Seeing 1

Preamble

This is a piece involving 3 lectures on the physics of sight. It will introduce you to all the topics on the first slide. These are of great importance in everyday life, in understanding the world about us and, quite literally in understanding how we perceive our environment. Most of the physics introduced is not just relevant to sight but to the whole area of optics. You know, there is hardly a science where optics of one kind or another doesn't play a part, whether it is in the form of microscopy, optical communication technology, fibre-optic sensors, laser techniques and so on. In short, **Light Science** is one branch of the whole of science well worth knowing something about. I hope you'll find these 3 lectures interesting.

The Electromagnetic spectrum

Do you think of yourself as completely in touch with the world around you? "Yes" Why not! We have at least 8 senses [*sight, hearing, smell, touch, taste, warmth* (temperature), *balance, muscular extension*] and surely that is enough to detect all of our surroundings? It's not. There is a complete spectrum of electromagnetic radiation filling the world in which we live and unaided we can detect only a tiny fraction of it with any sensitivity. That fraction we call light. Mankind has discovered the complete spectrum by a combination of experimentation and intellectual thought. It has been a long story, that I shan't go in to in these lectures. Our subject is the very small bit of the spectrum called light. Where is it? Sandwiched broadly between the longer wavelength radio waves and the shorter wavelength x-rays. More precisely, sandwiched between the comparatively extensive infra-red (IR) and ultra-violet (UV) regions.

Light obviously forms a spectrum of colour but there are simpler physical properties than colour associated with different parts of the electromagnetic spectrum. They are *wavelength* and *frequency*. The wavelengths of light run between 400 nm and 800 nm. You should remember these figures because they define the visible spectrum. I'll repeat them on several occasions.

A Spectrum of waves

Light is a wave phenomenon and simple waves have 3 basic properties:

- *wavelength* λ
- *frequency* f
- *speed of travel* ν. For light in vacuum, c is the universal letter used to represent the speed of light, presumably derived from the Latin *celeritas* meaning 'swiftness' or rapid motion. c is a fundamental constant of nature.

For any wave, these 3 properties are related by:

$$\lambda = \frac{\nu}{f} \qquad .$$

This relationship is also true for sound, waterwaves, tidal waves and so on.

Physics has been very successful in deducing quantitative relationships between different properties observed in nature. These quantitative relationships are found to be true so accurately that we have great confidence that the ideas they summarise are correct.

Example

Let's look at an example of this relationship in action. Our eyes don't just see the presence or absence of light (brightness and darkness). We have this wonderful extra dimension to vision called **colour** in which different frequencies of light appear as different sensations - the coloured spectrum.

What frequency is green light of wavelength 550 nm in vacuum, where $c = 3.0 \times 10^8\ \mathrm{ms^{-1}}$?
Answer:

$$f = \frac{c}{\lambda} = 5.45 \times 10^{14}\ Hz\ .$$

That is very fast, even compared with very fastest computers. [Let me digress. 5×10^{14} Hz is more than 100,000 times faster than the fastest PC you can buy in the shops today. I believe you won't yet find a PC running as fast as 5.45×10^{9} Hz. Put it the other way around, the cycle time of fastest PC is at least 100,000 times slower than period of vibration of light waves. 100,000 is a big factor. How long does it take you to find the product $8\times9 = 72$? Say 1 second. Imagine yourself thinking at the frequency of light. Now if I were to work 100,000 times slower, I still wouldn't have the answer at this time tomorrow. Light vibrations are very fast].

It is also astonishing that we have an organ that can detect energy at such high frequency. In our ears we have tiny hairs that respond to pulsations in the air at a frequency of 1,000 Hz. That's pretty remarkable. Most of us can even hear frequencies 10 times higher at 10,000 Hz. But our eyes can detect waves at 5×10^{14} Hz. Now that is truly astonishing.

Frequency (f) and wavelength (λ) are mathematically quite equal symbols in the relationship above but physically they not only represent different ideas but they have a different status. There are many techniques that let you measure the wavelength of light but there are no techniques that let you measure directly the enormously high frequency of light.

