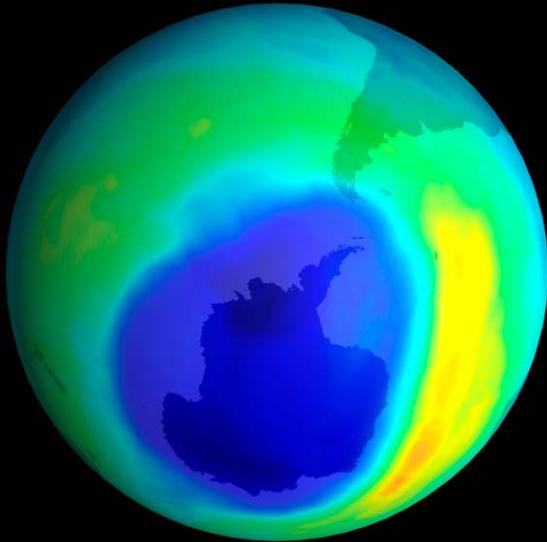


# Physics for an advanced world

A look at the vital contribution that physics research has made to a number of major technological developments



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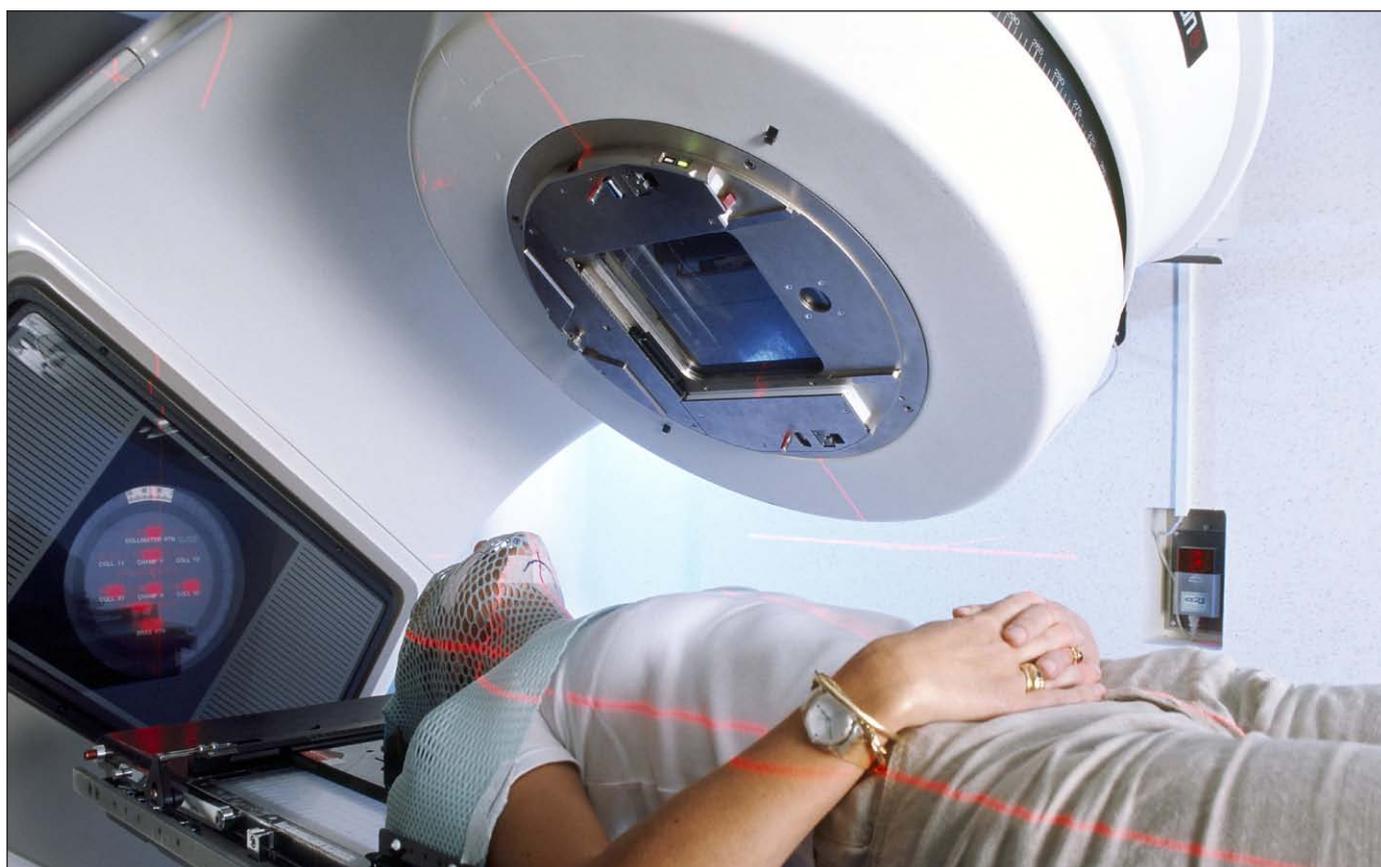
# Introduction

The application of physics provides a natural framework for commerce and technology to thrive. Significant technological advances have developed through curiosity-driven physics research, with tremendous social and economical benefits.

Focusing on 10 case studies – diagnosing and treating cancer, the structure of DNA, GPS in our daily lives, holographic techniques, the application of lasers, pioneering LCDs, life-saving MRI scanners, ingenious optical fibre technology, understanding and protecting the ozone layer and the World Wide Web – this booklet truly is a celebration of physics.

# Cancer diagnosis and treatment

Physics research has played, and continues to play, an essential role in improving the diagnosis and treatment of cancer.



## What is cancer?

Cancer refers to a wide group of diseases caused by cells that divide uncontrollably. The rapid growth usually produces a tumour, which can spread to and destroy surrounding tissues. The cancer cells often spread to other parts of the body. In the UK, more people die from cancer than from any other disease. While deaths from heart disease and strokes have declined in numbers since the 1950s, those from cancer have remained about the same. This is mainly because although the number of people suffering from cancer increases each year, advances in diagnosis and treatment continue to lower mortality rates.

Modern physics research plays a crucial role in improving both diagnosis and treatment. Ingenious techniques based on various types of radiation allow medical physicists not only to distinguish cancerous tissues but also to kill cancer cells in a controlled and safe way. Understanding, generating and manipulating that radiation has been made possible by basic physics research – into the structure and evolution of the universe (cosmology and

astrophysics) and the building blocks of matter (nuclear physics and particle physics).

Many of the recent advances in cancer therapy are the result of the development of novel radiation detectors (which act as imaging cameras) and other instruments originally constructed for physics research – combined with advanced software also developed mostly by physicists.

## The science

### ● Cancer diagnosis

One of the first ways of imaging and diagnosing tumours involved the use of X-rays. Some 40 years ago, by formulating clever computing techniques, Godfrey Hounsfield at EMI Laboratories in the UK developed a technique to reconstruct internal anatomy from many X-ray images taken around the body. Computerised tomography (CT scanning) is now a routine method for diagnosing tumours.

A more recent imaging technique is positron emission



tomography (PET). This relies on a type of radioactive decay in which positrons – the “antimatter” version of the electron – are emitted. The existence of the positron was first predicted by UK physicist Paul Dirac in 1928, and shortly after it was discovered in cosmic rays. A positron-emitting isotope attached to a bioactive material is injected into the body and accumulates in cells targeted by the bioactive compound. Positrons emitted by the isotope annihilate with nearby electrons. In this process, the mass-energy of both the electron and the positron is emitted as photons (light), which can escape from the patient. These can be detected and used to construct a three-dimensional image. Most cancers can be imaged using highly sensitive photon detectors, developed in astrophysics and particle-physics research. The accelerators used to produce positron-emitting isotopes for PET, and the detectors used to form PET images, were developed in the context of curiosity-driven particle-physics research.

Magnetic resonance imaging (MRI), the origins of which lie in nuclear-physics research, also plays a key role in the care of cancer patients. It offers greater soft-tissue discrimination compared with X-rays, so it is often the method of choice for diagnosing certain cancers, such as brain tumours. The related technique of magnetic resonance spectroscopy can be used to map the chemical composition of tumours and so characterise them without the need for an invasive biopsy. It is capable of predicting the response to chemotherapeutic drugs at an early stage in the treatment cycle, so that if a drug is not effective an alternative can be tried as soon as possible.

Other specialised MRI techniques with potential applications in cancer include perfusion imaging (for the characterisation of blood flow in a tumour and the impact of treatment) and whole-body diffusion imaging (for the detection of tumour metastases). In the developing field of interventional MRI, tumour surgery can be performed while the patient is inside the MRI scanner, with real-time imaging making sure that the whole tumour is removed,

**“Advances in physics-based diagnosis and therapy will continue to lower cancer mortality rates and improve the health of the nation.”**

avoiding the need for repeated operations.

In the future, imaging using low-energy terahertz (THz) radiation – light with wavelengths lying between the infrared and microwave bands – may have an important role to play in cancer detection. THz radiation can penetrate several millimetres of tissue with a low water content, such as fatty tissue, and it can also detect differences in water content and density. It could be used to detect skin cancer at an early enough stage to effect a cure. THz radiation has the advantage that it does not damage tissues as X-rays can. It might offer a safer and less invasive or painful method of detecting cancer of the epithelium – the tissue that lines the gut and genitourinary tracts. The first THz cameras were developed by astrophysicists to image the distant universe. A few years ago the European Space Agency set up a project at the UK’s Rutherford Appleton Laboratory to build the world’s first compact THz camera, and the field has since taken off. However, the main reason that THz cameras have not been employed in medicine has been the lack of cheap, portable THz-radiation emitters. Today, physicists are developing new types of lasers emitting THz light, based on a deep understanding of matter and

## Timeline

<b>1895</b>	German physicist Wilhelm Röntgen discovers X-rays and produces the first-ever X-ray photograph of a body part – his wife’s hand.
<b>1928</b>	Theoretical physicist Paul Dirac at the University of Cambridge postulates the existence of the positron, for which he was awarded the Nobel Prize in Physics in 1933. These particles are now routinely used for cancer detection in PET.
<b>1929</b>	Ernest Lawrence develops the idea of the cyclotron at the University of California, Berkeley, for which he won the Nobel Prize in Physics in 1939.
<b>1954</b>	The first treatment of cancer patients with beams of subatomic particles begins at Berkeley Radiation Laboratory, managed and operated by the University of California.
<b>1960</b>	The first images generated using THz radiation are produced.
<b>1963</b>	South African-born US physicist Allan Cormack devises a method for computerised tomography scanning.
<b>1969</b>	Godfrey Hounsfield creates the CT scanner at EMI Laboratories in Hillingdon. Hounsfield and Cormack share the 1979 Nobel Prize in Physiology or Medicine. In 1971 the first medical CT scan is taken, of a cerebral cyst patient in London.
<b>1970</b>	The first patient brain scan is made.
<b>1973</b>	The first PET image is created by biophysicist Michael Phelps and nuclear chemist Edward Hoffman, finding an important practical use for Dirac’s positron.
<b>1974</b>	The first commercial PET machine is built.
<b>1980</b>	The first clinically useful MRI image is produced.
<b>2003</b>	Peter Mansfield of the University of Nottingham wins the Nobel Prize in Physiology or Medicine, along with Paul Lauterbur of the University of Illinois, for their “discoveries concerning magnetic resonance imaging”.
<b>2004</b>	Scientists begin working on non-invasive cancer tests, such as the breath test, SIFT. Photocopier-sized devices are available by 2008.
<b>2007</b>	A compact device that can generate THz radiation portably is created at the US Department of Energy, making THz imaging in hospitals viable.



light at the basic quantum level.

Another recent development that provides images of just below the tissue surface depends on detecting the interference patterns of two beams of white light, one of which is delayed after being reflected from the tissue. This technique, known as optical coherence tomography (OCT), provides another non-invasive way of cancer detection. UK physicists and clinicians are collaborating in using OCT to map precancerous and cancerous tissues in the oesophagus and on the skin. UK researchers have been developing better light sources for OCT, such as fibre lasers.

Astrophysics research has produced other potential methods of non-invasive cancer detection, such as selected ion flow tube mass spectrometry (SIFT). Developed at the University of Birmingham to analyse the results of experiments investigating the chemistry of interstellar clouds, SIFT can detect tiny amounts of gaseous material. It is just one of several similar approaches designed to detect certain cancers just from a few organic molecules in a patient’s breath.

All of these techniques involve the design of novel sensors

that are compact and inexpensive. Many of the detectors used in medicine today have their origins in particle physics and astronomy research. New facilities such as the Large Hadron Collider (LHC) at CERN, which is designed to explore the first few moments of the universe after the Big Bang, are already producing new devices that will benefit cancer detection, as well as software systems to monitor cancer care on a national and international level.

### ● *Cancer treatment*

One of the most effective ways of treating malignant tumours is radiotherapy – high-energy radiation that includes not only X-rays but also beams of particles, such as electrons, protons (particles found in the atomic nucleus) and other nuclear particles. The beam energy is selectively deposited in the cancerous tissue and, if the dose is high enough, will kill the cells by breaking DNA strands in the cell nuclei. Radiotherapy is used as an alternative to surgery, and is also used after surgery to destroy any residual cancerous tissue. Around 40% of cancer cures are achieved using radiotherapy, compared with 50% using surgery and 10% using chemotherapy.

Radiotherapy was developed on the back of particle physics technology. Accelerators, which rely on powerful electric and magnetic fields to accelerate and guide a particle beam to very high energies, were originally developed as “atom smashers” to investigate the structure of atoms and nuclei, and to test the underlying theory. In the 1930s, through the work of several physicists – John Cockcroft, Ernest Walton, and later Robert van der Graaff at the University of Oxford and Ernest Lawrence at the University of California, Berkeley – these machines were quickly applied to generating beams of high-energy X-rays that could reach deep-seated cancers. Currently, electron linear accelerators generating X-rays are the workhorses of radiotherapy departments worldwide. Some 300 machines in the UK each treat about 40 cancer patients a day. These are the

close cousins of accelerators like the LHC.

The alternative approach of using high-energy protons to treat cancer was first suggested by American physicist Robert Wilson in 1946, while he was involved in the design of the Harvard Cyclotron Laboratory. The first treatments were delivered in the 1950s using accelerators originally built for curiosity-driven physics research. Unlike X-ray therapy, where the radiation dose decreases with depth in the tissue, protons and ions deposit the bulk of their energy at a fixed range. The particle energy can be selected to target the tumour while sparing the surrounding normal tissue. This is particularly important in treating children, where any radiation dose delivered outside the tumour risks causing secondary cancers in later life. The potential of proton and other nuclear beams for improving cancer treatment is reflected in the rapid increase in the provision of dedicated facilities worldwide. More than 30 000 people across the world have undergone proton therapy. In the UK, it is carried out at the Clatterbridge Centre for Oncology on Merseyside, which is a world leader in curing eye cancer.

As well as treating tumours directly, particle accelerators are used to make radioactive isotopes that are used to probe the underlying biology of cancer. Much of the initial research on the suitability of isotopes for clinical and research use is based on data from curiosity-driven nuclear-physics research.

## Current developments

One of most important requirements of radiotherapy is to deliver the correct dose of radiation to the tumour only. Physicists continue to work with clinicians to develop computer-based methods that, for example, “sculpt” the beam so that its shape matches that of the target tumour. The procedure relies on data obtained from an imaging technique such as PET, carried out simultaneously.

On the accelerator front, physicists are investigating new ways of accelerating particles and generating X-rays. The UK has invested in the development of a new compact device called a fixed-field alternating gradient (FFAG) accelerator, which is primarily being designed for particle-physics research. A collaboration of UK particle physicists is also planning to construct a prototype FFAG called PAMELA (Particle Accelerator for Medical Applications), designed for proton and ion therapy.

Other approaches to particle acceleration using high-power lasers are being investigated in the UK. So-called wakefield acceleration, in which particles surf on a wave of charged gas produced by a laser pulse, could lead to highly efficient, economic schemes, but research is still at an early stage.

## Impacts

All of these developments have the potential to improve people’s quality of life as well as having a beneficial economic impact on the cost of life-long healthcare. In the US alone, the National Institutes of Health estimate that the overall cost of cancer in 2006 was nearly \$206 bn. This included \$78 bn in medical costs for treating cancer patients; nearly \$18 bn in lost productivity due to illness; and more than \$110 bn in lost productivity due to premature death.

Cancer is the single biggest killer in the UK today – more than 130 000 die people every year, 65 000 of them under the age of 75. More than 250 000 people are diagnosed with cancer annually, and one in three will be diagnosed in their lifetime. As detection rates and treatment programmes improve and the understanding of what causes cancer increases, mortality rates will fall. In the decade after 1994, cancer mortality rates

dropped by 10% and they continue to decrease, even as the total number of cases continue to increase.

Advances in physics-based diagnosis and therapy will continue to reduce cancer mortality rates and improve the nation’s health.

## Key facts and figures

- There are more than 200 different kinds of cancer, affecting all parts of the body, and all can be fatal if left untreated. Annually in the UK, cancer is responsible for a quarter of all deaths.
- Modern technologies used to locate and treat cancers have developed as a result of studying stars and subatomic particles.

## Useful links

- <http://en.wikipedia.org/wiki/Cancer>
- [http://en.wikipedia.org/wiki/Positron\\_emission\\_tomography](http://en.wikipedia.org/wiki/Positron_emission_tomography)
- [www.petscaninfo.com/zportal/portals/pat](http://www.petscaninfo.com/zportal/portals/pat)
- [http://en.wikipedia.org/wiki/Computed\\_tomography](http://en.wikipedia.org/wiki/Computed_tomography)
- [http://en.wikipedia.org/wiki/Radiation\\_therapy](http://en.wikipedia.org/wiki/Radiation_therapy)
- [www.ccotrust.nhs.uk/default.aspx](http://www.ccotrust.nhs.uk/default.aspx)

● Thanks go to Colin Baker and Peter Weightman, University of Liverpool, Stephen Keevil, King’s College London, Stuart Green, University Hospitals Birmingham NHS Foundation Trust, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock and the Science Photo Library.

# DNA and physics

The discovery of the structure of DNA heralded the birth of the field of molecular biology, in which physicists, chemists and biologists work together to unravel the basic processes of life.



## What is DNA?

DNA is a large polymeric nucleic acid molecule found in the cells of all living organisms, from bacteria to humans. It consists of a very long strand comprising four distinct molecular units (“bases” – G, C, A and T), which are combined to be read as triplets (“codons”), which then code for individual amino acids making up unique proteins. The complete DNA sequence – the genome – is unique to each organism and provides its particular attributes.

