Revision Guide for Chapter 1

Contents

Revision Checklist

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Assumed previous knowledge:

know the meaning of frequency, wavelength and amplitude of a wave and be able to use the relationship $v = f\lambda$ Revision Notes: amplitude, frequency, wavelength and wave speed	
know about the electromagnetic spectrum and some uses of radio waves, microwaves, infrared and visible light in communications Revision Notes: electromagnetic spectrum	

I can show my understanding of effects, ideas and relationships by describing and explaining:

how a thin converging (positive) lens produces a real image by changing the curvature of a wavefront Revision Notes: lens, focal length, power and magnification of a lens Summary Diagrams: Rays and waves spreading, Rays and waves focused, Formation of an image, Action of a lens on a wavefront, Where object and image are to be found	
how images are stored in a computer as an array of numbers which may be manipulated to alter the image Revision Notes: images, pixel, resolution, image processing, average	
how computerised (digitised) images may be improved by smoothing and reducing 'noise', changing brightness and contrast, detecting edges and using false colour Revision Notes: image processing, average	

I can show my understanding of the physics involved by using the following words and phrases accurately:

in the context of computerised images: *pixel, bit, byte, amount of information, resolution* Revision Notes: images, pixel, bits and bytes, amount and rate of transmission of information, resolution, prefixes Summary Diagrams: Bits and bytes, Comparing logarithms base 2 and base 10	
for lenses: *focus, focal length, power (dioptre), magnification, refractive index* Revision Notes: lens, focal length, power and magnification of a lens	

I can show my understanding of the physics involved by sketching and interpreting:

how light passes through a lens using either ray diagrams *or* wavefronts Summary Diagrams: Rays and waves spreading, Rays and waves focused, Formation of an image, Action of a lens on a wavefront	
plots (graphs) using a logarithmic ('times') scale of distances and sizes Revision Notes: logarithms, logarithmic scales Summary Diagrams: 'Plus' and 'times' scales of information, Logarithmic ladder of distance, Logarithmic ladder of time	

I can calculate:

the amount of information (in bits) in an image by using the relationship *amount of information = number of pixels × bits per pixel* Revision Notes: bits and bytes, amount and rate of transmission of information Summary Diagrams: Bits and bytes, Comparing logarithms base 2 and base 10	
the power or focal length of a lens using the relationship *power = 1/(focal length)* Revision Notes: focal length, power and magnification of a lens Summary Diagrams: Where object and image are to be found	
the third quantity given any two using the equation $\frac{1}{v} = \frac{1}{u} + \frac{1}{f}$ Summary Diagrams: Rays and waves spreading, Rays and waves focused, Formation of an image, Action of a lens on a wavefront, Where object and image are to be found	
the magnification of an image, e.g. as the ratio of image and object size, using the relationship $m = v / u$ Revision Notes: focal length, power and magnification of a lens	

I can show my ability to make better measurements by:

identifying and estimating the largest source of uncertainty in optical measurements; plotting a graph including uncertainty bars, e.g. of object and image distances Revision Notes: uncertainty	

I can show an appreciation of the growth and use of scientific knowledge by:

giving examples of and commenting on the uses of digital imaging	

Revision Notes

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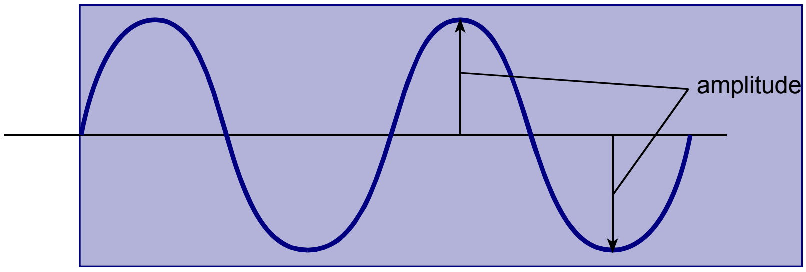
Amplitude, frequency, wavelength and wave speed

Waves are characterised by several related parameters: amplitude (how big they are); frequency (how rapidly they oscillate); wavelength (the distance over which they repeat) and their speed of travel.

The amplitude of a wave at a point is the maximum displacement from some equilibrium value at that point.

Amplitude of a transverse wave



The period *T* of an oscillation is the time taken for one complete oscillation.

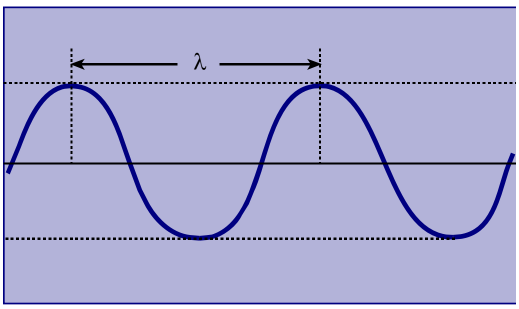
The frequency *f* of an oscillation is the number of complete cycles of oscillation each second.

The SI unit of frequency is the hertz (Hz), equal to one complete cycle per second.

The wavelength λ of a wave is the distance along the direction of propagation between adjacent points where the motion at a given moment is identical, for example from one wave crest to the next.