"Electromagnetic - meaning what*?"*

The great discoverer that light is an electromagnetic wave was James Clerk Maxwell, former Professor of Natural Philosophy at Marischal College, Aberdeen. Maxwell established the basic set of mathematical relationships that describe the behaviour of electric fields and magnetic fields. To this day they are known throughout the world as Maxwell's equations. He used these equations to predict the existence of waves whose speed is given by two electromagnetic constants. Maxwell worked out that the value of this speed was the same as that of the known speed of light and he put two and two together. If you ask physicists around the globe "who are the three greatest historical names in your field", many will list Newton, Maxwell and Einstein. Maxwell was that good, for a great many reasons. In coming to Aberdeen, you've come to the right place to learn about light.

Hot body emission

All bodies emit electromagnetic radiation - you, me, the walls, the floor the sky, the grass - everything. Its spectrum depends almost entirely on the temperature of the body. The slide shows the spectrum emitted by a body at 5700°C, about the temperature of the Sun. Even for such a luminous body, less than half the radiation is visible light.

Appearance of hot bodies

As bodies are heated to become self-luminous, the coolest bodies are a dull red; hotter still: orange, yellow, white and blue. Sometimes you'll hear the word 'colour temperature' used to label a source of light whose colour matches that of a hot body of a particular temperature. Thus a north blue sky might be described as having a colour temperature of 12000°C because the colour is similar to a body glowing at that temperature. [Temperatures on the slide are shown in degrees K, which are the same size as degrees Celsius but measured relative to a much lower origin. It's not the place to discuss degrees K here but for the purposes of making sense of the slide, subtract about 300 from the figures shown to get degrees C.]

Cooler bodies

The spectrum of emissions at any temperature is known as the Planck radiation law, after a famous physicist of 100 years ago. We, i.e. people, at a temperature just over 30°C, emit in the so-called far infra-red, the radiation peaking at wavelengths around 10 μm, following Planck's law. Man-made detectors can see at these wavelengths. We can't.

Seeing in the IR

Meteorological satellites, amongst others, take pictures in the visible and in the IR with equal ease. The slide shows the world as seen from a geostationary satellite at midnight at a wavelength of 6.5 μm, where water vapour absorbs and radiates well.

You or I at the same place as the satellite would see very little, a black world against a black star-studded sky. The satellite doesn't see like you or I but scans the scene with a very narrow beam of vision, building up the picture line-by-line like at TV picture is built up. This scanning can be done by having the sensor look out through a mirror and oscillating the mirror to sweep the line of sight. For some of the geostationary satellites, the scanning is done by the whole satellite rotating at about 2 revolutions per second. The idea is shown on the next overhead.

How a picture is built up

The two different methods of creating an image are called **raster scanning** and **area detection**. Our eye has an area detector, called the retina. When you see 'images' produced by many different technologies, particularly if they come from sensors detecting in the non-visible parts of the electromagnetic spectrum, it is worth remembering that they may well not be pictures in the same sense as we are used to seeing with our eyes.

A pin-hole eye

Everyone knows the eye has a lens, but a lens is not essential to the formation of an image at the back of the eyeball. All you need is a hole. You can make your own pin-hole camera over Christmas. With a small hole the image is quite respectable and if you contrive to put photographic film at the back and expose for several minutes, you'll get a picture. Make your pin-hole camera much longer than an eyeball. You'll find some ideas on the web.

An eye with a lens

The purpose of the lens is to improve the illumination on the screen that takes the image. This 'screen' is the film in a camera, the back of the eyeball for ourselves, and so on. To a lesser extent a lens can improve the image quality but if the lens doesn't perform well it could make the image quality worse. The lens works by bringing together all the rays that strike the front of the eye from a single object point, back to a single image point. The lens focuses every cone of incident rays, hopefully onto the back of your eyeball where the light is detected. In a later lecture I'll tell you what happens if the lens fails to do its job properly.

