

The Virtual Physical Laboratory



Version 14

June 2018

Dr. John Nunn

www.VPLab.co.uk

*“Great are the works of the Lord;
they are pondered by all who delight in them.”
Psalms 111:2*

INTRODUCTION

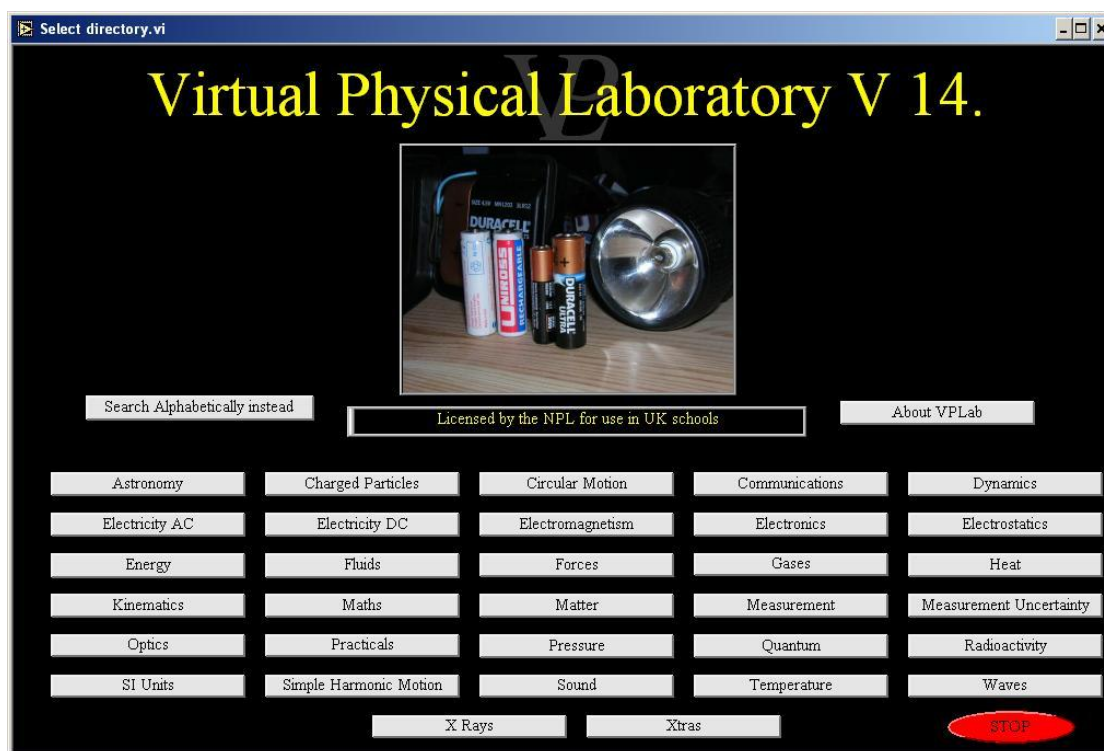
I had the privilege of teaching physics at Hebron School in Ooty in Tamil Nadu, South India between August 2000 and June 2003. It was both a privilege and a challenge, but it enriched my appreciation for my own teachers before me. It is one thing to think you understand something, it is quite another to help someone else understand it.

During my all too brief ‘teaching career’, I became convinced of the value of interactive simulations as an aid to teaching physics. The ‘experiments’ can be set up instantly, they work first time, they cannot be ‘broken’! Anyone can safely be ‘let loose’ to investigate for themselves. Every user will quickly reach the level at which they are learning something new. This will be true not only for pupils, but for teachers too; I have certainly learned a lot of physics along the way too.

Although I am no longer actively teaching pupils in school, I have spent thousands of hours over the past eighteen years developing this resource in order to help those learning physics as well as those who are already teaching it – to encourage both of them in their on-going learning of this interesting subject.

There seems to be an ever increasing amount of science that we do not yet understand, nevertheless, I am continually fascinated by the amount of natural world around us that is understandable. It is my sincere hope that teachers and students alike will *enjoy* using this resource; that they will explore, ‘experiment’ and discover for themselves the fascination of physics.

John Nunn
June 2018



The Virtual Physical Laboratory illustrates and animates most of the topics taught in a modern physics curriculum. Some of the animations and virtual experiments go beyond what is required at school, but are included to stretch the more able pupils.

The Virtual Physical Laboratory is endorsed by The National Physical Laboratory, The Institute of Physics and Cambridge International Examinations. The resource is not tied to any particular syllabus, it has been used successfully in a broad range of curricula worldwide.

The simulations are arranged firstly in alphabetic order of topic, and then in alphabetic order of simulation. With each simulation I have given an indication of the level for which each simulation has been written, (Advanced or Basic) however this is merely indicative. Given the international diversity of curricula it is difficult to state comprehensively what grade a particular simulation is targeted at. I have been designated as 'Basic' and others as 'Advanced' level. 'Basic' level is broadly suitable for 12 to 16 year olds, and 'Advanced level' for 17 to 19 year olds. Not all curricula will include all the topics included in this resource, however they are included in this work as a way of covering most eventualities and also as a means to stretch and stimulate the more able pupils.

WHAT IS NEW IN VERSION 14 OF THE VPLab?

As well as a few improvements to simulations that were already present in earlier versions. V14 has a completely new "Practicals" chapter which contains 26 new simulations to help students prepare for the set experiments listed in the curriculum by AQA (12), Edexcel (16) and OCR (11). You will notice that these simulations have minimal instructions as they are designed to illicit the student's own experimental skills and procedures. Any data generated will need to be recorded, plotted and analysed manually - just like normal school experiments. This brings the total number of simulations in the VPLab to 370.

AQA

- 1 Waves on a string
- 2 Double Slit Interference
- 3 Gravity by Free Fall
- 4 Young's Modulus by Extension
- 5 Resistivity of Wire Samples
- 6 EMF and Internal Resistance
- 7 Simple Harmonic Motion
- 8 Charles and Boyles Gas Laws
- 9 Capacitor Charging and Discharging
- 10 Lorentz Force on Conductor
- 11 Search Coil in Magnetic Field
- 12 Gamma Rays Inverse Square

Edexcel

- 1 Acceleration of Free Fall
- 2 Resistivity
- 3 EMF and Internal Resistance
- 4 Viscosity by Falling Ball
- 5 Young's Modulus
- 6 Speed of sound
- 7 Vibrating Strings
- 8 Wavelength by Diffraction
- 9 Force and Momentum
- 10 Collisions
- 11 Capacitors
- 12 Thermistors
- 13 Latent Heat
- 14 Pressure and Volume
- 15 Alpha Beta Gamma
- 16 Masses on Springs

OCR

- 1 Acceleration of Free Fall
- 2 Young Modulus by Extension
- 3 Resistivity of Metals
- 4 Potential Divider Circuits
- 5 Wavelength by Young's Slits
- 6 Planck's Constant by LEDs
- 7 Absorption of Alpha, Beta, Gamma
- 8 Absolute Zero Estimation
- 9 Capacitor Charging / Discharging
- 10 Factors affecting Simple Harmonic Motion
- 11 Specific Heat Capacity

LICENSING OF THE VPLAB

With the exception of the simulations of the Diamond Synchrotron and Isis, the Virtual Physical Laboratory software library is the copyright of VPLab. There are a number of possible licences that can be purchased.

Student license: For private use. Single user and single machine.

Teacher license: For public demonstrations by a teacher. Single machine.

Site License: For use within a single site educational establishment. Multiple concurrent users on networked computers, but excludes pupils personal computers.

VLE License: Using this version, the teacher can select simulations and make them available to his pupils to download from a school based fileshare. The students can then unzip the files on their own computers (typically 2Mb in size) and they can then run them for a period of one week. After that period has expired, that simulation will no longer run. The VLE version of the VPLab needs to be purchased separately.

For further details please visit the website www.vplab.co.uk. For any enquiries please email john.nunn@vplab.co.uk.

INSTALLING THE VIRTUAL PHYSICAL LABORATORY

There are a number of different ways in which you may have received the Virtual Physical Laboratory. It may come as a CD ROM or as a download from a web server.

If you are installing from a CD ROM, simply follow the instructions given on the screen, and if you accept the default options, the software will install itself in C:\program files\Virtual Physical Laboratory. It will also create a shortcut from the start menu under programs called VPLab.

If you received the Software via a download, it will normally download as a compressed or 'zipped' folder. The first step must be to 'unzip' it. Once this is done, copy the entire contents to a folder of your choice. The top level directory contains a n executable file called VPLab13.exe. Double clicking this executable opens up the program and runs it. You can also create a shortcut and place it on your desk top.

It is important that you preserve the directory structure of the Virtual Physical Laboratory, otherwise the individual simulations will not be found by the top level program.

When a school site licence has been purchased, it is possible to install the software installing the software on a server so that it can be accessed by multiple users. An easy alternative is to place the Virtual Physical Laboratory folder on a shared drive which networked computers can access. In this way any number of users can access the resource at the same time.

CUSTOMISING THE VIRTUAL PHYSICAL LABORATORY

Version 14 of Virtual Physical Laboratory has 370 simulations, and it is easy to lose the ones you are interested in! It is possible to customise the content of the VPLab to make it easier for you to find your way around.

There are two ways in which you may customise your content: Guided and Manual.

Guided method to populate My VPLab

"My VPLab.exe" was written to enable you to keep track of the simulations you want to use.

A - Run My VPLab.exe by double clicking on it.

B - Once it opens up you have the option to "Search whole VPLab Content" or "Search my Customised Content" using the button at the bottom of the screen.

Note: The first time you run My VPLab it will warn you that "You have not yet made any folders in "My VPLab" Search whole VPLab content instead.

C – Press the "Search whole VPLab Content", and the familiar chapter buttons will appear.

D – Search around for the simulation you want to use, and run it.

E - When you close it, you will see a pop-up box asking “Do you want to copy this last simulation into My VPLab”. If you answer “No” the top level program will return to your last selected chapter. If you answer “Yes” a new window will open up.

F – Initially you will need to create a new folder by pressing the “Create an New Folder” button at the bottom of the screen.

G – A small field will appear for you to enter the name of the folder you want to create. (e.g. Year 11 Term 1). Enter the text and press the “Make it” button. The folder will then appear on the vertical list above.

H – Click in the little tick box to the right of the folder name where you want to save the simulation and press the “save it here” button. (you can only save the simulation into one folder at a time).

I – Press the red “Stop or cancel Last” button to exit from that window and return to the chapter you selected.

J – Press the green “Back” button to return to the top level program with all the chapter buttons.

K – Press the “Search My Customised Content” at the bottom of the screen, and now a button with the folder you have just created should appear (e.g. Year 11 Term 1).

L – Press the new button and it should open up a new window showing its contents (perhaps just the last simulation that you have just placed in to it.)

To add more simulations to this folder, or to create new folders to populate, repeat steps B to L above.

Manual Method to Customise My VPLab.

It is also possible to create your customised sub-folders using your windows explorer. The important thing is to remember to COPY and paste (NOT cut and paste!) otherwise you will gradually start to lose the simulations available from the entire content of the VPLab.

If you have many files you want to move into the customised content directory the manual method is much quicker.

A - In the top level directory of the Virtual Physical Laboratory (where “VPLab8.exe” and “My VPLab.exe” are located), create a new folder called “My VPLab” (if it does not already exist).

B – Inside that folder (“My VPLab”), create a new folder (e.g. “Year 12 Heat”).

C – Open this folder (e.g. Year 12 Heat).

D – The virtual Physical Laboratory in another window.

E – Open the folder containing the chapter you are wanting to draw from (e.g. Heat)

F – COPY the simulation you want and PASTE it into your new folder (e.g. “Year 12 Heat”). Copy as many simulations as you wish into your new folder.

G – IMPORTANT: Make sure you also copy “lvrt.dll” and “lvsound.dll” into your new folder. These two dynamic link files can be found in every chapter folder, and also in the top level directory of the VPLab. (You only need to do this the first time you are populating your new folder).

H – Create as many folders in the “My VPLab” folder, but note that you should not create sub folders within your new folders. The folders may only be one level deep; deeper sub-folders will not be searched by “My VPLab.exe”.

It is possible to use both methods (the guided and the manual) to populate your customised content folders.

After you have finished customising your content, run “My VPLab.exe” to verify that the files are in the places you wanted them to be.

HINTS ON USING THE VIRTUAL PHYSICAL LABORATORY

This section addresses some of the most frequent questions arising out of the use of the Virtual Physical Laboratory in schools and colleges.

1 – Colours of graphs.

The colour red does not project very well, especially narrow red lines on a black background. The solution offered here will work in most cases (but not all).

To change the colour of a line on a graph, right click somewhere inside the graph and select 'show' and then 'legend' (some graphs already have the legend showing). A box near the top right hand corner of the graph will appear. Right click inside it, and you will be able to select 'colour'. A colour palette will appear. Select your preferred colour and it will change the plot accordingly. You can then hide the legend box again by right clicking somewhere inside the graph and selecting 'show' and selecting 'legend' again. Your change will be a temporary one; it will be lost as soon as you quit the simulation.

Changes of colour may also be advisable in some simulations in order to make things easier for colour blind pupils.

Notice also that right clicking on the legend also offers the possibility of changing the 'linewidth'. This may be a useful change to visually impaired students or where the projection is particularly poor.

2 - Re-scaling graphs, gauges, dials, knobs and sliders.

If a graph, gauge, dial, knob or slider goes out of range, or if you want to change the range in order to improve resolution, left-click and drag over the number at the top (or bottom) of the scale and type the new value you would like to have. The scale should automatically adjust to the new value. Your change will be a temporary one, it will be lost as soon as you quit the simulation.

If you want a graph to automatically re-scale, right click somewhere inside the graph and select 'AutoScale X' or 'AutoScale Y'

3 – Using just one or two simulations without installing the whole package. Simulations can be run independently without recourse to the top level library.

All the files which make up the Virtual Physical Laboratory are contained in a folder on the hard drive (normally in c:\program files\virtual physical laboratory). They are grouped by the same chapter divisions as shown in the top level program of VPLab.

Create a new directory with a name of your choice using windows explorer. It can be created anywhere on your computer, including on a USB memory stick, or a shared folder on a network.

Two dynamic link libraries are needed for this to work. 'lvrt.dll' (normally located in c:\program files\virtual physical laboratory) and 'lvsound.dll' (normally located in c:\program files\virtual physical laboratory\sound\data) will need to be copied (not cut

& pasted or dragged) into your new directory. Now copy (not cut & paste, and not drag) any of the simulations you want into your new folder.

These simulations will now run on any machine supporting windows 95 onwards, without needing the full installation. If using a USB memory stick, it can be transported to any other computer, and the simulations can be made to run simply by using windows explorer and double clicking on any of the '*.exe' files that you have selected to copy.

4 – Printing diagrams from the VPLab simulations.

The reason the majority of the VPLab screens are black is that it is much quicker to refresh the screen, and the graphics side of the simulations can run more smoothly. If you want to print part of a screen, the semi-satisfactory way to do this is as follows:

Press “Shift-Print Screen”, and then open Microsoft Paintbrush (Normally “Start-Programs-Accessories-Paint”). Now press “Ctrl V” (or right click and select ‘paste’). The entire screen should have dumped into the Paint Brush window. Click on the select rectangle button of paintbrush to box the part of the image you want. While it is still boxed, click on the ‘Image’ button at the top of the Paint Brush window and select ‘invert colours’ All the black should have turned to white, and all the colours are unrecognisable! This might be good enough for your purposes, but if you want to recover the original colours carry out the next step.

Now click on the ‘fill with colour’ button on the left hand side of the Paint Brush Screen (it looks like a bucket of paint), and select the black colour at the bottom left hand side of the screen and paint all the white back to black again! Then select ‘Edit – Select all’ (or Ctrl A) and then ‘Image-invert colours’ again in order to return back to the original colours (without the black). Notice that the screen pieces contained inside hollow letters may need some special attention!

5 – Printing Text from the VPLab simulations.

Unfortunately this cannot be done satisfactorily. It was not a deliberate policy, but just the way it turned out. They can only be dumped as graphics. Sorry!

6 – Exporting experimental data from the VPLab simulations.

This is possible in a limited number of programs. Normally only those that actually acquire data through the audio input of the computer (e.g. AC coupled Oscilloscope the AC Transient Recorder and the Power Logger). The option of exporting simulated data has not been made available as it would not be meaningful in any real sense.

SIMULATIONS

No	Chapter	
	1	Astronomy
1	1.1.	Cepheid Variables
2	1.2.	Gravity on Planets
3	1.3.	Day Year
4	1.4.	Hubble
5	1.5.	Kepler
6	1.6.	Lander
7	1.7.	Moon Phases
8	1.8.	Orbits
9	1.9.	Parallax
10	1.10.	Sun Earth Moon
11	1.11.	Tides
	..	
	2	Charged Particles
12	2.1.	Cathode Ray Oscilloscope Inside
13	2.2.	Cockroft Walton
	2.3.	Diamond Synchrotron
14	2.3.A	Electron Gun
15	2.3.B	Linac
16	2.3.C	Dipole
17	2.3.D	Quadrupole
18	2.3.E	Electromagnetic Waves from Charges
19	2.3.F	Residual Molecules
20	2.3.G	RF Cavity
21	2.3.H	Undulator
	2.4.	ISIS Neutron Source
22	2.4.A	The Ion Source
23	2.4.B	The Vacuum System
24	2.4.C	The Linac
25	2.4.D	The Dipole
26	2.4.E	The Quadrupole
27	2.4.F	The Stripping Foil
28	2.4.G	The Synchrotron
29	2.4.H	The Extraction Kicker
30	2.4.I	The Target
31	2.4.J	The Instruments
32	2.4.K	Muons
33	2.5.	e/m Tube
34	2.6.	Maltese Cross
35	2.7.	Mass Spectrometer

36	2.8.	Oscilloscope
37	2.9.	Velocity Selector
	..	
3	..	Circular Motion
38	3.1.	Angular Inertia
39	3.2.	Belt Drive
40	3.3.	Centripetal Force
41	3.4.	Circular Motion
42	3.5.	Cogs
43	3.6.	Coriolis
44	3.7.	Hub Gears
45	3.8.	Worm Screw
	..	
4	..	Communications
46	4.1.	Digital Image Grey
47	4.2.	Digitising
48	4.3.	Fourier
49	4.4.	Modulation
50	4.5.	Noise in transmission
51	4.6.	Sampling
52	4.7.	Transmitting Images
	..	
5	..	Dynamics
53	5.1.	Bullet Speed
54	5.2.	Loop the Loop
55	5.3.	Momentum
56	5.4.	Power
57	5.5.	Roller Coaster
58	5.6.	Stopping Distance
59	5.7.	Work
60	5.8.	2D Collisions
	..	
6	..	Electricity AC
61	6.1.	AC Power
62	6.2.	AC Rectification
63	6.3.	Capacitor Reactance
64	6.4.	Generator
65	6.5.	Inductor Reactance
66	6.6.	LCR Reactance
67	6.7.	Power Distribution
68	6.8.	Three Phase Supply
69	6.9.	Transformer
	..	
7	..	Electricity DC

	7.1.	Circuits
70	7.1.A	Parallel
71	7.1.B	Series
72	7.2.	Decomposing Water
73	7.3.	Electrolysis
74	7.4.	EMF and Internal Resistance
75	7.5.	Explaining Electricity
76	7.6.	I V Characteristics
77	7.7.	Potential Divider
78	7.8.	Potentiometer
79	7.9.	Resistivity
80	7.10.	Strain Gauge
81	7.11.	Unbalance Wheatstone
82	7.12.	Wheatstone
	..	
8	..	Electromagnetism
83	8.1.	AC Generator
84	8.2.	Bell
85	8.3.	Coil Transformer
86	8.4.	Current Balance
87	8.5.	DC Motor and Generator
88	8.6.	Dynamo
89	8.7.	Eddy Current Pendulum
90	8.8.	Hall Probe
91	8.9.	Hysteresis
92	8.10.	Induction
93	8.11.	LVDT
94	8.12.	Magnetic Fields
95	8.13.	Moving Coil
96	8.14.	Switched Mode Transformer
	..	
9	..	Electronics
97	9.1.	Capacitor
98	9.2.	Capacitor Combinations
99	9.3.	Diodes
100	9.4.	High Pass Filter
101	9.5.	Light Dependent Resistor
102	9.6.	Light Emitting Diodes
103	9.7.	Logic Gates
104	9.8.	Low Pass Filter
105	9.9.	Operational Amplifiers
106	9.10.A	Voltage Comparator
107	9.11.B	Non Inverting Amplifier
108	9.12.C	Inverting Amplifier

109	9.13.D	Adder
110	9.14.E	Difference Amplifier
111	9.15.F	Differentiating Amplifier
112	9.16.G	Integrator
113	9.17.H	Digital to Analogue
114	9.18.I	Subtractor
115	9.19.	Oscillator
116	9.20.	Photodiodes
117	9.21.	Semiconductors
118	9.22.	Thermistor
119	9.23.	Transistor
120	9.24.A	Input Characteristics
121	9.25.B	Output Characteristics
122	9.26.C	Current Transfer Characteristics
123	9.27.D	The Transistor as an Audio Amplifier
124	9.28.	Zener Diodes
	..	
	10	Electrostatics
125	10.1.	Electrometer
126	10.2.	Electrostatic Induction
127	10.3.	Electrostatic Pendulum
128	10.4.	Van Der Graaf
	..	
	11	Energy
129	11.1.A	Coal
130	11.2.B	Oil
131	11.3.	Domestic Solar Heating
132	11.4.	Gas
133	11.5.	Geothermal
134	11.6.	Hydroelectric Power
135	11.7.	Nuclear Power
136	11.8.	Solar Power
137	11.9.	Tidal Barrage
138	11.10.	Wave Energy
139	11.11.	Wind Power
140	..	
141	12	Fluids
142	12.1.	Bernoulli
143	13.2.	Hydrostatics
144	12.3.	River
145	12.4.	Viscosity
	..	
	13	Forces
146	13.1.	Balance

147	13.2.	Balanced Forces
148	13.3.	Car Forces
149	13.4.	Centre of Gravity
150	13.5.	Equilibrium
151	13.6.	Force and Acceleration
152	13.7.	Friction
153	13.8.	Hookes Law
154	13.9.	Ladder
155	14.10.	Lift
156	13.11.	Pulleys
157	13.12.	Rotational Equilibrium
158	13.13.	Springs
159	13.14.	Tip or Slip
160	13.15.	Torques and Moments

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14

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Gases

161	14.1.	4 Stroke Engine
162	14.2.	Boyles Charles
163	14.3.	Diesel Engine
164	14.4.	Diffusion
165	14.5.	Heat Pump
166	14.6.	Isothermal Adiabatic
167	14.7.	Steam Engine
168	14.8.	Stirling Engine

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15

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Heat

169	15.1.	Conduction
170	15.2.	Constant Flow
171	15.3.	Convection
172	15.4.	Gas Expansion
173	15.5.	Heat and Area
174	15.6.	Heat Capacity
175	15.7.	Latent Heat
176	15.8.	Liquid Expansion
177	15.9.	Melting
178	15.10.	Mixtures Method
179	15.11.	Radiation
180	15.12.	Solid Expansion
181	15.13.	Vapourisation
182	15.14.	Weather

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16

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Kinematics

183	16.1.	Ballistic Trolley
184	16.2.	Bounce Meter

185	16.3.	Bouncing Graphs
186	16.4.	Falling Target
187	16.5.	Graphs
188	16.6.	Gravity
189	16.7.	Projectiles
190	16.8.	Terminal Velocity
191	17.9.	Ticker Timer
	..	
17	..	Maths
192	17.1.	A sin Bx
193	17.2.	Graph Plot Read
194	17.3.	Instant Equation Plotter
195	17.4.	Interactive Polynomial Plotter
196	17.5.	Matrices
197	17.6.	Numerical Integration
198	17.7.	Plotting
199	17.8.	Polar Coordinates
200	17.9.	Resolving Vectors
201	17.10.	Sin Cos Tan
202	17.11.	Trigonometry to Waves
203	17.12.	Vectors
	..	
18	..	Matter
204	18.1.	Alpha Scattering
205	18.2.	Atomic Density
206	18.3.	Brownian Motion
207	18.4.	Density
208	18.5.	Elastic Plastic
209	18.6.	Floating Density
210	18.7.	Hardness
211	18.8.	Moduli
212	18.9.	Molecular Model
213	18.10.	Toughness
214	18.11.	Youngs Modulus
	..	
19	..	Measurement
215	19.1.	Acceleration
216	19.2.	Calibration
217	19.3.	Micrometer
218	19.4.	Reflex Time
219	19.5.	Velocity
220	19.6.	Vernier
221	19.7.	Mouse Click Timer
222	19.8.	Mouse Displacement Recorder

223	19.9.	Mouse X Position Recorder
224	19.10.	Mouse X Position Recorder
	..	
20	..	Measurement Uncertainty
225	20.1.	Precision Accuracy
226	20.2.	Random Systematic
227	20.3.	Significant Figures
228	20.4.	Uncertainties in Area
229	20.5.	Uncertainties in Volume
	..	
21	..	Optics
230	21.1.	Air Wedge
231	21.2.	Colour Filters
232	21.3.	Colour Match
233	21.4.	Colour Photography
234	21.5.	Dispersion
235	21.6.	Eye
236	21.7.	Grating Measurement
237	21.8.	Holography
238	21.9.	Imaging
239	21.10.	Lenses
240	21.11.	Mirrors
241	21.12.	Mirror Images
242	21.13.	Newtons Rings
243	21.14.	Polarisation
244	21.15.	Prisms
245	21.16.	Refraction
246	21.17.	Speed of Light
	..	
22	..	Practicals
	..	AQA
247	22.1.	Waves on a string
248	22.2.	Double Slit Interference
249	22.3.	Gravity by Free Fall
250	22.4.	Youngs Modulus by Extension
251	22.5.	Resistivity of Wire Samples
252	22.6.	EMF and Internal Resistance
253	22.7.	Simple Harmonic Motion
254	22.8.	Charles and Boyles Gas Laws
255	22.9.	Capacitor Charging and Discharging
256	22.10.	Lorentz Force on Conductor
257	22.11.	Search Coil in Magnetic Field
258	22.12.	Gamma Rays Inverse Square
	..	Edexcel

rpt	22.13.1	Acceleration of Free Fall
rpt	22.14.2	Resistivity
rpt	22.15.3	EMF and Internal Resistance
259	22.16.4	Viscosity by Falling Ball
rpt	22.17.5	Young's Modulus
260	22.18.6	Speed of sound
rpt	22.19.7	Vibrating Strings
rpt	22.20.8	Wavelength by Diffraction
261	22.21.9	Force and Momentum
262	22.22.10	Collisions
rpt	22.23.11	Capacitors
263	22.24.12	Thermistors
264	22.25.13	Latent Heat
rpt	22.26.14	Pressure and Volume
265	22.27.15	Alpha Beta Gamma
266	22.28.16	Masses on Springs
	..	OCR
rpt	22.29.1	Acceleration of Free Fall
rpt	22.30.2	Young Modulus by Extension
rpt	22.31.3	Resistivity of Metals
267	22.32.4	Potential Divider Circuits
rpt	22.33.5	Wavelength by Young's Slits
268	22.34.6	Planck's Constant by LEDs
269	22.35.7	Absorption of Alpha, Beta, Gamma
270	22.36.8	Absolute Zero Estimation
rpt	22.37.9	Capacitor Charging / Discharging Factors affecting Simple Harmonic Motion
271	22.38.10	
272	22.39.11	Specific Heat Capacity
	..	
	23	Pressure
	..	
273	22.1.	Aneroid Barometer
274	22.2.	Hydraulic Jack
275	22.3.	Manometer
276	22.4.	Mercury Barometer
277	22.5.	Pressure from Molecules
	..	
	24	Quantum
	..	
278	23.1.	Absorption Spectrometer
279	23.2.	Emission Spectrometer
280	23.3.	Energy Levels
281	23.4.	Franck Hertz
282	23.5.	Light Quanta
283	23.6.	Millikan
284	23.7.	Photoelectric Effect

	..	
25	..	Radioactivity
285	24.1.	Beta Penetration
286	24.2.	Cloud Chamber
287	24.3.	Geiger Muller
288	24.4.	Half Life
289	24.5.	Inverse Square
290	24.6.	Nuclear Reactions
291	24.7.	Nuclear Stability
292	24.8.	Random
	..	
26	..	S.I. Units
293	25.1.	Ampere
294	25.2.	Old Ampere
295	25.3.	Candela
296	25.4.	Josephson Junction
297	25.5.	Kelvin
298	25.6.	Kilogram
299	25.7.	Metre
300	25.8.	Mole
301	25.9.	Quantum Hall Effect
302	25.10.	Second
	..	
27	..	Simple Harmonic Motion
303	27.1.	Coupled Pendulums
304	27.2.	Damping
305	27.3.	Hoop Resonance
306	27.4.	Newtons Cradle
307	27.5.	Pendulum Array
308	27.6.	Resonance
309	27.7.	Resonant Tube
310	27.8.	SHM Phases
311	27.9.	Simple Harmonic Motion
	..	
28	..	Sound
312	28.1.	Beating
313	28.2.	Doppler
314	28.3.	Echo
315	28.4.	HIFU
316	28.5.	Impulse Excitation
317	28.6.	Lisothotropy
318	28.7.	Pipes
319	28.8.	Sonar
320	28.9.	Sound Experiments

321	28.10.	Sound Generator
322	28.11.	Sound Level
323	28.12.	Spectrum Analyser
324	28.13.	Spectrum Visualiser
325	28.14.	String
326	28.15.	Tumours
327	28.16.	Velocity from Doppler
	..	
29	..	Temperature
328	29.1.	Absolute Scale
329	29.2.	Bimetallic Strip
330	29.3.	Platinum Resistance
331	29.4.	Thermistor
332	29.5.	Thermocouple
333	29.6.	Thermometer
	..	
30	..	Waves
334	30.1.	Diffraction
335	30.2.	Group Velocity
336	30.3.	Huygens
337	30.4.	Lissajou
338	30.5.	Longitudinal Transverse
339	30.6.	Microwaves Youngs Slits
340	30.7.	Phasors
341	30.8.	Red Shift
342	30.9.	Reflection Transmission
343	30.10.	Ripple Tank
344	30.11.	Single Slit Diffraction
345	30.12.	Slinky
346	30.13.	Standing Microwaves
347	30.14.	Stationary Waves
348	30.15.	Water Diffraction
349	30.16.	Wave Interference
350	30.17.	Wave on a String
351	30.18.	Wave Speed
352	30.19.	Youngs Slits
	..	
31	..	X Rays
353	31.1.	Bragg Diffraction
354	31.2.	Clinical Linac
355	31.3.	Radiotherapy
356	31.4.	Tomography
357	31.5.	X Rays
	..	

	32	..	Xtras
358	32.1.		AC Oscilloscope
359	32.2.		AC Transient Recorder
360	32.3.		Atomic Force Microscope
361	32.4.		Gravimeter
362	32.5.		Morse Code Receiver
363	32.6.		Morse Code Transmitter
364	32.7.		Odometer Mouse
365	32.8.		PID Control
366	32.9.		Power Logger V2
367	32.10.		Scanning Electron Microscope
368	32.11.		Signal Generator
369	32.12.		Thermal Wave Imaging
370	32.13.		Water Rocket

CHAPTER 1

ASTRONOMY

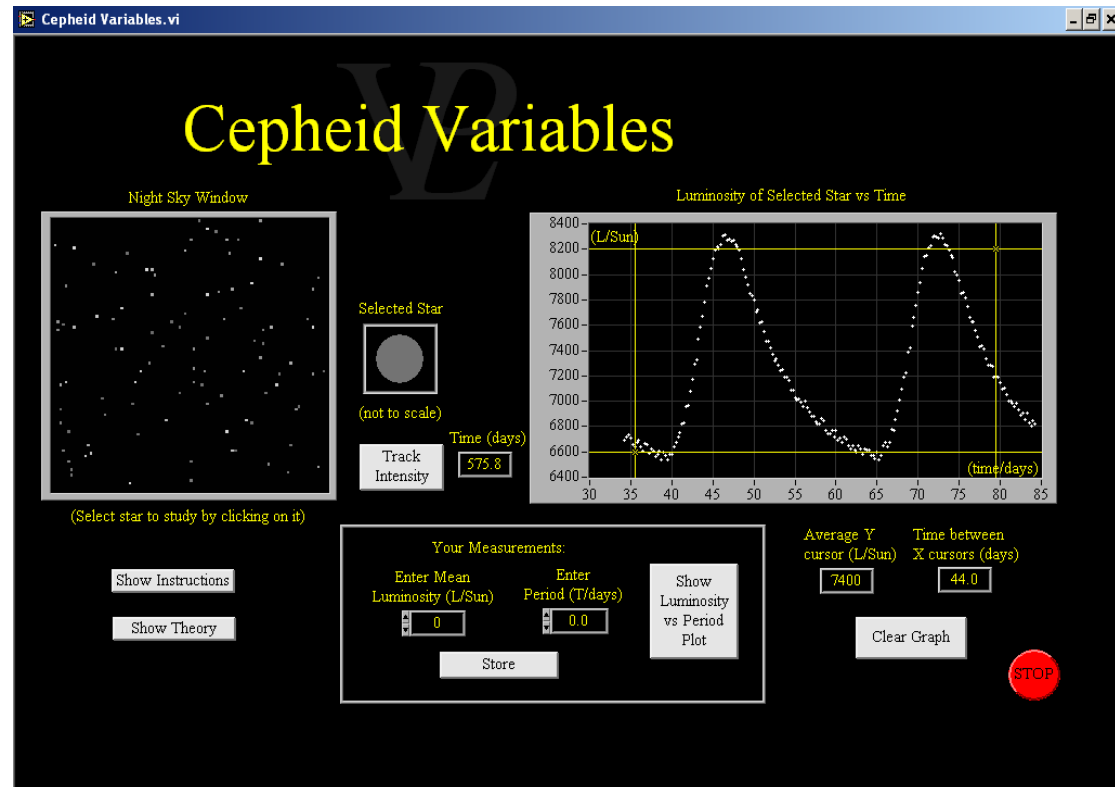


The moon looks different as the month progresses.
What makes it “change shape”?

1.1 Cepheid Variables

Advanced

This simulation allows the student to carry out his own measurements on the period of the variability of the intensity of different stars, and so determine the relationship between the two.



Cepheids are a type of star whose Luminosity pulsates with a regular period. Edward Piggot first discovered them in 1784! Their periods range from around 1 day up to about 100 days, so the pulsation is difficult to observe by eye. Very careful measurements need to be made in order to detect the variability in Luminosity. The shape of the variation looks a little like a "Shark's Fin" (falling slowly and rising rapidly).

In 1908 Henrietta Swan Leavitt discovered a pattern between the period of the fluctuation of the Luminosity. The higher the Luminosity of a Cepheid, the longer its period becomes.

Measuring the Luminosity of a star is not a trivial thing because the apparent brightness depends on how far away from the observer it is!

In order to do this study properly it was necessary to first determine the distance to the individual Cepheid stars using the parallax method. Once the distances have been determined it is then possible to convert the brightness measurements observed on Earth in to absolute Luminosity measurements.

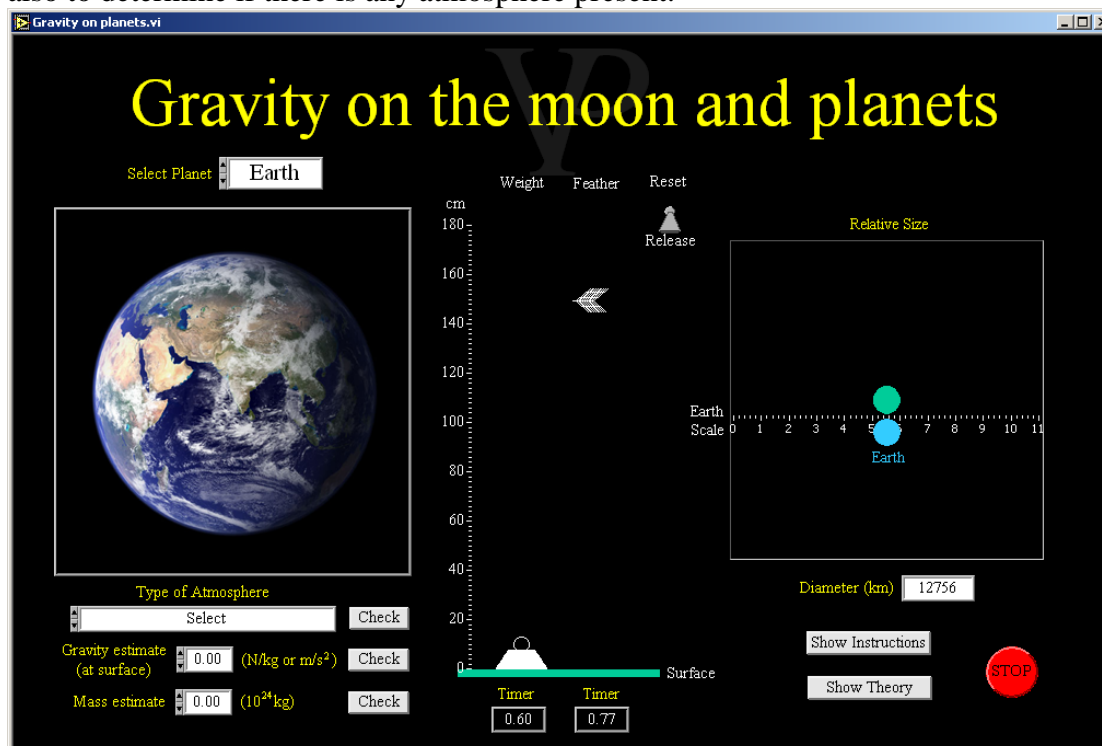
The Cepheids studied were much more Luminous than the Sun (typically from 1000 to 30,000 times more Luminous!).

Once the relationship between the period and the Luminosity was found, it enabled astronomers to calculate the Luminosity of a Cepheid simply by measuring its period. (even without needing to know how far away it was!). This gave rise to a method for measuring astronomical distances known as "the standard candle".

1.2 Gravity on Planets

Basic/Advanced

This simulation enables the pupil to explore the way on which objects fall under gravity on different planets, and so compare the local gravity with that of Earth, and also to determine if there is any atmosphere present.



One of the many things that Isaac Newton discovered is that the force that makes objects fall to the ground is also the force responsible for keeping the Moon orbiting round the Earth.

In the absence of air resistance all objects whether heavy or light would fall at the same rate. However drag due to the atmosphere makes things like feathers fall slower (quickly reaching terminal velocity).

All masses attract each-other with a force which is proportional to the product of their masses, and inversely proportional to the square of the distance between their centres. The constant of proportionality is called the Universal Gravitational constant "G".

$$F = G M m / R^2$$

Where $G = 6.67 \times 10^{-11} \text{ N kg}^{-2} \text{ m}^2$

M = Mass of planet

m = mass of object (or other planet!)

R = Distance between their centres

Near the surface of a planet the gravitational strength is very nearly constant and is simply given the symbol "g". It is possible to measure g directly by dropping an object and measuring the time taken for a given fall using the following equation

$$g = (2 \times \text{fall}) / t^2$$

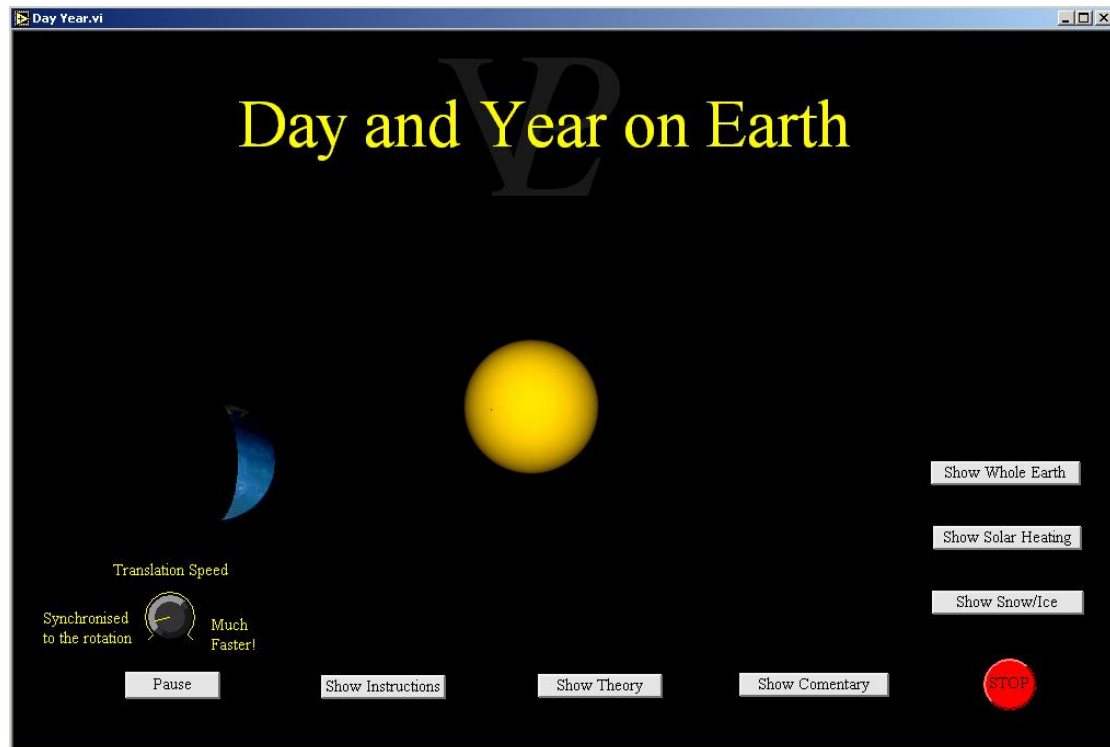
Once g has been measured if the diameter or radius of a planet is known it is possible to calculate the mass of the planet by equating as follows: $F = mg$ so

$$G M m / R^2 = mg \text{ (notice that m cancels out) so } M = g R^2 / G$$

1.3 Day Year

Basic/Advanced

This simulation shows how the days and years are related to the rotation and translation of the Earth. It also shows the effect of the tilted axis of the Earth and how this gives rise to temperature variations and the seasons.



The movement of the Earth around its own axis, as well as around the Sun, and also the tilt of the Earth's axis are interesting and important features of Creation which not only govern temperatures, climates and seasons, but also make life on Earth possible. The time taken for the Earth to complete one rotation about its own axis is called a Day. If the Earth did not spin, or if it rotated too slowly one side would roast, and the other would freeze! If it rotated too fast, there would not be a sufficient difference between the temperatures of the day and the night to evaporate water during the day and release it as dew during the night.

One complete translation of the Earth as it orbits around the Sun is called a Year. The plane that this orbit marks out is called the Ecliptic. The axis of rotation of the Earth is tilted by 23.44 degrees with respect to the perpendicular to the Ecliptic.

Summer Solstice (mid summer's day) is when the axis of the Earth is inclined directly towards the Sun.

Winter Solstice (mid winter's day) is when the axis of the Earth is inclined directly away from the Sun.

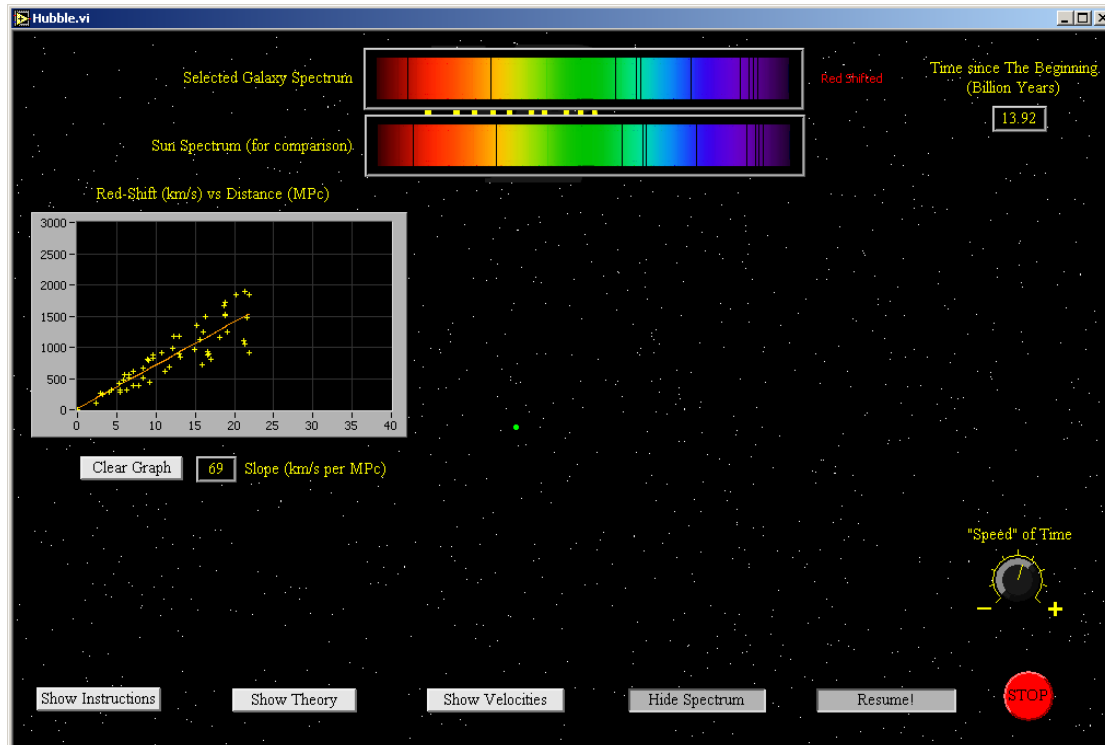
The Vernal and Autumnal Equinoxes are the days when the axis of the Earth is inclined in a direction which is parallel to its orbit (neither towards or away from the Sun). On these two days the number of sunlight hours and night hours are exactly the same.

If the axis of the Earth was not tilted the length of days and nights would be constant all year round and there would be no seasons. This would reduce the surface area of the Earth that could grow vegetation.

1.4 Hubble

Basic/Advanced

This simulation enables the student to notice the expansion of this 'universe' by measuring the red shift in the spectra from distant galaxies. After sufficient measurements the student can obtain his own value for the Hubble constant.



Everything in the universe seems to be moving away from us! This does not mean that we are at the centre of the universe, we think that any observer located anywhere in the universe would notice the same thing: The universe is expanding.

Distances and speeds are impossible to measure directly; they need to be inferred from intensities and red-shifts respectively. More distant galaxies will appear less intense, and using an inverse square approximation it is possible to obtain a measure of their distance from us. Hubble used the intensity of Cepheid Variables (stars whose intensity is related to the period of fluctuation in their intensity) to determine distances. The velocity of the galaxy is obtained by looking at the red shift z , where $z = d\lambda/\lambda$, where λ is the wavelength.

Edwin Hubble measured around 50 different galaxies and noticed a correlation between the speed of recession and the distance of a galaxy. At the time, it was thought that the spectral shift was due to the Doppler effect, however further advances in relativity have given rise to the concept of a "cosmological shift" which is related to the expansion of the universe. At small values of red shift the velocity obtained using Doppler theory is close to that obtained from the Cosmological model.

From his data, Hubble obtained a relationship of around 500 km/s per Mpc. Today's accepted value is closer to around 68 km/s per Mpc.

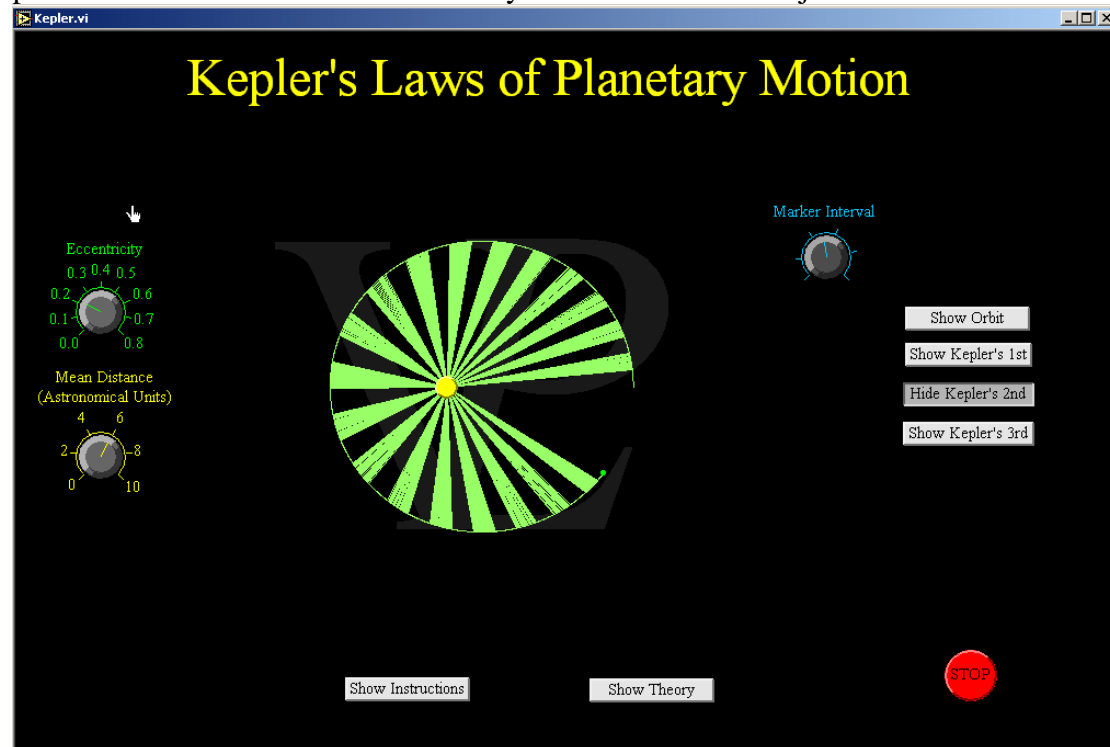
Hubble's "Law" states that $V = H_0 D$ where V is the velocity in km/s, H_0 is Hubble's constant and D is the distance to the galaxy.

