Information Pack: Unit 16 Working Waves

1 WHAT IS ELECTROMAGNETIC RADIATION?

1.1 Specification

- Describe the features common to all waves
- Describe the features belonging to some waves, but not others
- Describe the features unique to electromagnetic waves
- Recall and use $v = f\lambda$
- Identify the regions of the electromagnetic spectrum and describe qualitatively their similarities and differences of:
  - (i) Speed
  - (ii) Wavelength
  - (iii) Frequency
  - (iv) Production
  - (v) Detection
  - (vi) Properties, e.g. penetration of matter.

1.2 General Wave Properties

All waves can be characterised by their wave patterns, speed, wavelength, frequency, and phase. For all waves, their velocity, v, frequency, f, and wavelength, λ, are linked by the equation $v = f\lambda$. The velocity of a wave is likely to change as it passes from one material (called a medium) to another. This causes a corresponding change in the wavelength.

Some waves are transverse – they oscillate in a direction at right angles to the wave direction. Others are longitudinal – they oscillate in a direction at along the wave direction. The wave direction is sometimes called the direction of propagation.

Some transverse waves are polarised. They only oscillate in one of the infinite number of possible directions at right angles to the wave direction of propagation.

Most waves have a regular, repeating pattern. Common simple shapes are sine (Fig. 1), square (Fig. 2), and saw tooth shapes (Fig. 3).

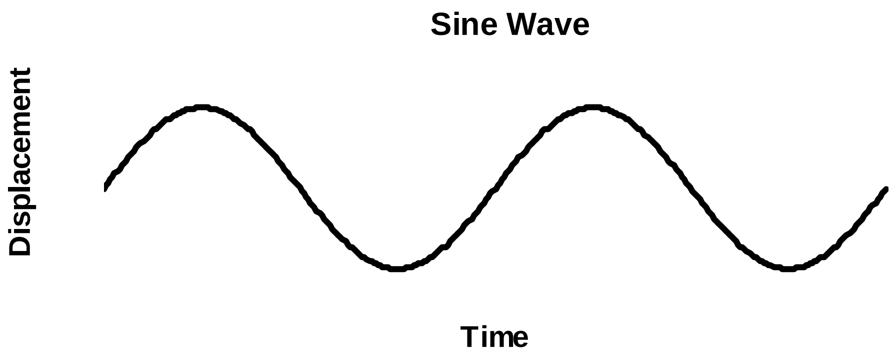

Fig. 1

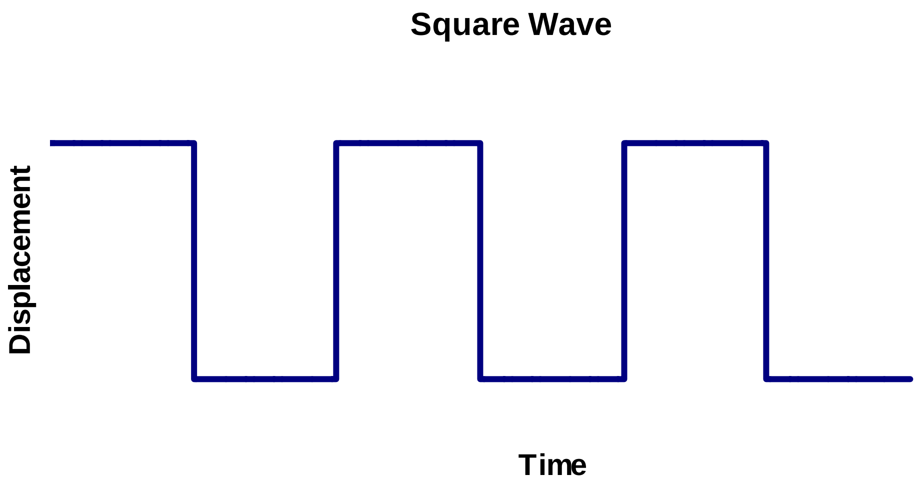

Fig. 2

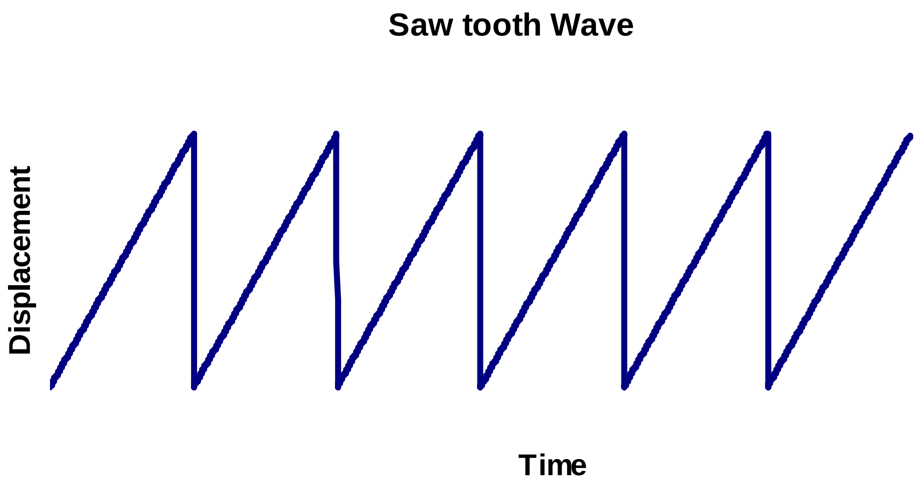

Fig. 3

Much more complex shapes occur in, for example, the sounds from musical instruments which are composed of many superimposed frequencies. Fig. 4 is just a simple example of this.

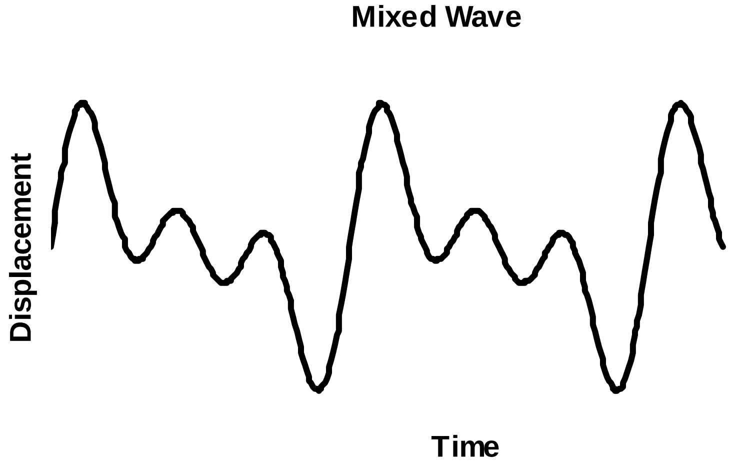

Fig. 4

Some repeating patterns gradually change in size. For example the pure note from a tuning fork as it gradually fades, (attenuates). See Fig. 5. and amplitude modulated (AM) radio signals section 4.3.

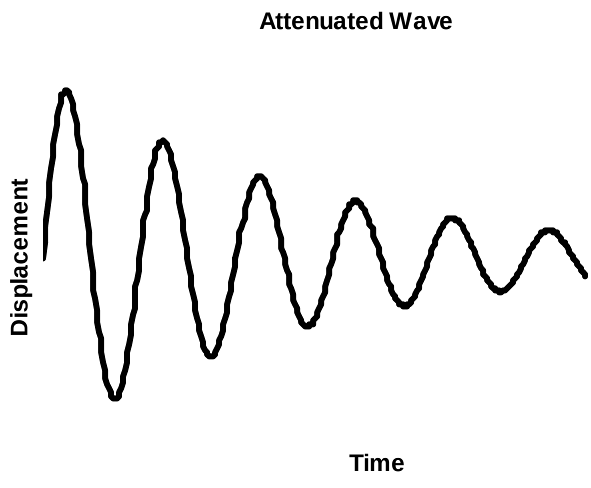

Fig. 5

1.3 Electromagnetic Waves

Electromagnetic waves can be created by moving electric charges. Moving charges cause a magnetic field. Changes in the motion (acceleration), of the charges produce an electric field. The electric and magnetic fields are at right angles to each other. This emits an electromagnetic wave. Both fields are at right angles to the wave direction i.e. electromagnetic waves are always transverse.

