

Revision Guide for Chapter 3

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

<p>how a complex signal (waveform) can be constructed from or broken down into a set of simpler signals (waves) of single, different frequencies</p> <p>Revision Notes: superposing signals, spectrum of a signal</p>	
<p>how a complex signal (waveform) can be described in terms of the spectrum of frequencies it contains</p> <p>Revision Notes: spectrum of a signal</p> <p>Summary Diagrams: Atlas of sound spectra</p>	
<p>how a continuous signal can be digitised</p> <p>Revision Notes: analogue systems, digital sampling, analogue to digital conversion</p> <p>Summary Diagrams: Signal sampling, Digitising samples</p>	
<p>how a digitised signal has an important advantage in its ability to reduce the noise in the signal</p> <p>Revision Notes: noise</p> <p>Summary Diagrams: Effect of noise on analogue and digital signals</p>	
<p>how there may be some loss of detail in a digitised signal if sampling is not frequent enough</p> <p>Revision Notes: digital sampling</p>	
<p>the evidence for electromagnetic waves being transverse waves, and how this feature allows them to be polarised</p> <p>Revision Notes: polarisation</p> <p>Summary Diagrams: Polarisation</p>	

I can use the following words and phrases accurately when describing effects and observations:

<p>analogue signal, digital sampling, sampling frequency (sampling rate), amplitude, spectrum, bandwidth, noise, superposition</p> <p>Revision Notes: analogue systems, digital sampling, analogue to digital conversion, spectrum of a signal, bandwidth, superposing signals</p> <p>Summary Diagrams: Signal sampling, Digitising samples</p>	
<p>polarisation</p> <p>Revision Notes: polarisation</p> <p>Summary Diagrams: Polarisation</p>	

I can interpret:

waveform diagrams <i>i.e. wave amplitude plotted against distance or time</i> Revision Notes: superposing signals	
diagrams of the spectra of waves Revision Notes: spectrum of a signal Summary Diagrams: Atlas of sound spectra	

I can calculate:

wavelengths, wave speeds and frequencies by using the relationship $v = f\lambda$ Revision Notes: amplitude, frequency, wavelength and wave speed	
the quantity of information (data) in a signal Revision Notes: amount and rate of transmission of information	
the rate of transmitting information = samples per second \times bits per sample <i>i.e. in bits per second</i> Revision Notes: amount and rate of transmission of information, bandwidth	
the minimum necessary rate of sampling ($2 \times$ maximum frequency of signal) Revision Notes: digital sampling, bandwidth	
the maximum number b of bits per sample limited by the ratio of total voltage variation to noise voltage variation $2^b = V_{\text{total}} / V_{\text{noise}}$ Revision Notes: noise, digital sampling, bandwidth Summary Diagrams: Signal, noise and bandwidth	

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

giving examples of and commenting on applications and social impact of digital signalling	
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Revision Notes

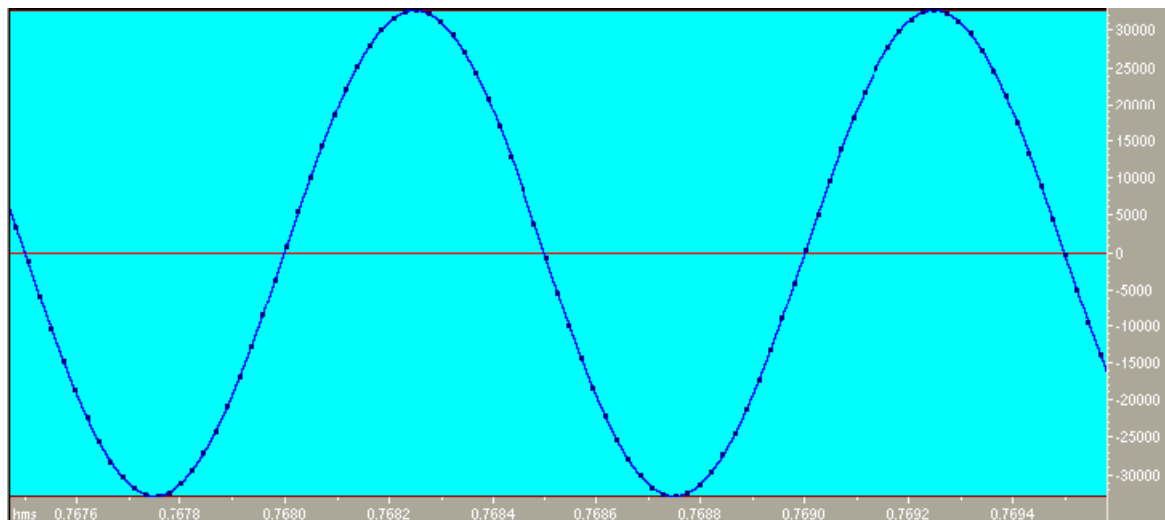
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Superposing signals

Signals can be added together to make a new signal. That is, one signal can be superposed on another.

Here is an example. Below, you see a small time-slice from a 1000 Hz signal. There is just this one frequency present. The waveform is sinusoidal.