Hubble's law is one of the pieces of evidence leading scientists to believe in the "Big Bang" theory. It should be noted however, that H_0 has not necessarily been constant over all time. It is simply the value of the slope of the graph today.

1.5 Kepler

Advanced

This simulation illustrates the three planetary motion laws of Kepler. The mean Sun-planet distance and also the eccentricity of the orbit can be adjusted.



Johannes Kepler (1571-1630) studied the astronomical observations that Tycho Brahe had recorded over nearly 30 years.

1st Law: In 1605 he discovered that "planets move in elliptical orbits with the Sun at one focus".

2nd Law: In 1609 he discovered that "the line joining the planet to the Sun sweeps out equal areas in equal times".

3rd Law: In 1618 he discovered that "the squares of the periods of the planets are proportional to the cubes of their mean distances to the Sun".

These three laws summarised decades of observations and measurements, and helped Isaac Newton formulate his gravitational theory.

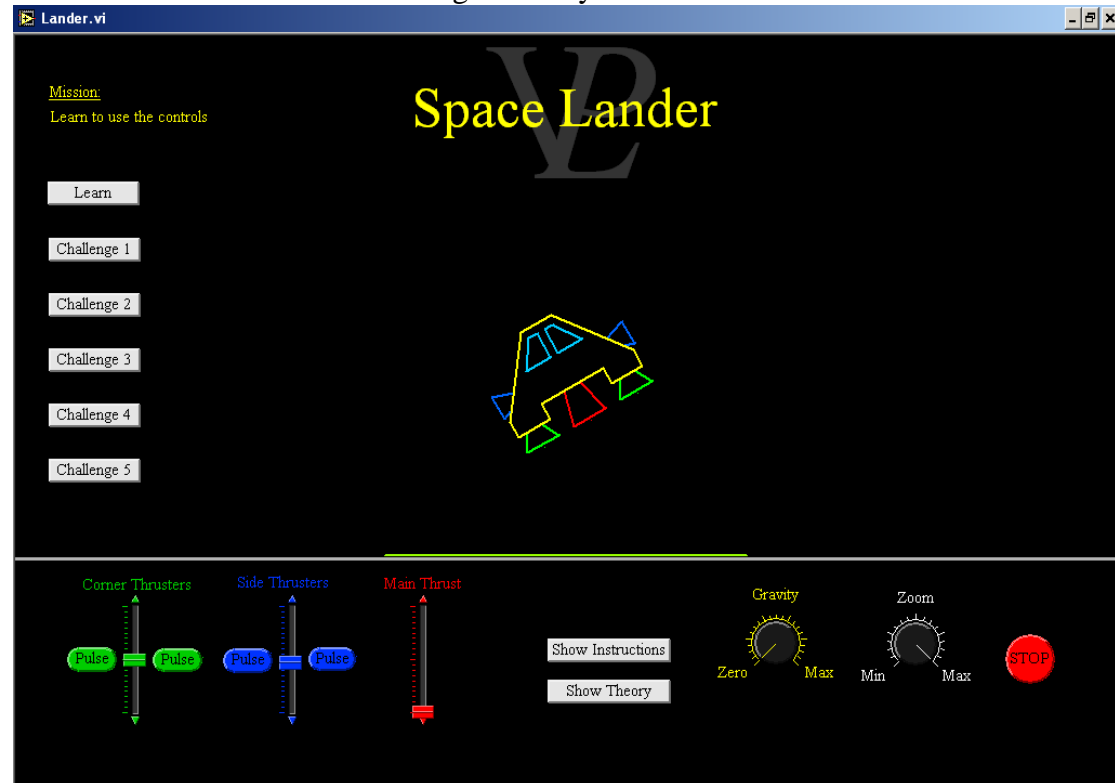
Most planets have a small eccentricity value, meaning that their orbit is very nearly circular, and their distance from the sun is roughly constant. In the case of the Earth, that is an important thing; it makes life possible!

Planet	Orbital Period (yr)	Semi-major axis (au)	Eccentricity
Mercury	0.2408	0.3871	0.206
Venus	0.6152	0.7233	0.007
Earth	1.000	1.000	0.017
Mars	1.8809	1.5273	0.093
Jupiter	11.862	5.2028	0.048
Saturn	29.458	9.5388	0.056
Uranus	84.01	19.1914	0.046
Neptune	164.79	30.0611	0.010
Pluto	248.54	39.5294	0.248

1.6 Lander

Advanced

This simulation shows how difficult it is to navigate a spacecraft and land it safely in the absence of friction. It is also a good study of action and reaction.



This simulation is just a game to visualise Newton's laws of motion. As well as the linear motions, the lander is also free to rotate. The angular motion also follows similar principles to those of Newton's three laws. In conditions of zero gravity, once the spaceship starts moving it will continue moving in the same direction and at the same speed unless an external force acts upon it.

Rocket thrusters propel very hot gasses at very high speeds away from the rocket nozzle. Newton's Third Law tells us that since action and reaction are equal and opposite, the force that the thruster exerted on the hot gasses in order to expel them will cause an equal and opposite force to act on the rocket causing it to recoil.

If the position of the rocket nozzles is such that the line of force passes through the centre of mass of the rocket, it will cause linear motion without any rotation. However, when the line of action of the thruster does not pass through the centre of mass, it will cause a change of linear motion as well as some rotation.

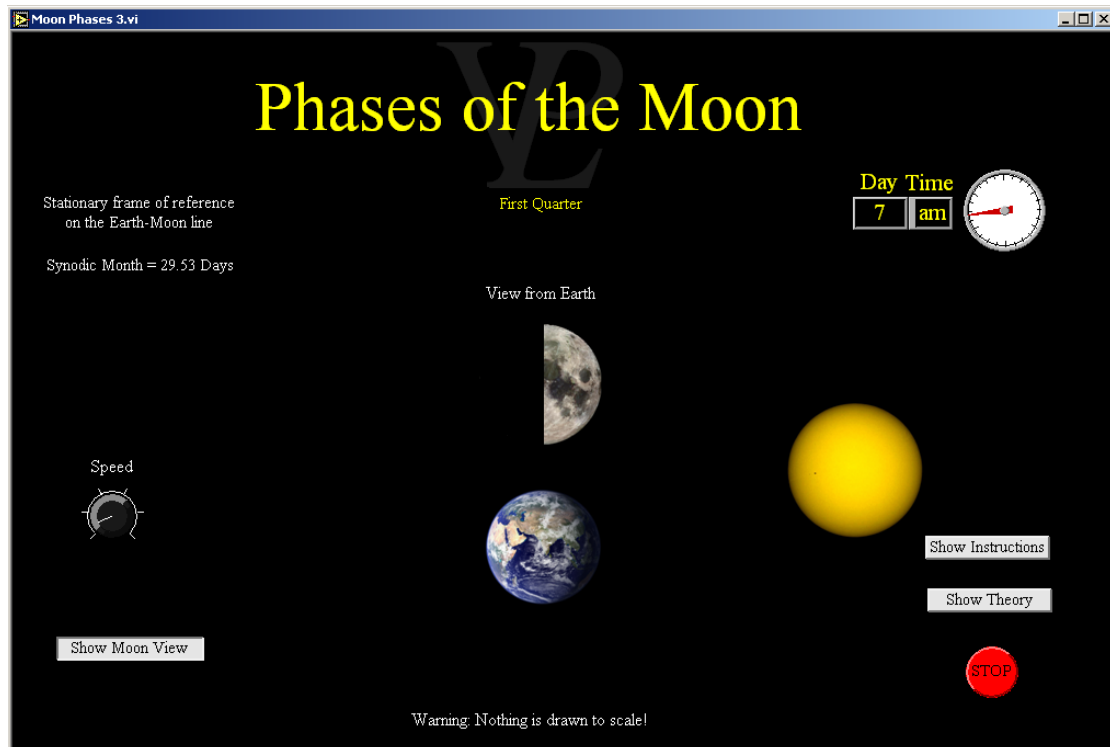
A consequence of Newton's Second Law of motion is that the change of momentum is equal to the impulse. (Momentum is the product of the mass and the velocity of an object. Impulse is the product of the Force and Time for which that force is acting).

Because there is no friction in space, once a motion is started it will continue indefinitely (Newton's First Law) until an impulse that is equal and opposite to the initiating impulse is fired. The same is true of any rotation; once it is started you have to deliberately act to stop it!) That makes detailed space navigation quite tricky because there is no convenient brake pedal to press!

1.7 Moon Phases

Advanced

This simulation shows how the appearance of the moon changes during the month. The user can toggle between Earth's view and a view from space.



The phases of the moon are something you have probably observed for years. Perhaps you have wondered why it looks the way it does. It is all to do with which side of the Moon the sun is at, and how the sunlight falls upon the Moon.

It is natural for an Earth observer to look upon things as if he were stationary and the Moon and Sun are rotating about him. Lunar months are not the same as calendar months. What is more, there are several different ways to define a lunar month. The two most common are:

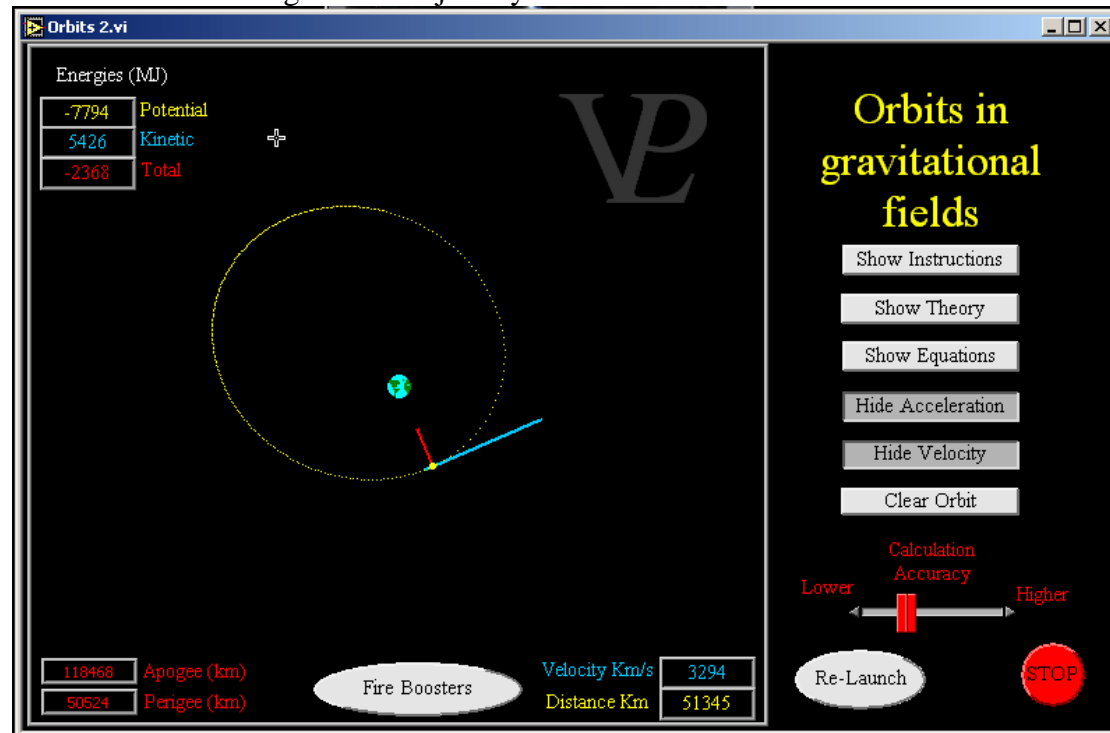
A Synodic Month. This is what the common Earth observer would note. It is the time it takes to go from a New Moon to the next New Moon. (or from Full Moon to Full moon). It is 29.53 days long. This is the cycle that also governs the tides.

A Sidereal Month is the time taken between the Moon going past a fixed star out in space (as seen from Earth) until the next time it goes past the star. This takes slightly less time to complete, 27.32 days!

1.8 Orbits

Advanced

This simulation maps out orbits of satellites in the Earth's gravitational field. The initial conditions may be varied in order to achieve bound orbits or give the satellite sufficient energy so that it can escape! The potential and kinetic energies are calculated at each stage of the trajectory.



The trajectory of orbits is a good example of the interchange there is between kinetic and potential energy because in space there is hardly any friction. Potential energy is defined as being zero at infinity; any closer than that to the mass of the Earth (or to any other mass) and the potential becomes negative. That is a mathematical way of saying that you will then need to supply energy in order to get your satellite back out to infinity again.

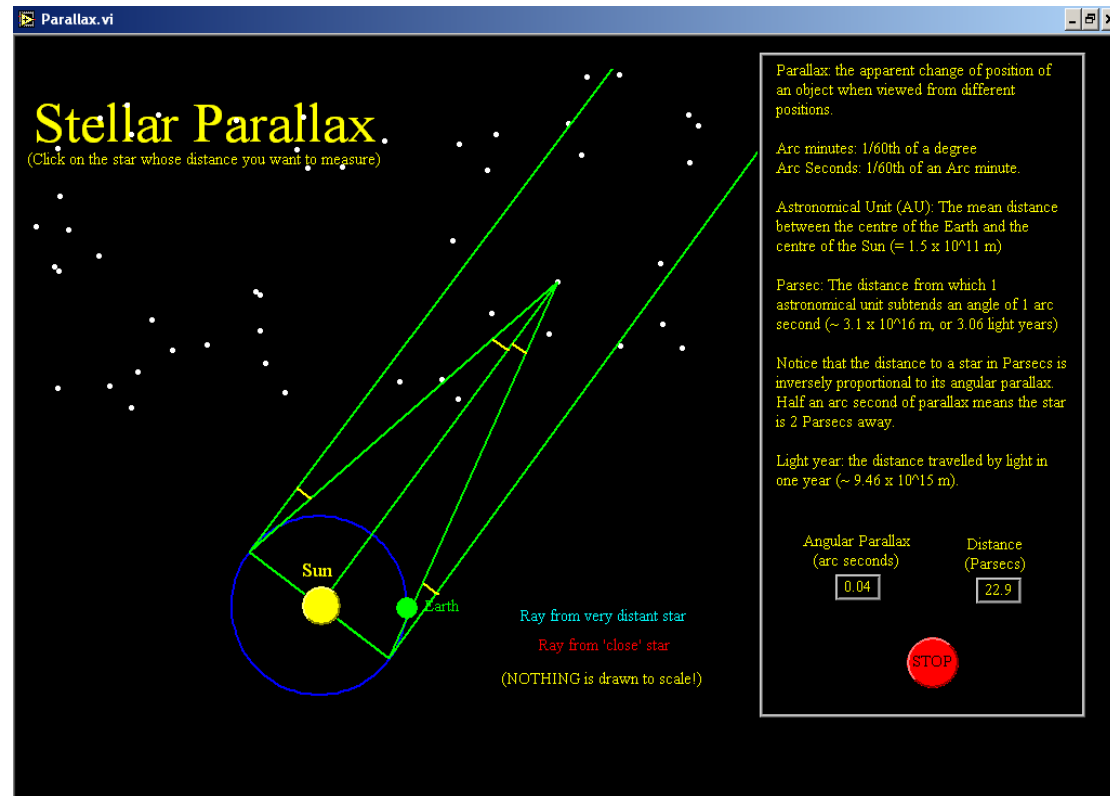
Satellites resting on the surface of the Earth have a large 'energy debt' (negative potential) which needs to be 'paid for' in order to get the satellite in orbit. If the entire 'debt' is paid, then the satellite escapes the Earth's gravitational field completely. If it is only partially paid, then the satellite will be set into orbit provided it has enough tangential velocity to balance the centripetal force due to gravity. Once in orbit, you will notice that if the satellite is moving further away from the Earth, its kinetic energy will start to decrease, it is using up some of its kinetic energy to pay for some of its 'energy debt'. On the other hand, if the trajectory is getting closer to the Earth, its kinetic energy will increase; it is getting into a greater potential energy 'debt' and is spending that energy in increasing its velocity.

The total energy of the orbit will be constant. The only way to change the energy of the orbit is to use thrust rockets. This uses chemical energy to provide kinetic energy. Since the available chemical energy on board satellites is very limited, boosters are only used to correct for small errors after the satellite has been placed in orbit by its parent spacecraft.

1.9 Parallax

Advanced

This simulation explains the definition of parallax, and enables the user to measure the parallax of different 'stars'.



Parallax is the name given to the apparent change of position of objects due to the movement of the observer. When looking out one of the side windows of a car, distant things hardly appear to move while closer things appear to move very fast. The magnitude of the movement is an inverse measure of how far away things are from the observer. When recording the position of stars, astronomers noticed that some appear to move (by a very small amount - that is why it took astronomers such a long time to notice it!) and others remain 'fixed'.

The distance between the centre of the Earth and the centre of the Sun is called an "Astronomical Unit". It is a huge unit ($\sim 1.5 \times 10^{11}$ m), but it is a suitable unit to help us get a scale on the universe. The movement of the Earth around the Sun makes its position change by two Astronomical units every 6 months. However, depending on which way you are looking out in to space, you may need to wait anything up to a full year to make sure you have observed the maximum parallax in both directions (astronomy takes patience!).

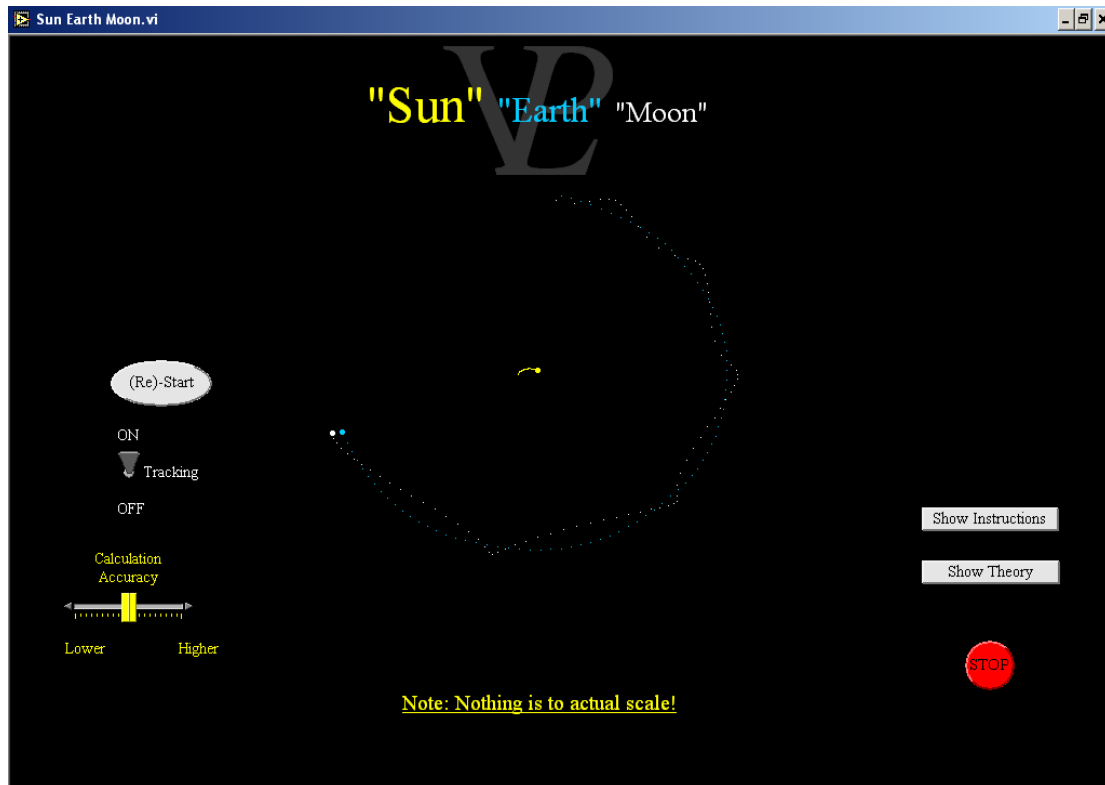
The parsec is defined as the distance from which one astronomical unit subtends one second of arc. This is an even larger unit! ($\sim 3.26 \times 10^{16}$ m or 3.26 light years) The maximum angular movement detected in a star is that of Proxima Centauri, and it is only 0.7687 ± 0.0003 seconds of arc! This means that it is 1.3 parsecs away (4.24×10^{16} m or about 4.5 light years away - and that is the nearest star!)

1.10 Sun Earth Moon

Advanced

The

This simulation allows the student to adjust the initial distances and velocities of the three, and then see how this 'solar system' will develop.



The forces and trajectories of objects in space are governed by gravitational forces. The Moon continues to orbit around the Earth because it is attracted by Earth's gravitational pull. However an equal and opposite pull also acts on the Earth pulling it towards the moon! In actual practice the Earth-Moon system 'dances' around like a heavy and a light skater holding hands and swinging round in an endless pirouette (how poetic!).

The Earth-Moon pair are both pulled by the gravitational attraction of the much more massive Sun. And the Sun is also attracted towards the Earth and the Moon (and all the other planets), except that their mass is so small compared to that of the Sun that their effect is negligible!

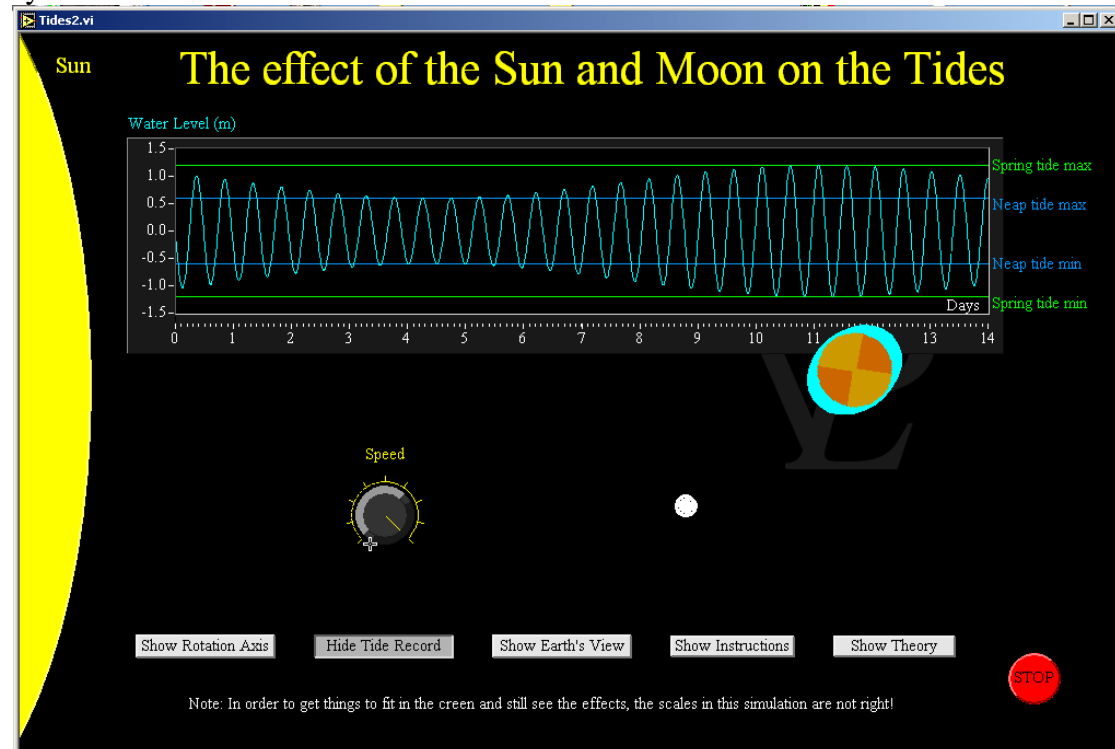
The Sun is also attracted to all the other stars in the galaxy (the 'milky way'). The stars may be very far away, but there are so many of them that through mutual attraction, the Sun is brought to revolve around the centre of 'our' Galaxy.

Studying the trajectory of stars around galaxies has lead astronomers to conclude that there is not enough mass in the visible stars to account for the strong attraction they seem to have towards the centre of the Galaxy! This has lead to the suggestion of 'Black Holes' at the centre of the galaxy, and also the concept of Dark Matter"

1.11 Tides

Advanced

This simulation shows how tides are governed by the combined gravitational pull of the Moon and the Sun. It also shows the effect due to the fact that the Earth-moon system rotates about their combined centre of mass.



A basic explanation of the tides is not difficult to understand, however the detailed theory is very complicated!

The basics first: The Moon is attracted to the Earth by gravity, (that is why it keeps rotating around us rather than fly off in a straight line). The Earth is also attracted to the Moon by an equal and opposite force. Since the oceans are not rigid, they can flow in the direction of attraction (towards the moon) causing a high tide.

The opposite side of the Earth also has a high tide, and this seems counter intuitive! The explanation for this is that the Earth-Moon system does not rotate about the centre of the Earth, but about the centre of their combined masses (which is still somewhere inside the Earth because the Earth is much more massive than the Moon). This 'lop-sided' rotation causes the waters on the opposite side of the Earth to the moon to 'fling away' a little.

More complicated stuff: The Sun also has an effect on the tides, but a little weaker than the Moon because it is so much further away. When the Sun, the Earth and the Moon are aligned in a straight line they cause extra high tides called 'spring tides'. When the Sun and the Moon are at right angles to each-other (as seen from the Earth) their effects do not add up quite so well, and that gives rise to smaller tides called 'neap tides'.

Extra difficult stuff: The orbits of the Earth about the Sun and that of the Moon about the Earth are elliptical, so when both of them are at their closest they produce even higher tides! Another important effect is that due to river estuaries, islands and ocean depths. These can modify the basic tides enormously. Some places of the world only have one high tide per day!

CHAPTER 2

CHARGED PARTICLES

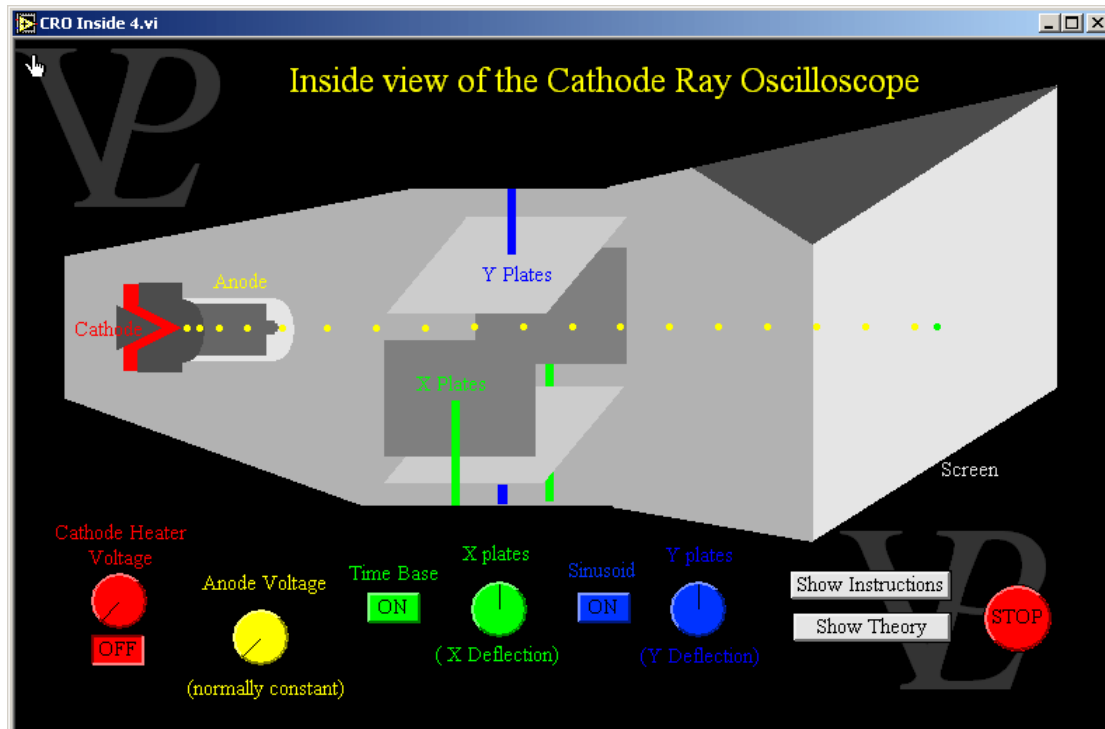


Charged particles make computer monitors glow.
How do they get there?

2.1 Inside a CRO

Basic/Advanced

This simulation shows the internal workings of a cathode ray oscilloscope, including the cathode, anode, X and Y deflection plates and the time-base.



When a metal is heated sufficiently, electrons can escape from the surface. This is called thermionic emission. The hotter the metal, the more electrons will jump out of it.

Normally the electrons will simply fall back into the metal and there is no net current flowing away from the metal.

In order to get the electrons to flow away from the metal surface it is necessary to place a positively charged anode in front of it to attract them away.

In a CRT the anode has a small hole in the middle of it, and that allows the electrons to pass through. In this way an electron beam is made.

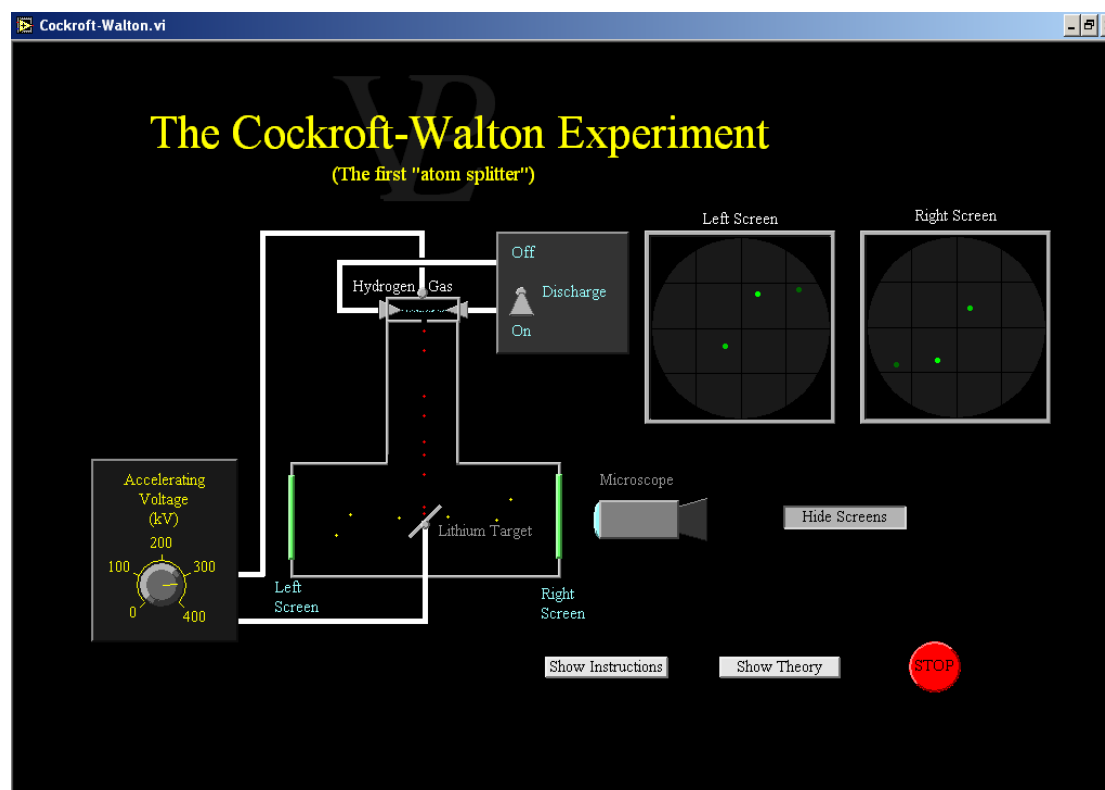
The electron beam then passes between the X and Y plates where it gets deflected one way or the other by voltages applied to them.

Finally the electron beam strikes the scintillating screen of the oscilloscope, where the kinetic energy of the electron gets converted into light.

2.2 Cockroft Walton

Advanced

This simulation enables the user to repeat the ground-breaking experiment that was done in 1932. The first demonstration of Einstein's energy mass equivalence and artificial transmutation of elements.



In 1932 the English physicist John Cockroft and the Irish physicists Ernest Walton were the first scientists to achieve artificial atomic transmutation (converting one element in to another!). Their experiment also was the first experimental demonstration of Einstein's (1919) $E=mc^2$ equation!

They applied an electrical discharge through Hydrogen gas in order to ionise some of the gas atoms (producing protons). They then accelerated the protons through a large potential difference and aimed them at a Lithium target. By bombarding Lithium atoms with high energy protons they noticed that occasionally a pair of alpha particles (Helium atoms) were produced. The two Alpha particles travelled in opposite directions (conserving momentum). $P + Li = 2 He + \text{Kinetic Energy}$

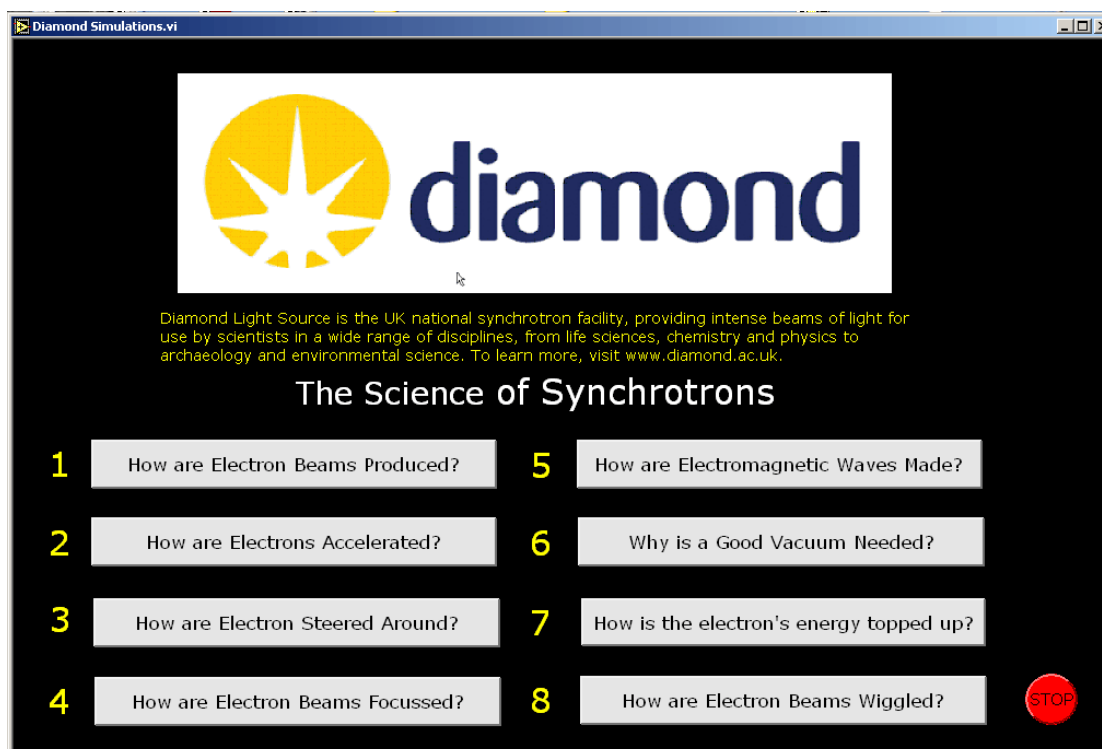
It is difficult to get a proton close to an atomic nucleus because of the large electrostatic repulsion it will experience as soon as it gets inside the electron cloud of the Lithium atom.

In their experiment, Cockroft and Walton found that with accelerating voltages as low as 125 kV occasional Alpha particles were produced. At 400 kV (the maximum voltage achievable with their equipment) they were able to observe over a hundred Alpha particle pairs per minute! This nuclear reaction is an exothermic one; more energy is liberated than is required to make it happen.

2.3 Diamond Synchrotron

Advanced

Take a tour round the essential components of an electron synchrotron from electron gun to the undulator where the X Rays are produced. These simulations are sponsored by Diamond Light Source www.diamond.ac.uk.

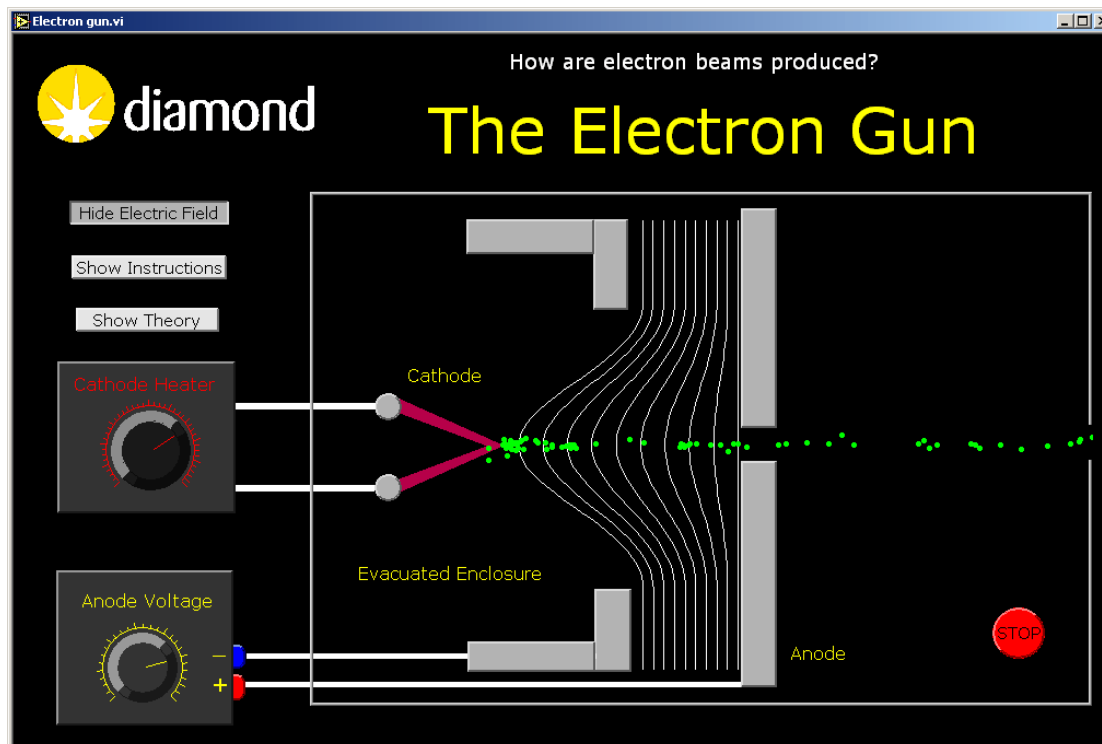


The theory for each of the simulations on the Diamond synchrotron is listed with each of the simulations.

2.3-A The electron Gun

Advanced

See the basic components of the electron gun. See how the electric field extracts and accelerates the electrons from the cathode.



The electrons that Diamond uses begin their journey at the Electron Gun. When metals get very hot, they start to lose electrons through a process called "Thermionic Emission". Normally the electrons simply fall back so that no net current flows away from the metal surface.

When an electric field (a positively charged surface) is brought close to the surface that is emitting electrons, the electrons are attracted away and no longer return to the filament. The stronger the electric field (the more positive the anode is made) the faster the electrons are accelerated away.

The kinetic energy acquired by the electrons is equal to the electrical work done by the field in ripping them away from near the surface of the filament.

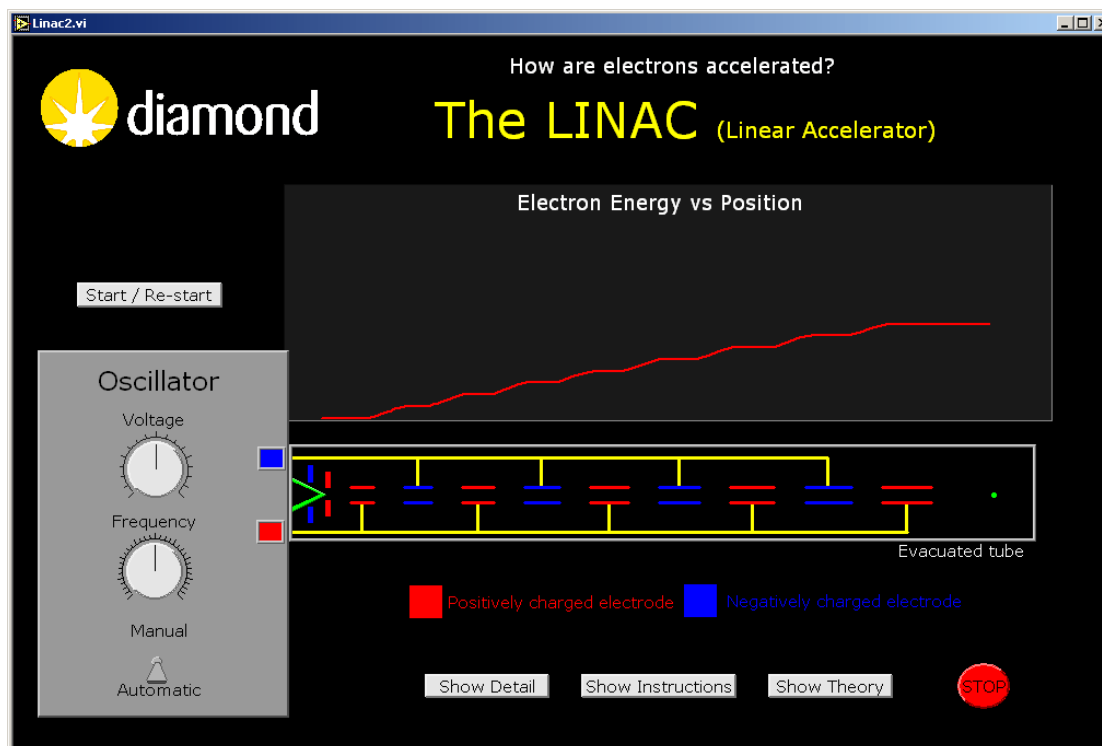
So we can say Kinetic Energy = Electrical work done or $\frac{1}{2} m v^2 = e V$
 where m is the electron mass
 v is its velocity as it leaves the gun
 e is the charge of the electron
 V is the Voltage on the anode.

Electrons are so light that very quickly they get to speeds close to the speed of light. Trying to accelerate electrons much further starts to bring in relativistic effects: the velocity does not increase much more, but the electron mass starts to increase instead! Sounds quite complicated, but that is relativity for you!

2.3-B The LINAC

Advanced

See the internal workings of a Linear Accelerator. Operate it manually and see what maximum electron energy you are able to achieve.



To produce the very bright X-rays used by our scientists, Diamond needs to generate a beam of electrons which travel at very close to the speed of light. Once electrons have left the Electron gun they are passed into the linear accelerator, or linac.

In theory, this could be achieved by passing the electrons through a very strong electric field. However, in practice it is not possible to generate high enough voltages, so a linac achieves the same goal by accelerating electrons through a series of smaller fields. Each time the electron travels through a conducting tube (where there is no electric field) the polarity of the tube is changed, so that when the electron leaves one tube it is accelerated towards the positive tube in front of it.

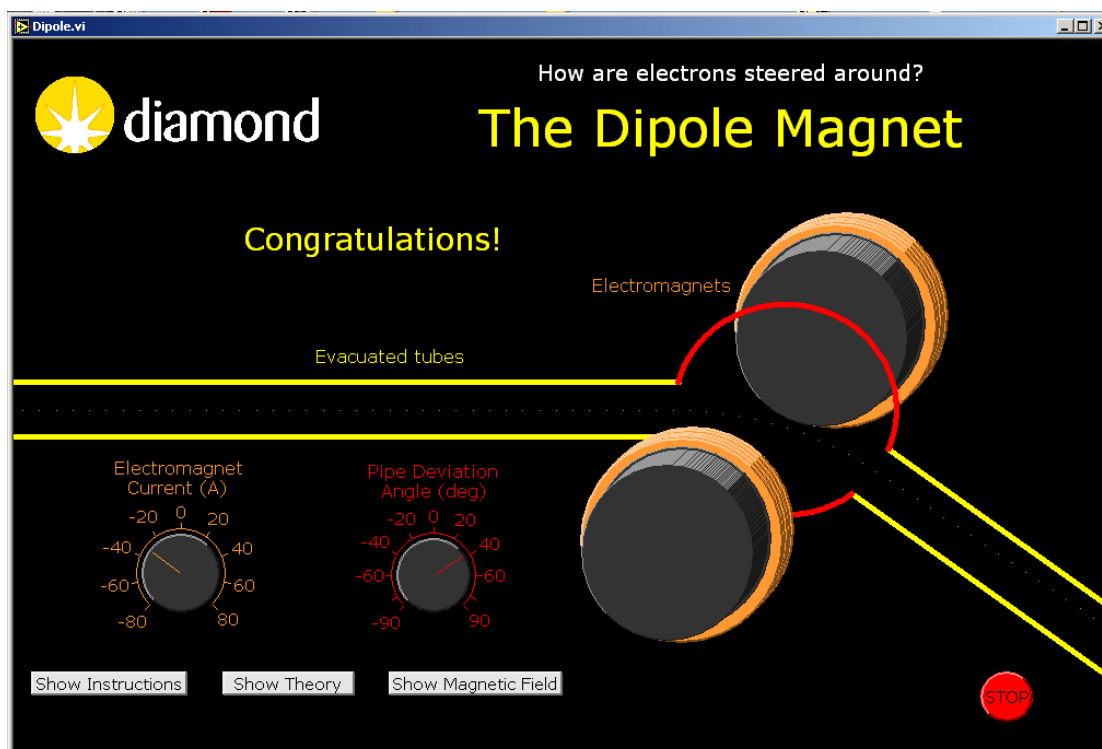
You will notice that the tubes get longer as they go along; this is so that all the tubes can be powered by a single oscillator. When the electrons are travelling slowly, they only travel a short distance before the polarity changes. The faster they are going the further they will travel in the same amount of time, before the polarity switches again.

At high energies, the length of the drift tube becomes roughly constant again. This is because as the electrons approach the speed of light, increasing their energy no longer increases their speed, instead relativity means that their mass increases.

2.3-C Dipole

Advanced

See how magnetic dipoles can be used to bend electrons round the main ring of the synchrotron (Fleming's left hand rule). Adjust the dipole current to match the curvature of the track.



Stationary electric charges do not experience any forces at all when they are inside magnetic fields. However, when electric charges are moving inside magnetic fields, they experience a sideways force which deflects them into a circular path. The direction of the force is given by 'Fleming's Left Hand Rule' and is given by the equation $F = B q v$ where B is the magnetic field strength, q is the charge on the particle and v is the velocity of the particle.