The SI unit of wavelength is the metre.

Wavelength



Relationships
Frequency f and period T

$$f = \frac{1}{T}$$

$$T = \frac{1}{f}$$

Frequency f, wavelength λ and wave speed v

$$v = f\lambda$$

Displacement s at any one point in a wave, where ϕ is the phase.

$$s = A\sin(2\pi ft + \phi)$$

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Electromagnetic spectrum

The electromagnetic spectrum covers the full wavelength range of electromagnetic waves from gamma radiation and x-radiation at the short-wavelength end of the spectrum to radio and TV waves at the long-wavelength end.

Summary of the main bands of the electromagnetic spectrum

Waveband	Wavelength range	Typical source	Detector	Application
Gamma radiation	< 1 nm	Radioactive decay of a nucleus	Geiger counter, film, ionisation chamber	Medical imaging, therapy, sterilisation of medical instruments
X-rays	< 1 nm	Inner shell atomic electron transitions	As above	X-ray imaging in medicine and dentistry
Ultraviolet	1–400 nm	Atomic electron transitions	Photocell, film	Sun bed, security marker
Visible	400–700 nm	Outer-shell atomic electron transitions	Eye, film, CCD, photocell	Camera, seeing
Infrared	700 nm–1 mm	Vibrations of atoms and molecules	Thermopile, solid state detectors	Thermography in medicine, fibre-optic communications
Microwave	1 mm–0.1 m	Electrons in resonant cavities (e.g. magnetron)	Microwave diode	Cooking, line-of-sight communications, satellite communications
Radio and TV	> 0.1 m	Electrons accelerated and decelerated in an aerial	Aerial	Communications

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Lens

Lenses are used in optical instruments such as the camera, eye, microscope and telescope to form images. The effect of a lens is to change the curvature of the wave fronts passing through it.

A **converging lens** adds to the curvature of wave fronts of light falling on it, making light from a point object converge (or diverge less).

Images from a converging lens

Object position	Image position	Type of Image	Magnification	Which way up?	Application
Beyond 2F	Between F and 2F	Real	Diminished	Inverted	Camera, eye
At 2F	At 2F	Real	Same size	Inverted	Inverter lens
Between F and 2F	Beyond 2F	Real	Magnified	Inverted	Projector lens
Between the lens and F	Beyond 2F	Virtual	Magnified	Upright	Magnifying glass

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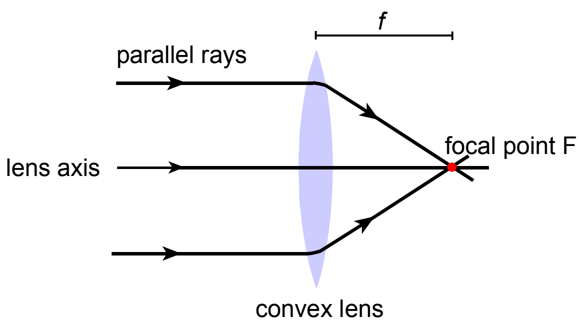
Focal length, power and magnification of a lens

The focal point *F* of a converging lens is the point where light from a very distant point object on the axis of the lens is brought to a focus by the lens. This point is also called the **focus**. The focal length *f* of a thin lens is the distance from the centre of the lens to *F*.

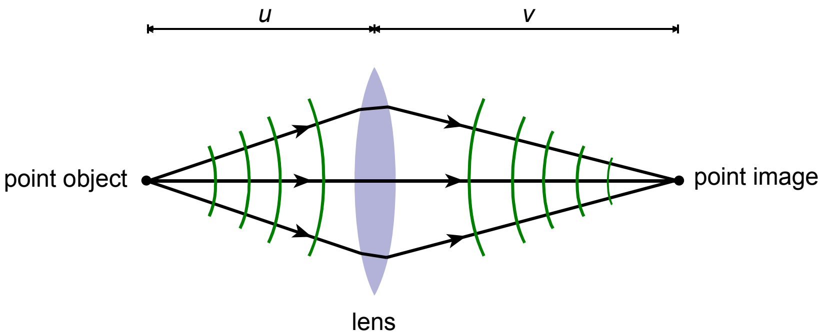
Definition of focal length of a convex lens



Converging lenses are assigned positive values of *f*. Diverging lenses are assigned negative values.

The **power of a lens** in dioptres = 1 / *f* where *f* is the focal length in metres. The shorter the focal length, the more powerful the lens.

Lens sign convention



Cartesian convention $\frac{1}{v}=\frac{1}{u}+\frac{1}{f}$ where distances from lens are assigned $\left.\right\}$ – values to left
+ values to right

In the Cartesian convention, distances measured to the left from the lens are assigned negative values and distances measured rightwards are assigned positive values, as in the rules for the *x*-axis of a graph. The object is usually assigned to be on the left of the lens.

The lens equation
The curvature of a spherical wave front of radius r is $1 / r$. A converging lens adds curvature $1/f$ to the wave fronts passing through it. Thus for a point object at distance u from a lens, the radius of curvature of the wave fronts at the lens is changed from $1 / u$ to $1 / u + 1 / f$. Therefore the image of a point object is formed at distance v from the lens, where $1 / v = 1 / u + 1 / f$.