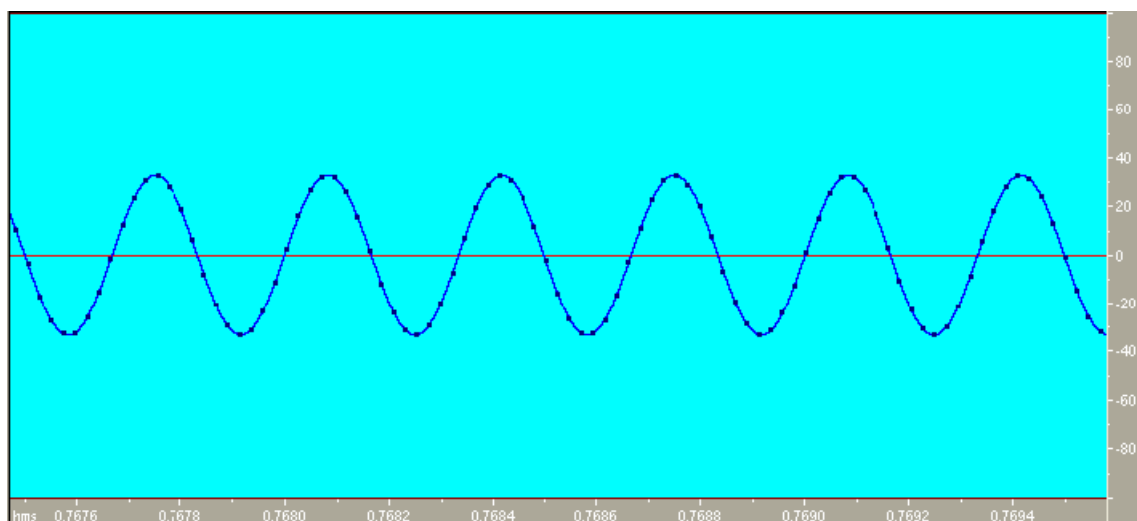
A 1000 Hz signal

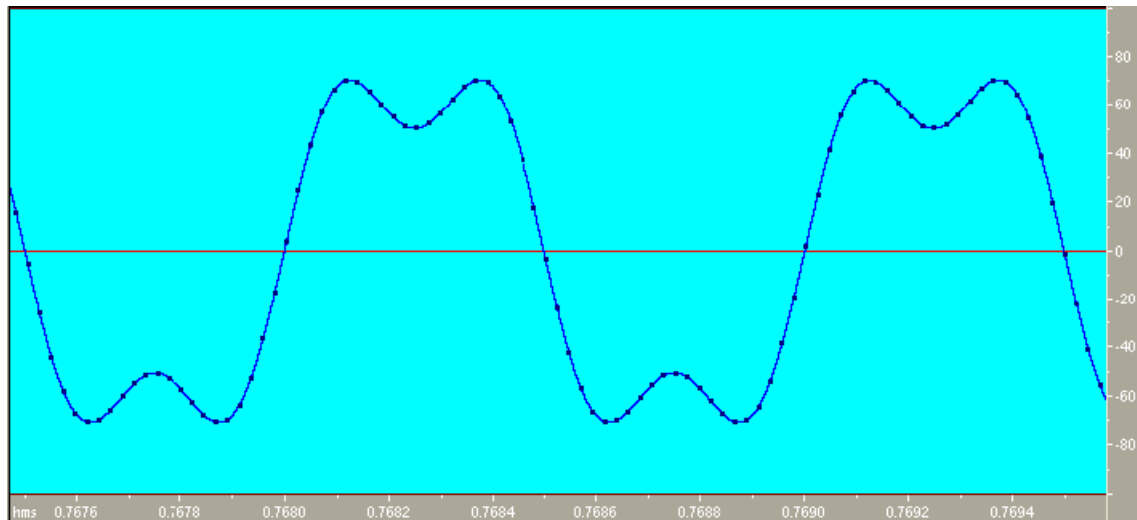


Now we will add another signal to the 1000 Hz signal. The added signal will have a frequency three times larger, that is, 3000 Hz. It will have 33% of the amplitude of the 1000 Hz signal.

Below you can see first the added 3000 Hz signal, and then the result of combining the two.

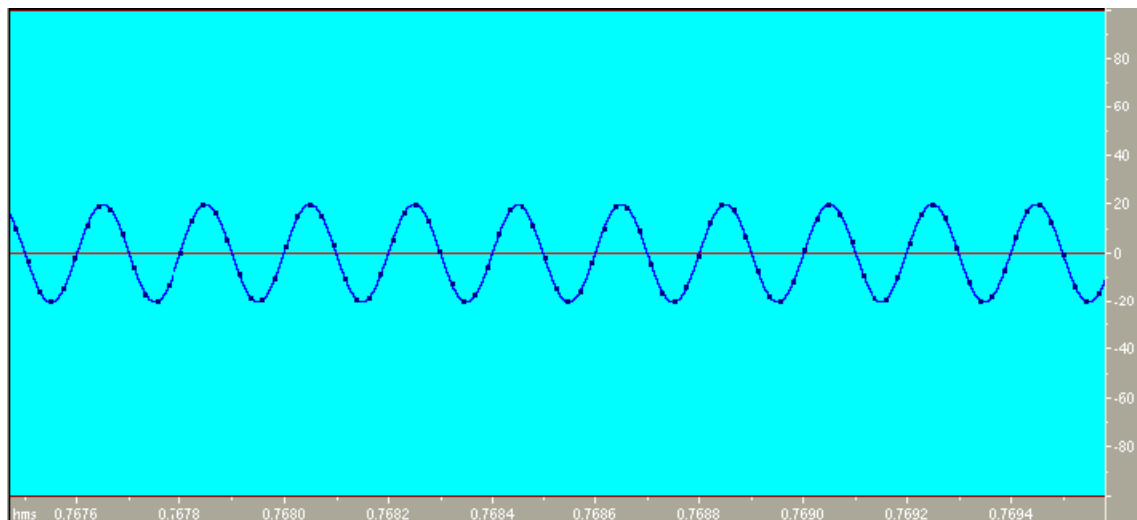
Added 3000 Hz signal, with 33% of the amplitude of the 1000 Hz signal



The combination of the 1000 Hz signal (100%) with the 3000 Hz signal (33%)

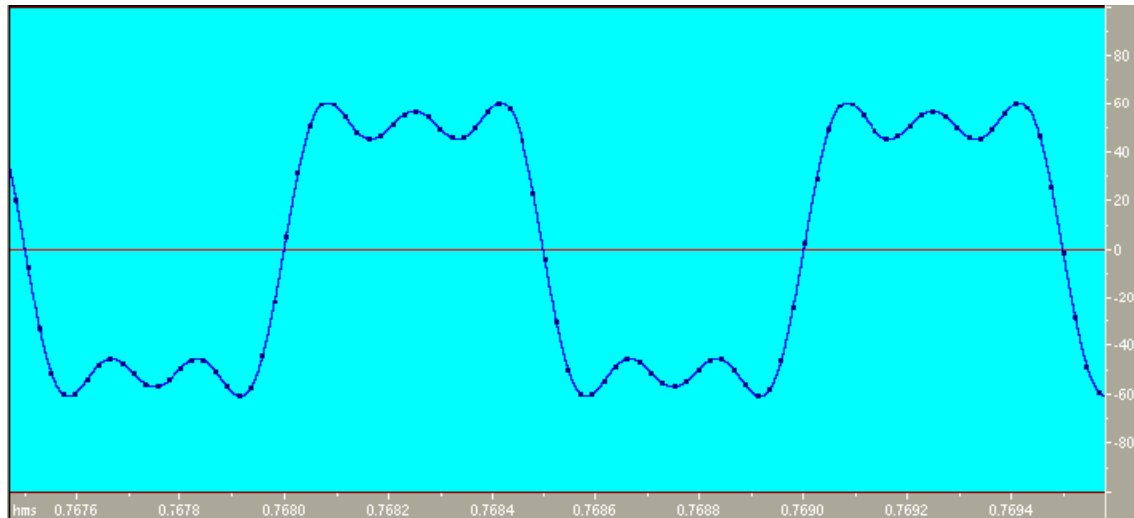
Notice that the new signal makes extra small oscillations within the slower, larger oscillation at the original frequency. These come from the added, higher frequency signal.

Finally, we will add a third signal to the combination. The new addition will have a frequency of 5000 Hz, and amplitude 20% of the original 1000 Hz signal. Here below is this extra addition.

Extra 5000 Hz signal, with amplitude 20% of the 1000 Hz signal

To finish off, here below is the result of superposing all three signals.

Superposition of three signals: 1000 Hz (100%), 3000 Hz (33%) and 5000 Hz (20%)



Taking signals apart

If signals can be combined, they can be taken apart again. For example, filters passing frequencies of 1000 Hz, 3000 Hz and 5000 Hz would detect these frequencies to be present. The spectrum of this compound signal would have just three components, one at each of these frequencies.

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Spectrum of a signal

The spectrum of a signal is the set of values of the amplitude of each component frequency in the signal.