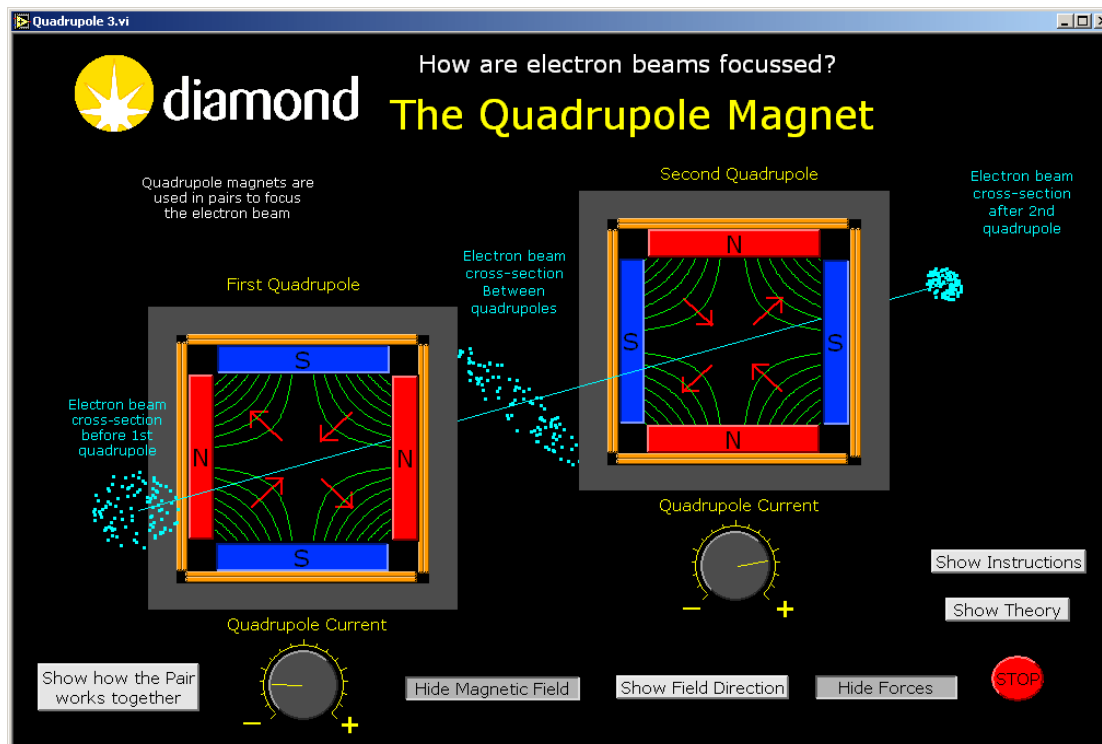
As soon as the electrons experience the first bit of sideways force, their direction of travel will also change. Since the direction of travel will change, the electromagnetic force will also change in such a way that it is always perpendicular to the motion. It is this change of force direction which causes the electrons to travel in a circular path until they escape from the region of the magnetic field.

In a Synchrotron the magnets need to be very strong because the electrons have a much larger mass than normal (due to relativistic effects). The electromagnets are not circular, but rather slightly 'kidney bean' shaped. The field strength needs to be adjusted very precisely to keep the electrons travelling along the desired track!

2.3-D The Quadrupole

Advanced

See how a pair of magnetic quadrupoles can be used to focus an electron beam when it starts to diverge.



The force experienced by a charged particle which is flying perpendicularly across a magnetic field follows Fleming's left hand rule. Notice that the magnetic field is not at all uniform inside the quadrupole! It is actually very complicated. But notice that right in the middle the field strength is zero. This means that electrons flying exactly through the middle of a quadrupole are not deviated at all. They don't need to be focussed because they are already travelling down the axis!

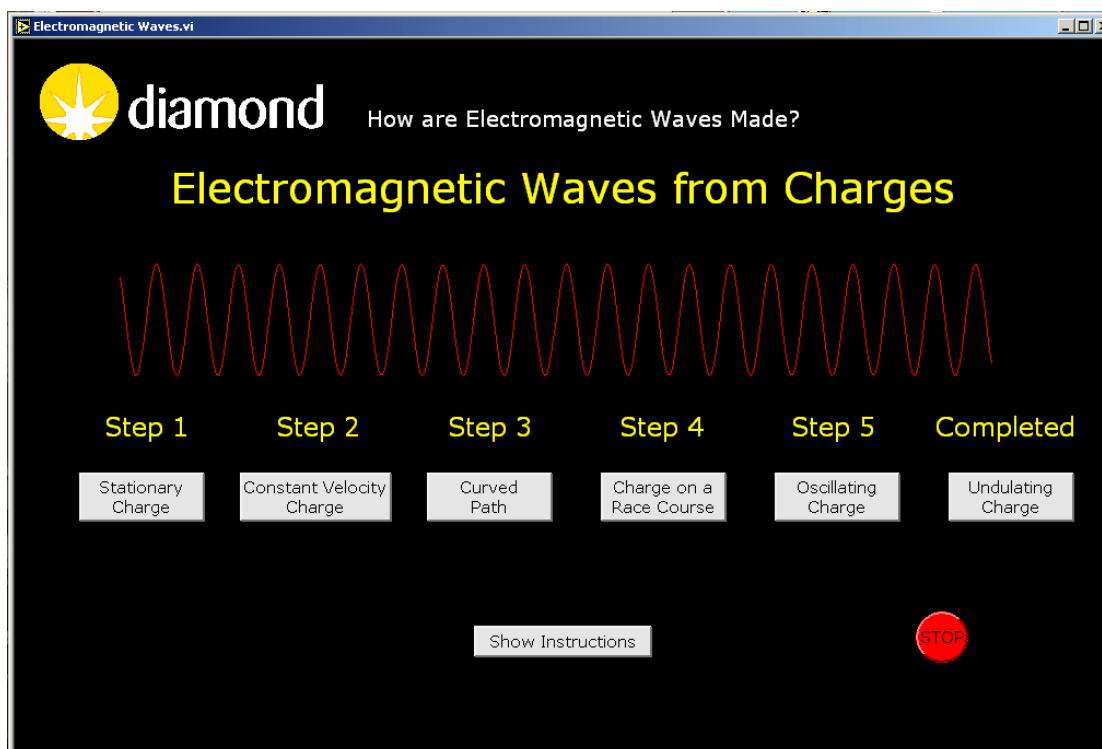
When the current is flowing in the positive direction, electrons travelling along top left or bottom right experience a force which pushes them back towards the centre of the quadrupole (focussing them). Electrons travelling along the top right or bottom left experience a force that pushes them further out. This seems disastrous! But this is where the second quadrupole does its trick.

The polarity of the second quadrupole is always arranged to be the opposite to the first one. Notice that the magnetic field strength is greater further away from the middle (getting towards the corners). The electrons that experienced a moderate force outwards in the first quadrupole will experience a larger inward force in the second quadrupole. The electrons that were pushed towards the middle by the first quadrupole will be travelling through the weakest part of the magnetic field of the second quadrupole, so they hardly experience a defocussing force in the second quadrupole! The net effect of the two quadrupoles is that the electron beam gets focussed in to a fine beam. I warned you it was complicated!

2.3-E Electromagnetic Waves from Charges

Advanced

See how the acceleration of charges produces curvature in the electric field radiating away from a charge. See how the most effective method is to undulate the electron while it travels along to produce a continuous wave train.



When charges are stationary, or travelling at constant velocity, they do not radiate away any energy in the form of electromagnetic waves. The electric field lines simply point radially away from a positive charge (or radially inward towards a negative charge).

When charges accelerate, (either by changing their speed or direction), then the electric field lines start to bend, and this disturbance travels radially away from the charge carrying energy away from the charge in the form of electromagnetic waves.

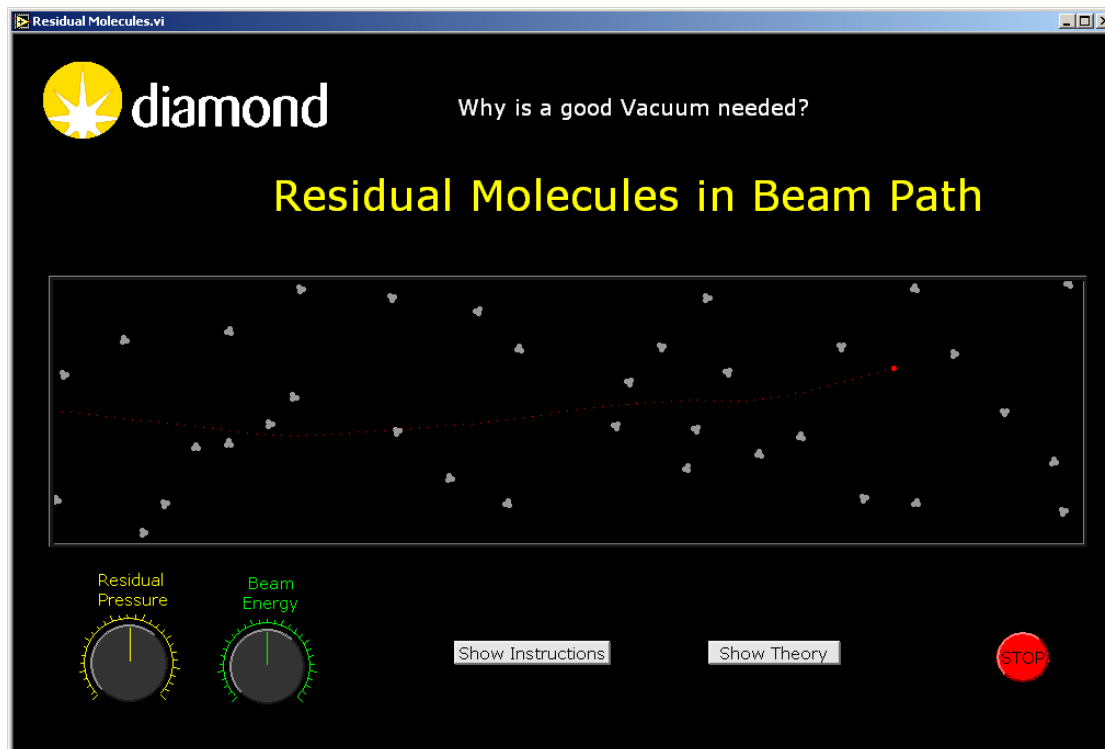
To generate the very bright light used in experiments, Diamond uses arrays of magnets called undulators, which cause the electron to follow a wiggling path. The wavelength of the light depends on the strength of the magnetic field and the spacing between the magnets. Because the electrons themselves are travelling at close to the speed of light, relativity and the Doppler effect mean that the wavelength of this light is very short - it is in the form of X-rays.

The light produced is very intense, because the light produced by each wiggle of the electron beam adds up. Changing the magnetic field by changing the separation of the magnets mean that the wavelength of the light can be tuned for different experiments.

2.3-F Residual Molecules

Basic

See why a good vacuum is needed in order to keep electrons going round the circular track. Adjust the number of residual molecules and see how the electrons are affected.



An electron beam travelling through air will quickly lose electrons as they collide with air molecules and lose energy. To keep the electron beam circulating in the storage ring of the synchrotron, the tube they travel through must be kept at a very high vacuum.

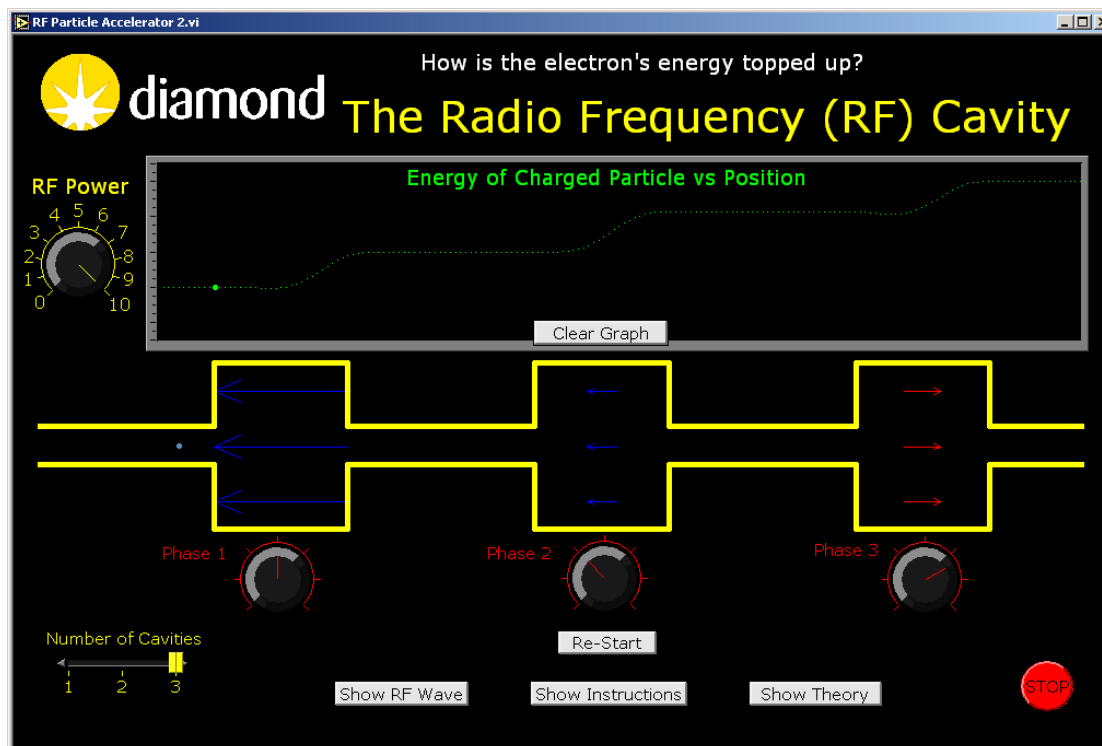
It is never possible to create a perfect vacuum; there will always be some residual air molecules left in the system. The electrons accidentally hitting the residual gas molecules, will lose energy and will be eventually lost in the chamber wall. However, the vacuum at Diamond is good enough to keep the electron beam circulating for more than 10 hours before it needs to be refilled!

It is worth noting that usually the mass of electrons is thousands of times less than that of the air molecules. However, at very high velocities (99.999% of the speed of light) relativistic effects mean that the mass of the electrons can become greater than the mass of the air molecules!

2.3-G The Radio Frequency Cavity

Advanced

See how a resonant cavity with an electromagnetic field inside it can be used to top-up the energy of electrons as they pass through. Try to adjust the phase of the cavities to obtain the maximum kinetic energy increase.



As the electron beam travels round the synchrotron it loses energy in the form of synchrotron light. This energy is replaced by the RF cavities. As the electron enters the RF cavity it sees an oscillating electric field, which is tuned so that the field is always in the right direction to accelerate the electrons further. The timing and frequency need to be tuned very precisely indeed!

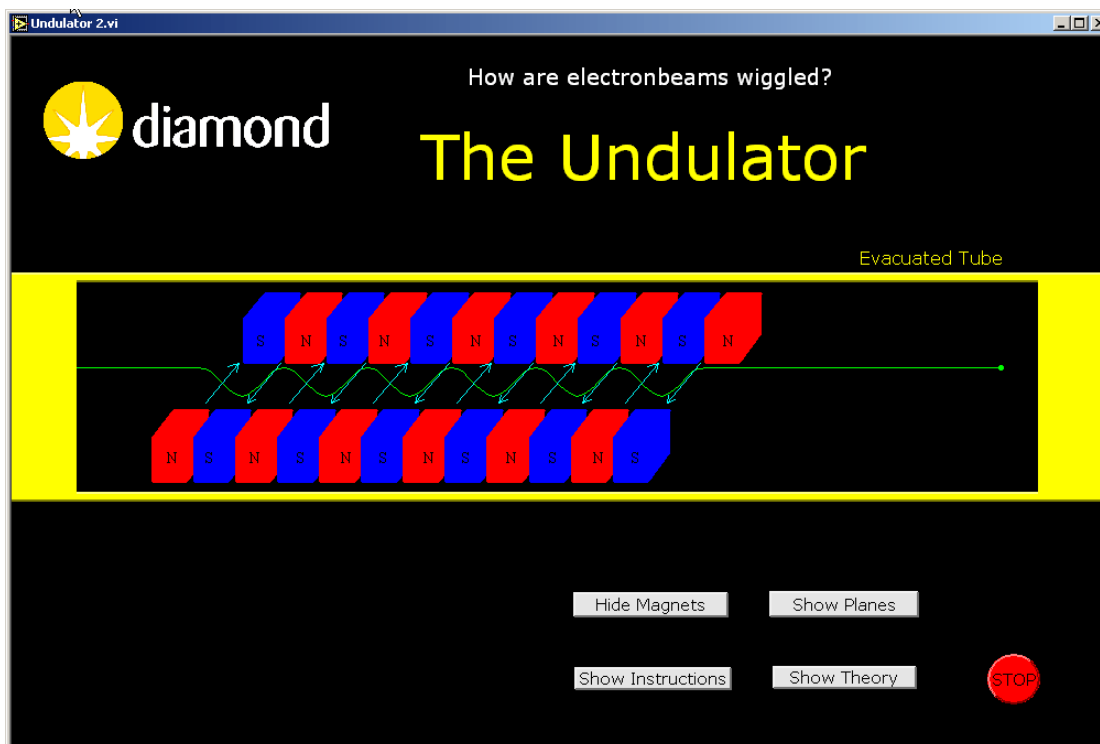
The electrons are travelling so close to the speed of light that the increase in their velocity is negligible, but the kinetic energy of the electron will increase, and relativistic effects will cause each electron to increase its mass significantly.

The larger the amplitude of the RF wave, the larger the increase in energy will be. Having more cavities will also give the electrons a larger total energy at the end. Diamond uses three cavities to ensure the electron beam can keep travelling around the storage ring with the desired energy of 3 GeV. From the start of the electron gun to here the electrons have seen the equivalent of being accelerated through a potential difference of 3 000 000 000 Volts!

2.3-H The Undulator

Advanced

See how an array of opposing magnets can be used to undulate the trajectory of electrons. See the Doppler shifted X Rays being generated in the process.



Undulators are one of the key components of the synchrotron; it is the undulators that generate the very bright X-rays used in experiments.

They consist of arrays of magnets arranged in such a way as to cause the electron beam to "wobble" as it passes through. In fact there is a special type of undulator called a wiggler!

The wobbling path causes the beam to create electromagnetic waves in the form of light. The light from each successive wiggle add up to produce a very intense beam of light in the forward direction. Because the electrons themselves are travelling at close to the speed of light, relativity and the doppler effect mean that the wavelength of this light is very short - it is in the form of X-rays.

These intense X-rays are then channeled into Diamond's beamlines to be used in experiments.

2.4 The ISIS Neutron Source

Advanced

Take a virtual trip around the Neutron Source Facility to see how it works and learn some of the physics behind it.

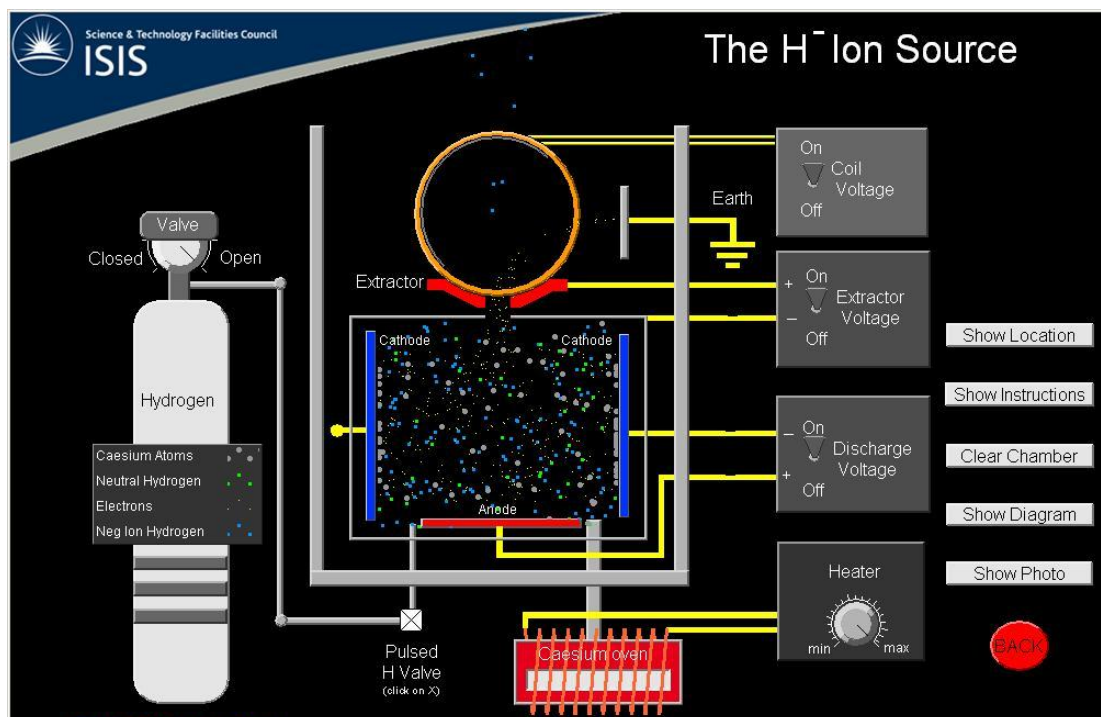


This is the introductory page that leads to the 10 simulations sponsored by the ISIS Neutron Source Facility.

2.4.A The Ion Source

Advanced

The Facility starts by producing Negative Hydrogen Ions. See how they are produced and separated from the electrons (which are also negatively charged).



The Ion Source is designed to produce negatively ionised Hydrogen atoms (Neutral Hydrogen plus an additional electron). To do this, it is necessary to get a Hydrogen atom to collide with a fairly slow electron.

In order to get the electrons to flow fairly easily away from a negatively charged electrode, it is necessary to lightly coat the surface of the electrode with Caesium. This reduces the 'Work Function' making it easier for the electrons to break away from the surface.

Once the electrons are flowing in sufficient numbers, if there is sufficient Hydrogen in the chamber, some of it will get ionised negatively by acquiring one additional electron. This will leave the Hydrogen atom with an overall negative charge.

A hollow electrode is connected to a positive Voltage (an Anode), to attract the negatively charged Hydrogen ions and accelerate them away from the chamber. Unfortunately, the Anode will also accelerate electrons out of the chamber, so the beam of particles coming out is a mixture of negatively charged Hydrogen ions and electrons.

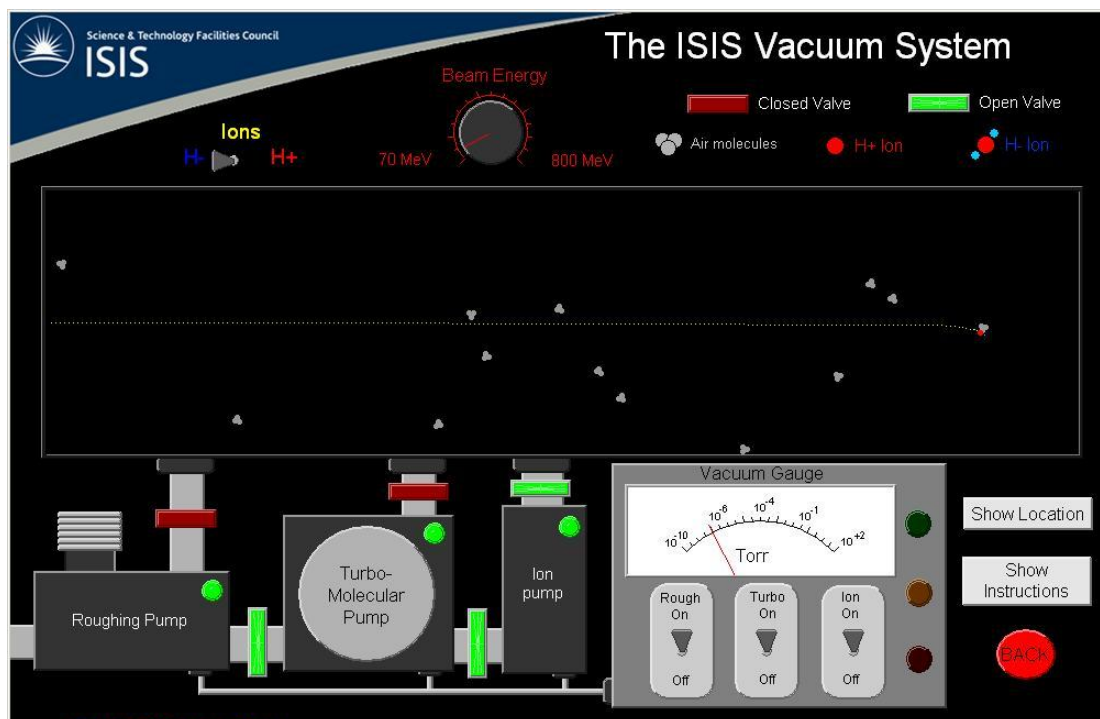
To separate the electrons out and get rid of them, a magnetic field is applied. This causes charged particles to travel in an arc. Since electrons are very light (their mass is thousands of times less than that of Hydrogen), the electrons travel in a short arc and collide on to an earthed electrode. The heavier Hydrogen Ions continue their journey towards the accelerator.

The Caesium coating on the electrodes gradually wears out by a process called 'sputtering' (electrons bombarding the surface can break the atoms away). For that reason it is necessary to continue feeding the gun with both Hydrogen and Caesium.

2.4.B The Vacuum System

Advanced

See why a good vacuum is so important at ISIS, and learn what type of pump are used.



An Ion beam travelling through air will quickly get dissipated as the ions collide with air molecules and lose energy and change direction. To keep the Ion beam travelling through the Linac and round the Synchrotron, the tubes they travel through must be kept at a very high vacuum.

There are many different units of pressure (or vacuum). Atmospheres, Bar, Pascals, Torr...

A commonly used unit used in vacuum systems is the Torr. It is equivalent to the pressure of a millimetre of mercury in a manometer. So there are 760 Torr in one atmosphere.

Vacuum pumps must be operated in the right order, and there are some valves and safety interlocks designed to protect the pumps from being switched on before the system has achieved the correct operating vacuum range.

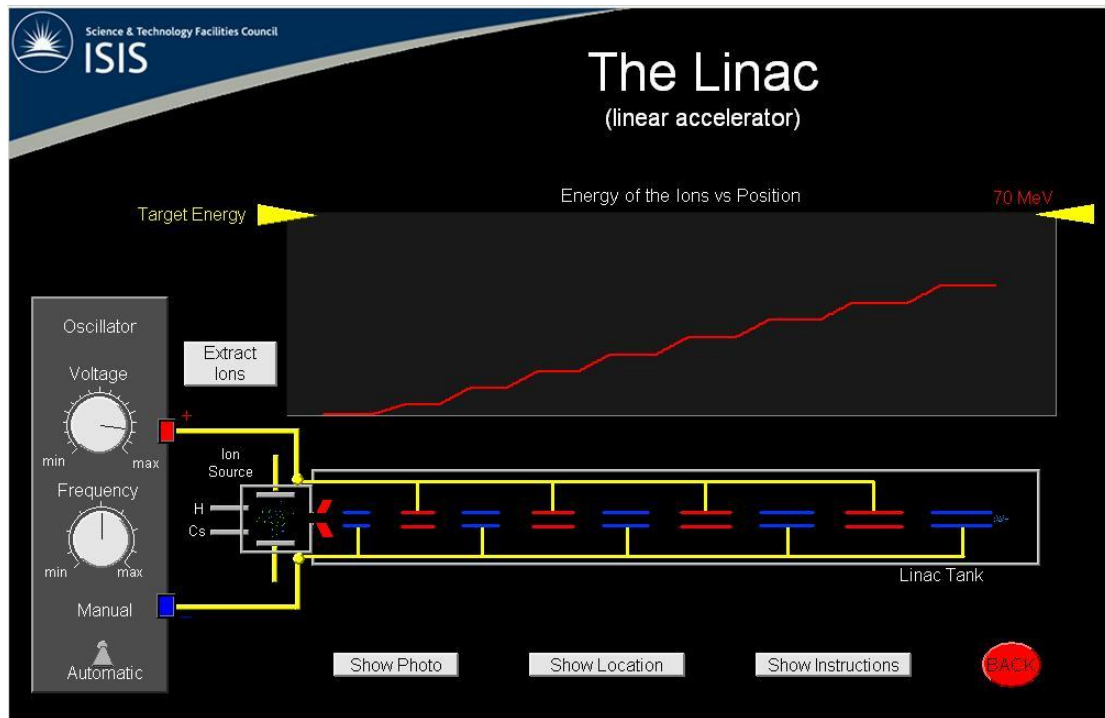
The higher vacuum pumps need to have the lower vacuum pumps working behind them in order to function properly.

It is never possible to create a perfect vacuum; there will always be some residual air molecules left in the system. The Ions accidentally hitting the residual gas molecules, will lose energy and eventually hit the chamber wall. However, the vacuum at ISIS is around 10^{-7} Torr (~ one ten billionth of an atmosphere!) good enough to deliver the proton beam to the target and produce an intense burst of neutrons.

2.4.C The Linac

Advanced

See how a Linac accelerates charged particles up to around 70 MeV before they enter the Synchrotron.



After being extracted from the Ion Source, and before the H⁻ ions can be injected into the synchrotron it is necessary to speed them up to around 37% of the speed of light. This is done in the linear accelerator, or Linac.

In theory, this could be achieved by passing the Ions through a single very strong electric field. However, in practice it is not possible to generate a high enough voltage, so a Linac achieves the same goal by accelerating Ions through a series of smaller fields. Each time the Ions travel through a conducting tube (inside of which there is no electric field) the polarity of that tube is made negative and that of the tube ahead is made positive, so that when the Ions leave the negative tube they are accelerated towards the positive tube in front of them.

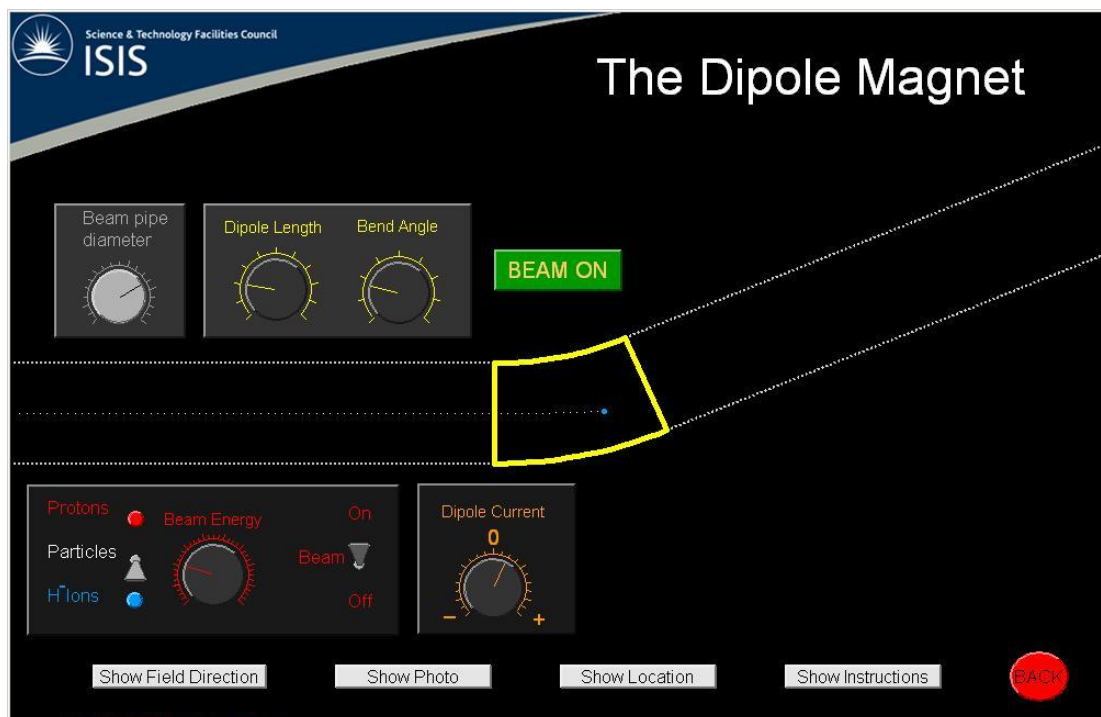
You will notice that the tubes get longer as they go along; this is so that all the tubes can be powered by a single oscillator operating at a constant frequency. When the Ions are travelling slowly, they only travel a short distance before the polarity changes. The faster they are going the further they will travel in the same amount of time, before the polarity switches again.

At ISIS, the Linac is used to get the Ions travelling up to around 37% of the speed of light

2.4.D The Dipole

Advanced

See how large magnets are used to steer the ions around bends to keep them travelling around the synchrotron



Stationary electric charges do not experience any forces at all when they are inside magnetic fields. However, when electric charges are moving inside magnetic fields, they experience a sideways force which deflects them into an arc. It is the same force that makes electric motors turn. (Ask your physics teacher about "Fleming's Left Hand Rule"!)

If the charged particles are very light, or if they are travelling slowly, a magnetic field can bend their trajectory into a circle. The stronger the dipole magnet, the smaller the diameter of the arc.

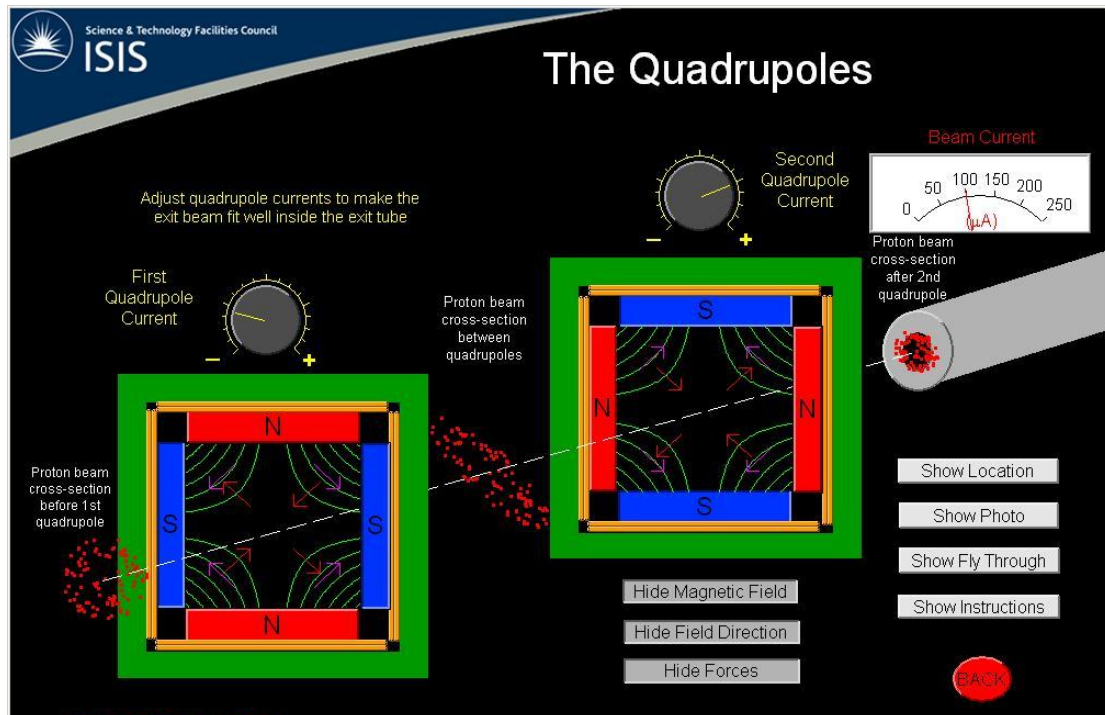
However, at ISIS, the particles are reasonably massive (about 2000 more massive than electrons), and they are also travelling very fast. This makes them much harder to steer: the magnetic fields need to be very strong, this needs large currents. Even with these strong magnets the dipoles only manage to steer the charged particles through a fairly small angle.

Since the moment charged particles exit from the dipoles they will again travel in straight lines, in order to make the deflection angle as large as possible it is necessary to try to keep the particle inside the dipole for as long as possible. That is why the dipoles are so long!

2.4.E The Quadrupole

Advanced

These are devices to focus and reshape the beam profile. See if you can figure out how they work.



The force experienced by a charged particle which is flying perpendicularly across a magnetic field follows Fleming's left hand rule and is given by the equation $F = B q v$, where B is the magnetic field strength, q is the charge on the particle and v is the velocity of the particle. Notice that the magnetic field is not at all uniform inside the quadrupole!

Right in the middle the field strength is zero. This means that protons flying exactly through the middle of a quadrupole are not deviated at all. They don't need to be focussed because they are already travelling down the axis!

Protons travelling along top left or bottom right experience a force which pushes them back towards the centre of the quadrupole (focussing them). Protons travelling along the top right or bottom left experience a force that pushes them further out. This seems disastrous! But this is where the second quadrupole does its trick.

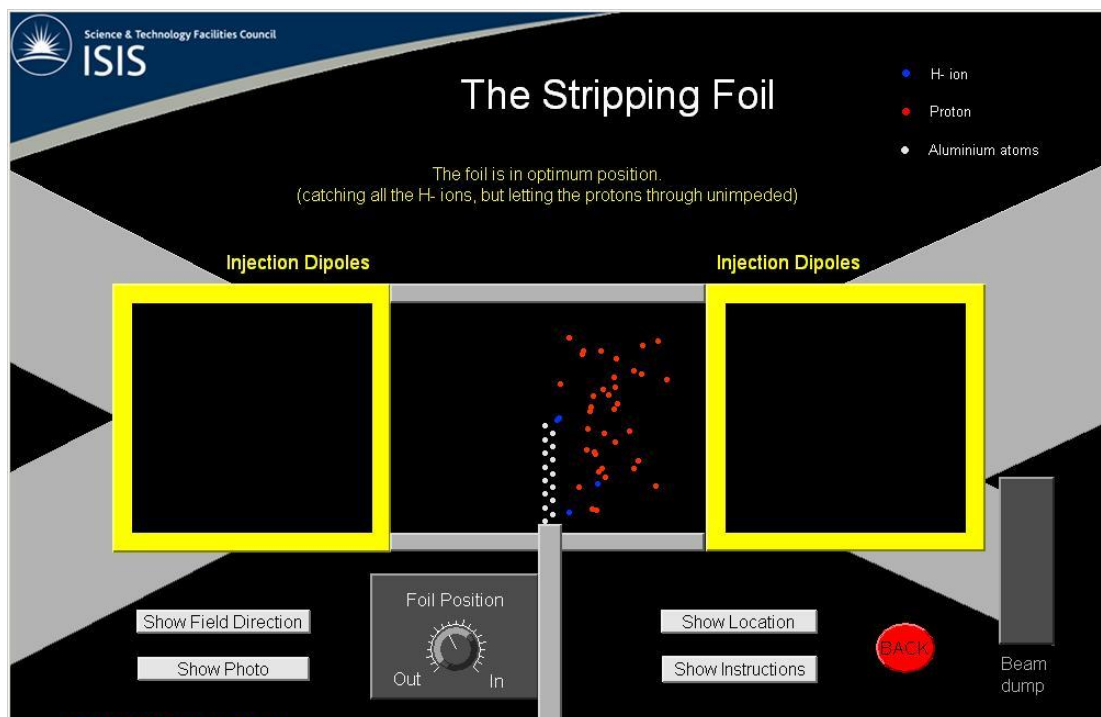
The polarity of the second quadrupole is always arranged to be the opposite to the first one. Notice that the magnetic field strength is greater towards the corners. The protons that experienced a moderate force outwards in the first quadrupole will experience a larger inward force in the second quadrupole. The protons that were pushed towards the middle by the first quadrupole will be travelling through the weakest part of the magnetic field of the second quadrupole, so they hardly experience much of a defocussing force in the second quadrupole!

The net effect of the two quadrupoles is that the proton beam gets focussed in to a fine beam. I warned you it was complicated!

2.4.F The Stripping Foil

Advanced

A stripping foil is needed to rip the electrons off the H^- ion to convert them into H^+ ions (protons). See if you can figure out why this is necessary.



The injection of different polarity particles into a single beam is achieved by directing them at two different incident angles through a single dipole magnet. Since the particles have opposite charges, they experience opposite forces whilst inside the magnetic field. This causes them both to curve round in opposite directions until they emerge travelling parallel to each other (although not exactly coaxially - the reason for this is explained in the second section).

The high energy near collision between a H^- ion and an aluminium atom causes the two electrons of the H^- ion to get stripped off (hence the name of this section). The kinetic energy of the H^- ion and the interaction with the electron cloud around the aluminium atoms causes the electrons of the H^- ion to acquire sufficient energy to break away from the H^- ion. The "stripping" process is not 100% efficient. So there are a small number of H^- ions remaining after passing through the foil. However, when they pass through the first dipole after the foil, they are deflected in the opposite direction to the protons.

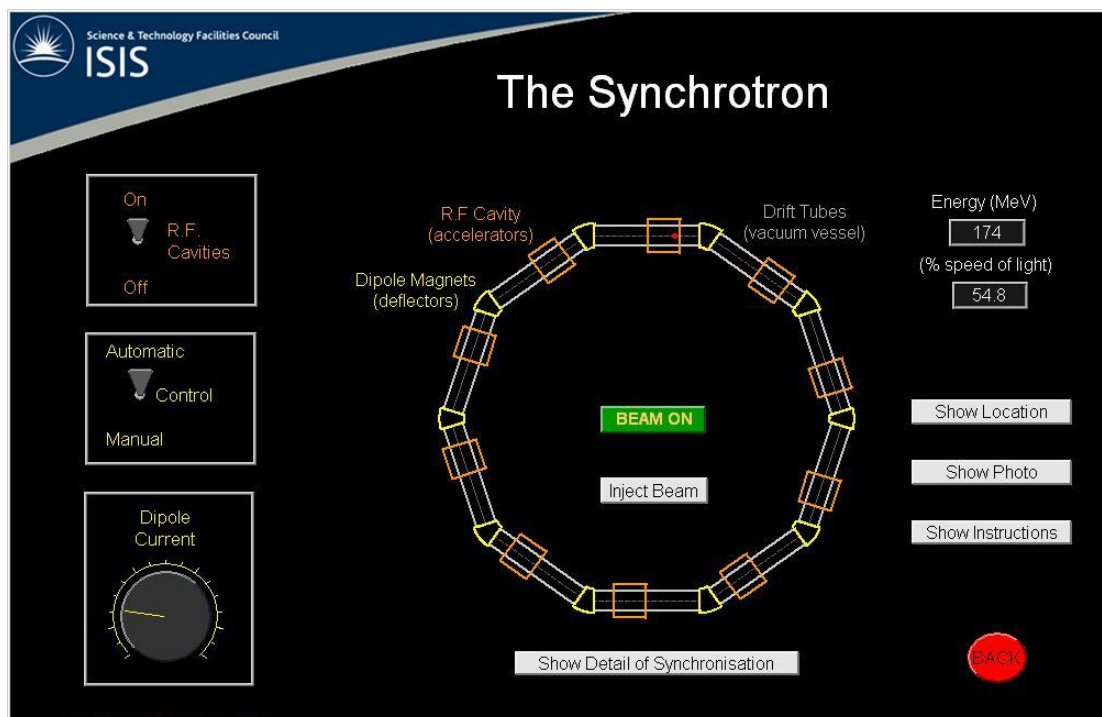
The re-circulating proton beam (already in the synchrotron) is purposefully kept slightly away from the H^- beam so that it does not need to pass through the foil again. If it did, it would slightly reduce the number of protons, but it would also overheat the foil and burn a hole in it!

Once a high enough number of protons have been injected into the synchrotron, the dipoles deflecting the main ring into the stripper are switched off, and the protons continue their accelerating journey round and round.

2.4.G The Synchrotron

Advanced

This is perhaps the cleverest part of the whole machine. It all happens so quickly, see if you can follow how it is done.



The ISIS synchrotron is made up of 10 sections called 'super periods'. Each straight section has a R.F. Cavity accelerator (RFQ for short) in it and also focusing quadrupole to stop the beam of protons from spreading out too much. So at the end of each section the protons are travelling a little faster than at the beginning.

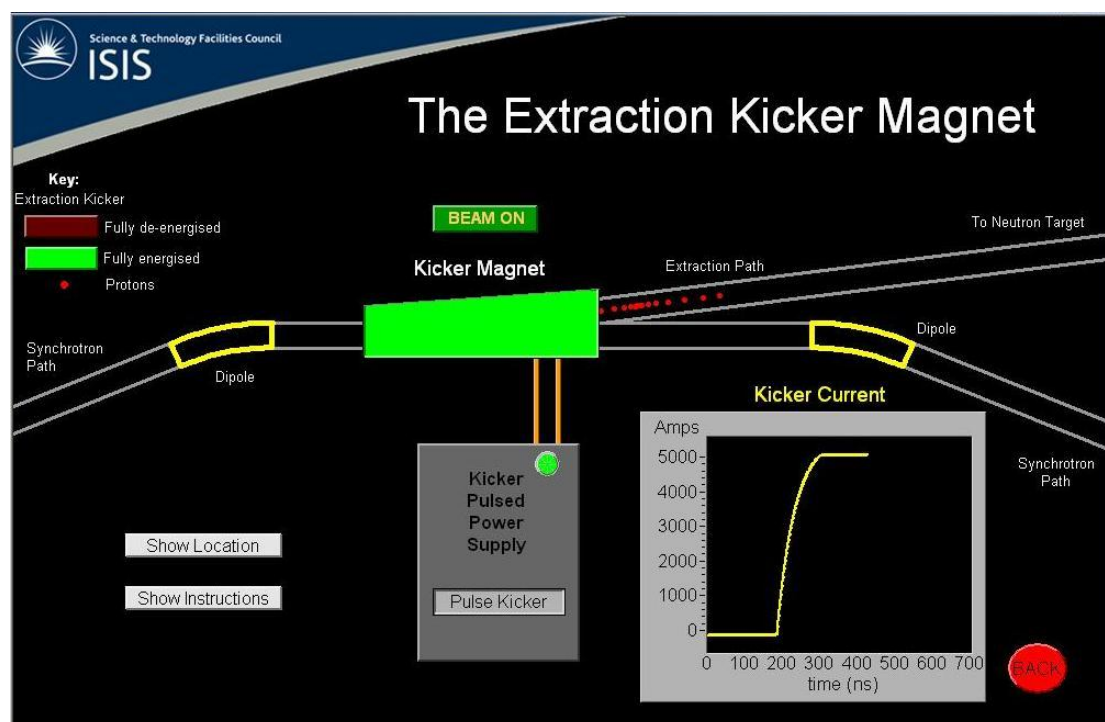
At ISIS, the synchrotron receives the protons from the Linac at about 37% of the speed of light, and by the time they have completed 10,000 rotations inside the synchrotron they are travelling at 84% of the speed of light. Amazingly this entire process takes only 1/50th of a second! Getting the synchronisation between the dipole current and the frequency (and phase) of the RFQ is crucial to the operation of the Synchrotron. If the current through the dipoles was not gradually increased, faster protons would not bend enough and would soon hit the sides of the tubes and so the beam would be lost. In practice, the dipoles are driven by an offset alternating current operating at mains frequency (50 Hz). During the rising time of the sinusoid, the field in the Dipoles is increasing. This is the time when it is possible to propel ever faster protons through the synchrotron. To do this it is necessary to speed the protons up by just the right amount in each revolution. RFQ cavities are synchronised in such a way that they are always presenting an accelerating electric field to the protons at just the right time when they go past.

Because the protons are travelling faster and faster after each revolution, the frequency of the RFQ needs to be increased accordingly. Just before the Dipole reaches its maximum field strength, the proton beam is kicked out of the synchrotron towards the target.

2.4.H The Extraction Kicker

Advanced

Learn how a powerful electromagnet is triggered at just the right time to extract two long pulses of protons from the synchrotron.



The Kicker is a powerful dipole magnet used to deflect the protons out of their orbital path round the synchrotron. Unlike the normal dipoles which are energised nearly all the time, and whose current is gradually increased as the protons travel faster and faster, the kicker needs to be fully energised in about 100 nanoseconds, and then switched off again! To achieve this, a large bank of capacitors is used which can be used to drive a very large current for a small time; just long enough to deflect the protons out through the extraction tube. The current needed is very large; of the order of 5000 Amps (this would require about 380 normal household fuses!).

The additional challenge is to fire the kicker at just the right time: If it is activated just before the protons arrive at the kicker, the current will not have risen sufficiently to kick them out properly, so the beam will be lost!

The kicker current is switched ON just after the protons have gone past it. In this way there is just enough time to build up the magnetic field to a maximum before the next bunch of protons arrives.

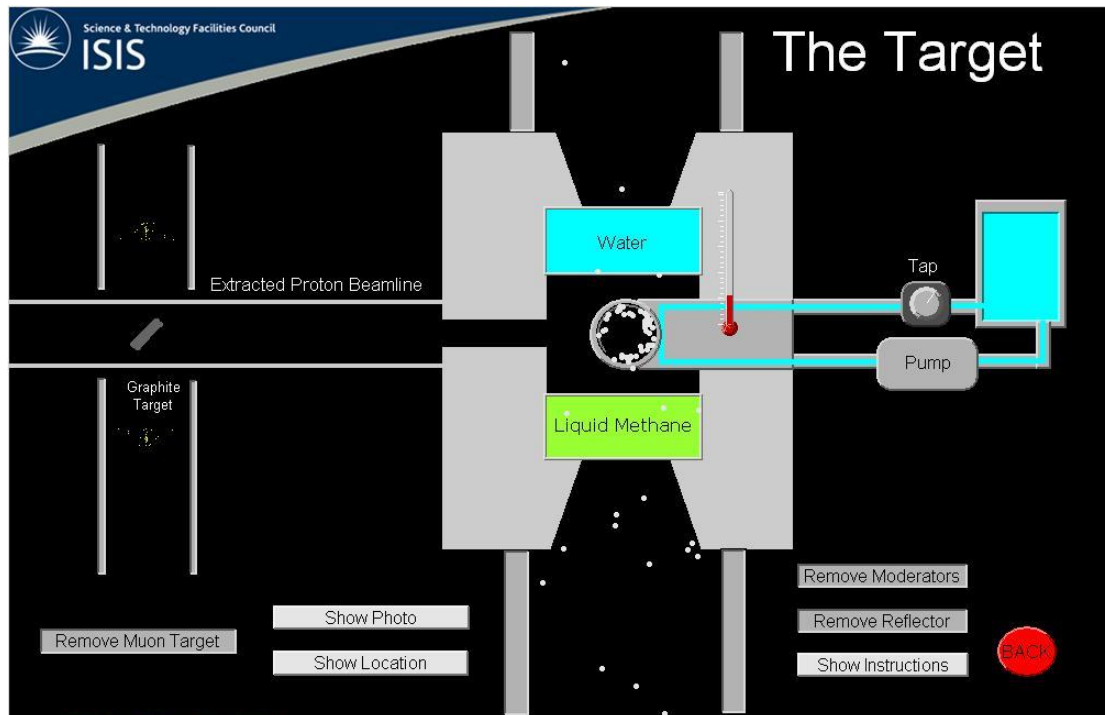
At ISIS, the kicker is carefully timed so that it extracts protons 50 times every second, but is switched completely off in between so that the protons can go round the synchrotron about 10000 times in between 'kicks'.

