# The Use of Interactive Multimedia in the Communication of Science

Susan J. Bennett

Susan Bennett.

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All work presented is the author's own unless otherwise stated.

Faculty of Science,
The Australian National University.

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# Executive Summary

Two interactive multimedia pieces have been constructed to demonstrate the potential this new medium has for communicating science. They form the major part of the work for this Masters project.

This accompanying report serves as an introduction to the basic concepts of interactive multimedia and briefly describes aspects of the project, focussing on the practical nature of this work.

The multimedia component is presented on the accompanying floppy disks. Installation details can be found in the appendix to this report.

# Motivation

This project aims to explore the potential offered by interactive multimedia for the communication of scientific information, ideas and concepts. This has involved the construction of two quite different pieces of work - a university level physics tutorial and an interactive exhibit suitable for a science museum. The presentations have been developed to the prototype stage and are ready for testing on prospective users.

Due to external constraints on the project there has not been sufficient time to test the prototypes on target audiences, nor to interview any representatives from those groups to research further their needs from such a project. This is a much larger task. Instead, this project endeavours to showcase the kind of presentations that can be created using this new and exciting method of communication. The formats developed can easily be generalised to other projects requiring a similar pedagogic framework.

# Introduction

## What is multimedia?

Multimedia brings together of a number of different types of media. Definitions are widely varying - a slide show accompanied by music, an information kiosk with a touch screen, a video game with animation and music are but a few. In recent times multimedia has come to mean an interactive, computer programme which can incorporate text, colour graphics, photographic images, sound, animation and compressed digitised video in a seamless fashion. The main advantage of this type of multimedia is that the entire package can be constructed and presented on a desktop computer.

Giving the user control is the power of interactive multimedia. The philosophies and practicalities of multimedia presentations have been recently reviewed - see for example Latchem (1993). The level of interactivity offered to the user varies greatly depending on the material presented and the aims of the developers.

Some presentations offer only minimal interactivity with the user having control only over starting and stopping - much like watching a video. Others allow the user to navigate along various pathways depending on their interests. Quizzes or games may be included to emphasise main points or make the material more appealing. More sophisticated presentations are adaptive, modifying themselves according to the user's response. This allows the user to create a personalised programme.

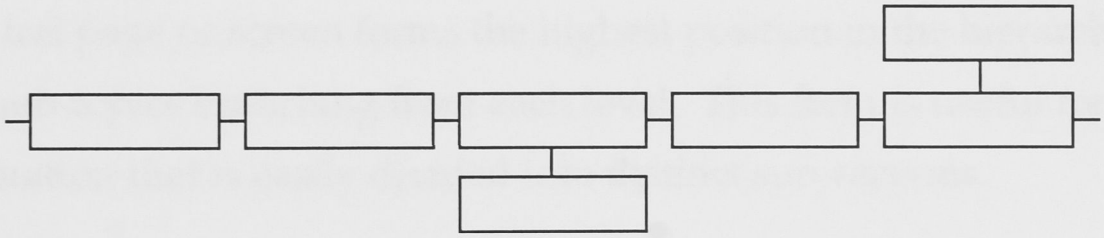
"Clickable" buttons or words (hypertext) usually provide the interactive navigation, whether moving to the next or previous page or to some related part of the programme. Buttons are also useful for reducing the amount of information that appears on the screen by revealing pop-up windows that can later be hidden when they are no longer of interest.

The structure of multimedia presentations also varies greatly. A few commonly used frameworks are * (Stocklmayer, 1995):

**Linear**

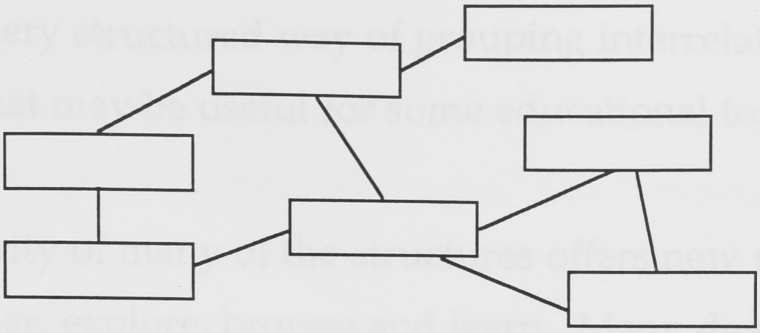
While this structure is the easiest to follow most users are likely to find it unexciting because it doesn't offer them the novelty they expect.

**Branched linear**



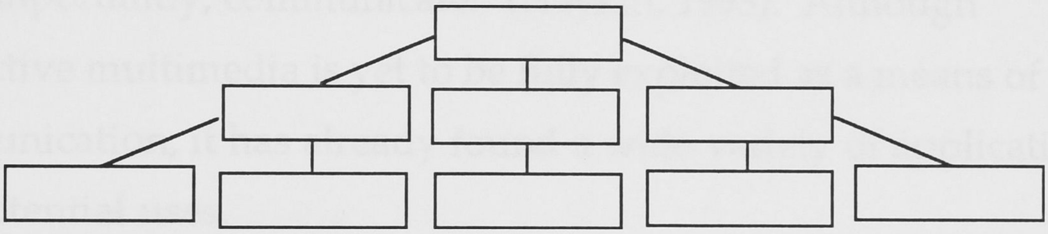
This is a linear structure with diversions slightly off the main topic. The structure is still easy to follow, but offers scope for user exploration and choice. This kind of structure is widely used for educational multimedia.

**Referential**



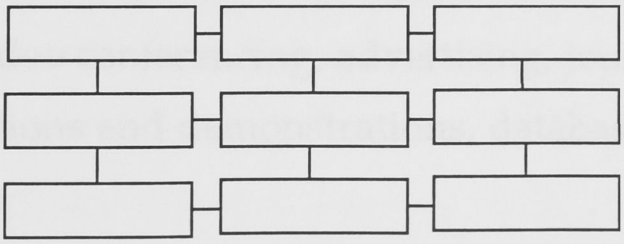
This kind of structure is useful for large amounts of interrelated information. The user can explore according to their own interests thus making the experience more personal. However, this kind of structure may be confusing for those trying to learn and frustrating for users who like to "know where they are going".

**Hierarchical**



A central page or screen forms the highest position in the hierarchy with sub-topics branching from each level. This form is useful for information that is easily divided into distinct sub-sections.

**Cross tabular**



In this structure the sub-topics have well-defined relationships to one another. This is helpful for dividing up subjects with common sub-topics, for example comparing the properties of different chemicals. This offers a very structured way of grouping interrelated information that may be useful for some educational topics.

The non-linearity of many of the structures offers new ways to make links and gather, explore, browse and learn. Many developers believe it is this feature that is the major strength of interactive multimedia. For some educators, however, this remains a contentious issue (Reeves, 1993).

### The uses for multimedia

"Multimedia enhances the way that people work, learn, play and, most importantly, communicate." (Haykin, 1993). Although interactive multimedia is yet to be fully exploited as a means of communication, it has already found a wide variety of applications and potential uses.

In an education context and as a learning tool: lectures, tutorials, practical or laboratory exercises, remedial or extension material, computer-based training, distance and external education

For other types of communication: public information kiosks, sales and marketing, video conferencing, advertising, journals, books, business presentations and demonstrations, databases, encyclopedias, scientific seminars

For recreational purposes: games, infotainment, hobbies, children's stories, art, film, music, museums and galleries

## Current theories of multimedia design

The area of design theory is largely unexplored because interactive multimedia is such a recent development. Most current ideas on what makes a presentation good or otherwise come from graphic design principals, anecdotal evidence or "gut feeling". Reeves (1993) asserts that "much of the development and most of the implementation of IMM [interactive multimedia] seem to be guided by habit, intuition, prejudice, guesswork or politics".

General rules have been established largely through trial and error. There continues to be a need for research into how people use interactive multimedia and what they expect and require from it. From such studies, theories will develop to ensure proper treatment of content and offer guidelines for good design.

## The merits of multimedia

In order to establish where the use of multimedia communication can be successful it is important to address the issue of what is good and bad about interactive multimedia. It should not be assumed that this kind of presentation is suitable or desirable in every context simply because it can be used. Although this kind of presentation has many claims over more traditional forms, not all material is suitable for multimedia treatment. Nor should it be assumed the multimedia somehow "automatically supports learning" without any kind of pedagogic framework (Reeves, 1993). The significant cost of producing interactive multimedia means that if the task can be performed equally well using a different medium then the latter is preferable.

**Advantages**

In general, interactive multimedia :-

- can reach a large number of people over large distances.
- can provide immediate and consistent feedback that may be unavailable, for example, due to a lack of staff.
- is a good way to extend students or help those who require more attention.
- allows users to choose their own path according to their interests and work at their own pace.
- can make connections and comparisons that traditional media can not.
- is generally more easily updated then other forms of media.
- seems to elicit a positive response from students.
- allows people to work in their own environment provided they have access to the necessary hardware.

For science communication, interactive multimedia :-

- allows people to experience phenomena and events that might otherwise be impossible because they are too expensive or too dangerous, for example "desktop surgery".
- may provide a substitute for laboratory work that cannot usually be done due to difficulty or expense.
- can, through its power to animate, communicate dynamic and three-dimensional information more accurately than a diagram.
- can help people visualise phenomena that cannot be seen, for example chemical reactions.

- allows students to concentrate on the main concepts rather than being concerned that their experiment doesn't work.
- offers new ways for museums to present scientific information in an attractive and interactive format.
- may offer a method by which students can be introduced to increasingly complex instruments and techniques with close guidance.

**Disadvantages**

In general, interactive multimedia :-

- may be significantly more expensive than other media for very specific audiences or for small developers.
- may cause the students to feel detached from the teacher or lecturer.
- does not encourage interaction with other people.
- technology is not sufficiently widespread and inexpensive at the current time for most people to use.
- may allow the user to become too passive.
- can be difficult to use if it is poorly designed.
- may elicit a negative response from some users because of generational or cultural reasons.