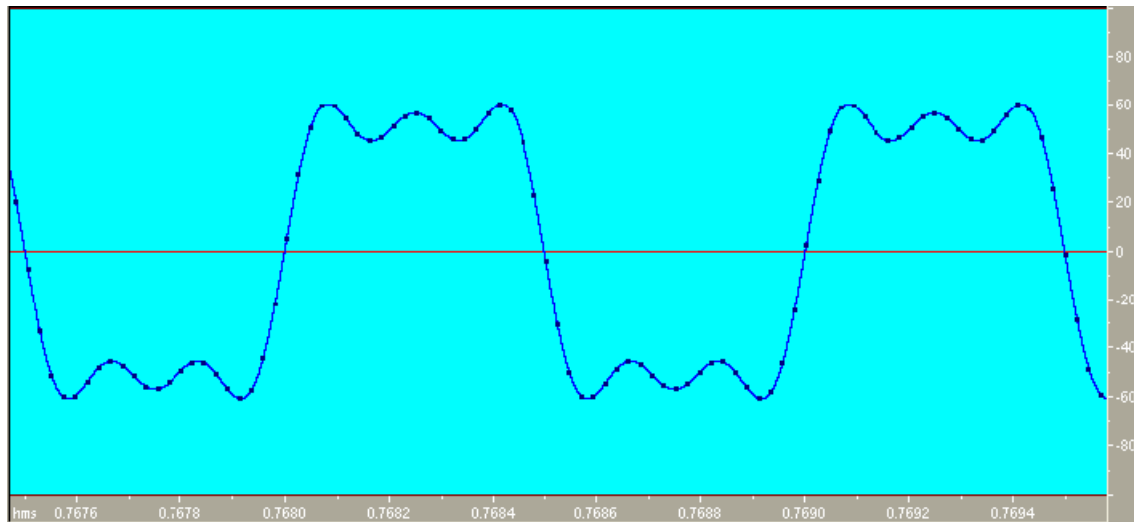
The spectrum is often displayed as a bar chart or a graph showing the amplitude of each frequency present.

Any signal can be analysed into frequency components, each component being an oscillation of a certain frequency and amplitude. The frequency analysis of a signal can be achieved by:

1. Using filters, each filter allowing a narrow range of frequencies through so the output represents the amplitude of that frequency component.
2. Using a computing process known as **Fourier analysis**. In effect, the computer tries filtering the signal at each possible frequency, and calculates the amplitude of any component at that frequency.

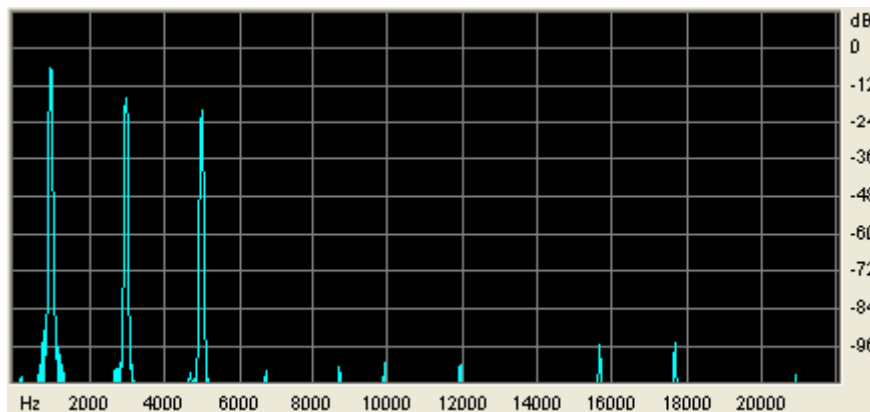
For example, the Revision Note [Superposing signals](#) shows how three signals can be combined (superposed) to make a more complex signal. Here below is the complex signal, built of signals of frequency 1000 Hz, 3000 Hz and 5000 Hz.

Compound signal containing frequencies 1000 Hz, 3000 Hz and 5000 Hz



Here below is the spectrum of the signal shown just above. You can see three large peaks in its frequency spectrum. The first, largest peak is at 1000 Hz. The other two smaller peaks are at 3000 Hz and at 5000 Hz.

Spectrum of signal with components of frequency 1000 Hz, 3000 Hz and 5000 Hz

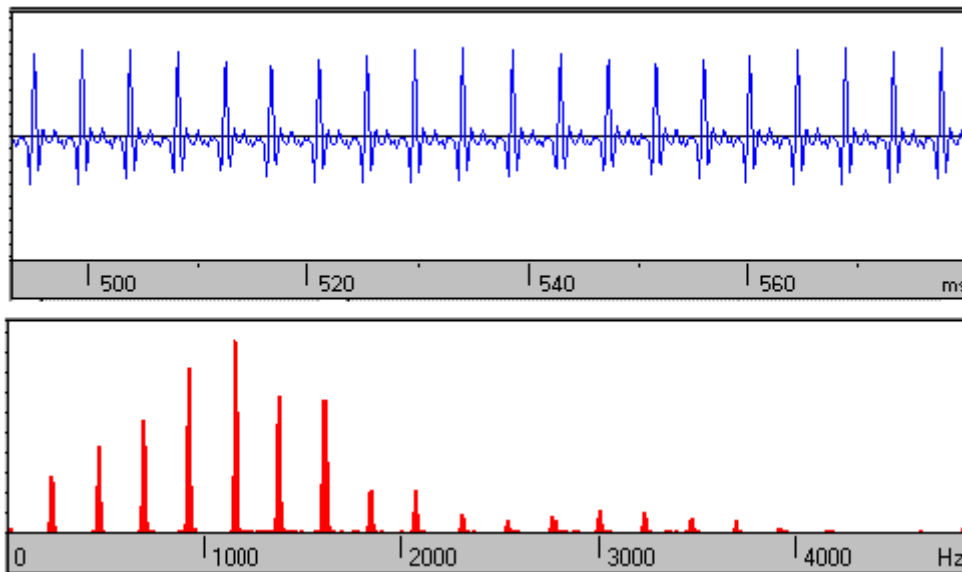


Examples of a sound spectrum

Below is shown the waveform of a note played by an oboe, together with the frequency spectrum of this note.

The oboe produces a complex sound, with a considerable number of different frequencies in its spectrum. The musical character of the sound is indicated by the discretely spaced frequencies, having simple numerical relationships to one another.

Sound waveform and frequency spectrum of an oboe



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Analogue systems

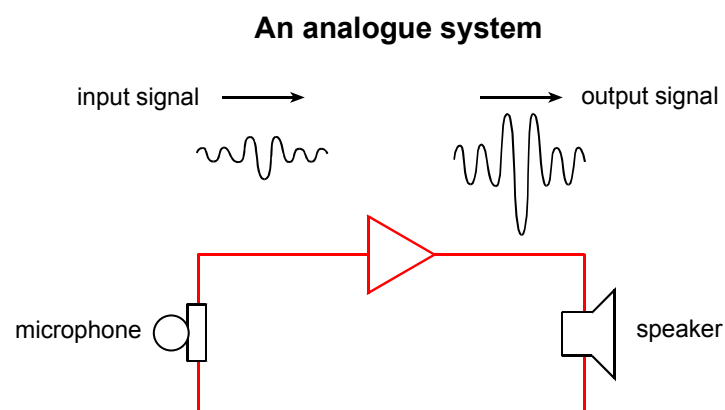
A vinyl long-playing record is an analogue system because the shape of the groove replicates the variations of the recorded sound. A compact disc is a digital system, recording the sound as digitised samples.

An analogue system is a signal system in which the signal (e.g. a p.d.) faithfully follows the variations of another signal (e.g. sound).

Analogue systems are used where physical variables are converted using transducers into electrical signals and are then processed.

In an **analogue signal** the value of the signal can vary smoothly to any value from zero to a maximum.