Linear magnification
The linear magnification is the ratio of the height or length of the image to the height or length of the object viewed directly.

linear magnification $m = \dfrac{\text{height of image}}{\text{height of object}}$

Because the heights of image and object are proportional to their distances v and u from the lens:

linear magnification m $\dfrac{v}{u}$

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Images
Images are very efficient ways of representing and communicating information. Human beings are very good at seeing patterns in visual displays.

Images include, besides photographs and drawings or paintings, patterned displays of data, mathematical forms, and graphs and charts.

Images can represent objects more or less as they are seen, as in a photograph or realistic painting or drawing. But images can also be used to represent unseen objects, for example organs inside the body, or astronomical objects 'seen' at wavelengths outside the visible region. An example is an image of the cosmic microwave background, detected at microwave wavelengths.

Images can be altered and manipulated, particularly if in digital form. See Image Processing.

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Pixel

A digital image consists of a rectangular array of picture elements, called pixels. Similarly, a television picture consists of an array of dots of different brightness and colour. A million or more pixels make up a typical image. You can see individual pixels by looking at a computer screen with a magnifying glass.

Each pixel is stored as a number. A typical grey-scale image may have 256 alternative levels of brightness for each pixel, using one 8-bit byte per pixel to store its value ($2^8 = 256$). More bits can be used for a scale with higher brightness resolution. Three bytes are often used for colour images, one byte for each of three primary colours.

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Resolution

The resolution of an image is the scale of the smallest detail that can be distinguished. The size of the pixels sets a limit to the resolution of a digital image. In an ultrasound system, the pixel dimensions may correspond to about one millimetre in the object imaged. A high-quality CCD may have an array about 10 mm × 10 mm consisting of more than 2000 × 2000 light-sensitive elements, each about 5 μm in width. In a big close-up picture of a face 200 mm across, the width of each pixel would correspond to 1 / 10 mm in the face photographed.

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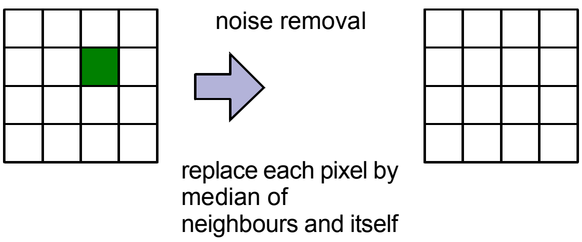
Image processing

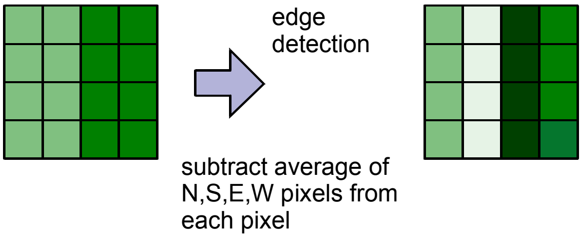
Noise reduction: noise in an image can be reduced by replacing the byte representing a pixel with the median of the values of that pixel and its neighbours.

Noise reduction



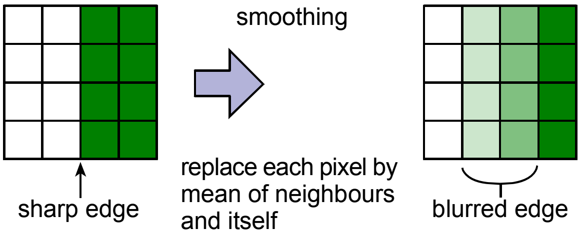
Edge detection: edges in an image can be located and enhanced. An edge is a place where the gradient of light intensity across the image changes sharply. Where the gradient is smooth the average of values either side of a pixel will be equal to the value of that pixel. Thus a difference between the value of a pixel and the average of its neighbours indicates a possible edge.

Edge detection



Smoothing: Smoothing of sharp edges can be achieved by replacing a pixel with the mean of its value and its neighbours.

Smoothing



False colour: the usefulness of some images can be enhanced using false colour. One way this can be done is to assign different colours to different ranges of brightness.

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Average

Here are two different kinds of average:

1. The arithmetic mean
2. The median.

For a set of N readings or values, x_1, x_2, x_3, x_4, …,x_N: The **mean** value:

$$x_m = \frac{x_1 + x_2 + x_3 + x_4 + \ldots + x_N}{N}.$$

is the sum of the values divided by their number. The mean is often called 'the average'. In smoothing images, it is often useful to replace pixels by the average of themselves and their neighbours.

The **median** value is the middle value of the set when the values are arranged in order of magnitude. Median values are important in the processing of digital images, for example removing noise by replacing the value of a pixel with the median of it and its neighbours.

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Bits and bytes

Bits and bytes are amounts of information, expressed in digital form.

A **bit** is the smallest unit of digital information, represented as a 0 or a 1.

A finite sequence of bits is referred to as a word. An n-bit word can represent 2^n alternatives.

A **byte** is an eight bit word, able to represent one of 256 (= 2^8) alternatives. The ASCII system uses 8-bit words (bytes) to represent up to 256 keyboard symbols including the numerals 0 to 9 and the letters of the alphabet.