For science communication, interactive multimedia :-

- does not help students develop the practical laboratory skills that are the basis of scientific research.
- is no substitute for hands-on experience.

According to Latchem (1993) interactive multimedia allows students to build, test and apply knowledge in new ways by providing "browsable chunks" of information with "predetermined links". Environments in which the students are "empowered to control their own learning" will replace a domain traditionally controlled by the teacher. This, Latchem claims, will foster "deep learning" which is self-motivated and self-directed. Changes in the nature of education towards open learning and more flexible training could be supported by the use of interactive multimedia through the reduction of training time, travelling costs and disruption to work schedules. Multimedia also offers libraries and museums new ways for presenting the ever increasing amount of information available (Latchem, 1993).

Much of the focus of multimedia proponents has been on the popularity of interactive multimedia with students. Studies show that the retention rate of students learning through multimedia is 40% greater than more traditional forms and that their motivation and self esteem are higher (Clarke and Swearingen, 1994).

Whitnell et. al. (1994) also report increased student interest resulting from their multimedia treatment of chemistry lectures. They also found, however, that students who didn't like the lectures were not likely to change their opinions by the end of the course. Some students complained that multimedia lectures didn't encourage note-taking or interruption. This reflects more widespread concerns that multimedia can be too passive and does not cater for different learning styles. Students felt that the treatment was most successful in the features most different from usual lectures, but disapproved of the "same old things" just disguised using multimedia. There was also a feeling amongst the students that they were disconnected from the lecturer.

Other projects have attempted to use multimedia in order to overcome the problems of large class sizes, widely varying student backgrounds and fewer tutors (Ladiges et. al., 1994). This approach still covers traditional lecture material and further aims to focus students on the key concepts, provide quality feedback and encourage self study. Accompanying worksheets can be modified to suit the course and may include further reading, extension questions and prepared model answers. Ladiges et. al. found that students enjoyed the course more than expected, were more motivated and particularly liked having something to write down.

Zollman et al (1994) report on the use of interactive video to enhance physics demonstrations. The interactivity gives control to the students and allows them to "answer their own inquiries at a pace that is comfortable for them" with "freedom to investigate and question in their own manner". A notable example in this work is a simulation of Rutherford scattering. The aim is for students to "understand why Rutherford drew some of the conclusions he did about the nature of the atom". This approach teaches students about the process and philosophy of science without them being distracted by laboratory equipment and getting the experiment done.

# About this project

To fulfil the aims of this project two distinctly different multimedia titles were developed for two very different audiences - university students and the general public. These groups are often identified as main targets for improved scientific communication.

The first year university tutorial is titled "Introduction to Quantum Physics, Module 1 - Photons". This module explores the blackbody spectrum and the photoelectric effect as a focus for a discussion of basic quantum physics. The material is sufficiently general to allow it to be included in any first year physics or engineering course and the approach is similar to traditional treatment found in an introductory text. As the title suggests this is only the first module in what could be a series that covers all aspects of quantum physics.

The interactive exhibit is designed for use by the general public interested in learning more about science. "Photochemistry in the Atmosphere" provides a basic introduction to the nature of photochemical reactions and their role in the atmosphere. The focus of the material is the link between photochemistry and air pollution. This approach aims to engage the user by focusing on environmental concerns which they can relate to. Whilst this piece uses a combination of hierarchical and branched structures, it would be relatively simple to expand it into a referential database to create an "environment kiosk" (see figure 1).

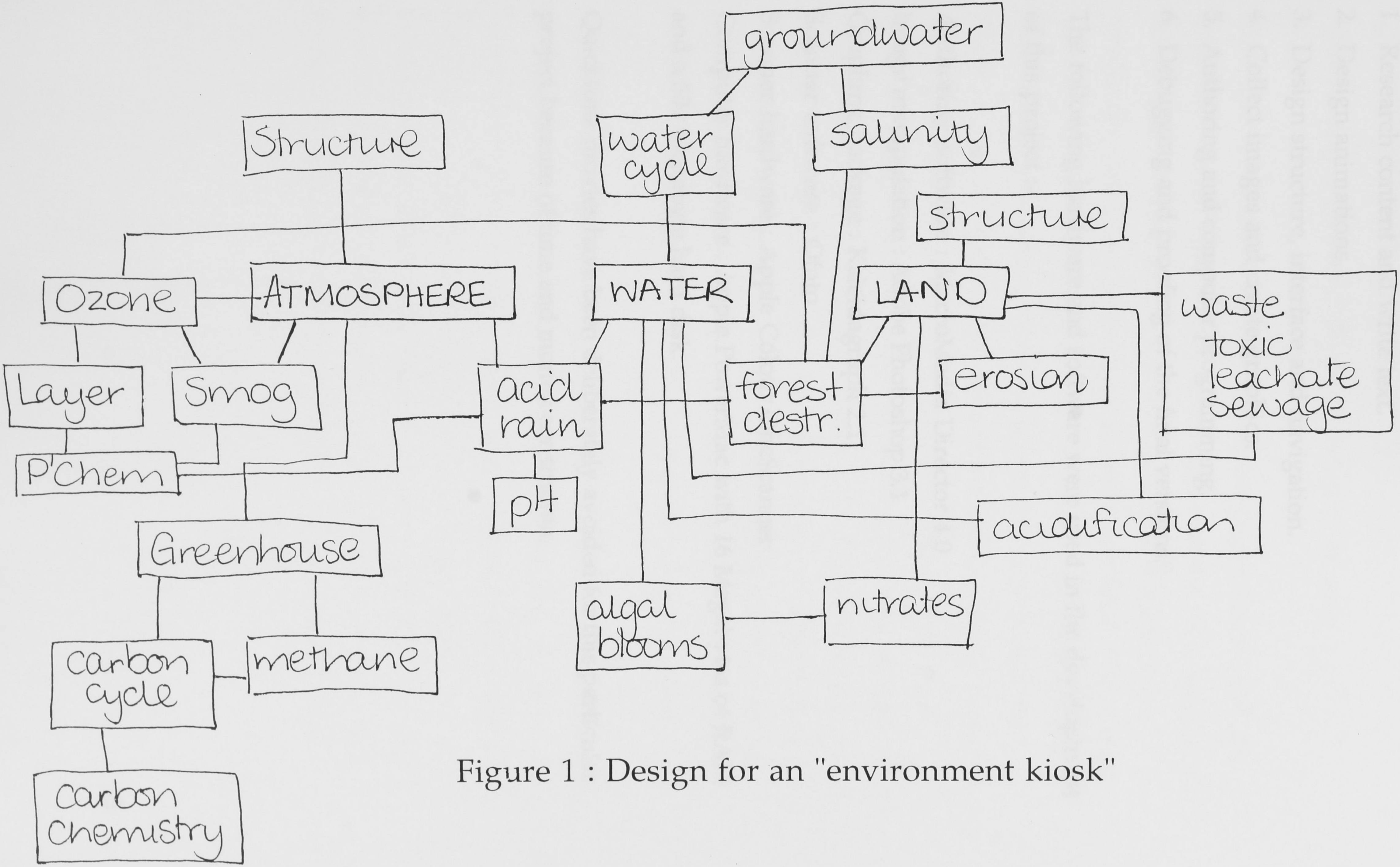


Figure 1 : Design for an "environment kiosk"

The following process was used to design each of the presentations:-

1. Research content and write text.
2. Design animations.
3. Design structure, interface and navigation.
4. Collect images and create graphics.
5. Authoring and computer programming.
6. Debugging and proofing of the final versions.

The following hardware and software were used in the development of this project :-

Authoring software : MacroMedia Director 4.0
Image manipulation : Adobe Photoshop 3.1
Graphing package : Kaleidagraph 2.1
Scanner software : Ofoto
Scanner hardware : Apple Colour OneScanner
Computer hardware : Apple PowerMac with 16 Megabytes of RAM and a 500 Megabyte hard disk.

Quicktime movies have been deliberately avoided for this particular project because of time and money constraints.

# Discussion

## Introduction to Quantum Physics, Module 1 : Photons

The tutorial features a text-based contents page which allows to students to move easily to any of the main sections. Navigation tools are limited to forward and backward buttons and a quit button always appears on screen to allow an exit at any time. The tutorial uses a branched linear structure with diversions to mathematical derivations, biographies of famous scientists and historical notes. These provides more detailed explanation and context for those who are interested. The interface is deliberately simple with large amounts of white space in order to make the text easier to read. The presentation is very straight using only a few transitions, no humour and limited sound. These have been deliberately avoided as they become very tedious when frequently reviewing material. The help provided is very limited as it is assumed that this tutorial would be used in conjunction with some level of supervision or instruction.

Animations, both interactive and non-interactive, have been designed to enhance the students understanding of the material. A variety of interactions such as type-in answers and multiple choice questions have been incorporated into the body of the tutorial to emphasise main points and to maintain interest. To ensure that it is easy for students to review material, after they have typed in an answer it remains in the field so they can re-enter it to pass the screen again.

Another section leads the students through an analysis of some data from a photoelectric effect experiment. They are required to select a line of best fit by dragging the correct line across to the graph and then use the information to calculate various quantities. The procedure is very similar to data analysis students at this level are expected to perform in laboratory classes.

A multiple choice quiz at the end of the module is designed for the students to test their understanding of the material. It is emphasised that this is not an assessment task, but merely for their own information. In this case the students cannot go back to the main body of the module. The computer keeps track of their score and their nominated answer and feedback is provided on any question upon completion of the quiz.

This tutorial uses a number of different testing styles. For some questions corrections are given after one attempt, while for others the students cannot proceed until they enter the right answer. Some questions allow one or more wrong answer and then provide hints on how to do the problem. Addressing issues of measuring student progress and public versus private testing are important when designing these types of interaction. Students may feel uneasy if they think the computer is keeping track of them and be distracted from the content. While multiple choice questions are easy to implement they may not be suitable for particular groups of students.