For example, a microphone connected to an amplifier connected to a loudspeaker is an analogue system in which sound waves are converted to an audio-frequency signal which is then reconverted to sound waves.



Analogue systems suffer from attenuation, distortion and noise when used to process or transmit signals, unlike digital systems in which the signal can be regenerated and wiped free of noise.

In a **digital signal** the potential difference of an electrical signal can have one of two values.

Data from a transducer can be transferred to another location in analogue form or in digital form. Corruption or loss of data in transmission is less likely if the data are transferred in digital form.

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Digital sampling

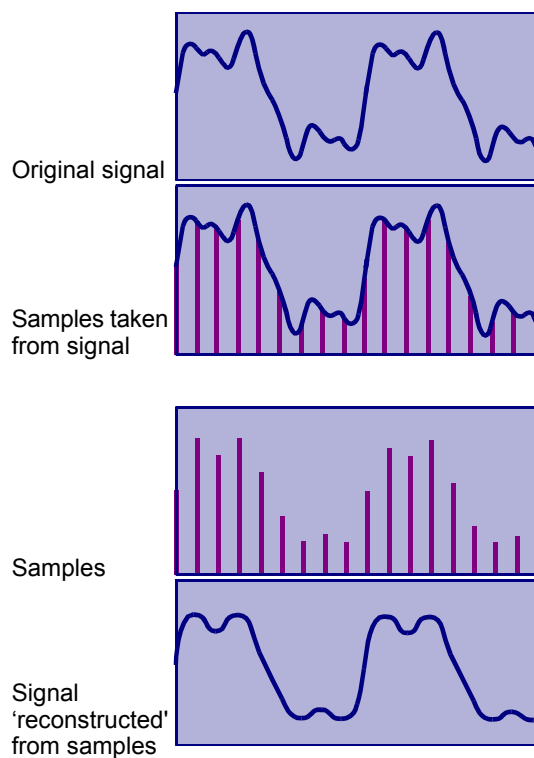
Digital sampling is the process of repeated measurement and conversion of an analogue signal into a digital signal consisting of a stream of pulses.

An analogue signal is a rapidly varying p.d. When an analogue signal is sampled, the magnitude of the signal is measured and converted to a digital value before the next sample is taken. If the samples are taken sufficiently frequently, the digital signals can be used to re-create the analogue signals.

Nyquist's theorem states that the **sampling frequency** should be at least twice the maximum frequency in the analogue signal's frequency spectrum. In practice, larger sampling frequencies are used. If the sampling frequency is less than twice the maximum frequency, the re-created signal can contain spurious low-frequency signals not present in the original signal, and the digital signals cannot be used to re-create the original analogue signal.

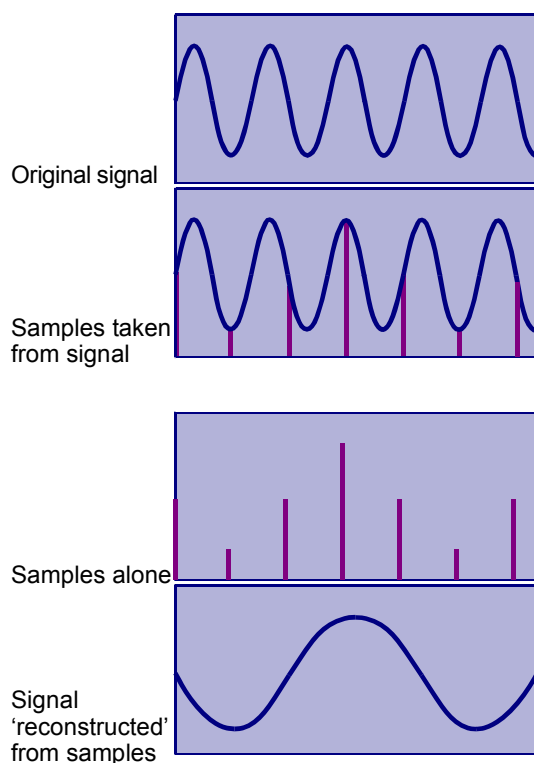
Problems with sampling

Sampling too slowly misses high frequency detail in the original signal



The generation of spurious low-frequency signals, known as **aliasing**, is illustrated in the diagram below.

Sampling too slowly creates spurious low frequencies (aliases)



The analogue samples are converted to digital signals by means of an [analogue to digital converter](#). For an audio signal of bandwidth 4 kHz, the highest frequency in the signal is 4 kHz, therefore the minimum sampling rate is 8 kHz. If each sample is converted into an 8-bit byte, the bit rate for data transfer must be at least 64 000 per second, or 64 kbit s^{-1} .

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Analogue to digital conversion

An analogue-to-digital converter is a circuit used to convert an analogue signal to a digital signal.

An analogue signal varies smoothly in potential difference. A digital signal is a sequence of on/off pulses.

In an analogue to digital converter, the voltage of the analogue signal is sampled at frequent intervals. The value of each sample of the analogue signal is then converted into a binary number.

At each interval, the analogue signal can be used to open an electronic gate for a time in proportion to the voltage of the analogue signal at the instant it was sampled. When the gate is open, a continuous stream of pulses passes through the gate. The number of pulses through the gate is therefore in proportion to the voltage of the analogue signal. The digital signal is therefore represented by the number of pulses.

The table below shows how a 3-bit converter would distinguish 8 different levels of the signal. For comparison, an 8-bit converter would distinguish 256 different signal levels. Notice that

there is always some error in assigning the nearest binary number to a given analogue value. This is called **quantisation error**.

Analogue signal level	Binary number
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

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Noise

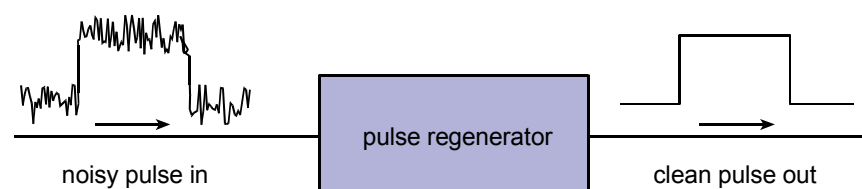
Noise arises from random fluctuations which may degrade a signal or image.

Electrical noise is generated in resistors due to the random motion or the random discrete arrival of electrons. Electrical noise in an amplifier connected to a loudspeaker can be heard as a hissing sound when there is no audio signal.

An amplifier is designed to amplify an input signal. However, noise carried by the input signal will also be amplified and additional noise may also be generated in the amplifier itself. An analogue signal which has been attenuated in transmission is not improved in terms of signal-to-noise ratio by passing it through an amplifier.

However, digital pulses that would become indistinct due to noise can be cleaned by passing the signal through a regenerator circuit which is designed to produce sharp pulses from fuzzy input pulses.

Regenerating a pulse



Noise in an image can be reduced by replacing each pixel by the median value of itself and the surrounding pixels. This process removes pixel values which are far from the common pixel values in that region of the image.