If the electric field is always in the same direction, the wave is said to be polarised.

This is how radio waves are produced. Not all frequencies of electromagnetic radiation can be produced in this way because we can not make the charges oscillate at a high enough frequency. Even radio waves have a frequency of up to a million Hz. At the other end of the spectrum γ rays have a frequency of 100 million million million Hz.

Electromagnetic radiation is also produced by hot bodies and by molecules. Electrons in atoms and nuclei fall to lower energy levels, shedding excess energy as electromagnetic radiation.

Most waves need a medium to move in. For example, sound waves travel through air and other materials such as water or walls. One special characteristic of electromagnetic radiation is that it does not require a medium and can travel through a vacuum.

The speed in a vacuum of all types of electromagnetic radiation is always the same, approximately 300,000,000 m s^{-1}.

All electromagnetic radiation is part of the same family varying only in frequency, wavelength and amplitude. Some electromagnetic radiation is monochromatic consisting only of a single pure frequency (a single colour in the case of visible light). Other electromagnetic radiation is a combination of frequencies. Line spectra are a set of discrete frequencies. Continuous spectra are made up of all the frequencies within a particular range. White light is an example of a continuous spectrum – it can be split up into all the colours of the rainbow.

The different types of electromagnetic radiation differ only in wavelength and frequency. However these differences lead to big differences in their properties and in the way they are produced e.g.:

- By artificial means such as oscillating charges
- By artificially excited atoms
- Occurring naturally such as sunlight and radiation from uranium found in the earth.

Fig. 6 shows the regions of the electromagnetic spectrum. The divisions between the regions are not precisely defined.

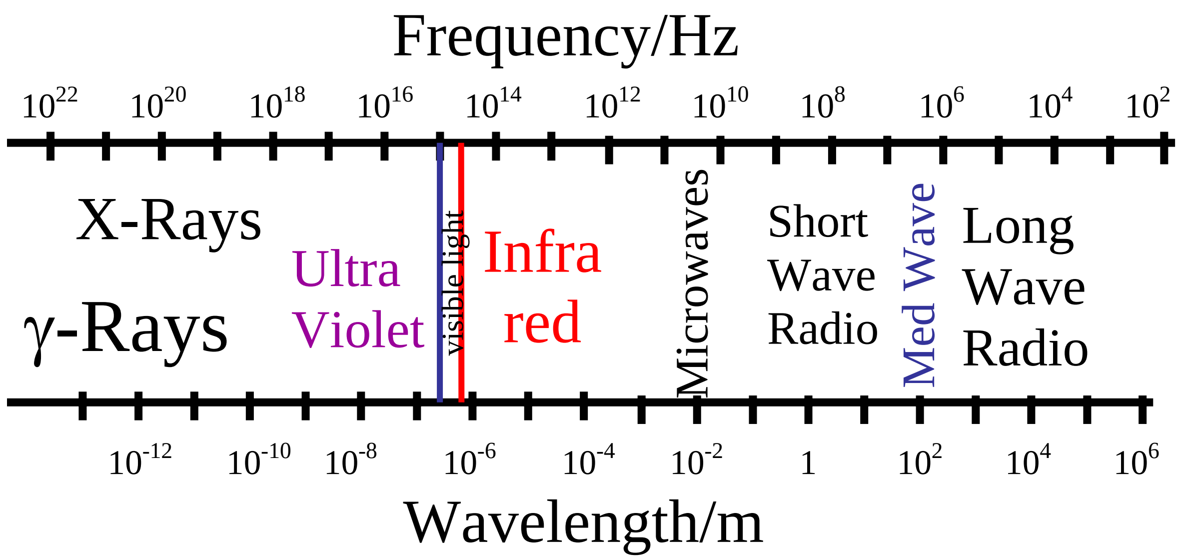

Fig. 6

Notice that visible light is only a small part of the spectrum.

Long radio waves are produced by large transmitting aerials.

Visible light is produced by the charges within atoms.

Gamma radiation has the shortest wavelength. γ-rays are produced by changes within the nucleus.

> **VISIT THE WEB**
>
> Visit **http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html** to see a pictorial version of fig 1. Pictures also help students to visualise the sizes of the wavelengths and these are reinforced by a short set of questions.

> **VISIT THE WEB**
>
> Visit **http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html** for more information about what the different parts of the spectrum are used for and how they are produced. The last section explains why astronomers have to get above the earth's atmosphere to observe some types of electromagnetic radiation coming from space.

2 HOW INFRA-RED IMAGING WORKS

2.1 Specification

- Describe how the spectrum of 'hot-body' radiation varies with temperature
- Describe how the total radiation given off by a surface varies with temperature
- Describe how thermal imaging cameras produce images corresponding to surface temperatures
- Explain applications of thermal imaging including:
  - (i) Detection of disturbed ground
  - (ii) Night sights
  - (iii) Weapon systems
  - (iv) Burglar alarms
  - (v) Remote sensing from satellites
  - (vi) Detecting survivors in collapsed buildings
  - (vii) Medical, (e.g. to reveal quantitative details of circulatory problems, arthritis and rheumatism)
  - (viii) Forensic
  - (ix) Engineering, (e.g. non-destructive testing, electric circuit fault detection).
- Outline the advantages of thermal detecting/imaging systems.

2.2 Hot-body Radiation

Most continuous spectra are from hot objects such as the sun or a furnace. This is also called thermal radiation. Cold bodies also emit thermal radiation but it is not in the visible part of the electromagnetic spectrum. It is infra-red radiation. It has a higher wavelength and lower frequency than visible light. Any solid, liquid and dense (thick) gas at a temperature above absolute zero will produce a thermal spectrum.

Sometimes this is called black body radiation. A perfect 'black body' is an object that absorbs all the light falling on it and reflects none. No object is a perfect 'black body' but matt black objects and most stars are a very good approximation. Perfect black bodies are also the most efficient emitters of thermal radiation.

Fig. 7 shows the range of frequencies and wavelengths given off by bodies at four different temperatures.