Included in the appendix to this report is a sample worksheet for this module. A worksheet is valuable for two reasons - it ensures that the student is not being too passive in their learning and provides them with a record of their to take away with them.

The tutorial could be enhanced by the inclusion of a glossary. Other developers have found that students look up definitions far more frequently than expected. Other options could allow students to save their work or use a bookmark to keep track of where they are.

The question remains, with regard both to lectures and tutorials, of whether interactive multimedia should supplement or replace traditional teaching methods. It is conceivable that a comprehensive set of modules could replace lectures and/or tutorials. Although the problems with students feeling dislocated and isolated from the teachers and colleagues require further consideration.

### Photochemistry in the Atmosphere

This programme is designed to be used as an interactive exhibit in a science museum. The target audience is members of the general public who are not necessarily interested in learning a lot of facts and details. This kind of audience requires conceptual information in small chunks that have some significance to them. The programme is designed to allow exploration of the topics with no preferred order enforced upon the user.

Snippets of information appear on each screen with pop-up buttons to provide further explanation if desired. This ensures that the screen isn't too crowded, which can be disconcerting, and the user has control over the level of detail. The writing style is familiar and the explanations use simple language. Highlighted glossary words provide a definition when scientific terms can not be avoided (see the smog section).

The interface for this package is much more visually attractive than the physics tutorial. There is also a more extensive help system to allow people to use the package unassisted. The overall hierarchal structure is formed by a central contents page with a branched linear structure being adopted in the individual sections. The large, coloured text is supplemented by pictures and diagrams. A special cursor allows the user to zoom in on some of the pictures and rollover diagrams are used to reveal additional information. Buttons provide a help screen, an option to start all over again, a route to the contents page and an exit at any time. Sound is used to add interest and let the user know when they have clicked on a button. The inclusion of glossary words, reaction buttons and further information buttons allows the user to explore depending on their own interests and background.

# Conclusion

It remains to be seen whether multimedia promoters can deliver on their promises of a revolutionary new form of communication. However there is no doubt that, properly used, interactive multimedia has much to offer in the area of science communication. It offers the public a novel and attractive experience of science and students a stimulating learning environment.

Interactive multimedia has the capacity to illuminate science accurately and effectively through its combination of many media. It can be entertaining and fun, provide many levels of information and can support both learning and exploration. The main drawback of interactive multimedia is the lack of understanding that is inevitable in a new field.

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# Appendix

A. Installation instructions.

B. Text from "Introduction to Quantum Physics"

C. Student worksheet from "Introduction to Quantum Physics"

D. Information sheets for "Photochemistry in the Atmosphere"

# How to install the programmes

The two multimedia programme have been compressed and segmented to fit on floppy disks. Follow the following procedure to restore them. Firstly, copy all the files on the disks across to your hard drive into the folder of your choice. You should have four files: Quantum, Photochem.#1, Photochem.#2 and Photochem.#3.

To restore "Introduction to Quantum Physics, Module 1 : Photons" :-

1. Double click on the file Quantum.
2. Nominate the destination folder you want the uncompressed file to appear in and click on the extract button.

To restore "Photochemistry in the Atmosphere" :-

1. Double click on the first file of the archive Photochem.#1.
2. When prompted load the final segment, Photochem.#3, by selecting it an clicking the load button.
3. Nominate the destination folder you want the uncompressed file to appear in and click on the extract button.
4. When prompted load the second segment, Photochem.#2, by selecting it and clicking the load button.

The restored files will appear in your folder. To run the programmes simply double click on the icon.

# Introduction to Quantum Physics
## Module 1 : Photons

### Navigation

You can navigate through the tutorial using the next and previous buttons. At some stages in the tutorial the next button will be unavailable because you need to answer a question or type in a number before being allowed to proceed.

You can quit at any stage by clicking on the Q button. At any time you can return to the contents page by clicking on the appropriate button. From there you can go to any section by clicking on the title or look at the map to see where you are.

### Buttons

There are a few different buttons and boxes you need to know about before you get started. Biographical Button - gives you information about a famous scientist. Information Button - gives you further explanation or information. Answer box - just type in your answer. If the cursor isn't blinking just click inside the blue box with the mouse. Enter button - enters your answer for the computer to check.

### Contents

## Objectives

At the end of this module you should be able to :-

- Describe the blackbody spectrum and why classical theory couldn't explain it.
- Describe Planck's theory and the assumptions behind it.
- Compare equations derived from classical theory to Planck's equation
- Describe Einstein's photon theory.
- Explain the connection between wave and particle theory
- Describe the photoelectric effect experiment and its main results
- Explain the problems in understanding the photoelectric effect and how Einstein solved them.
- Analyse data from the photoelectric effect experiment.

## Introduction

At the turn of the century scientists believed that light behaved like a continuous wave. This wave, or classical, theory of light had been accepted for hundreds of years.

In the early part of the 20th century scientists realised that classical theory could not explain the way matter behaved on the atomic scale.

A revolutionary new theory was proposed. If light was treated as a stream of particles many of the problems could be understood. This new approach was called quantum physics.

In this tutorial we will examine two phenomena which sparked the quantum physics revolution and can only be explained using the particle theory of light.

## A Brief History of Light

The ancient Greeks were the first to ponder the nature of light. Pythagoras and his followers suggested that light was composed of tiny particles which travelled in straight lines from the source. Plato and others believed the eye emitted "sight rays" which combined with a ray from the sun and an object to create vision.

Leonardo Da Vinci (1452 - 1519) may have been the first to suggest that light was similar to a wave. He likened ripples on the water to light and sound and the image formed in a mirror to an echo.

In 1672, Isaac Newton first published his view that light was composed of "fiery corpuscles". He observed that when white light was passed through a prism it was dispersed into the colours of the spectrum. He theorised that white light was a mixture of different particles which were sorted according to colour by the prism.

A contemporary Christian Huygens disputed Newton's ideas believing instead that light propagated because of regional differences in pressure. While similar to a wave theory, the impulses were not periodic but followed each other at irregular intervals.

Around 1800 , Thomas Young performed his famous interference experiment and explained the results using the superposition of waves. He also asserted that different coloured beams of light travelled with different frequencies. This further strengthened the case for the wave theory.

In the middle of the 19th century the speed of light in water was finally measured. Scientists thought this would be a good test for the particle versus wave argument because the two theories predicted different results. According to particle theory light should travel faster in air than water whereas wave theory predicted the opposite. The measurement supported wave theory and it was around this time that it became almost universally accepted.

In 1872, Maxwell developed the wave equation which gave a full electromagnetic description of the properties of light. This formed the basis of the classical theory of light which prevailed until early in the next century.

Maxwell's equation predicted the speed of light to be 300 000 000 m/s. This value was later confirmed by Hertz when he became the first person to produce electromagnetic waves in 1887.

## Objectives

At the end of this module you should be able to :-

- Describe the blackbody spectrum and why classical theory couldn't explain it.
- Describe Planck's theory and the assumptions behind it.
- Compare equations derived from classical theory to Planck's equation
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- Describe the photoelectric effect experiment and its main results
- Explain the problems in understanding the photoelectric effect and how Einstein solved them.
- Analyse data from the photoelectric effect experiment.

## Continuous spectra

Any hot object emits radiation depending in its temperature. At low temperatures the radiation is in the infrared part of the spectrum so we cannot see it, but we can sometimes feel the heat. As the object heats up it begins to glow red, like a stove or toaster element. At higher temperatures still the object appears white, like the tungsten filament in a light globe.

Hot dense materials, like liquids and solids, emit a spectrum of radiation. This spectrum is a continuous distribution over all wavelengths from the infrared to the ultraviolet.

This effect was first discovered in the late 19th century and no explanation for it could be arrived at. This provided the first hint that classical theory would fail.

## A Blackbody

The continuous spectrum which is emitted by hot objects is called blackbody radiation. A blackbody is a perfect system which absorbs all the radiation incident on it and therefore appears black. The radiation given off by a blackbody depends only the temperature and not what the object is made of. For this reason blackbodies are a useful tool in the study of thermal radiation.

The inside of a hollow object is a close approximation to a blackbody. Radiation enters through a small opening. It is then partly absorbed and reflected every time it hits the walls of the cavity until eventually it is fully absorbed. Click on the GO button to see this happen.

The colour seen through the hole depends on the temperature of the cavity walls. An industrial furnace is also like a blackbody. The colour seen through the furnace door indicates how hot it is inside.

## Blackbody radiation

By 1900 blackbody radiation had been studied by many scientists. A formula had been found for the total intensity, I, of the radiation and is known as the Stefan-Boltzmann law.

$I = \sigma T^4$ Watts/m

where $\sigma = 5.67\times10^{-8}$ W/m$^2$K$^4$ and is called the Stefan-Boltzmann constant and T is the temperature in Kelvin.

Fill in the missing word.
This equation shows that the total intensity of the radiation is a very strongly dependent on of the ___________ of the body. (temperature)

## Experimental results

Scientists discovered that the intensity is not uniformly distributed over all wavelengths. Light is emitted more strongly at some wavelengths than others. The intensity measured at a particular wavelength, $I(\lambda)$, is called the spectral emittance.

Measured spectral emittance values show a peak at a particular wavelength depending on the temperature of the body. The wavelength at the maximum intensity, $\lambda_m$, is described by Wein's displacement law.

$\lambda_m T = 2.90\times10^{-3}$ metres Kelvin

This equation shows that the peak wavelength is inversely proportional to temperature of the body. Select different temperatures by clicking on the buttons opposite and observe changes in the peak wavelength.

What quantity does the area under the curve represent ?
A. The total power given off.
B. The total intensity of the light.
C. The temperature of the body.

No/Yes/No. The area under the curve is the total intensity of the light. It can be found by integrating the spectral emittance values over the wavelength distribution and is given by the equation $I = \quad I(\lambda)d\lambda$

## Classical theory

All efforts to theoretically explain the shape of the blackbody curve failed. The best attempt was the Rayleigh-Jeans law

$$I(\lambda,T) = \frac{2\pi ckT}{\lambda^4}$$

From the graph, we can say the Rayleigh-Jeans law...
A. works well for long wavelengths.
B. works well for short wavelengths.
C. works well for all wavelengths.

