Suitable materials are some clear plastics or some crystals, often with doping to improve the absorption of radiation and the generation of the light. Detecting the incident radiation is now a matter of detecting a burst of several thousand optical photons.





If you relied on a photocell to detect a few thousand photons, the best you could hope to get is a few thousand photoelectrons. The charge on a single electron is just 1.6×10^{-19} C. Hence if 1000 electrons arrive in a pulse 1μs long, this gives a current of 1.6×10^{-10} amps, since an amp is a coulomb per second. Such a pulse would need highly sensitive electronics to detect it and it would be easy to lose it in natural electronic noise present in all circuitry. The answer is to arrange multiplication of the original photoelectron signal in a special device called a photomultiplier.

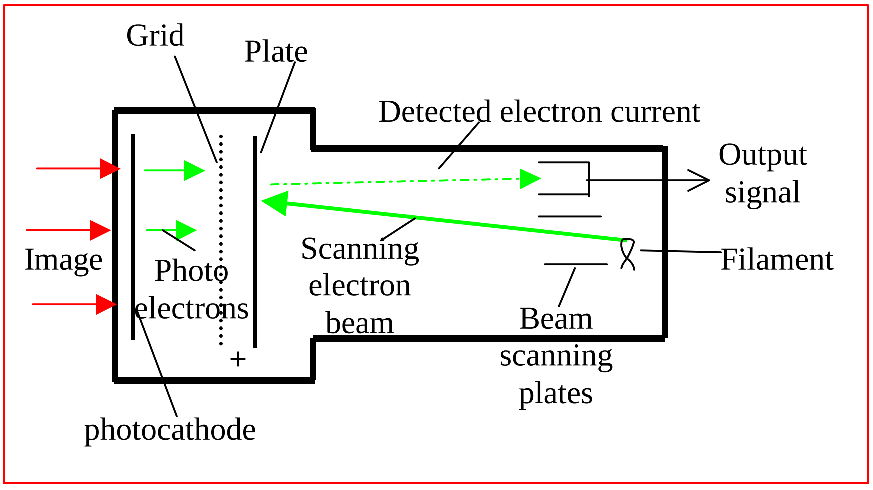
A photomultiplier is a larger glass tube than the photocell mentioned earlier. It consists of a photosensitive surface that emits electrons, the photocathode, followed by a set of metal plates called *dynodes*, each one kept at perhaps 100V positive compared to the previous one nearer the photocathode. The photoelectrons are attracted to the first dynode by the accelerating voltage. Each one strikes it with an energy of about 100 eV. Many electrons will be released, overcoming the work function Φ of the dynode, each electron having an energy of a few eV. These electrons are then accelerated towards the second dynode and the process repeated. At each stage the electron pulse is multiplied by a factor of between 5 and 10, depending on the details of what happens. A typical photomultiplier has around 10 stages, giving a multiplication of at least 10^6. The resulting pulse is then easily amplified by simple and cheap electronics.

Photomultipliers can be produced to give an electronic output pulse for a single optical photon received. It is comparatively easy to make a radiation detector to detect single X-ray or γ-ray photons, each of which produce 1000 or more optical photons in a bunch. One of the hardest practical problems to solve for the radiation detector is to keep stray light out of the photomultiplier, for the slightest light leakage will produce a spurious signal!

Image intensifiers

Photomultiplier technology aims to give a clean electrical pulse for each photon received, wherever it is on the photodetector. Image intensifiers aim to give an electronic version of a picture. This technology in one form or another is behind all television.

The **image orthicon** tube is based on photoelectron technology and the following few sentences try to convey the gist of what is quite a complicated device. The image is focused onto a large photocathode. A positive voltage on a plate within the tube accelerates the released photoelectrons, which collide with the plate and produce even more electrons. These are collected by a fine metal grid, leaving the plate with a positive charge distribution that follows the irradiance of the original optical image. This plate is then scanned by an electron beam at the rate a TV picture is scanned and the scattered electron current is collected to form the signal that

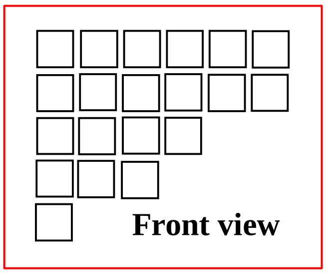


matches the original irradiance pattern. The most important detail as far as the optics course is concerned is that it is the photoelectric effect that produces the electrical signal in the first place.