Data transferred between computers can be corrupted in the transmission process. Extra information is transmitted so that errors can be detected and corrected.

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Amount and rate of transmission of information

Information is stored in a computer memory in bits, that is as zeroes or ones.

A sequence of n bits has 2^n different possibilities. An 8-bit byte can thus represent $2^8 = 256$ different binary numbers. In the same way, a message containing information I, can be one of 2^I alternative possibilities.

For a certain number of alternatives $N = 2^I$, then the amount of information $I = \log_2 N$.

A digital colour camera with 1 million pixels, each pixel generating three bytes, one for each primary colour, would need a storage capacity of about 3 megabytes. Digital cameras use image compression methods to reduce this to less than 1 Mbyte per image.

A CD-ROM can store about 650 MB. This is only a few seconds worth of viewing of a TV movie. DVD discs store each bit in a smaller space, and have larger capacity, but data compression is needed for them to store a whole movie.

Relationships

Information $I = \log_2 N$ where N is the number of alternatives.

Number of alternatives $N = 2^I$

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Prefixes

The letter 'k' in 'km' (kilometre) is the symbol for the prefix kilo, meaning one thousand. The prefix 'm' in 'ms' (millisecond) is the symbol for the prefix milli, meaning one-thousandth.

Power of ten	Prefix	Symbol
10^{-18}	atto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{+3}	kilo	k
10^{+6}	mega	M
10^{+9}	giga	G
10^{+12}	tera	T
10^{+15}	peta	P
10^{+18}	exa	E

Examples of the use of prefix symbols include mA for milliampere, kV for kilovolt and MΩ for megohm. Other prefixes not included in the above table include deci (d) = 10^{-1} and centi (c) = 10^{-2}.

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Logarithms

Logarithms can be thought of as a way of turning multiplying into adding (and dividing into subtracting).

The number 100 can be written as 10^2. Similarly, the number 1000 000 = 10^6. The powers of ten here, 2 and 6, are called the logarithms (base 10) of 100 and 1000 000 respectively.

Notice that when numbers are multiplied, the logarithms simply add:

$$\text{As numbers}: 100 \times 1000\,000 = 100\,000\,000$$

$$\text{As powers}: 10^2 \times 10^6 = 10^{2+6} = 10^8$$

$$\text{As logarithms}: 2 + 6 = 8$$

When a number is written as a power of a base number, the power is called the logarithm of the number to that base. If $n = b^p$, then $p = \log_b n$. The base does not have to be an integer (whole) number.

Three bases are used widely for logarithms in physics and engineering:

Base 10 logarithms, written lg or $\log_{10}$ (or sometimes just 'log'); the base 10 logarithm of a number n is therefore $p = \log_{10} n$ where $n = 10^p$. Thus $\log_{10} 100 = 2$, and $\log_{10} 10^6 = 6$.

Natural logarithms, also referred to as base e logarithms, written ln or $\log_e$. The natural logarithm of a number n is therefore $p = \ln n$ where $n = e^p$. e = 2.718…

Base 2 logarithms, written $\log_2$. The base 2 logarithm of a number n is $p = \log_2 n$, where $n = 2^p$.

Product rule
The logarithm of a product (or a quotient) is equal to the sum (or the difference) of the individual logarithms.

If $z = x\,y$, then $\log z = \log x + \log y$.

Quotient rule
If $z = x / y$, then $\log z = \log x - \log y$.

Inverse rule
The inverse of the logarithm of a number is equal to that number.

For $p = \log_{10} n$, then $10^p = n$. Also $\log_{10} 10^p = p$.
For $p = \ln n$, then $e^p = n$. Also, $\ln e^p = p$.

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Logarithmic scales

Logarithms are related to 'times' scales, where a quantity is multiplied by a constant at each step.

For example, the Richter scale for earthquakes is a logarithmic scale on which every extra point on the scale corresponds to 10 times larger amplitude of vibration. Thus an earthquake at point 8 on the Richter scale is 100 times more powerful than an earthquake at point 6.

It is often convenient to use a logarithmic scale when the range of values of a quantity is very large. Examples where logarithmic scales are used include:

1. Brightness of stars
2. Loudness of sounds
3. Strengths of materials
4. Information stored in a computer (see Summary Diagram 'Plus' and 'times' scales of information.

See Summary Diagrams Logarithmic ladder of distance and Logarithmic ladder of time for further examples.

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Uncertainty

The uncertainty of an experimental result is the range of values within which the true value may reasonably be believed to lie. To estimate the uncertainty, the following steps are needed.