Feedback : Yes/No/No

The Rayleigh-Jeans formula works well for large wavelengths, but fails to reproduce the experimental results for short wavelengths. In fact as the wavelength goes to zero the intensity approaches infinity, which is clearly impossible. This inconsistency is known as the ultraviolet catastrophe!

The Rayleigh-Jeans law is based on the classical theory that thermal radiation originates from accelerated charged particles near the surface of the material. The discrepancy with the experimental results showed that this could not really be the case.

Planck's Law

In 1900 Max Planck empirically derived an equation which agreed completely with the experimental results.

$$I(\lambda,T) = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kt} - 1)} \qquad \text{Planck's law}$$

where h is Planck's constant equal to $6.63\times10^{-34}$ Js.

Click on the FIT button opposite to fit Planck's curve to the blackbody data.

How would you use Planck's law to derive the Stefan-Boltzmann law?
A. Integrate Planck's equation over all wavelengths.
B. Differentiate Planck's equation and set the derivative to zero.
C. Take the classical limit ie. when the wavelength is very large.

Yes/No/No. Using the Stefan-Boltzmann law we can find the total intensity for a given temperature. Thus by integrating Planck's equation over all wavelengths we get the Stefan-Boltzmann law.

How would you use Planck's law to derive Wein's displacement law?
A. Integrate Planck's equation over all wavelengths.

B. Differentiate Planck's equation and set the derivative to zero.
C. Take the classical limit ie. when the wavelength is very large.

No/Yes/No. Wein's law gives the wavelength at which the spectral emittance is a maximum. To find a maximum (or minimum) for any curve we must find the point at which the derivative (ie the slope) is zero.

How would you use Planck's law to derive the Rayleigh-Jeans law?
A. Integrate Planck's equation over all wavelengths.
B. Differentiate Planck's equation and set the derivative to zero.
C. Take the classical limit ie. when the wavelength is very large.

No/No/Yes. The classical limit corresponds to the case where the wavelength is very large and the energy of the photon becomes very small. This means the energy becomes continuous rather than quantised. Using this limit reduces Planck's equation to the classical Rayleigh-Jeans law.

## The Quantum Approach

After determining the mathematical description for blackbody radiation, Planck set out to develop a coherent theoretical framework. He found that two radical assumptions were needed to make his formula work.

Assumption 1. The molecules within the object, which vibrate to produce the radiation, may only have certain energies given by
$E_n = nhf$
where n is a positive integer, f is the frequency of vibration and h is Planck's constant. The energy of the molecules is said to be quantised and each different energy corresponds to a different quantum state.

Assumption 2. Energy is emitted or absorbed by the molecules in discrete units of light energy called quanta. As the molecules change energy they jump from one quantum state to another. If a molecule absorbs energy it jumps to a higher quantum state. If it moves to a lower quantum state energy is emitted. The energy of the radiation corresponding to the energy difference between two states is hf.

## Max Planck (1858 - 1947)

Max Planck was born into an academic family with his father a professor of civil law at the University of Kiel. When Planck announced his intention to become a physicist he was told that all of the major discoveries had been made in that field. Ignoring this advice, he studied physics at university in Berlin and Munich and received his PhD in 1880. Afterwards he held positions in Kiel and Berlin, becoming professor of physics at the University of Berlin in 1892. In 1900 he presented his quantum theory to the Berlin

Physical Society. Although it was some time before his ideas were accepted, this was the start of the quantum physics revolution.

In 1930 he became head of the Kaiser Wilhelm Institute, but resigned in 1937 as a protest against the Nazi treatment of Jews. Although he did not make his views public he spoke personally to Hitler. Planck expressed concern that the racial laws which barred Jews from research positions would adversely affect German science. Hitler reportedly replied that Germany could "do without science for a few years".

After the war Planck returned to his position and the Institute was named after him. He received the 1919 Nobel prize for physics. He described his blackbody formula as "lucky guess work" and searched in vain for a physical interpretation.

Despite his many awards the later years of his life were bitter ones. Not only had he witnessed the destruction of German science he also suffered great personal tragedy. His second son was killed in the war, his twin daughters died at birth and his eldest son was executed for plotting against Hitler. Planck is immortalised on the German two DM coin.

## A Useful Analogy

We can think of a vibrating molecule as being like two masses connected by a spring. The masses vibrate with a particular amplitude which corresponds to a certain energy. If the system loses energy the amplitude will decrease. If energy is gained the amplitude will increase. The quantised molecule is very similar except it gains or loses energy in discrete units. If it loses one quantum the system drops to the next lowest allowed energy state. Click on the GO button to start the animation. The graph shows the difference between classical and quantum theories. Classical theory predicts that all energies, and therefore all amplitudes, are allowed. Quantum theory says that only particular states are permitted.

## What did this mean?

Planck's theory governs the way energy is gained or lost by any object. It states that there is a limit to how small this amount of energy can be and the smallest unit is a quantum, hf. Any amount of energy which is gained or removed must be some multiple of that quantum. By clicking on the picture opposite zoom in to see more and more detail. The picture really consists of individual pixels even though we can't see them in the original. On an everyday scale everything has so much energy that the tiny discrete units go unnoticed. On the subatomic scale though the individual quanta of energy become very important.

## Photon Theory

In 1905, Albert Einstein extended Planck's quantisation concept to explain the mysterious behaviour of light. Einstein suggested that any form of electromagnetic radiation can be thought of as a stream of particles. These particles are discrete bundles of energy known as photons. He proposed that the energy of a photon is given by $E = hf$, where f is the frequency of the radiation and h is Planck's constant.

## Albert Einstein (1879 - 1955)

Albert Einstein didn't start life as a genius. In fact he didn't speak until the age of three, hated school and was expelled for being disruptive. One of his exasperated teachers told him, " You know Einstein, you will never amount to anything!". Shortly after his family moved to Italy, he renounced his German citizenship and was stateless for 5 years until becoming a Swiss national. Einstein tried to enter the Polytechnic in Zurich to study electrical engineering, but failed the entrance exams. The next year he passed, but to study physics and mathematics instead. He graduated without particular merit and found a job at the Swiss Patent Office where he earned a modest income for seven years. It was during this period that he used his spare time and weekends to work on theories which would change the face of physics in the twentieth century.

In 1905, he published his three great papers on photon theory, special relativity and Brownian motion. For his work on the first he was awarded the 1921 Nobel prize for physics. In 1913, he took up a special position at the Kaiser Wilhelm Institute created so he could devote all his time to research. He published his theory of general relativity in 1915. This theory was dramatically confirmed during an eclipse in 1919 after which he suddenly became a world celebrity. Einstein left Germany in 1933 when Hitler came to power and accepted a position at Princeton University where he remained for the rest of his life. He became an American citizen in 1940 and, although a pacifist, urged the president to initiate a research effort to develop the nuclear bomb. After the war he was asked to become president of Israel but he declined.

## Photon Momentum

Einstein also suggested that photons have linear momentum. The relativistic relationship between momentum and energy is given by

$$E^2 = (pc)^2 + (mc^2)^2$$

A photon has zero mass because it traves at the speed of light, (click on the relativity button for an explanation, so the above equation becomes

$$E = pc.$$

Substituting in for $c = \lambda f$ and $E = hf$ and then rearranging we get

$$p = \frac{h}{\lambda}$$

Particle or wave?

$$p = \frac{h}{\lambda}$$

It is important to note that this equation links the particle and wave nature of light. On the left hand side p refers to the momentum of the particle. On the other side $\lambda$ refers to the wavelength of the corresponding wave.

Relativity

To find the mass of a photon we start with the general equation for the relativistic mass of any particle

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where $m_0$ is the rest mass, v is the velocity of the particle and c is the velocity of light.

Squaring both sides, multiplying everything by $c^4$ and rearranging gives

$$m_0 = m\left(1 - \frac{v^2}{c^2}\right)$$

A photon travels as the speed of light and substituting for $v = c$ gives

$$m_0 = m\left(1 - \frac{c^2}{c^2}\right) = 0$$

Therefore any particle travelling at the speed of light has zero rest mass.

The Photoelectric Effect

In the late 19th century, experiments showed that when monochromatic light falls on a metal surface electrons (called photoelectrons) are emitted. This phenomenon, known as the photoelectric effect, was another to defy explanation by classical physics. Click on the diagram to investigate the photoelectric effect apparatus. A metal plate and a collector electrode are placed inside an evacuated glass cell called a phototube. The electrodes are connected to an ammeter and a variable voltage source. Click on the animation button to see an animated version of the photoelectric effect.

Pop-up
When the light strikes the plate electrons are emitted. The electrons are then attracted towards the positive collector electrode. As a result, current flows in the circuit.

## The Effect of Voltage

If a suitable potential difference is applied, the photoelectrons flow from the metal plate to the collector and are detected as a current by the ammeter. If the terminals are reversed, so the collector is negative and the plate is positive, the electrons will now be repelled from the collector. At small negative voltages the fastest electrons will still reach the collector, but as the reversed voltage is increased a point is reached where the current becomes zero. This is called the stopping voltage, $V_0$.

## The Experiment

Using the slider bar below vary the applied voltage and watch what happens on the graph.

Now see what happens when the intensity of the light is changed.

Finally, vary the frequency of the incoming light to see what effect this has.

## Voltage Variation

As the applied voltage is increased from some negative value the photoelectric current remains zero for a while. At some threshold voltage the current registers on the ammeter. This voltage is the stopping voltage. The current continues to rise until it reaches a saturation level for large voltage values.

## Intensity Variation

As the intensity of the incident light is increased the photoelectric current increases. Notice also that the shape of the curve and stopping voltage remain the same.

## Frequency Variation

When the frequency of the incident light is varied the stopping voltage changes. When the frequency is increased the stopping voltage becomes more negative. This is because an increased negative voltage is needed to stop the fastest electrons. Decreasing the frequency causes the stopping voltage to become less negative. Click on the Graph button to see another way of expressing this data.