DNA in cells usually exists as two strands wound round each other in a double helix. This beautiful structure was uncovered using X-ray crystallography halfway through the last century. Since then, physicists, chemists and biologists have collaborated to analyse and understand how the DNA code works. This involves experimental techniques, many of which, like X-ray analysis, arose from basic physics research. In 1990 an international project – the Human Genome Project – was founded to map the 25 000 genes found in human DNA by sequencing more than 3 billion pairs of bases. Scientists of all disciplines are now working to identify proteins that the genes code for and to unravel the molecular mechanisms that they control. The aim is to find the causes of disease and their cure. This research is of particular importance in understanding diseases with a genetic component, such as cancer, and also processes such as aging.

## The science

More than 2000 years ago, Greek philosopher Aristotle recognised that the characteristics of one generation are passed on to the next. However, it was not until the early 20th century that scientists worked out that chromosomes, found in cell nuclei, are the vehicle responsible. Further research showed that chromosomes are composed of proteins and DNA, but scientists were unsure which component carried the hereditary code.

Even more important in life-science studies is the use of X-ray crystallography – it was the X-ray picture of DNA that led US biologist James Watson and UK physicist Francis Crick to suggest that the structure of DNA is a double helix. Even though, by training, Crick was a physicist, he was interested in fundamental unsolved problems in biology, such as how molecules make the transition from the non-living to the living. He realised that it was his knowledge of physics that made him qualified to undertake such research.

Earlier in the century, physicists Lawrence Bragg with his father Sir William Bragg had shown that X-rays were scattered by an array of atoms in a crystal to produce a characteristic pattern that revealed its three-dimensional molecular structure. After the Second World War, Lawrence Bragg, then at the Cavendish Laboratory at the University of Cambridge, became interested in the structure of proteins and using physics to solve biological



problems. He provided the necessary support to Crick and Watson, who were investigating DNA structure at the Cavendish. In parallel, Maurice Wilkins and Rosalind Franklin were working on X-ray studies of DNA in the physics department at King's College London. The story is well known how Crick and Watson made the seminal discovery using Franklin's high-quality X-ray image. Crick and Watson, with Wilkins, were awarded the Nobel Prize in Physiology or Medicine in 1962.

As well as passing on genetic information from one generation to the next, DNA also passes it on as molecular information (in the form of another nucleic acid, known as messenger RNA – mRNA) for the manufacture of proteins. Crick, perhaps with a physicist's highly logical view of nature, then made predictions of the need for additional molecular species for the transmission of molecular information. He successfully predicted the need for another nucleic acid (now known as transfer-RNA – tRNA), the role of which is now understood to be essential in the manufacture of proteins with great fidelity. Another physicist, Russian-born George Gamow, postulated that a three-letter code must be employed to encode the 20 standard amino acids used by living cells to encode proteins.

The Cavendish work was central to a major new research field in which X-rays were used to analyse large biological molecules. Cambridge physicist Max Perutz solved the X-ray structure of the protein haemoglobin at around the same time, winning a Nobel Prize in Chemistry in 1962. Eventually, a dedicated laboratory was set up at Cambridge, the Laboratory of Molecular Biology (LMB), which was to see several more Nobel Prizes awarded to its researchers over the ensuing decades.

Physicists have continued to be involved in genetics research, bringing to bear their deep understanding of the properties of matter and developing new techniques to aid analysis. They often collaborate with biologists in this area. In the 1970s, theoretical particle physicist Walter Gilbert, with Allan Maxam in the US and Fred Sanger at the LMB, developed methods of sequencing the bases of DNA, which also led to a Nobel Prize. These methods used radioactive isotopes for labelling to map the DNA sequences of genes. They paved the way for the fast, automated methods eventually employed to sequence the human genome.

To make the most of the information provided by DNA mapping, physicists have also played a major part in developing advanced methods of exploring biological structures, such as

**“By training, Francis Crick was a physicist, interested in fundamental unsolved problems in biology... He realised that it was his knowledge of physics that made him qualified to undertake such research.”**

proteins, at the nanoscopic level. Over the past decades a new type of extremely bright X-ray source – a synchrotron – has increasingly been used in genetics and biological research. Synchrotrons are large, circular particle accelerators emitting intense electromagnetic radiation, which is siphoned off down “beamlines” to experimental areas around the accelerator ring. These machines, as well as all of the highly novel analytical instruments and detecting equipment, were and are developed by the high-energy physics community, of which the UK is a world leader. The first dedicated synchrotron facility, the Synchrotron Radiation Facility at the Daresbury Laboratory in Warrington, was built in the UK in 1980. Alongside X-ray studies, physicists have also developed a range of analogous scattering techniques using beams of subatomic particles – neutrons. Their production depends on either a nuclear reactor or an accelerator. The UK has one of the most powerful neutron-scattering facilities in the world: ISIS at the Rutherford Appleton Laboratory near Oxford. Modern biological research often involves synchrotron and neutron studies combined with genetic manipulation techniques, as well as other methods of analysis invented by physicists, such as nuclear magnetic resonance. In fact, modern biology and genetics research could not progress without them.

## Timeline

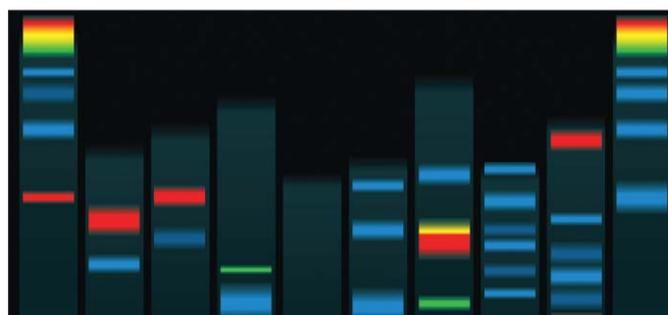
<b>1869</b>	DNA (first called nuclein) is identified by Swiss biologist Friedrich Miescher as an acidic substance found in cell nuclei. The significance of DNA is not appreciated for another 70 years.
<b>1905</b>	The word “genetics” is coined by William Bateson while studying biological heredity at the University of Cambridge.
<b>1915</b>	UK physicists Sir William Henry Bragg and William Lawrence Bragg are awarded the Nobel Prize in Physics for X-ray crystallography.
<b>1944</b>	American scientists Oswald Avery, Colin MacLeod and Maclyn McCarty make the portentous discovery that DNA is the material responsible for mediating heredity. However, most people were sceptical of these findings until 1952.
<b>1952</b>	Bacteriophage-labelling experiments by Alfred Hershey and Martha Chase confirm the 1944 results, thereby convincing the scientific community.
<b>1953</b>	Francis Crick and James Watson announce their discovery of the double-helical structure of DNA.
<b>1959</b>	Ribonucleic acid is discovered as the intermediary between DNA and proteins, and it is called “messenger RNA”.
<b>1962</b>	Francis Crick, James Watson and Maurice Wilkins are awarded the Nobel Prize in Physiology or Medicine “for their discoveries concerning the molecular structure of nuclear acids and its significance for information transfer in living material”.
<b>1973</b>	Recombinant DNA, formed by combining segments of DNA from different organisms, is first constructed.
<b>1975</b>	The first complete DNA genome is sequenced – that of bacteriophage $\phi$ X174.
<b>1977</b>	Walter Gilbert and Allan Maxam, and Fred Sanger, independently publish methods of DNA sequencing.
<b>1980</b>	Fred Sanger and Walter Gilbert receive the Nobel Prize in Chemistry.
<b>1982</b>	The first synthetic human insulin is produced using genetically engineered bacteria.
<b>1984</b>	Medical Research Council scientists decipher the complete DNA sequence of the Epstein–Barr virus.
<b>1985</b>	Sir Alec Jeffreys at the University of Leicester reports the development of the DNA fingerprinting technique.
<b>1987</b>	Applied Biosystems markets the first automated sequencing machine.
<b>1990</b>	The first approved gene therapy is performed at the US National Institute of Health. A properly functioning gene is inserted into the white blood cells of four-year-old Ashanthi DeSilva in an attempt to cure her severe combined immunodeficiency. The procedure strengthens her immune system by 40%.
<b>1994</b>	American computer scientist Leonard Adleman proposes the DNA computer.
<b>1997</b>	The first cloning of a mammal, to produce Dolly the sheep, is carried out by researchers at the Roslin Institute in Scotland, in collaboration with Scottish company PPL Therapeutics.
<b>2000</b>	The human genome is reported to be completed. This project was partly funded by the UK’s Wellcome Trust.
<b>2001</b>	The sequence of the human genome is released and the “post-genomic” era officially begins.
<b>2007</b>	The UK Diamond Light Source starts operation.

## Applications

### ● *Treatment of disease*

Knowledge of gene sequences, as well the crystal structure of proteins and more complex assemblies of cellular material, is essential for unravelling biological processes, leading to an understanding of disease and the development of new therapies. This was the remit of the Human Genome Project. The strategy is to discover all of the proteins that the genes code for and then study their function – a field now called proteomics. Physics-based methods are essential tools in achieving this goal.

A more publicised, and sometimes misunderstood, application of DNA analysis is genetic engineering, in which new genes are introduced into the genomes of living organisms. This approach provides a vital tool for biological and medical research. Biologists introduce DNA sequences into a bacterium so that it will produce a protein or other molecules of research interest. One of the first commercial uses, in 1982, was to make human insulin to treat diabetes. It also offers the methodology to replace a defective gene in humans with a correctly functioning one. Gene therapy is proving to be extremely difficult and there is a long way to go before it becomes a routine procedure. In 2007, however, Moorfields Eye Hospital and University College London’s Institute of Ophthalmology carried out a gene-therapy trial to treat an inherited retinal disease causing blindness, and it produced modestly encouraging results.



### ● *Agriculture*

One of the most controversial applications of genetic engineering is the production of genetically modified crops, designed to be more resistant to pest infection, to stay fresh longer or simply to grow larger. Much work is going into developing crops that can grow in difficult environments where there is a shortage of water, for example, and thus increase food production.

### ● *Forensics and identification*

Fast DNA sequencing has also led to the development of another controversial application: genetic profiling. “DNA fingerprinting”, as it is sometimes called, was first developed at the University of Leicester in the mid-1980s by Sir Alec Jeffreys. It depends on analysing frequency patterns of repeating sections of DNA

of different lengths, which vary from individual to individual. It is widely used to identify people from samples of their DNA, particularly those found at crime scenes. Today, the UK National DNA Database contains more than 3 million samples. In 2005, 45 000 crimes were matched against the database.

#### ● *Biometrics*

More sophisticated methods of gene analysis can identify specific human characteristics, such as racial mix. Research groups in the UK and the US are already looking at methods for predicting hair and eye colour from DNA samples. Biometric data based on DNA profiling has the potential to provide information about how individuals respond to drugs, thus creating the possibility of designing a drug treatment to the patient's needs, and avoiding possible side-effects.

### Current developments

Physicists are working ever more closely with biologists to develop new facilities and techniques for research inspired by DNA. The UK has just constructed a new synchrotron facility, the Diamond Light Source, which is a major resource for research in proteomics. New, extremely powerful X-ray devices, known as “free electron lasers”, are being developed that will enable snapshots of molecular biological processes to be recorded as they take place. A new neutron source, the European Spallation Source, is also being planned, and this will take biological studies much further.

Another area where physicists are contributing is in the development of portable DNA microchips and sensors. Chips hosting thousands of spots of DNA segments can be used as a diagnostic tool to identify diseases and genetic disorders. They offer the prospect of monitoring the whole genome on a single chip, giving researchers a better understanding of the interactions between thousands of genes – on a device not much bigger than a postage stamp. The technology requires the exploitation of physical effects for detecting DNA, such as fluorescence or a change in refractive index, as well as fast signal-processing and read-out methods.

Finally, the structure of DNA is inspiring physicists to exploit it as a building material for nanoscale devices designed to self-assemble. Physicists at the University of Oxford are working on devices that change state in response to an external trigger and that might be used for molecular sensing, intelligent drug delivery or programmable chemical synthesis. Biological “molecular motors” that carry cargoes inside cells have inspired the construction of synthetic molecular machinery. It has even been possible to create DNA motors that move autonomously, obtaining energy by catalysing the reaction of DNA fuels. Even more futuristic is the concept of using DNA's four bases as the coding elements of a biological computer. A few years ago, Israeli researchers unveiled a programmable molecular computing machine, composed of enzymes and DNA molecules, that can perform much faster computation than a silicon microchip.

### Impacts

The benefits of DNA-based technology to global health are, and will continue to be, huge. In 2004 the *Canadian Medical Journal* reported that infectious diseases (e.g. HIV/AIDS, tuberculosis and malaria) account for around one-third of deaths worldwide (~17 million). New diseases are emerging and microbial resistance to drugs is increasing. The DNA sequencing of infectious agents can help in understanding drug and insecticide resistance and it is important in the development of new drugs

and vaccines. Rapid diagnostic gene sequencing applied to emerging diseases, such as the coronavirus – the causative agent of bird flu – is one example of the value of DNA-based research. New types of vaccine based on DNA have considerable potential in treating these and other viral infections, including HIV.

While the developing world bears the heaviest burden of infectious diseases, the West has become concerned about the treatment of diseases of old age such as dementia. Advances in these areas will build on the legacy of knowledge and techniques derived from the early work on DNA and the other molecules of life. Several reviews of American data have estimated that spending just \$2 bn over 10 years on this research could generate a 4 to 30-fold economic return. Indeed, according to the UK's Medical Research Council, the global market for DNA chips has already reached almost £1.6 bn in 2005. Other reports have indicated that the global market for DNA-sequencing technology and related services had exceeded \$7 bn by 2006.

### Key facts and figures

- Physicist Francis Crick with James Watson uncovered the structure of the DNA double helix at the Cavendish Laboratory, enabling scientists to understand the genetic make-up of all forms of life.
- Research funded by the UK sequenced one-third of the human genome.
- Physics-enabled analytical techniques are central to genetic research and to the study of the causes of disease.

### Useful links

- [www.dnaftb.org](http://www.dnaftb.org)
- <http://en.wikipedia.org/wiki/DNA>
- [http://en.wikipedia.org/wiki/X-ray\\_crystallography](http://en.wikipedia.org/wiki/X-ray_crystallography)
- [http://en.wikipedia.org/wiki/DNA\\_sequencing](http://en.wikipedia.org/wiki/DNA_sequencing)
- <http://en.wikipedia.org/wiki/Proteomics>
- [www.diamond.ac.uk/default.htm](http://www.diamond.ac.uk/default.htm)

● Thanks go to Paul O'Shea, University of Nottingham, Andrew Turberfield, University of Oxford, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# The Global Positioning System

Satellite-based navigation and positioning technology, underpinned by physics research, is no longer the preserve of the military but is now an invaluable aid in all aspects of life.



## What is the GPS?

The Global Positioning System (GPS) is a satellite-based navigation system consisting of a network of around 24 satellites operated by the US Department of Defense. It uses specially coded satellite signals that can be processed in a GPS receiver, enabling it to calculate position, velocity and time. Although originally intended for military use, today anyone can use it. GPS became fully operational in 1993.

GPS operates 24 hours a day in all weather conditions and is free of charge. It is widely used by the armed forces of many nations, including the UK's, on battlefields all over the world. It is also a standard feature of all modern military planes, along with being the navigation system behind "smart" bombs. The first civilian users were airlines and shipping companies, and the system also rapidly became popular with hikers and mountaineers. Today, GPS technology is integral to mobile telecommunications and is fundamental to the satellite-navigation systems used in many vehicles. Modern cars often

have several GPS devices – for theft tracking, fleet management and insurance purposes.

GPS has its foundations in a range of physics research spanning the past century, including the invention of atomic clocks, derived from an understanding of quantum theory, and Albert Einstein's general theory of relativity. UK physicists and engineers are currently developing the next generation of GPS – the European project Galileo – which will provide more accurate information to an increasing number of users. This new system is projected to produce a substantial economic benefit for the UK through aerospace contracts and applications.

## The science

The launch of the first manufactured satellite, *Sputnik*, in 1957 marked the start of a new era in communications technology – not least because US space scientists tracking it noted that the radio signal that it was transmitting could be used as a means of navigation: if the satellite's position is known, the position of the



observer can be calculated. US physicist Ivan Getting, working for the US Air Force, soon proposed a system involving many satellites orbiting the Earth that could provide an accurate and reliable positioning system. His idea was put into practice, and by the early 1990s there were more than 20 GPS satellites in orbit, providing global coverage.

To pinpoint a location requires a measurement of the distance between the user and at least three satellites. This is achieved by registering the time taken for a signal sent by a satellite to reach the user. The transmission contains the time at which the signal was sent, along with the exact position of the satellite, which can be compared by the GPS computer with the signals sent by the other satellites. Accurate time measurement is central to the GPS because the signal's transit time is so short (it travels very close to the speed of light) and the satellites must carry the most accurate clocks available. These are atomic clocks, which exploit the fundamental quantum physics of the atom and are accurate to just one-billionth of a second in a day. It was physicists Louis Essen and Jack Parry who built the first reliable atomic clock in 1955 at the National Physical Laboratory in the UK. These are now the gold standard for time – even Big Ben's clock is checked against one. They are based on the frequency of microwave radiation absorbed or emitted when an atom (typically of caesium) undergoes a particular quantum-energy transition.

Yet another phenomenon described by fundamental physics research has to be taken into account in the time measurement: the effect of gravity on time. The difference in the strength of the Earth's gravitational field on the ground and in space means that a ground-based clock runs a fraction of a second slower than a clock on the orbiting satellite – an effect predicted and explained by Einstein's general theory of relativity. Fortunately, the theory also enables physicists to make the essential time corrections, and the satellite-based clocks are manufactured to run slightly slower when on Earth so that they will keep the "correct" time once in orbit. The users' GPS equipment can make further corrective calculations as it determines its position. Without these corrections, positioning errors would increase at the rate of around 10 km per day.