Some designs of pulsed power supply make use of the collapsing magnetic field (after the activation) to help re-charge the capacitors ready for the next pulse.

2.4.I The Target

Advanced

Study how a high energy collision of a proton against a dense target is used to produce neutrons, and what media are used to moderate the neutrons.



The proton beam has a mean current of 200 micro Amps (100 times less than the current through a typical LED!), however the energy of these protons is 800 MeV. Remembering (from your physics classes!) that power can be calculated by multiplying the current by the Voltage, you will see that the protons collectively carry an average power of 160 kW (enough to power around 80 electric kettles!).

Only a fraction of this energy goes into producing the neutrons, the vast majority turns to heat. Tungsten is a good material for the target because it has a high melting temperature. Nevertheless it is still essential to cool the target to remove this heat before the target melts and then vapourises!

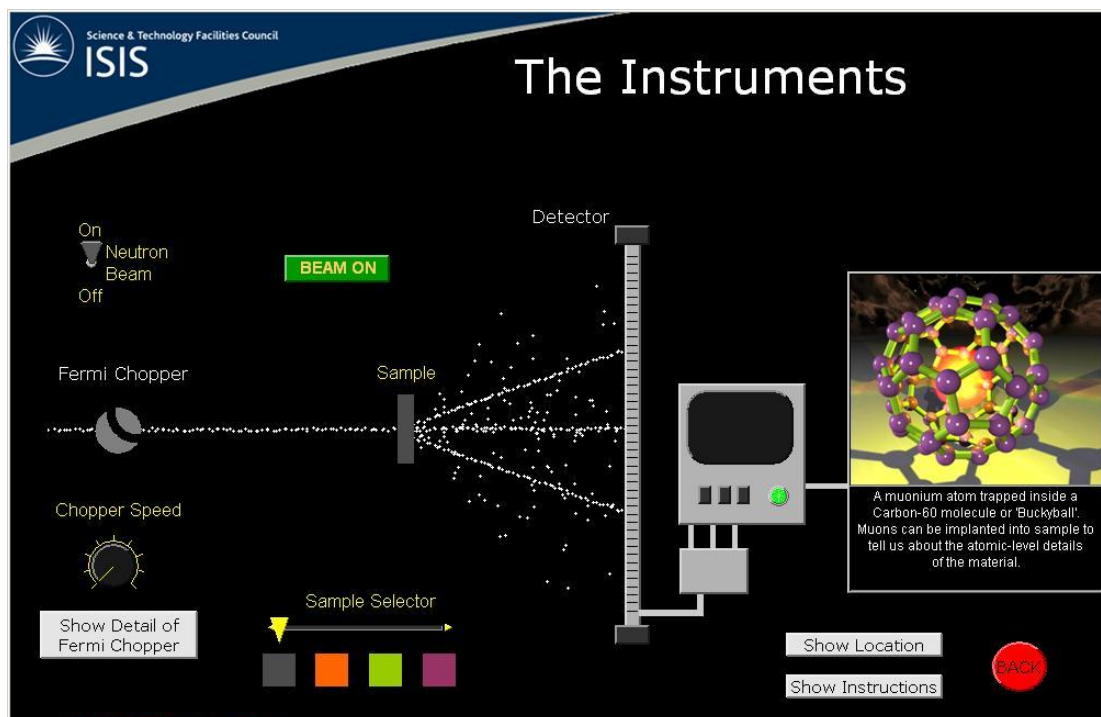
When the high energy proton hits a Tungsten atom, it can break up the nucleus into two or three pieces, each of which has more neutrons than it can accommodate stably. Therefore, very soon afterwards these new nuclei eject high energy neutrons and settle into more stable isotopes. At ISIS, each incoming proton produces on average around 15 high energy neutrons. These Neutrons spread out radially in all directions at high speeds - too fast to be useful. Ideally we want slower neutrons travelling in slightly more controlled directions. To help achieve this, the target is surrounded by a 'Reflector' with openings at either side, and by 'Moderators' to slow the neutrons down. Room temperature water, as well as gases at very low temperatures can be used as moderators.

Muons are also produced at ISIS using a 7 mm thick graphite slab orientated at 45 degrees to the proton beam. This encourages them to come out predominantly in two useful directions.

2.4.J The Instruments

Advanced

This is where the neutrons are used to probe matter and reveal high resolution details of materials.



All particles exhibit a dual nature, sometimes behaving like particles, and sometimes like waves. The effective wavelength of particles depends on their mass and their velocity. Relatively massive particles like neutrons (2000 times more massive than electrons) have much shorter wavelengths than even X rays.

The effective wavelength can be further varied by changing the speed of the neutrons. These can no longer be accelerated because they are not charged, but they can be slowed down by multiple inelastic collisions (in a "moderator") so that they lose some of their kinetic energy. Another means of selecting the velocity of the neutrons is with a "Fermi Chopper". This is a time-of-flight method where only neutrons travelling at the desired speed can make it through the chopper.

Generally it is difficult to resolve structures and features that are smaller than the wavelength being used. The short wavelength of neutrons enables us to resolve very small details, and because neutrons are not charged, it enables them to penetrate matter more easily and probe structures and properties of matter that would otherwise be impossible.

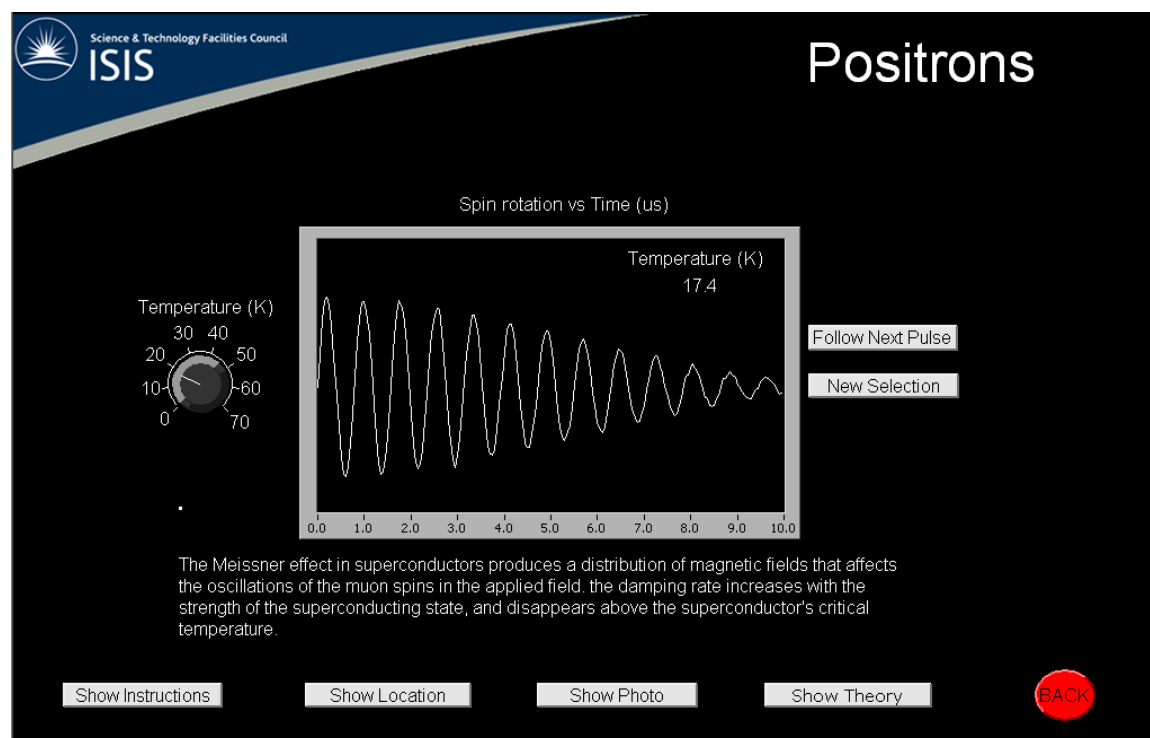
As an added bonus, the magnetic properties of neutrons make it possible to probe inter-atomic magnetic fields! The directions of the neutrons scattered by the specimen do not produce a direct image on the detector, a fair amount of computation and interpretation is needed to produce the final images displayed on the screen.

Instrument lines are equipped with a means of micro-manipulating the position and orientation of the specimens to make it possible to obtain the maximum amount of information.

2.4.K Muons

Advanced

This simulation shows how muons can be used to probe material for elemental composition as well as for mapping local magnetic fields.



When high energy protons pass through a 10mm graphite target they produce + and - pions, which decay quickly into + and - muons.

+muons have spins, their internal direction is exploited to measure magnetic fields inside materials. The muons stop inside the sample and their spins precess about any magnetic fields they experience. When the muons decay the positron emitted is most likely to travel in the direction the muon spin was pointing. By recording the directions positrons are emitted as a function of time we can build up a picture of what the muons have done in the sample, and from that infer the sample's magnetic properties.

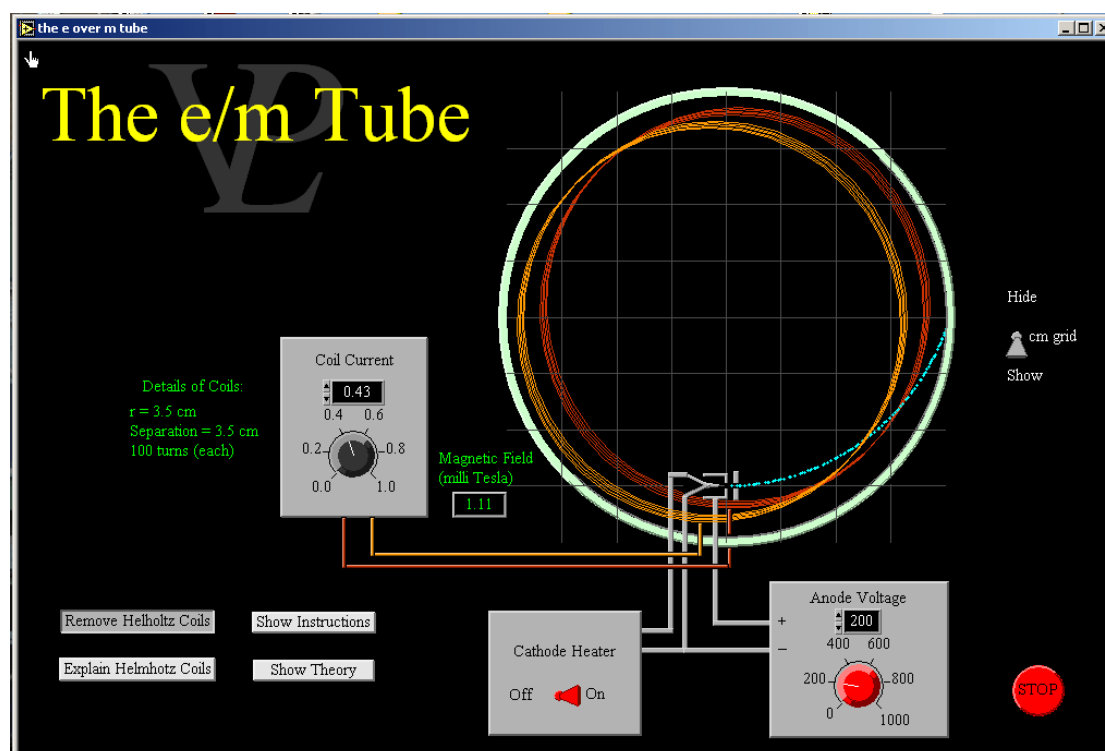
Superconductors exclude magnetic fields from their interior ('Meissner effect'). +muons are used to study how they work and to probe the field distribution inside them as a function of temperature and applied field. +muons are a standard technique for determining the properties of new superconductors.

-muons behave like heavy electrons when they are implanted into a sample and are captured by the atomic nuclei. This process produces X-rays with energies that are characteristic of the element that captured the muon. These are detected by X-ray detectors placed around the sample. Because the muons stop at random within the sample the different energies of X-rays tell us what elements are present.

2.5 The e/m Tube

Advanced

This simulation shows how Helmholtz coils can be used to cause an electron beam to follow a circular path. Measurement of the radius permits the user to calculate the ratio of the electron charge to its mass.



When electrons are made to pass through a low pressure gas they can make it glow. The shape of the glow reveals the trajectory followed by the electrons. Electric or magnetic fields deflect the electrons' trajectories.

Helmholtz coils are the name given to a pair of matching coils separated by a distance equal to their radius. This geometry is used because it produces a fairly uniform magnetic field between the two coils.

The magnetic field produces a force on the electrons which is perpendicular to the magnetic field, and also perpendicular to their velocity. This causes the electrons to follow a circular path. If the radius is small enough, a complete circle may be seen.

The velocity of the electrons can be calculated from $\frac{1}{2} m v^2 = e V$ (1) where m is the mass of the electron, e is its charge, v is its velocity and V is the anode voltage.

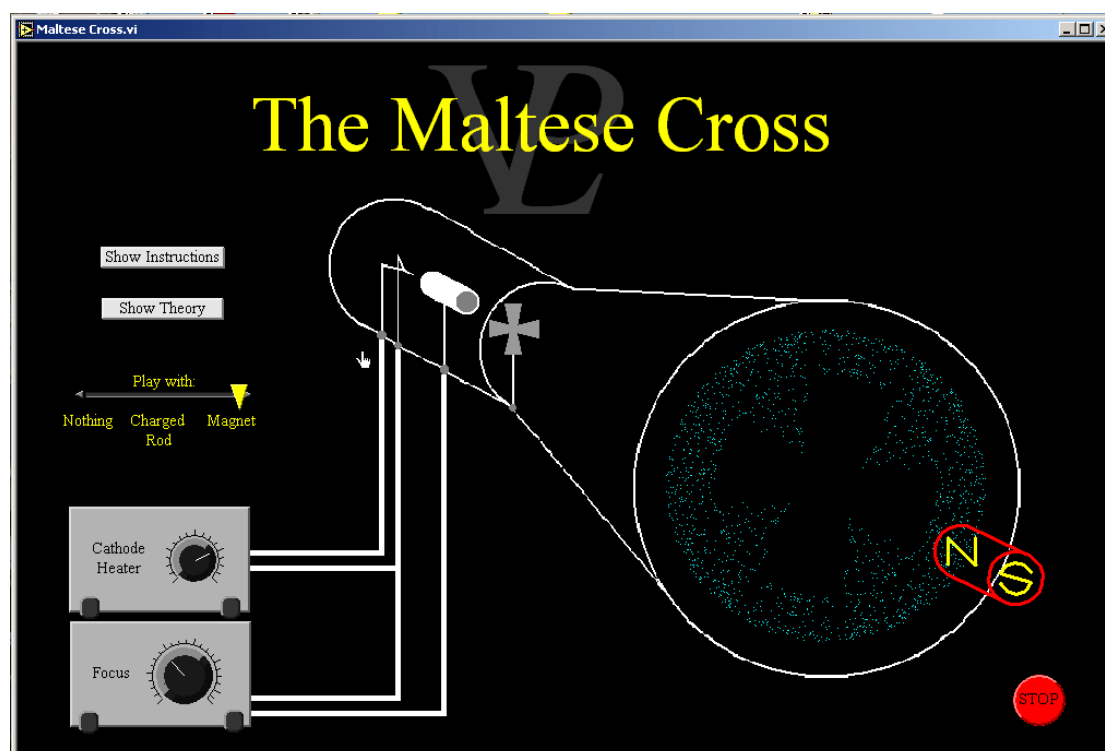
The centripetal force is given by $m v^2 / r = B e v$ (2) where B is the magnetic field strength and r is the radius of the trajectory.

Combining 1 and 2 we find the electron charge to mass ratio $\frac{e}{m} = \frac{2 \cdot V}{r^2 B^2}$

2.6 The Maltese Cross

Advanced

This simulation shows how invisible electrons seem to travel in straight lines from the cathode in such a way that a cross placed between the cathode and the screen causes a shadow to be cast. Electric charges and magnetic fields cause the shadow to move.



When sharp pieces of metal are heated up in a vacuum, 'things' seem to stream away from them and cause a scintillating screen to light up at the end of a tube.

If we place an object between the cathode and the screen, a shadow of the object is cast on the screen, just as if rays were coming from a light box!

From this we learn that these invisible rays travel in straight lines. We gave them the name 'Cathode Rays' even before we really knew what they were!

These rays are deflected by both electrostatic charge as well as by magnetic fields (in different ways). So we learned that Cathode Rays have an electromagnetic nature.

Today we know that cathode rays are actually electrons which stream away from a heated metal point by a process which we call 'Thermionic Emission'.

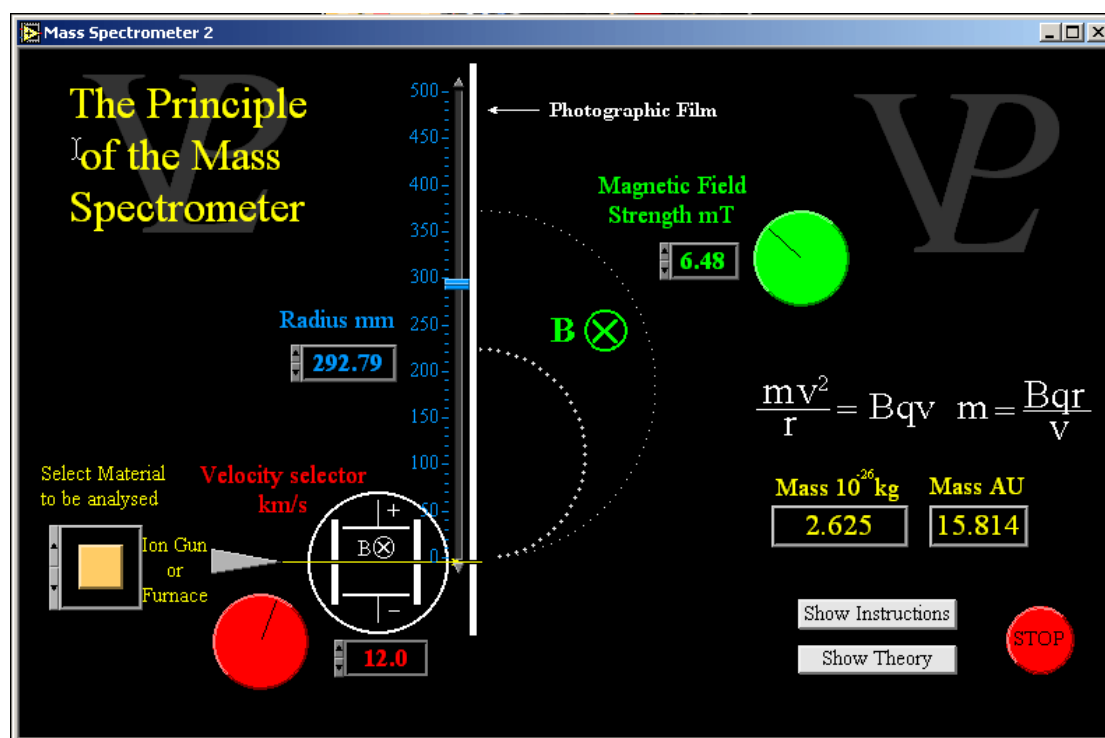
Since their discovery we have now learned to steer electron beams and we use them to draw lines on screens (in the oscilloscope), to display images (in television sets), to bombard surfaces (in electron microscopes and other scientific equipment) and to radiate electromagnetic waves (in microwave ovens).

Who would have thought such useful applications would have developed from the curious discovery of cathode rays!

2.7 Mass Spectrometer

Advanced

This simulation shows the workings of a mass spectrometer, where the mass of the ions and the magnetic field strength can be varied, thus producing circular paths of different radius.



When a charged particle travels across a magnetic field it experiences a force which follows Fleming's left hand rule. The direction of the force will be perpendicular to the magnetic field and also to the direction in which the charged particle is travelling.

When any object experiences a force which is perpendicular to its velocity it will travel in a circle with the force providing the centripetal acceleration.

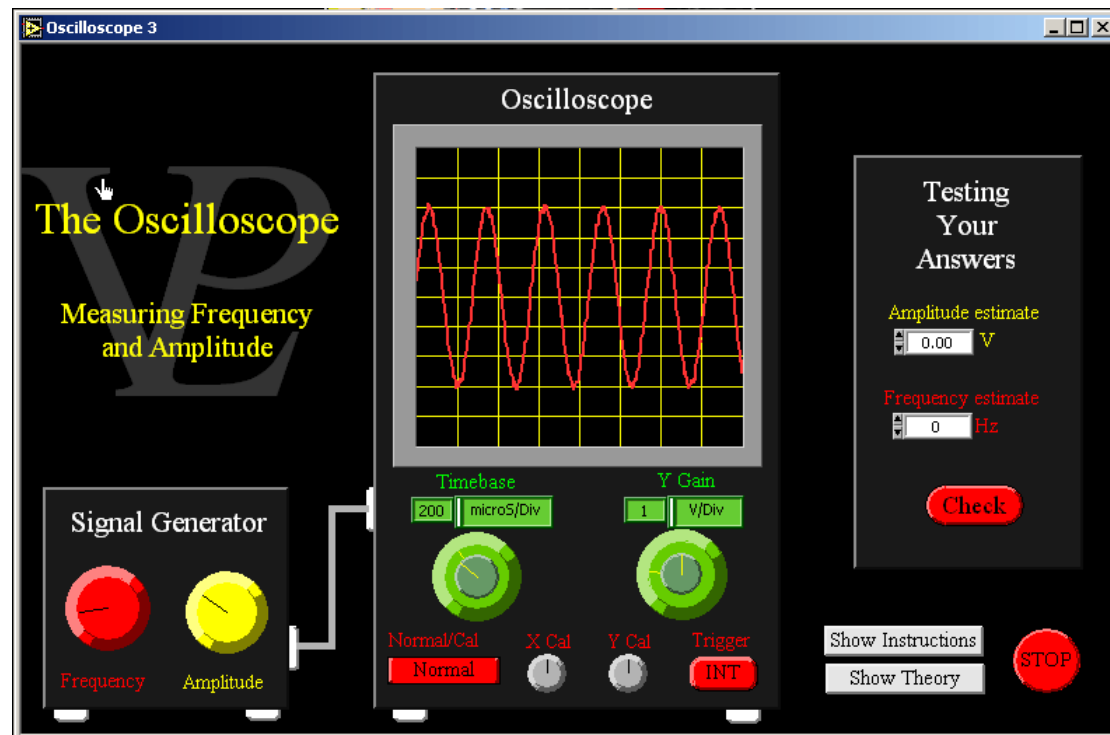
In this simulation the magnetic field (symbol B) is directed perpendicularly into the screen. The centripetal force is equal to the force due to the charge travelling through the magnetic field. Therefore $\frac{mv^2}{r} = Bqv$, where m is the mass of the particle, v is its velocity, r is the radius of its trajectory, B is the magnetic field strength and q is the electric charge on the particle. Rearranging we find that $m = \frac{Bqr}{v}$

So knowing the velocity and charge of the ion, the radius of the trajectory and the field strength it is possible to calculate the mass of the ion. This is how many isotopes were discovered.

2.8 Oscilloscope

Basic/Advanced

This simulation combines a signal generator and an oscilloscope, with variable gain and time-base so that it can be used to measure the amplitude and frequency of the signal.



The amplitude is defined as the distance between the mid point of a signal, its central axis and the maximum (or minimum). This is the same as half the peak to trough distance.

The period is the time taken to complete one cycle.

The frequency is defined as the number of cycles completed in one second. The frequency is the inverse of the period.

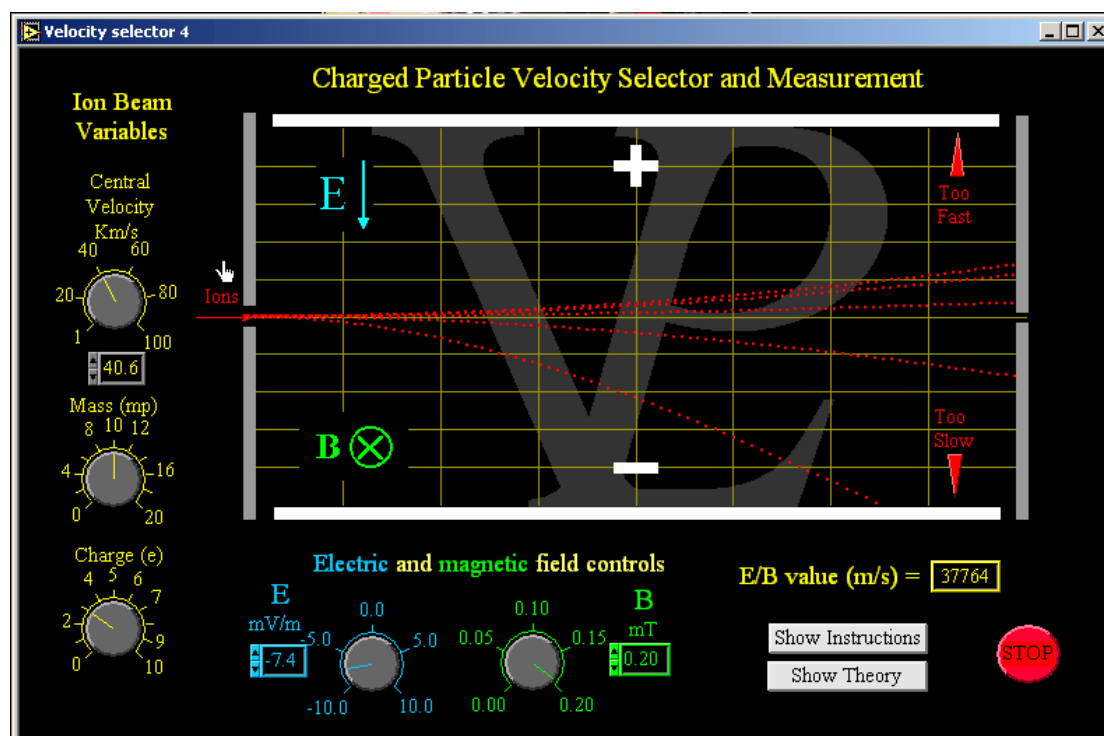
The Y gain shows how many Volts make up a division on the scale. Multiply this number by the number of divisions that make up the amplitude to get the amplitude in Volts.

The timebase shows the time taken for the beam to sweep one division horizontally. Count the number of divisions that make up one complete cycle and multiply it by the timebase to get the period of the signal. Take the inverse of the period to find the frequency of the signal.

2.9 Velocity Selector

Advanced

This simulation shows how crossed electric and magnetic fields can be used to select a charged particle with a particular velocity and exclude all other velocities.



The Ion Velocity Selector is used in order to separate ions which are travelling at one particular velocity from all the other ions which may be travelling in a range of velocities.

Left to themselves all the ions would travel in the same direction. If crossed electric and magnetic fields are applied only ions at one particular velocity will make it through the small aperture on the right hand side.

The electric force is equal to Eq , where E is the electric field strength and q is the charge on the ion.

The magnetic force is equal to Bqv , where B is the magnetic field strength, q is the charge on the ion and v is the velocity at which the ion is travelling.

When these two forces are balanced, the ions will travel in a straight line. In this case $Eq=Bqv$, so $v=E/B$.

CHAPTER 3

CIRCULAR MOTION

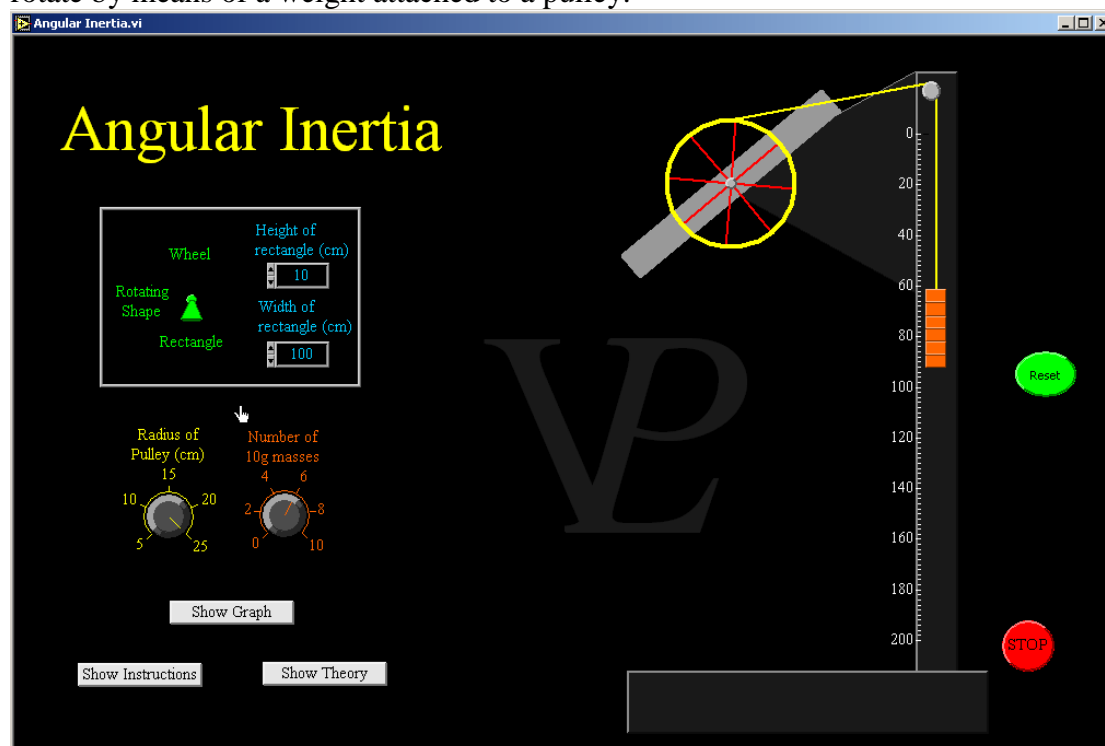


Old record players turn at constant angular velocity.
Is the tangential velocity constant too?

3.1 Angular inertia

Advanced

This simulation introduces the concept of angular inertia using a rectangular plate as well as a circular disc. The selected object, of variable dimensions is then made to rotate by means of a weight attached to a pulley.



Just as objects stay at rest or continue to move in a straight line unless an external force acts upon them (Newton's First Law), so objects also refuse to rotate, or continue rotating at constant angular velocity unless acted upon by an external torque (or couple). The property of mass which is responsible for Newton's First Law is called 'inertia', and when applied to rotational motion we call it 'angular inertia'.

The linear inertia of an object is simply its mass, but its angular inertia depends on the position of the axis about which it is going to rotate. (it is easier to swing a ruler about a central axis than around an axis which is at one end of it!).

The angular inertia I of a rigid object can be calculated by using the following equation: $I = \sum m r^2$ where m is an element of mass and r is its perpendicular distance to the axis of rotation. Once this is done, many of the equations of linear motion apply in a similar way to those of rotational motion:

Circular Motion

$$T = I \alpha$$

$$\omega_f = \omega_i + \alpha t$$

$$\theta = \omega_i t + \frac{1}{2} \alpha t^2$$

$$\omega_f^2 = \omega_i^2 + 2 \alpha \theta$$

$$\text{K.E.} = \frac{1}{2} I \omega^2$$

Linear motion

$$F = m a$$

$$v = u + a t$$

$$s = u t + \frac{1}{2} a t^2$$

$$v^2 = u^2 + 2 a s$$

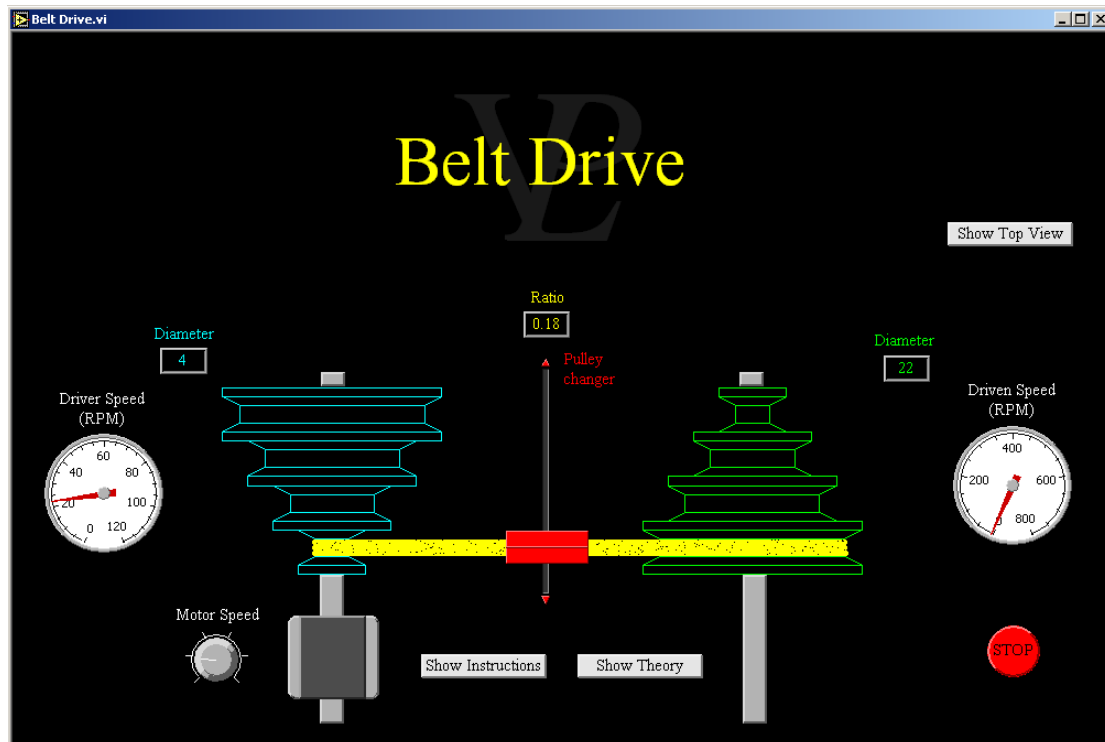
$$\text{K.E.} = \frac{1}{2} m v^2$$

Where T = torque, I = angular inertia, α = angular acceleration, ω_i = initial angular velocity, ω_f = final angular velocity, θ = angle and K.E. = kinetic energy

3.2 Belt Drive

Basic

This simulation shows how rotational speeds and torques can be interchanged by varying the radius of the pulleys being used.



The belt drive is probably one of the oldest methods of transmitting rotation from one shaft to another. It is used in a large range of systems from spinning wheels to record players. It is useful in applications where the exact angular positions of the shafts are not critical (belts generally allow a little slippage). One of the advantages of belt drives is that it reduces the amount of vibration that gets transmitted through from the driver shaft to the driven shaft.

Drive belts can be used to increase or decrease the speed (and torque) of rotating shafts. For each complete rotation of the driving pulley with diameter d , the belt will have travelled a distance of $d\pi$. This will force the driven pulley with diameter D rotate by an amount equal to $d\pi/D\pi$. Notice that the π cancels out. So the ratio of the rotational speeds is the inverse of the ratio of the diameters. $V/v = d/D$ Where the capital letters refer to the driven and the lower case letters refer to the driver.

A similar reasoning will show that the torque T of the driven is related to the torque t of the driver by $T/t = D/d$

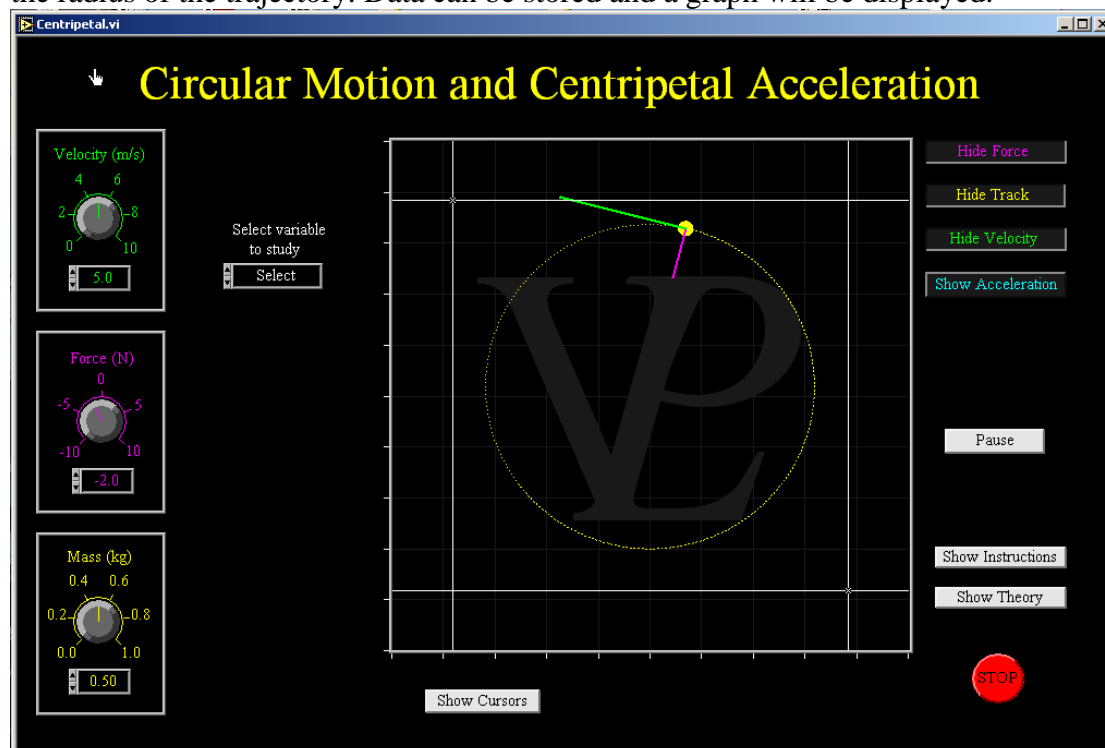
Blocks of pulleys are always arranged in opposite order of size so that the belt runs straight. Belts can tolerate small misalignments, but large misalignments lead to side thrusts and wear the belt out.

In fast speed systems it is important to install 'belt guards' so that if the belt snaps it does not cause any injury as it flies off. In applications where the angular positions of the shafts are critical (as in the crank shaft - cam-shaft of a car motor) it is possible to use toothed belts which lock in to teeth in the pulleys. These types of belts are not used in variable gearing pulley systems.

3.3 Centripetal Acceleration

Advanced

This simulation allows the user to adjust the mass and velocity of a puck and then apply a centripetal force and see how its trajectory is affected. Each of the variables can be changed during motion, and a study can be made of how each of these affects the radius of the trajectory. Data can be stored and a graph will be displayed.



Whenever an object which is travelling at constant speed is acted upon by a force which is always perpendicular to its instantaneous velocity, the motion that follows will be circular.

This force will be causing the object to accelerate (to change its velocity) but because the acceleration is always perpendicular to the velocity, it only changes the direction of the velocity, not its speed. This is an important concept. The object is continually accelerating towards the centre of the circle, but never gets any closer to it!

The force needed to keep the object travelling in a circular path is called "Centripetal Force". Its relationship to the velocity, mass and radius of trajectory is given by:

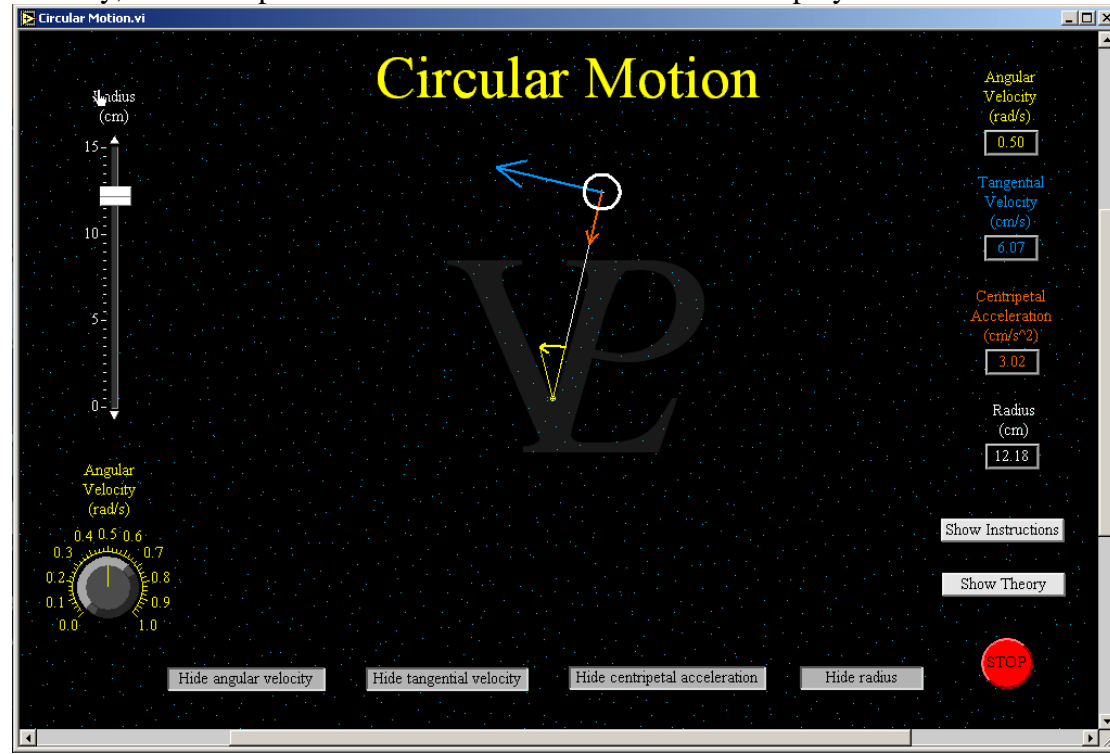
$$F = \frac{mv^2}{r}$$

The centripetal force needed to keep satellites in orbit is provided by gravitational attraction to the Earth. When planets travel in such a way that their velocity is not always perfectly perpendicular to the gravitational attraction to the Sun, the orbits are not circular but elliptical; neither the velocity nor the radius is constant.

3.4 Circular Motion

Basic/Advanced

This simulation introduces the concept of circular motion, tangential velocity, angular velocity, and centripetal acceleration. Vectors of each are displayed.



There is some new terminology associated with circular motion. This simulation simply aims to illustrate what these terms mean.

Angular velocity is the rate of change of the angle subtended by the position of the object and the zero degrees (or radians). It is normally given the Greek symbol ω (Omega). For reasons that will become clear a little further on, the preferred units for angular velocity are radians per second (and not degrees per second).

The tangential velocity is the instantaneous velocity of the object a straight line. If the angular velocity is given in radians per second, the tangential velocity is simply $v = \omega r$ (the angular velocity multiplied by the radius). However, if the angular velocity was given in degrees per second, the tangential velocity is calculated as $v = \omega \pi r / 180$. (Now you can see why it is easier to use radians!)

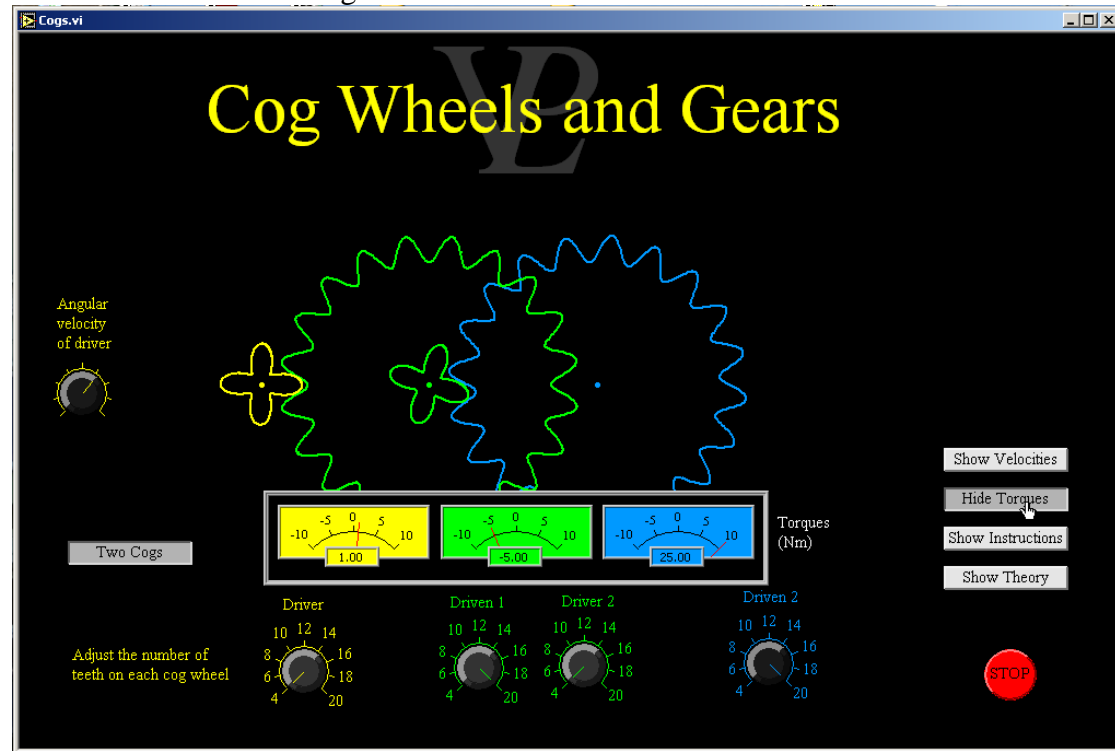
Centripetal acceleration is the rate of change of the tangential velocity. Notice that although the magnitude of the tangential velocity is not changing, its direction is changing, and this constitutes an acceleration. The centripetal acceleration is numerically equal to the square of the angular velocity multiplied by the radius.

$a_c = v^2/r = \omega^2 r$. The units of centripetal acceleration are ms^{-2}

3.5 Cogs

Basic/Advanced

This simulation shows a system of two or four meshing cog wheels and shows how the ratios of the angular velocities and of the torques depend on the ratio of the number of teeth on the cogs.



Cog wheels are used inside many machines from engines to clocks. Their purpose is to increase or decrease the angular velocity of the driven wheels. For cogs to engage or mesh properly they must have teeth of equal sizes.

The ratio of the angular velocities of two meshing cog wheels is inversely proportional to the ratio of their number of teeth.

$$\frac{V_1}{V} = \frac{N_2}{N_1}$$

A consequence of changing the angular velocity is that the torque also changes. As a rule, when the angular velocity of the driven cog is greater, its torque is smaller. The ratio of the torques is directly proportional to the ratio of the number of teeth.