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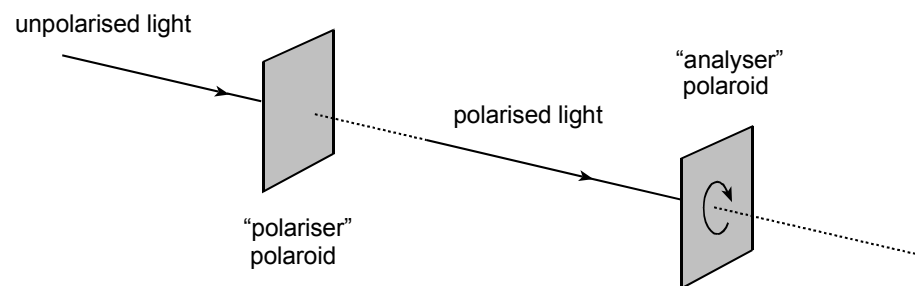
Polarisation

Polarisation is used to distinguish between transverse waves and longitudinal waves.

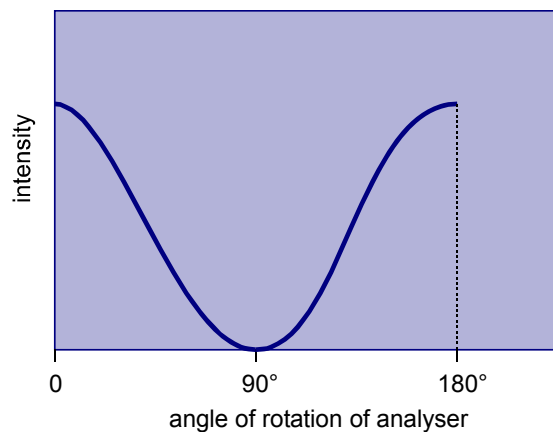
Transverse waves are waves where the vibrations are perpendicular to the direction of propagation of the waves. Examples include electromagnetic waves and waves on a vibrating string. Longitudinal waves are waves where the vibrations are parallel to the direction of propagation of the waves. Sound waves in air are an example.

Transverse waves are linearly polarised if they vibrate in one plane only. Unpolarised transverse waves vibrate in a randomly changing plane.

Light from non-laser sources is unpolarised but can be polarised by passing it through a polaroid filter, one type of which consists of molecules aligned in parallel lines. If polarised light is incident on a second polaroid 'analyser' filter, the intensity of the light transmitted by the filter is greatest if the molecules are parallel in the two filters, and is least if the filters are aligned so their molecules are perpendicular.

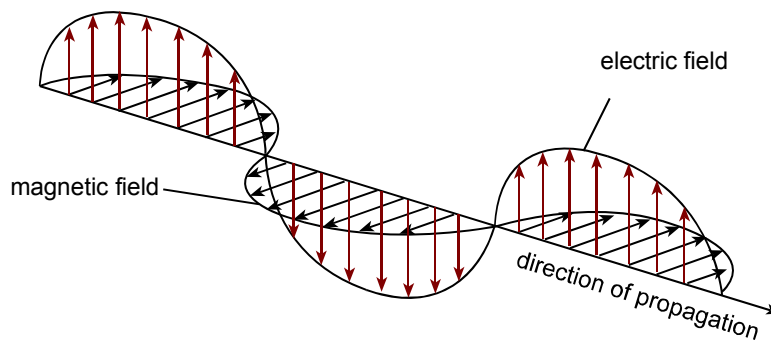


The graph below shows how the intensity of the transmitted light changes with angle as the second filter is rotated about the incident light direction.



Electromagnetic waves are transverse waves which consist of oscillating electric and magnetic fields at right angles to each other and to the direction of propagation. The plane of polarisation of a polarised electromagnetic wave is defined as the plane of oscillation of its electric field.

A plane polarised electromagnetic wave



A typical TV aerial is set up to point towards the transmitter, and to have the rods of which it consists parallel to the plane of oscillation of the electric field of the waves to be received. If the aerial is rotated so that its rods are at right angles to the electric field, little or no signal is detected. This is further evidence that the waves are polarized.

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Bandwidth

The bandwidth of a signal is the range of frequencies which it contains.

The human ear can detect sound waves from about 20 Hz to about 20 kHz. Telephone circuits have a bandwidth of 4 kHz, which means that frequencies above 4 kHz are not transmitted. As a result, your voice sounds different over the phone than in direct conversation.

The frequency spectrum of a signal may be shown as a graph of amplitude against frequency. The bandwidth of a signal is the spread of frequencies in its frequency spectrum.

A radio or a TV channel is a band of frequencies which carries a broadcast from a single station. No other station within range is allowed to broadcast in the frequency band allocated to a station, so that only one station is tuned in at a time.

Radio stations broadcasting amplitude-modulated carrier waves at frequencies up to 30 MHz are allocated channels of bandwidth no more than 10 kHz. This is sufficient to reproduce audio signals clearly.

Above 30 MHz, radio stations broadcast frequency-modulated carrier waves in channels of bandwidth 250 kHz, allowing high-quality music programmes to be transmitted.

Television broadcasts occupy an 8 MHz channel, which includes an audio channel of bandwidth 250 kHz and a video channel of bandwidth about 6 MHz.

The faster the rate at which a channel has to transmit information, the greater the bandwidth it must have.

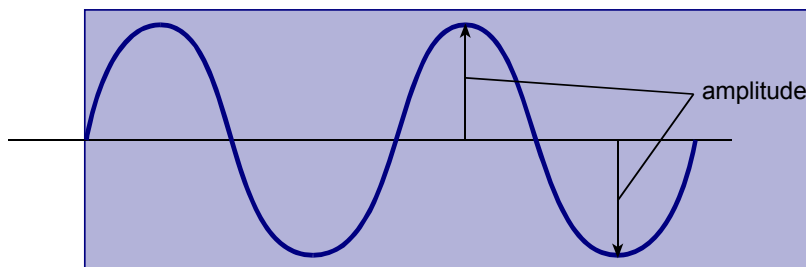
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Amplitude, frequency, wavelength and wave speed

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.

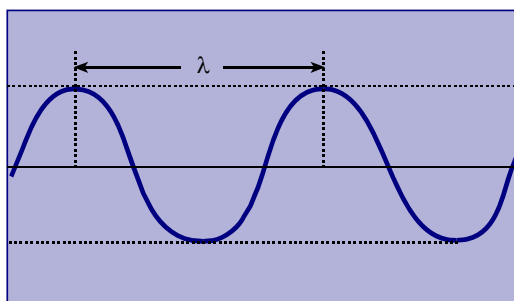
The frequency f of an oscillation is the number of complete cycles of oscillation each second.

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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Amount and rate of transmission of information

Information is stored in a computer memory and transmitted in a digital signal in bits, that is as zeroes or ones. A digital signal consists of a stream of bits, transmitted at a certain rate, measured in bits per second.

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 of diameter 100 mm stores data with a bit occupying an area of the order of $1 \mu\text{m}$ in width. Such a disc would be able to store of the order 10^{10} bits or about 1 gigabyte (over 500 Mbyte is possible in practice). DVD discs store each bit in a smaller space, and have larger capacity, but data compression is still needed for them to store a whole movie.

A single TV frame has 625 lines, each containing about 500 colour pixels. Using 1 byte per pixel, with 8 bits per byte, the TV frame requires $625 \times 500 \times 8$ or 2.5 million bits of information. This information has to arrive in $1/25$ s, since there are 25 frames per second.

Thus the rate of transmission of information that seems to be needed is over 60 Mbit s^{-1} . In practice, this rate of transmission of information is much reduced by data compression, with a typical channel having a bandwidth of 8 MHz.