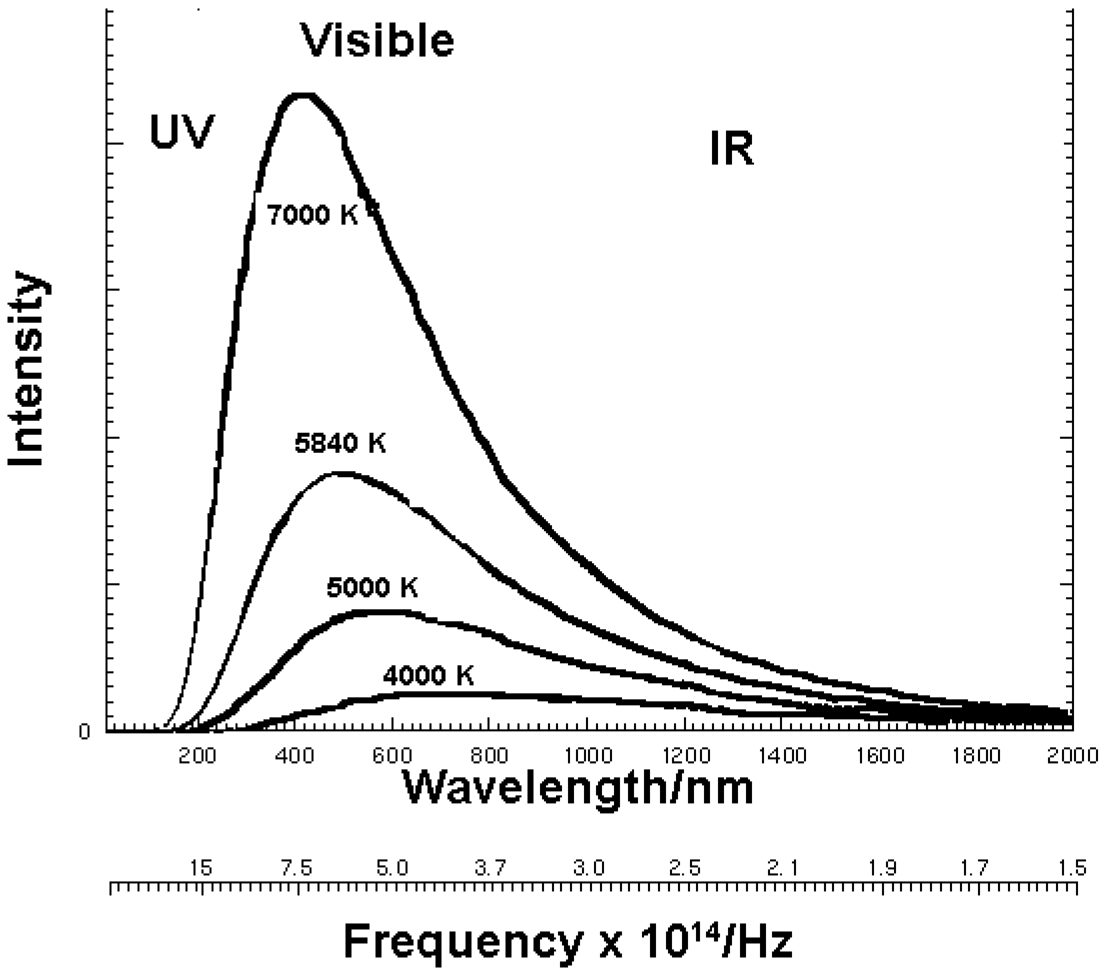

Fig. 7

A small change in temperature of an object causes a very large change in the amount of energy emitted.

2.3 How Thermal Imaging Works

Thermal imaging works by focusing the infra-red radiation given off by an object using a lens. The image is detected by a 'phased array' of several thousand detector elements. These create a thermogram – a picture of the infra-red image in. This takes about 0.03 s. Then the image is converted to electric impulses. These are sent to a processing unit containing a special chip that sends the information to a standard video monitor. The display assigns false colours to each temperature detected. See Fig. 8.

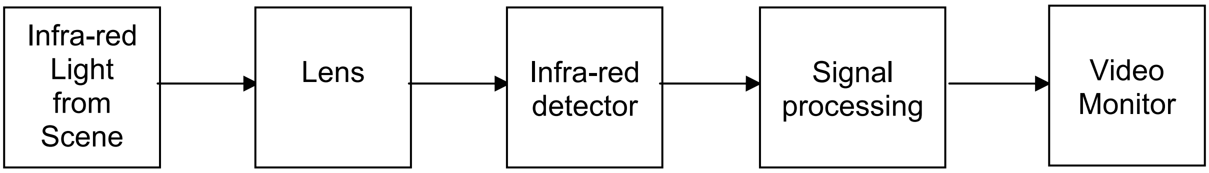

Fig. 8

Typically detectors can sense temperatures from -20 to 2000 ^{o}C and are sensitive to changes in temperature of as small as 0.2 ^{o}C. Cryogenically-cooled devices are especially sensitive and can detect temperature difference of 0.1 ^{o}C from 300m. The cooling cuts out noise from the radiation emitted by the device itself. Cryogenically-cooled devices are more expensive and less robust.

Thermal imaging works well in complete darkness. Do not confuse thermal imaging with another form of night vision called image enhancement that works by collecting tiny amounts of light, and amplifying it.

2.4 Applications of Thermal Imaging

2.4.1 Forensic Science

Thermal imaging can reveal whether ground has been disturbed e.g. to bury something. The police have used this to find things hidden by criminals, such as bodies, money, and drugs. Similarly, thermal imaging can detect recent changes to walls.

2.4.2 Non Destructive Testing

VISIT THE WEB

Visit **http://www.cedip-infrared.com/applications.php?id=2** for images showing examples of applications involving non destructive testing of materials

2.4.3 Medical Imaging

VISIT THE WEB

Visit **http://www.electrophysics.com/infrared-cameras/** for images showing examples of applications involving medical imaging, non destructive testing and research and development

2.4.4 Other Applications

Other applications include:

- Observing wildlife
- Military/Surveillance
- Hunting
- Security
- Navigation
- Entertainment.

3 HOW OPTICAL FIBRES CARRY DATA

3.1 Specification

- Explain how ASCII code can be used to convert text to binary signals and use this to encode a short message.
- Explain total internal reflection and critical angle in terms of refraction at glass-air and glass-glass interfaces – you will be expected to relate critical angle to refractive index and wave velocity.
- Explain how total internal reflection prevents light from leaking through the sides of the fibres.
- Explain applications of coherent an incoherent optical fibre bundles.
- Explain why step-index fibres are coated with glass of lower refractive index.
- Explain how the shape of a square wave signal is degraded in multimode (multipath or step-index) fibres (diameter ~ 60 μm) and how this can be overcome with graded index or monomode (single path) fibres (diameter ~ 1 to 10 μm).
- Explain that solid state lasers are normally used to produce the light used in fibre optics communications and suggest values for the infra-red wavelengths and frequencies used.
- Measure the refractive index of glass.
- Measure the critical angle of a sample of glass and relate this to the refractive index.
- Send a light signal down an optical fibre and detect it with a photodiode.
- Identify the advantages of fibre optic transmission i.e.:
  (i) Very large information capacity
  (ii) Low material costs
  (iii) Small cable size
  (iv) Negligible crosstalk
  (v) High immunity to interference
  (vi) Complete electrical isolation
  (vii) Large repeater spacings.

3.2 ASCII Code

Table 1 gives the ASCII code binary equivalents of the alphanumeric characters and a few of the most commonly used other characters.

Char	Binary	Char	Binary	Char	Binary	Char	Binary
Space	0100000	8	0111000	P	1010000	h	1101000
!	0100001	9	0111001	Q	1010001	i	1101001
"	0100010	:	0111010	R	1010010	j	1101010
#	0100011	;	0111011	S	1010011	k	1101011
$	0100100	<	0111100	T	1010100	l	1101100
%	0100101	=	0111101	U	1010101	m	1101101
&	0100110	>	0111110	V	1010110	n	1101110
'	0100111	?	0111111	W	1010111	o	1101111
(	0101000	@	1000000	X	1011000	p	1110000
)	0101001	A	1000001	Y	1011001	q	1110001
*	0101010	B	1000010	Z	1011010	r	1110010
+	0101011	C	1000011	[	1011011	s	1110011
,	0101100	D	1000100	\	1011100	t	1110100
-	0101101	E	1000101	]	1011101	u	1110101
.	0101110	F	1000110	^	1011110	v	1110110
/	0101111	G	1000111	_	1011111	w	1110111
0	0110000	H	1001000	`	1100000	x	1111000
1	0110001	I	1001001	a	1100001	y	1111001
2	0110010	J	1001010	b	1100010	z	1111010
3	0110011	K	1001011	c	1100011	{	1111011
4	0110100	L	1001100	d	1100100	|	1111100
5	0110101	M	1001101	e	1100101	}	1111101
6	0110110	N	1001110	f	1100110	~	1111110
7	0110111	O	1001111	g	1100111	Delete	1111111

Table 1

VISIT THE WEB

Visit **http://www.neurophys.wisc.edu/www/comp/docs/ascii.html** for a more extensive list. (Also given are decimal, octal and hexadecimal equivalents).