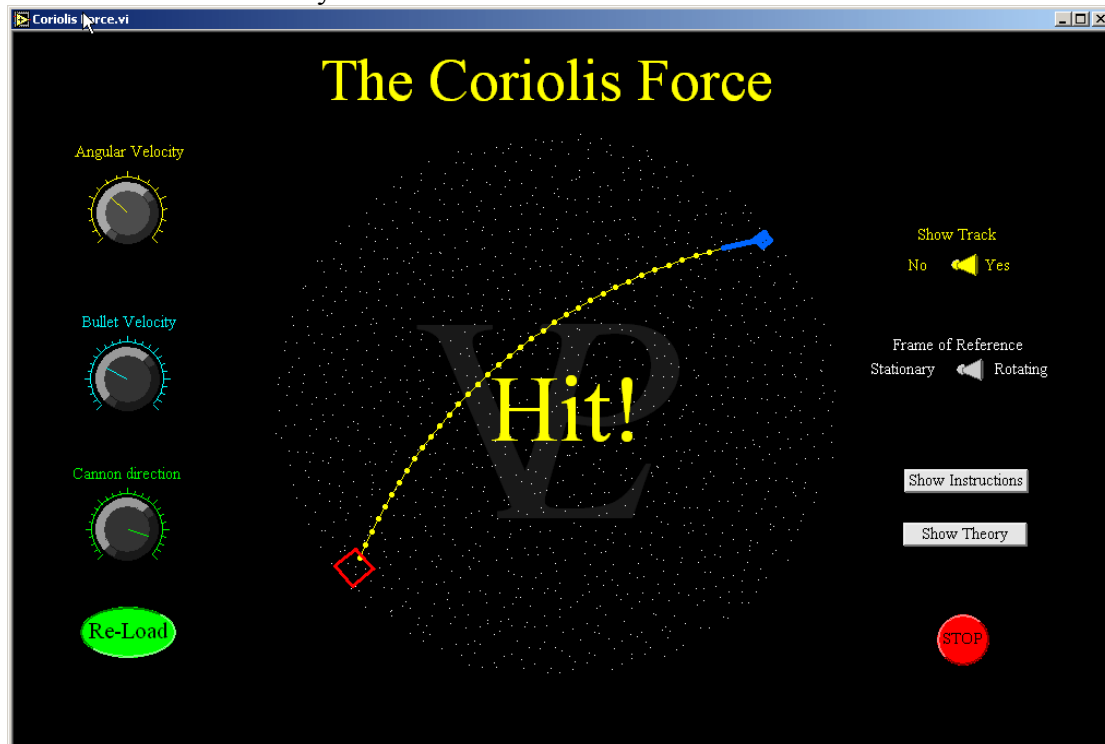
$$\frac{T_1}{T} = \frac{N_1}{N_2}$$

When there is a train of cogs all driven by the first one, the velocity and torque of the final one can be calculated from the product of the ratios of the meshing cogs.

3.6 Coriolis Force

Advanced

This simulation shows how unexpected things happen when an observer is sitting in a rotating frame of reference. Newton's first law of motion no longer appears to hold true! Select the 'bird's eye' view to see that Newton's first law is not broken!



The strange behaviour of objects moving relative to a rotating frame of reference was studied by Gaspard-Gustave Coriolis in 1835. The 'Coriolis Force' is a pseudo-force (not real), but it appears real to an observer that is travelling in a rotating frame of reference (like we are on Earth). The effect is most noticeable closer to the North and South poles, and is responsible for the way in which tornadoes and other large-scale movements of masses rotate.

The centripetal force is experienced even when an object is 'stationary' in a rotating frame of reference. The Coriolis force is only experienced when an object is moving relative to a rotating frame of reference.

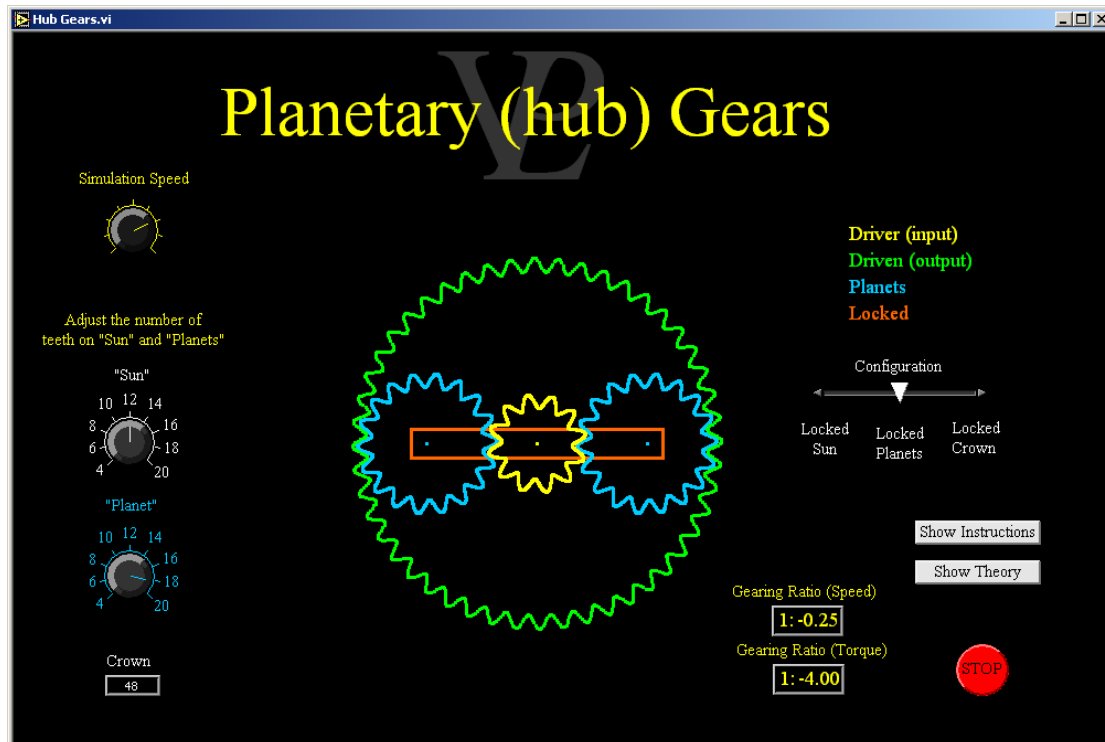
You can feel this strange force if you hold a heavy book in one hand and try to move it towards - and away - from your face continually while sitting on a revolving office chair! (you will feel the centripetal force acting radially even when your arm is stationary, but when your arm starts moving you will also feel a strange tangential force!)

For a fuller explanation and a derivation of the equation, please consult a text book. Only a superficial explanation is given here. The expression for the Coriolis force F_c is given by $F_c = -m 2\omega \otimes v$ where ω = angular velocity, v is the velocity, m is the mass and \otimes is the vector cross product, but if you don't know what that is, don't worry!

3.7 Hub Gears

Advanced

Hub gears are quite difficult to visualise. This simulation was produced to enable students to see the internal workings inside a Sturmey-Archer hub.



Planetary gear systems are quite difficult to understand! First some terminology:

The "sun" is the cog which is in the middle

The "planets" are the cogs that rotate around the sun

The "crown" is the outer cog.

The planets are held in place by a planetary carrier.

The size of the crown (and the number of teeth on it) is determined by the size of the sun and planets. The relationship is given by $N_{\text{crown}} = N_{\text{sun}} + 2 \times N_{\text{planet}}$

In addition to this, there are different ways in which hub gears can be operated! It is possible to lock the sun, the planetary carrier, or the crown, and drive one of the remaining two; using the other as the output.

The gearing ratio here is defined as the angular speed of the output divided by the angular speed of the input. The torque ratio is the inverse of the speed ratio.

With the sun locked, and driving the planetary carrier, the gear ratio is given by $R = 1 + (N_{\text{sun}} / N_{\text{crown}})$

With the planetary carrier locked, and driving the sun, the gear ratio is given by $R = -N_{\text{sun}} / N_{\text{crown}}$. (reverse!)

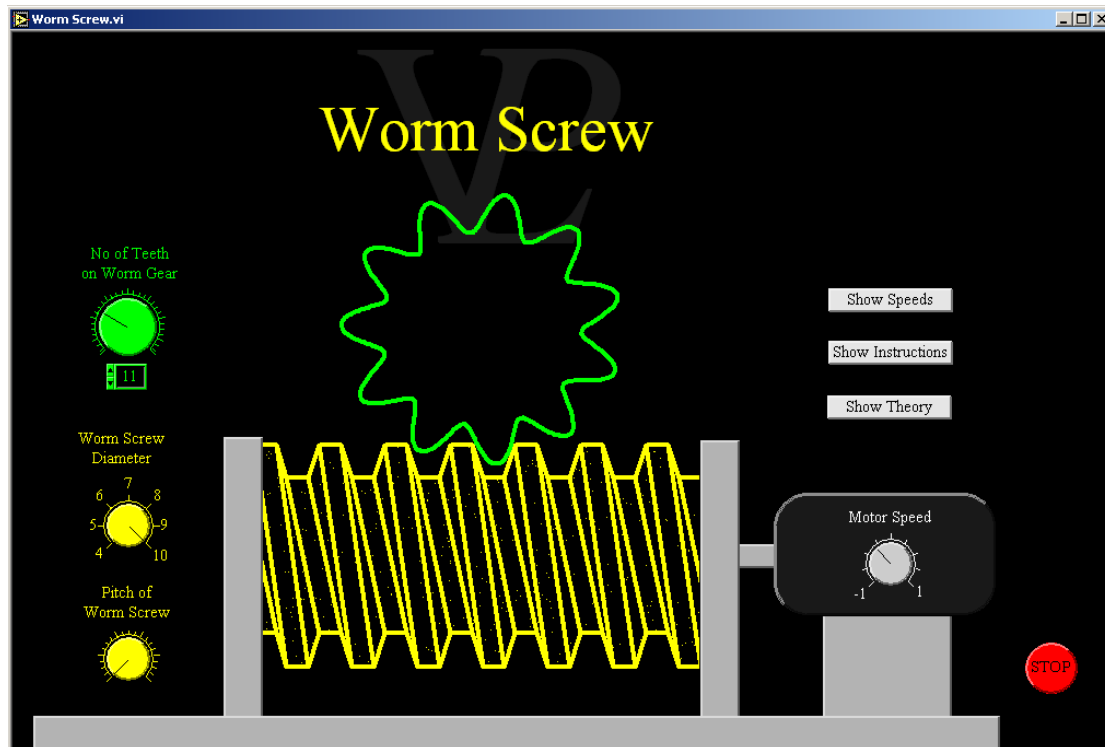
With the crown locked, and driving the sun, the gear ratio is given by $R = N_{\text{sun}} / N_{\text{crown}}$

It may seem that the number of teeth on the planets has no effect, but remember that the number of the teeth on the crown is partly dependent on the number of teeth on the planets!

3.8 Worm Screw

Advanced

This simulation was produced to complete the series of simulations on transmission of rotational motion.



Worm Screws are used whenever a very large gear reduction is needed. Typical examples are a crane or a winch. The gearing ratio is always the number of the teeth on the worm gear to 1, regardless of the diameter or pitch of the worm screw.

They are generally not very energy efficient as they have a significant amount of friction, but they make it possible to generate a very large torque from a fairly small motor.

Unlike many other gear systems, the worm screw cannot be driven backwards (trying to force the worm gear round will not cause the worm screw to rotate). For this reason this system is often used where a natural break is wanted. A typical example of this is application is the tuning pegs in a guitar; the tension in the string does not drive the worm screws round. The friction present in the worm Screw is enough to 'lock' the system.

CHAPTER 4

COMMUNICATIONS

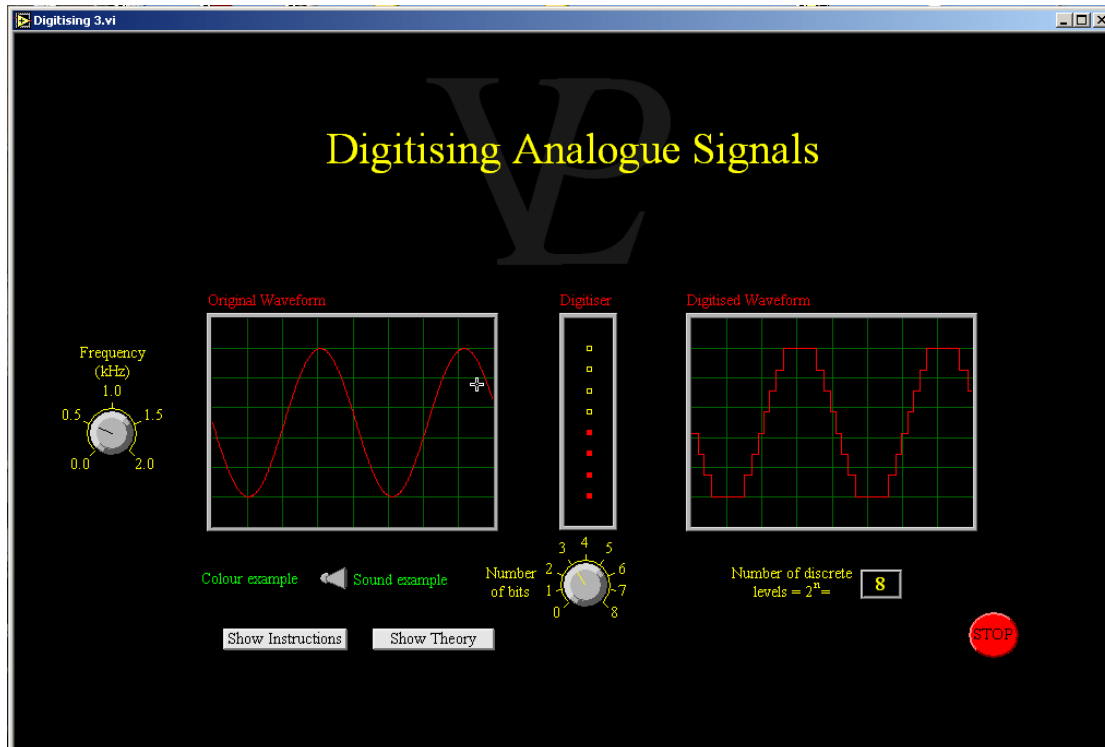


**Mobile phones and short-wave radios,
What do their waves look like?**

4.1 Digitising

Advanced

This simulation shows what digitisation is, and how it affects a signal, a colour level, and a sound signal. The number of bits can be varied by the user.



Digitising is the process of converting a continuously varying quantity into discrete integers. Provided enough integers are available in the digitiser, the quality of the quantity variation does not suffer significantly.

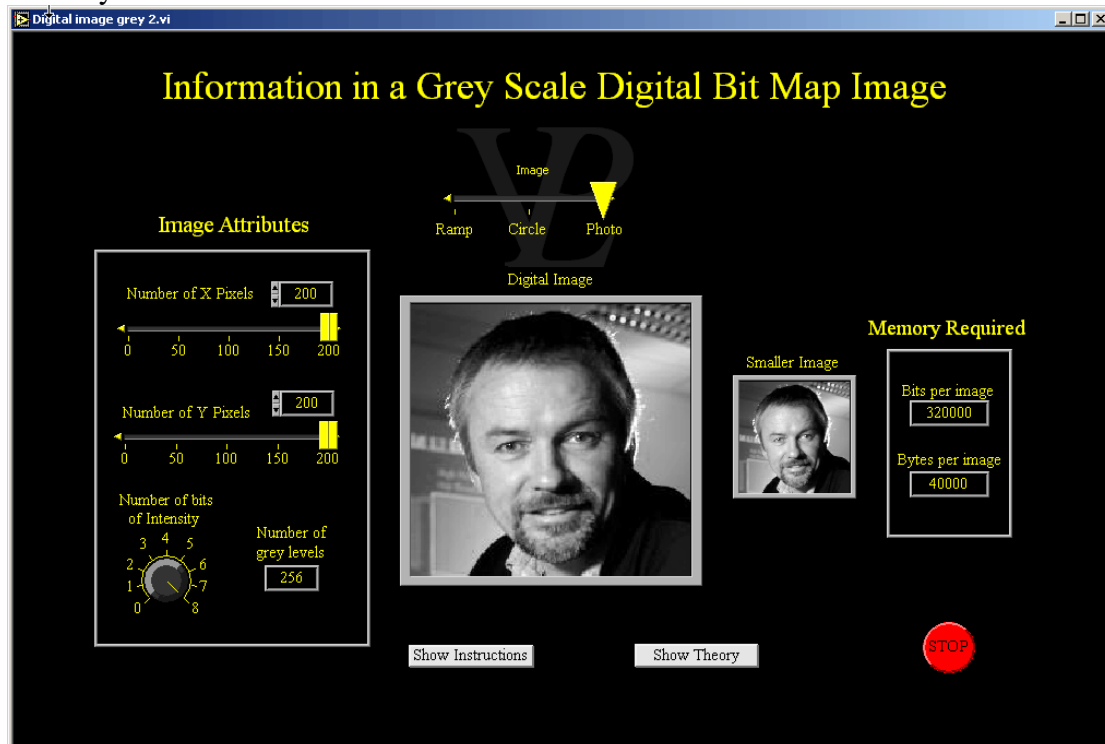
With my laptop computer, in the sound wave case, digitisation higher than 4 bit offered little improvement to what I could hear although laptops do not have the best speakers or sound cards. (Maybe it is just my computer that is old!)

In the case of the colour ramp, 6 bit digitisation is as good as my computer monitor could display. Perhaps your monitor is better than mine.

4.2 Digital Image Grey

Advanced

This simulation shows the relationship between image quality and the number of grey levels and the number of pixels used. It also shows the number of bits and bytes of memory used.



A large amount of information is required to make a digital picture. Firstly there is the number of pixels required. A reasonably sharp medium size picture needs at least 800 by 600 pixels (480,000 elements). The maximum this simulation permits is 200 x 200.

In addition to that, it is necessary to store the intensity value that represents each pixel. If the image is simply pure white and pure black, these can be represented with 0 or 1. If there are grey levels which need to be reproduced, then more 'bits' of information need to be stored.

- 1 bit stores 2 grey levels (black or white)
- 2 bits store 4 grey levels
- 3 bits store 8 grey levels
- 4 bits store 16 grey levels
- n bits store 2^n grey levels.

The total number of bits needed can be calculated as follows:

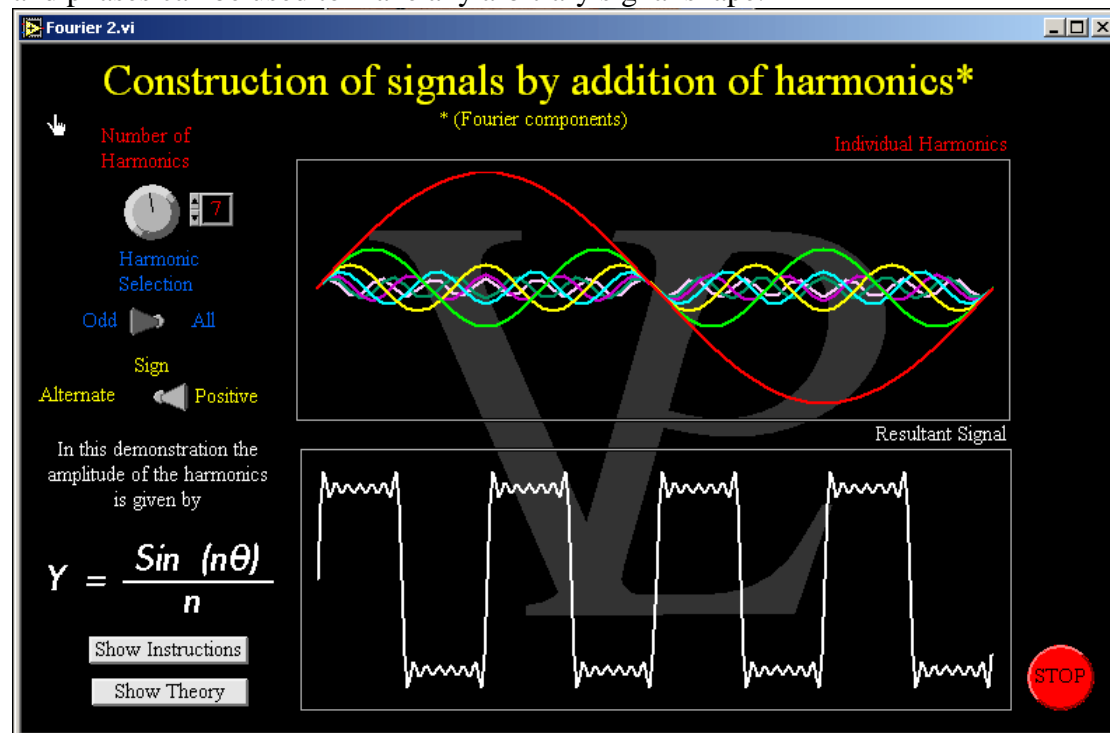
Total bits = X pixels x Y pixels x No of intensity bits.

Colour images require three times more memory because an intensity number needs to be stored for each of the three primary colours! A byte is equal to 8 bits. You can see how a good quality colour picture quickly uses up Mega bytes of storage!

Clever image compression methods make it possible to lump some pixels of the same colour together, and so reduce the amount of information which actually needs to be stored.

4.3 Fourier Components Advanced

This simulation shows how sinusoidal signals with different amplitudes, frequencies and phases can be used to make any arbitrary signal shape.



Fourier theory tells us that it is possible to make up any repeating signal shape by a suitable choice of sinusoids with different amplitudes. You will only need to study this properly in more detail at university level.

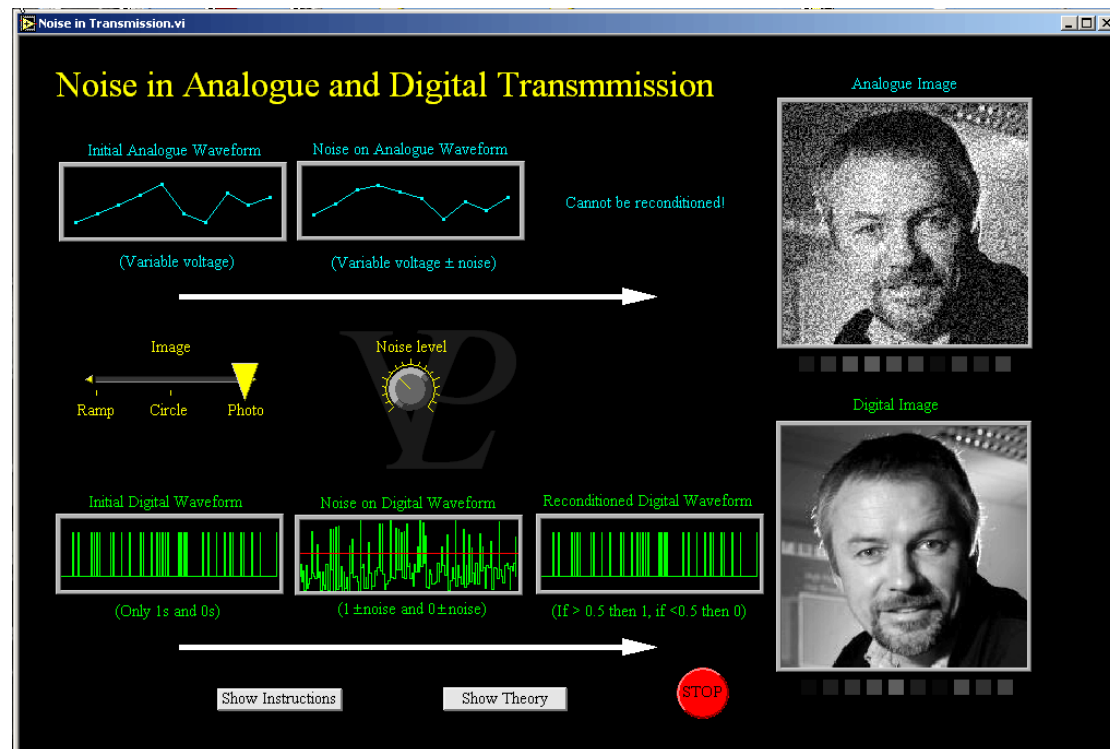
The examples shown are just a small subset to help visualise how this may be possible.

The different waves that are used to make up the overall waveform are called Fourier components.

4.4 Noise in Transmission

Advanced

This simulation shows how noise affects the quality of the signal received at the other end of a cable. It shows the improvement in noise suppression that can be achieved using digital transmission.



Noise is a fundamental problem in the transmission of signals. Random electrical fluctuations and interference from other sources introduce noise to the original signal and so distort what arrives at the other end the cable.

Analogue signals can have any value between zero and a maximum, so if they become distorted the receiver has no way of knowing what the original levels were. The noise cannot be corrected so audio signals will have 'crackle' on them, and video signals will have 'snow' on them.

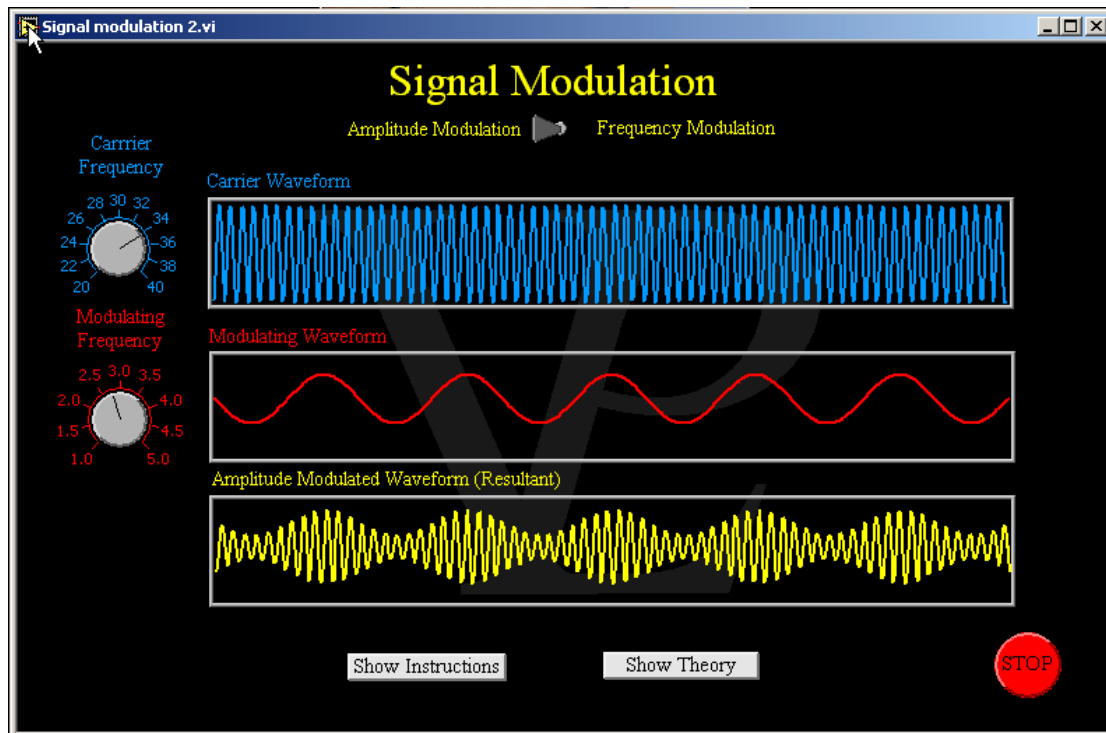
When digital signals are used, the values can only be highs and lows (1 or 0). When noise gets added to them, the receiver can recondition the signals by triggering at the mid point between the high and the low; anything less than say 0.5 is made back to a 0, and anything greater than 0.5 is made back into a 1. This gives clear audio signals and sharp images free from interference.

The noise level can become quite large (nearly 50% of the used range) before it starts to damage digital signals beyond recovery. When this limit is exceeded, the reconditioned digital signal will have errors in it, and the audio and video signals will be corrupted.

4.5 Signal Modulation

Advanced

This simulation shows the difference between amplitude modulation (AM) and frequency modulation (FM). The modulation frequencies can be changed by the user.



In the case of amplitude modulation (AM Radio), the amplitude of a carrier signal is adjusted (modulated) by the signal we wish to transmit (music, data etc) and the frequency of the carrier is left unchanged.

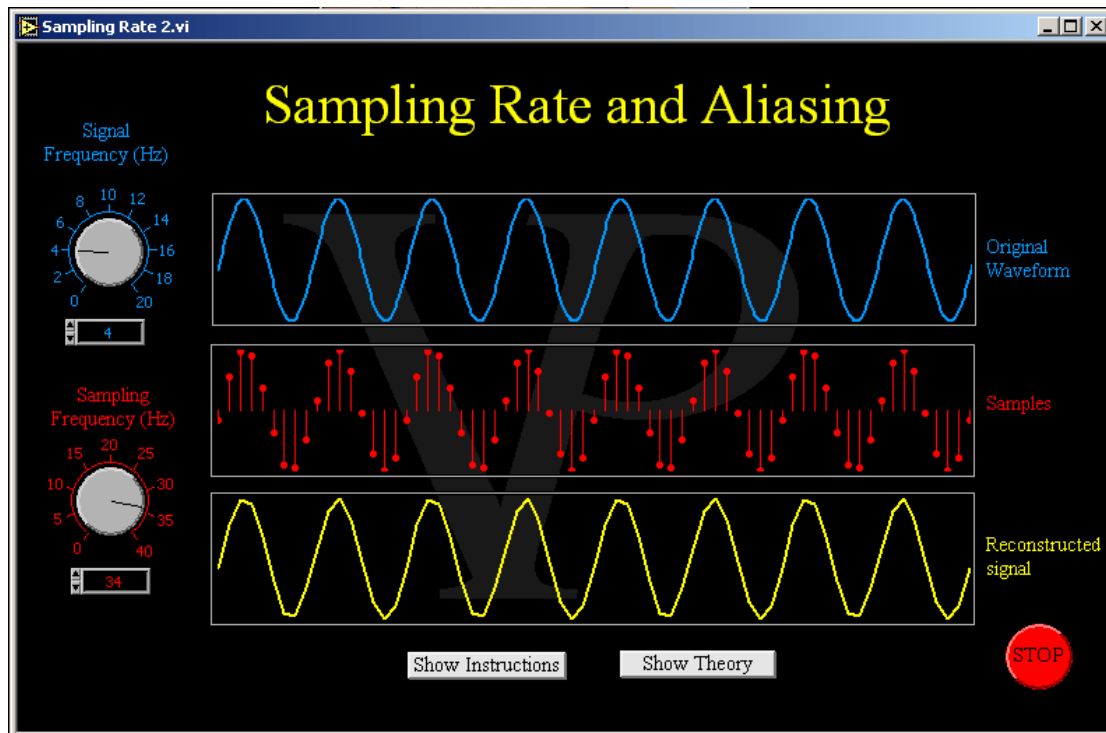
In the case of frequency modulation (FM Radio), the frequency of the carrier is modulated by the signal we wish to transmit, and the amplitude of the carrier is left unchanged.

In this simulation, the transmitted signal is simply a single note - very boring. In real transmissions, the amplitude (in AM transmission) and the frequency (in FM transmission) are changing all the time to accommodate for all the frequencies of the music you are trying to listen to.

4.6 Sampling Rate

Advanced

This simulation shows the effect that the sampling frequency has upon the reconstructed signal. It also shows how insufficient sampling can lead to aliasing.



F_o is the frequency of the signal we wish to transmit, and F_s is the sampling frequency.

If $F_s \gg F_o$: the reconstructed signal will be of good quality.

If $F_s < F_o$: the reconstructed signal will have a totally different frequency from F_o .

It has taken on a new frequency. We call this aliasing.

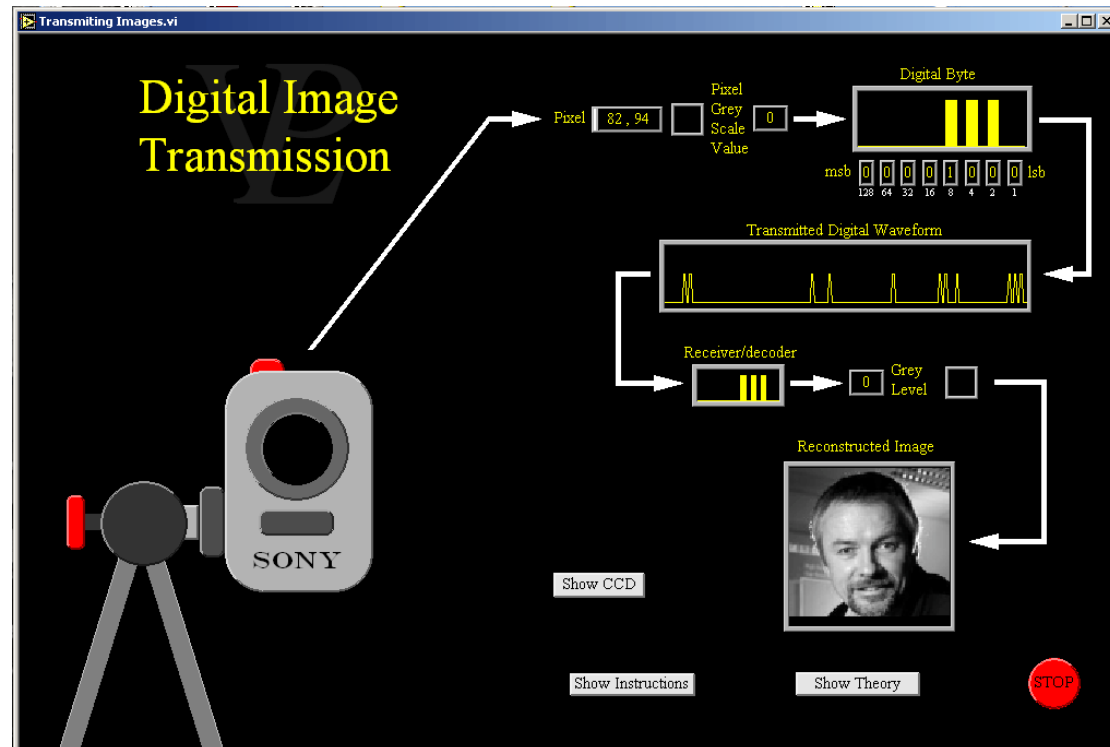
To guarantee adequate reproduction of the original signal we must ensure that $F_s > 2F_o$.

In practice you want to sample well above $2F_o$ if you want a reasonable signal.

4.7 Transmitting Images

Advanced

This simulation shows how the intensity level recorded on a CCD array must be digitised and then transmitted in order to re-construct the image at the far end of the cable.



In order to transmit a digital image it is first necessary to convert the grey levels recorded on each of the pixels into bytes with an analogue to digital converter.

Notice that digital transmission is achieved through use of high and low pulses (1s and 0s). These are then sent electrically down a wire, or broadcast through an aerial.

The receiver then needs to convert the pulses back into a number representing the grey level of each pixel before displaying it on the monitor.

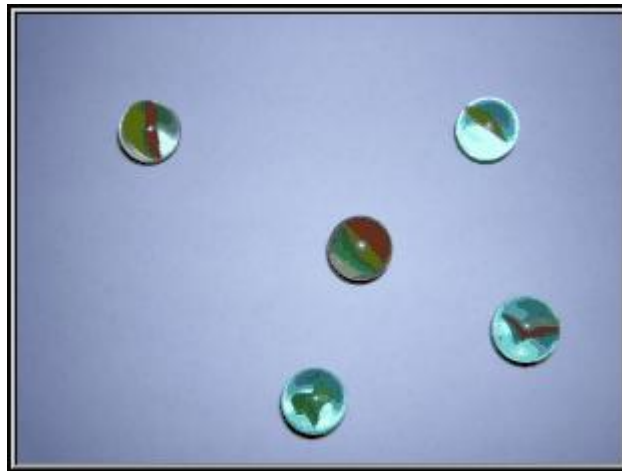
In order to know which pixel to allocate the intensity to, the transmitter also sends some special code at the beginning of each frame (so that the receiver knows that the pixel that follows is the top left hand pixel), and also adds a special code at the end of each line of pixels (so that the receiver knows when it is time to move on to the next line of pixels).

In practice the transmission of digital images is more complicated than this! This simulation simply illustrates how the basics work. Different networks use slightly different encoding algorithms.

One thing should be clear from all of this: transmitting images rapidly requires very fast conversion, because there is a lot of information to get across in a very short time! Normal televisions display something like 25 fresh images every second. This is a considerable technical achievement, but now we just take it for granted!

CHAPTER 5

DYNAMICS

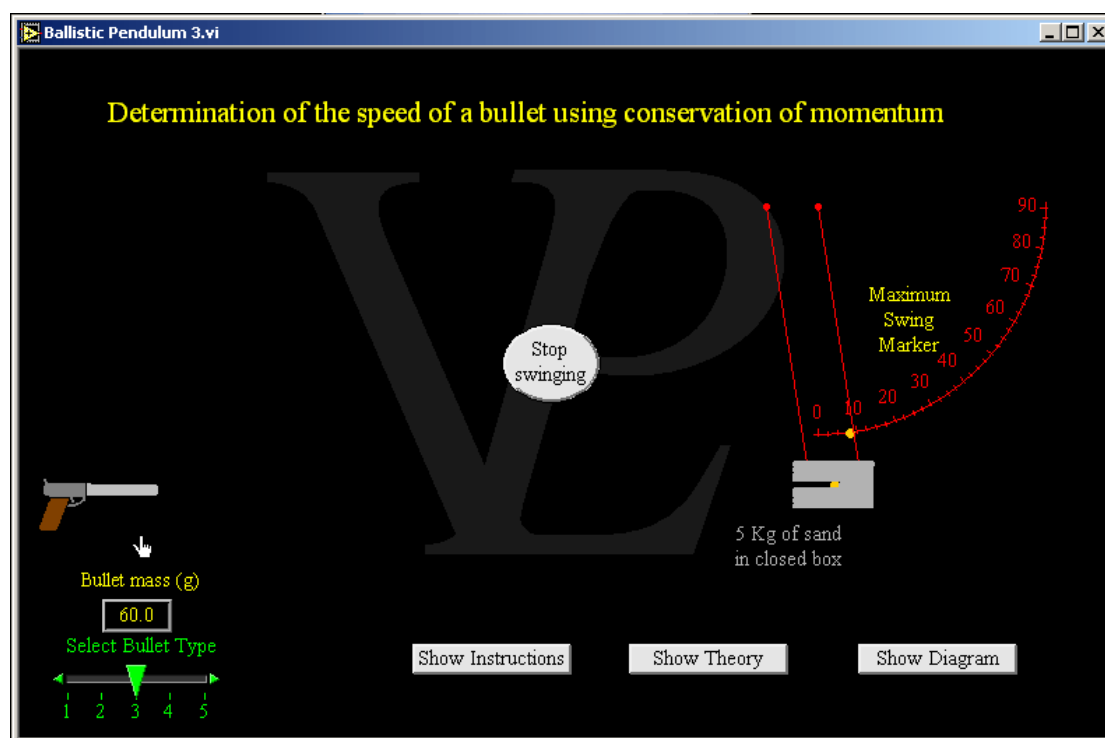


Marbles are nearly out of fashion now.
What do they have to do with dynamics?

5.1 Bullet Speed

Advanced

Calculate the speed of a bullet! From the maximum angle of swing it is possible to determine the speed of the bullet that struck it. It is a study on conservation of momentum (at the collision) and conservation of energy (during the swing).



The collision between a bullet and a sand-bag is inelastic. By this we mean that energy is not conserved. However, momentum is always conserved, so we can know that the momentum of the sandbag and embedded bullet immediately after the collision must be the same as the initial momentum of the bullet.

We say $mv = (M+m) V$, where m = mass of bullet, M = Mass of sand
 v = velocity of bullet (to be found), V = Velocity of sand and bullet
 rearranging we get $v = ((m+M)/m)V$ (1)

We can work out the final velocity V by looking to see how far up it swings. In this part of the motion energy is conserved, although it will lose it gradually after many swings. So we say $\frac{1}{2}(M+m) V^2 = (M+m) g h$. The masses cancel out reducing the equation to $V = (2 g h)^{1/2}$ (2)

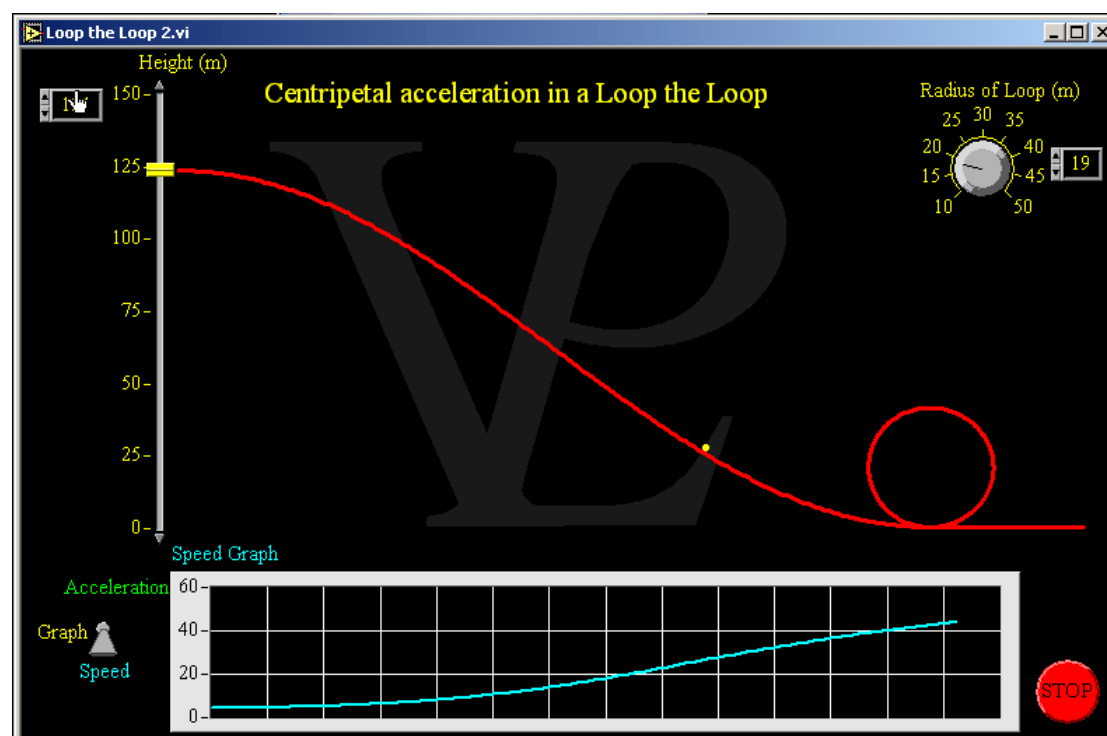
h can be calculated from knowing the maximum angle, θ through which the strings swing. $h = r (1 - \cos \theta)$ (3) where r = radius of swing (given as 1 m).

By using equations 1, 2 and 3 it is possible to calculate the speed of the bullet. It is a bit complicated, I know, but compared to the alternatives it can work very well.

5.2 Loop the Loop

Advanced

In this simulation a variable Loop the Loop ride is being tried out. The shuttle runs down a slope powered only by gravity. Get a wrong combination for height and radius and the trolley falls off the rails killing the occupants!



Centripetal acceleration is given by the equation $a = v^2 / r$ (1)

You need to make sure $a > g$ at the top of the loop, or else gravity will pull the shuttle off the track. So v^2 must be $> r g$ (2)

The easiest way to work it out is to make use of the kinetic energy equation since that also has a v^2 in it.

At the top of the loop: $KE = PE$ lost

(note that it has fallen by h , but it has climbed again by $2r$)

so $\frac{1}{2}mv^2 = mg(h-2r)$. The mass m cancels out so $v^2 = 2g(h-2r)$ (3)

From (2) & (3) we deduce that $2g(h-2r) > rg$. Notice that gravity g cancels out.

So $2h > 5r$ or $h > 2.5 r$

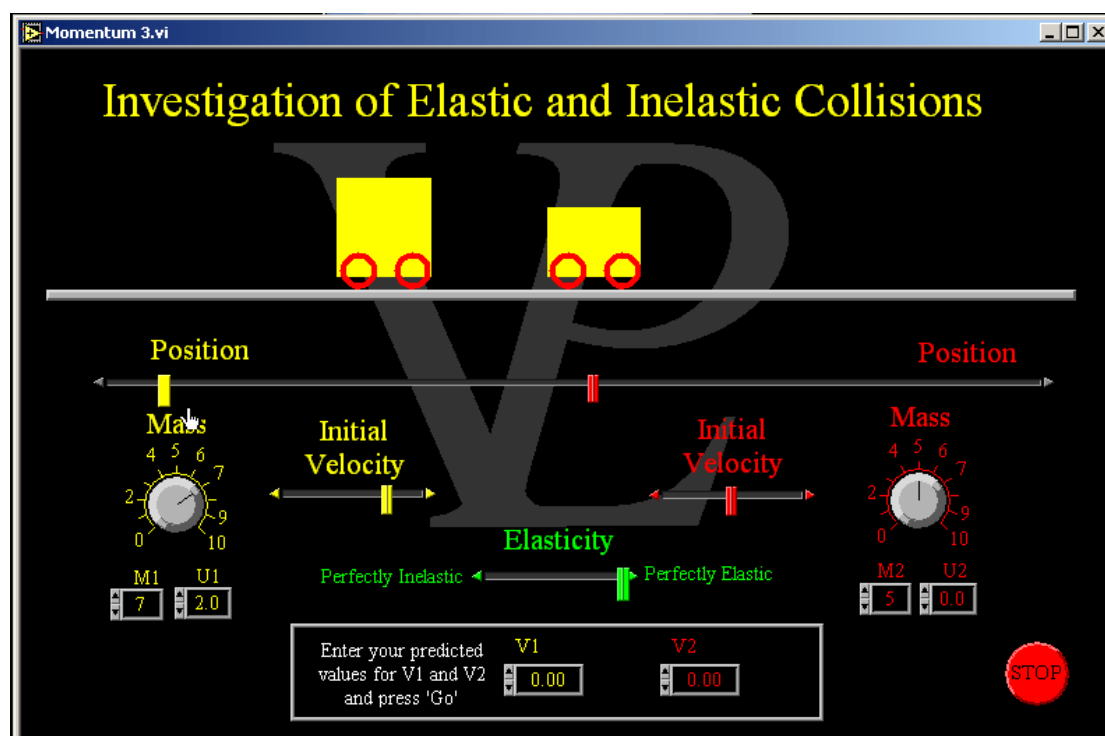
As long as h is more than $2.5 r$ the shuttle should stay on the track.

NB: In real life air and track friction would play a very significant role.

5.3 Momentum

Advanced

In this simulation trolleys of variable mass are made to collide with each other. Investigate elastic and inelastic collisions. Predict the final velocities of the trolleys and see if you get them right!



Momentum is defined as the product of the mass and the velocity of an object. The special thing about momentum is that it is a quantity which is always conserved unless outside forces are acting upon a system. So in a collision between two objects we can say Initial momentum = Final Momentum.

Or expressed as an equation $(M_1 U_1) + (M_2 U_2) = (M_1 V_1) + (M_2 V_2)$ (1)

On the other hand kinetic energy may or may not be conserved. We speak of two types of collision:

1 - Elastic collisions in which all the kinetic energy is conserved. It may be passed from one body to another, but it is not lost.

2 - Inelastic collisions, where not all the kinetic energy is conserved. That does not mean that it is all lost, but just that it is not all conserved.

For an elastic collision we say K.E. before collision = K.E. After collision.

Or in equation form $(\frac{1}{2} M_1 U_1^2) + (\frac{1}{2} M_2 U_2^2) = (\frac{1}{2} M_1 V_1^2) + (\frac{1}{2} M_2 V_2^2)$ (2)

If we combine equations (1) and (2), we can obtain a more useful result which tells us that for an elastic collision,

relative velocity of approach = - (the relative velocity of separation)

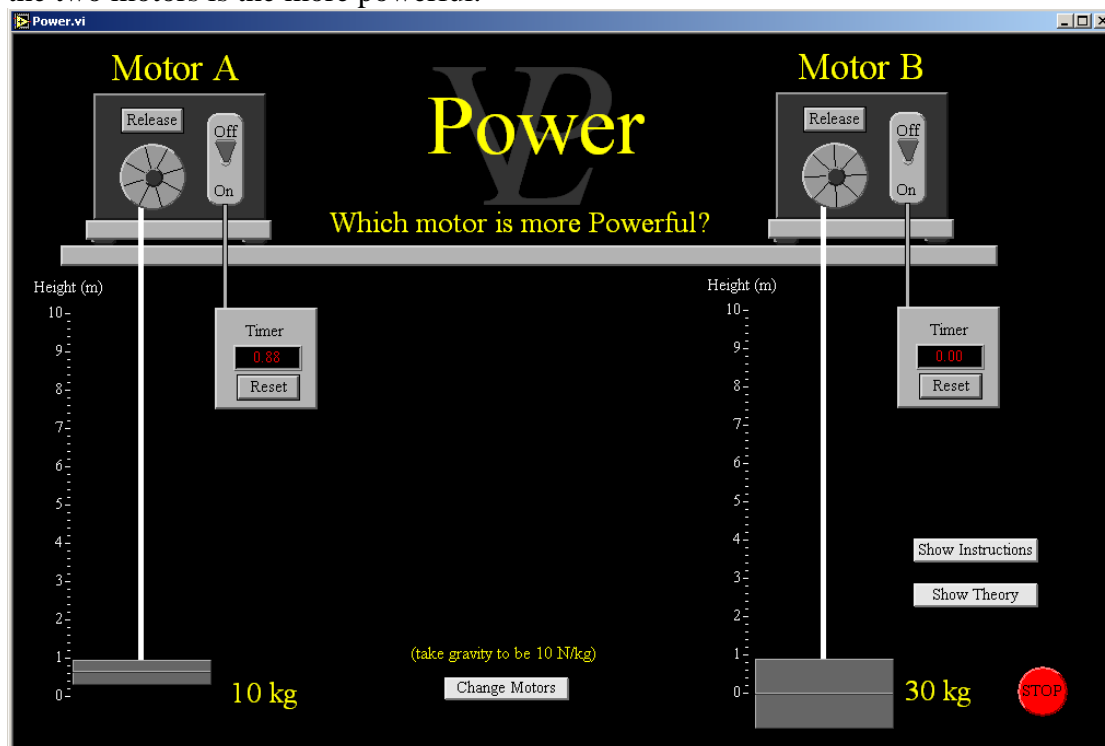
Or in equation form $U_1 - U_2 = -(V_1 - V_2)$ (3)

This result is very useful, because it allows us to work out if a collision was elastic or not. If the relative velocities before and after the collision don't match, it was not an elastic collision (energy was lost).