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Summary Diagrams

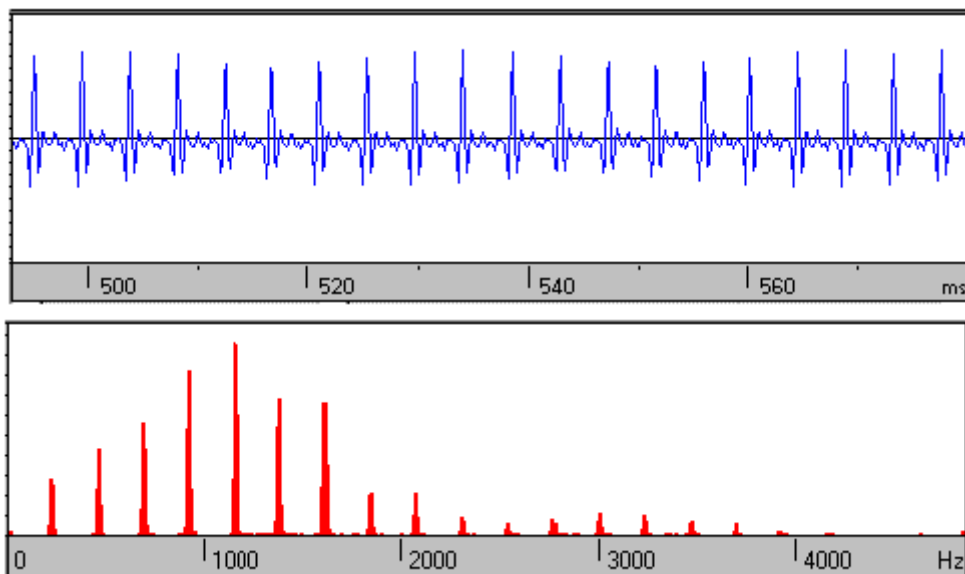
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Atlas of sound spectra

Here you can see the waveforms and spectra of a variety of sounds, some natural and some electronically generated.

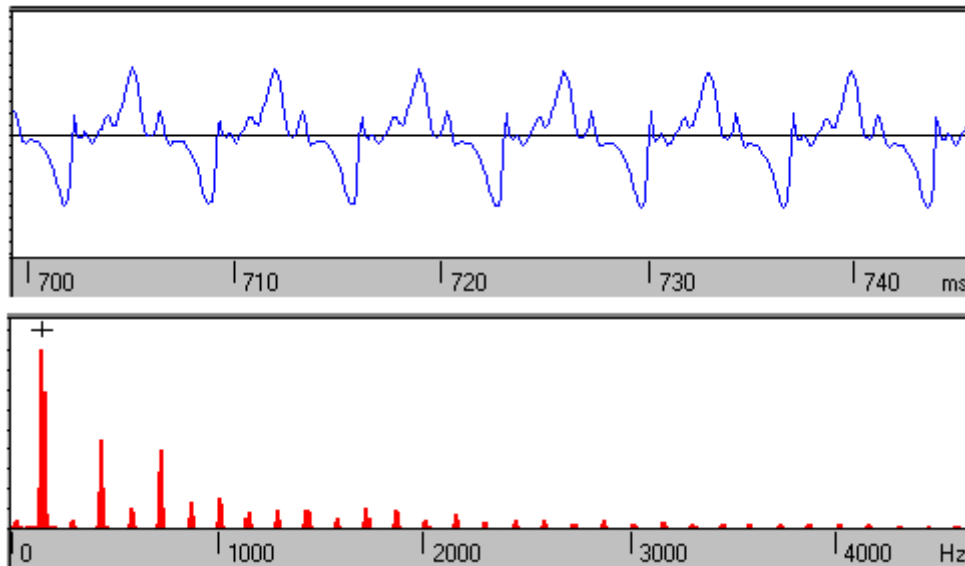
The oboe

The oboe produces a complex sound, with a considerable number of different frequencies in its spectrum. The musical character of the sound is indicated by the discretely spaced frequencies, having simple numerical relationships to one another.

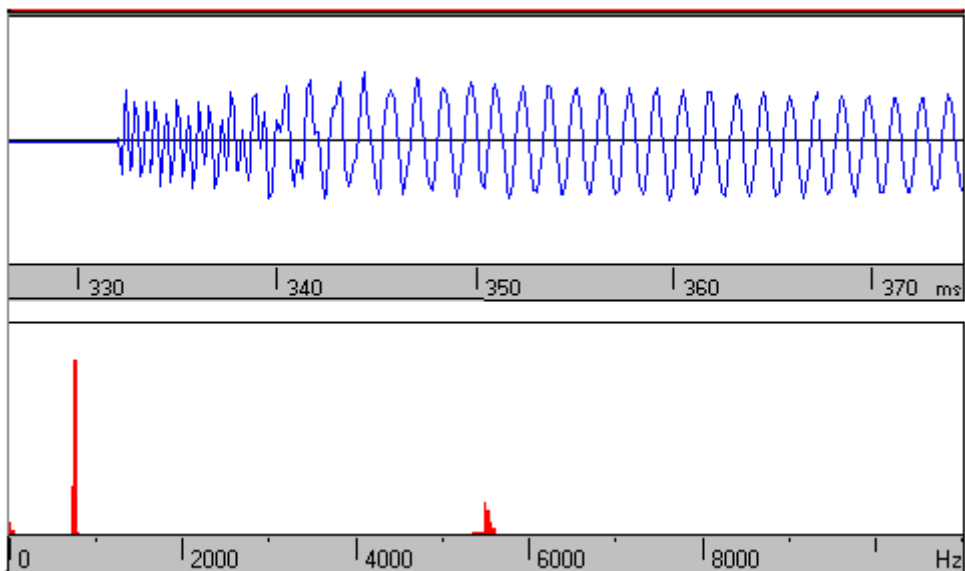


The clarinet

The clarinet, like the oboe, produces a range of discrete frequencies simply related to one another. The lower frequencies are rather dominant, but the spectrum extends over a wide range.

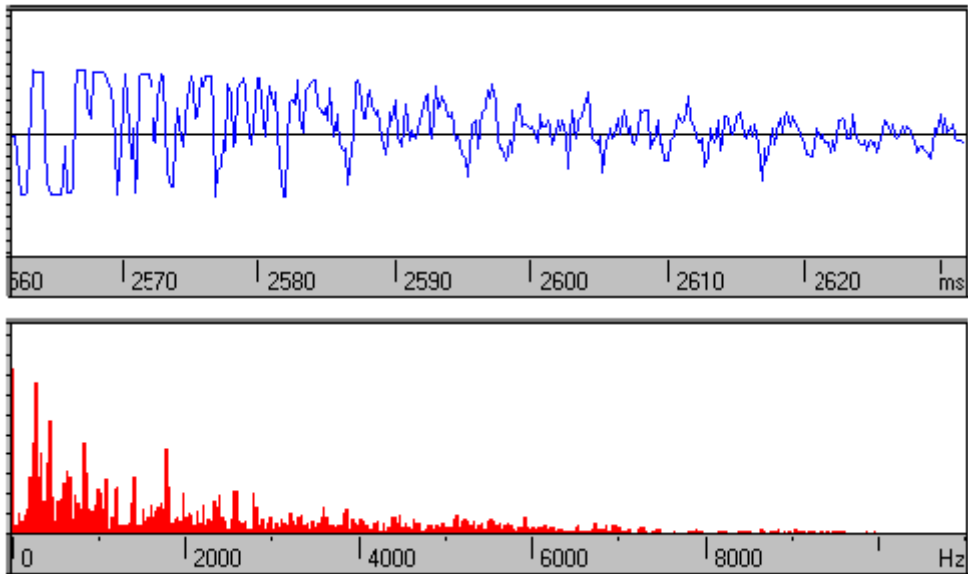
**The xylophone**

The sound of the xylophone has been caught just as a note is struck. Initially the sound contains a high-frequency 'ringing', but this dies away and the sound becomes the pure tone being struck.