3.3 Total Internal Reflection

If you are a good swimmer, try sitting at the bottom of a swimming pool and look up. You will only see out of the water through a circle above your head, beyond this you will just see a reflection of the bottom of the pool. This is due to an effect called total internal reflection.

Waves travel at different speeds in different materials. For example light travels more slowly in glass than in air. Because of this the direction of the wave changes as it goes from one material (medium) into another. This is called refraction. You can see the effect of refraction if you look at a straw, part of which is immersed in a glass of water. It appears bent.

When a wave enters a medium in which it moves more slowly, it is deviated towards the normal. See Fig. 9.

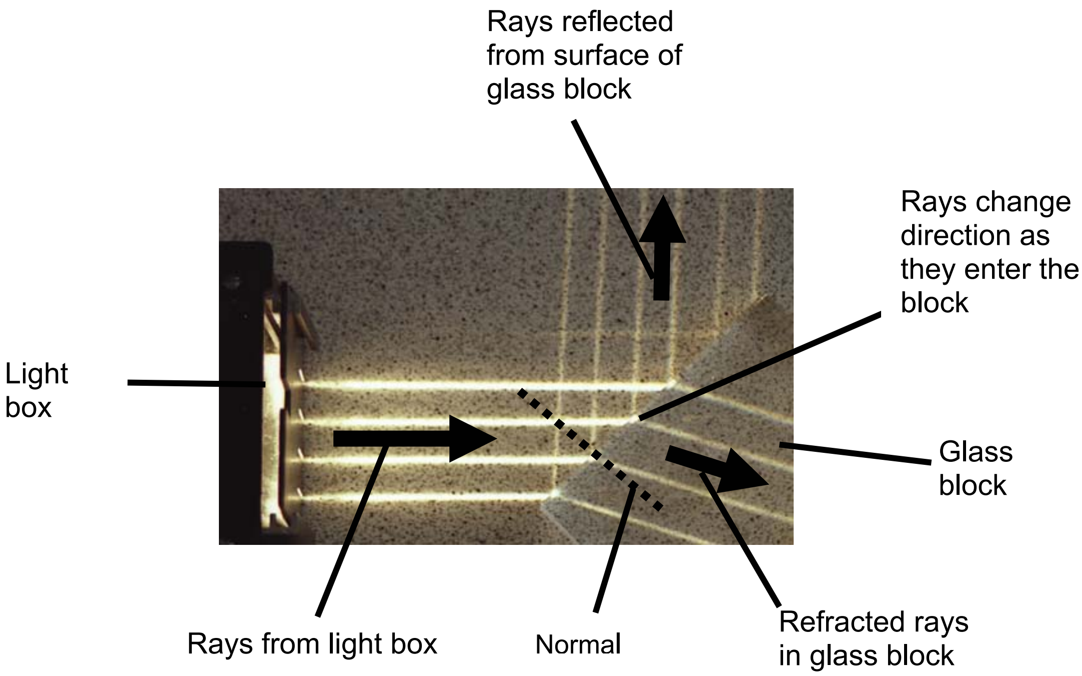

Fig. 9

When a wave enters a medium in which it moves faster, it is deviated away from the normal. See Fig 10.

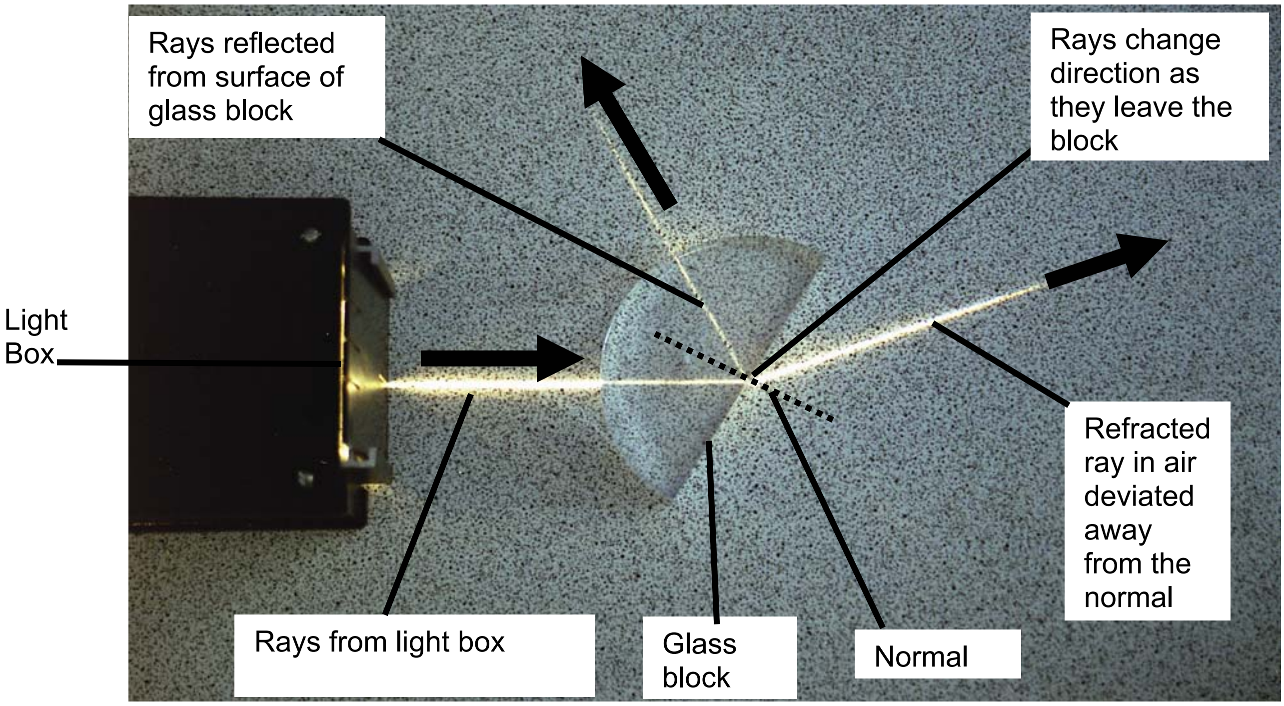

Fig. 10

Fig 10 also shows that some of the light is always reflected back into the block. The angle of reflection is always equal to the angle of incidence. If we carry on increasing the angle of incidence, the angle of refraction will grow to 90o. We call this angle of incidence the critical angle. ‘c’. See fig. 11.