1. Removing from the data **outlying** values which are reasonably suspected of being in serious error, for example because of human error in recording them correctly, or because of an unusual external influence, such as a sudden change of supply voltage. Such values should not be included in any later averaging of results or attempts to fit a line or curve to relationships between measurements.
2. Estimating the possible magnitude of any **systematic error**. An example of a constant systematic error is the increase in the effective length of a pendulum because the string's support is able to move a little as the pendulum swings. The sign of the error is known (in effect increasing the length) and it may be possible to set an upper limit on its magnitude by observation. Analysis of such systematic errors points the way to improving the experiment.
3. Assessing the **resolution** of each instrument involved, that is, the smallest change it can detect. Measurements from it cannot be known to less than the range of values it does not distinguish.
4. Assessing the magnitude of other small, possibly random, unknown effects on each measured quantity, which may include human factors such as varying speed of reaction. Evidence of this may come from the spread of values of the measurement conducted under what are as far as possible identical conditions. The purpose of repeating measurements is to decide how far it appears to be possible to hold conditions identical.
5. Determining the combined effect of possible **uncertainty** in the result due to the limited resolution of instruments (3 above) and uncontrollable variation (4 above).

To improve a measurement, it is essential to identify the largest source of uncertainty. This tells you where to invest effort to reduce the uncertainty of the result.

Having eliminated accidental errors, and allowed for systematic errors, the range of values within which the true result may be believed to lie can be estimated from (a) consideration of the resolution of the instruments involved and (b) evidence from repeated measurements of the variability of measured values.

Most experiments involve measurements of more than one physical quantity, which are combined to obtain the final result. For example, the length *L* and time of swing *T* of a simple pendulum may be used to determine the local acceleration of free fall, *g* , using

$$T=2\pi\sqrt{\frac{L}{g}}$$

so that

$$g=\frac{4\pi^2 L}{T^2}.$$

The range in which the value of each quantity may lie needs to be estimated. To do so, first consider the resolution of the instrument involved – say ruler and stopwatch. The uncertainty of a single measurement cannot be better than the resolution of the instrument. But it may be worse. Repeated measurements under supposedly the same conditions may show small and perhaps random variations.

If you have repeated measurements, ‘plot and look’, to see how the values vary. A simple estimate of the variation is the $\text{spread} = \pm\frac{1}{2}\text{range}$.

A simple way to see the effect of uncertainties in each measured quantity on the final result is to recalculate the final result, but adding or subtracting from the values of variables the maximum possible variation of each about its central value. This is pessimistic because it is unlikely that ‘worst case’ values all occur together. However, pessimism may well be the best policy: physicists have historically tended to underestimate uncertainties rather than overestimate them. The range within which the value of a quantity may reasonably be believed to lie may be reduced somewhat by making many equivalent measurements, and averaging them. If there are N independent but equivalent measurements, with range R, then the range of their average is likely to be approximately R divided by the factor $\sqrt{N}$. These benefits are not automatic, because in collecting many measurements conditions may vary.

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Summary Diagrams

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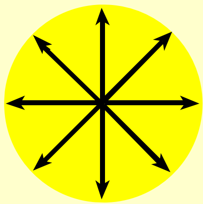
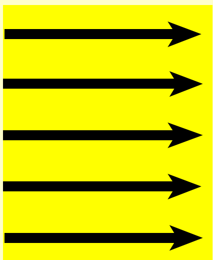
Rays and waves spreading

This compares and contrasts the complementary descriptions of light as waves and rays.

Ray point of view

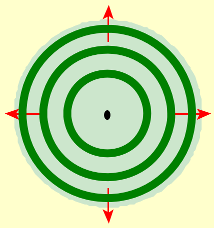


Light travels out in straight lines from a small source

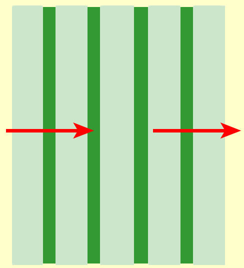


Light in a parallel beam or from a very distant source has rays (approximately) parallel to one another

Wave point of view



Light spreads out in spherical wavefronts from a small source



Wavefronts in a parallel beam or from a very distant source are straight (not curved) and parallel

Ray and wave points of view show the same thing but in different ways

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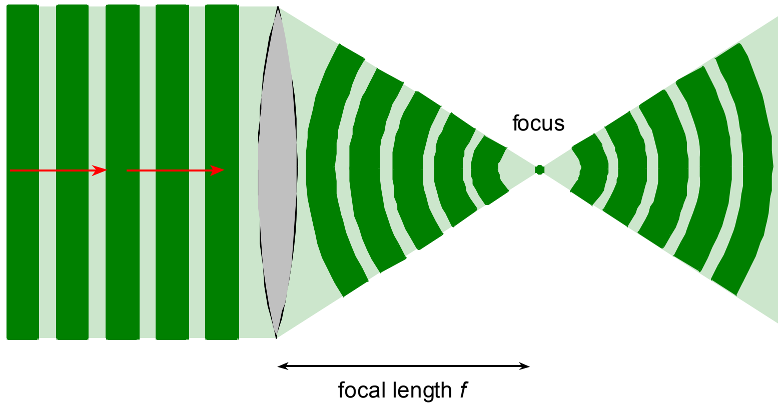
Rays and waves focused

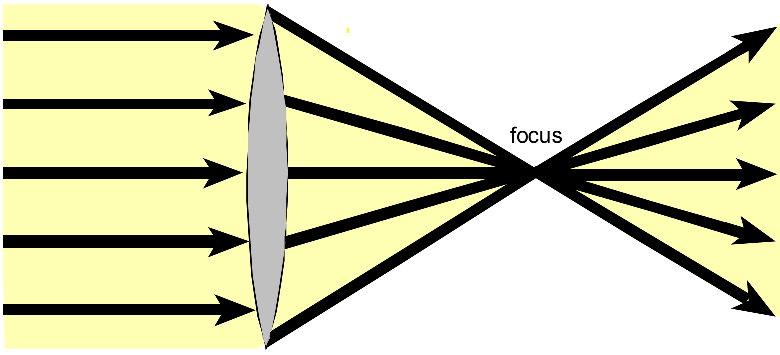
This compares and contrasts the complementary descriptions of light as waves and rays.