The CCD detector

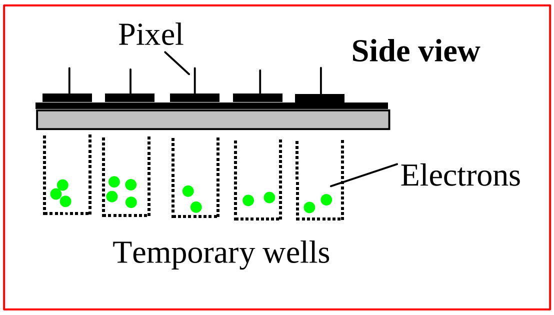
CCD detectors are the sensitive light detectors of the moment. They are used in video cameras, digital cameras and numerous technical contexts. They have virtually replaced the observer's eyeball in professional astronomy. CCD detectors are based upon semiconductor technology and are the product of billions of pounds of development money. They have the benefit of mass production and mass markets. They integrate well with standard electronics and have desirable optical performances. CCD detectors can give a signal that is proportional to irradiance over a much wider range of light than photographic film; they can respond to lower light levels than conventional TV cameras and film and, like film but unlike conventional TV cameras, can add up the light received over long exposures before giving their signal, if necessary. Better than film, this storage is achieved without loss of performance.

CCD stands for *Charge Coupled Device*. A CCD detector is based on photodiode technology, with an ingenious way of storing the electrons generated by the incident photons. The device is fabricated on a silicon chip. A piece of silicon wafer is divided into an array of separate elements, usually a rectangular array but sometimes hexagonal. Each element is a device constructed so that photoelectrons emitted when light strikes the area are trapped in place. The photoelectrons constitute the electronic signal corresponding to the light received. The array elements are connected together by transparent wires and, when required, the stored electrons can be read-out by arranging that they travel to the edge along the wires. Outside the detection area are integrated circuit electronics for on-board signal processing. It is easy to get sucked into the electronics and semiconductor physics of CCDs once you start looking into them so this brief account will be as electronics free as I can make it. In short, there are four stages in the CCD reception of light:



1) expose the detector to light, generating the photoelectrons
2) store the photoelectrons in electrical 'wells' directly beneath their pixel
3) transfer the stored charges to the edge of the device
4) read-out the charge and generate a suitable digital number to represent the light irradiance.

The photoelectric process has been covered in some detail. In a CCD, like other semiconductor devices, the photoelectrons don't leave the device but do their work in the same piece of semiconductor where they are generated.



The surface of the CCD, or sometimes the back, is divided up into thousands of pixels by a transparent conducting layer with electrical connections. CCDs can now be produced with 2048×2048 pixels each about 9 μm wide.

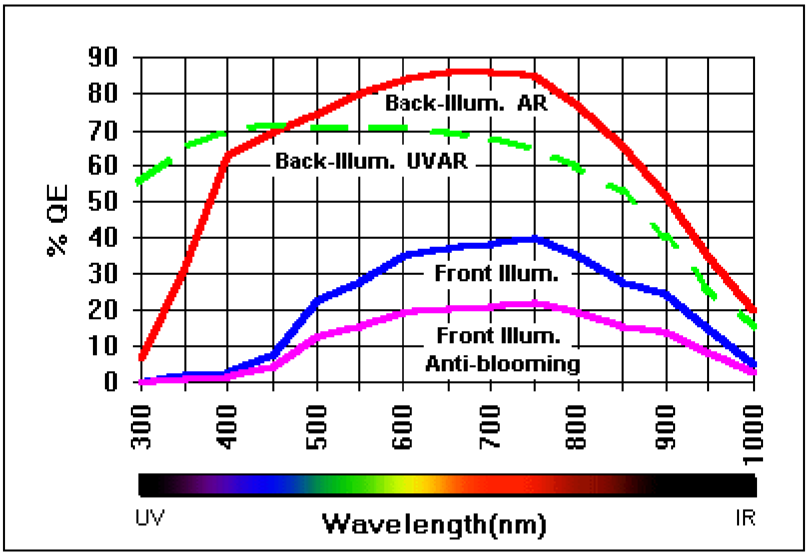
Fewer pixels are needed for a standard TV picture, which uses 625 lines (a few of which contain non-pictorial information).