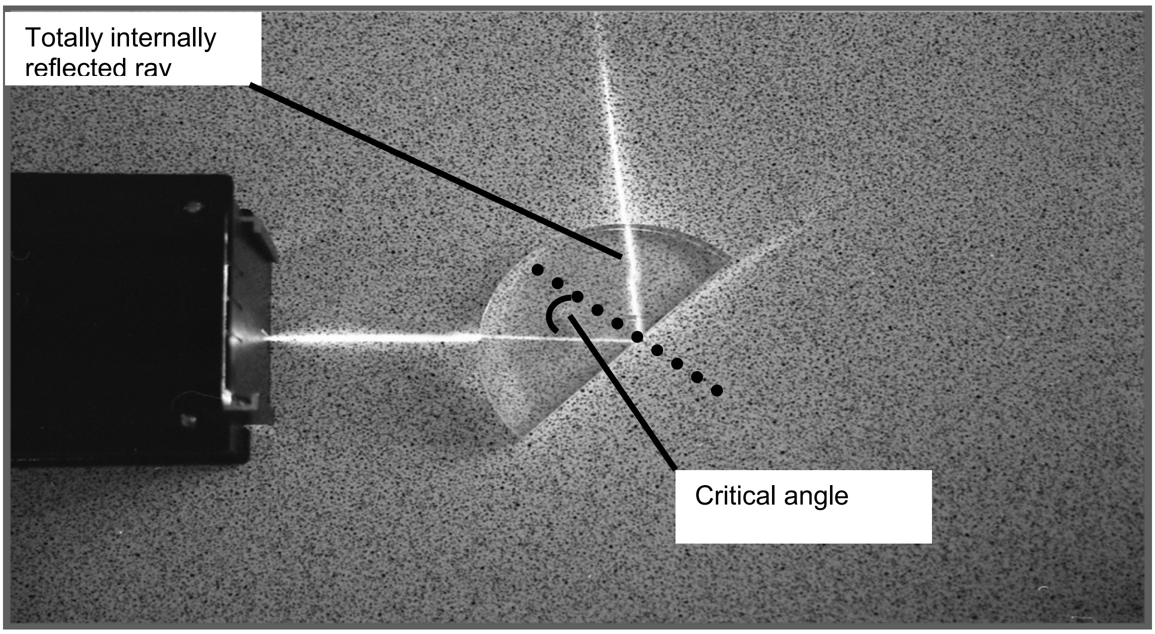

Fig. 11

$$\sin c = \frac{1}{n}$$

where n = refractive index

For glass n is about 1.5.

for glass, $n = \dfrac{\text{velocity of light in air}}{\text{velocity of light in glass}}$

If the angle of incidence inside the block is increased more, no light will emerge. All the energy of the incident ray goes into the reflected ray. This is called **total internal reflection**.

Experimental Note

Fig. 11 shows a simple laboratory experiment to measure critical angle. The block is placed on a sheet of paper. The ray is aimed towards the centre of the circle (i.e. the mid-point of the straight edge of the semicircular block). The block is then rotated about this point to find the position at which the emerging ray just disappears.

The rays and the outline of the block should be drawn on the paper to make it easy to measure the critical angle.

Because the ray enters and leaves the curved surface of the block along the normal (i.e. at right angles to the surface) it is not deviated at the curved surfaces. When the block is removed, the path of the ray inside the block can be drawn by extending the lines entering the curved surface.

3.4 Optical Fibres

Optical fibres are made of very thin strands of glass or, sometimes, plastic, typically of diameter about 120 μm. They can carry signals as light pulses up to 50 km without the need of repeater stations.

VISIT THE WEB

Visit **http://www.tiscali.co.uk/reference/encuclopaedia/hutchinson/m0005088.html** for some useful pictures of optical fibres.

Light travels along optical fibres because of total internal reflection. The ray enters the fibre at an angle grater than the critical angle, so it cannot 'leak' out of the sides.

Several hundreds or even thousands of fibres are packed into bundles. These bundles may be made up as rods or ribbons and sheets. They are flexible so can conduct light and images around corners. The bundle may be **incoherent** i.e. the arrangement of the fibres within the bundle random or **coherent** i.e. the fibres are arranged in the same order at both ends. This is necessary if a picture or data is sent along the fibre.

The light travels along the thin glass (or plastic) centre of the fibre called the core. An outer 'cladding' reflects the light back into the core. This is then coated with a buffer layer to protect the optical surface from moisture and damage. Special connectors couple the light from the source to the fibre and from the fibre to the detector.

For telecommunications applications, an electrical signal is converted to an infrared light signal, and then transmitted along the fibre. The light source is either a light emitting diode (LED) or a semiconductor laser diode. An input modulator modulates the incoming signal with a light beam. An output modulator separates the signal from the light beam at the receiving end.

The simplest type of optical fibre is called '**step index**'. There is a sharp change of refractive index between the core and the cladding. Core sizes range from 50 to 1500 μm. There is no variation of the refractive index within the cladding or within the core. The disadvantage of step-index fibres is that light rays entering the fibre at different angles travel different distances. The signals therefore arrive at slightly different times and this distorts the signal. This is called multimode or multipath distortion. Step-index is the cheapest type of cabling. Multimode fibre is commonly to carry signals between the hubs of local area networks (LANs) from where copper coaxial cable takes the data to the desktop.

In '**graded index**' fibre the refractive index changes gradually from the core to the cladding. Core sizes range from 50 to 100 μm. The rays of light follow sinusoidal paths and all reach the end of the fibre at the same time, eliminating multimode distortion. Unfortunately this takes place at only one wavelength.

Monomode fibre, also known as **single-mode**, is used for the longer distances and high capacity requirements. The inner core is much smaller, with a diameter of 5-10 μm. It is so narrow that the light is concentrated in a single path. It can retain the shape of each light pulse over a longer distance without dispersion. Attenuation is less than with multimode fibre. Cladding needs to be thicker and the 'acceptance angle' for the light source is less.

3.5 Uses of Optical Fibres

3.5.1 Telecommunications

A pulsed **laser** is used to send **digital** signals down a fibre optic link. Cable TV networks use optical fibre because of its very low power consumption.

Advantages compared to standard copper cabling:

- Safer, no risk of electrocution
- Larger bandwidth capacity. This means that more information can be sent down a single connection
- Less attenuation over long distances
- More secure (but it is still possible to tap into a fibre link)
- Less chance of cross-talk between channels, because the light beams in the fibre do not interact
- Weigh less.

Disadvantages compared to standard copper cabling:

- Cables are expensive to install
- Connections to fibre optics cables are complex and require special tools
- More fragile than copper cable.

VISIT THE WEB

http://ilearn.senecac.on.ca/techwrite/**fibre_optics**.ppt is a useful PowerPoint presentation on fibre optics

3.5.2 Medical Uses

Endoscopy

Endoscopes are used to examine parts of the body otherwise inaccessible without surgery. They contain two bundles of fibre. One delivers light to the part of the body under examination illuminate it. The other brings an image back to the surgeon's eye.

The first bundle is usually incoherent. The arrangement of the fibres within the bundle is not important. The bundle carrying the image must be coherent. The fibres must be arranged the same way at both ends – otherwise the elements of the picture would be jumbled up!

Photographs may be taken using an endoscope. Special endoscopes that include surgical devices are used for Biopsies (taking tissue samples).

To deliver light signals

Special drugs are light-activated. A light signal from a fibre optic can be used to activate drugs at a particular place in the body. Similarly a laser beam can be sent down a fibre to destroying the targeted tissues by heating.

Other uses

- Decorative purposes
- 'Leaky' fibres can be used to make light 'ropes' for use, for example, for low-level lighting in aircraft.

4 MODERN COMMUNICATION SYSTEMS: HOW CELL-PHONES AND BROADBAND WORK

4.1 Specification

- Explain the difference between AM and FM radio transmissions
- Explain how broadband transmission increases the speed of data connection to the internet
- Distinguish between analogue and digital systems
- Use and understand binary coding
- Explain Pulse Code Modulation (PCM), analogue to digital conversion and digital to analogue conversion
- Explain how the splitting of a geographic area into many small cells (0.5 to 20 miles in radius) increases the number of users a network can carry and the range over which an individual user can communicate
- Discuss the factors affecting the distribution of base stations
- State the factors affecting mobile phone signal strength (intensity) – e.g. obstructions, distance from base station (inverse square law)
- Explain the terms up-link and down-link bands as applied to mobile phones
- Compare the full duplex system used for mobile phones with half-duplex devices such as CB radios
- Compare cellular access technologies

  (i) Frequency Division Multiple Access (FDMA)

  (ii) Time Division Multiple Access (TDMA)

  (iii) Code Division Multiple Access (CDMA).

  and identify TDMA as the global system for Mobile Communications (GSM)

- Compare the advantages of dual-band and dual-mode technologies.

4.2 Analogue and Digital

Analogue signals vary continuously according to the size of the signal.