## Graph

This graph of the stopping voltage, $V_0$, versus the frequency of the incident light, f, shows a linear relationship. The blue dots are experimental data points and the red line is a line of best fit. Later in the tutorial you will use this plot to do some calculations.

## Einstein's explanation

In 1905 Einstein suggested that these experimental results could be used as a test of his photon theory. Treating the light as a stream of discrete particles rather than a wave he gave the following explanation for the photoelectric effect. When a photon hits the metal its energy is transferred to an electron close to the surface. If this energy is sufficient to overcome the forces holding the electron inside the material it escapes. Let's have a brief look at the three main problems Einstein's theory solved.

## The Intensity Problem.

The photoelectric effect experiment shows that when the intensity of the incident light is increased the current detected by the ammeter increases. On the opposite graph the upper curve is for a higher incident intensity resulting in a larger current. Notice that the stopping voltage doesn't change. This indicates that the kinetic energy of the electrons doesn't change with variation in the intensity. Click on the buttons below to compare classical and quantum explanations.

## Classical Theory

If light is thought of as a wave then as the intensity is increased the magnitude of the electric field also increases. Since the force of the electric field is directly proportional to the magnitude of the field, an increased force acts on the electrons. This results in the electrons being thrust out with greater kinetic energy. The stopping voltage required to stop the electrons will be more negative. The current remains the same because no more electrons are be ejected with the increased intensity.

## Quantum Theory

Quantum theory predicts that an increase in light intensity simply means there are more photons in the beam. If the intensity of the light is doubled there are twice as many photons. This means there are more photons to collide with the metal and so more photoelectrons are produced. As the frequency of the light is the same the photon energy and, therefore, the maximum kinetic energy of the photoelectron will not change either. This means the stopping voltage will stay the same.

The Frequency Problem.

The photoelectric effect also shows that below a certain frequency no photoelectrons will be emitted, no matter how intense the incident light is. This cutoff frequency is a characteristic of the particular metal used. The graph opposite shows the linear variation of photoelectron kinetic energy with incident frequency. The experimental results also show that the kinetic energy of the ejected electrons increases as the frequency of the incident light increases.

Classical Theory

Classical theory predicts that photoelectrons will be emitted at any frequency provided the intensity is high enough. Click on the graph opposite which shows the wave theory prediction.

Feedback : Yes/No. This graph illustrates the classical prediction that electrons will be emitted at any frequency and at constant kinetic energy for a given intensity.

Quantum Theory

Quantum theory predicts that a photoelectron will only be emitted if the incoming photon has enough energy to overcome the forces holding the electron within the metal. So there will be some minimum energy required to break the electron free. This means there will be some frequencies of light for which the photons in the beam do not have enough energy to release the electrons from the metal.

The Time Delay Problem.

The photoelectric effect also shows that even at low intensities electrons are emitted less than a nanosecond ($10^{-9}$ s) after the metal is illuminated. The graph opposite shows the results of the photoelectric experiment using a pulse of light. The upper trace shows the intensity of the laser pulse. The lower trace shows the immediate detection of the current by the ammeter.

Classical Theory

Classical theory predicts that there will be a time delay between when the light hits the plate and the photoelectrons are emitted. This is because the wave delivers energy over an area of the metal and the electrons in the metal will take time to soak up sufficient energy to escape. Click on the graph opposite which illustrates the wave theory prediction.

Feedback : Yes/No. This graph shows the delay between the start on the light pulse and the detection of the current as predicted by classical theory.

## Quantum Theory

Quantum theory explains that if the photon frequency is above the cutoff value an electron in the metal will absorb energy from a single collision and escape immediately. This is because the concentrated energy of the photon is passed directly to the electron rather than being spread over a large area.

## A New Theory of Metals

Now that we have a quantum theory for light we also need to develop a new understanding of the electrons in a metal. The metal can be thought of as an energy bucket in which the electrons sit. The electrons are held in place by their attraction to the positive nuclei of the atoms, so that energy must be added to remove them from the metal. Electrons which are deeper in the bucket are held more tightly and so more energy is required to release them. The energy which must be overcome for the electrons to just reach the surface is called the work function. It is given the symbol $\phi$ and is measured in electron volts. The energy in Joules which corresponds to the work function in given by $E_\phi = \phi e$, where e is the charge on the electron.

## The Fermi Level

At absolute zero (0K) the electrons in the metal fill up to a certain energy level called the Fermi level. At higher temperatures the Fermi level is the energy level where there is a 50% chance of finding an electron. The work function is actually the energy that must be given to an electron located at the Fermi level for it to become free. Electrons below the Fermi level (deeper in the bucket) will need more energy and those above will need less.

## The Work Function.

If the energy of the incident photons is greater than the work function the electrons which are ejected convert what is leftover into kinetic energy. The electrons which are the least tightly held by the metal will have the most kinetic energy. Because the total energy of the system must be conserved the energy of the incident photon must equal the work function plus the

kinetic energy of the ejected electron.
$E_p = hf = E_\phi + KE$

For sodium the work function, $\phi$, is 2.28 eV. Type in the photon frequency which is needed to just get the electron to the surface of the metal. Round your answer off to one decimal place and click Enter.

Feedback : Right answer! Now click on the FIRE button to see what will happen./ Wrong answer. Go back and try again!/ You seem to be having some trouble with this one. Here's a hint! We know that $\phi = 2.28$ eV and $KE = 0$. The energy corresponding to the work function is $E_\phi = e\phi = 1.60\times10^{-19} \times 2.28 = 3.65\times10^{-19}$J. This must also be the energy of the incident photon. $E_p = E_\phi + KE = 3.65\times10^{-19}$J. Rearranging for f gives $f = \frac{3.65\times10^{-19}}{h}$. Now go back and try again!

On exit : The electron escapes!

If the incident photon has energy $5\times10^{-19}$J, at what speed will the photoelectron be travelling immediately after it is ejected? Round your answer off to one decimal place and click Enter.

Feedback : Good! Now click on the Fire button to see what happens to the electron! / That's not right! Firstly you must rearrange the formula for kinetic energy $KE = E_p - E_\phi = 5\times10^{-19} - 3.65\times10^{-19} = 1.35\times10^{-19}$J. Using $KE = (1,2)mv^2$ we get $v = \sqrt{\frac{2KE}{m}}$. Now go back and try again!

On exit : This electron has more than enough energy to escape the metal. Extra energy from the photon has been converted to kinetic energy.

If the incident photon has energy $3.6\times10^{-19}$J, will a photoelectron be ejected?
Yes
No
Feedback : Right! Now click on the Fire button to see what happens to the electron!/ Wrong! Compare the energy of the incident photon to the energy corresponding to the work function. Try again.

On exit : This electron doesn't have enough energy to overcome the forces holding it in the metal, so it cannot escape.

## A Closer Look at the Phototube

The work done to move an electron through a potential difference of V volts is W = eV. To move the electron from the plate to the collector the work done is equal to the change in kinetic energy. Only electrons with energy greater than eV can reach the collector.

The applied voltage can be varied until only the fastest electrons are collected. This is the method for measuring the maximum kinetic energy.

$KE_{max} = eV_0$

where $V_0$ is the stopping voltage.

### Inside the Phototube

Click on the GO button to start the voltage supply. Then using the slider bar vary the applied voltage until you find the stopping voltage. Type in your estimate of the stopping voltage (to one decimal place).

Feedback : Right Answer!/ Wrong! You can find the stopping voltage by varying the applied the voltage until the electron just makes it from the metal plate to the collector. Go back and have another go.

### The New Model Revisited

We can think of the stopping voltage as a small modification to the energy bucket model we looked at before. The stopping voltage is like an extra barrier for the electron needs to jump in order to reach the collector and be counted. If the photon energy is only just enough to overcome the work function, the electron will be ejected from the atom. However, it won't have enough energy to jump the stopping voltage barrier and make it to the collector. For a higher frequency the electron may have enough energy to escape from the metal, overcome the applied voltage and contribute to the photocurrent.

### The Stopping Voltage

Using the conservation of energy expression

$$hf = E_\phi + eV_0$$

determine which of the following equations has been correctly rearranged for the stopping voltage.

$$V_0 = \frac{he}{f} - E_\phi$$

$$V_0 = \frac{hE_\phi - f}{e}$$

$$V_0 = \frac{hf - E_\phi}{e}$$

$$V_0 = \frac{hf}{e} - E_\phi$$

Feedback : Yes/No. The correct equation is $V_0 = \frac{hf - E_\phi}{e}$.

Note that using $\phi = eE_\phi$ we can rewrite it as $V_0 = \frac{hf}{e} - \phi$.

## Data Analysis Part 1

This graph shows the relationship between the stopping voltage and the frequency of the incident light. Drag the lines onto the graph to determine which is the line of best fit. When you think you have it right line in the right position click on the Check button.

Feedback : Yes, you chose the correct slope. The red line shows you how close you were to the correct position./ No, that line doesn't have the right slope. You should have chosen the one at the bottom. Compare your answer to the correct line of best fit, which is shown in red.

## Data Analysis Part 2a

We have already introdcued the formula relating stopping voltage and incident frequency.

$$V_0 = \frac{hf}{e} - \phi$$

How would you use this formula and the graph to calculate a value for Planck's constant?

Use the slope of the line.
Use the intercept with the y axis.
Use the intercept with the x axis.

Feedback : Yes, you would use the slope to find a value for h. Comparing this with our stopping voltage formula we see that the slope of the line must equal h/e./ Wrong! You need to use the slope to calculate a value for h. Remember that the equation of a straight line is $y = mx + c$ where m is the slope and c is the y intercept. Comparing this with our stopping voltage formula we see that the slope of the line must equal h/e.

## Data Analysis Part 2b

Now use the formula to estimate the slope. Type in your answer to one decimal place and click the Enter button.