In addition, to maintain the accuracy of the GPS, the environment around the Earth also has to be taken into



account. The signal from a GPS satellite travels through a small amount of material in the upper atmosphere that is ionised (the ionosphere). This slows the signal down to slightly less than the speed of light so it can generate errors of several tens of metres in GPS receivers if left uncorrected. The error depends on factors such as "space weather", which are hard to predict, and much effort has been devoted to this "ionospheric correction"

## Timeline

<b>1916</b>	Albert Einstein publishes his general theory of relativity, which describes how time is affected by gravity.
<b>1919</b>	British physicist Arthur Eddington leads an expedition to Principe Island in West Africa to observe the total solar eclipse, in which the bending of light rays was predicted by general relativity. He was the first to appreciate the importance of Einstein's theories of special and general relativity, and he published a treatise on the subject.
<b>1955</b>	The first reliable atomic clock is built by physicists at the UK's National Physical Laboratory.
<b>1957</b>	<i>Sputnik</i> is launched and people realise that this "artificial star" could be used for navigation.
<b>1960</b>	The first navigation satellite is launched for use by the US Navy.
<b>1960</b>	Physicist Ivan Getting proposes the idea of a space-based multisatellite positioning system for land forces.
<b>1967</b>	The second is redefined as an exact measure of time in terms of atomic clocks.
<b>1978</b>	The first GPS satellite is launched equipped with an atomic clock.
<b>1990</b>	The first GPS in-car navigation system is launched by the Pioneer Corporation.
<b>1993</b>	The GPS is fully operational, giving worldwide coverage.
<b>2001</b>	Scientists at the University of Wales, Aberystwyth demonstrate that up to 30% of the GPS ionospheric correction arises from the plasmasphere – the tenuous extension of the ionosphere up to altitudes of 20 000 km.
<b>2003</b>	The US system providing GPS ionospheric corrections (Wide Area Augmentation System) fails during a severe space weather storm.
<b>2004</b>	A GPS navigation systems costs less than £100.
<b>2005</b>	The first Galileo satellite, GIOVE-A, built by Surrey Satellite Technology Limited, a spin-out company from the University of Surrey, is launched.
<b>2008</b>	The second Galileo satellite, GIOVE-B, built by the UK-based aerospace company Astrium, is launched.
<b>2008</b>	GPS-enabled mobile phones come onto the market.

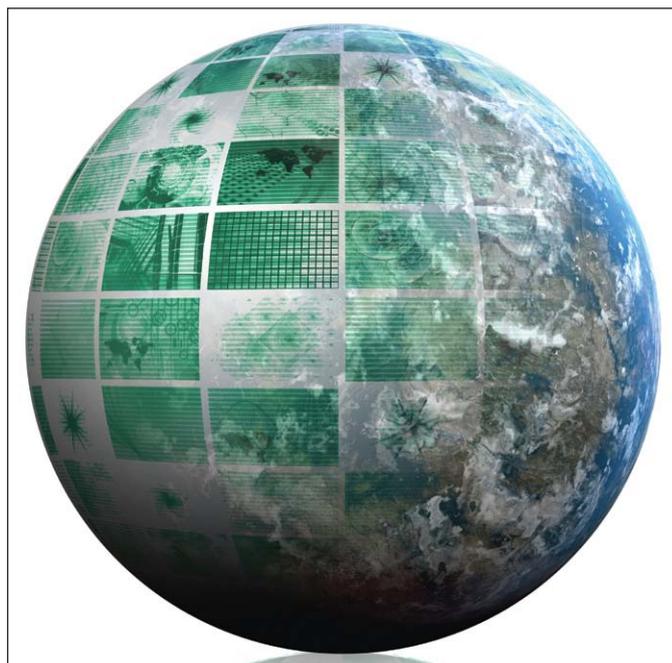
## “Satellite-based navigation would not be possible without accurate time keeping, which depends on an understanding of the two main theories of modern physics: quantum theory and general relativity.”

because it is a key factor in improving the accuracy of the GPS. For example, the US and Europe have deployed networks of instruments across the globe to determine the local correction, which is fed to GPS receivers. This remains an active area of physics research because of the strong interest in improving GPS accuracy and reliability.

### Applications

#### ● Defence

The GPS was initially designed for military use. It is used to track and coordinate troop movements and supplies, for search and rescue, and to track and guide missiles and smart bombs. The first missile guided by a GPS-based targeting system was developed in 1993 and was first used in Bosnia in 1995. Modern armaments carried by the Royal Navy, such as the Stormshadow missile manufactured by BAE Systems, carry GPS



technology that is used to navigate and locate targets. The target coordinates are programmed into the missile prior to launch, and the GPS constantly checks the missile's position against an optimum flight plan as it travels towards the target. This "fire and forget" technology allows the missile to be launched from planes hundreds of miles away from the target, thus reducing the danger of the aircraft and crew being shot down.

#### ● Mobile communications

To handle the ever-increasing volume of traffic, modern communication systems must be able to transmit many different phone calls at once though individual phone lines. This is achieved by using computers at each end of the cables to switch between separate calls thousands of times every

second – a process known as multiplexing. For this to work, the computers, located miles apart, must be able to determine which conversation is being sent when so that they can join the sections back together again in the correct sequence. This requires precise synchronisation, which is supplied by a GPS-based timing system.

#### ● *Time-keeping services*

The GPS is increasingly being used to provide accurate time-keeping in many areas of human activity, such as financial services, computer systems, energy supply and security.

#### ● *Location-based services*

GPS navigation systems can, of course, now be incorporated into vehicles and are increasingly built into mobile phones. This relatively new application expands the potential of the GPS immensely. When combined with internet services, it can provide a personalised weather service or be used to find the nearest cashpoint or restaurant, or even a lost child. In this way it becomes a significant aid to society and commerce, enabling vehicles such as taxis to be tracked or providing a conduit for directed advertising.

### Current developments

Europe is now implementing an alternative satellite-based positioning system called Galileo. Initiated by the European Commission and the European Space Agency (ESA), it is designed to work alongside the US GPS and also the Russian Glonass system. Galileo comprises 30 satellites and a ground support network, which aims to provide a guaranteed service in all but the most extreme circumstances (unlike the present GPS service). It will also provide coverage of even the remotest locations with much more accurate positioning to less than 1 m (compared with 20 m for the GPS). When this reliability and accuracy is achieved, Galileo will be suitable for safety-critical actions, such as landing aircraft, and it will be a major aid to air-traffic control, particularly in poor weather conditions. The satellite constellation should be complete by 2013.

The UK plays a major role in Galileo. Through ESA, of which it is a member, the UK was involved in developing the design concepts. It has a strong synergy with the space-science arm of ESA, which involves collaborations of academic physicists in developing new space-based technologies. The first Galileo satellite, GIOVE-A, launched in 2005, was built by Surrey Satellite Technology Limited – a spin-out company from the University of Surrey. The second satellite, GIOVE-B, launched in 2008, was built by Astrium and Thales Alenia Space. Astrium is an aerospace subsidiary of the European Aeronautic Defence and Space Company, based in Portsmouth and Stevenage.

### Impacts

Britain is a world leader in the manufacture of satellites. The space industry is currently worth £7 bn to the UK economy and the sector is growing rapidly. Galileo will underpin a range of new business opportunities. One recent study found that, between 2013 and 2025, Galileo is likely to bring economic benefits to the UK economy of tens of billions of pounds. The UK is also strongly positioned to develop novel services that will exploit the accurate position and timing data from the GPS and Galileo.

The UK could benefit further if Cardiff is successful in bidding to host the Galileo Supervisory Authority, which will own Galileo assets, oversee its contractors and regulate its services. Cardiff Bay has the advantage that it will be the first area in the world

where all domestic and business connections are linked through a new-generation advanced software-driven communications network (BT's 21CN project).

### Key facts and figures

- UK physicists developed the world's most accurate time-keeping device, the atomic clock, which is used in GPS.
- The UK is involved at every level in developing the next generation of satellite navigation technologies.
- The European Commission has estimated that 100 000 high-skill jobs will be created with the advent of Europe's new satellite navigation system, Galileo, establishing a market worth around €10 bn per year.
- The economic benefits of Galileo to the European aviation and shipping segments are estimated to reach €15 bn by 2020.

### Useful links

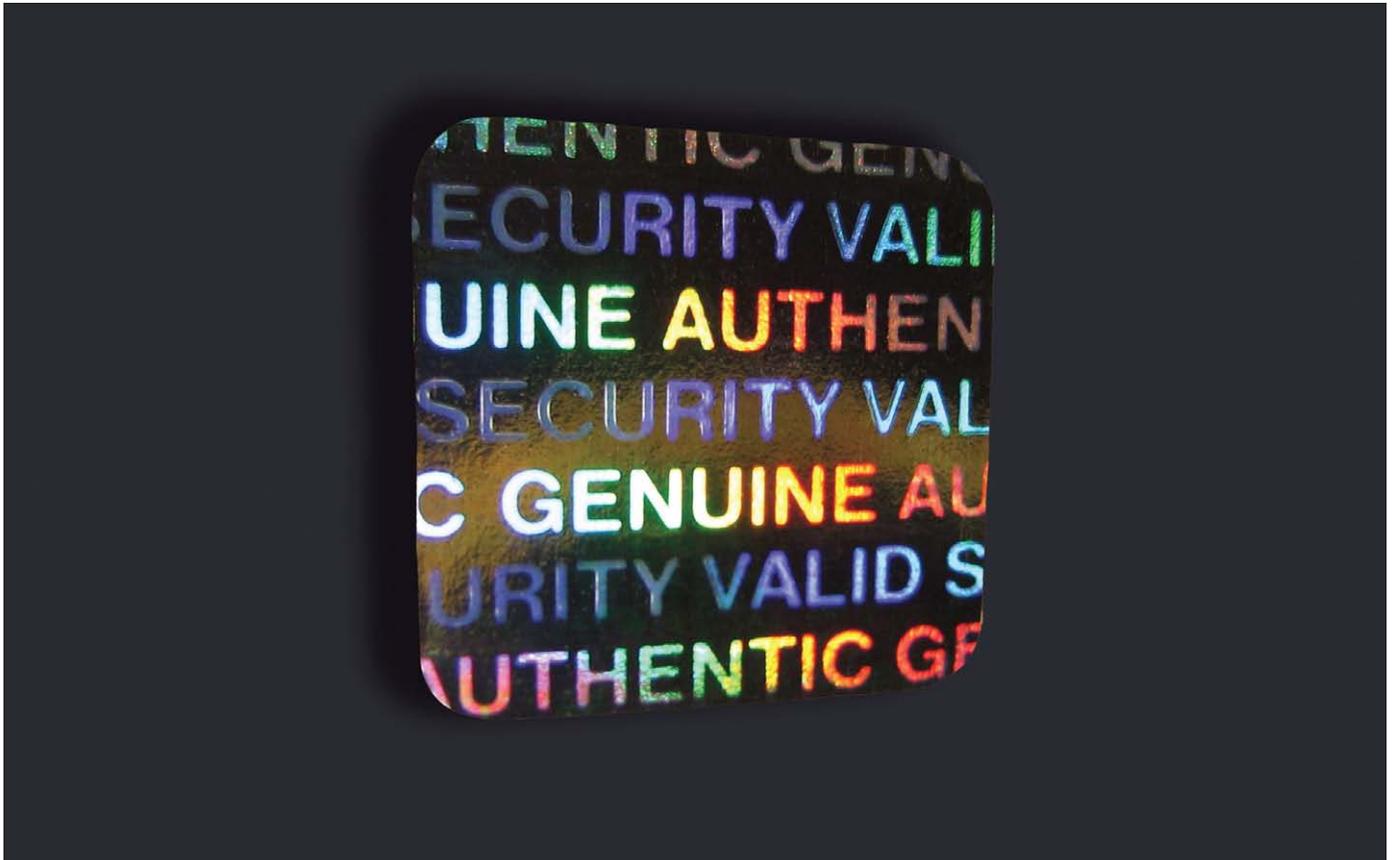
- [http://en.wikipedia.org/wiki/Global\\_Positioning\\_System](http://en.wikipedia.org/wiki/Global_Positioning_System)
- [www.trimble.com/gps/index.shtml](http://www.trimble.com/gps/index.shtml)
- [www.rand.org/pubs/monograph\\_reports/MR614/MR614.appb.pdf](http://www.rand.org/pubs/monograph_reports/MR614/MR614.appb.pdf)
- [www.npl.co.uk/server.php?show=ConWebDoc.560](http://www.npl.co.uk/server.php?show=ConWebDoc.560)
- [www.npl.co.uk/server.php?show=nav.390](http://www.npl.co.uk/server.php?show=nav.390)
- [www.esa.int/esaNA/galileo.html](http://www.esa.int/esaNA/galileo.html)
- [www.dft.gov.uk/pgr/scienceresearch/technology/downstreamstudy?page=10](http://www.dft.gov.uk/pgr/scienceresearch/technology/downstreamstudy?page=10)

● Thanks go to Mike Hapgood, Rutherford Appleton Laboratory, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# Holography

A technique creating three-dimensional images based on the physics of light waves, and invented in the UK, has a range of applications – from security to data storage.



## What is holography?

Holography refers to the technique of recording the patterns of light waves that are scattered from an object and then using the resulting information to reconstruct a three-dimensional image that appears to the viewer exactly as it was when it was recorded. The image changes in position and orientation just as the real object would when viewed from different angles – unlike a simple two-dimensional photograph, which records the scattered light as seen from only one viewer position. Using both eyes, the viewer can also obtain stereoscopic, depth information, just as they can when viewing a real scene. The process depends on encoding the optical information as a complex field of interfering light waves. Each point in the resulting hologram contains all of the encoded information that is needed to reconstruct the whole original object in three dimensions.

Until the 1990s, holograms were considered to be exotic curiosities, belonging to the realms of science fiction and seen only occasionally in museums and art galleries. However, thanks to a series of technological advances, they have now become commonplace. They can be printed cheaply and are not easily replicated. They provide a secure measure against counterfeiting and as a result they can be found on credit cards, passports and banknotes. The underlying technology is used in supermarket checkout scanners, and in CD and DVD players. Holography

also provides an efficient method of capturing and storing data, and is of increasing interest in advanced optical information processing. Holograms are also finding use as convenient, inexpensive medical diagnostic sensors and monitors of plankton distribution in the oceans.

## The science

The development of holography, like many physics discoveries that have led to the development of ground-breaking technologies, was the incidental result of research into another field – improving the resolution of electron microscopes (electrons, like light, can be regarded as waves). The work was carried out by a Hungarian-born physicist, Dennis Gabor, at the British Thomson-Houston Company in Rugby, which filed a patent for the invention in 1947. In 1948 he moved to Imperial College London, where he spent the rest of his career.

To make a hologram, a light beam scattered from an object falls on the recording medium. A reference beam illuminates the medium so that interference occurs between the two beams. (Two light waves in phase will reinforce each other; out of phase they will cancel each other out to produce an interference effect.) The resulting varying field of light appears random, but when the reference beam shines again on the hologram, the object is revealed. The recording wave and reference wave must bear



a constant phase relationship with each other. This therefore requires sources of light in which the waves are in phase and thus of one colour – a “coherent” source. Gabor’s light source was a mercury arc lamp, which limited what he could achieve.

In fact, there were no significant advances in holography until the first demonstration of the laser by physicist Theodore Maiman at Hughes Research Laboratories in 1960. Lasers provide the necessary coherent light, so the following years saw a resurgence of interest in holography. In curiosity-driven research, Emmett Leith and Juris Upatnieks at the University

of Michigan in the US made the first transmission holograms of three-dimensional objects, using a laser and a technique borrowed from radar. Around the same time, Yuri Denisyuk in the Soviet Union produced a white-light reflection hologram, which could be viewed with an ordinary light bulb. In 1968 Stephen Benton at the Polaroid Research Laboratories invented the rainbow transmission hologram, which eventually made possible the mass-production of embossed holograms stamped onto a plastic surface. The arrival of low-cost solid-state lasers (invented by physicists), mass-produced for applications such

## Timeline

<b>1947</b>	UK-based physicist Dennis Gabor invents holography.
<b>1960</b>	The laser is invented, providing the coherent light source needed for holography research to flourish.
<b>1962</b>	Soviet physicist Yuri Denisyuk invents the white-light reflection hologram.
<b>1962</b>	Emmett Leith and Juris Upatnieks create transmission holograms at the University of Michigan.
<b>1965</b>	Robert Powell and Karl Stetson, also at the University of Michigan, publish the first paper on holographic interferometry.
<b>1967</b>	T A Shankoff of Bell Labs and Keith Pennington at IBM develop the use of a dichromated gelatin as a holographic recording medium.
<b>1968</b>	Stephen Benton invents white-light transmission holography while researching holographic television at Polaroid Research Laboratories.
<b>1971</b>	Dennis Gabor receives the Nobel Prize in Physics for his 1947 invention and development of holography.
<b>1972</b>	American physicist and holographer Lloyd Cross develops the integral hologram by combining white-light transmission holography with conventional cinematography to produce moving three-dimensional images.
<b>1980</b>	E G Williams and J D Maynard at the Penn State University invent near-field acoustical holography. This has been used to study vehicle and aircraft vibrations as well as violins.
<b>1983</b>	MasterCard International, Inc., becomes the first organisation to use hologram technology in bank-card security as a mark of authenticity. Holograms have become one of the most common public security features on branded goods and valued documents.
<b>1988</b>	A photopolymer film is developed by Polaroid, which allows very bright reflection holograms to be mass-produced.
<b>1999</b>	Geola (General Optics Laboratory) a small corporate group of four companies based in the UK and Lithuania, patents printers for colour digital hologram printing with pulsed lasers.
<b>2008</b>	Savas Tay and colleagues at the University of Arizona, Tucson, develop a novel rewriteable thin-film polymer in which high-resolution holographs can be created in minutes. Normally holographic image creation is a lengthy and delicate process. The material remains stable throughout hundreds of write and erase cycles. These holograms are potentially useful for surgeons to guide them during operations, or for pharmaceutical researchers to study molecular interactions for new drugs during simulations.

as DVD players, also rapidly increased the applicability of holographic techniques in a range of technologies.

## Applications

Holography is used in applications as wide-ranging as precision measurement and biomedical research.

### ● *Measurement and imaging*

Gabor's original intention – to improve optics with holography – is now realised. Holographic interferometry is used to measure the position of objects to a precision of fractions of the wavelength of light. It is often applied to transparent media, to analyse and visualise flowing fluids, and to measure stress, strain and vibration in engineering structures. Holography can improve the resolution of optical microscopes – a technique known as interferometric microscopy. Thanks to these techniques, resolution approaching a quarter of the wavelength of light used in recording is now possible, and it allows for the imaging and manipulation of events on a molecular (nano) scale.