Wave and ray points of view:

Wave point of view:
The lens adds curvature to the wave, centring it on the focus



Ray point of view:
The lens bends the rays, bringing them to a focus



A lens changes the curvature of a wavefront: this is equivalent to bending the rays

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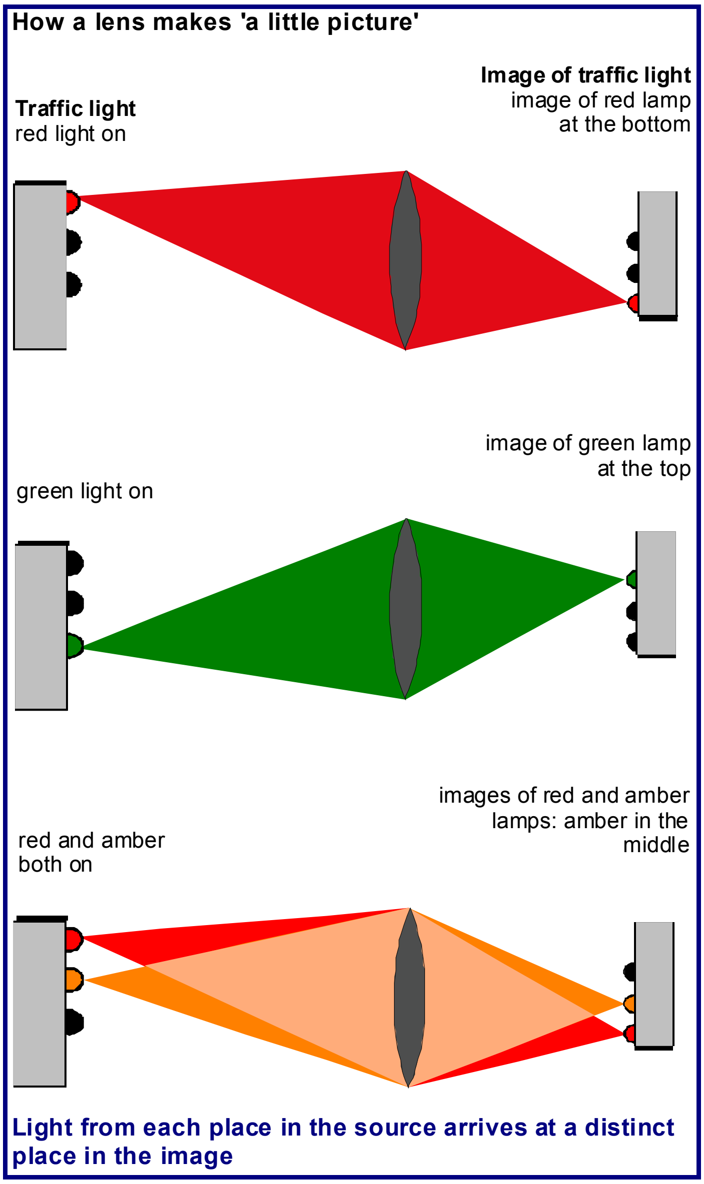
Formation of an image

This set of diagrams illustrates why the image is inverted.



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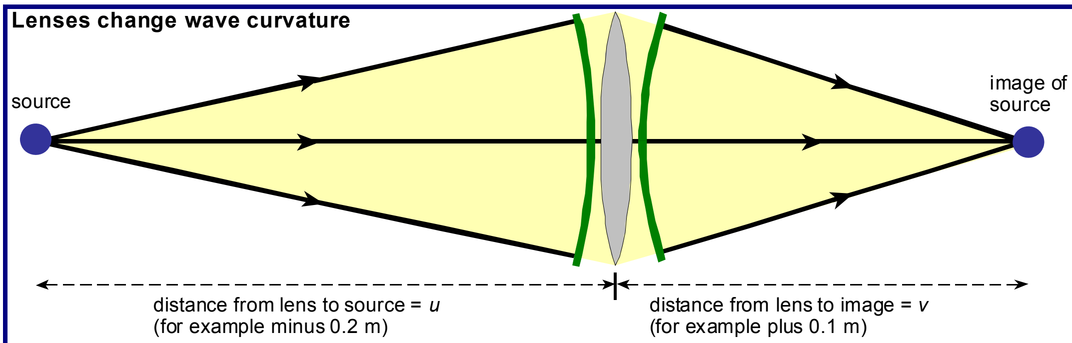
Action of a lens on a wave front

This diagram shows the importance of the curvature of the wave front in describing the action of a lens.