Feedback : Right! The slope of the line of best fit is about $0.4 \times 10^{-14}$ V/Hz. The units can also be written as Vs remembering that Hz is just $s^{-1}$./ Wrong! To determine the slope of the line you need to divide the rise by the run. The slope is about $0.4 \times 10^{-14}$ V/Hz. The units can also be written as Vs remembering that Hz is just $s^{-1}$.

## Data Analysis Part 2c

Now calculate a value for Planck's constant to one decimal place. Type in the numerical answer and the units, then click on the Enter button.

Feedback : Correct! Notice that our experimental value is different to the theoretical value for Planck's constant, which is about $6.63 \times 10^{-34}$ Js. Why do you think that is?/ You got the units right but not the value of h. The value determined from the graph is about $6.4 \times 10^{-34}$ Js. This is different to the theoretical value for Planck's constant, which is about $6.63 \times 10^{-34}$ Js. Why do you think that is?/ You got the value of h right but not the units. Planck's constant is measured in Joules seconds or Js. The value of h from the graph is different to Planck's theoretical value of $6.63 \times 10^{-34}$ Js. Why do you think this is?/ Wrong! The value determined from the graph is about $6.4 \times 10^{-34}$ Js. This is different to the theoretical value for Planck's constant, which is about $6.63 \times 10^{-34}$ Js. Why do you think that is?

## Data Analysis Part 3a

Using the stopping voltage formula

$$V_0 = \frac{hf}{e} - \phi$$

and information from the graph how would you find a value for the work function?

A. Use the slope of the line.
B. Use the intercept with the y axis.
C. Use the intercept with the x axis.

Feedback : Yes! You would use the y intercept to find a value for the work function./ Wrong! You need to use the y intercept to calculate a value for the work function. Remember that the equation of a straight line is $y = mx + c$ where m is the slope and c is the y intercept. Comparing this with our stopping voltage formula we see that the y intercept must relate to the work function.

Data Analysis Part 3b

Now estimate a value for the work function in electron volts. Type in your answer, to one decimal place, and click Enter.

Feedback : Yes! That's a good estimate for the work function./ No! That's not right! From the graph the y intercept is about -1.8. So the value of the work function must be about 1.8 eV.

Data Analysis Part 4

The cutoff frequency, $f_0$, is the frequency at which electrons are only just ejected from the metal. They have no extra kinetic energy so the stopping voltage must be zero. Recall the stopping voltage formula

$$V_0 = \frac{hf}{e} - \phi$$

Which of the expressions below is a correct derivation for the cutoff frequency?

A. $f_0 = \frac{h}{e\phi}$

B. $f_0 = \frac{eh}{\phi}$

C. $f_0 = \frac{e\phi}{h}$

D. $f_0 = \frac{\phi}{eh}$

Feedback : Right Choice/ Wrong Answer. With KE = 0 the expression becomes $0 = \frac{hf_0}{e} - \phi$. Rearranging gives $f_0 = \frac{e\phi}{h}$

Data Analysis Part 5

Estimate $f_0$ from the graph and use it to work out the cutoff wavelength, $\lambda_0$. Round your answer off to three significant figures and click Enter.

Feedback : Yes that's right! In this case the cutoff wavelength is the red part of the visible light spectrum./ Wrong! From the graph we can estimate the cutoff frequency to be about $4.5 \times 10^{14}$ Hz. Using $c = f\lambda$, the cutoff wavelength must be about 666 nm, in the red part of the visible light spectrum.

Practical Applications

Automatic door openers, burglar alarms and smoke detectors make use of photoelectric circuits. When the light beam is interrupted by a person or smoke, there is a sudden drop in the current. This activates a switch to open the door or operate a bell. Click on the Go button to start an animation of a smoke detector. Photocells in automatic doors use the photocurrent to open the doors. For many applications today the photocell has been replaced by a semiconductor device called a photodiode.

## Scientific Applications

The photoelectric effect is also used in very sensitive light detectors. One example is a photomultiplier tube. A single photon is incident on the top surface and an electron is emitted. This electron is directed to a special electrode where its impact causes several secondary electrons to be released. These electrons are directed towards a third electrode which produces more electrons. The process continues until millions of electrons reach the bottom and are measured as a current. In this way the arrival of a single photon at the top surface can be detected. Click on the Go button to start the animation of a photomultiplier.

## Main Points

Light sometimes acts like a stream of particles rather than a wave.

The particles, called photons, have energy $E = hf$ and momentum $p = h/\lambda$

The photoelectric effect can only be adequately explained using photon theory.

According to the theory, a photon incident on a metal surface will eject an electron provided it has sufficient energy.

The electrons are held in the metal by attractive forces. The work function is the energy that must be overcome to eject an electron from the material.

The photoelectric effect is the basis for many familiar devices.

Quiz

This is a short multiple choice quiz so you can test how well you understood the material. this is not an assessable task. It's just for you to find out what you need to go back and review later. During the quiz you cannot go back into the module. But you can get feedback on your answers after you finish. Click on the answer you think is correct and you will automatically move on to the next question.

Question 1

Why can't you see a bath of hot water in the dark?

A. The temperature of the water is too low for the radiation to be visible.

B. The peak wavelength of the radiation is in the ultraviolet region.

C. Hot water doesn't radiate any energy.

Feedback :
Yes/No/No. The bath of water is really at quite a low temperature and emits light in the infrared region of the spectrum. Light of these frequencies can't be seen by the human eye.

Question 2

Which of the following statements is correct?

A. A photon of wavelength 400 nm has more energy than a photon of wavelength 500 nm.

B. The energy of a photon is inversely proportional to the wavelength.

C. A photon is the smallest amount of energy a body can absorb.

D. All of the above.

Feedback :
No/No/No/Yes. All of these statements are true, so D is the best choice. The energy of a photon is inversely proportional to the wavelength, thus a photon of smaller wavelength has a higher energy. The photon is the smallest amount of energy that can be emitted of absorbed by any object.

Question 3

Why does ultraviolet light cause sunburn while visible light does not?

A. Ultraviolet light travels faster through the air than visible light.

B. Visible light doesn't have enough energy, but ultraviolet does.

C. Visible light is absorbed by molecules in the air.

D. Visible light has a shorter wavelength.

Feedback :
No/Yes/No/No. The correct answer is B. Ultraviolet light has a higher frequency (shorter wavelength) and thus higher energy than visible light. Unlike those in the visible region, UV photons have sufficient energy to cause damage to our skin.

Question 4

If photon A has twice the energy of photon B what can you say about their momentum?

A. Their momentum is the same.

B. Photon A has twice the momentum of photon B.

C. Photon A has half the momentum of photon B.

Feedback :
No/Yes/No. Photon A must have twice the frequency of photon B since the energy of a photon is given by $E = hf$. Remember that the momentum of a photon is given by $p = h/\lambda = hf/c$. So using this formula photon A must have twice the momentum of photon B.

Question 5

A pulse of light has energy $4.05\times10^{-18}$J and a wavelength of 540 nm. How many photons are there in the pulse?

A. 1

B. 10

C. 100

Feedback :
No/Yes/No. First find the frequency of the photon using $f = c/\lambda$. Next

work out the energy of an individual using E = hf = $3.7\times10^{-19}$J. The number of photons in the pulse is just the total energy of the pulse divided by a single photon. This gives 10 photons.

Question 6

A metal plate is illuminated by light of a particular frequency. What factors will determine whether photoelectrons are emitted?

A. The intensity of the incident light.

B. The area of the plate which is exposed.

C. The material that the plate is made of.

Feedback :
No/No/Yes. Photoelectrons will only be emitted if the frequency is sufficient to overcome the work function of the particular metal. Therefore the material that the plate is made of will make a difference. The intensity of the light and the area which is illuminated are not important.

Question 7

Which of the following statements is correct?

A. The magnitude of the photocurrent depends on the light intensity.

B. The work function depends of the light intensity.

C. The magnitude of the photocurrent depends on the light frequency.

Feedback :
No/No/Yes. The frequency of the incident light will affect the magnitude of the photocurrent. If the frequency is below the cutoff no electrons will be emitted so there will be no current measured. As the frequency is increased, the photocurrent increases as more electrons are pulled from the metal until a saturation point is reached. The intensity of the light has no effect on either the work function or the photocurrent.

Question 8

Which of the following statements is consistent with quantum theory?

A. The kinetic energy of the photoelectrons depends of the light frequency.

B. There will be a time delay between the light hitting the plate and the ejection of electrons.

C. Photoelectrons will not be emitted if the intensity is too low.

D. Increasing the intensity of the light will increase the kinetic energy of the photoelectrons.

Feedback :
Yes/No/No/No. The kinetic energy of the photoelectrons depends of the energy, hence the frequency, given to them by the incoming photons. The intensity has no effect on the kinetic energy. The process is a one to one instantaneous collision so electrons will still be emitted at low intensities and there will be no time delay.

### Question 9

If the threshold wavelength increases when the metal plate is changed, what can you say about the work function of the second plate?

A. The work function of the second plate is the same as the first.

B. The work function of the second plate is greater than the first.

C. The work function of the second plate is less than the first.

Feedback :
No/No/Yes. The increase in threshold wavelength corresponds to a decrease in threshold frequency. This means lower energy photons are sufficient to eject an electron thus the work function must be lower for the second plate than the first.

### Question 10

A metal plate is illuminated with ultraviolet light. At first electrons are emitted, but after a while no more are detected. Why?

A. There are no more electrons in the metal.

B. The light energy is too low to release all the electrons.

C. The intensity of the light is too low to overcome the work function.

Feedback :
No/Yes/No. There are still electrons in the metal but the incoming photons don't have sufficient energy to release them because they are deeper in the

energy "bucket". The intensity of the light has no effect on the emission of electrons.

Results

Your score is __ out of 10. If you would like some feedback on your answers click on the button below. Otherwise that is the end of Introduction to Quantum Physics, Module 1 : Photons. To end now click on the quit button.