Holograms are generated from encoded wave patterns, and this concept can be applied to many kinds of wave, including X-rays and sound waves. Acoustic holography, for example, uses an array of pressure and/or particle velocity transducers to measure sound fields. This is particularly useful in vehicle and aircraft design. As new intense, coherent X-ray sources come online, X-ray holography becomes possible, offering the potential to image the behaviour relevant to novel advanced materials at the scale of atoms.

### ● *Sensors*

A particularly interesting use of holograms is as sensors. Spin-out company Smart Holograms, started by physicists and biochemists at the University of Cambridge, is producing responsive holograms that can test for tiny amounts of water

**“The underlying physics of holography will continue to be exploited in novel optical technologies predicted to have a strong commercial future.”**

in materials or can be modified for medical diagnosis. The hologram is recorded in a gel, the optical properties of which are changed by contact with the material being analysed. The company developed an inexpensive blood-glucose monitor that enables diabetics to measure their glucose levels continuously. Similar technology may soon yield a rapid anthrax-identification system for the emergency services dealing with terrorist threats.

### ● *Holographic optical tweezers*

One unusual application of the holographic concept is in using intense laser light to trap and manipulate microscopic objects (optical tweezers). Holographic optical tweezers involve using computer-generated holograms to create a pattern of optical traps, which have applications in areas as diverse as biomedical testing and diagnostics, biological and chemical sensor fabrication, and complex nanostructured materials. The UK is heavily involved in this field of research.

### ● *High-speed imaging and processing*

Some holograms record information in real time, opening up

applications such as optical cache memories, image processing and optical computing. Operations are performed in parallel on the entire image, which means that a large amount of information is processed simultaneously. This field is known as dynamic holography. A unique underwater camera that captures three-dimensional images of living organisms in their natural environment in a non-intrusive and non-destructive way has been developed by researchers at the University of Aberdeen to gain insight into the ocean environment. To date, eHoloCam has recorded more than 290 digital undersea holographic videos and demonstrated the deepest-known deployment of holography more than 400 m below sea level in the North Sea. Industry partner CDL is now developing the camera for commercial applications. Archaeologists, too, are creating holographic archives of valuable or fragile museum artefacts. The 2300-year-old Iron Age man unearthed at Lindow Moss, a peat bog in Cheshire, has been immortalised by pulsed laser holography, a widely used technique using rapid bursts of laser light that can also capture images of high-speed events.

## Current developments

One of the most exciting future applications of holography is in storing and accessing data. Currently, billions of gigabytes of data are generated globally each year, and the figure is growing, so new data-storage methods are needed. In the next decade or so, surface storage media, such as computer hard drives and DVDs, are predicted to be replaced by holographic data storage, which would enable data to be encoded in a three-dimensional volume. Many holograms could be recorded within the same space. Recent advances in other physics-based technologies (e.g. new light sources, detectors) have led to considerable progress in holographic data storage. Companies such as Optware and Maxell are planning to release a type of optical disk called a holographic versatile disc, which uses a holographic layer to store up to 200–300 gigabytes of data, with prospects of increasing the amount to 3.9 terabytes. Another company, InPhase Technologies, is developing a competing format.

The science-fiction concept of free-standing moving holograms may still be on the horizon, but mobile handsets that project, capture and send three-dimensional images have already been developed by Indian company Infosys, and these will be on the market by 2010. In addition to three-dimensional films, games and virtual goods, the handsets may help accident investigators, teachers and doctors to work remotely by instantly relaying realistic depictions of car damage, injuries, medical scans or educational aids. A large European Commission-funded project to develop three-dimensional TVs, in which UK scientists took part, has been completed, but it may be at least another decade before true three-dimensional video displays are available.

## Impacts

Holography is a highly profitable sector and has been growing by 30% a year over the past 15 years. According to Global Industry Analysts, Inc., the world industrial holography market is projected to reach \$11.33 bn by 2010. Sales of surface holograms for security, printing and packaging are estimated to be \$19.5 m a year. This is not surprising given that at least 6% of world trade – \$200 bn per year – involves counterfeit goods, and embossed holograms offer a cheap method of authentication. When holographic storage disks enter the mass market, then clearly the economic returns will be huge for the companies that develop

and make them. The underlying physics of holography will also continue to be exploited in novel optical technologies predicted to have a strong commercial future.

## Key facts and figures

- Modern holography is the product of more than 60 years of research.
- Its British-based inventor, Dennis Gabor, was awarded a Nobel Prize in Physics.
- Holography is a unique tool benefiting many fields, including security and data storage, biomedical applications, vibration analysis and high-resolution imaging.
- UK researchers are at the cutting edge of developing new applications, from the fabrication of novel materials to underwater research and three-dimensional televisions.
- A holographic data-storage disk could store 4 million million bytes of data – compared with the latest Blu-ray optical disk, which holds up to 50 gigabytes (1000 million bytes).

## Useful links

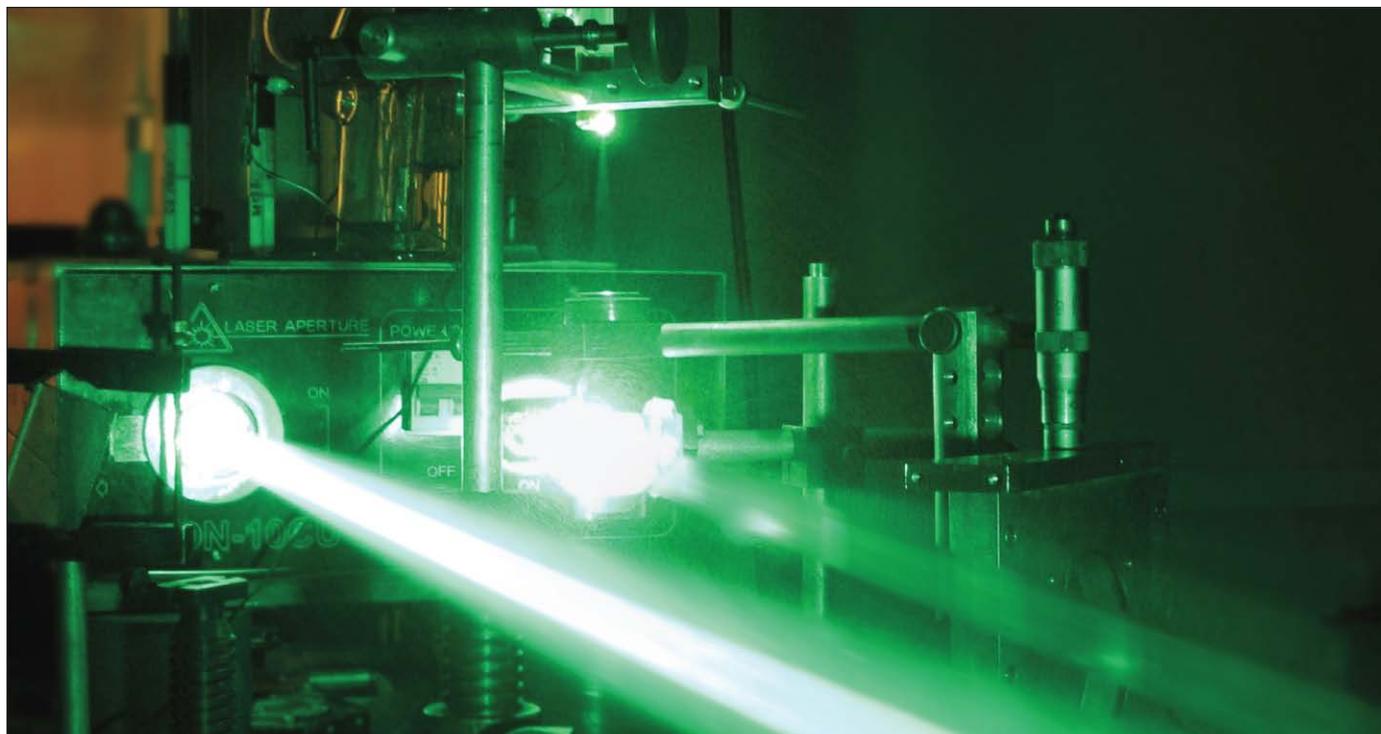
- [www.3dtv-research.org/index.php](http://www.3dtv-research.org/index.php)
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- [www.holophile.com/history.htm](http://www.holophile.com/history.htm)
- [www.research.ibm.com/journal/rd/443/ashley.html](http://www.research.ibm.com/journal/rd/443/ashley.html)
- <http://physicsworld.com/cws/article/print/32689>

● Thanks go to John Watson, University of Aberdeen, Helen Carmichael and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# Lasers

Lasers provide the archetypal example of how a discovery in basic physics led to an invention, several decades later, that was unpredictably world-changing.



## What are lasers?

Lasers are devices that emit narrow beams of intense electromagnetic radiation (light). The term laser originated as an acronym for “light amplification by stimulated emission of radiation”. A laser beam has the special property that the light waves emitted are all in step with one another – coherent – and usually of one wavelength, or colour. There are many different kinds of lasers, from giant installations emitting powerful pulses of high-energy radiation, such as X-rays, to tiny devices etched onto semiconductor chips producing infrared light. Many different kinds of material can be made to “lase” – such as gases, crystalline solids, glasses and polymers – and which one is used depends on the application. Some lasers are designed to emit a continuous beam while others can spit out rapid pulses of light that are ultra-short. The wavelengths of light generated by certain types of laser can even be “tuned” for specific applications, making them extremely versatile.

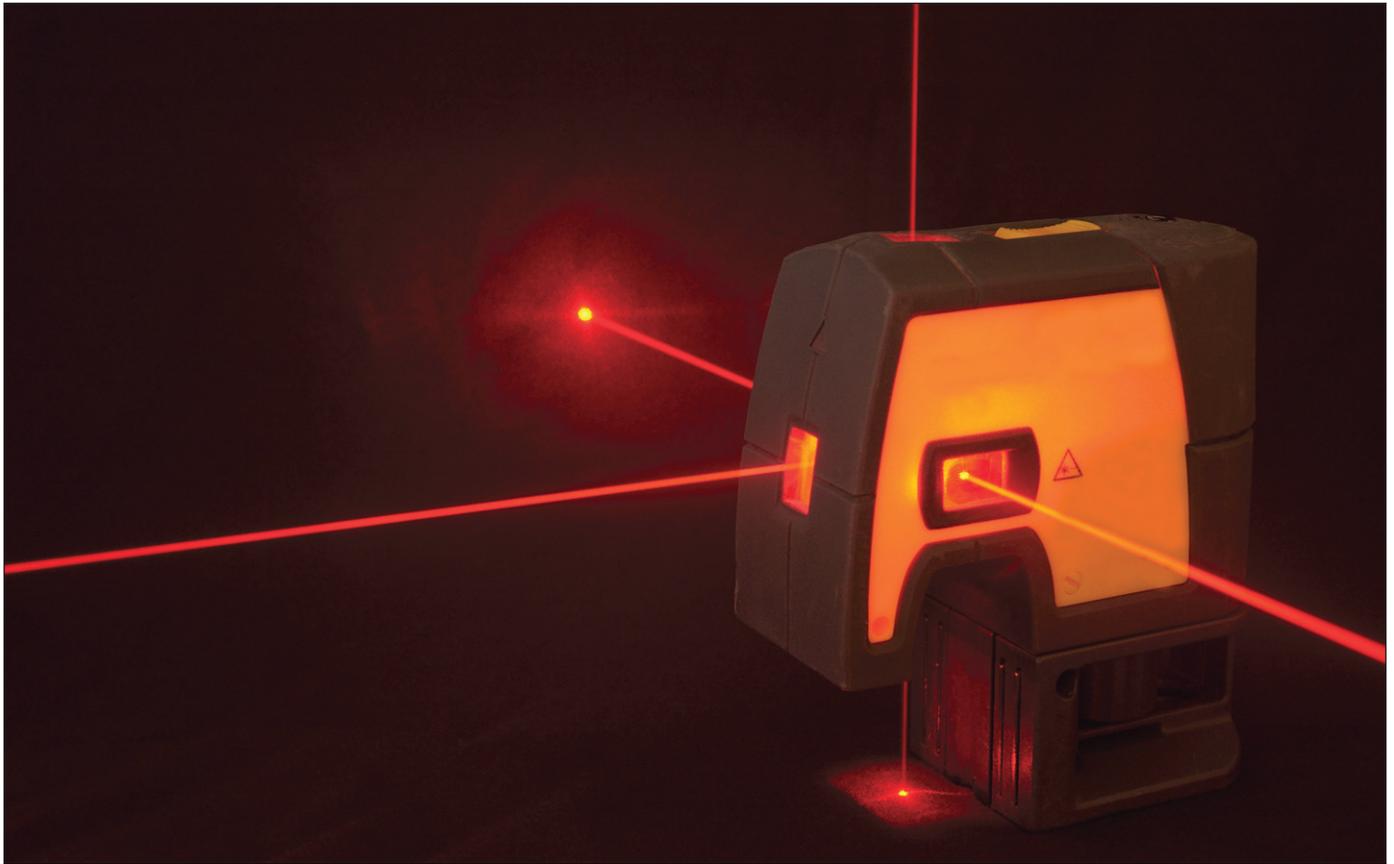
Lasers offer a way of generating, controlling and directing intense light in remarkable ways, yet when they were first invented, physicists were not sure what they could be used for – they were famously described as a “solution looking for a problem”. In fact, although the first laser was constructed in the 1950s, practical applications did not appear until a couple of decades later – as is often the case in science. Since then, thanks to research activity in both university physics departments and companies, including those in the UK, lasers have become ubiquitous and are central to many technologies that are used in manufacturing, communications, medicine and

entertainment. Today, lasers are key tools in manipulating and communicating information (in CD and DVD players, supermarket barcode readers and broadband telecommunications), in measurement (surveying and environmental studies), chemical analysis (of foods, medical specimens and materials) and, increasingly, in transforming materials (welding, cutting and etching, printing, and surgery).

Research into lasers continues apace – new types of laser are being developed with a variety of characteristics and potential applications. In some cases, the result is a cheaper, more compact portable device designed for a specific use, or a more powerful laser used to generate power, for instance. UK university physics departments are at the forefront of many of these areas. In particular, physicists in the Central Laser Facility (CLF) at the Rutherford Appleton Laboratory develop novel high-powered laser systems and make them available for both pure and applied research.

## The science

The laser would never have been developed without a profound understanding of an area of fundamental physics – quantum theory. The principle behind the laser goes back to the world’s most famous physicist, Albert Einstein, who in 1917 proposed a theory of stimulated light emission. Einstein had previously shown that light was composed of tiny packets of wave energy called photons (the wavelength depending on the energy). He theorised that if the atoms that make up a material are given excess energy and so emit photons, these photons could



**“Without lasers, many recent discoveries would never have been made, which illustrates the synergistic relationship between developments in physics and in other fields.”**

stimulate nearby atoms to emit further photons, creating a cascade effect. All the photons would have the same energy and wavelength and move off in the same direction.

However, it was not until 40 years later that physicists were able to convert this idea into a practical laser. The principle is that the “active” material has first to be pumped with energy from another light source or an electrical current. The resulting stimulated light emission is then amplified by bouncing the light back and forth through the lasing material in a mirrored cavity, so stimulating more emission, before it escapes through a transparent mirror section as a laser beam. A device that amplified microwaves was constructed in 1953 by Charles Townes and colleagues at Columbia University. Townes shared a Nobel Prize in Physics in 1964 with Nikolay Basov and Aleksandr Prochorov of the Lebedev Institute in Moscow (who independently also demonstrated what came to be called a maser). The next few years saw a race to build the first visible light laser. Theodore Maiman at Hughes Research Laboratories in California pipped Townes and his team at the post when he built the first working laser in 1960 using ruby as a lasing medium –

although who should be credited for the laser’s invention was then hotly contested.

Initially the laser concept was not taken very seriously, nevertheless the 1960s saw a huge expansion in laser research including the development of high-power gas lasers, chemical lasers and semiconductor lasers. However, they were still rather specialised research tools. By the 1970s, semiconductor lasers that worked at room temperature had been developed and this led to the advent of the compact disc (CD).

Without the discovery of lasers, the entire fundamental field of cold atoms would never have opened up. Research in this field has led to the award of several Nobel Prizes in Physics, including the discovery of Bose–Einstein condensates (BEC). BEC has opened the door to a host of applications such as atom lasers, improved atomic clocks and quantum computers.

Today, semiconductor diode lasers are the most common type, found in industry, commerce and the home.

## Timeline

<b>1917</b>	Albert Einstein develops the concept of stimulated emission of photons.
<b>1928</b>	The process of stimulated emission is confirmed by US physicist Rudolph Landenburg.
<b>1947</b>	Physicist Willis Lamb demonstrates stimulated emission for the first time. Lamb was awarded the Nobel Prize in Physics in 1955 while at the University of Oxford.
<b>1953</b>	Charles Townes at Columbia University, Alexander Prokhorov, Nikolai Basov at the Lebedev Institute of Physics in Moscow and Joseph Weber at the University of Maryland independently invent the maser.
<b>1957</b>	Physicist Gordon Gould conceives the laser and coins the term. He failed to file for a patent for his invention until 1959. As a result, Gould's patent was refused and his technology was exploited by others. It took until 1977 for Gould to win his patent war and receive his first patent for the laser.
<b>1958</b>	Arthur Schawlow and Charles Townes publish a paper describing an optical maser (the laser), independently of Gould's research.
<b>1960</b>	Theodore Maiman at the Hughes Research Laboratory constructs the first optical laser, based on a ruby.
<b>1961</b>	Ali Javan, working with William R Bennett and Donald Herriot, makes the first gas laser using helium and neon at Bell Laboratories.
<b>1962</b>	Robert Hall at General Electric Laboratories invents the semiconductor diode laser. It is still used today in everyday appliances and in telecommunications.
<b>1964</b>	Charles Townes, Alexander Prokhorov and Nikolai Basov share the Nobel Prize in Physics for their fundamental work, which led to the construction of the laser.
<b>1964</b>	The first working Nd:YAG laser and the CO <sub>2</sub> laser are developed at Bell Telephone Laboratories.
<b>1964</b>	The argon ion laser is developed at Hughes Research Laboratories.
<b>1965</b>	The first chemical laser is developed at the University of California, Berkeley.
<b>1966</b>	The first dye laser is demonstrated at IBM Laboratories.
<b>1970</b>	The excimer laser is developed at the Lebedev Laboratories, Moscow. Excimer lasers are now used in eye surgery.
<b>1973</b>	The first laser barcode scanner is installed in a supermarket.
<b>1975</b>	Diode Laser Laboratories of New Jersey introduces the first commercial room-temperature semiconductor laser.
<b>1977</b>	John Madey's research group at Stanford University introduces the first free electron laser.
<b>1977</b>	Vulcan, the UK's high power laser for X-ray and plasma research is commissioned.
<b>1978</b>	The laserdisc player is introduced – the first successful consumer product to include a laser.
<b>1980</b>	Geoffrey Pert's research group at the University of Hull reports on X-ray lasing action for the first time.
<b>1984</b>	Researchers at the Lawrence Livermore National Laboratory report on the demonstration of a laboratory X-ray laser.
<b>1985</b>	Compact discs are introduced. A low-power laser beam reads data that have been encoded in the form of tiny pits on an optical disc. The drive then feeds the data and converts the signal into music.
<b>1985</b>	Arthur Askin of Bell Laboratories invents laser tweezers to manipulate atoms, molecules and biological cells, using the radiation pressure of a focused laser beam.
<b>1994</b>	Laser technology is first trialled in the UK to inform drivers of excess speed.
<b>1997</b>	Steven Chu, Claude Cohen-Tannoudji and William Phillips share the Nobel Prize in Physics for the development of methods to cool and trap atoms with laser light.
<b>2001</b>	Eric Cornell, Wolfgang Ketterle and Carl Wieman share the Nobel Prize in Physics for the discovery of Bose–Einstein condensates.
<b>2005</b>	John Hall and Theodor Hansch share the Nobel Prize in Physics for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique.
<b>2007</b>	The laser industry is estimated to be worth \$6 bn.