The snare drum

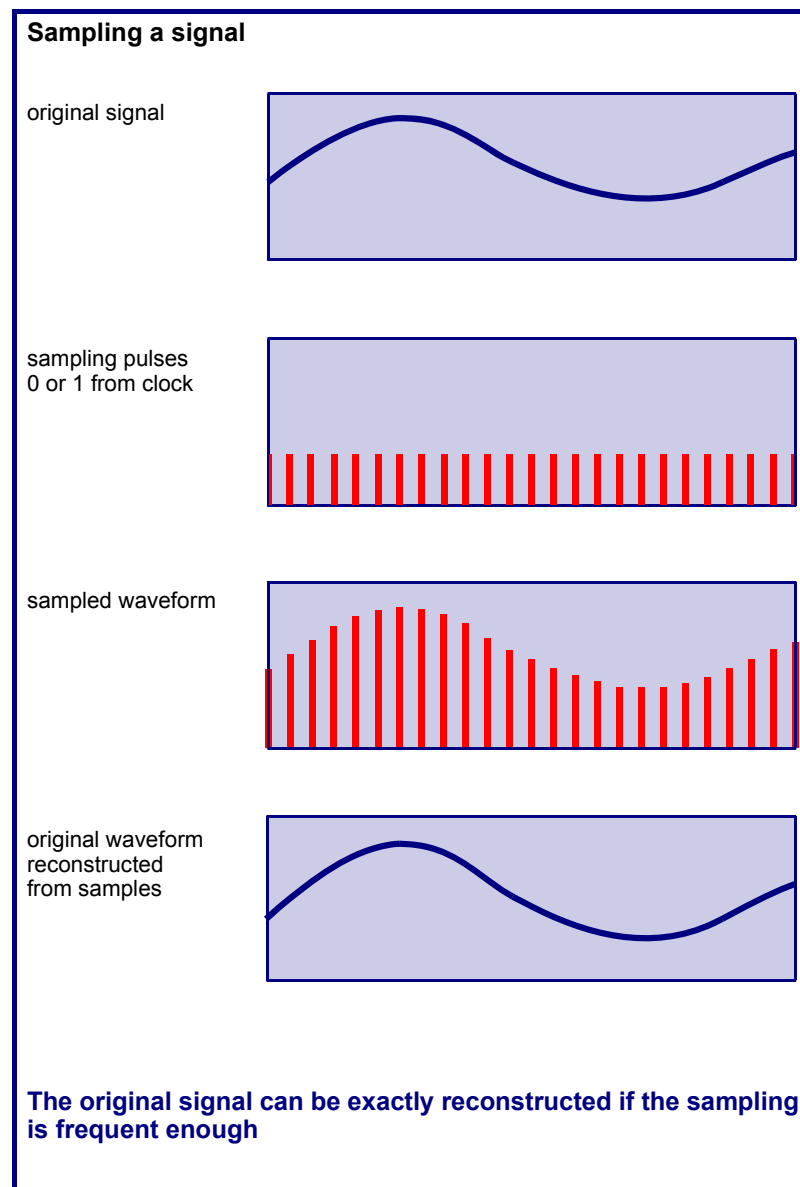
A drum does not produce a simple musical tone consisting of one or more discrete related frequencies, but instead produces a spectrum covering a wide range of frequencies. The sound has a pitch, decided by the range of frequencies over which the spectrum is centred.



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Signal sampling

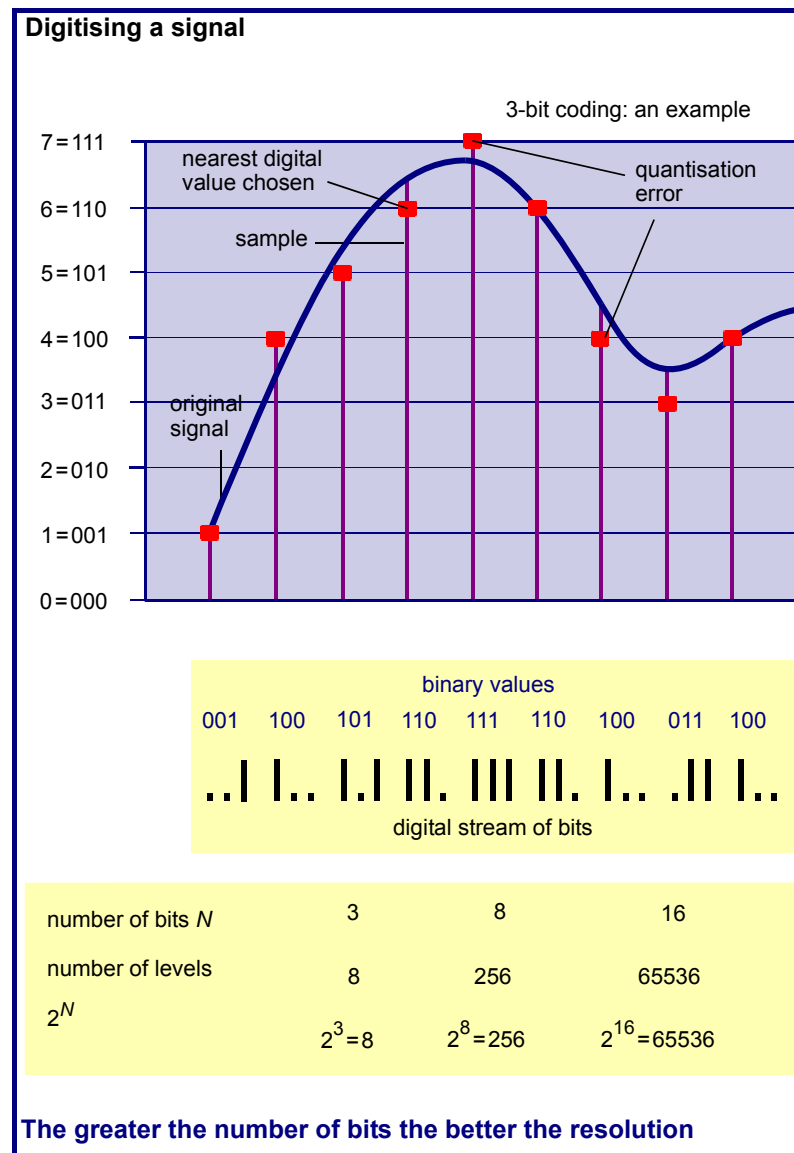
For digital transmission, signals must be sampled at discrete intervals.