# Introduction to Quantum Physics
# Module 1 : Photons

## Objectives

At the end of this module you should be able to :-

- Describe the blackbody spectrum and why classical theory couldn't explain it.
- Describe Planck's theory and the assumptions behind it.
- Compare equations derived from classical theory to Planck's equation
- Describe Einstein's photon theory.
- Explain the connection between wave and particle theory
- Describe the photoelectric effect experiment and its main results
- Explain the problems in understanding the photoelectric effect and how Einstein solved them.
- Analyse data from the photoelectric effect experiment.

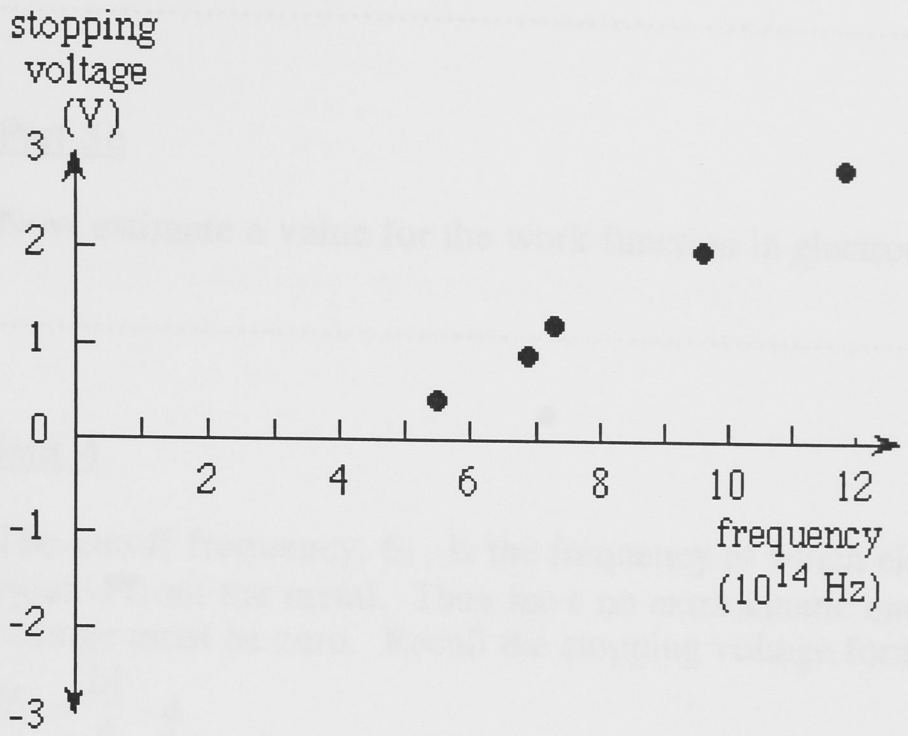
## Data Analysis

Useful Data
Speed of light = c = $3.0 \times 10^{8}$ ms$^{-1}$
Planck's constant = h = $6.6 \times 10^{-34}$ Js
mass of an electron = $m_e$ = $9.1 \times 10^{-31}$ kg
charge on an electron = e = $1.61 \times 10^{-19}$ C

Units
J = Joule
eV = electron volt
m = metre
kg = kilogram
s = second
C = coulomb
1 electron volt (eV) = $1.61 \times 10^{-19}$ Joules

## Part 1

Draw in the line of best fit on the graph.



## Part 2a

Recall the formula relating stopping voltage and incident frequency.

$$V_0 = \frac{hf}{e} - \phi$$

How would you use this formula and the graph to calculate a value for Planck's constant?

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## Part 2c

Now calculate a value for Planck's constant to one decimal place.

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## Part 3a

Using the stopping voltage formula

$$V_0 = \frac{hf}{e} - \phi$$

and information from the graph how would you find a value for the work function?

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### Part 3b

Now estimate a value for the work function in electron volts.

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### Part 4

The cutoff frequency, $f_0$, is the frequency at which electrons are only just ejected from the metal. They have no extra kinetic energy so the stopping voltage must be zero. Recall the stopping voltage formula

$$V_0 = \frac{hf}{e} - \phi$$

Which of the expressions below is a correct derivation for the cutoff frequency?

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### Part 5

Estimate $f_0$ from the graph and use it to work out the cutoff wavelength, $\lambda_0$. Round your answer off to three significant figures and click Enter.

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## Quiz

You might like to make some notes here on your answers to the quiz questions.

### Question 1

Why can't you see a bath of hot water in the dark?

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Question 2

Which of the following statements is correct?

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Question 3

Why does ultraviolet light cause sunburn while visible light does not?

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Question 4

If photon A has twice the energy of photon B what can you say about their momentum?

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Question 5

A pulse of light has energy $4.05\times10^{-18}$J and a wavelength of 540 nm. How many photons are there in the pulse?

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Question 6

A metal plate is illuminated by light of a particular frequency. What factors will determine whether photoelectrons are emitted?

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Question 7

Which of the following statements is correct?

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Question 8

Which of the following statements is consistent with quantum theory?

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### Question 9

If the threshold wavelength increases when the metal plate is changed, what can you say about the work function of the second plate?

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### Question 10

A metal plate is illuminated with ultraviolet light. At first electrons are emitted, but after a while no more are detected. Why?

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**Acid Rain**

Rainwater is naturally a bit acidic with a pH of about 5.6. Carbon dioxide gas ($CO_2$) in the atmosphere dissolves in water vapour and forms weak carbonic acid ($H_2CO_3$). In some places though human activities have caused rain to be far more acidic than normal. It's not just rain either - snow, hail and fog can also be acidic.

In Central Europe rain has an average pH of 4.1. Rain as acidic as vinegar has fallen in Scotland and snow in the United States was found to have a pH of 2.1. Even smog can be acidic. Los Angeles has recorded air with a pH of 1.7. The effects of acid rain have been most obvious in Europe and North America where forests have been destroyed and buildings eroded.

Reactions involving sulfur dioxide ($SO_2$) in the atmosphere are largely blame for the increasing acidity of rain. When sulfur dioxide dissolves in water it forms weak sulfurous acid ($H_2SO_3$) that doesn't cause much damage. It is the photochemical reaction of sunlight and sulfur dioxide that leads to the formation of the much stronger sulfuric acid ($H_2SO_4$).

All living things contain sulfur including the creatures that, over millions of years, formed fossil fuels. When the fuel is burned the sulfur is converted to sulfur dioxide. Power stations and industrial furnaces, burning fossil fuels, release large amounts of sulfur dioxide gas into the atmosphere.

Ultraviolet-A light passes through the atmosphere, is absorbed by the sulfur dioxide molecule and excites it. A series of reactions with other molecules produces sulfur trioxide ($SO_3$). The sulfur trioxide then combines with water to form sulfuric acid that falls from the sky as acid rain.

Sulfur dioxide reaches the atmosphere via a number of natural sources - volcanoes, rotting vegetation and forest fires. However, around half comes from industrial emissions. About 80% of that comes from burning coal and oil and the rest from smelting and refining. This graph shows how estimated sulfur emissions have increased steadily since 1860.

Tall chimneys that keep the industrial pollution away from suburban backyards allow the gases to travel 100s of kilometres to do their damage. For example, forest destruction in Sweden was caused by sulfur dioxide blown over from the United Kingdom. Acid rain has become a source of conflict between those who produce sulfur dioxide and those who suffer its effects.

A less common source of acid rain is nitrogen dioxide ($NO_2$). Cars emit nearly half the nitrogen oxide that leads to acid rain. The high temperatures in car engines generate both nitrogen dioxide and nitric oxide (NO) from nitrogen present in the petrol. The nitric oxide is quickly converted to nitrogen dioxide that in turn reacts to form nitric acid.

Although very acidic rain can damage leaves directly, changes in the chemistry of the soil are far worse. The metals magnesium and aluminium occur naturally in the soil, but are "bound up" in forms that are insoluble in water. The acid dissolves the metals out of the soil allowing them to reach concentrations that are toxic to plants. Essential plant nutrients, like calcium, are also dissolved out of their useful forms. The soil is left infertile, unable to support the growth of new plants.

The contaminants leach out of the soil into the water supply, poisoning rivers and lakes. Many lakes in the northern hemisphere are crystal clear but contain no aquatic life. Fish suffocate because of a build up of toxic aluminium mucus in their gills. Crayfish suffer from weakened shells leaving them vulnerable to parasites. Acid rain can also affect the human population. The famous London smog of 1952, that had a pH of 1.6, killed 4000 people because their lungs were unable to cope with the acidic air.

The former copper mining town of Queenstown in Tasmania is our own example of acid rain destruction. These days tourists come to see the spectacular barren hills that were once covered in lush rainforest. Most of the damage was done at around the turn of the century. Iron sulfide used in the smelting process produced the sulfur dioxide that formed acid rain.

Later coal was used in the smelters, generating more sulfur dioxide, and enough acid rain fell to stop trees growing back. Apart from occasional acidic showers in Sydney, Australia has little experience of acid rain. We are lucky to have low pollution compared to countries in the northern hemisphere, but as our cities expand acid rain is likely to become more common.

Acidity and alkalinity are measured using the pH scale. Something is acidic if it has a pH of less than 7. A pH reading of over 7 means the substance is alkaline. A neutral substance, like pure water, has a pH of exactly 7. The pH scale is logarithmic - meaning that a change of one unit in pH is equivalent to a tenfold change in acidity or alkalinity. For example a substance with a pH of 3 is 10 times more acidic than a substance with a pH of 4.

## The atmosphere

The atmosphere is a thin layer of gas surrounding the Earth which protects us from extreme temperatures and harmful radiation. The atmosphere determines the environment we live in by giving us our climate and weather. The composition of the atmosphere is unique in our solar system. The high concentration of oxygen is needed for higher organisms, like ourselves, to survive. It also allows us to make fires and burn fuel.

Even gases which only occur in very small concentrations are important. Greenhouse gases heat the earth, ozone absorbs ultraviolet radiation and carbon dioxide provides raw material for photosynthesis. Life on the planet helps maintain the atmosphere, but can also harm it. The activities of modern humans are responsible for the quality of the air we breathe, the formation of acid rain, the damage to the ozone layer and the threat of global warming.