## Applications

### ● Information technology

The largest application of lasers is in optical storage devices (e.g. CD and DVD players), in which a focused beam from a semiconductor laser, less than 1 mm wide, scans and reads the disc surface. Other everyday uses include barcode readers, laser printers and laser pointers. Over the past 25 years the publishing and newsprint industries have been revolutionised by the use of lasers, which have replaced traditional “hot metal” printing.

### ● Telecommunications

The second largest application is in fibre-optic communications. Broadband depends on the transmission of light pulses along

optical fibres, which are generated and relayed via lasers. This is made possible by fibre amplifiers, invented in the UK, which are an important component in long-distance fibre links.

### ● Medicine

Lasers can deliver concentrated energy in the form of fine controllable light beams, so physicians soon took advantage of them to perform micro-surgery, which involves less pain and scarring, lower blood loss and shorter recuperation time in hospital. Laser beams delivered via flexible optical fibres allow surgeons to reach inside the gut, for example, and seal a bleeding ulcer. One of the most publicised uses of lasers is in eye surgery to treat disease and, increasingly, improve bad eyesight.

### ● *Manufacturing*

Lasers can deliver enough power to heat and melt metal joints, and so are used for welding, as well as for cutting. When controlled by a computer, a laser can cut complex designs into a material such as wood or paper, as is increasingly being seen in furniture and other home goods.

### ● *Measurement and analysis*

Lasers have long been used by the military for range-finding, but now even estate agents employ laser tape measures. Because lasers can be tailored to produce specific wavelengths, they are used to analyse chemical and physical structure, and so are used in factory quality control and to monitor environmental pollutants remotely. Lasers can be used for a type of measurement called interferometry which can measure tiny changes in distance.

### ● *Scientific research*

Virtually every university science department in the UK relies on lasers for some aspect of its research programmes – they have become indispensable research tools. Without lasers, many recent discoveries would never have been made, which illustrates the synergic relationship between developments in physics and other fields. Lasers interact with matter at the quantum level in very specific ways and so are important probes in research. They can be used to follow chemical reactions and elucidate structure at the atomic and molecular scale. Increasingly, life scientists are employing lasers in new types of microscopy designed to highlight cellular structures.

## Current developments

Physicists are continually developing new lasers and many UK teams are involved in these projects. These include nanoscale devices that emit light and that are expected to find use in chemical and biological sensors on “lab-on-a-chip” devices. The University of St Andrews, for example, has developed laser optical tweezers to manipulate biological cells to contribute to the burgeoning area of biophotonics. Several UK research groups are developing a new semiconductor laser called the quantum cascade laser, which promises to be an excellent source of terahertz radiation (between infrared and microwaves) now being introduced for national security screening. New laser technology will also play a role in developing the all-optical computer.

Researchers at the universities of Bath and Southampton pioneered a type of laser based on micro-structured optical fibres, which can produce light across the entire visible spectrum. Fibre lasers can be made to emit low-power light, allowing physicists to manipulate single photons. These are needed for fundamental experiments aiming to explore strategies underpinning the developing concept of quantum computing, which would allow the processing of unbelievable amounts of data, and also quantum cryptography, which offers an ultra-secure means of transmitting data.

Fibre lasers may also provide the next generation of very high power devices, producing X-rays for many kinds of enabling research, particularly in the life sciences. The European X-ray free electron laser (XFEL), a large facility being constructed in Germany, is expected to offer X-rays at intensities not achieved before, and the UK is supporting this project. The UK’s CLF also hopes to host the world’s most powerful laser set-up, HiPER, which could demonstrate nuclear fusion as a potential clean, renewable source of energy.

Looking further ahead, researchers are undertaking nuclear physics research that could eventually lead to a gamma-ray laser

to store nuclear energy, while exploitation of the atom laser might produce a whole gamut of new, and probably unanticipated, applications for the future.

## Impacts

Lasers have become a multi-billion dollar industry. Even by 1994, the US National Academy of Sciences estimated that the economic impact of laser technology was \$100 bn a year. In 2004, excluding diode lasers, about 131 000 lasers were sold worldwide with a value of \$2.19 bn, and about 733 million diode lasers valued at \$3.2 bn. In 2008, the rapidly growing fibre-laser market alone was worth \$240 m and is expected to reach \$500 m by 2011.

Lasers are one of the most important enabling technologies to have been developed in the past 50 years and it is difficult to evaluate their impact. Lasers not only drive the modern information economy, allowing data to be transferred quickly across the internet and to be stored economically and efficiently, but they are also an essential research tool without which modern science, technology and medicine would not progress.

## Key facts and figures

- Lasers are essential for optical communications, on which the information superhighway depends, and for high density optical information storage devices among many other applications.
- Lasers are now used in almost every field of human activity.
- The physicists investigating the principles leading to the laser had no applications in mind, and it was not obvious for some years what the applications would be.
- The commercial use of lasers is now worth many billions of dollars a year.

## Useful links

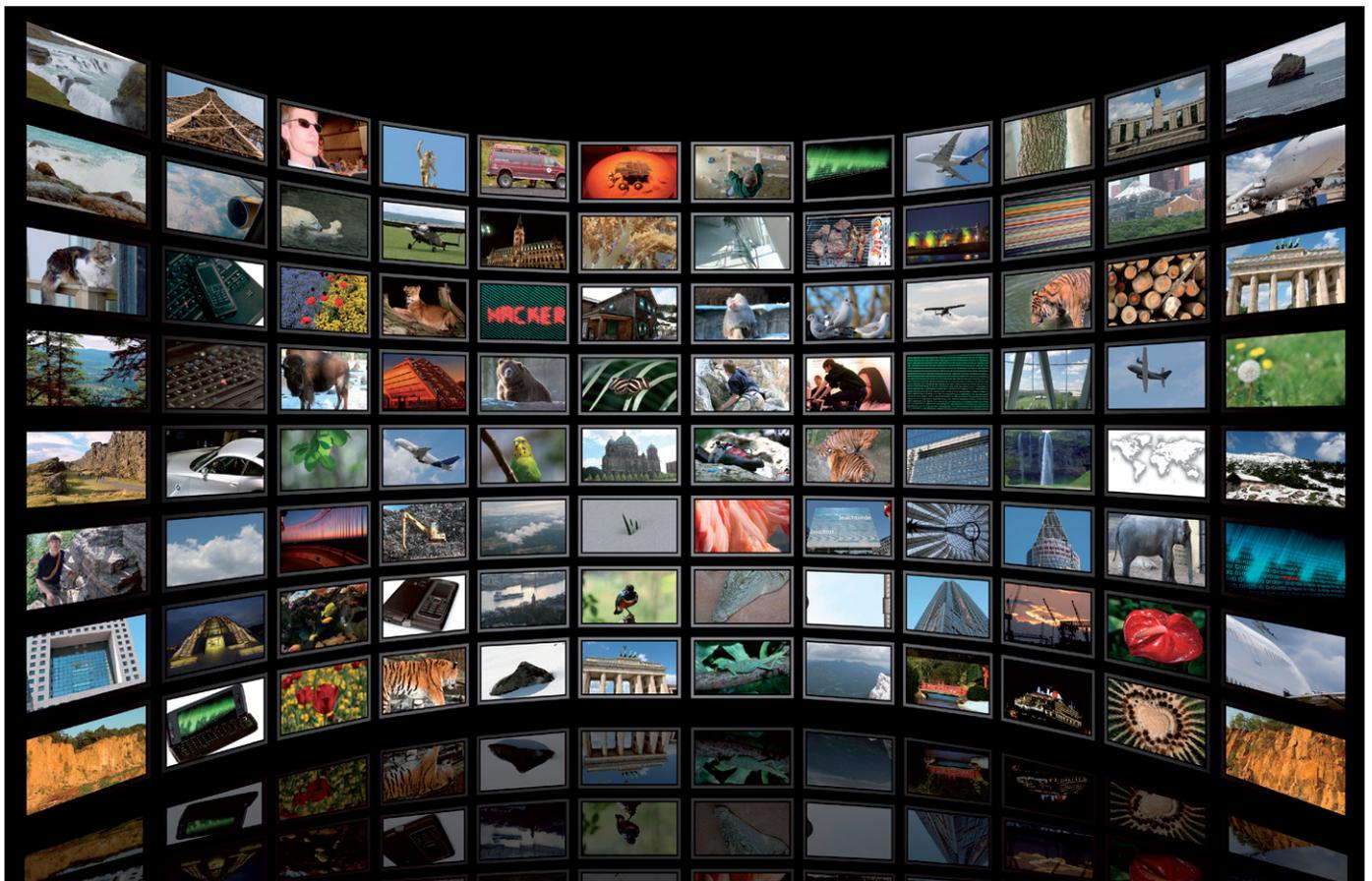
- <http://en.wikipedia.org/wiki/Laser>
- [www.clf.rl.ac.uk](http://www.clf.rl.ac.uk)
- [www.bell-labs.com/history/laser](http://www.bell-labs.com/history/laser)
- [www.orc.soton.ac.uk/61.htm](http://www.orc.soton.ac.uk/61.htm)

● Thanks go to Anne Tropper, University of Southampton, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# Liquid-crystal displays

Liquid-crystal displays have become the image-display technology of choice, following a long chain of physics-based R&D initiated by pioneering work in the UK.



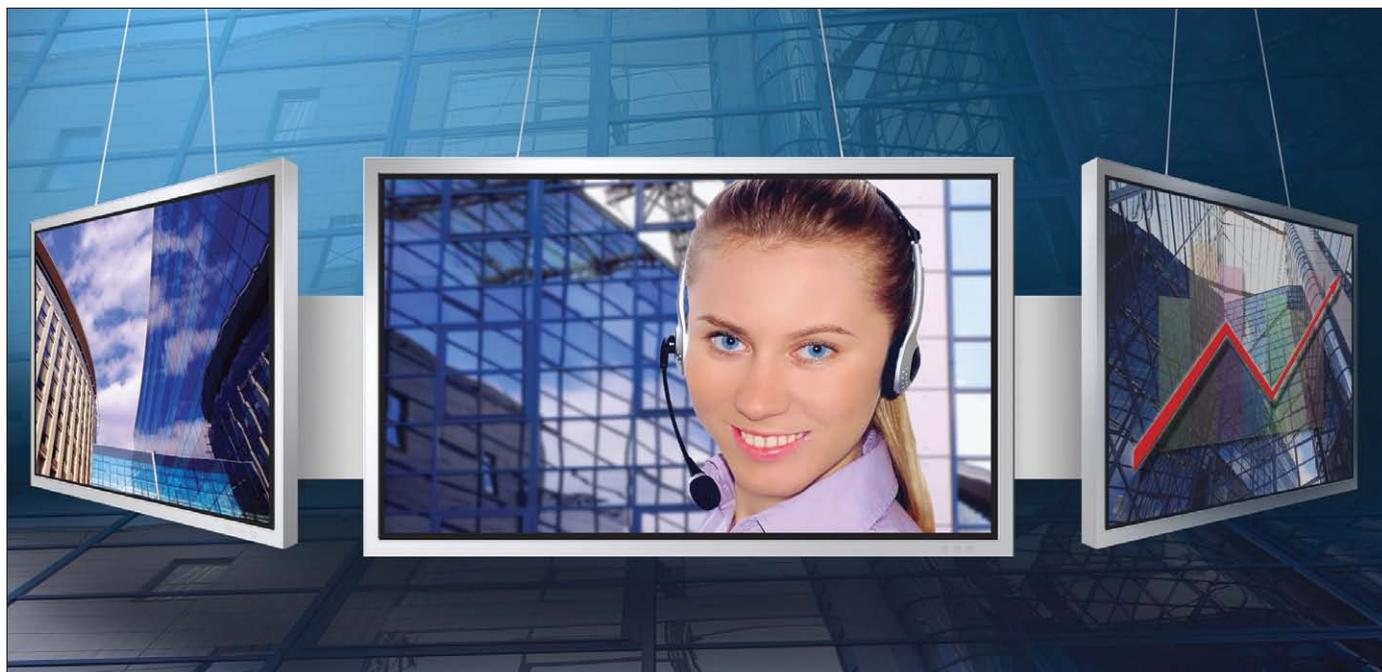
## What is an LCD?

A liquid-crystal display is a type of electrically generated image shown on a thin, flat panel. The first LCDs, seen in the 1970s, were tiny screens used mostly in calculators and digital watches displaying black numbers on a white background. Today, the latest LCD flat-panel TVs, which have largely replaced the traditional, bulky cathode-ray-tube kind, can produce high-definition colour images up to 108 inches on the diagonal. LCDs are now found everywhere – in home-electronics systems, mobile phones, cameras and computer monitors, as well as watches and TVs.

The technology is based on remarkable electrically sensitive materials called liquid crystals, which flow like liquids but have a crystalline structure. In crystalline solids, the constituent particles – atoms or molecules – sit in regular geometrical arrays, whereas in the liquid state they are free to move about

randomly. Liquid crystals consist of molecules – often rod-shaped – that organise themselves in the same direction but are still able to move about. It turns out that liquid-crystal molecules respond to an electrical voltage, which changes their orientation and alters the optical characteristics of the bulk material. It is this property that is exploited in LCDs.

An LCD display panel, on average, consists of thousands of picture elements (“pixels”), which are individually addressed by a voltage. They have become popular because they are thinner, lighter and have a lower voltage of operation than other display technologies, and they are perfect for battery-powered devices, for example. However, behind the large colour LCD TVs, which are now available in every superstore, are several decades of R&D. Physicists, chemists and technologists working together have had to solve many problems.



## The science

Liquid crystals were discovered by accident in 1888 by Austrian botanist Friedrich Reinitzer. He showed that a plant derivative, cholesteryl benzoate, had two melting points, becoming a cloudy liquid at 145 °C and turning clear at 179 °C. To seek an explanation, he passed his samples to physicist Otto Lehmann. Using a microscope fitted with a heating stage, Lehmann showed that the in-between cloudy state had optical properties typical of some crystals, yet was a liquid – and so the term “liquid crystal” was born.

It is understood that most liquid crystals, like cholesteryl benzoate, consist of molecules with long, rod-like structures. It is the combination of the attractive forces that exist between all molecules coupled with the rod-like structure that causes the liquid-crystal phase to form. However, the interaction is

not quite strong enough to hold the molecules firmly in place. Many different kinds of liquid-crystal structures have since been discovered. Some organise further into layers, while others are even disc-shaped and form columns.

Throughout the 1920s and 1930s, researchers studied the effects of electric and magnetic fields on liquid crystals. In 1929, Russian physicist Vsevolod Freedericksz showed that liquid-crystal molecules, in a thin film sandwiched between two plates, changed their alignment when a magnetic field was applied. This was the forerunner of the modern voltage-operated LCD. The first patent for a liquid-crystal device was taken out by the UK Marconi Wireless Telegraph company in 1936. However, it was not until after the Second World War that LCDs generated serious interest. As physicists started to develop ever-smaller electronic devices and integrated circuits for everyday appliances, it

Timeline	
1888	Botanist Friedrich Reinitzer synthesises cholesteryl benzoate, in which he first observes the liquid-crystal state.
1889	Physicist Otto Lehman publishes a paper on liquid-crystal behaviour, recognising that liquid crystals represent a new state of matter.
1922	Georges Friedel describes the structure and properties of liquid crystals and classifies them into three types (nematics, smectics and cholesterics).
1929	Vsevolod Fredericksz reports the use of a magnetic field to reorient an aligned layer of nematic liquid crystal. The electrical version of this switching effect is the basis of virtually all current LCDs.
1936	The first patent claiming a potential display application of liquid crystals is granted to the Marconi Company.
1958	UK theoretical physicist Sir Charles Frank brings together several existing ideas in a classic paper on the continuum theory of liquid crystals. His approach is the basis of the static modelling of LCDs and was later extended to include dynamics by Scottish mathematician Frank Leslie.
1968	Researchers at the RCA company report the first useful display based on liquid crystals – the dynamic scattering LCD.
1971	Physicists Martin Schadt and Wolfgang Helfrich invent the twisted nematic LCD.
1972	Physicist Peter Raynes collaborates with chemists George Gray and Ken Harrison to invent E7 – a mixture of several biphenyl liquid crystals – which is stable over the full temperature range necessary for electronic displays. E7 proves to be the standard material used for many years.
1972	Several companies are involved in producing LCDs and LCD watches. The Liquid Crystal Company manufactures the first twisted nematic LCD.
1973	Sharp produces the first portable calculator, using an LCD screen. The calculator using the twisted nematic LCD followed shortly.
1979	In the UK, physicists Cyril Hilsum and Tony Hughes make the first LCD picture elements switched by amorphous silicon thin-film transistors (TFTs), using TFTs made by physicists Peter LeComber and Walter Spear. This TFT/LC combination is used in most current display devices.
1979	A Queen's Award for Technological Achievement for LCDs is awarded jointly to the Solid State Physics and Devices Division of the Royal Signals and Radar Establishment, the University of Hull and BDH Chemicals.
1981	Physicists Peter Raynes and Colin Waters at RSRE Malvern invent the supertwisted nematic (STN) LCD, used in the first generation of mobile phones, personal organisers, laptops and PC monitors.
1985	Seiko-Epson unveils the first commercial LCD colour TV set, which has a 2 inch view.
1986	Mass-production of monochrome VGA STN LCDs is under way.
1992	Mass-production of 14 inch colour TFT LCDs is also under way.
1992	A Queen's Award for Technological Achievement for LCDs is conferred on the Optical and Display Science Division of the Defence Research Agency, Malvern, jointly with Merck Ltd, Poole.
2004	Philips demonstrates a 20 inch three-dimensional LCD at the CeBIT technology conference in Hannover, Germany.
2007	For the first time, LCDs surpass cathode-ray tubes in worldwide sales.
2008	Around 70% of the 200 million TVs sold in 2008 are LCDs.