Digital signals have certain discrete levels only. In practice, for virtually all computing, telecommunications and recording applications this means just two levels. i.e. most digital systems are binary. The signal is sampled at regular intervals. In cell phones this is typically 8000 samples per second. The amplitude of each is expressed as a binary number - a set of 1s and 0s. The information can then be transmitted, stored or processed as a digital signal. Pulse Code Modulation **(PCM)** is system for binary encoding analogue signals.

4.3 AM and FM

Radio frequencies are much higher than audio frequencies. In analogue radio signals the radio (carrier) wave is varied (modulated) by the audio signal. This can be done in two ways.

In Amplitude (A.M.) signals, the amplitude (strength) of the carrier signal varies. See Fig. 12.

Amplitude Modulated Wave

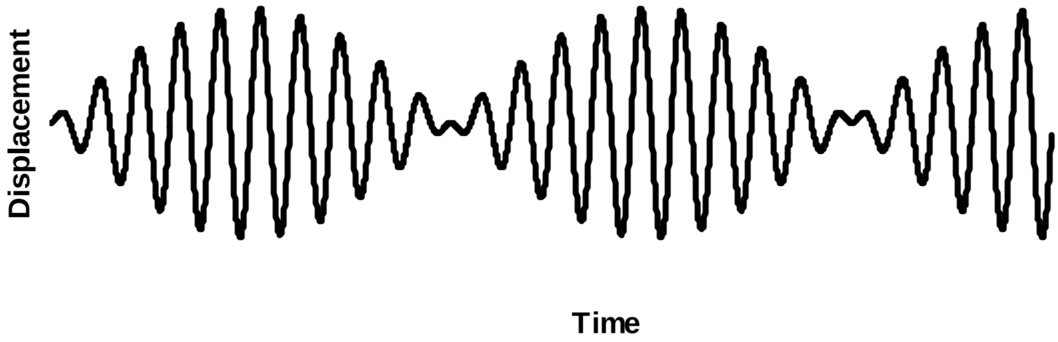

Fig. 12

In Frequency Modulated (F.M.) signals, the frequency of the carrier signal varies. See Fig. 13.

Frequency Modulated Wave

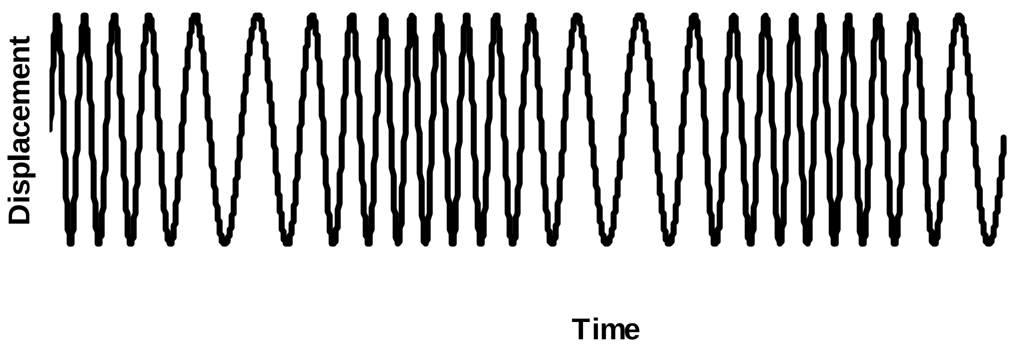

Fig. 13

Amplitude Modulated radio uses carrier frequencies of several hundred to around 1500 kHz. Frequency Modulated radio uses carrier frequencies around 100 MHz.

4.4 Cell Phones

Cell Phones are sophisticated radios. Before cell phones the nearest thing available to the public was a CB radio. CB radios are a **simplex** devices - only one person can talk at a time because both people communicating use the same frequency. Cell phones are **duplex** devices - both people can talk at once because they use separate frequencies.

Cell phones have many more channels available than CB radios. The frequencies available to mobile phones are shared between many users. The key to why this is possible is in the term 'cell'. The country is divided into geographical areas, called cells. Each cell contains a base station which receives from and transmits to phones in its area. The base station emits relatively weak signal so that the same subset of channels can be used in a cell elsewhere. Typical, every seventh cell uses the same set of channels.

Each cell phone is identified by the cellular system when it makes or receives a call. Cell phones switch from cell to cell as they move around. One cell base station registers that a phone's signal strength is getting smaller and the next cell notes that the signal is increasing. The switching happens automatically.

4.4.1 Cellular Access Technologies

Older systems were analogue and modern systems are digital.

Frequency Division Multiple Access (**FDMA**) is an analogue transmission technique. It allocates part of the frequency spectrum to each pair of communicators. The receiver discriminates between the signals by tuning to the appropriate frequency. FDMA was used in the **1G** (**first-generation**) analogue networks.

Time Division Multiple Access (**TDMA**) is a digital transmission technique and can carry far more channels. It allocates the entire available frequency spectrum to each pair of communicators, but only for a part of the time, their signals are interleaved with others. Because binary code can be sent faster than the audio signals they represent, a whole second worth of speech can be sent in a fraction of a second - the rest of the time is then available to other users.

In Code Division Multiple Access (**CDMA**) uses codes to identify connections. Every communicator will be allocated the entire spectrum all of the time.

The advantage of CDMA compared to TDMA and FDMA is that the number of CDMA codes is very large. CDMA is well suited to large numbers of phones each making calls occasionally and at irregular intervals. It avoids the overhead of continually allocating and de-allocating a limited number of time slots or frequency channels.

The Global System for Mobile Communications (**GSM**) is one of the world's **second generation** (2G) **mobile phone** systems. It is the international standard in Europe, Australia and parts of Africa and Asia. GSM networks use a combination of **FDMA** and **TDMA**. GSM was developed for voice communication, but there is also a limited data-handling capacity called **Short Message Service** (**SMS**), permitting the user to send and receive **text messages**.

GSM operates in the three main **frequency bands** of 900 **MHz**, 1800 MHz, and 1900 MHz.

In the USA, it operates in the 1900 MHz **frequency band**.

Dual band phones can switch automatically between two TDMA frequencies bands e.g.

- 800/850 and 1900 MHz (United States)
- 900 and 1800 MHz (Europe).

Dual mode phones can switch automatically between analogue and TDMA.

Tri-mode can mean that a phone supports:

- Two digital technologies, e.g. CDMA and TDMA, as well as analogue
- One digital technology in two bands and as well as analogue.

A popular version of the tri-mode type of phone for people who do a lot of international travelling has GSM service in the 900-MHz band for Europe and Asia and the 1900-MHz band for the United States, in addition to the analogue service.

5 THE WORK OF RADIOLOGISTS X- AND γ-RAY IMAGING AND THERAPY

5.1 Specification

- State qualitatively the differential absorption of X-rays by air, fat, other soft tissues and bone and the appearance of X-rays on film after passing through these media.
- Explain techniques for improving quality of X-ray images; use of a grid, narrow beam, filtration.
- Explain how X- and γ–radiations damage cells through ionisation.
- Evaluate the consequent health hazards and identify the radiological protection measures taken in an X- and γ–ray imaging and radiotherapy treatment areas, to monitor and minimise the dose received by staff and the damage done to healthy tissue of patients; half-thickness value of lead screening used.
- Describe how the use of image intensifying screens reduces dose rates.
- Describe how CAT scanners can produce much more detailed information than conventional X-rays.
- Describe the principle of the γ–camera used to image radioactive tracers administered to the body.
- Identify the advantages of technetium-99m as a radioactive tracer.
- Describe how X- and γ–radiations are used therapeutically.

5.2 Health Hazards

X- and γ–rays are hazardous because of their ionising properties. This is a significant difference in properties from other parts of the electromagnetic spectrum. Ionisation in living cells can lead to death or mutation of the cell and cause acute and long term effects and somatic and genetic effects.