Lenses change wave curvature



curvature of wavefront after leaving the lens $= \frac{1}{v} = \frac{1}{0.1} = 10$

curvature of wavefront on reaching the lens $= \frac{1}{u} = \frac{1}{-0.2} = -5$

curvature added by lens = power of lens = curvature after – curvature before

$= \frac{1}{v} - \frac{1}{u}$

$= 10-(-5) = 15$ dioptre

power of lens $\frac{1}{f} = 15$ dioptre

focal length of lens $f = \frac{1}{\text{power}}$

$= \frac{1}{15}$

$= 0.067$ m

$= 67$ mm

A lens adds curvature 1/f to waves passing through it

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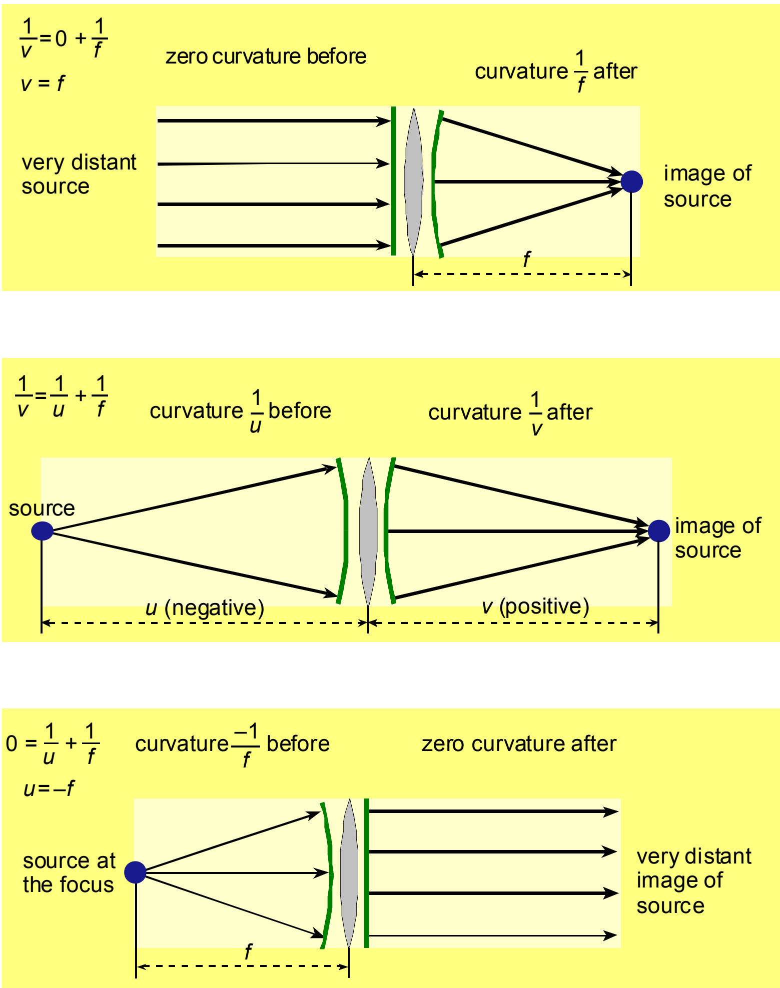
Where object and image are to be found

This diagram shows some important special cases of object and image distances.

Lenses add constant curvature 1/*f*



A lens adds the same curvature to all waves passing through it

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Bits and bytes

Bits and bytes

	8 bit = 1 byte				4 bit		2 bit	1 bit	Decimal value	Number of alternatives
	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	1	1	
	0	0	0	0	0	0	1	0	2	$2^1=2$
	0	0	0	0	0	0	1	1	3	
	0	0	0	0	0	1	0	0	4	$2^2=4$
	0	0	0	0	0	1	0	1	5	
	0	0	0	0	0	1	1	0	6	
	0	0	0	0	0	1	1	1	7	
	0	0	0	0	1	0	0	0	8	$2^3=8$
									....	
	0	0	0	0	1	1	1	1	15	
	0	0	0	1	0	0	0	0	16	$2^4=16$
									....	
	0	0	0	1	1	1	1	1	31	
	0	0	1	0	0	0	0	0	32	$2^5=32$
									....	
	0	0	1	1	1	1	1	1	63	
	0	1	0	0	0	0	0	0	64	$2^6=64$
									....	
	0	1	1	1	1	1	1	1	127	
	1	0	0	0	0	0	0	0	128	$2^7=128$
									....	
	1	1	1	1	1	1	1	1	255	
1	0	0	0	0	0	0	0	0	256	$2^8=256$