5.4 Power

Basic

This simulation illustrates the concept of rate of working by studying two motors lifting different weights at different speeds. The user is invited to calculate which of the two motors is the more powerful.



Power is defined as the rate of working. An easier way to remember it is to think of the work done divided by the time taken. $\text{Power} = \text{Work Done} / \text{Time taken}$. If the work is given in Joules and the time is given in seconds, then the unit of power is the Watt (W).

A powerful motor can do a lot of work in a short time. A less powerful motor could do the same work, but it would take it longer.

Another useful relationship for mechanical power is $\text{Power} = \text{Force} \times \text{Velocity}$. From this relationship you can see clearly why (for a constant resistive force) a powerful car can travel faster!

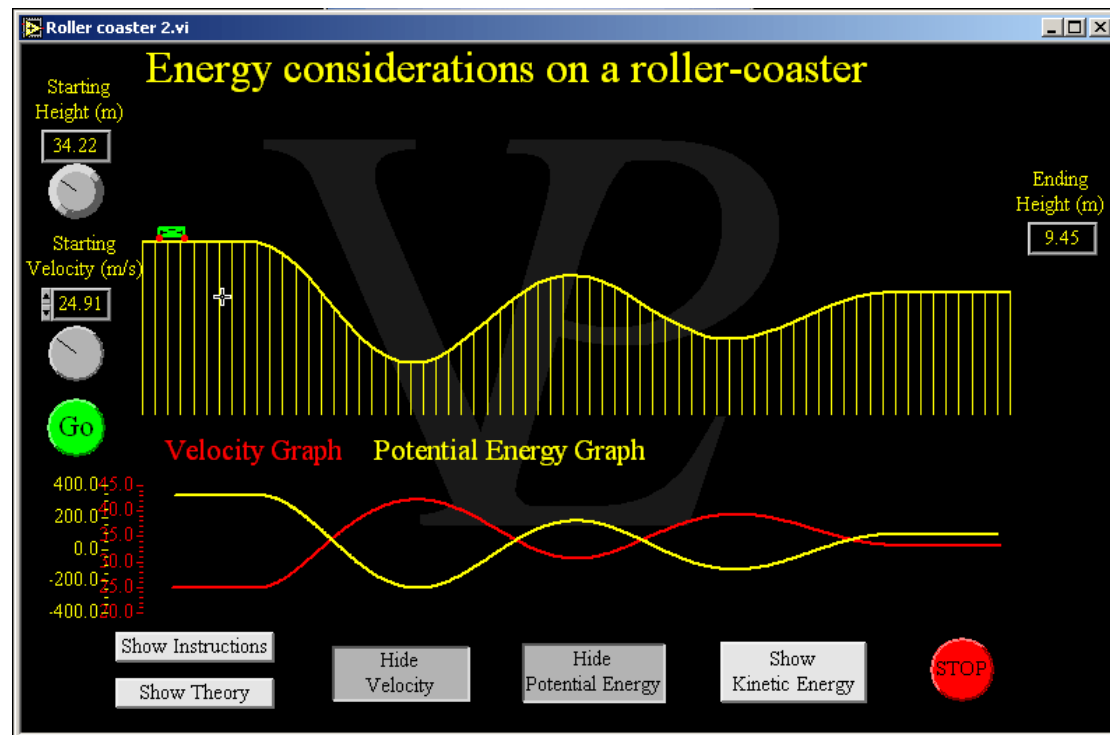
The Horse Power is a different unit of power which ranges between about 735 and 745 Watts. (You can see what the Watt is the preferred unit of power!). Typical car engines have power outputs between around 50,000 and 200,000 W

Like most units it has multiples and sub-multiples: The most common are:
 mW (eg the power consumption of light emitting diodes)
 kW (eg the power output of kettles)
 MW (eg the power output of small power stations)
 GW (eg the power of a large power station).

5.5 Roller Coaster

Advanced

This simulation shows how the potential and kinetic energies vary along a Roller Coaster. If insufficient starting kinetic energy is given, the trolley cannot make it to the other side!



When a trolley like this is in motion on a track there will be a continuous interchange between kinetic and gravitational potential energies.

Although speed and height may not be conserved, the total energy, in the absence of friction, is.

Total energy = kinetic energy + gravitational potential energy

Where there is friction from the air and track we can still say that the total energy is conserved but now the total energy is given by

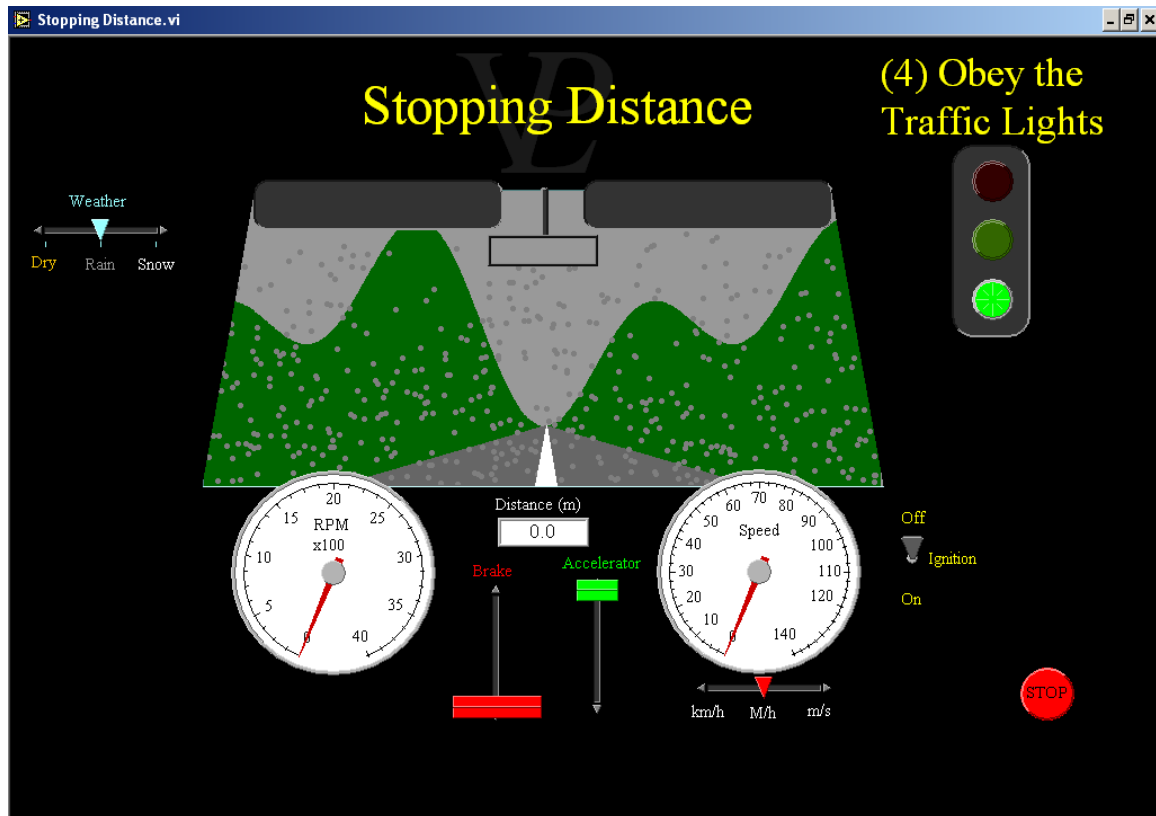
Total energy = kinetic energy
 + gravitational potential energy
 + thermal energy of air
 + thermal energy of trolley
 + sound energy.

So although strictly speaking energy is still conserved, in practice it is converted into forms that we did not want and are less useful, so we say it is wasted or not conserved.

5.6 Stopping Distance

Basic/Advanced

This simulation studies the factors affecting stopping distances in dry, wet and icy conditions.



The stopping distance of a car is made up of two components: The thinking distance and the braking distance. The thinking distance is the distance that the car travels before the driver has been able to react. (function of car speed and driver reactions)
The braking distance is the distance travelled by the car while the brakes are applied. (function of car speed, car condition and road conditions)

When a car is travelling along a road it has a fair amount of kinetic energy. In order to get the car to stop it is necessary to dissipate all its kinetic energy through the brakes. The car does work against the frictional force F exerted by the road on the tyres. The braking distance X can be calculated if the frictional force F is known by equating the kinetic energy to the frictional force multiplied by the braking distance.

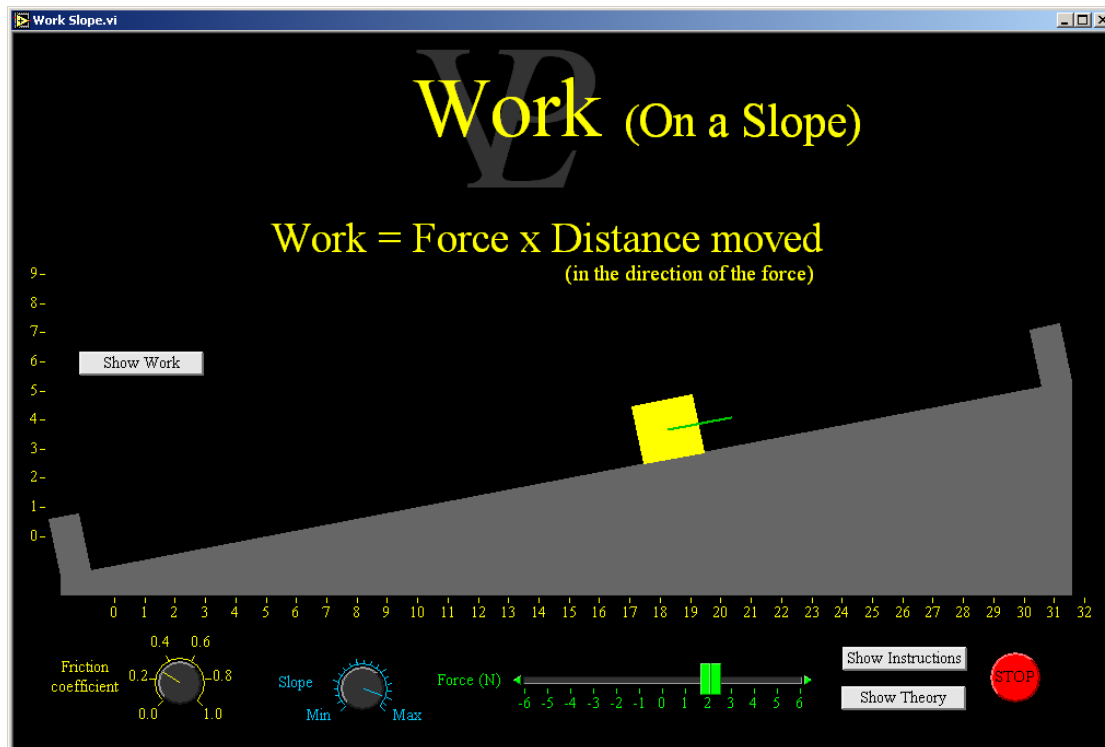
$$\frac{1}{2} M V^2 = F X.$$

The frictional coefficient of the contact between the tyres and the road depends on the type of tyres and the condition of the road. Good tyres on clean dry roads give a frictional coefficient of around 0.6 to 0.7. Wet roads can more than halve this value, and icy roads reduce it down to around 0.05. An alert driver will ensure that his thinking distance is as short as possible, but however alert the driver is, he cannot shorten his braking distance - this is determined by the tyres, the road and the speed at which the car was going. Wise drivers ensure their tyres are in good condition, and they restrict their speed to match the road conditions. The condition of the brake shoes and shock absorbers also affect the stopping distance of a car.

5.7 Work

Basic/Advanced

This simulation shows how work can be done against gravity only (in a vertical plane), against friction only (in a horizontal plane), or against both simultaneously (in an inclined plane). Plots of work, frictional losses, potential energy and kinetic energy can be displayed.



Work is defined as the product of a force and the distance moved in the direction of the force. If no movement occurs, no work is done however great the force! If the movement occurs in the opposite direction to that of the force, negative work is done!

If a force causes something to move, but at a slight angle to the force that caused the movement, the work done is the product of the force and the component of the displacement that is parallel to the force. If the force is perpendicular to the movement (as in the case of centripetal force), the force does no work.

When work is done by a force, it can take a number of different transformations. The following are the most common:

- 1 - Kinetic energy
- 2 - Potential energy (elastic or gravitational)
- 3 - Heat (work against friction)

In the absence of friction (or other losses), the work input will always be matched by the sum of the kinetic and the potential energies.

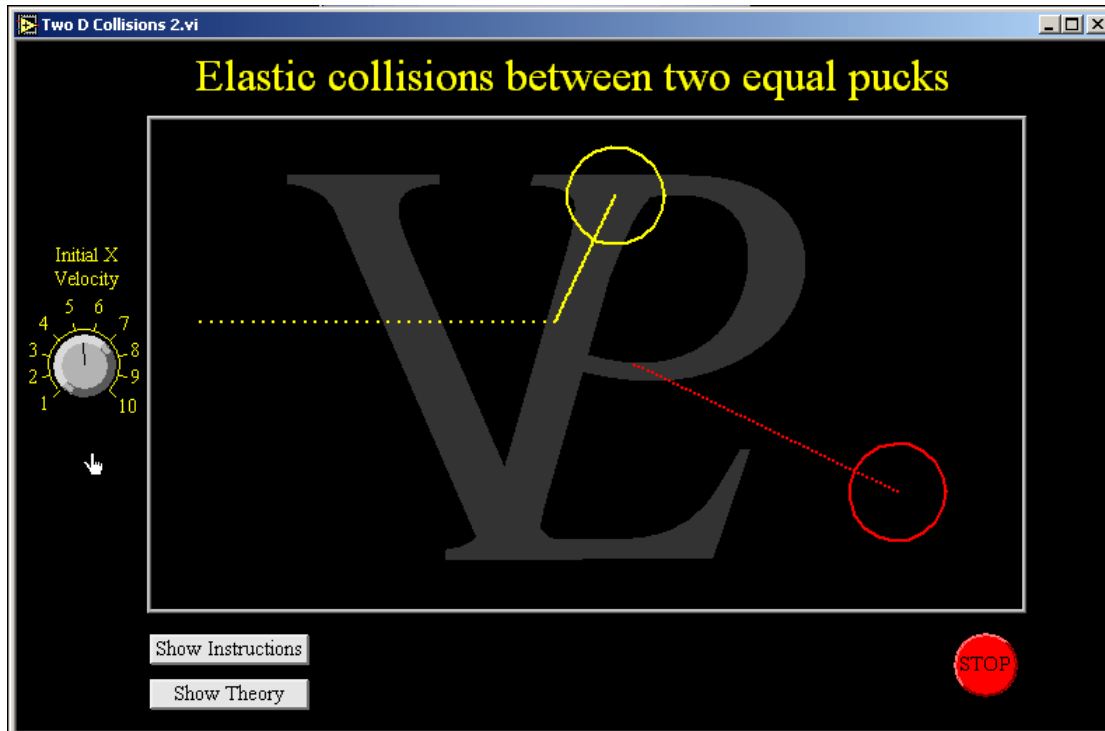
Work done against friction is energy that cannot be recovered; it is permanently wasted (unless heat is what you wanted in the first place!).

During a collision, the kinetic energy is converted into heat and sound, and so is also permanently lost.

5.8 2D Collisions

Advanced

This simulation shows how momentum is conserved in two dimensional collisions. It will appeal to pool or billiards players!



This program simulates the collision between two equal size pucks.

Try many different positions for the yellow mass. What do you notice about the paths of the yellow and red masses after collision? This is a special case where the two masses are equal.

Notice what happens to the overall momentum before and after collision.

Although energy is not normally conserved, except in the case of a perfectly elastic collision, momentum is a quantity which is always conserved. This is true in 1D, 2D and 3D collisions.

CHAPTER 6

ELECTRICITY AC

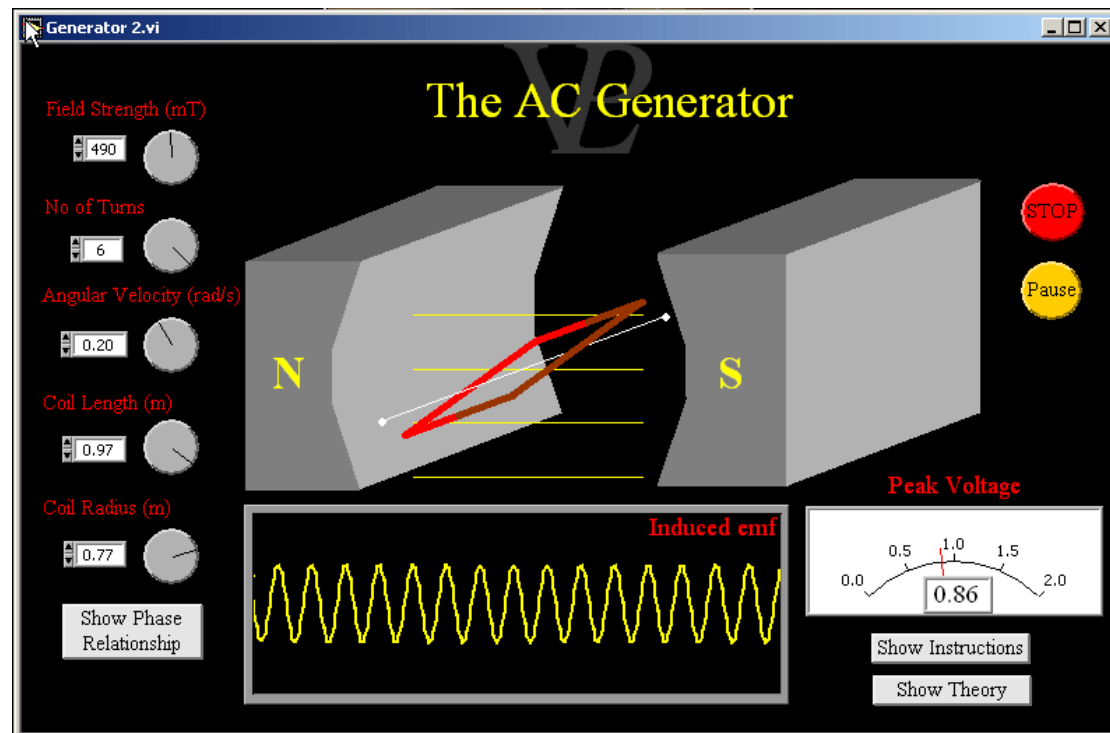


AC electricity has 101 uses around the house.
What exactly is AC?

6.1 AC Generator

BASIC/Advanced

This simulation shows how alternating currents are induced in a rotating coil. The coil parameters can be varied in order to investigate the effect. The phase relationship between the coil orientation and the induced emf are also shown.



Michael Faraday, sometimes known as the 'Father of Electricity', discovered that whenever a conductor cuts across magnetic field lines it causes a 'electromagnetic force' (known as an emf) to be induced across the ends of that conductor. The unit of emf is Volts, so it is also correct to describe the emf as an induced voltage.

The size of the voltage induced depends on the strength of the magnetic field, the length of the conductor cutting across the field and speed with which the wire cuts through. If additional wires are connected in series with the first one, that can also increase the induced voltage.

The AC generator is the way in which almost all electricity is produced today. Water or steam driven turbines are used to turn coils inside large electromagnets.

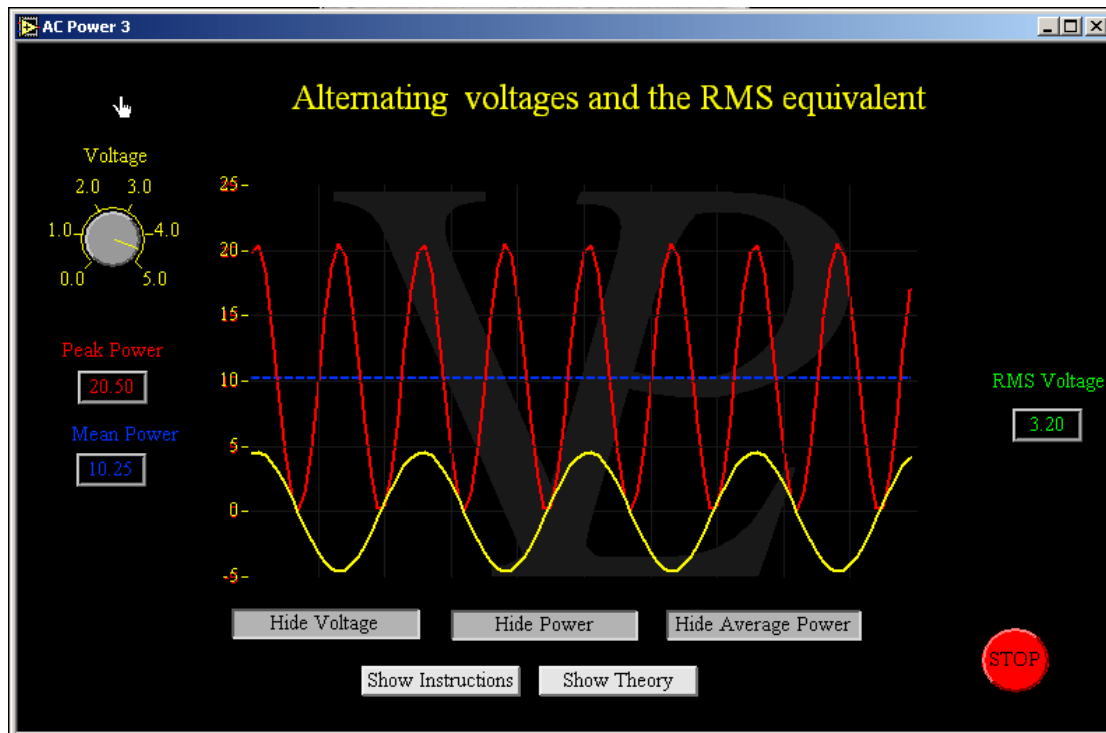
Although the magnetic flux through the coil is maximum when the plane of the coil is perpendicular to the magnetic field, the rate of change of flux at that position is a minimum so the induced emf is also minimum

The magnetic flux through the coil is minimum when the plane of the coil is parallel to the magnetic field, however the rate of change of flux at that position is a maximum. Since the induced emf is equal to the rate of change of flux linkage, the emf (and consequent current) is maximum when the plane of the coil is parallel to the magnetic field.

6.2 AC Power

Advanced

This simulation shows how the average power coming from AC is equal to the Root Mean Square (RMS), and how the RMS is related to the peak value



The power dissipated in a purely resistive circuit (one where there is no capacitance or inductance) is given by $\text{Power} = V^2 / R$ where V is the applied voltage and R is the resistance of the circuit.

Notice that although the voltage may go negative the power will always be positive because it is related to the square of the voltage.

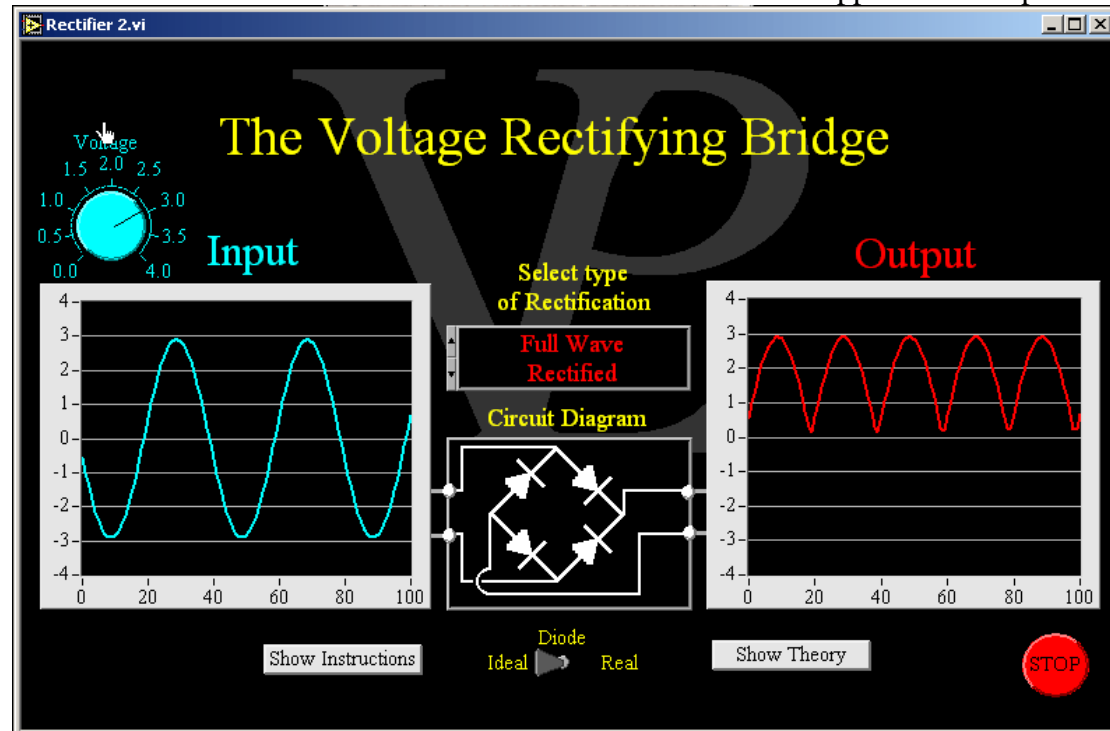
When dealing with AC, scientists prefer to use a new quantity called the 'root mean square' or RMS for short. The RMS voltage is the value of the equivalent DC voltage that would deliver the same power.

It can be calculated by $\text{RMS} = \text{Peak} / 2^{1/2}$

6.3 AC Rectification

Advanced

This simulation shows how AC currents can be rectified with diodes. Half and full wave rectification are shown, together with the effect of a smoothing capacitor. It also shows how the size of the electrical load affects the amount of ripple in the output.



Rectifying bridges are found in every power adapter for things like mobile phones and electronic games. They convert alternating currents (AC) into direct currents (DC).

The key component in a rectifying bridge is the diode. This component has a large resistance in the reverse direction, ideally infinite. It will also have a small resistance in the forward direction, ideally zero. There will always be a drop of about 0.6 V across the diode in the forward direction.

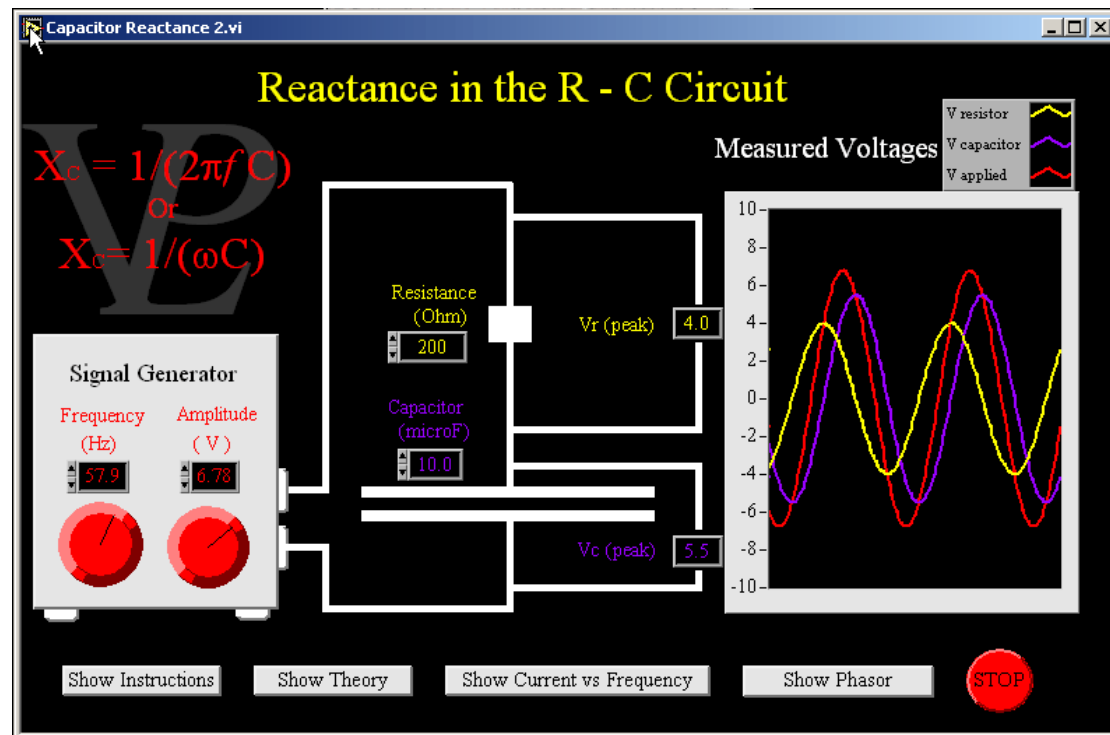
Try to follow the route the current will follow in the full way rectified circuit. Remember that the current needs to flow through the right hand and all the way back to the left hand side again.

Capacitors are used to smooth the output voltage. They charge up when the peak is passing and then slowly discharge through the load until the next peak comes. If the load is large (i.e. the resistance is low) the capacitor discharges quickly and the smoothing is not very effective. This shows that the capacitor needs to be chosen for the particular application.

6.4 Capacitive Reactance

Advanced

This simulation shows the reactive behaviour that a capacitor presents to alternating currents at different frequencies. It includes phase relationships, using phasor diagrams, and leads on to the concept of impedance.



When a capacitor is connected in series with a resistor and the pair are driven with an alternating voltage, the combination becomes a potential divider which is frequency dependent. The reason a resistor is included in this circuit is to help in the understanding of what is going on. The current flowing through the resistor and the voltage across it are always in phase and proportional to each other as described by Ohm's Law.

Now, the capacitor gets more interesting. Strictly speaking, no current can flow through a capacitor, but alternating current can charge and discharge the capacitor, making it look as if it is flowing through it. The interesting thing is that in this situation the current and the voltage have a different type of relationship:

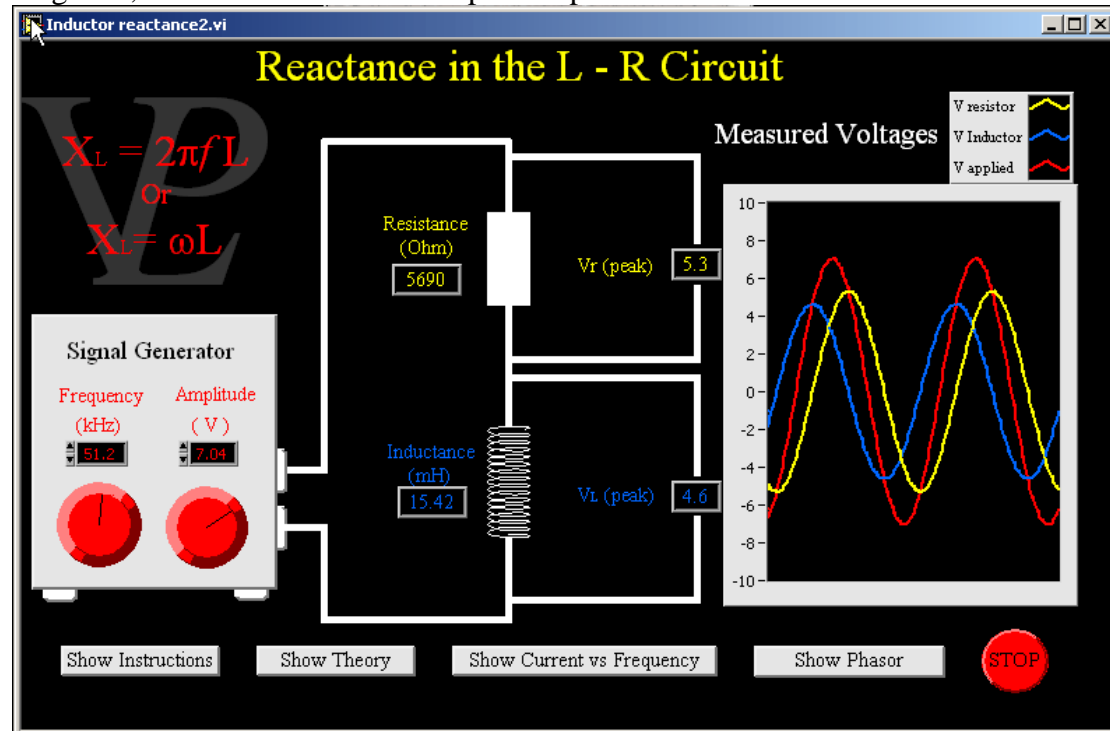
You probably already know that $C = Q/V$ (definition of capacitance), so $Q = CV$. If $I = dQ/dt$ then $I = C (dV/dt)$. If you apply a sinusoidal voltage of the form $V = V_0 \sin(\omega t)$, you obtain $I = \omega C V_0 \cos(\omega t)$. (ω is the angular frequency $\omega = 2\pi f$)

Notice that the current I leads the voltage V by 90 degrees, they are said to be in phase quadrature. The maximum current is flowing 'through' the capacitor at the time when the voltage across it is zero.

6.5 Inductive reactance

Advanced

This simulation shows the reactive behaviour that an inductor presents to alternating currents at different frequencies. It includes phase relationships using phasor diagrams, and leads on to the concept of impedance.



When an inductor (a coil or solenoid) is connected in series with a resistor and the pair are driven with an alternating voltage, the combination becomes a potential divider which is frequency dependent. The reason a resistor is included in this circuit is to help in the understanding of what is going on. The current flowing through the resistor and the voltage across it are always in phase and proportional to each other.

However, the current flowing through the coil causes it to produce a magnetic field which threads the coil. If the magnetic field is changing, the self inductance of the coil causes an emf to be induced across it (Faraday's Law) which will try to oppose the change producing it. (Lenz' Law). Since the system is being driven by an alternating current, the magnetic field (and the emf) are continually changing. This gives rise to a strange relationship between the current and the voltage in the inductor.

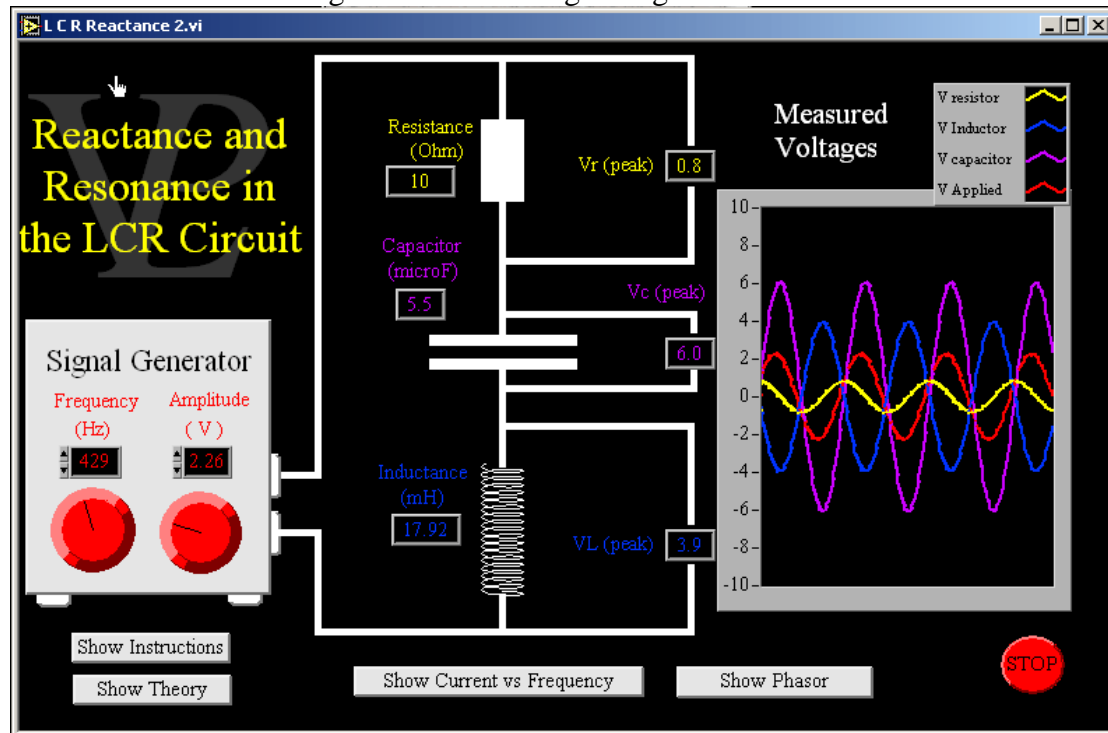
You probably already know that $\text{emf} = -L \frac{dI}{dt}$ (L is the self inductance of the coil). If this is new to you, it is probably better to read the steps leading to that equation in a physics text book. If the current is a sinusoidal one, such that $I = I_0 \sin(\omega t)$ the emf induced across the inductor will be $\text{emf} = -L \omega I_0 \cos(\omega t)$, where $\omega (=2\pi f)$ is the angular frequency. The current leads the voltage by 90 degrees (because of the minus sign in the equation). The current and the voltage are said to be in phase quadrature. The maximum current is flowing 'through' the inductor at the time when the voltage across it is zero!

If we try to find an 'equivalent resistance' called reactance X_L by using something like Ohm's Law $X_L = V/I = L \omega I / I = L \omega$. Its reactance is greatest (allows least current to flow) when L is large, and when the frequency is high.

6.6 LCR reactance

Advanced

This simulation demonstrates the behaviour of a capacitor in series with an inductor (and a resistor). It illustrates how this circuit can be tuned to oscillate at a particular frequency. The phasor diagram shows how the voltages across the capacitor and the inductor can be much larger than the driving voltage!



When an inductor (a coil or solenoid) and a capacitor are connected in series and the pair are driven with an alternating voltage, the combination becomes a very interesting circuit; one that can even resonate if driven at the right frequency. The reason a resistor is included in this circuit is because any real circuit has at least some resistance. It also helps to see how resistance affects the resonance of the circuit.

To understand this circuit, it is necessary to have understood the simulations on capacitive reactance and inductive reactance ($X_C = 1/\omega C$ and $X_L = L\omega$)

Notice that V_L and V_C point in opposite directions. Their combined effect is $V_L - V_C$. Using Pythagoras, the applied voltage V_a can be seen to be related to the other voltages as follows: $V_a^2 = (V_L - V_C)^2 + V_R^2$ (1) The overall current I will lead the voltage V_a by an angle θ where $\tan \theta = (V_C - V_L)/V_R$, or $\tan \theta = (IX_C - IX_L)/IR$, or $\tan \theta = (X_C - X_L)/R$ (2)

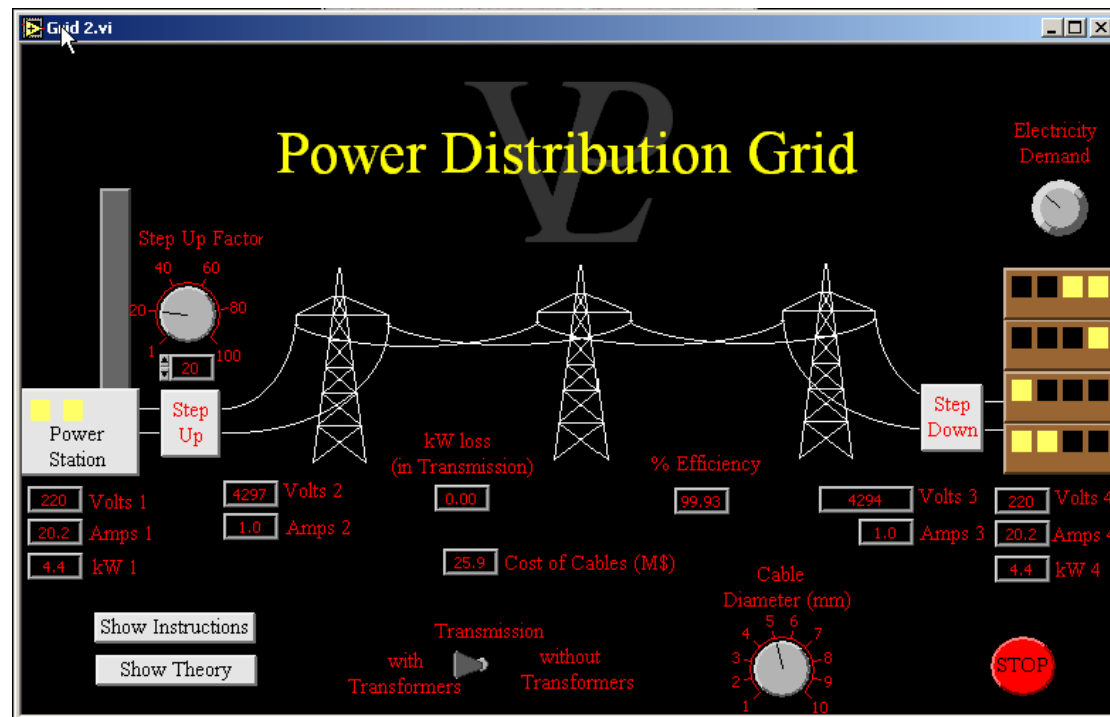
If $X_C > X_L$ the current will lead the applied voltage, and if $X_C < X_L$ it will lag behind it. In the special case where $X_L = X_C$ the current will be exactly in phase with the current. Notice that this condition does not only depend on the values of L and C , but also on the frequency.

From equation 1 we can deduce the overall impedance Z : $(IZ)^2 = (I(X_C - X_L))^2 + (IR)^2$ or $Z = ((X_C - X_L)^2 + R^2)^{1/2}$ (3) and the overall current I is given by $I = V/Z$. Equation 3 tells us that Z is minimum when $X_C = X_L$. This is the resonance condition where a small applied voltage can cause a large current to flow. This happens when $1/\omega C = \omega L$ or $f = 1/(2\pi LC)^{1/2}$. This is the principle of the radio oscillator. A capacitor is adjusted until the circuit resonates at the frequency of the station.

6.7 Power Distribution

Advanced

This simulation illustrates why it is necessary to distribute electrical power at high voltage. Power losses are shown and current limits due to the cable diameter are imposed.



Power distribution is an important practical and economic challenge.

Without using transformers to step up the voltage (and step down transformers to stabilise the voltage near the consumers) the potential at the delivery point drops as the customers load the grid with their demand. Above a particular demand (or loading), the power delivered actually starts to fall.

You can improve matters a little by increasing the diameter of the cables, but this makes the cables more expensive, and the efficiency of transmission is still poor (power wasted as heat in the cables).

Using step-up and step-down transformers helps to reduce the energy wasted and keeps the cost of the transmission wires down. National grids go as high as 400,000 Volts.

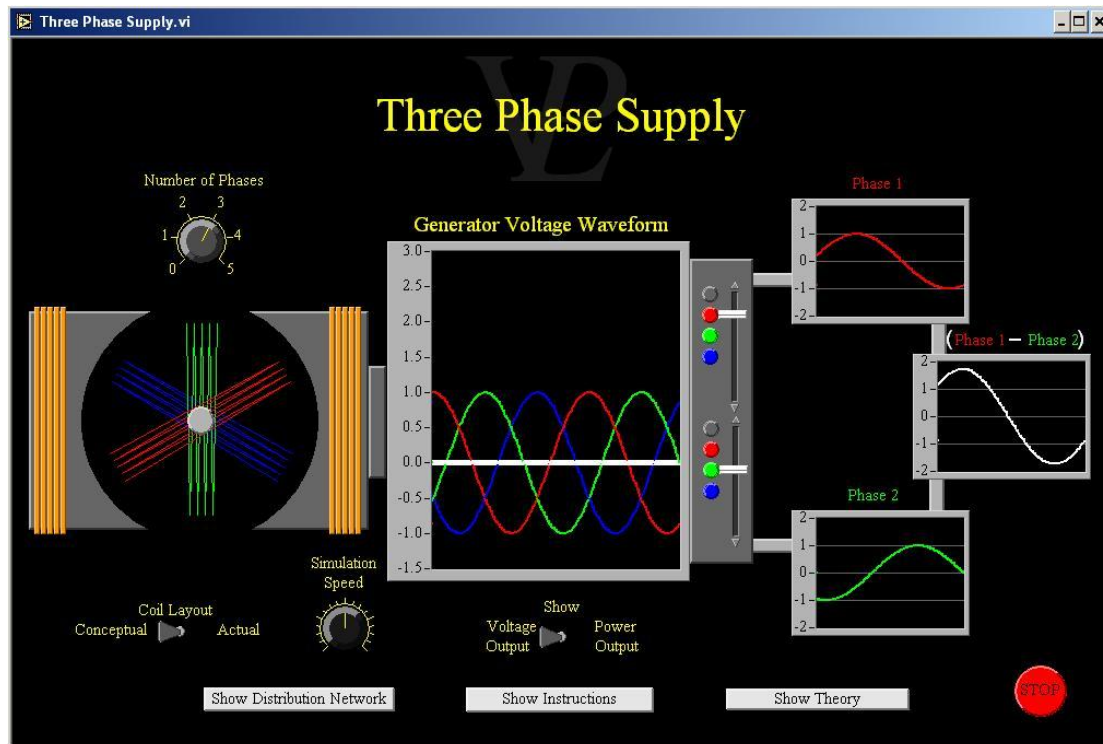
High voltage transmission is used for the following reasons:

- 1 - It makes transmission more efficient
- 2 - It makes it possible to use thinner cables (cheaper cables and pylons)
- 3 - It makes larger power delivery possible.

6.8 Three Phase Supply

Advanced

This simulation shows the difference between two phase and three phase electricity both in the way it is produced and the way it is distributed and consumed.



Lets start the discussion with single phase electricity, and build it up from there:

(1) Single Phase: When a single sinusoidal Voltage is being produced, the load on the generator fluctuates between zero (at the cross-over points) and a maximum (at the peaks and the troughs). This cycling load leads to vibration, cyclic fatigue and wear. Two wires are needed to deliver a single phase (50% utilisation efficiency).

(2) Two Phase: If two phases were to be used (P1 and P2) the coils would be at 90 degrees to each-other. The two Voltages would be in phase quadrature, and the sum of the powers (Sine squared + Cosine squared) would be constant. This means that the torque loading on the generator shaft would be constant, minimising vibration. Three wires (Phase 1, Phase 2, and Neutral) would be needed to deliver two phases (67% utilisation efficiency). The peak Voltage between P1 or P2 and the Neutral is still V_p , but the peak Voltage between P1 and P2 is $1.42 \times V_p$.

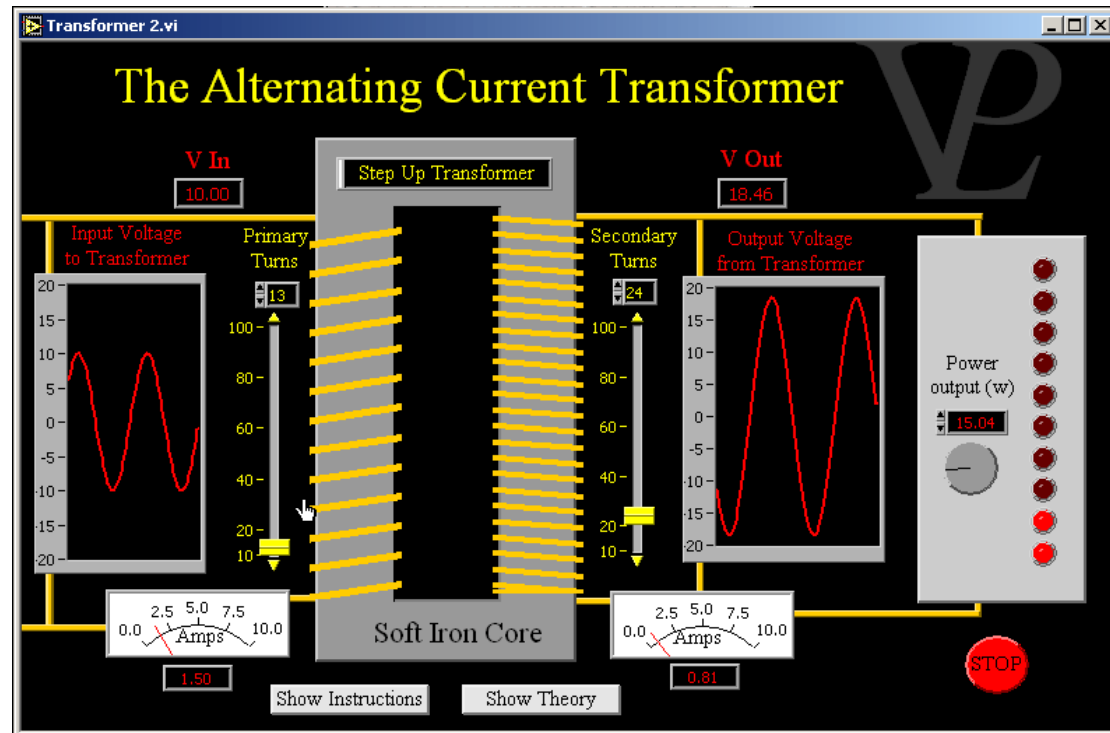
(3) Three Phases: When three phases are used, each coil is orientated 120 degrees from the others. The sum of the squares of the three Voltages adds up to a constant, so again there will be minimum vibration. Notice also that the sum of the three Voltages is zero! In principle, this means that the Neutral wire was not needed. (this would only be true if each of the phases was equally loaded by consumers - which is what engineers try to achieve). In practice, the Neutral wire is still used (though is often thinner). Four wires are used to deliver 3 phases (75% utilisation efficiency). The Voltage between any of the three phases and Neutral is still V_p - and can be used in normal households. Roughly a third of the houses is connected to each phase. The inter-Phase Voltage difference peaks at $1.73 V_p$, and so can deliver significantly more power at similar currents.