Acute effects caused by very large doses:

- Blood changes
- Vomiting, fatigue, loss of appetite
- Loss of hair
- Damage to gastro-intestinal tract
- Damage to central nervous system (CNS); death in hours
- Spasmodic seizures.

Long term effects include:

- Leukaemia
- Cancer
- Cataract formation
- Life-shortening

Cancer causes cells to divide more rapidly than a normal cell. The defect is transmitted to daughter cells, so the population of abnormal cells builds up to the detriment of the normal cells in the organ.

The above effects are **somatic**. They arise from damage to the ordinary cells of the body and affect only the irradiated person.

The **genetic** (or hereditary) effects are due to damage to the cells in the reproductive organs, the gonads. The damage may be passed on to the person's children and to later generations.

A substance that has been irradiated may be damaged but is not normally radioactive.

The activity of a source is the number of disintegrations per second. The SI unit is called the **becquerel** (Bq) 1 Bq = 1 disintegration s^{-1}.

The dose of radiation received by a person is measured as the energy absorbed per kilogram of their body. The SI unit is the gray (Gy) = 1 J/kg

Quality factor (Q.F.) is a measure of the relative harm caused by different types of radiation. The quality factor for X- and γ–rays is close to 1.

The dose equivalent in **sievert** (Sv) is the absorbed dose of radiation in gray (Gy) x quality factor.

Dose to staff can be reduced by:

- Reducing the size of source used
- Increasing distance from the source (inverse square rule)
- Reducing time of exposure
- Inserting materials such as lead or concrete between the source and the person.

Dose to X-ray patients can be reduced if more sensitive X-ray emulsions or image intensifying screens are used.

For radiotherapy patients, careful planning can reduce dose to parts of the body not undergoing treatment.

A balance must be struck between risk and benefit to patients when exposed to radiation as part of medical diagnosis or treatment.

The Half-Life of a radioactive substance is the time taken for the number of active nuclei to be halved.

The physical half-life relates to the decrease in active nuclei due to their radioactive disintegration. The number of active nuclei in a patient's body also decreases if the substance is excreted. The biological half-life is the time taken for the number of active nuclei to be halved due to excretion. For tracers such as technetium-99m both must be taken into account. The Physical half-life T_P of ^{99}Tc = 6 hours. Not all the ^{99}Tc remains in the body of the patient. If the biological half-life T_B is also 6 hours, the effective half-life T_E can be calculated using:

$$\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_R}$$

$$\frac{1}{T_E} = \frac{1}{6} + \frac{1}{6}$$

$$= \frac{2}{6}$$

$$= \frac{1}{3}$$

$$T_E = 3\,\text{hours}$$

5.3 X-ray Images

X-rays are a type of electromagnetic radiation towards the high frequency end of the spectrum. They penetrate matter. Materials with a high atomic number (number of protons in the nucleus) absorb X-rays more than materials with a low atomic number. Bone contains Calcium (atomic number 20) so it absorbs X-rays readily. Fat, made up largely of Carbon (6), Hydrogen (1) and Oxygen (8) does not absorb X-rays as much.

An 'X-ray' is a 'shadow image'. The patient is placed between the X-ray machine and the film. Parts of the body which absorb radiation cast an X-ray shadow which shows up white on the film. This means that bone produces a white image on the film. Air (e.g. lung, bowel gas) produces the darkest (black) image. Other soft tissues produce an effect between these two extremes. Fat appears grey.

Several types of tissue have very similar atomic numbers so they absorb the X-rays by similar amounts. So, there is little contrast between them. 'Contrast media' are used to distinguish between them. These are of very high atomic number e.g:

(i) Iodine is injected into blood vessels to study blood flow. Contrast given intravenously is excreted by the kidneys so can be used to look at kidney function showing blockages e.g. due to kidney stones.

(ii) A thick suspension of Barium Sulphate is swallowed to show up the intestines and stomach. This 'Barium meal' passes into the gastrointestinal tract. The barium absorbs the X-rays more than the surrounding tissue and therefore the tract shows up clearly.

X-ray images can be seen either directly on a fluorescent screen or recorded on photographic film. Increasingly, digital pictures are used. They can be accessed by any computer on a hospital network or sent to specialists at other centres.

The fluorescent screens absorb X-rays which have passed through the patient and re-emit the X-ray energy as visible light. This enables dynamic processes such as blood flow to be observed, but a high dose of X-rays is needed to produce an image bright enough to view directly.

Photographic film is not very sensitive to X-rays. Large doses of radiation would be harmful to patients, so intensifying screens are used to avoid long exposure times.

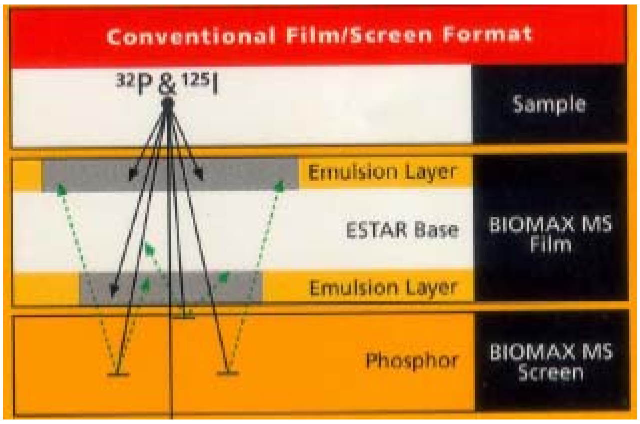

Diagram reproduced courtesy of www.kodak.com

(see also: **astro.ocis.temple.edu/~rchristm/Rad%20Image%201/RadImage1.html**)

The intensifying screen is made up of a sheet of double-sided film, sandwiched between two sheets of white plastic, coated with fluorescent crystals. A metal plate at the back of the cassette stops radiation from being scattered back from the beneath. Some of the light from the fluorescent crystals goes straight to the film. The rest is reflected back to it by the white plastic. Film is more sensitive to light than to X-rays, so exposure time can be reduced to 1/250th.

5.3.1 Image Quality

Sharpness

X rays are produced by firing fast-moving electrons at a metal target. If X-rays were produced at a single point on the target, the shadow would be sharp. In practice they are produced in the small area of the target called the focal spot, so the shadows do not have sharp edges. This effect is minimised by focusing the electron beam to make the focal spot small and by arranging the target at an angle to the electron beam so that the X-rays appear to come from a smaller area. See Fig. 14.

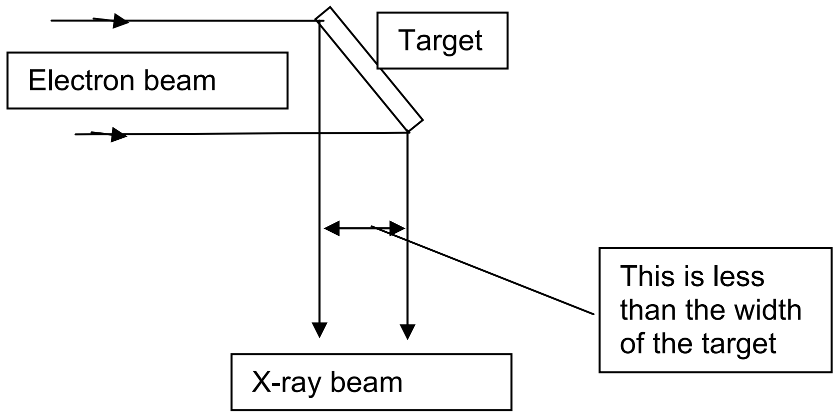

Fig. 14

The sharpness of the image can be increased by putting the film closer to the object (decreasing the film to object distance) and by increasing the target to film distance. The latter decreases the X-rays intensity reaching the film so exposure time has to be increased.

Scattering

Some of the X-rays will be scattered as they pass through the patient. This means they are deflected to the wrong part of the film. This can be prevented by placing a grid between the patient and the film. See Fig. 15. The grid is made of strips of lead.