The physical and electrical structure of the device creates below each pixel a 'potential well' that traps photoelectrons generated at the pixel site. Each well can hold up to ~10^5 electrons. In effect, the wells are tiny capacitors, for what are electrical capacitors but devices for holding electrical charge?

When the exposure has been made, the device can be 'read-out'. Photography has made us used to this concept, except the reading out process in photography is chemical, it happens to the whole area at once and it is comparatively slow. In the CCD, the readout is electronic, it is serial and it is comparatively rapid. During readout, the photoelectric generation has to be stopped. An ingenious cycle of voltages applied to the device moves the trapped charges along a line of pixels until they reach gates at the edge. As each charge reaches the edge, an on-board amplifier changes the microscopic charge of a few electrons into a workable voltage, around a few microvolts per electron. Eventually, a digital number corresponding to the irradiance received at each pixel is produced. This number is transferred to memory and then processed as appropriate for the device.

The attention to detail needed to make CCDs work is very substantial. They are complicated devices. The properties that make them very desirable are:

1) they are intrinsically digital
2) they are highly linear: twice the irradiance produces twice the output voltage
3) they have a large dynamic range (the maximum to minimum light levels that can be detected)
4) they can integrate the light for many seconds, allowing the imaging of sources too weak to be seen by eye
5) they have a low 'noise', or dark signal, made even lower by cooling. A few electrons per pixel is an achievable noise signal.
6) The 'quantum efficiency', the conversion of photon energy into electrons, is very high. The energy required to create a photoelectron (actually and electron hole pair) in silicon is 1.14 eV. The accompanying graph from *apogee-ccd.com* shows variations in quantum efficiency across the spectrum for different fabrication techniques.