Electricity AC 6.9

6.9 Transformer

Advanced

This simulation illustrates a simple transformer where the number of turns in the primary and secondary may be adjusted independently. Graphs show the input and output AC voltages, and dials monitor (V_{in} , I_{in}) and (V_{out} , I_{out}) showing power is conserved.



The primary coil produces a varying magnetic field through the soft iron core of the transformer. The changing magnetic field induces an electro-motive force in the secondary coil. If the number of turns in the secondary coil is greater than the number of turns in the primary coil, the induced emf will be larger than the input voltage to the transformer. This is called a step-up transformer. If the number of turns in the secondary coil is smaller than that in the primary, the emf will be smaller. This is known as a step-down transformer.

The ratio of the voltages will be equal to the ratio of the turns of the two coils.

$$\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}}$$

A transformer does not create energy from nowhere. The increase in voltage is achieved at the expense of the current. If the output voltage is greater, the output current will be smaller. Large transformers can be very efficient and in an idealised situation where there is no power loss we can say that Power In = Power out

$$V_{in} I_{in} = V_{out} I_{out} \quad \text{Therefore} \quad \frac{I_{out}}{I_{in}} = \frac{N_{in}}{N_{out}}$$

CHAPTER 7

ELECTRICITY DC

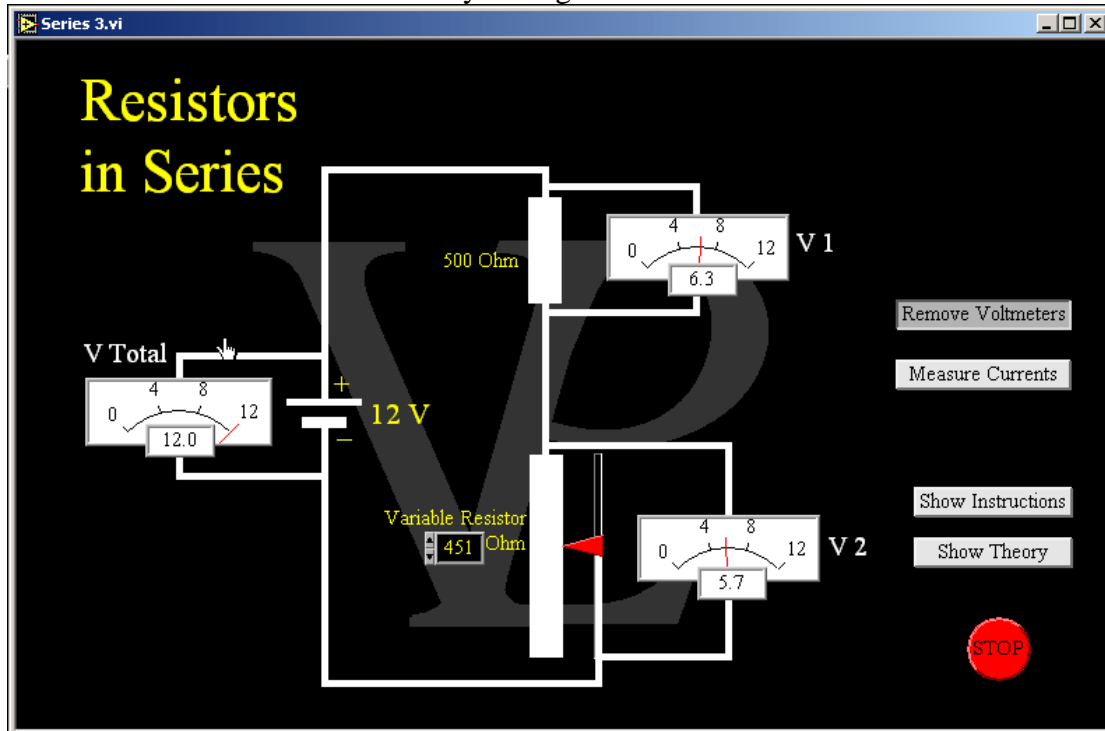


DC electricity is used in most of our portable appliances.
How do these circuits work?

7.1-A Series Circuit

Basic/Advanced

This simulation shows how voltages and currents behave in series circuits where one of the resistors is variable. It ends by testing the student on series circuits.



Understanding series and parallel circuits is a very important skill in electricity.

Components and appliances that must all receive the same voltage as that supplied by the source must be connected in parallel. Power sockets and lighting circuits in a house are all connected in parallel.

Components that must share the source voltage between them are connected in series. Many Christmas lights and decorations are connected in series.

A series circuit is one in which the current only has one possible path through which it can flow.

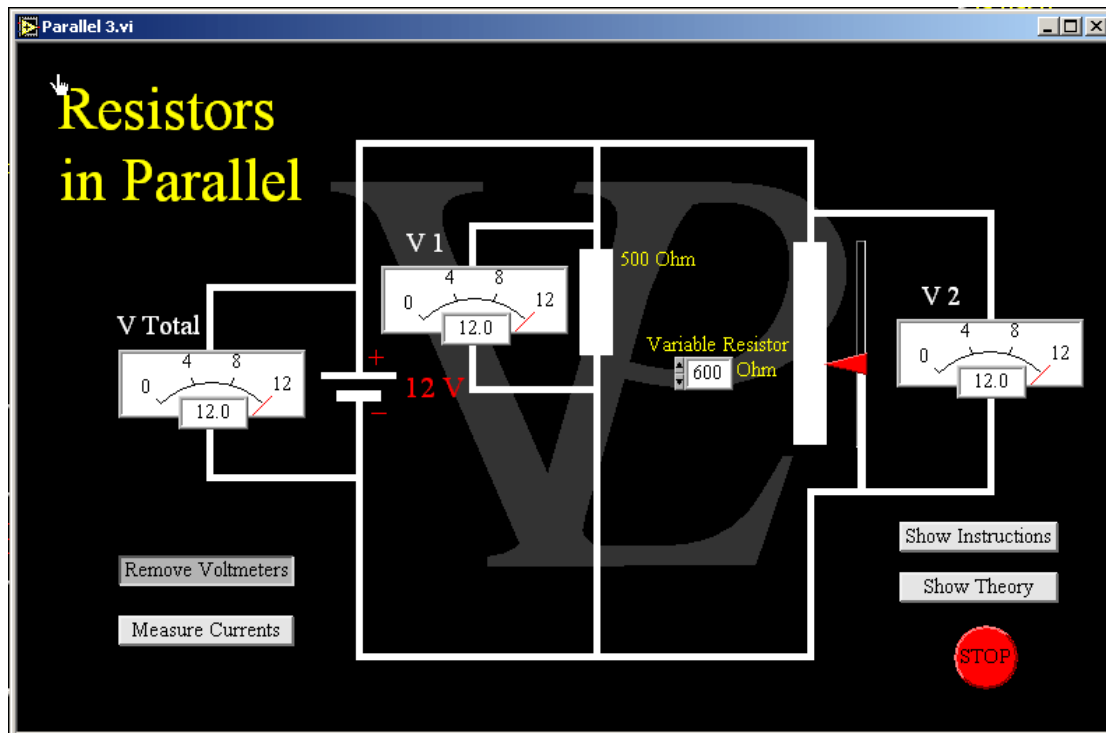
You can ignore the voltmeters in the circuit because these have such a large resistance that virtually no current can flow through them.

Since the current only has one path, the currents have to be equal everywhere in the circuit. However, the potential differences across the resistors will vary depending on their resistance ratio. The larger resistor will always get a larger share of the total Voltage available. Can you see why this circuit is also called a potential (=Voltage) divider?

7.1-B Parallel Circuit

Basic/Advanced

This simulation shows how voltages and currents behave in parallel circuits where one of the resistors is variable. It ends by testing the student on parallel circuits.



Understanding series and parallel circuits is a very important skill in electricity.

Components and appliances that must all receive the same voltage as that supplied by the source must be connected in parallel. Power sockets and lighting circuits in a house are all connected in parallel.

Components that must share the source voltage between them are connected in series. Many Christmas lights and decorations are connected in series.

A parallel circuit is one in which the current only has more than one possible path through which it can flow. Whenever a circuit has T junctions, ignoring those going to voltmeters, it is a parallel circuit.

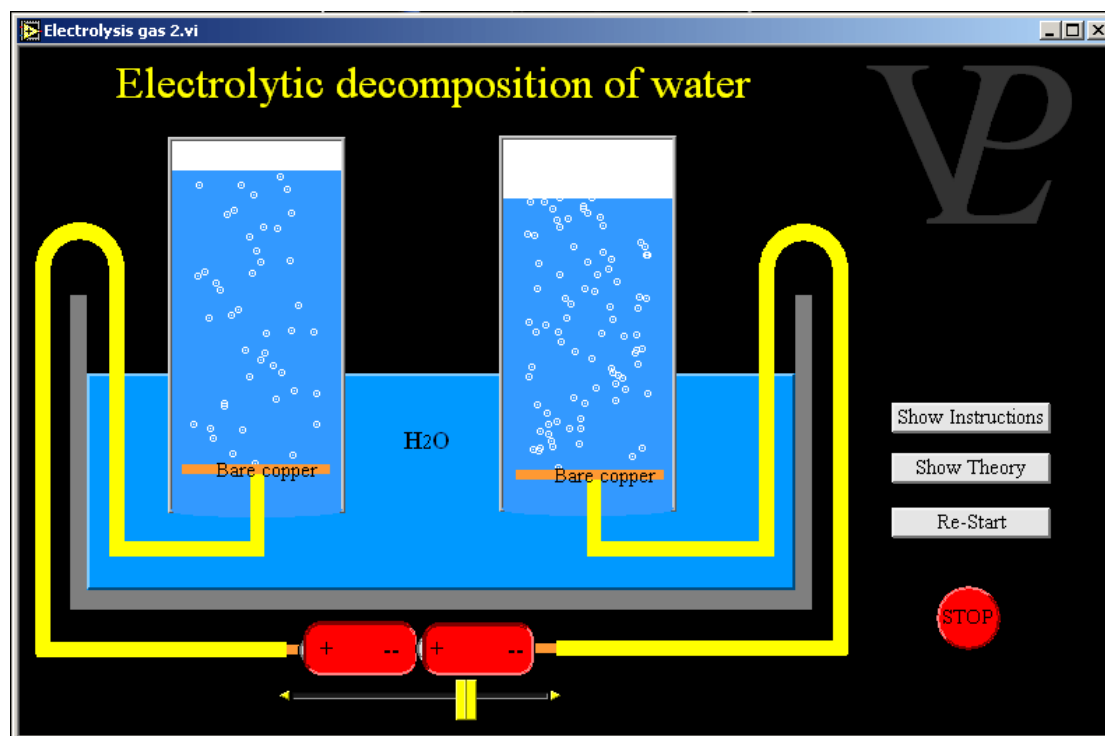
The currents in the two possible routes need to add up to the current that is flowing through the battery.

The voltage of the battery is applied to both resistors. The voltages across the battery, R1 and R2 are all equal.

You can ignore the voltmeters in the circuit because these have such a large resistance that virtually no current can flow through them. You can also ignore the Ammeters in the circuit. As their resistance is effectively zero the current flows through them as if they were not there.

7.2 Decomposing Water

This simulation shows how water is decomposed into oxygen and hydrogen when an electric current is passed through it.



In order for electrolytic decomposition of water to occur there need to be at least a few impurities in the water. Slightly acidic water works well.

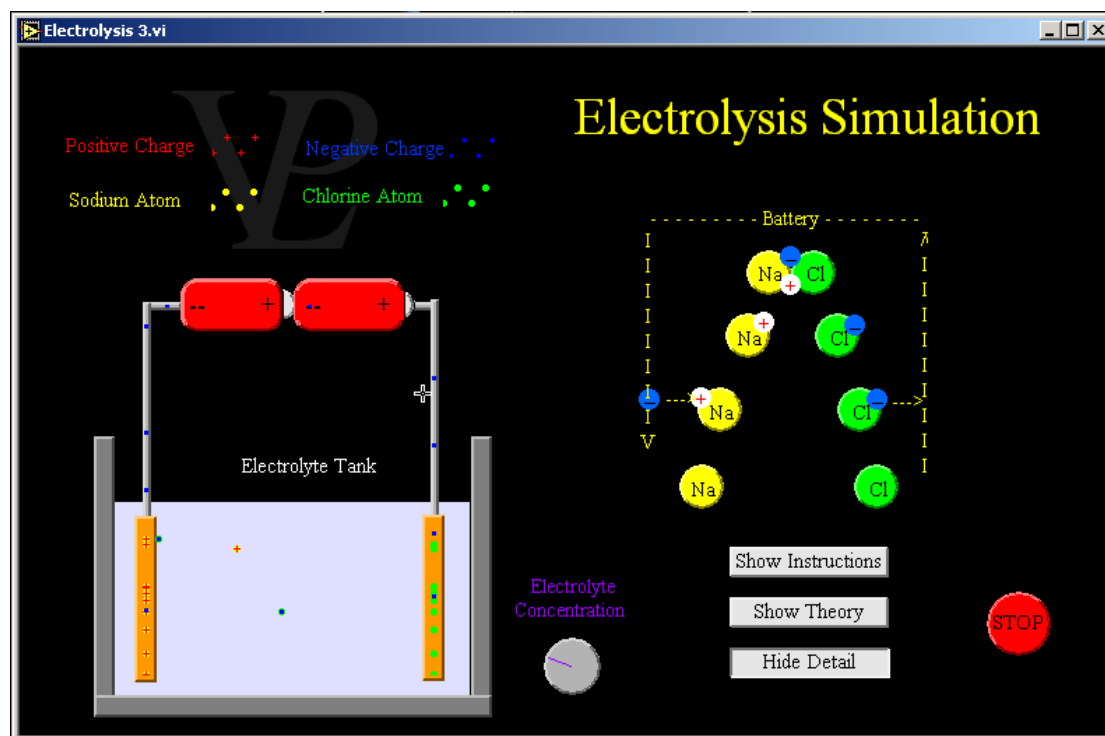
The energy delivered to the water molecules causes a reaction to happen at each of the electrodes at the same time. The bonds holding the water molecules together are broken and the oxygen is released at the +ve terminal and hydrogen at the -ve terminal.

Hydrogen is very useful as a fuel because it can be oxidised again quite easily back into water and in the process it releases energy. Unfortunately this is not as much energy as was used to separate it from the water in the first place.

7.3 Electrolysis Liquid

Basic

This simulation shows how an electrolyte is decomposed such that ions are deposited on the electrodes. The deposition rate and polarity and the electrolyte concentration may be adjusted.



When an electric field is applied across to sodium chloride molecules it causes them to separate into sodium and chloride ions.

The sodium loses one of its electrons to the chloride, so it ends up positively charged, and the chloride steals away one electron from the sodium so it ends up negatively charged.

The electric field then causes these ions to move in opposite directions until they reach the electrodes. Since the electrodes are conductors, they will very readily donate or receive electrons thus enabling charge to flow round the circuit.

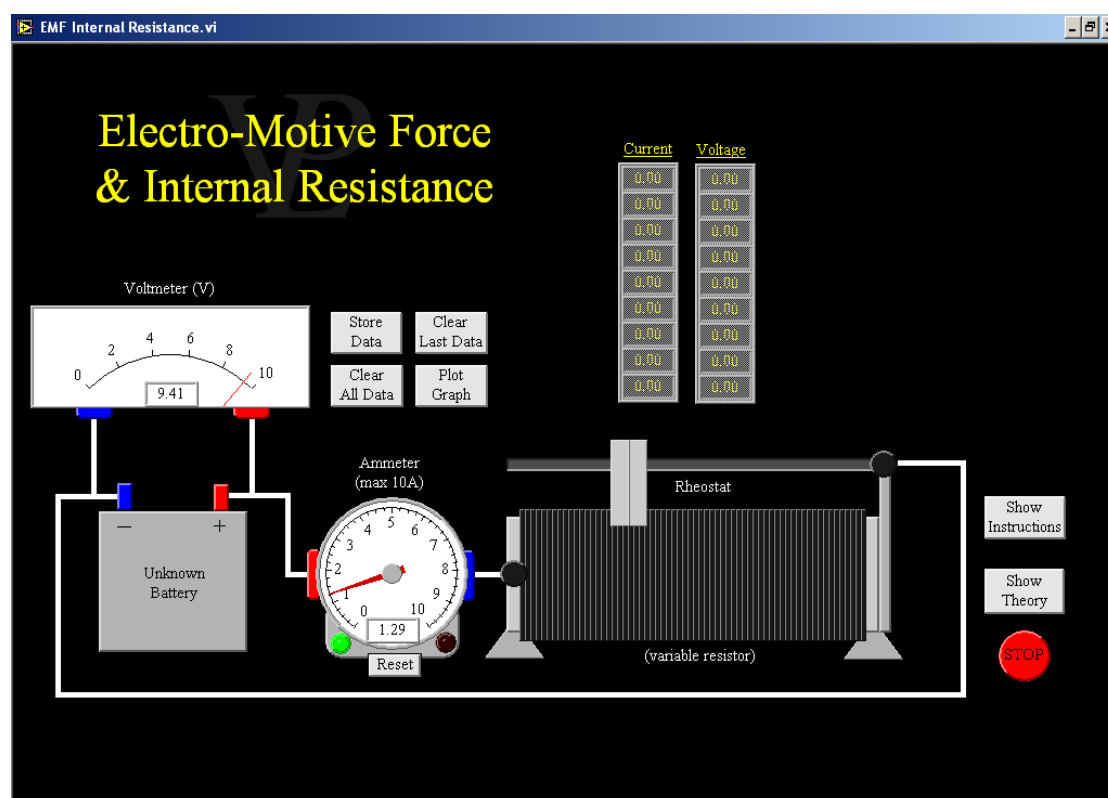
Notice that it is only in the electrolyte that the positive charges can move. Once they reach the electrodes, it is only the electrons that move.

The negatively charged chloride ions surrender their negative charge to the electron upon arrival at the electrode and so become neutral again. The positively charged sodium ions wait until they receive an electron from the battery and then they are neutral atoms again.

7.3 EMF and Internal Resistance

Advanced

This simulation shows how both the EMF and the internal resistance of a battery can be obtained by recording the voltage across the terminals of the battery whilst drawing different currents.



The Electro-Motive Force of a battery is the name given to the amount of energy given to each Coulomb of charge as it goes through the battery. If 1 Joule of energy is given to each Coulomb of charge as it goes past, the battery is said to have an EMF of 1 Volt.

Batteries are not able to deliver all the energy they have given to the charges to an external load, some of the energy gets used up internally, overcoming what is called the "internal resistance" of the battery. (You may be able to feel that a battery can sometimes get warm when it is delivering a significant current to an external load).

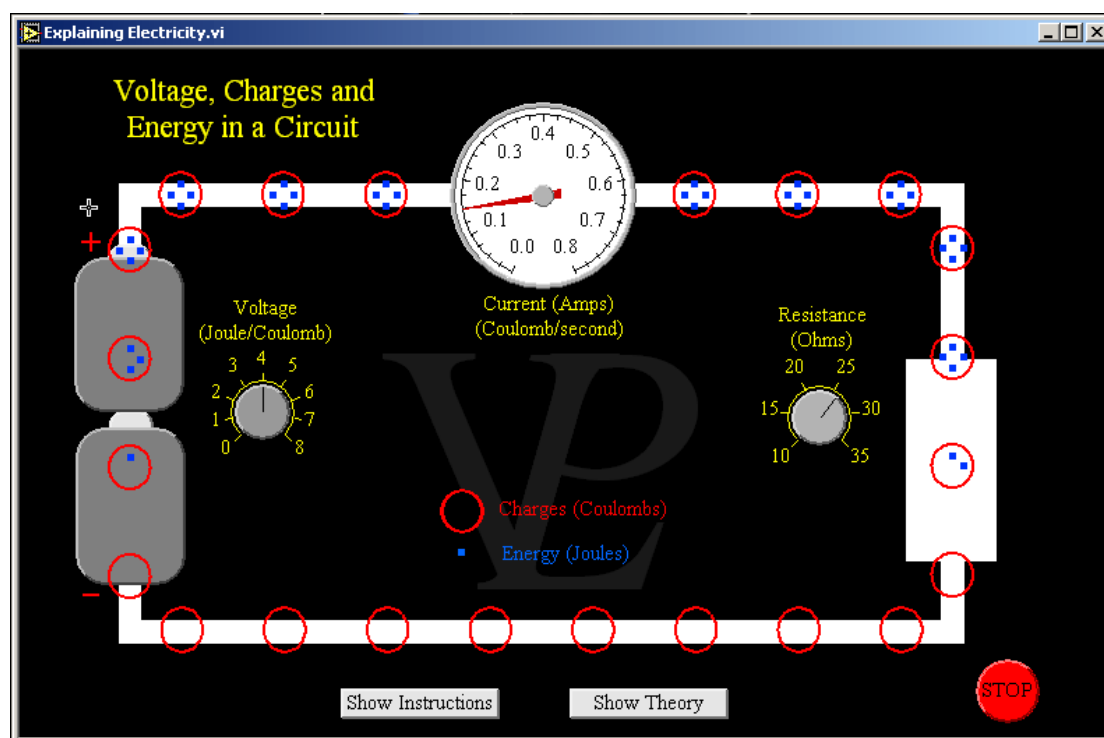
A suitable model of a real battery (of Voltage V) is a perfect battery (of Voltage E) in series with a small resistor (of resistance r). E cannot be measured directly because it is somewhere inside the battery, but V can be measured across its terminals. When a load is connected to the battery, it will be noticed that the Voltage V across the terminals drops. The bigger the load (the larger the current drawn), the lower the Voltage V across the battery terminals will become.

Mathematically we say $V = E - I r$ where V is the Voltage across the terminals of the battery, E is the EMF of the battery, I is the current flowing through the battery, and r is the internal resistance of the battery.

7.5 Explaining electricity

Basic

This visualisation program shows Coulombs of charge travelling round a circuit. They receive Joules of energy at the battery and dissipate them in the resistor. They finally return empty back to the battery to be re-filled.



This simulation is designed to show how the concepts of voltage, charge, current energy and resistance relate to each-other.

Charges exist in the wires of a circuit at all times, even if they are not connected to a battery! However, they are not moving. The unit of charge is the Coulomb (C). When a battery is connected to a circuit, it causes the charges to move from the positive terminal towards the negative one.

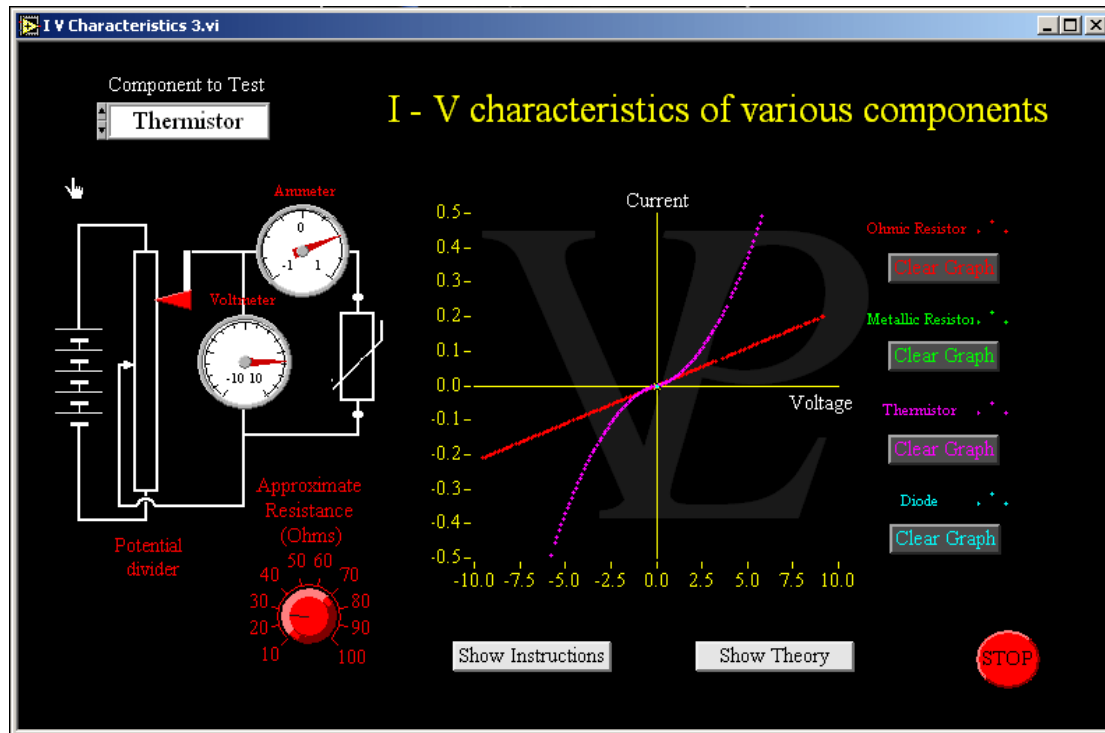
Potential difference (or Voltage) is measured in Volts. One volt will give each Coulomb of charge an energy of one Joule (a battery of 4 Volts will give each Coulomb of charge 4 Joules of energy). The charge will then travel around the circuit, but it will only spend that energy when it encounters resistance in the circuit. After the charge has spent its energy it will return to the battery in order to receive another 'allowance' of energy.

When the Voltage is increased, not only does each charge receive more Joules of energy to spend, but the charges also travel around the circuit faster (the current increases).

7.6 I V Characteristics

Basic

This simulation allows the student to investigate the relationship between the current and the voltage for several components: the Ohmic resistor, a metallic resistor, a thermistor and a diode.



The relationship between I and V is only linear for ohmic resistors in an idealised case. Real resistors, as well as thermistors are affected by temperature. Since the current flowing through them causes some self heating, the resistance is not constant. For that reason the slope of the lines they form is not constant. The resistance is the inverse of the gradient, since $I/V = 1/R$

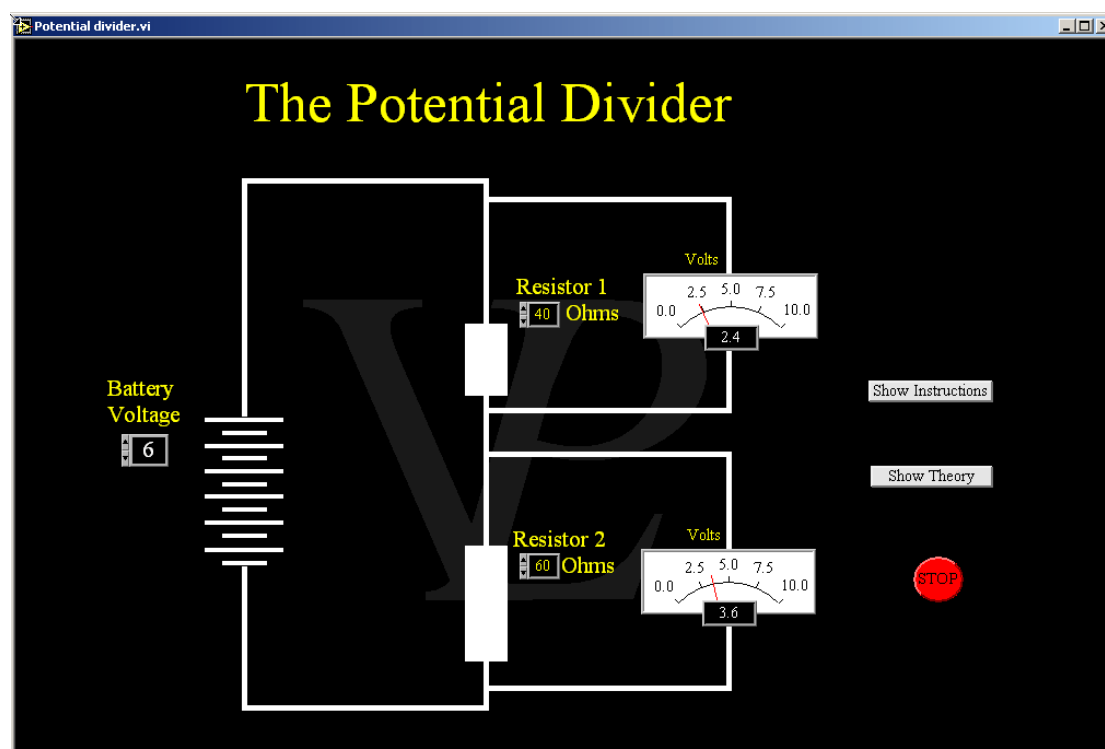
In a metal, as the temperature increases the vibrating atoms tend to get in the way of the conducting electrons and so slow them down. This causes the resistance to increase.

In a semiconductor, like a thermistor, the resistance decreases as the temperature increases because electrons acquire enough thermal energy to break loose and start conducting.

7.7 Potential Divider

Basic

This simulation illustrates how a voltage can be shared unequally across two resistors and how the ratio of the voltages is equal to the ratio of the resistances used.



The potential divider is a simple circuit which consists of at least two resistors and one battery.

The voltage (or potential difference) is divided into two voltages across each of the resistors. The share is not normally equal, it depends on the relative values of the two resistors. If R_1 is twice as large as R_2 , then V_1 will be twice as large as V_2 .

The proof of this is as follows:

The total resistance of the circuit is $R = R_1 + R_2$

The current I flowing around the circuit is given by $I = V / (R_1 + R_2)$

Notice that the same current flows through both resistors, so the potential difference across R_1 will be $V_1 = I R_1$ or $V_1 = V R_1 / (R_1 + R_2)$, and the potential difference across R_2 will be $V_2 = I R_2$ or $V_2 = V R_2 / (R_1 + R_2)$

Dividing the first equation by the second we find $V_1 / V_2 = R_1 / R_2$

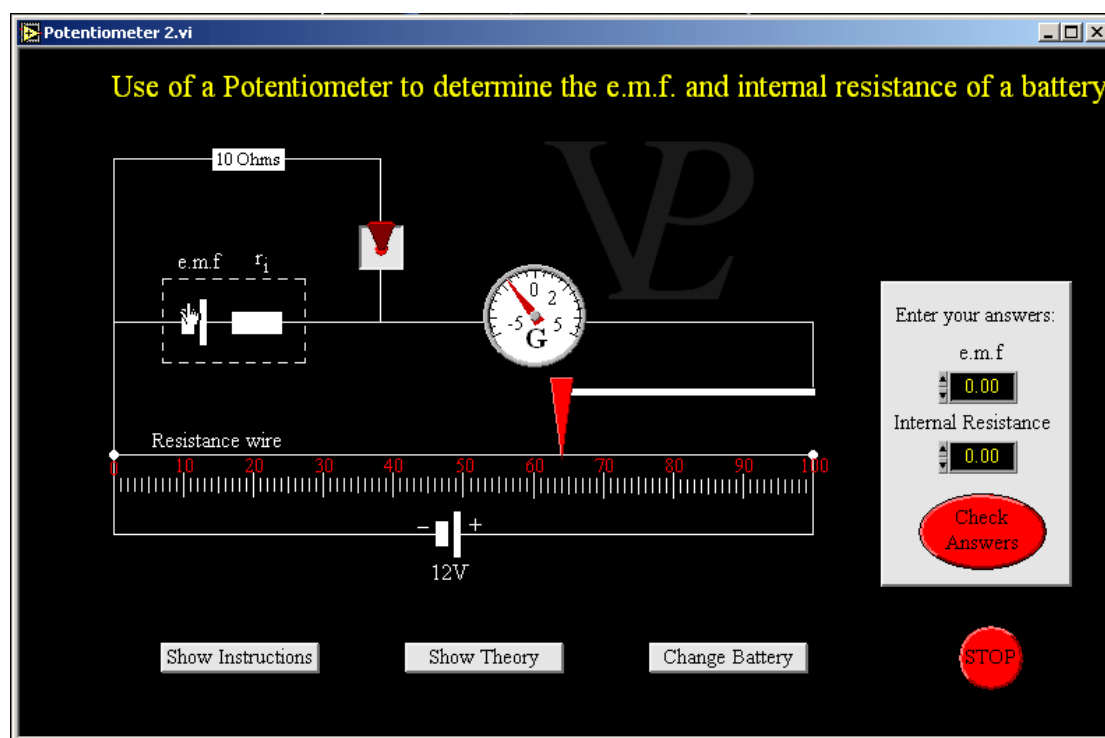
In other words the ratio of the voltages is equal to the ratio of the resistors.

Notice also that $V_1 + V_2 = V$.

7.8 Potentiometer

Advanced

This program simulates a slide-wire potentiometer which is used to measure the emf of an unloaded battery and also its p.d. when it is loaded with a known resistor. From these measurements the internal resistance of the battery may be calculated.



The potentiometer wire was a very clever way of turning a simple metre ruler into a voltmeter. The method is now outmoded because digital voltmeters are so good and cheap. However it is quite instructive and that is why it is included here.

The potentiometer is a simple ratio meter: 100 is to 12V as the balancing length is to the unknown voltage.

When the switch is open the balancing length is L_o , and the emf will be given by

$$\text{emf} = L_o \times 12/100 \quad (1)$$

When the switch is closed the balancing length is L_c , and the Voltage V will be given

$$\text{by } V = L_c \times 12/100 \quad (2)$$

The voltage of the battery is related to its emf by

$$V = \text{emf} - I r \quad (3)$$

where I is the current flowing through the battery and r is the internal resistance of the battery.

From Ohm's Law we know that

$$I = V/R \quad (4)$$

where I is that same current flowing through the battery, and R is the external resistor (10 Ohms).

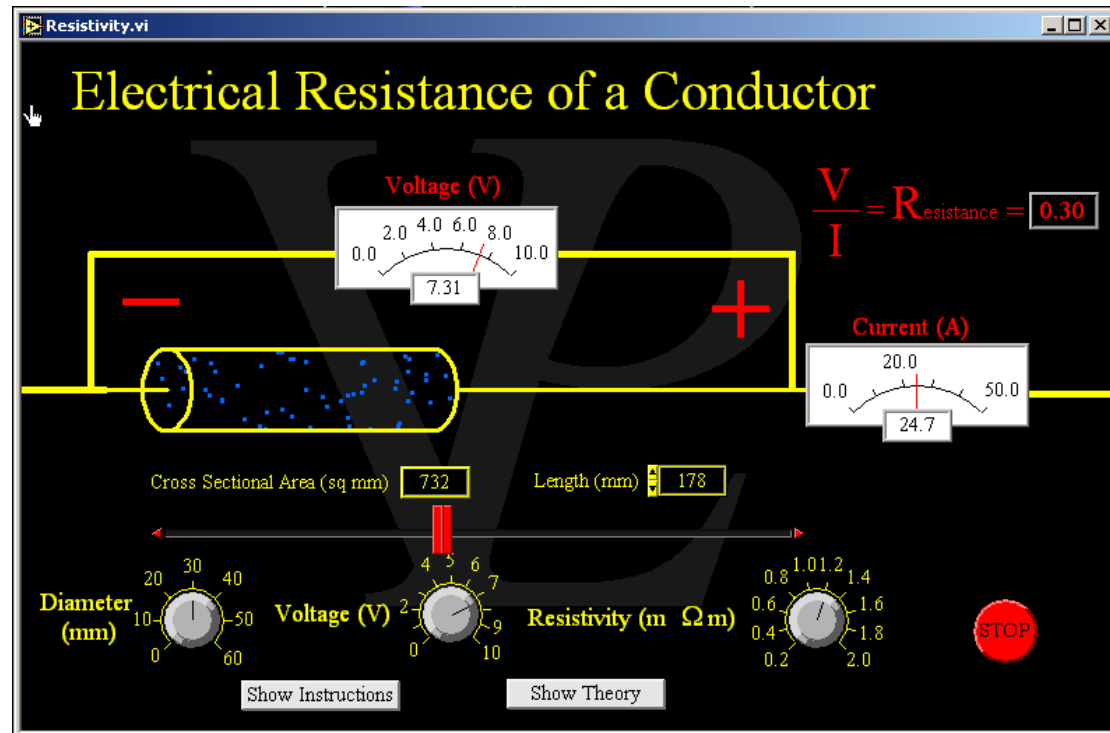
Substituting 4 into 3 we obtain

$$r = R(\text{emf} - V)/V \quad (5)$$

7.9 Resistivity

Basic/Advanced

This simulation illustrates how the resistance of a conductor is affected by length and diameter of the conductor, as well as the number of charge carriers in the material. This leads to the concept of Resistivity.



The resistivity of any conductor depends on the density of free charge carriers. In this case the material is a metallic conductor. Notice that the charge carriers (electrons) are flowing from -ve to +ve.

Charge carriers experience some resistance to their motion as they try to move along. The longer the wire is, the longer the electrons have to fight in order to get through to the other side. This increases the electrical resistance.

If the cross sectional area of the conductor is larger there will be more charge carriers available to transport the charge around the circuit. This decreases the electrical resistance.

A complete study of resistivity will show that:

$$R = \rho \frac{L}{A}$$

Where R is the resistance

L is the length of the conductor

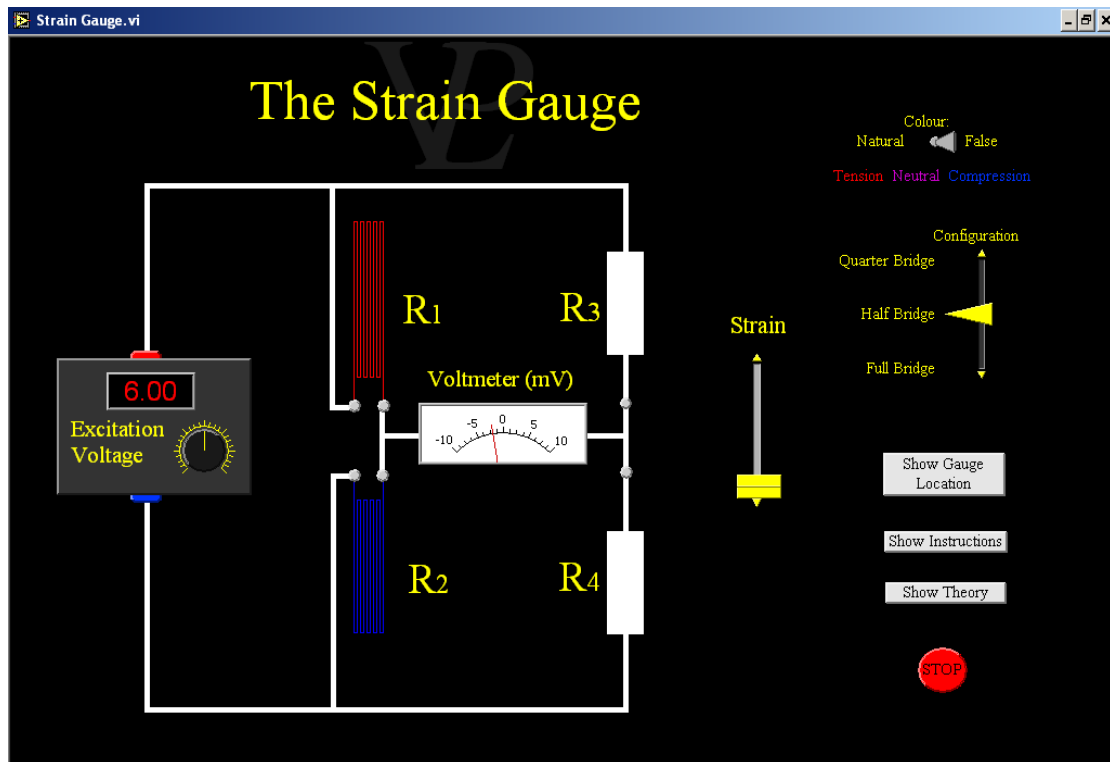
A is the cross sectional area of the conductor

and ρ is a constant for the material called the resistivity. It has units of Ohm metre.

7.10 Strain Gauge

Advanced

This simulation illustrates how a very small change in resistance of a thin wire as it is stretched can be used to measure strain. It uses a Wheatstone bridge to convert the change in resistance into a change in Voltage



Strain Gauges are very useful resistors which vary their resistance by a very small amount when stretched or compressed. When stretched, their resistance increases (because the very thin wires get longer and thinner) and when compressed their resistance decreases (because the very thin wires get shorter and thicker).

The mathematical relationship governing its resistance change with strain is $\frac{dR}{R} = G e$, where R is the mean resistance of the Gauge, dR is the change in resistance, G is the Gauge Factor and e is the strain. It is good practice to match the remaining resistors so that they have approximately the same resistance as the unstrained gauge.

From the principle of the Wheatstone Bridge it can be shown that $V_{out} = V_{ex} \frac{dR}{4R}$ or $V_{out} = V_{ex} \frac{G e}{4}$ (for the Quarter Bridge)

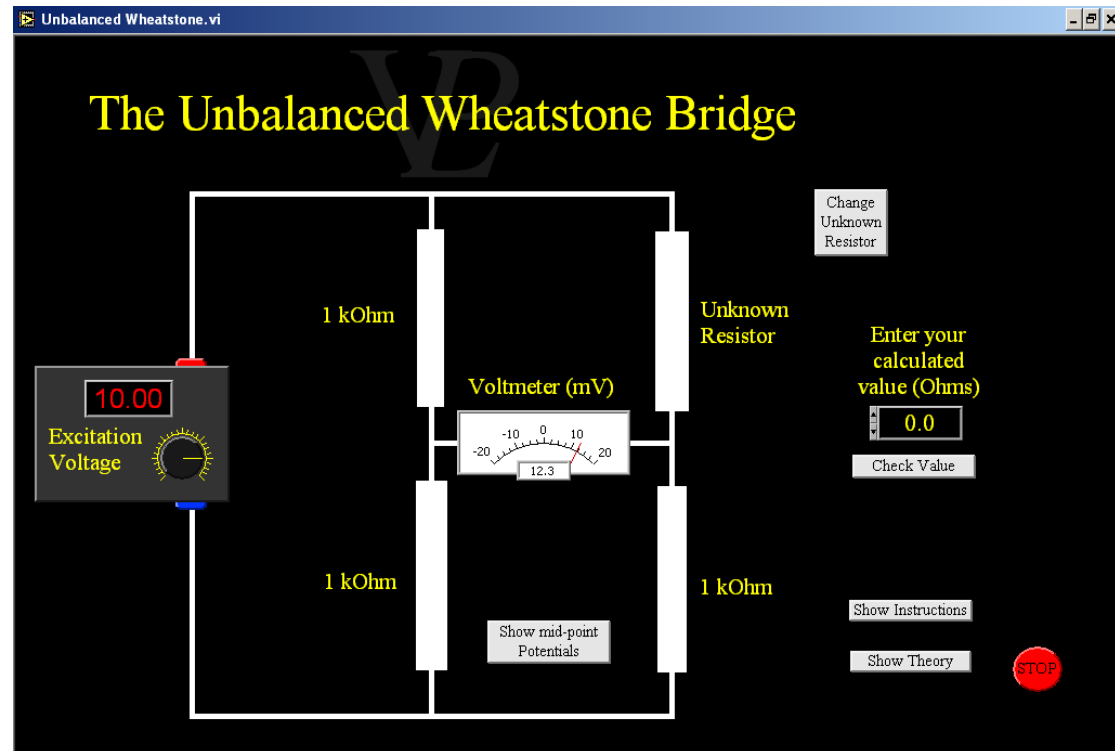
So the output Voltage (normally a few milliVolts) is a measure of the amount of strain.

The Voltage sensitivity to strain of the Half Bridge configuration is twice that of the Quarter Bridge (because the second strain gauge varies its resistance in the opposite way, thus doubling the effect).

7.11 Unbalanced Wheatstone

Advanced

This simulation shows how a Wheatstone bridge can be used to find the resistance of an unknown resistor.



The Unbalanced Wheatstone Bridge is a very useful circuit which has many practical applications. Its main application is to measure very small changes in resistance. It achieves this by measuring the potential difference between the two unbalanced potential divider arms. Unlike the balanced Wheatstone, this circuit has no moving parts.

The Wheatstone Bridge is essentially a double potential divider, with a galvanometer (or very sensitive ammeter) measuring any small current which might flow between the mid points of the two potential dividers.

The potential at the mid point of the left hand side is given by

$$V_{\text{left}} = V_{\text{exc}} \frac{R_2}{(R_1 + R_2)}$$

The potential at the mid point of the Right hand side is given by

$$V_{\text{right}} = V_{\text{exc}} \frac{R_3}{(R_u + R_3)}$$

So the potential difference $\Delta V = V_{\text{left}} - V_{\text{right}}$

$$\Delta V = V_{\text{exc}} \left\{ \frac{R_2}{(R_1 + R_2)} - \frac{R_3}{(R_u + R_3)} \right\}.$$

Solving for R_u and defining $V_f = \Delta V / V_{\text{exc}}$ (the fractional voltage change - therefore dimensionless) we obtain

$$R_u = [V_f (R_1 R_3 + R_2 R_3) + R_1 R_3] / [R_2 - V_f (R_1 + R_2)]$$

If $R_1 = R_2 = R_3 (= R)$, this expression reduces to

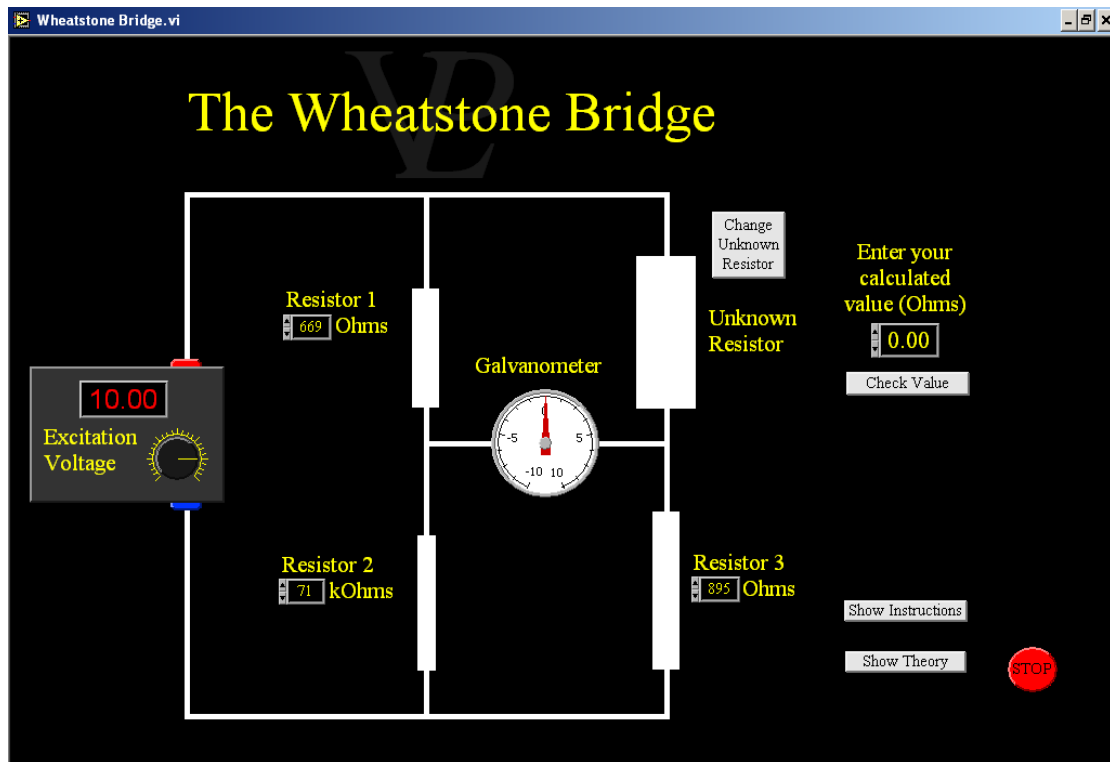
$$R_u = R (1 + 2V_f) / (1 - 2V_f)$$

Since ΔV and the V_{exc} are both known, if the fixed resistances are known it is possible to calculate the variable unknown resistance. (Although it is not a linear function, at least it can be calculated explicitly!).