(X-ray scatter grid, original removed due to copyright issues)

(see: **www.e-radiography.net** - *click on 'Rad - tech' in sidebar, then 'Grid'*)

Fig. 15

Movement blur

Involuntary movements of the organs being examined will blur the image. If this is likely to happen exposure times have to be kept short.

Filtration

Filters are used to select the X-ray frequencies that will produce the best results. Unwanted low-frequency radiation is removed. Contrast and sharpness are improved.

5.3.2 Application of X-rays in Medical Imagining

Bones

One of the most well-known applications of X-rays is to look for a suspected bone injury. Bone has excellent natural contrast so produces clear images. See Fig. 16. Two images at right angles to each other are normally produced to diagnose of fractures, dislocations, etc. Other abnormalities, such as from tumours and cysts in the spine and arthritis can also be detected.

(X-ray of a skull fracture, original removed due to copyright issues)

(see: any internet search engine 'image' library)

Fig. 16

The chest

Chest X-rays are used to diagnose pneumonia, and a variety of lung diseases. See Fig. 17. (Lung malignancies will be confirmed with high resolution CT).

(Chest radiograph (X-ray) showing a cancer in the lung, original removed due to copyright issues)

(see: **www.quitsmokingsupport.com/lungphotos.htm**)

Fig. 17

Mammograms (Breast X-rays)

Special film is used to get the high resolution needed to distinguish between similar soft tissues. See Fig. 18.

(Mammograms, original removed due to copyright issues)

(see: **medocs.ucdavis.edu/MDS/400c/IMAGES/Exhibit1.htm**)

Fig. 18

Dental X-rays

Dentists routinely use small X-ray units, to examine the hidden parts of teeth. X-rays can reveal dental abscess or decay.

Foreign bodies

X-rays are used to identify and locate objects that have been accidentally swallowed, so that they can be removed. They are sometimes used to check for magnetic or metallic implants before MRI examinations – not routinely.

5.3.3 Advantages and Disadvantages of Diagnostic X-rays

Advantages:

- Cheap and easy
- Can often be interpreted by non-radiologist e.g. accident and emergency physician, and then quickly acted on, e.g. bone fractures
- Quick and readily available
- Good bone resolution
- Mobile lung and breast screening units are possible.

Disadvantages:

- Ionising radiation is harmful (increasing cancer risk). Dose is cumulative.
- High-voltage supplies are a hazard
- Poor soft-tissue resolution (unless CAT is used)
- Contrast media can be unpleasant and hazardous.

5.4 CAT Scanners

5.4.1 Principles of CAT Scanners

The Computerised axial Tomographic Scanner or CAT or CT scanner uses X-rays to produce images of one slice of the body at a time. Conventional X-ray pictures show information from all depths in the body superimposed on each other.

X-rays cannot be focused onto one chosen plane in the body, so a sharp image is obtained by changing the direction of the X-rays and using multiple positions of the detector.

In a simple version an X-ray tube and the film cassette move in opposite directions so that only the chosen plane stays in the same place on the film. See Fig. 19.

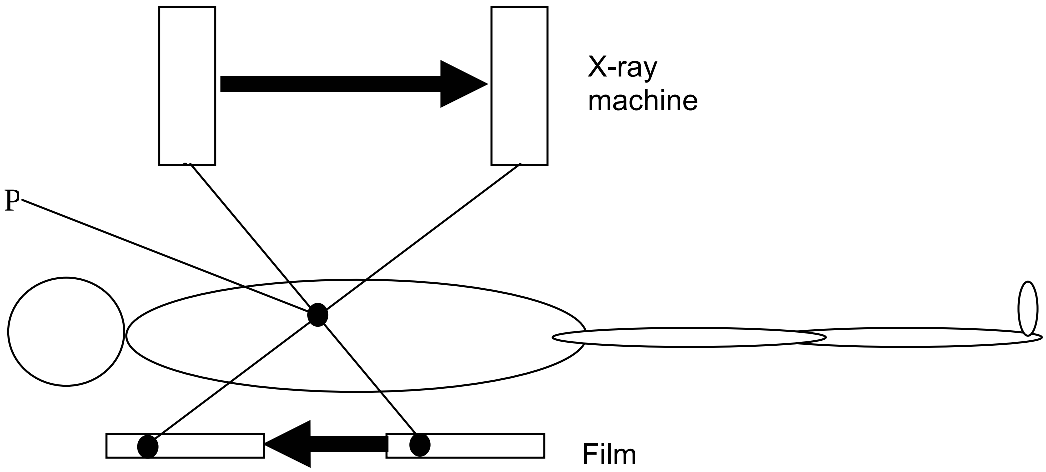

Fig. 19

As the X-ray machine moves to the right the film moves to the left. Objects in the chosen plane, such as P always produce a shadow on the same point on the film producing a sharp image. The shadow of objects not in that plane will move on the film and be blurred.

In modern scanners the X-ray tube produces a fan-shaped beam and is rotated round the subject. There is a ring of thousands of fixed detectors instead of the moving film. See Fig. 20.

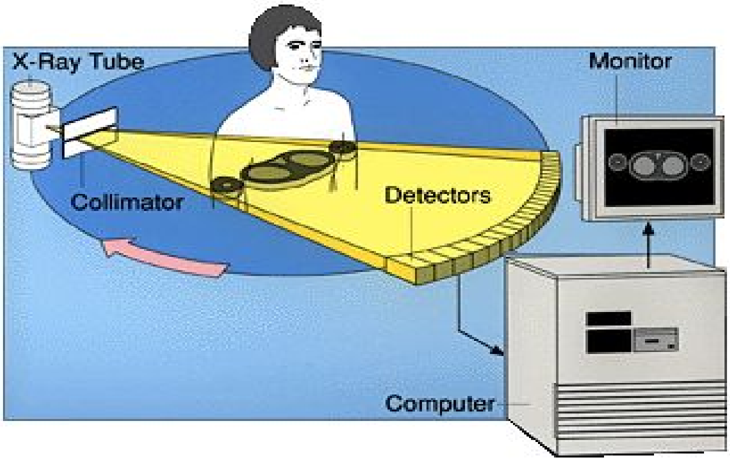

Fig. 20

Diagram courtesy of Siemens Medical Solutions

With thanks to www.Imaginis.com, the Breast Cancer Resource

In practice the X-ray tube rotates several times and the patient is moved through the machine making a spiral effect to get information about a whole volume. The patient has to remain very still and hold their breath, to make sure that the image is sharp.

The information from these scans is processed by a computer to obtain the final image. The computer program corrects for the differences in the depth of material that the X-ray beam passes through.

5.4.2 Uses of CAT Scanners

CT scanners can detect very small differences in X-ray attenuation. This makes them very good for examining soft tissue.

They are used:

- To produce detailed images of the brain see Fig. 21.
- To produce detailed images of chest abdominal or pelvic organs e.g. lungs, liver, kidneys, bladder. Contrast CT is used to examine the gut.

(CT head showing right sided infarction (stroke). CT and MRI images are viewed as if the patient's feet point towards the viewer, so the left side of the image represents the patient's right, original removed due to copyright issues)

(see: **http://www.uwo.ca/pathol/cases/Neuro/neuro.html**)

Fig. 21

5.4.3 Advantages and Disadvantages of CAT Scans

Advantages:

- Provide more detailed information than conventional X-rays particularly for soft tissues
- Often more quickly available than MRI in UK.

Disadvantages:

- Significantly higher radiation doses
- Much more expensive than conventional X-rays
- Requires a co-operative or sedated patient.

Many thanks to Dr Katherine Bull for her valuable suggestions which have added greatly to the accuracy of the notes in section 5, and in particular, for finding and selecting most of the original images.