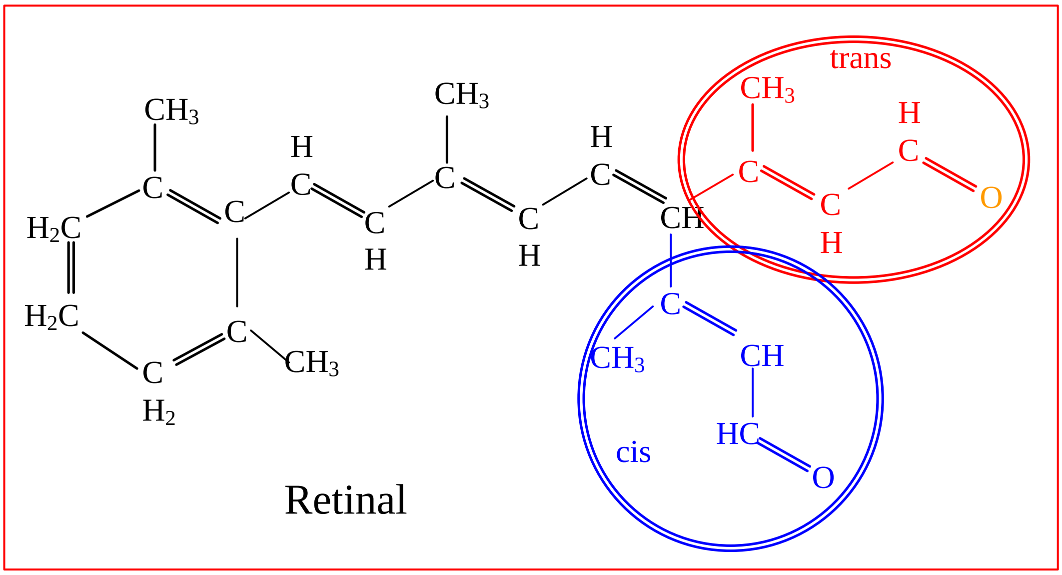


Detecting light by eye

The part within the eye that actually detects light is the retina. It is well known that we have a daytime retina consisting of cone cells and a twilight retina, consisting of rod cells. The two are interleaved, though the rod retina occupies most of the eye and the cone retina is concentrated near the centre. The mechanism by which the absorbed light generates an electrical signal that can activate our brain cells has been investigated for a long time. All man-made devices have been faced with the problem that the charge on a single photoelectron is incredible small, the 1.6×10^{-19} C already mentioned. Our devices have overcome this by various ingenious technologies certainly not present in anyone's eyes. Nature has the same problem. How has it managed to find an answer? There are two problems: first how to produce the photoelectron, secondly how to convert the single electron into a detectable pulse.

The answer to the question of how electrons are produced is a combination of chemistry and the inter-relation of structure with function. In one sense there's not a lot of optics in it but it's crucial to the working of what is arguably our most important sense. Not only that, virtually all the photoreceptors in the plant and animal kingdom work using similar molecules. Rudolph Marcus won the Nobel prize for Chemistry in 1992 for his work on electron transfer mechanisms that just involve a re-orientation of a molecule with no breaking of a chemical bond. Such a transfer is at the basis of our detection of light, and related biological uses of light including the use of chlorophyll to generate energy for plants.

The crucial detector molecule is *rhodopsin*, known colloquially as visual purple. Rhodopsin occurs in rods. Related compounds occur in cones. Rhodopsin is a protein, a single polypeptide chain of molecular weight about 40 kDa containing 348 amino acids. The rhodopsin molecule winds its way back and fore across a rod, which is long enough to contain many of them (see the lecture slides for an illustration). Most proteins are colourless substances that don't absorb light strongly. An efficient eye must absorb the light very well and it is not surprising that when you look into the pupil of someone's eyes it looks jet black. That's a sign that the system is well designed.



Embedded within rhodopsin, forming part of it, is a chromophore, a special molecule that absorbs light. This discovery was part of another Nobel Prize winning work, that of George

Wald in 1967. The particular chromophore in rhodopsin is called retinal. When it absorbs light, it alters only its configuration from what is called the *cis* state to the *trans* state. The gist of this change, which involves the twisting of a particular carbon double bond, is shown in the diagram. Before it receives light, the molecule has the end configuration shown in the blue circle. After reception of light, the configuration changes to that shown in red. The change happens exceedingly quickly, in $\sim 10^{-10}$ seconds. That's really the only bit of optics in the process, though it's only the beginning of the story. Following a complex sequence of molecular biochemical changes, unspecified by me, the single electron produced initiates a cascade process that results in a nerve impulse reaching the appropriate part of the brain. This cascade process happens much more slowly.

The 'quantum efficiency' of the eye is remarkably high, about 1%. This means that it takes only about 100 photons incident on the outer surface of the eye to produce an observable signal, on average. 50% of photons are lost in absorption crossing the eye, so the retina really is able to give a signal for only a small number of photons received. One photon of light is a minuscule energy and corresponds to a minuscule illumination. This efficiency is maintained over a range of irradiance of about 10^7. One interesting twist to the story is that we can't synthesise retinal from its constituents but have to make it from a minor chemical change to vitamin A. Eating raw carrots is indeed good for your night vision!

It is appropriate to have ended this course with two subjects that are very much in the limelight of modern science. Understanding the mechanism of sight is not simply an intellectual exercise but is important in being able to tackle the numerous problems people have with imperfect eyesight, from mild colour defective vision to blindness. It will also help us understand what other animals can see and, in the much longer term, help tackle the problem of giving vision to artificial intelligence. On the technological side, CCD cameras are part of everyday life and likely to develop even further, extending high quality vision outside the range of what is normally considered 'light'. There is plenty of good information on the WWW on all topics covered by our course. Do continue to make use of this resource now the course has finished.

End of photonics

JSR