The iris

Eyes first evolved in trilobites of the Cambrian age, around 540 million years ago. These shallow water, rather beetle like creatures were hugely successful and one of the longest lived animal types that has existed on Earth. What a fantastic advantage having eyes would have given in a world where every other animal was blind. Nowadays the 6 phyla of animals that have eyes are the most successful on the planet. In spite of this widespread occurrence of eyes in the animal kingdom and the luxury of such a lengthy time to evolve, it's a curious fact that the human eye is not an excellent imaging system, for all its complexity. If you were to buy a camera with optics as good as a typical person's eye, you'd soon take it back to the shop.

The purpose of the iris is to control the aperture of the eye and allow us (and animals) to use the smallest aperture consistent with a bright enough image. The smaller the aperture, the better the quality of the image. The iris, therefore, is mainly about quality control of the image. Yes, the iris does open wide in dim light but no more than 10 times the extra light is let into our eyes as a result of this. Dim light like that given by a full moon is one millionth that of full sunlight and hence the wide iris doesn't come anywhere near to compensating for the dimness.

Eye parts

Brief resumé - see the slide. You should know these names.

Cornea, lens, retina, optic nerve, humour, iris, pupil, fovea. Humour is an old fashioned word for body fluid. To be in bad humour is, literally, to have unpleasant fluids in your body.

The anatomy of the eye

This picture shows the eye and its surroundings at the proper scale.

Bending of light

Lenses work by bending light. This bending take place when light travels from one medium to another. It is called **refraction**. The law of refraction was discovered in the early 17th century after some 2000 years of enquiry, by a young Dutchman, Willebrord Snell. It's a rather sad story in the history of science, for Snell died before he realised that he had made a Nobel prize winning breakthrough, had there been Nobel prizes in the early 1600s. The law that had eluded centuries of search involves the sines of the angles of incidence and refraction, as defined in the diagram. It also involves a constant of the medium called the **refractive index**. Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad .$$

An example

should show how Snell's law works. Light strikes the cornea at an angle of 20°. The cornea has refractive index 1.376. What is the angle of refraction (θ_2) of the light? You need to know that air has refractive index 1.000.

$$1 \sin 20° = 1.376 \sin\theta_2$$

$$\therefore \sin\theta_2 = 0.249$$

$$\therefore \theta_2 = 14.4° \quad .$$

Hence the light leaves the cornea at 14.4° **to the surface normal**. So what?

Imaging by the eye

The imaging in the eye works according to Snell's law. If you wanted to follow through the imaging of the eye in numerical detail then you'd need to know the refractive indices of the different parts of the eye – the cornea, humours and lens – and their curved shapes. After that, the calculations can be done using Snell's law. Each transparent part of the eye contributes to the imaging.

Snells' law tells you that 75% of the imaging of your eye is done by the front of the cornea. Look after it.

The lens in your eye makes only a modest contribution to the image formation at the back of your eye. The lens is most useful to you when you are young. Then it is flexible and can be pulled by the ciliary muscles within the eye to alter its focusing power, thereby letting you focus on objects near and far. This ability, known as **accommodation,** declines with age, from age 10 or less when the eye can change its power by at least 10 dioptres to age 60, when a change of barely 2 dioptres is typical. Dioptres, as I'll tell you in the next lecture, are the units of power for a lens. Opticians make up spectacle prescriptions in dioptres.

Many even older people suffer from *cataracts,* which is clouding of the eye's lens that turns people more and more blind. Nowadays it is cured by an operation that replaces the defective cloudy lens by a clear plastic substitute. This artificial lens has no power of accommodation, for it is rigid. My mother had this operation, which is done under local anaesthetic. When the operation is being done to you, she said you can see a wire being inserted to pluck out the old lens after your eye is cut open. It doesn't bear thinking about.

Imaging by a convex lens

The eye's imaging system is like a powerful convex lens. Images are formed that are **small** and **inverted** on the retina. The **retina** is the crucial part of us that does the seeing, the part that converts light to brain impulses. The retina is the subject of tomorrow's lecture.

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