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Digitising samples

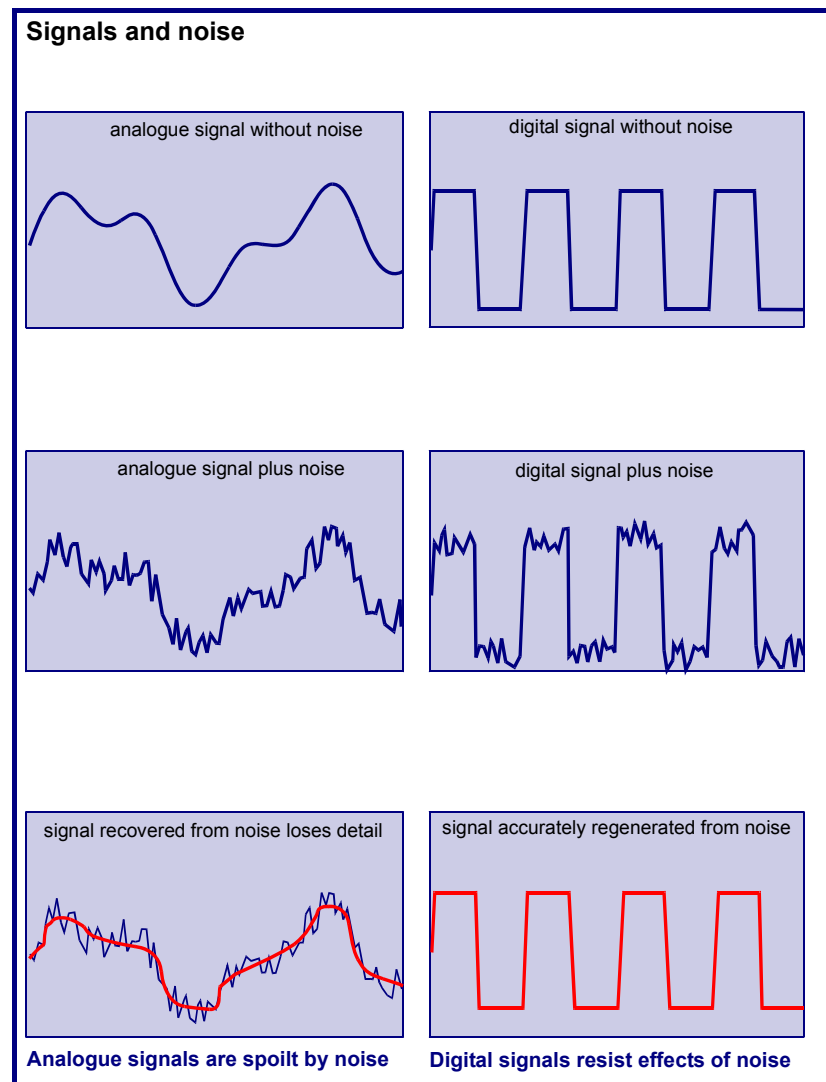
After a signal is sampled, the values must be digitised.



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Effect of noise on analogue and digital signals

Noise corrupts analogue signals. It can often easily be removed from digital signals.

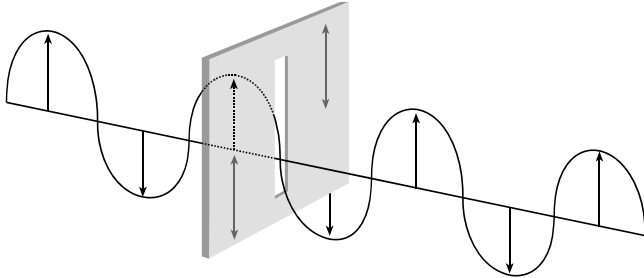


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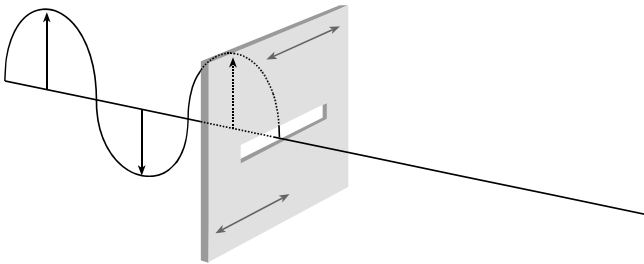
Polarisation

A reminder about polarisation of waves, using a mechanical analogue of waves on a rope passing through a slot.

When the permitted direction of vibration or polarisation of the filter is parallel to the direction of the polarisation of the wave, it is transmitted by the filter.

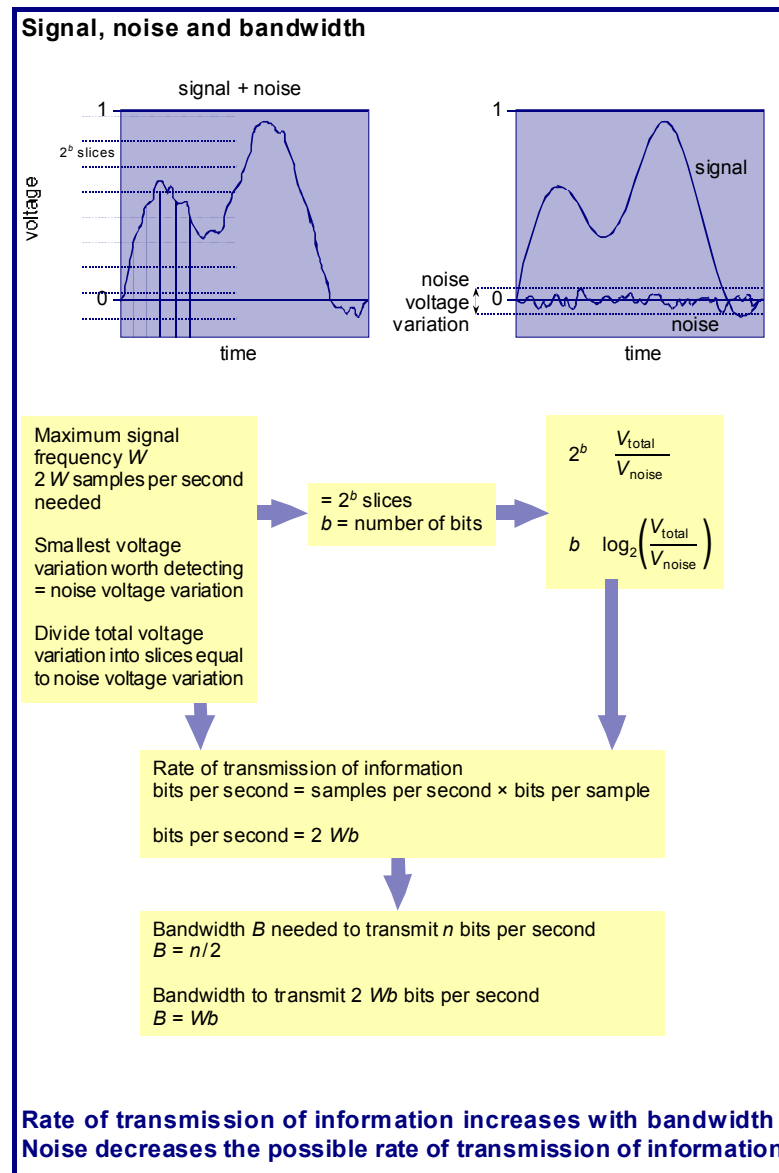


When the permitted direction of vibration or polarisation of the filter is perpendicular to the direction of the polarisation of the wave, it is absorbed or reflected but not transmitted.



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Signal, noise and bandwidth



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