One 8-bit byte stores $2^8=256$ alternatives

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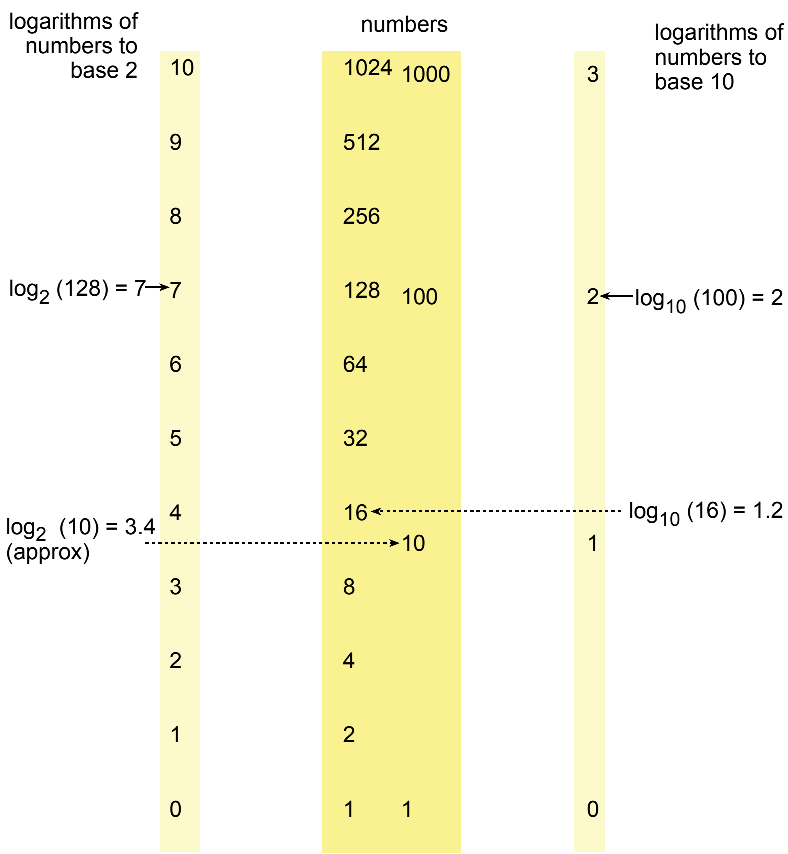
Comparing logarithms base 2 and base 10

Comparing logarithms base 2 and base 10

Logarithms and bases



$2^{10} = 1024$

$10 = \log_2(1024)$

If *base* ^{index} = *number*

Then *index* = logarithm $_{base}$ *(number)*

$10^3 = 1000$

$3 = \log_{10}(1000)$

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'Plus' and 'times' scales of information

'Plus' and 'times' scales of information

The OHT 'Bits and bytes' shows that the number of alternative values which can be represented grows rapidly as the amount of memory used increases.

If 8 bits of information are used:

number of alternatives $N = 2^8 = 256$

In general, if the amount of information is I bits:

number of alternatives $N = 2^I$

If the number of bits *increases by one*, the number of alternatives *doubles*. Information is measured on a 'plus' scale; the number of alternatives on a 'times' scale.

'PLUS' SCALE
(LINEAR)

amount of information

increase by equal additions

amount = I

amount = $\log_2 N$

'TIMES' SCALE
(LOGARITHMIC)

number of alternatives

increase by equal multiples

number of alternatives = 2^I

number of alternatives= N

$\log_2$ (number of alternatives) = information I = number of bits

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Logarithmic ladder of distance

Logarithmic ladder of distance

A ladder of distances in multiples of metres

Examples		
10^{21}	galaxy	
10^{18}	nearest stars	1 Em (exa)
10^{15}		1 Pm (peta)
10^{12}	distance to Sun	1 Tm (tera)
10^{9}	the Earth	1 Gm (giga)
10^{6}		1 Mm (mega)
10^{3}	small town	1 km (kilo)
10^{0}	human body	1 m
10^{-3}	width of a hair	1 mm (milli)
10^{-6}	microchip element	1 m (micro)
10^{-9}	molecule	1 nm (nano)
10^{-12}	atomic nucleus	1 pm (pico)
10^{-15}	quark	1 fm (femto)
10^{-18}		1 am (atto)

Equal multiple scales

A logarithmic scale is one on which equal spaces correspond to equal multiples.

In this distance scale each upward step multiplies the distance by 1000.

Each downward step divides the distance by 1000.

Each upward step adds 3 to the logarithm (base 10) of the distance.

Each downward step subtracts 3 from the logarithm of the distance.

$\uparrow$ × 1000

$\downarrow$ × 1/1000

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Logarithmic ladder of time

Logarithmic ladder of time

A ladder of times in multiples of seconds

Examples		
10^{21}		
10^{18}	age of Universe	1 Es (exa)
10^{15}		1 Ps (peta)
10^{12}		1 Ts (tera)
10^{9}	one year	1 Gs (giga)
10^{6}		1 Ms (mega)
10^{3}		1 ks (kilo)
10^{0}		1 s
10^{-3}	flap of a fly's wing	1 ms (milli)
10^{-6}		1 s (micro)
10^{-9}	light crosses a room	1 ns (nano)
10^{-12}		1 ps (pico)
10^{-15}		1 fs (femto)
10^{-18}		1 as (atto)

Equal multiple scales

A logarithmic scale is one on which equal spaces correspond to equal multiples.

In this time scale each upward step multiplies the time by 1000.

Each downward step divides the time by 1000.

Each upward step adds 3 to the logarithm (base 10) of the time.

Each downward step subtracts 3 from the logarithm of the time.

↑ × 1000

↓ × 1/1000

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