A long evolutionary process has given us the atmosphere we have today. About 4.8 billion years ago the primitive rocky earth was surrounded by a layer of hydrogen and helium. There was no gaseous oxygen at all. As meteors pounded the Earth it heated up and most of the original gases were driven off. Later the planet became geologically active and water vapour, carbon dioxide and nitrogen were thrust into the atmosphere by volcanoes. The small amount of argon present came from radioactive decay of potassium in the earth's crust.

After the volcanic activity stopped the planet began to cool down and condensed water vapour created oceans, lakes and rivers. Between 2 and 3 billions years ago life started in the sea. Small marine plants began using the carbon dioxide in photosynthesis and released oxygen as a waste product. The plants produced more and more oxygen and the oceans dissolved most of the carbon dioxide until the atmosphere we know today was formed.

The atmosphere is really very thin compared to the size of the Earth. It's like a coat of paint on a large beach ball. The diagram shows a slice of the atmosphere and how it is divided into four regions. Use the buttons to explore the changes in pressure, temperature and composition in the different parts of the atmosphere.

## Global warming

The earth stays warm because of a naturally occurring process called the greenhouse effect. Light that passes through the atmosphere is absorbed by the surface of the earth and then re-radiated. Greenhouse gases in the atmosphere absorb this radiation and stop it from escaping, keeping the planet at an average temperature of 15 degrees Celsius.

The best greenhouse gases are carbon dioxide and water vapour. While there hasn't been much change in the amount of water vapour in the atmosphere, the concentration of carbon dioxide has increased by 25% since the world became industrialised.

This extra carbon dioxide is what could cause global warming. Scientists believe that the more greenhouse gases in the atmosphere the warmer the earth will get.

There is more carbon dioxide in the atmosphere for two reasons. Some is released by burning fossil fuels (oil, gas and coal) and organic material, like wood. The increase also comes from removing plants which store carbon while they are alive.

While a warmer planet might not sound like such a bad thing, global warming is a serious threat. It could mean that sea levels rise, cyclones become more common, rainfall patterns change and many plants and animals die out.

## Ozone

Ozone ($O_3$) is made up of three oxygen atoms, unlike the oxygen we breathe which has only two. Ozone is a poisonous gas created when ultraviolet (UV) light interacts with $O_2$ molecules. There is "good" ozone and "bad" ozone. In the upper atmosphere it is good because it protects life on Earth from ultraviolet radiation. Ozone produced near the ground is a major component of smog and causes serious health problems.

Ozone is one of the most important trace gases high up in our atmosphere. It protects us from the UV radiation that would fry us in minutes. The ozone layer refers to the accumulation of ozone in the stratosphere. The highest concentration occurs at an altitude of about 35 kilometres. Although most of the UV light is blocked out some still gets through to cause sunburn and skin cancer.

600 million years ago only 1% of the atmosphere was oxygen. Dangerous ultraviolet-B (UVB) and ultraviolet-C (UVC) radiation passed through the atmosphere and reached the surface of the Earth. Life could survive only in places where it was shielded, like under the water. It was these organisms that changed the atmosphere.

Millions of tiny marine plants pumped oxygen into the atmosphere as a by product of their photosynthesis. This extra oxygen made the atmosphere more hospitable and helped form the ozone layer. These two changes allowed life to develop on land.

The ozone layer forms a shield for life on earth by absorbing UV rays from the sun. Ozone is continuously being made and destroyed by two naturally occurring photochemical reactions. These reactions use up nearly all of the UV light, so only a small amount can pass through to the Earth's surface.

When an oxygen molecule absorbs a UVC photon it splits into two highly reactive oxygen radicals. Each of the radicals can now combine with an oxygen molecule and form an ozone molecule. When an ozone molecule absorbs a UVB photon it splits into an oxygen molecule and an oxygen radical. Two radicals can pair up to make an oxygen molecule.

While these two reactions maintain the ozone layer, other photochemical reactions threaten this balance by destroying ozone molecules. Human-made chloroflourocarbons (or CFCs) are very stable and can survive until they reach the upper atmosphere. CFCs are used in refrigerators, air-conditioners and in making electronics. They were used in aerosols but have now been banned in most countries.

UV photons break these molecules apart releasing chlorine radicals. The chlorine radical reacts with an ozone molecule and breaks it apart. This new molecule now reacts with an oxygen radical. The chlorine detaches and leaves a molecule of oxygen.

The chlorine is now free to start the process over again. This means that one chlorine radical can destroy thousands of ozone molecules. This process has caused serious ozone depletion in some parts of the world.

Scientists know that there has been a steady drop in the amount of ozone over the Antarctic since 1960. But it has been happening much more quickly over the last 10 years. The graph shows how the amount of ozone has decreased over time. The biggest drops occur during spring when sunlight first shines after the long, dark winter.

In 1985 a team of British scientists told the world they had found a "hole" in the Antarctic ozone layer in which nearly half the ozone was gone. It covered an area almost the size of Australia. Since then the damage has spread with the size of the hole increasing and depletion sometimes occurring over the Australian continent.

Although ozone thinning is worse in the southern hemisphere, a smaller hole has been discovered over the Arctic region. Some depletion over Europe and North America has been measured too.

The ozone loss is worse in the coldest parts of the world because of a particular type of cloud in the stratosphere. These clouds allow reactions that produce chlorine radicals to occur that don't happen otherwise. The Antarctic hole is so much bigger than the one in the Arctic because the winters are so much colder.

Although we don't know exactly what will happen in a world of increased UV light, we can make some predictions. Phytoplankton ("the grass of the sea") would die off, removing an important food source for many marine animals. Phytoplankton also helps keep our climate stable by absorbing half the carbon dioxide in the atmosphere. Without it global warming could be made worse.

Fish larvae that swim close to the surface of the water would also be killed. Some species of plants may not flower or germinate causing them to become extinct. For humans and animals there will be a higher incidence of skin cancer and eye damage. Scientists believe that a 1% decrease in the ozone layer could result in 20 000 more skin cancer cases

Ozone is a major part of the photochemical smog that hangs over cities around the world. Unfortunately this ozone doesn't make it up to the stratosphere where it could help us out by filling the gap in the ozone layer. In fact the passage of extra UV light through the ozone-depleted atmosphere would only make more low level ozone.

## What is Photochemistry?

Photochemistry is about the interaction between light energy and molecules. Discrete packages of light called photons deliver the energy. The energy makes the electrons in the molecules jump from a lower energy state to a higher one. Shorter wavelengths have more energy and so they cause bigger jumps. Depending on the amount of energy carried by the photon, different things can happen. Click on the energy buttons to investigate.

Photons in the infrared part of the spectrum are in the lower energy range. This energy is too low to cause an electron to jump. The molecule uses up the energy in vibrations or rotations.

Shorter wavelength photons, such as X-rays, have enough energy to make the electron jump right out of the molecule. This process is called ionisation and it turns the molecule into an ion with a positive charge.

Ultraviolet and visible light is of medium energy. A photon in this energy range can make the electron jump to a higher energy state, but doesn't have enough energy to remove it altogether. It's what happens to these "excited" molecules that interests photochemists. Chose any of the options to see what can happen.

It can break apart to form highly reactive free radicals. It can react chemically with another molecule. It can rearrange itself to form a different isomer. It can emit light either quickly (fluoresce) or slowly (phosphoresce) and return to its original state.

Nearly all molecules respond in some way when exposed to ultraviolet and visible light. This corresponds to wavelengths of about 200 to 740 nanometres. (A nanometre is one billionth or $10^{-9}$ of a metre and is given the abbreviation nm.) We can see the visible light but not the ultraviolet. The diagram shows the colours of the spectrum in the UV-visible range.

The best known natural photochemical reaction is photosynthesis which enables plants to make food with energy from the sun. Plants take up carbon dioxide and water and use light energy to turn it into sugar and oxygen. Green plants contain cells called chloroplasts which house the photosensitive chlorophyll molecules. The chloroplast absorbs a photon giving the system enough energy for the photosynthetic reactions.

## Smog

Air pollution has been with us since the Industrial Revolution and is now a serious problem in many cities around the world. Photochemical smog is a unique type of pollution first recognised in Los Angeles in the 1940s. Since then a huge amount of research has been conducted to unravel the complex reactions which cause it. This type of smog is most noticeable in cities where there is not much industry, but a large number of cars.

Photochemical smog is a poisonous mixture of gases and suspended particles. It forms when sunlight interacts with nitrogen oxides and hydrocarbons which come from car engines. Smog tends to be worst during summer and in the middle of the day. This type of pollution is also more common in places with bright sunshine, like California and Australia. What's in smog? $NO_x$, $NH_3$, CO, $O_3$, $CH_4$. $SO_2$, hydrocarbons

Nitrogen dioxide is released into the atmosphere from car exhausts. Ultraviolet-A (UVA) light splits the nitrogen dioxide into nitrogen oxide and an oxygen radical. The oxygen radical then reacts with an oxygen molecule to form ozone. The ozone reacts with hydrocarbons and natural materials from plants to form peroxyalkyl nitrates (PANs).

Nitrogen dioxide forms when fossil fuels are burnt at high temperature. Car engines account for about 80% of the emissions with the rest coming from factories and power stations. Most of the hydrocarbon component of smog also comes from these sources. Fossil fuels, a mixture of various hydrocarbon, are usually burned inefficiently. The unburnt portion is emitted as exhaust.

Ozone is the most damaging constituent of smog. Close to the ground, the reactive and highly toxic gas has a disastrous effects. In humans and animals it causes inflammation of the mucus membranes leading to asthma, bronchitis and long-term lung damage. There is also evidence that it impairs the body's ability to fight off infections and may contribute to heart disease and some cancers.

Low atmosphere ozone also affects plants by causing damage to leaves and so interfering with photosynthesis. Crops like lettuce and alfalfa are particularly sensitive to chemicals from smog. Yields in affected areas can be reduced by up to 30%.