**“LCDs now hold a dominant position in the displays market, challenged in only a few niche areas, and this is unlikely to change in the near future.”**

became clear there was a need for a compatible display technology. LCDs became a candidate.

The first devices, which were developed in the late 1960s, consisted of a thin film of liquid crystal sandwiched between glass slides coated with transparent electrodes. An applied

electric field disrupted the liquid-crystal alignment, transforming its appearance from transparent to opaque. These and subsequent devices were rather sensitive, for example, to temperature and did not last long. However, the breakthrough came in the UK when physicist Peter Raynes at the Royal Signals and Radar Establishment (RSRE) collaborated with chemists George Gray and Ken Harrison of the University of Hull in developing novel LCD materials that worked, were stable at room temperature and were suitable for mass-production. This interdisciplinary collaboration was crucial in advancing LCD technology. The RSRE research programme led by a physicist, Cyril Hilsum, resulted in a number of key device inventions, including the supertwisted nematic LCD, thin-film transistors (TFTs) for driving LCDs, the defect-free twisted nematic device and the zenithal bistable display. TFT LCDs, which incorporate a thin-film silicon transistor, are now the main technology used in TVs and computer monitors.

### Current developments

UK physics research groups have continued to work on improving liquid-crystal technology to produce faster, more stable LCDs with wider viewing angles. So-called ferroelectric liquid crystals



promise to produce faster-responding displays, and liquid crystals are being combined with carbon nanotubes with the aim of creating new types of optical device, such as three-dimensional displays. Based on university research, Scottish company Exxelis has developed LCD back-lighting technology that is four times as efficient and will substantially improve picture quality and prolong battery life. Meanwhile, a Japanese electronics company is devising highly reflective LCDs that do not need backlighting at all. Another organisation, ITRI in Taiwan, is making ultrathin, lightweight, flexible LCD displays built on a plastic substrate.

UK physicists have also played a major part in developing newer, competing display technologies. Richard Friend and his team at the Cavendish Laboratory at the University of Cambridge pioneered the development of polymer organic light-emitting diodes (P-OLEDs) in the late 1980s while undertaking basic research into the physics of conducting organic polymers. P-OLEDs are now being produced by the university spin-out company Cambridge Display Technology. They are currently used in small displays, such as mobile-phone screens, but large TVs are on the horizon. They promise to be thinner and more efficient, though may not have the lifetime of LCDs.

## Impacts

The technology behind the evolution of LCDs from simple displays for watches and calculators into fast colour displays for mobile phones, computer monitors and TVs has generated substantial revenue for the UK, through sales of materials and royalty income from device patents. One of the inventions at the RSRE – the so-called “supertwist display” – has resulted in royalty income to the UK in excess of £100 m.

The pace of technological development since the early 1990s has been fast, and it continues to increase. The global market for LCDs is currently approaching \$100 bn, having grown from around \$60 bn in 2005 (\$24 bn in 2003). LCD manufacture is truly global, with display production concentrated in the Far East and growing in central and eastern Europe. US firms lead the way in production technologies.

LCDs now hold a dominant position in the displays market, challenged in only a few niche areas, and this is unlikely to change in the near future.

## Key facts and figures

- A UK interdisciplinary team of physicists and chemists was instrumental in developing the materials that made the production of LCDs possible.
- LCDs now have a 70% share of the TV market.
- LCD TVs are only one-tenth of the thickness and significantly lighter in weight than equivalent cathode-ray tube TVs.
- LCDs are vision-friendly, electricity-efficient and have a significantly longer life-span than other displays, such as plasma screens.

## Useful links

- [www.colorado.edu/physics/2000/laptops/liqcrys.html](http://www.colorado.edu/physics/2000/laptops/liqcrys.html)
- [http://en.wikipedia.org/wiki/Liquid\\_crystal\\_display](http://en.wikipedia.org/wiki/Liquid_crystal_display)
- [www.plasma.com/classroom/what\\_is\\_tft\\_lcd.htm](http://www.plasma.com/classroom/what_is_tft_lcd.htm)
- <http://plc.case.edu/tutorial/enhanced/files/lcd/intro.htm>

● Thanks go to Peter Raynes, University of Oxford, Cyril Hilsum and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# Magnetic resonance imaging

Magnetic resonance imaging, based on ideas from nuclear physics and developed in the UK, is now a routine, safe, clinical technique for seeing inside the body and diagnosing disease.



## What is MRI?

Magnetic resonance imaging (MRI) is a powerful technique that relies on a combination of very strong magnets and radio waves to obtain detailed images of the body's interior. It allows doctors to diagnose and treat patients rapidly and effectively.

Though capable of imaging almost every part of the body, MRI is most commonly used for examining the brain, the cardiovascular system, the musculoskeletal system and the abdomen. Whereas X-rays cannot distinguish the detailed structure of soft tissues, MRI can produce high-resolution images that show up damaged and abnormal tissue. The latest MRI machines can reveal physiological function, such as the motion of the wall of the heart, the perfusion of blood through organs

and digestion in the stomach. Functional MRI, as it is called, even allows researchers to image neurological changes in the brain that are associated with feelings such as hunger. As an emergency medical tool, MRI can detect and diagnose strokes quickly, limiting damage and allowing immediate treatment, and thereby promoting recovery.

MRI has many practical benefits for the clinician and patient alike. Patients require no preparation and there is no recovery time. It is non-invasive and can be used when exploratory surgery may be too dangerous. MRI does not deliver doses of ionising radiation that might damage tissues, so it is particularly suited to cases when a patient is to undergo several successive examinations within a short period. Indeed, the lack of harmful



effects on the patient and the operator make MRI well suited to “interventional radiology”, where the images produced by an MRI scanner are used to guide surgical procedures. This approach is ideal for operations on small children and babies.

Designed by British medical instruments firm EMI, collaboratively with others, full-body MRI scanners were first introduced to hospitals in the late 1980s. MRI is now a standard diagnostic tool in most hospitals, improving treatment, cutting waiting times and saving lives.

### The science

MRI depends on a fundamental property of matter – that certain atoms have magnetic nuclei that become aligned in a magnetic field. If radio waves of an appropriate frequency are applied, the nuclei tip slightly out of alignment but then re-emit signature radio waves when they tip back. The radiofrequency emitted depends not only on the type of atomic nucleus but also on its chemical environment. This is the basis of the important analytical technique, nuclear magnetic resonance (NMR), which preceded MRI, and which has been used in pharmaceutical and materials research since the 1960s. It was US physicist Isidor Rabi who first observed NMR in the early 1930s – work for which he was awarded a Nobel Prize in Physics in 1944. Further advances resulted in several more Nobel Prizes.

NMR is particularly good for picking out hydrogen atoms. In the 1970s, University of Nottingham-based physicist Peter Mansfield and US chemist Paul Lauterbur realised that the technique could be adapted to distinguish the spatial positions of hydrogen

atoms in biological tissue, particularly in the water component. Using complex mathematical methods, a three-dimensional image of a living organ could be constructed by scanning its water content using a version of NMR with variable-gradient magnetic fields. This breakthrough won them the Nobel Prize in Physiology or Medicine in 2003. By the 1980s, dedicated clinical instruments were being developed for a new technique, which by then had been renamed MRI.

In a conventional MRI scanner, the patient lies inside a large, cylindrical magnet. The magnetic fields used to align the hydrogen nuclei are typically 30 000–60 000 times as strong as those of the Earth. They are generated by superconducting magnets, which were also developed in the UK (somewhat in parallel with MRI) by the first physics-technology spin-out company from the University of Oxford, Oxford Instruments.

MRI can now be configured to distinguish between all types of tissue, so as to generate detailed images of organs. Contrast in selected structures can be enhanced by injecting magnetic contrast agents, such as gadolinium, or magnetic resonance-sensitive molecules that combine with specific receptors in the target tissue.

### Current developments

Research into MRI is a highly active area in the UK, with new applications and technical developments continually coming on-stream. Several of the country’s main hospitals have programmes to apply MRI to new clinical problems. For example, one advance is to deploy MRI during surgery, giving doctors

## Timeline

<b>1930</b>	US physicist Isidor Rabi develops a method for measuring the magnetic properties of atoms, atomic nuclei and molecules.
<b>1944</b>	Isidor Rabi wins the Nobel Prize in Physics for detecting NMR in molecular beams.
<b>1945</b>	The first NMR measurements are taken of a solid.
<b>1950</b>	Pulsed NMR is invented.
<b>1952</b>	Felix Bloch and Edward Purcell win the Nobel Prize in Physics for their development of new methods for NMR experiments in solids.
<b>1959</b>	J R Singer at the University of California, Berkeley proposes that NMR could be used as a non-invasive tool to measure <i>in vivo</i> blood flow.
<b>1969</b>	Raymond Damadian at Downstate Medical Center in New York shows that the NMR signals from tumours differ from those of normal tissue.
<b>1971</b>	Paul Lauterbur devises a way to create magnetic resonance images.
<b>1973</b>	Paul Lauterbur produces the first magnetic resonance images.
<b>1973</b>	Peter Mansfield at the University of Nottingham publishes a method to construct images quickly.
<b>1974</b>	Raymond Damadian receives the first patent in the field of MRI for the concept of NMR for detecting cancer.
<b>1976</b>	Peter Mansfield produces the first magnetic resonance image of a body part.
<b>1977</b>	The first magnetic resonance image of a human is made by Raymond Damadian.
<b>1980</b>	The first useful image of a patient in a hospital is taken.
<b>1984</b>	Full-body MRI scanners are introduced into hospitals.
<b>1986</b>	Technological advances mean that it takes less than 5 s to obtain an image.
<b>1993</b>	Functional MRI is developed, opening up whole new areas in terms of imaging brain function rather than just structure.
<b>2003</b>	Paul Lauterbur and Peter Mansfield are jointly awarded the Nobel Prize in Physiology or Medicine for their discoveries concerning MRI.
<b>Today</b>	Scientists are working towards combined MRI/PET scanners to produce real-time images of internal organs.

## “MRI technology is an excellent example of how discoveries in curiosity-driven physics research lead to economic and societal benefits for the UK.”

and surgeons a constantly updated, three-dimensional map of the patient they are treating. One way of accomplishing this is to fit arms on the inside of the MRI machine. These are guided manually by doctors and can be used to take tissue for medical testing from precisely the right point in a tumour. Currently, doctors working from a static MRI image cannot be sure whether they have collected tissue from the tumour or from the surrounding material, and they often take multiple samples to be sure. This method would speed up the process and cause less distress to patients.

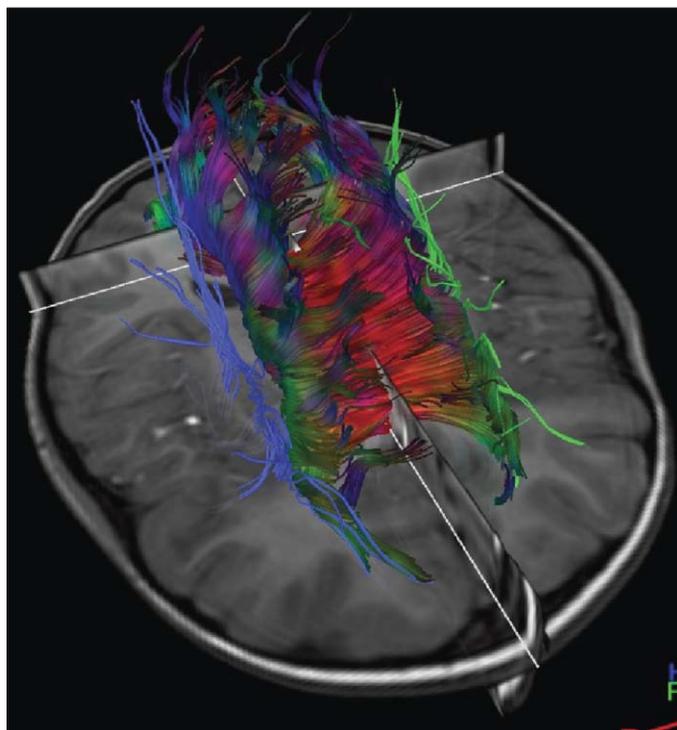
In recent years, “open MRI” machines have become increasingly available, offering more room for claustrophobic and large patients. In addition, small scanners for imaging specific body parts are now coming into use. Scientists and manufacturers are also working on improved designs that will further minimise risks that MRI scans pose to electronically sensitive devices, such as pacemakers. One such development



is a nanocoating for implants that will screen them from the radiofrequency waves, thus making MRI available to some patients who are currently excluded.

Another advance is to combine MRI with other imaging techniques, such as computerised tomography (CT/X-ray scanning) and positron emission tomography (PET) so as to combine the different strengths of these modalities.

Finally, the availability of ever-more powerful magnets is providing the sensitivity to allow researchers to explore biochemical changes by detecting the specific signals from particular molecules, perhaps labelled with an MR-sensitive isotope. In this way, MRI is becoming an invaluable tool in



studying the very processes of life, such as metabolism, respiration and thought.

## Impacts

MRI technology is an excellent example of how discoveries in curiosity-driven physics research lead to economic and societal benefits for the UK. Much of the early research was done in the UK and now there are obvious healthcare benefits worldwide. MRI scans are most commonly used to diagnose cancer patients (~35% of all scans) and patients with spinal problems (~30%). It is hard, however, to evaluate exactly just how much MRI has improved human health. (It is even more difficult to estimate how much its older relative – NMR – benefited society. Every chemistry laboratory in the country, whether academic or industrial, has a suite of NMR machines to help to develop new chemicals, materials and drugs, as well as to test for substances of environmental, security or forensic significance.)

There are at least 20 000 MRI scanners installed around the world and some 60 million examinations are performed every year. Around 500 scanners in UK hospitals alone carry out more than 1 million examinations every year, making a huge contribution to government targets for the diagnosis and treatment of cancer, for example. No record is kept of the number of patients who have received MRI scans worldwide, but it is probably in excess of 0.5 billion.

MRI has spawned a multibillion pound industry, from which the UK has benefited, for example, through the provision of superconducting magnets. In recent years, the NHS has invested hundreds of millions of pounds in MRI technology. According to a report by the US Global Industry Analysts, Inc., the global MRI equipment market is expected to reach \$5.5 bn by 2010. Another report, by Kalorama Information, predicts that the key factors for growth in 2010 will be increases in the use of interventional MRI in brain surgery and expanded use of MRI diffusion imaging to diagnose strokes and other injuries to the brain. In addition, cardiac MRI is expected to grow substantially in clinical use over the next decade.

## Key facts and figures

- MRI can create detailed images of the internal organs, which help in the diagnosis of conditions such as cancer, heart disease, multiple sclerosis and Alzheimer's disease. It can now follow physiological and biochemical changes in organs and tissues, providing information that is otherwise not easily obtained.
- MRI is the product of more than 70 years of physics research in a field where several Nobel prizes have been awarded.
- UK physicist and Nobel Laureate Sir Peter Mansfield at the University of Nottingham developed methods that enabled the rapid MRI scanning that is available today. Other important early work was carried out at the University of Aberdeen and at the Hammersmith Hospital in London.
- There are more than 20 000 MRI scanners installed around the world, and the global equipment market is worth billions of pounds a year.

## Useful links

- [http://en.wikipedia.org/wiki/Magnetic\\_resonance\\_imaging](http://en.wikipedia.org/wiki/Magnetic_resonance_imaging)
- <http://physicsworld.com/cws/article/news/27363>
- <http://health.howstuffworks.com/mri.htm>
- [www.medicalnewstoday.com/articles/104947.php](http://www.medicalnewstoday.com/articles/104947.php)
- [www.healthimaging.com/content/view/4913/89](http://www.healthimaging.com/content/view/4913/89)
- [www.beyonddiscovery.org/content/view.txt.asp?a=129](http://www.beyonddiscovery.org/content/view.txt.asp?a=129)

● Thanks go to Stephen Keevil, King's College London, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock.

# Optical fibres

Light-carrying glass fibres have transformed communications, thanks to pioneering work carried out by UK physicists.



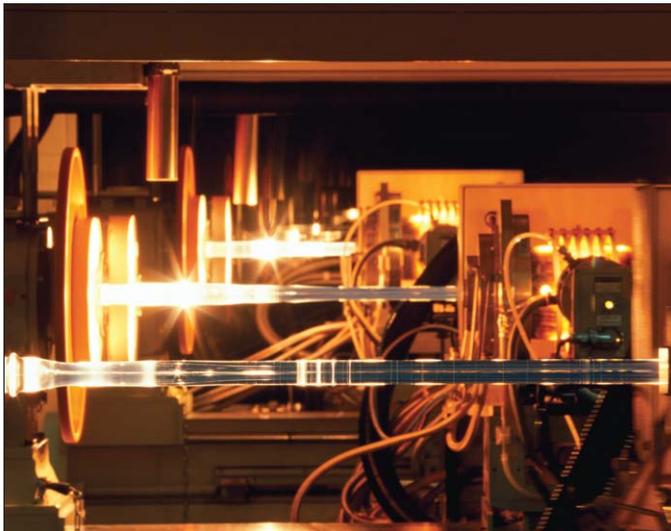
## What are optical fibres?

Optical fibres are fine threads of glass that can transmit light over long distances. They have a thin glass core through which the light travels, coated in a second glass layer that reflects light back into and guides it down the core. The fibre is protected by a plastic coating. A significant property of optical fibres is that they are flexible and thus provide a means of sending optical signals along a curved path. They can be used individually for precise experiments or arranged in bundles that are robust enough to be laid on the ocean floor.

Optical fibre technology has revolutionised telecommunication networks across the world. Information is sent as pulses of light down the fibres, with little loss of signal compared with

copper wires. This allows distances of as great as 30–50 km to be spanned without installing devices to regenerate the signal (repeaters). One fibre can carry many channels, each using a different wavelength of light, with rates per channel of 10 or 40 gigabits/s. This huge bandwidth has enabled broadband networks to reach into nearly every home in the UK. Innovations such as iTunes and other download services would not be feasible without the network speeds that are enabled by optical fibre technologies. Currently there are optical fibre links between all of the continents, except Antarctica, criss-crossing the globe at the bottom of the world's oceans. Some 3 million kilometres of optical cable have been laid in the UK alone.

Since their development in UK laboratories, optical fibres



**“Optical fibres enable vast amounts of data to be circulated and downloaded via the internet, which has had an incalculable effect on business, politics and everyday life.”**

have been used in many other fields, ranging from lighting to medicine and remote sensing. A particularly exciting use of fibres is as optical fibre lasers, which have applications ranging from industrial laser-cutting to medical imaging.

### **The science**

Developments underpinning optical fibres started as early as the 18th century. Spun-glass fibres were made in 1713 by the French physicist René de Reaumur, and later in the 19th century by English physicist Charles Vernon Boys. Meanwhile, Irish physicist John Tyndall demonstrated that light could be steered through a curved stream of water, thus showing that the path of propagation could be bent. In the 1920s, Scottish engineer John Logie Baird rediscovered the idea and attempted to use it to develop a mechanical television set, using glass rods to channel light to the screen. The notion of using glass fibres

for transmitting light, however, was first conceived in 1952 by physicists Harold Hopkins and Narinder Kapany at Imperial College London. Their aim was to use a bundle of optical fibres as a medical endoscope.

It was not until the 1960s that the idea of transmitting information through optical fibres was proposed. Engineers Charles Kao and George Hockham, working at the Standard Telephones and Cables (STC, now Nortel Networks) laboratories in Harlow, realised that light loss could be kept down to acceptable levels by removing impurities in the glass. Research continued and, in 1970, researchers at the Corning Glass Works in the US showed that glass fibres could transmit 65 000 times as much information as copper wires. In the 1980s, several UK-based companies, including British Telecom (BT), Plessey and GEC, made significant investments in optical-fibre development. A further boost to the technology came from

## Timeline

<b>1713</b>	French physicist René de Reaumur makes spun-glass fibres.
<b>1870</b>	Irish physicist John Tyndall demonstrates that light follows the curve of a stream of water pouring from a container.
<b>1887</b>	Charles Vernon Boys draws quartz fibres for mechanical measurements.
<b>1925</b>	UK engineer John Logie Baird presents the first demonstration of television. He later goes on to register more than 178 patents, including sending an image through an array of parallel tubes, transparent rods or clear fibres, which could be bent or curved.
<b>1952</b>	Harold Hopkins and Narinder Kapany at Imperial College London develop bundles of glass fibres for use as an endoscope.
<b>1961</b>	Physicists Elias Snitzer and Will Hicks at American Optics demonstrate that a laser beam can be directed through an extremely fine glass fibre.
<b>1966</b>	Charles Kao and George Hockham of STC Laboratories in Harlow first propose the transfer of information over glass fibres.
<b>1966</b>	The British Post Office Research Laboratories start fibre-optic communications research.
<b>1970</b>	Researchers at the Corning Glass Works develop a singlemode fibre with a loss of only 17 dB/km by doping titanium into the fibre core.
<b>1975</b>	The first non-experimental fibre-optic link is installed by Dorset Police after lightning knocks out their communication system.
<b>1977</b>	Television signals are transmitted using optical fibres.
<b>1977</b>	The Post Office Corporation begins sending live telephone traffic through fibres in underground ducts near Martlesham Heath in Suffolk.
<b>1977</b>	US telephone companies begin trials on sending customers' telephone calls through optical fibres.
<b>1978</b>	AT&T and the Post Office (to become British Telecom in 1980) announce a 10 year plan to develop a transatlantic optical fibre cable.
<b>1984</b>	British Telecom lays the first submarine fibre to the Isle of Wight.
<b>1986</b>	The first fibre-optic cable across the English Channel begins service.
<b>1987</b>	David Payne at the University of Southampton develops an "optical" amplifier that can boost light signals in fibres without first having to convert them into electrical signals and then back into light.
<b>1988</b>	The first transatlantic fibre-optic cable begins service.
<b>1991</b>	David Payne and P J Mears of the University of Southampton, along with Emmanuel Desurvire of Bell Laboratories, demonstrate optical amplifiers that are built into optical fibres.
<b>1991</b>	Japanese researchers successfully send a signal through 1 million kilometres of fibre.
<b>1996</b>	Philip Russell at the University of Southampton demonstrates the photonic crystal fibre.
<b>1997</b>	The 28 000 km "fibre-optic link around the globe" connects the UK and Japan through one continuous cable.
<b>2003</b>	Optical fibre cables connect all of the continents except for Antarctica.
<b>2009</b>	Charles Kao is awarded one half of the Nobel Prize in Physics for groundbreaking achievements concerning the transmission of light in fibres for optical communication.

the development of the erbium-doped fibre amplifier, which is based on the laser principle and was co-invented by physicists at the University of Southampton and AT&T Bell Laboratories. This reduced the need for repeaters and lowered costs. Building on these developments, in 1986 BT laid the world's first international optical-fibre submarine cable between the UK and Belgium. It is 112 km long with only three repeaters. BT was also a key partner in the first transatlantic optical-fibre cable system, which was capable of carrying 40 000 telephone calls at once.

## Applications

### ● *Medicine and industry*

One of the first uses of optical fibres was in the endoscope. This incorporates bundles of fibres to create a flexible "periscope" that allows doctors to see inside patients' bodies without expensive and invasive surgeries. This ability to see inside the body paved the way for a new surgical strategy called "keyhole surgery", whereby optical fibres not only illuminate the target site and relay imaging information to guide the procedure but also provide a conduit for a laser beam to carry out surgery through a tiny opening (or via the oesophagus in the case of stomach operations). A similar approach is employed in the aerospace industry to inspect the interior of jet engines for damage and



wear. Optical fibres can also be used to carry high-power laser beams for welding, cutting and drilling.

### ● *Lighting*

Everyone is familiar with fibre-optic table lamps and Christmas trees. Optical fibres can be used to carry light around building

interiors and even in cars.

#### ● *Short-range communications*

Light is not affected noticeably by electromagnetic fields, so fibre-optic technology is becoming important for interference-free short-range communications in aircraft and even in cars. Optical fibres are also increasingly being incorporated as active elements, such as amplifiers and filters, in novel optical circuits.

#### ● *Sensors*

Optical fibres make excellent and inexpensive sensors for environmental, chemical and biological monitoring in mines, oil wells and other remote locations. The principle is that the characteristics of light transmission change if the fibre is altered in some way, such as by stretching or heating. Moreover, they can register such changes all the way along their lengths. Several research groups in the UK work on developing fibre sensors. Physicists at the University of Southampton (which has one of the world's largest fibre-optics research groups) collaborate with York Sensors Ltd, a local Southampton company that leads the world in distributed-temperature sensing. Their aim is to produce a sensor working over 50 km. The group is also developing a strain sensor for monitoring large structures like bridges, dams and roads.

#### ● *Fibre lasers*

Fibre lasers are another recent significant advance. They can have active lasing regions of several kilometres long wound into efficient compact designs that can generate very-high-power beams. They are used in laser cutting and welding, and they are a candidate for the next generation of research lasers emitting extremely intense X-ray light.

### Current developments

One of the most exciting developments pioneered in the UK are microstructured fibres, sometimes called photonic crystal fibres. Philip Russell and colleagues, first at the University of Southampton and then at the University of Bath, developed fibres that have air channels surrounding the central core through which light travels. The new type of fibre allows light to be manipulated in many novel ways, leading to a whole new set of technologies. Currently this is a very active area of research in the UK, with several groups making different kinds of microstructured fibres with various applications in mind, such as high-power laser delivery and gas sensing. The most significant application is the laser generation of white light (supercontinuum generation), which, for example, can be tuned to particular wavelengths for advanced microscopy techniques in the biosciences.

UK researchers are also making optical fibres out of materials other than silica glass for various applications. For example, plastic optical fibres could be used for transmitting information around the house or be incorporated into textiles and clothing as sensors.

### Impacts

Optical fibres enable vast amounts of data to be circulated and downloaded via the internet, which has had an incalculable effect on business, politics and everyday life. At the moment, communication speeds are limited by the copper wires installed in homes years ago. Cable communications companies, which rely on fibre optics to deliver TV, broadband and telephone services, are aiming to supply an ultrafast service by laying

optical fibres cables right into houses.

The world market for fibre-optic components is now estimated at £15 bn, while the market for optical communications systems is approximately £40 bn. These are both likely to increase, driven by the demand for substantial increases in data traffic across the internet and telecommunications networks. The UK will benefit, because it remains a world leader in innovative fibre-optics research and has a strong manufacturing base in fibre optics, with plants in Wales and Southampton.

### Key facts and figures

- Some 25 million km of cable have been installed worldwide and more than 85% of the world's long-distance communications are carried over optical cables.
- In the UK there are 3 million km of optical fibre cable in the BT network alone.
- Internet broadband services could not operate without fibre-optic communications.
- The UK was a pioneer in developing and applying optical fibres and it remains a leader today.

### Useful links

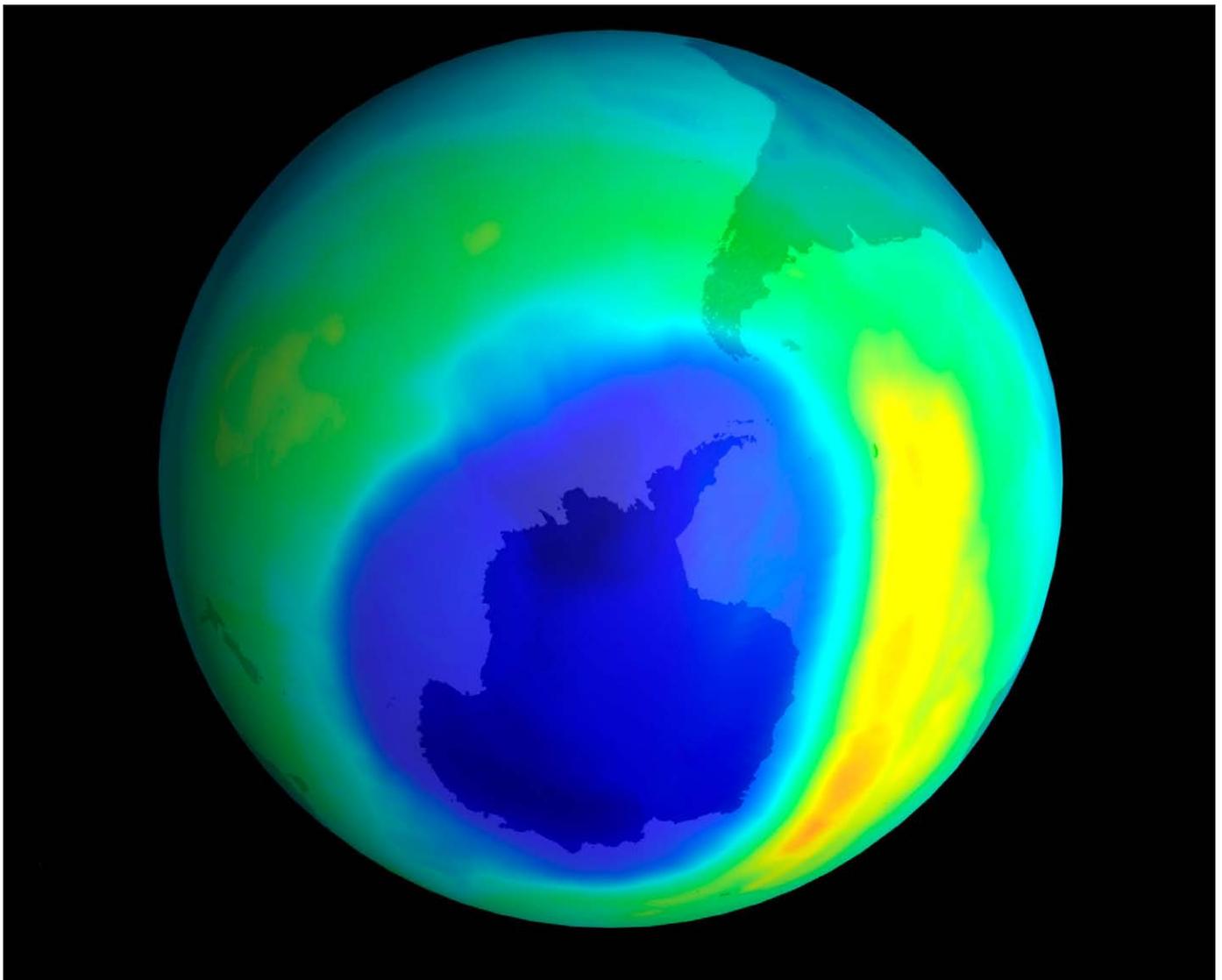
- [http://en.wikipedia.org/wiki/Optical\\_fiber](http://en.wikipedia.org/wiki/Optical_fiber)
- <http://electronics.howstuffworks.com/fiber-optic.htm>
- [www.orc.soton.ac.uk/education.html](http://www.orc.soton.ac.uk/education.html)

● Thanks go to Miles Padgett, University of Glasgow, and Nina Hall for their help with this case-study.

● Images courtesy of Shutterstock and the Science Photo Library.

# The ozone layer

Understanding and protecting the ozone layer in the upper atmosphere has been a major achievement in physics-based environmental research.



## What is the ozone layer?

The ozone layer is a naturally occurring region in the atmosphere between 10 and 35 km above the Earth's surface. It contains high concentrations of a form of oxygen molecule comprising three atoms of oxygen ( $O_3$ ), as opposed to diatomic oxygen ( $O_2$ ), which is required for respiration. Ozone is less stable than diatomic oxygen and is toxic to life. In fact, ozone becomes a health hazard if generated at ground level by photochemical reactions between pollutants, as sometimes happens on a hot summer's day in congested cities. It is a major contributor to photochemical smog.

Ozone is created in the upper atmosphere (the stratosphere) by the ultraviolet radiation in sunlight, which splits diatomic oxygen molecules into oxygen atoms. These then quickly combine with further oxygen molecules to form ozone. The layer of ozone that forms absorbs more than 90% of the ultraviolet light reaching the Earth, thus acting as a protective blanket against this potentially harmful radiation, which can cause skin cancer, cataracts and blindness, suppress the immune system and damage vegetation.

The ozone layer is thinnest in the tropics and denser towards the poles, although there are large seasonal fluctuations. In the



1970s and 1980s, scientists noted that the ozone layer was thinning over the South Pole, and a major research programme was begun to determine why and take action to reverse the trend.

### The science

The existence of ozone in the atmosphere was predicted in the late 1800s, but the discovery of the ozone layer in the stratosphere was made in 1913 by French physicists Charles Fabry and Henri Buisson. Its properties were explored in detail by UK meteorologist Gordon Dobson, who developed a simple “ozonemeter” (the Dobson ozone spectrophotometer) that could be used to measure stratospheric ozone from the ground. Between 1928 and 1958 he established a worldwide network of ozone-monitoring stations, which continue to operate today. The amount of ozone above a point on the Earth’s surface is now measured in Dobson units (DU) and is typically 260 DU near the tropics. In the UK it is around 300 DU.

Antarctic observations by the British Antarctic Survey (BAS) using a Dobson instrument started in 1957 and were originally curiosity driven: to understand the role of ozone in solar-energy absorption, the temperature profile of the stratosphere and wind circulation. For the first 20 years of monitoring, ozone concentrations followed a seasonal pattern, but significant variations were observed from the late 1970s onwards, with the ozone layer thinning significantly each spring. In the Antarctic spring of 1981, the BAS team, headed by geophysicist Joe Farman, found that the ozone level had dropped by 20%, although it increased in the following months. By the spring of 1985, however, the ozone layer had thinned by 50% and was finally dubbed an “ozone hole”. The discovery, which was

**“According to an analysis by the UK Natural Environmental Research Council, the benefits to the UK economy of discovering the ozone hole are estimated to be up to £42 m.”**

announced in a paper in British journal *Nature*, came as a shock to the scientific community, because the observed decline in polar ozone was far larger than anyone had anticipated.

An important conclusion, which was based on research carried out during the previous decade, was that the ozone depletion was being caused as a result of the release of artificial chemicals containing halogens (chlorine, fluorine and bromine), including chlorofluorocarbons (CFCs), and halons, which contain bromine. CFCs were (and sometimes still are) found in some products, such as refrigeration systems, air-conditioners, aerosols and solvents, and they are made during the production of some types of packaging, while halons were used in fire-extinguishing

<b>Timeline</b>	
<b>1881</b>	W Hartley predicts the existence of ozone in the higher atmosphere on the basis of the ultraviolet cut-off in stellar spectra, and he discovers ozone absorption bands.
<b>1913</b>	French physicists Charles Fabry and Henri Buisson make the first measurements of the total ozone column, and they show that most of the column is in the stratosphere.
<b>1928</b>	The ozone layer's properties are explored in detail by UK meteorologist Gordon Dobson, who develops a simple "ozonemeter" (the Dobson ozone spectrophotometer) that can measure stratospheric ozone from the ground. Between 1928 and 1958, Dobson establishes a worldwide network of ozone-monitoring stations, which continues to operate today.
<b>1930</b>	The photochemical mechanisms that give rise to the ozone layer are identified by UK physicist Sidney Chapman.
<b>1957</b>	During the International Geophysical Year, polar scientists make measurements of the ozone layer over Antarctica for the first time.
<b>1972</b>	After developing his electron capture detector in the late 1960s, James Lovelock is the first to detect the widespread presence of CFCs in the atmosphere. Without this extremely sensitive detector, the realisation of the threat to the ozone layer would have been delayed.
<b>1974</b>	Chemists Sherry Rowland and Mario Molina discover that CFCs can destroy ozone in the stratosphere.
<b>1977</b>	The United Nations Environmental Programme holds the first international meeting to discuss ozone depletion.
<b>1981</b>	NASA's satellite monitors reveal very low ozone levels across Antarctica.
<b>1985</b>	A British Antarctic Survey (BAS) research group publishes a paper in <i>Nature</i> , stating that the depletion in ozone in Antarctica (by 40%) is now so great that it is described as a "hole". The Vienna Convention, calling for additional research and exchange of information about ozone depletion, is signed by international negotiators. However, negotiators fail to agree on worldwide CFC regulations. NASA shows satellite photos confirming the existence of an ozone hole over Antarctica.
<b>1986</b>	CFC manufacturers suggest that safe substitutes for the chemicals might be possible for a high enough price.
<b>1987</b>	International negotiations on ozone protection resume in Geneva after a 17 month delay, eventually proposing worldwide CFC reduction of 95% by the next decade.
<b>1989</b>	The Montreal Protocol is opened for signature and entered into force. It was designed to protect the ozone layer by phasing out the production of a number of substances believed to be responsible for ozone depletion. The NASA Antarctic ozone expedition ends with chlorine chemicals found to be the primary cause of ozone depletion.
<b>1989</b>	European countries and the US agree to faster CFC reductions, but developing countries oppose the new timetable citing the costs of substitutes and scientific uncertainty.
<b>1992</b>	Worldwide ozone in the stratosphere drops to its lowest levels in recorded history.
<b>1993</b>	DuPont's R&D arm produces substitutes for CFCs. These include partially hydrogenated chlorofluorocarbons (HCFCs) and totally hydrogenated fluorocarbons (HFCs).
<b>1995</b>	Automobile manufacturers begin installing air-conditioning units in cars that use HCFC-134a – a substitute for CFC-12. The largest hole in the ozone over Antarctica begins to form. When its growth is complete, the hole encompasses the entire continent of Antarctica and is the largest hole ever recorded.
<b>1997</b>	180 countries, including the UK, sign the amended Montreal Protocol, agreeing to bring greenhouse emissions, including HFCs, to levels below those of 1990.
<b>1998</b>	The ozone hole over Antarctica grows to 16.4 million square kilometres.
<b>1999</b>	Japan commits to reducing its emissions of HFCs and CFCs to 6% below 1990 levels.
<b>2000</b>	An ozone hole three times the size of the US is recorded.
<b>2001</b>	BAS scientists win the Institute of Physics Charles Chree Medal and Prize for their part in the discovery of the ozone hole over the Antarctic and for linking this to the growth of CFCs in the atmosphere.
<b>2003</b>	The UN talks on protecting the ozone layer end without a deal, after the US asks to continue using a chemical that it had previously agreed to ban.
<b>2005</b>	DuPont is ranked 66th in the Fortune 500 on the strength of nearly \$28 bn in revenues and \$1.8 bn in profits.
<b>2007</b>	Ozone loss is the fourth largest on record, and severe polar losses are expected over the coming decades. The Montreal Protocol is strengthened in line with a scientific assessment that states that accelerated HCFC phase-out in developing countries would produce the equivalent savings of 18 billion tons of carbon dioxide emissions by 2050.
<b>Today</b>	All but two of the 196 UN member states have ratified the basic Montreal Protocol.

systems. These substances react with ultraviolet radiation in the upper atmosphere to produce active chemicals that break up ozone. The chemistry is complex but now well understood: a CFC molecule takes about 15 years to reach the upper atmosphere from the ground, and it can stay there for about a century, destroying up to 100 000 ozone molecules in the process.

The work carried out by the BAS represented one of the landmark discoveries of environmental physics during the 20th century. It provided the driving force behind the first international treaty aimed at combating pollution – the Montreal Protocol, which was signed in 1987 to phase out ozone-depleting substances. In 2001, BAS geophysicists Joe Farman, Brian

Gardiner and Jonathan Shanklin were awarded the Institute of Physics Charles Chree medal and prize for their part in the discovery of the ozone hole over the Antarctic and for linking it to the growth of CFCs in the atmosphere. Shanklin recently said that, if it weren't for his training in physics in the Cavendish Laboratory at the University of Cambridge, it is likely that the discovery would not have been made.

## Current developments

The ozone layer, and the usage and effects of ozone-depleting chemicals, continue to be monitored. These substances are also greenhouse gases. The long atmospheric lifetimes of many of them means that stratospheric concentrations are not likely to fall to their 1980 levels until beyond the middle of the 21st century. If the Montreal Protocol is complied with, the ozone layer should start to recover in the coming decades as the amounts of ozone-depleting substances decline. The worst level of ozone depletion in history was recorded in 2006, and the Antarctic ozone hole is expected to exist for decades, with ozone concentrations increasing by 5–10% until 2020. This is 10–25 years later than predicted in earlier assessments, and it takes into account revised estimates of atmospheric concentrations of ozone-depleting substances resulting from future use in developing countries. Detectable recovery will not occur until around 2024, with ozone levels recovering to 1980 levels by around 2070.

## Impacts

The main public concern has been the effects of ultraviolet radiation on human health. However, so far there is no direct evidence that ozone depletion has damaged health. Nevertheless, were the high levels of depletion seen in the ozone hole over Antarctica ever to become more widespread, the effects could be substantial. When the ozone hole breaks down in the spring, ozone-depleted air can affect southern parts of Australia and New Zealand, so environmentalists have been concerned that the increase in surface ultraviolet radiation could have a significant impact.

Indeed, the United Nations World Meteorological Organisation estimates that, without the Montreal Protocol, there would have been 100 excess cases of skin cancers per million people per year by 2020. In 1992 it was projected that there would be around 40 extra cases per million people per year. Therefore the Montreal Protocol and its subsequent amendments have reduced the number of excess skin cancers by more than 60 cases per million people per year.

According to an analysis by the UK Natural Environmental Research Council, the benefits to the UK economy of discovering the ozone hole are estimated to be up to £42 m. This includes reducing the healthcare costs of treating skin cancer, and contributions to international policy-making. In fact, exposure to ultraviolet radiation caused the loss of 1.6 million “disability adjusted life years” in 2000, and the cost of skin cancer in England in 2002 was estimated by Imperial College London to be in excess of £190 m at 2001 prices (or £209 m at 2006 prices).

However, the long-term societal significance of the discovery of the hole in the ozone layer is that, for the first time, it led to a widespread appreciation and acknowledgement that human activity can have a major impact on the global environment. It thus prepared the path for concerted international action on a different and more long-term environmental threat – that of global warming.

One surprising side-effect of the Montreal Protocol has been

its success in helping to reduce potential global warming. Without it, large amounts of CFCs, halons and other greenhouse-active gases would have entered the atmosphere and these would have made a significant contribution to global warming.

## Key facts and figures

- The photochemical mechanisms producing the ozone layer were discovered by UK physicist Sidney Chapman.
- The British Antarctic Survey discovered the ozone hole that led to the signing of the Montreal Protocol in order to phase out ozone-depleting substances.
- By 2020 the United Nations' World Meteorological Organization estimates that, without the Montreal Protocol, there would have been 100 excess cases of skin cancers per million people per year.
- The economic benefits of the discovery of the ozone hole are estimated to be as much as £42 m to the UK alone.
- Protecting the ozone layer has also contributed to reducing potential global warming.

## Useful links

- [www.atm.ch.cam.ac.uk/tour](http://www.atm.ch.cam.ac.uk/tour)
- [www.theozonehole.com](http://www.theozonehole.com)
- [www.ace.mmu.ac.uk/eae/Ozone\\_Depletion/ozone\\_depletion.html](http://www.ace.mmu.ac.uk/eae/Ozone_Depletion/ozone_depletion.html)
- [www.eoearth.org/article/Lessons\\_from\\_the\\_Montreal\\_Protocol](http://www.eoearth.org/article/Lessons_from_the_Montreal_Protocol)
- [www.esrl.noaa.gov/csd/assessments/2006/](http://www.esrl.noaa.gov/csd/assessments/2006/)
- [www.nerc.ac.uk](http://www.nerc.ac.uk)

● Thanks go to Jonathan Shanklin, British Antarctic Survey, Alan Aylward, University College London, Neil Harris, University of Cambridge, Ann Webb, University of Manchester, and Nina Hall for their help with this case-study.

● Images courtesy of the British Antarctic Survey, Shutterstock and the Science Photo Library.

# The World Wide Web

The World Wide Web is an outstanding example of how research in particle physics changed the world in a totally unforeseeable way.



## What is the World Wide Web?

The World Wide Web (the Web) is a system of interlinked computer documents – webpages – that can be accessed via the internet – a network of computers that is distributed all over the world and that communicate with one another. The key to the Web is lines of computer code (hypertext) that generate links (hyperlinks) that provide pathways to information that is held on millions of different computers. Every webpage, which may contain text and images, has a unique address, and the hyperlinks provide an intuitive way to travel through pages, allowing users to view these pages and hop between them by clicking key icons or words displayed on the computer screen –

known as “surfing the net”. Using software called a web browser, the user can jump between sites devoted to everything from news through government projects to home shopping.

Before the invention of the Web, the internet and all of the information on it was the preserve of the military and academics. Though plentiful, it wasn't easily accessible – it could be seen only by finding and downloading individual files onto the user's computer. The Web allows people anywhere easy and uncomplicated access to the vast quantities of information stored on computers around the world, which can be searched and viewed as easily as pages in a magazine.

Originally conceived as a means of transferring and searching



through vast quantities of scientific data, the Web has developed into a true tool of the people. It remains a valuable tool for scientists, but it also extends into every field of commerce and reaches into every country. The Web has given people the ability to share knowledge across borders and across continents, and to trade with distant customers just as easily as they trade with their neighbours. It is increasingly user driven and user shaped, with websites such as Wikipedia and social-networking sites providing new ways for individuals to control and manipulate information. Currently it is difficult to imagine a world without the Web, and impossible to measure the economic and societal benefits that it has brought. Quite simply, it has changed the way we live our lives.

### The science

The first step that enabled rapid and reliable transfers of files between computers came about with the concept of packet-switching, independently developed in the 1960s by UK physicist Donald Davies working at the National Physical Laboratory and Paul Baran at the Rand Corporation in the US. The information is assembled into small chunks, each with an address, and sent round the computer network and then reassembled at its destination. Using this idea, the US government-funded military-based Advanced Projects Agency (ARPA) constructed the first computer network – ARPANET – that spanned the US.

The technology was robust but not versatile, and the internet, as it soon became known, was used predominantly by scientists and defence organisations, although private groups were developing their own networks. With its continuing growth, the internet soon became cumbersome and difficult to use. By the 1980s, people had started to develop enabling approaches. For example, Andy van Dam at Brown University on Rhode



Island built the first clickable hypertext system. However, the next big step was to happen at the world's foremost particle-physics laboratory – CERN in Geneva – where the UK is a major participant in the ground-breaking large-scale collider experiments. In the 1980s, teams of hundreds of physicists from around the world were embarking on a huge experiment called the Large Electron–Positron collider. New ways of communicating and sharing the huge amounts of data that would be generated were essential.

In 1990, Tim Berners-Lee, together with Robert Caillau, set about building a hypertext system for CERN's computer network. Following this, Nicola Pellow, a British student who was working at CERN, wrote a browser that could be used on many different computers. Soon, other physics laboratories around the world were linked in via the new software, and Berners-Lee called the system the World Wide Web.

Berners-Lee had written two key pieces of computer code: the uniform resource locator (URL) and the hypertext markup

## Timeline

<b>1969</b>	The first computer network, ARPANET, is constructed.
<b>1980</b>	Physicist and computer scientist Tim Berners-Lee writes a hypertext routine to make searching his computer easier.
<b>1990</b>	Tim Berners-Lee and Robert Caillau build a hypertext system for CERN's computer network.
<b>1991</b>	Internet usage reaches 600 000 people.
<b>1992</b>	The Mosaic Web browser is invented, which can present webpages as if they are pages from a magazine.
<b>1993</b>	CERN relinquishes intellectual property rights for the Web software and places it in the public domain.
<b>1993</b>	The Web accounts for only 1% of internet traffic.
<b>1995</b>	Amazon and e-Bay are launched.
<b>1996</b>	40 million people use the internet.
<b>1999</b>	150 million people have internet access.
<b>2001</b>	More than half the UK population has Web access.
<b>2002</b>	420 million people have Web access.
<b>2003</b>	MySpace is launched.
<b>2004</b>	Facebook is launched.
<b>2004</b>	Tim Berners-Lee is knighted.
<b>2005</b>	YouTube is launched.
<b>2008</b>	The Web hosts 63 billion pages on 100 million websites.
<b>2008</b>	One-quarter of the world's population – 1.5 billion people – use the Web on a daily basis.
<b>2008</b>	e-Commerce spending was \$6.8 tn; approximately 15% of global GDP.

**“The requirements of physics research are driving the next internet revolution. The latest collider experiment at CERN – the Large Hadron Collider – is expected to generate 1000 million million bytes of data every year, which will be shared between thousands of physicists at hundreds of institutes around the world.”**

language (HTML). A URL is a simple means of specifying the location of a page or document in a single title, which includes the name of a computer and how to find it, directions to find the file on the computer and a way of retrieving the file from that machine. HTML is a means of embedding codes into a simple text file that describes the structure and appearance

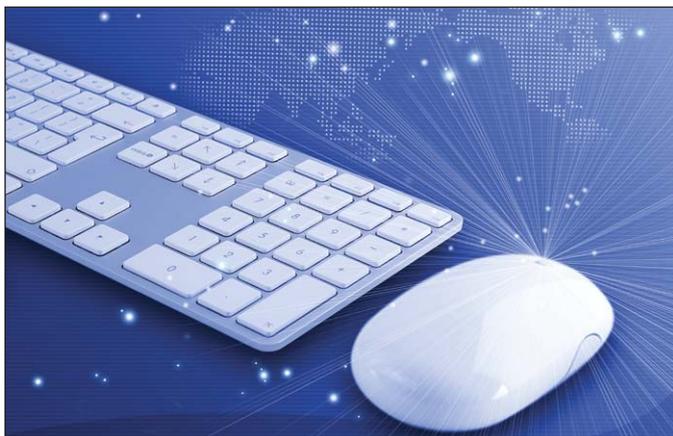
of the document, including links to other documents on the network. This file can be read by other machines, which can then recreate the original page, complete with the links to other pages. It is these hyperlinks that are the strands of the Web. They allow pages to be linked and retrieved, no matter where the information is stored.

In 1993, CERN relinquished all intellectual property rights and placed all of its Web software in the public domain. New browsers soon came along, such as Mosaic, which was developed by the US National Centre for Supercomputing Applications. For the first time, this browser made the Web instantly accessible to everyone who had a desktop computer and an internet connection. Since then, browsers and search engines have come and gone, and today the search engine Google has come to dominate the Web to such an extent that it has now become a verb.

Over the past decade, use of the Web has grown exponentially, fuelled by ever-faster computer technologies and high-speed optical fibre networks that allow information to be transmitted between computers at speeds not possible using copper wire. Broadband allows the home user to download movies and TV broadcasts, and it gives instant access to many online activities. The future will bring even faster speeds and new ways of interacting online. The way in which the Web is being used is also evolving, with the development of web-based virtual communities and hosted services, such as social-networking sites, video-sharing sites, wikis and blogs.

### Current developments

The requirements of physics research are driving the next internet revolution. The latest collider experiment at CERN – the Large Hadron Collider – is expected to generate 1000 million million bytes of data every year, which will be shared between thousands of physicists at hundreds of institutes around the world. To deal with the data deluge, scientists have devised a distributed computing resource called the Grid, which is spread over clusters of computers across the world and through which



information can be stored, processed and shared. Grid-based computing is already finding applications outside particle physics in areas such as medical science and Earth observation. The UK is playing a major part in developing both suitable software tools and applications. The Grid is regarded as the precursor to the next-generation internet, and it will revolutionise our ability to access and manipulate vast amounts of information.

In the meantime, home-computer users can already participate in schemes involving distributed computing by allowing their PCs to be used via the internet. Complex problems that would once have required a supercomputer to solve them can now be analysed using desktop computers around the world. Programs similar to screensavers can be downloaded that take advantage of the computer's processing power to analyse chunks of data while the machine is idle. The computer transmits the data back to the originator via the Web. Such distributed computing is currently being used by scientists on many projects, including work that may one day lead to a cure for cancer.

In another development of distributed computing, called cloud computing, customers can access their computing needs – data, software and processing power – through a single point of access provided by a Web-based online resource. As files are stored in the cloud, they are accessible from an internet-enabled computer anywhere.

## Impacts

Of course, it is almost impossible to overestimate just how much the Web and the internet have affected human activities and progress. Internet use is rising at a staggering rate and, in the US alone, 42% of homes have a broadband connection. A report by market research company Jupiter Research says that currently more than 1 billion people regularly access the Web and it anticipates that, by 2011, 22% of the Earth's population will surf the internet on a regular basis.

It is now hard to imagine conducting any kind of business or organisational activity without a presence on the Web. In 1999, CERN estimated that business on the Web was then worth about \$20 bn a year. Now it would be impossible to calculate. However, an idea of online activity is given through the number of servers that exist. It has been estimated that more than 27 million servers had been installed by the end of 2005, with about 3 million new ones being added every year. Jonathan Koomey at the Lawrence Berkeley National Laboratory in the US believes that the electricity bill for operating those servers and associated infrastructure (such as cooling) in 2005 was about \$2.7 bn for the US and \$7.2 bn for the world. This leads to an estimate that about 5% of the world's energy is used to power the Web.

## Key facts and figures

- One-quarter of the world's population now has access to the Web.
- In the UK, 41% of homes now have broadband, using more than 4 million broadband connections.
- British citizens spend twice as much time online as they spend reading newspapers and magazines.
- The next-generation internet, based on distributed computing, is also driven by the needs of physics research.

## Useful links

- [http://en.wikipedia.org/wiki/World\\_Wide\\_Web](http://en.wikipedia.org/wiki/World_Wide_Web)
- [www.gridpp.ac.uk/explain.html](http://www.gridpp.ac.uk/explain.html)
- [http://en.wikipedia.org/wiki/List\\_of\\_distributed\\_computing\\_projects](http://en.wikipedia.org/wiki/List_of_distributed_computing_projects)
- [www.youtube.com/watch?v=6PNuQHUIV3Q](http://www.youtube.com/watch?v=6PNuQHUIV3Q)

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