7.12 Wheatstone Bridge

Advanced

This simulation explains the basic function of a Wheatstone Bridge. By varying the values of known resistors it is possible to balance the bridge and calculate the value of the unknown resistor.



The Wheatstone Bridge is a very useful circuit which has many practical applications. Its first application was to measure the resistance value of a small resistor.

The Wheatstone Bridge is essentially a double potential divider, with a galvanometer (or very sensitive ammeter) measuring any small current which might flow between the midpoints of the two potential dividers.

Current will only flow (in either direction) if the potential at the midpoint of one potential divider is different to the potential at the midpoint of the other.

If the resistances can be adjusted in such a way that no current flows at all, then the potentials at the two midpoints must be exactly equal. Algebraically this can be expressed as: $V_{exc} \frac{R_2}{R_1 + R_2} = V_{exc} \frac{R_u}{R_u + R_3}$ where

V_{exc} is the excitation voltage

R_1 & R_2 are the top and bottom resistors in the first potential divider, and

R_u & R_3 are the top and bottom resistors in the second potential divider.

R_3 is the unknown resistor.

(Notice that the value of the excitation voltage does not matter as it cancels out!)

Rearranging this equation we find that $R_u = R_1 \left(\frac{R_3}{R_2} \right)$

CHAPTER 8

ELECTROMAGNETISM

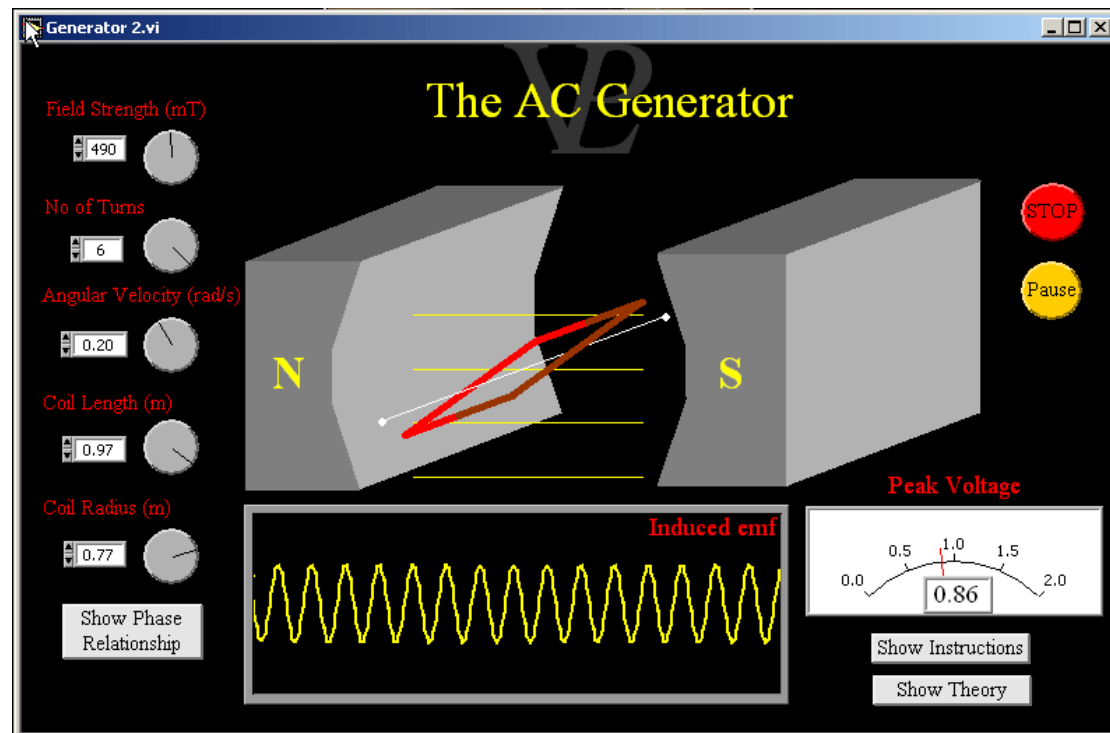


Electromagnetism is even used to mix food.
How do electricity and magnetism mix?

8.1 AC Generator

Basic/Advanced

This simulation shows how alternating currents are induced in a rotating coil. The coil parameters can be varied in order to investigate the effect. The phase relationship between the coil orientation and the induced emf are also shown.



Michael Faraday, sometimes known as the 'Father of Electricity', discovered that whenever a conductor cuts across magnetic field lines it causes a 'electromagnetic force' (known as an emf) to be induced across the ends of that conductor. The unit of emf is Volts, so it is also correct to describe the emf as an induced voltage.

The size of the voltage induced depends on the strength of the magnetic field, the length of the conductor cutting across the field and speed with which the wire cuts through. If additional wires are connected in series with the first one, that can also increase the induced voltage.

The AC generator is the way in which almost all electricity is produced today. Water or steam driven turbines are used to turn coils inside large electromagnets.

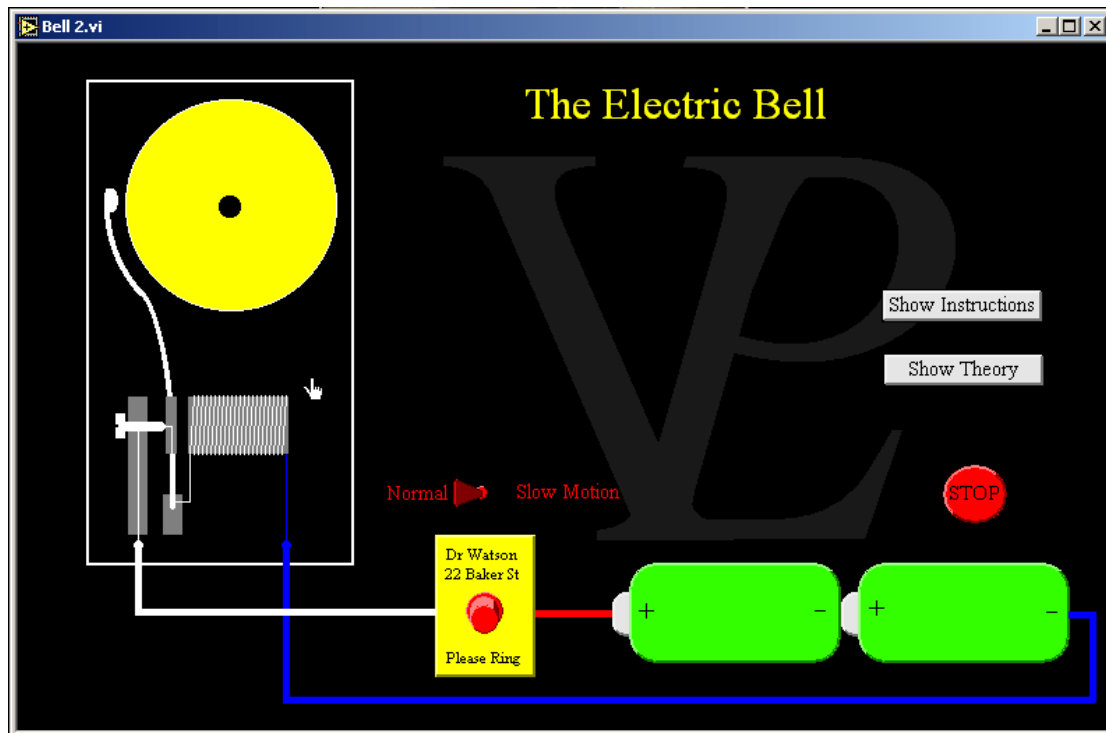
Notice that although the magnetic flux through the coil is maximum when the plane of the coil is perpendicular to the magnetic field, the rate of change of flux at that position is a minimum. By contrast, notice that although the magnetic flux through the coil is minimum when the plane of the coil is parallel to the magnetic field, the rate of change of flux at that position is a maximum.

Since the induced emf is equal to the rate of change of flux linkage, the emf (and consequent current) is maximum when the plane of the coil is parallel to the magnetic field.

8.2 Bell

Basic

This simulation shows the energising and de-energising of the electromagnet that operates an electric bell. Fast and slow motion are included.



When the hammer is in its resting position, the arm is resting against the screw, making electrical contact so that current will reach the electromagnet and create a magnetic field.

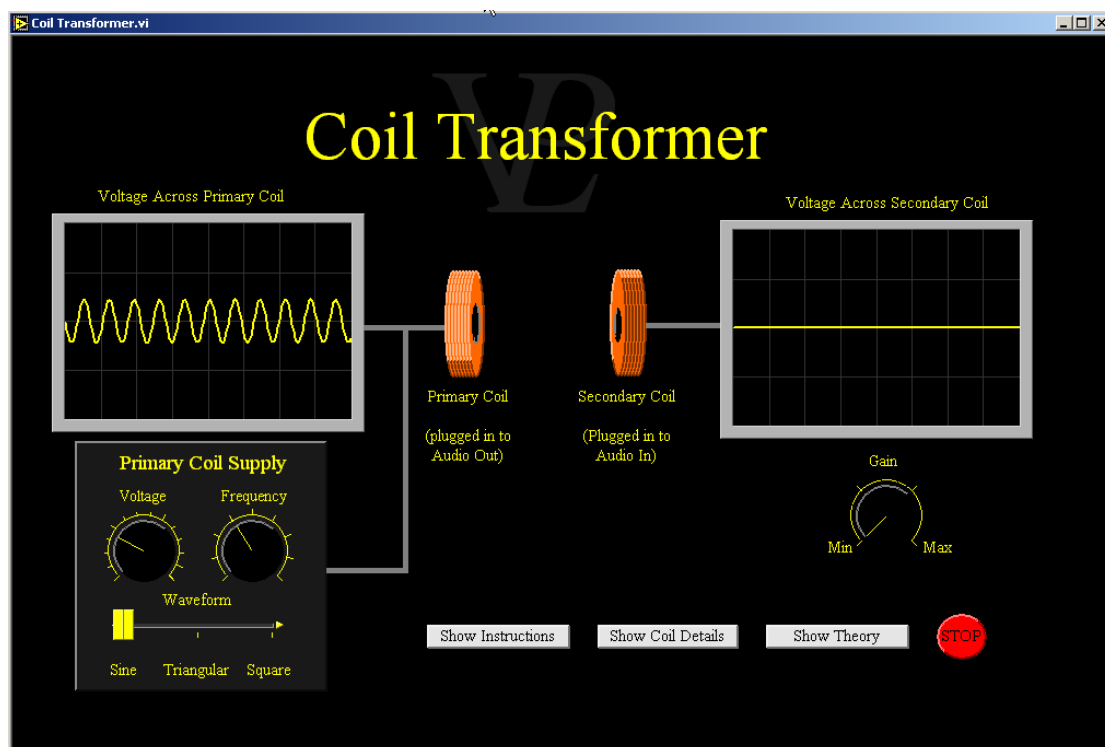
The electromagnet will attract the hammer towards the bell and make it strike the bell. As the hammer hits the bell, it opens up the circuit, so that the current no longer flows through the electromagnet. This means that it no longer has a magnetic field and so no longer attracts the hammer.

The hammer then springs back to its resting position, from where the operation starts all over again.

8.3 Coil Transformer

Advanced

With this program the user can plug in a small coil to the audio output of his computer, and plug a similar coil in to the audio input of the computer. When a common iron core is inserted between the coils an emf is induced in the secondary coil and is displayed on the right hand display.



The principle of the transformer is explained in the "Transformer" simulation in the "Electromagnetism" and "AC Electricity" chapters of the Virtual Physical Laboratory.

This program was written to enable the user to experiment with real coils (provided he makes them first!).

A coil or solenoid connected to a DC current becomes an electromagnet. If the coil is connected to an AC current supply, then the direction of the magnetic field threading the coil will alternate in direction.

If a second coil is brought in to close proximity to the first one, some of the magnetic field will penetrate the turns of this secondary coil causing an induced emf (electromotive force) or Voltage.

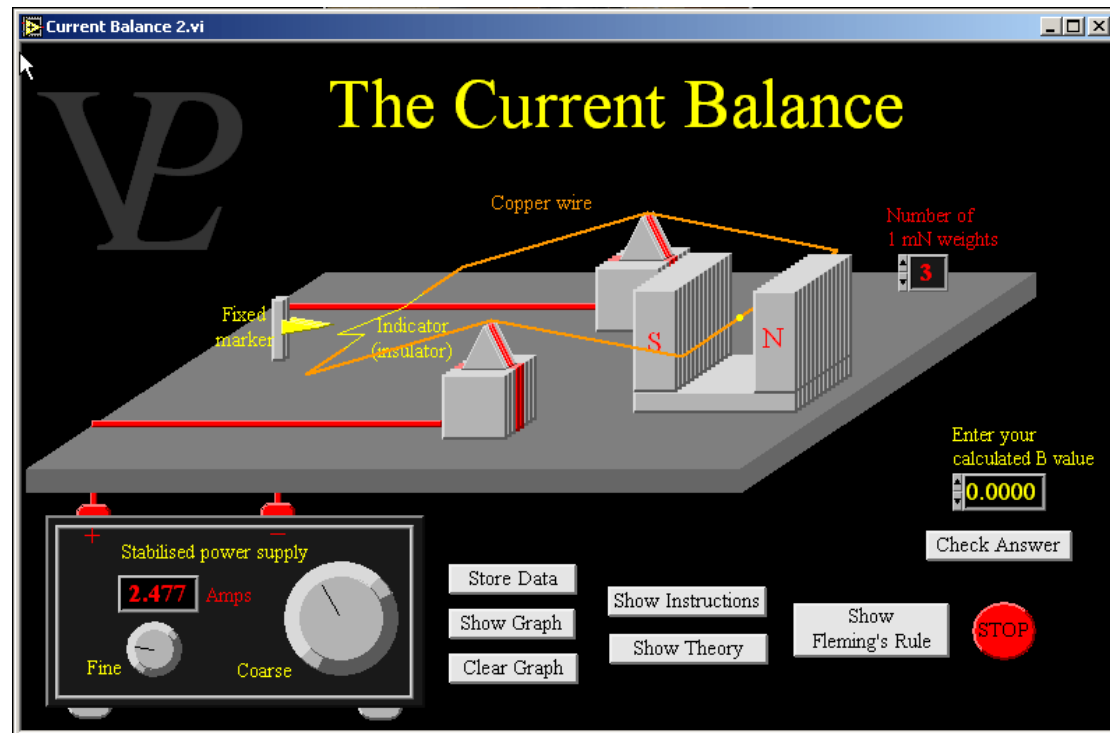
If a soft iron rod is inserted through both coils, this will strengthen the magnetic field inside both of them, and so the induced Voltage in the secondary coil will also increase.

If the iron core is made moveable, the user will be able to verify that the secondary Voltage is proportional to the position of the iron core. This is the principle of LVDTs (Linear Voltage Displacement Transducers).

8.4 Current Balance

Advanced

This simulation explains how a current balance works. In this example it is used to measure the strength of the magnetic field in which the wire moves.



The force experienced by a current which flows perpendicularly across a magnetic field follows Fleming's Left Hand Rule. The size of the force is given by the equation $F = BIL$ where

B is the magnetic field strength,

I is the current,

L is the length of the conductor inside the magnetic field

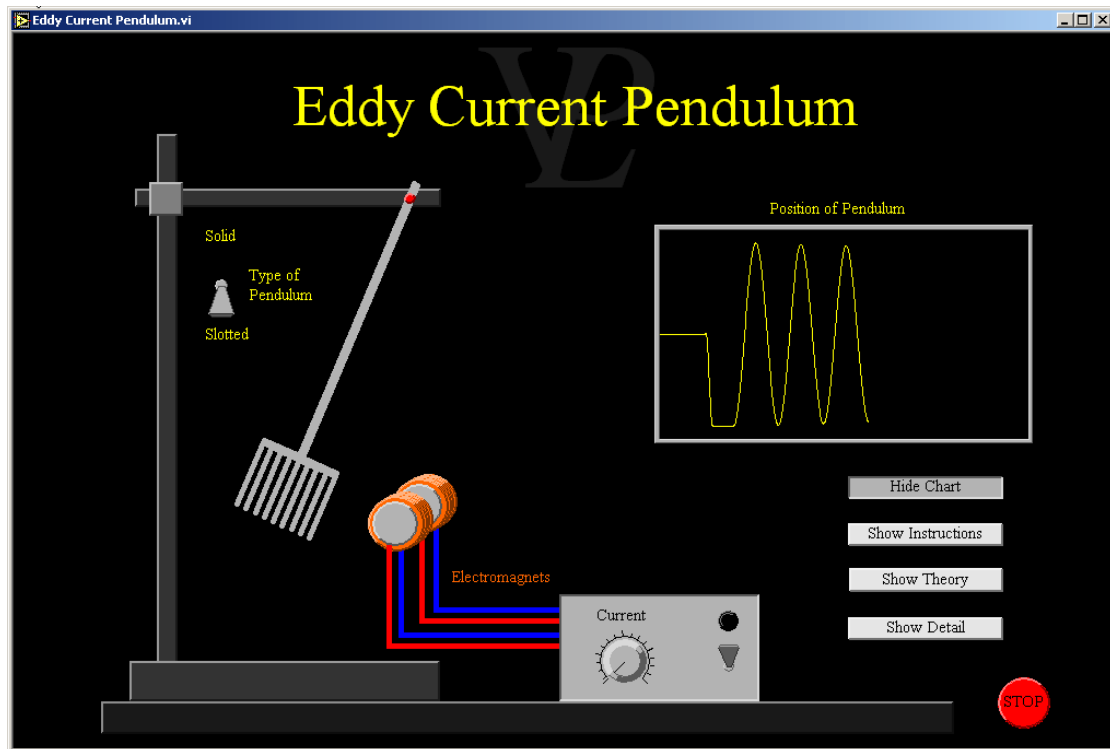
When balanced, $BIL = W$, where W is the weight of the additional masses on the wire.

Notice that because the balance is not perfect, some small current is required to balance it even when it is unloaded. If data pairs for weight and current are obtained, a graph of weight vs current can be plotted and the gradient will be equal to BL . The length of the conductor inside the magnetic field in this simulation is 5 cm.

8.5 Eddy Current Pendulum

Advanced

This simulation shows the damping effect that eddy currents can have on the free swinging of a pendulum. It is a graphic illustration of how induced current flow to oppose the change producing them.



This experiment is known as Waltenhofen's pendulum. It is a simple demonstration to show the truth of Lenz's Law of electromagnetic induction. When a conductor cuts perpendicularly across a magnetic field, an electromotive force is induced which tries to drive a current which will oppose the change producing it. If it is possible for the current to flow, the motion will be opposed.

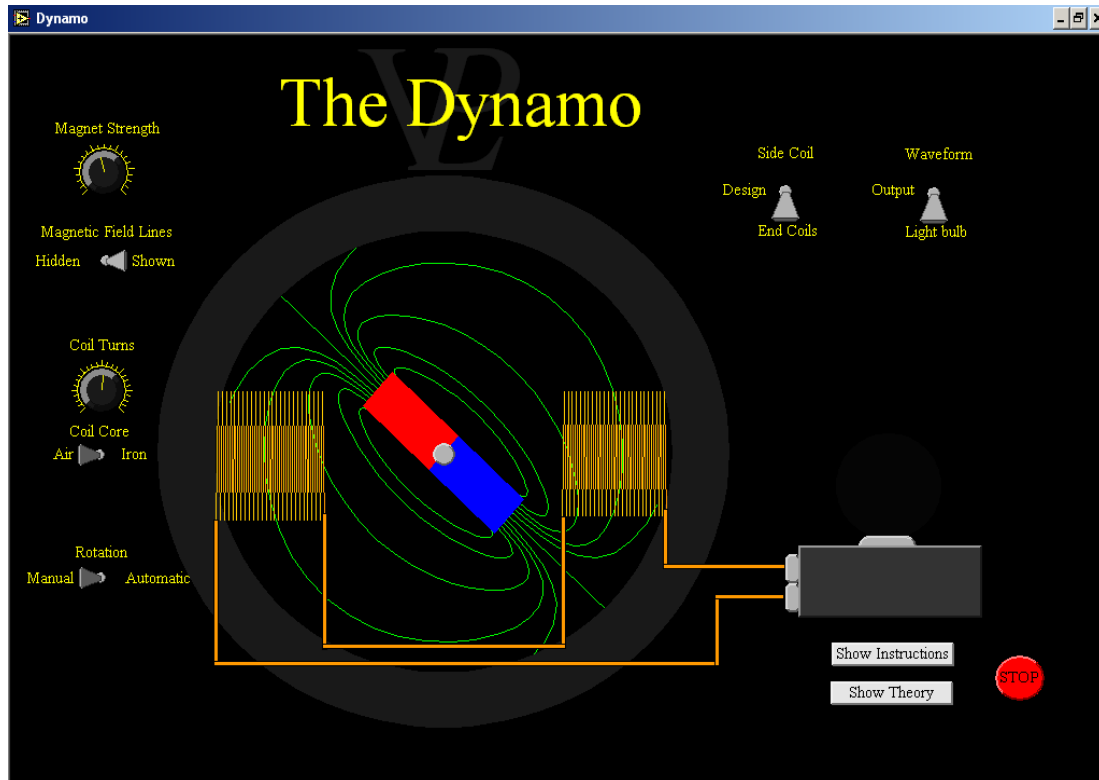
When a conducting plate is dragged across through a magnetic field, emfs are induced and these will drive eddy currents which will oppose the motion. In the case of the pendulum, the oscillation is severely damped.

When a slotted conducting plate is dragged through a magnetic field, the emf is still induced, but the currents cannot find a conduction path, so the eddy currents cannot flow. Consequently the motion is not opposed. The slotted pendulum will continue to swing much longer.

Eddy currents are used to good effect in large trucks and trains fitted with electromagnetic braking. Powerful electromagnets are placed around the brake disks or the steel wheels of trains, and when the magnets are energised, they cause eddy currents to flow through the discs. The kinetic energy of the truck or train is turned into heat in the discs without friction. This means that there is very little wear. It should be noted however, that electromagnetic braking cannot be used to bring a vehicle to a complete stop. Conventional brakes must still be used.

8.6 Dynamo

This simulation shows the internal workings of a dynamo, and how the magnetic field threads through the coils to produce an emf when it is changing.



Michael Faraday, sometimes known as the 'Father of Electricity', discovered that whenever a conductor cuts across magnetic field lines it causes a 'electromagnetic force' (known as an EMF) to be induced across the ends of that conductor.

The unit of emf is Volts, so it is also correct to describe the EMF as an induced Voltage. The size of the Voltage induced depends on the strength of the magnetic field, the length of the conductor cutting across the field and speed with which the wire cuts through.

The Dynamo is one of the simplest types of electrical generator, where only the magnet spins round and the coils remain stationary. This means that no sliding contacts are needed, so the friction is kept as low as possible. This makes the dynamo a good type of generator for a bicycle where the cyclist does not want to waste energy in unnecessary friction.

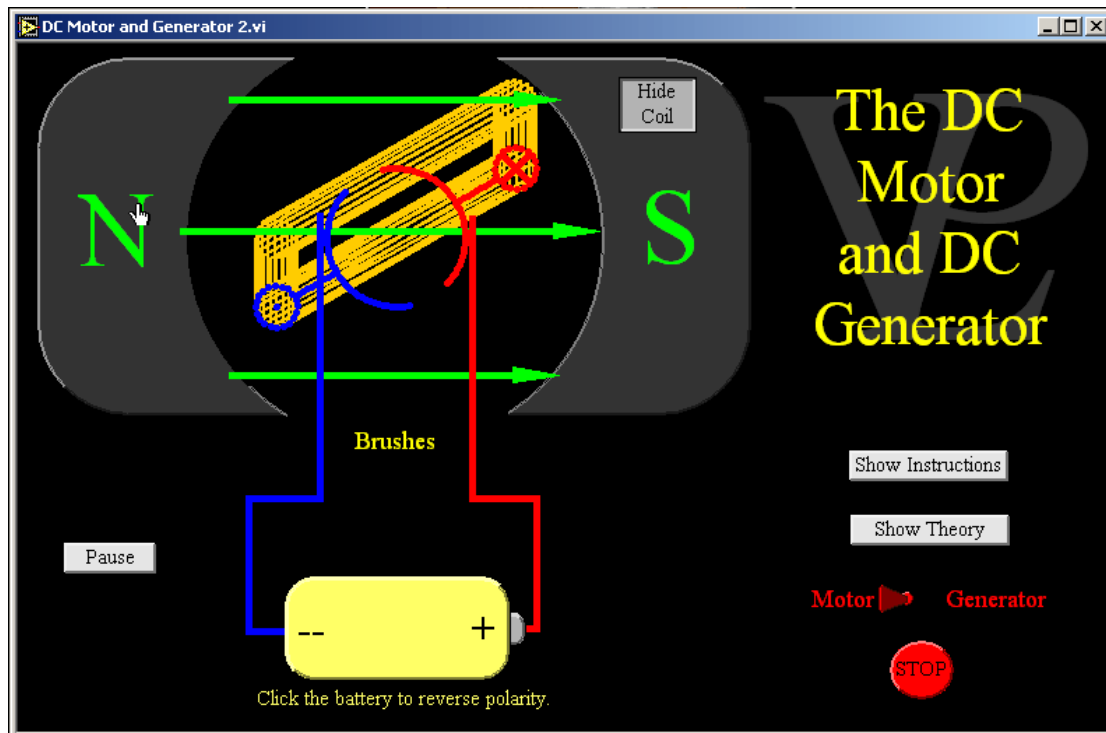
The EMF is a maximum when the magnet is strong, the coils have many turns and have iron cores, and the magnet is turning as fast as possible.

The output waveform from a dynamo is alternating, but it does not have a clear or consistent pattern. The output from dynamos is normally only used for powering incandescent light bulbs, where the bulb stays lit (hot) for a short while even when the Voltage drops to zero (so the bulb does not appear to be flashing on and off). In principle the alternating Voltage could also be rectified and used to charge batteries as in the case of a wind-up torch which stays alight for a few minutes after the movement has stopped.

8.7 DC Motor & Generator

Basic/Advanced

This simulation shows how a DC Motor and Generator are essentially the same thing which differs depending on whether current or motion are supplied to it.



The Generator: Notice firstly that the generator has to be driven by an external source of motion. A current is only induced when the conductor is cutting across the magnetic field lines. When the conductor is cutting the magnetic field downwards the current flows outwards (+ve) towards the commutator and down the brush. This follows Fleming's Right Hand Rule.

In this simple case no current is flowing at the time that the brushes are changing contact on the commutator so no sparks are generated. If the direction of rotation is changed, the polarity of the current is reversed. If the velocity of rotation is increased, the amplitude of the induced current increases.

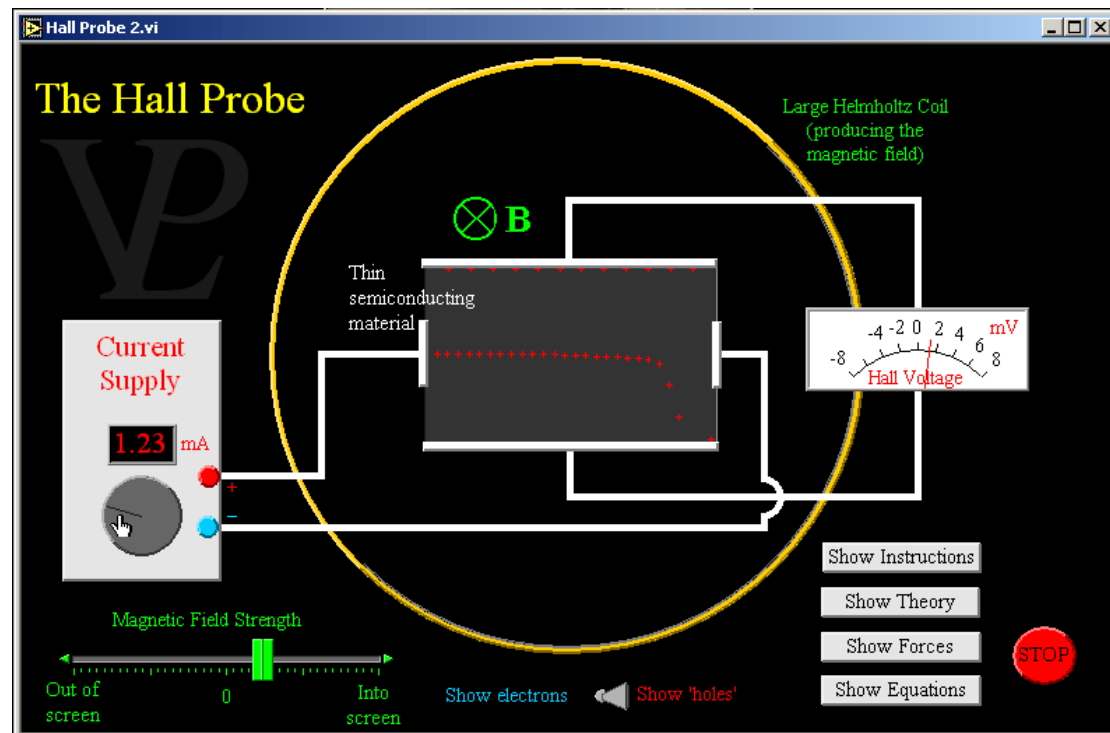
The DC Motor: Even though the brushes are always positive and negative, because they are connected to the battery, a current only flows when the split ring is touching the brushes. When this happens, the current flowing perpendicularly across the magnetic field (into the screen), experiences an upward force. This follows Fleming's Left Hand Rule.

When the current is flowing perpendicularly across the magnetic field and out of the screen, the conductor experiences a downward force (also Fleming's Left Hand Rule). If the battery is connected the other way round, the direction of the current is reversed, so the direction of the force is also reversed, and so is the direction of rotation.

8.8 Hall Probe

Advanced

This simulation aims to show what is going on inside a Hall probe. It illustrates clearly how the electrostatic and magnetic forces balance. The current and the magnetic field strength can be adjusted



When charges travel across a magnetic field they experience a lateral force which follows Fleming's left hand rule. This happens immediately. If the charges which have been pushed sideways accumulate on an electrode at the top or bottom, they will start to repel additional charges from coming their way (they create an opposing electric field). This happens in less than a microsecond, in this simulation the effect is delayed for clearer visualisation.

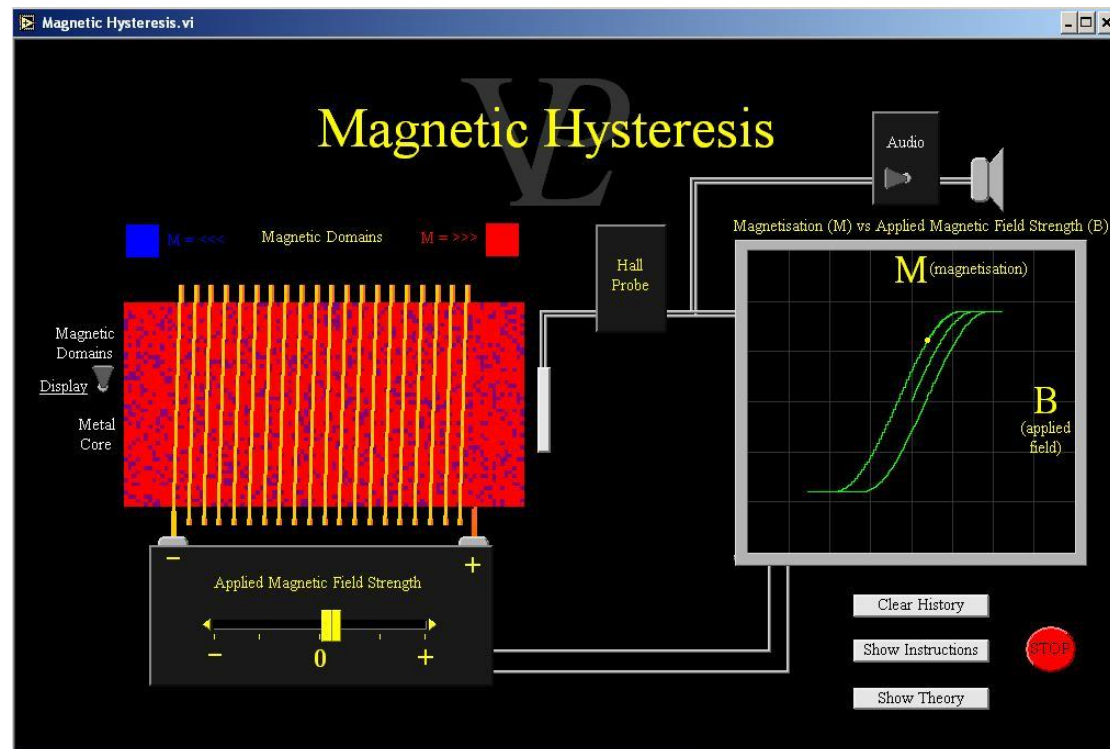
It is important to realise that the electric field is produced as a consequence of the electromagnetic force on the charge carriers which causes them to accumulate on one electrode. Very soon, the electric field will exert a force on the charges which is equal and opposite to the magnetic field. In this steady state there will be a potential difference between the top and the bottom electrodes. If the direction of the magnetic field is reversed, then the forces on the charges will also be reversed, so the electric field will also reverse, and so invert the potential difference.

The potential difference developed across the semiconductor is called the 'Hall Voltage' and can be used as a measure of the magnetic field strength. The Hall voltage is greatest when the number of charge carriers per unit volume is small (semiconductor) and the thickness of the material is very small. This principle is incorporated into what is known as the Hall Probe, a device which measures magnetic field strength.

8.9 Hysteresis

Advanced

This simulation shows how magnetic domains align with the externally applied field and how they remain slightly magnetised after the external field is removed.



When an external magnetic field is applied to a ferromagnetic material, the individual magnetic domains inside the material try to start to align with the direction of the applied field. Those magnetic domains already oriented in the right direction will try to grow by widening their boundary into surrounding domains until they cause them to flip to the applied direction.

When this happens, there is a small (but discrete) jump in the overall magnetisation of the material. If a magnetic sensor is placed in close proximity, and the signal is amplified, and connected to a speaker it will produce a series of small clicks called "Barkhausen Noise". This was the first direct piece of evidence for the existence of magnetic domains.

"Magnetically soft" materials (like soft iron) will magnetise fairly easily, but will lose their magnetism the moment the external field is switched off. These materials are good choices for electromagnets and the cores of transformers.

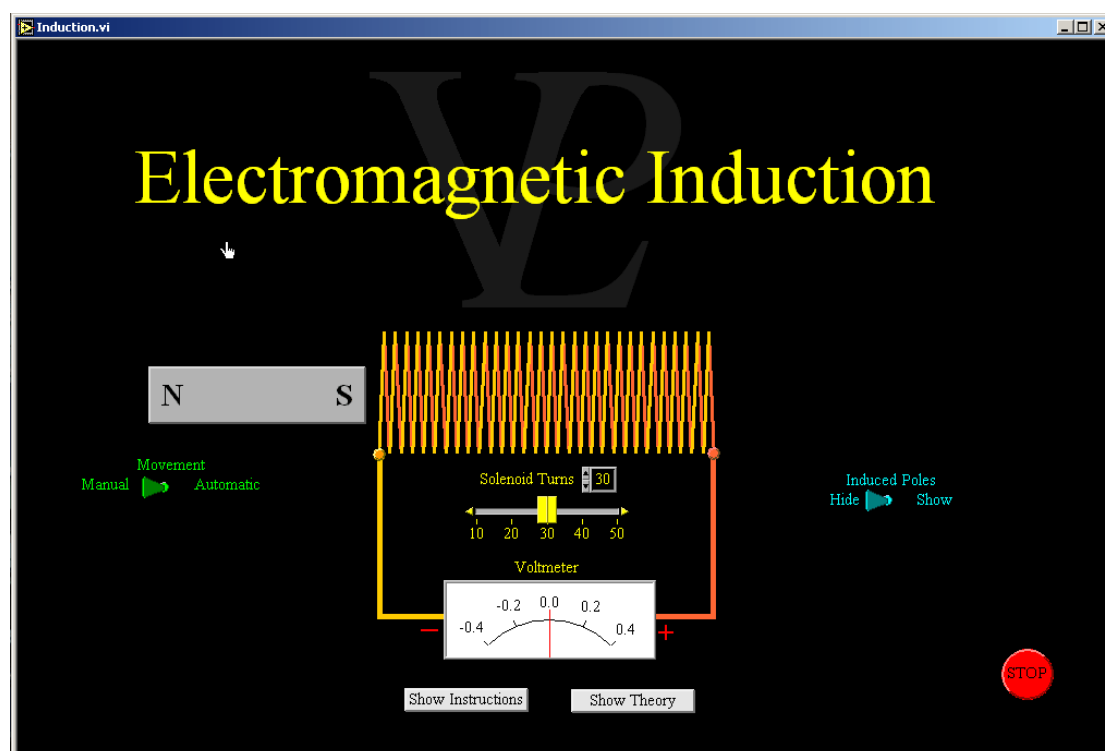
"Magnetically hard" materials (like steel, cobalt and neodymium) are harder to magnetise, but retain their magnetism even when the applied field is switched off. What is more, in order to demagnetise them, an opposite magnetic field must be applied. The strength of the opposite magnetic field required to demagnetise the material is called its "Coercivity".

The remanence and coercivity of a material mean that the amount of magnetisation achieved at any one point will depend on the magnetic history of the material. If the material is fully magnetised one way, and then fully magnetised the opposite way, and the level of magnetisation is plotted versus the applied magnetic field strength, the result is a 'hysteresis loop' that is characteristic for that material.

8.10 Induction

Basic/Advanced

This simulation allows the user to slide a magnet left and right through a wire coil to see how an electric current is made to flow through a galvanometer. The effect of the direction and speed can also be studied.



When a magnet is pushed through a coil it will try to make a current flow through it. Current will only be able to flow if the circuit is completed with a bulb, a Voltmeter, or other electrical component.

The current flowing through the coil will turn it into an electromagnet, and this electromagnet will always take on a polarity which will try to oppose the movement of the magnet that caused the change. This 'opposition' is described by Lenz's Law: Induced currents always flow in such a way as to try to oppose the changes producing them. This 'opposition' is a consequence of conservation of energy. If the current flowed the other way it would try to increase the change producing it. This would make the change bigger, and the current would also become bigger... and so on to infinity!

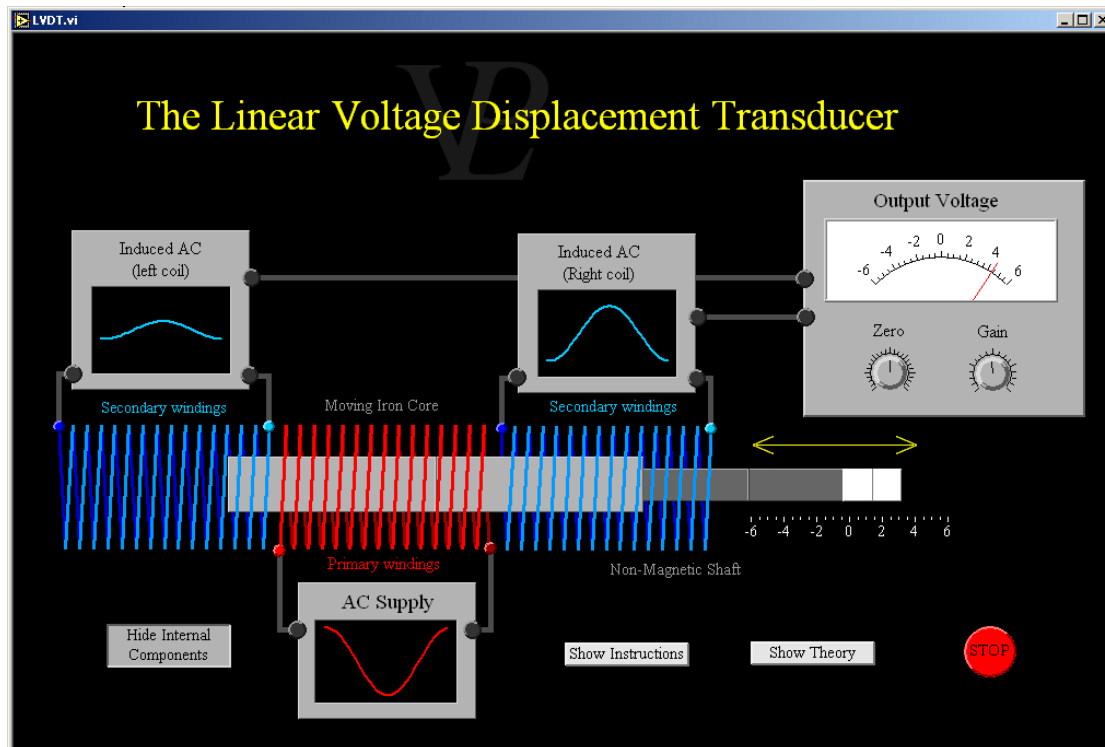
The work done against the 'magnetic opposition' gets converted into electrical energy. As soon as the work stops, the electrical energy also stops. This is why dynamo operated lights go out as soon as the bicycle stops.

Note: It is easier to understand the effect when the magnet is mostly outside of the solenoid! When the magnet is well inside a long solenoid, the movement does not produce much of an induced current, because the effect of the North inside the solenoid moving to the right is cancelled by the South (also inside the solenoid also moving to the right!).

8.11 LVDT

Advanced

See how the Linear Voltage Displacement Transducer (LVDT) works as a practical application of electromagnetic induction. The transducer converts displacement into Voltage.



The LVDT is a little like a pair of variable transformers (one primary coil and two secondaries)

In a normal transformer, the Voltage (or Electro Motive Force) induced in the secondary coil is proportional to its number of turns. In the LVDT, what determines the magnitude of the Voltage induced in each secondary is the length of iron core that is inside it.

When there is virtually no iron core inside a secondary coil, the magnetic field from the primary is not coupled through very well, and so the induced voltage is nearly zero. However, when there is a good length of iron rod inside both the primary and the secondary, a good voltage is induced in the secondary.

Note that only the inner part of the rod is iron (the wider lighter part). The outer part (thinner and darker) is made of a non magnetic material so that it does not affect the performance of the LVDT.

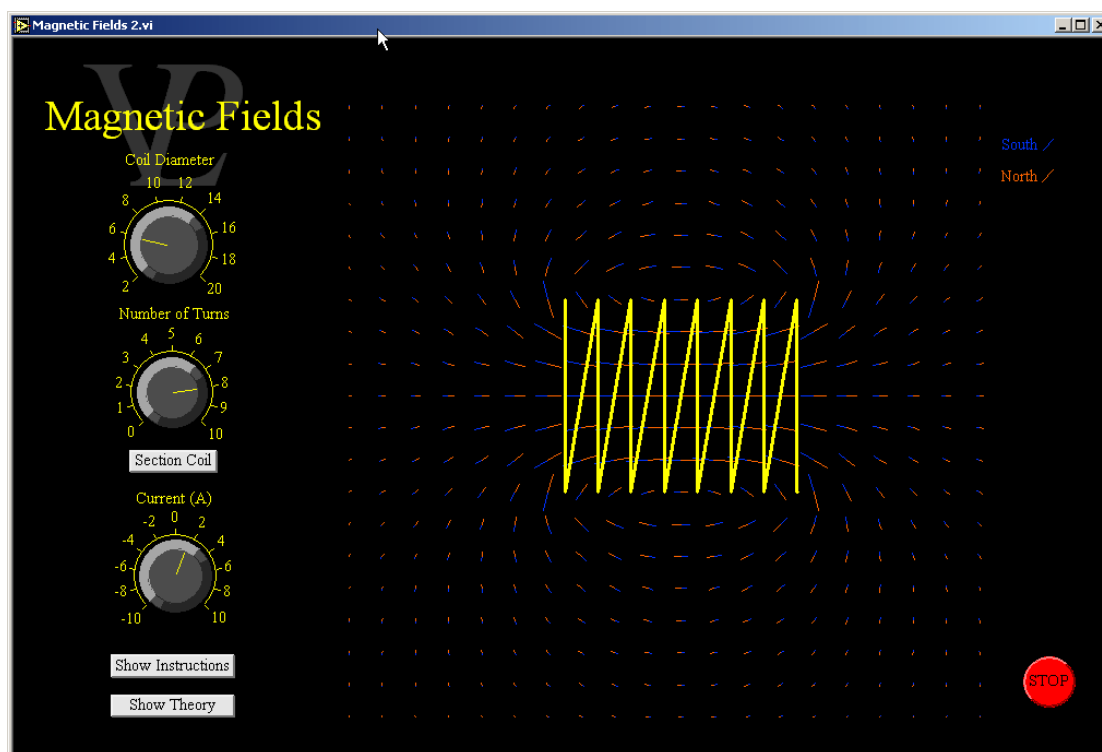
The difference in the emf induced in the left and right hand secondary coils is a measure of the position of the iron rod inside. In this way the voltage difference between the two is a measure of the displacement of the rod.

Good LVDTs are sensitive to movements as small as a few micrometres!

8.12 Magnetic Fields

Basic/Advanced

This simulation shows an array of compasses mapping out the magnetic field around a coil or solenoid with a variable number of turns. The length of the compasses shows the relative magnetic field strengths around the plane bisecting the coil.



There is always a magnetic field around a current carrying conductor. It follows the 'cork-screw rule'; when a current is flowing away from you, the magnetic field around it will be in a clock-wise direction. (If the thumb on your right hand indicates the direction of the current, the fingers of your right hand will indicate the direction in which the magnetic field wraps itself around the current. If the direction of the current is reversed, the magnetic field is also reversed.

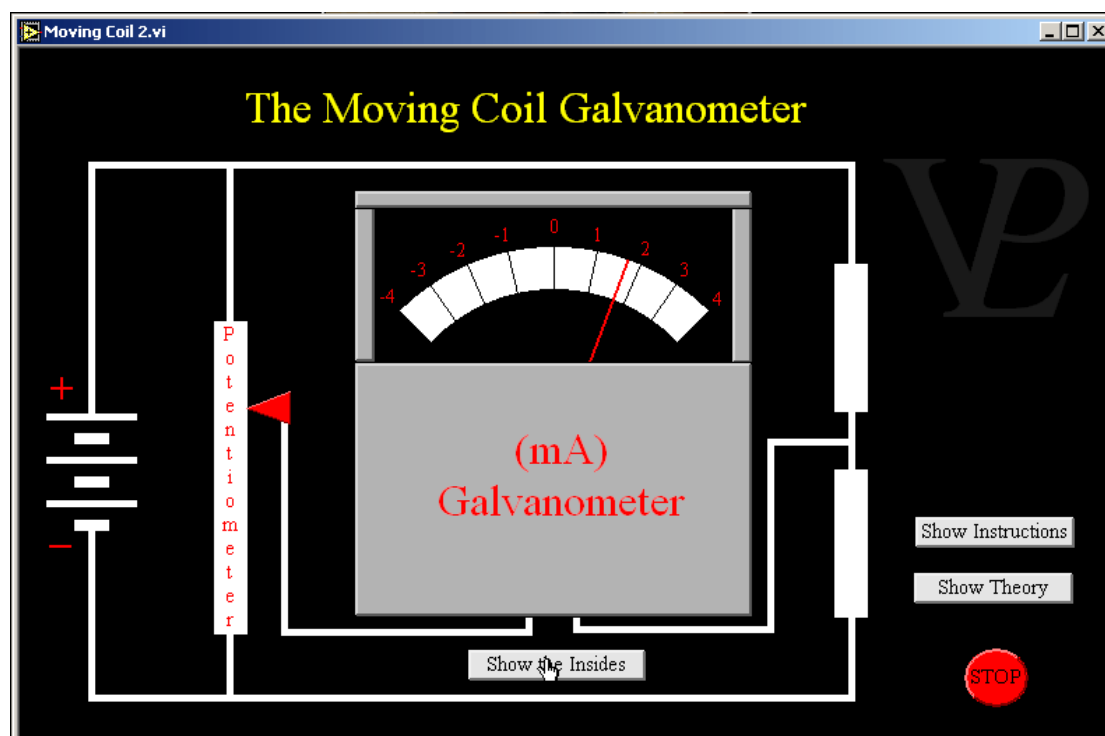
When there are a number of current carrying conductors, the magnetic field will be the sum of the fields produced by each of the currents. In a coil these tend to add up, so that the magnetic field inside the coil is stronger.

When a coil is long compared to its diameter it is called a 'solenoid'. The magnetic field inside a long and thin solenoid with many turns can be made to be very strong and very uniform.

8.13 Moving Coil

Advanced

This simulation shows the internal workings of a moving coil galvanometer. This is the basis of every analogue electrical meter.



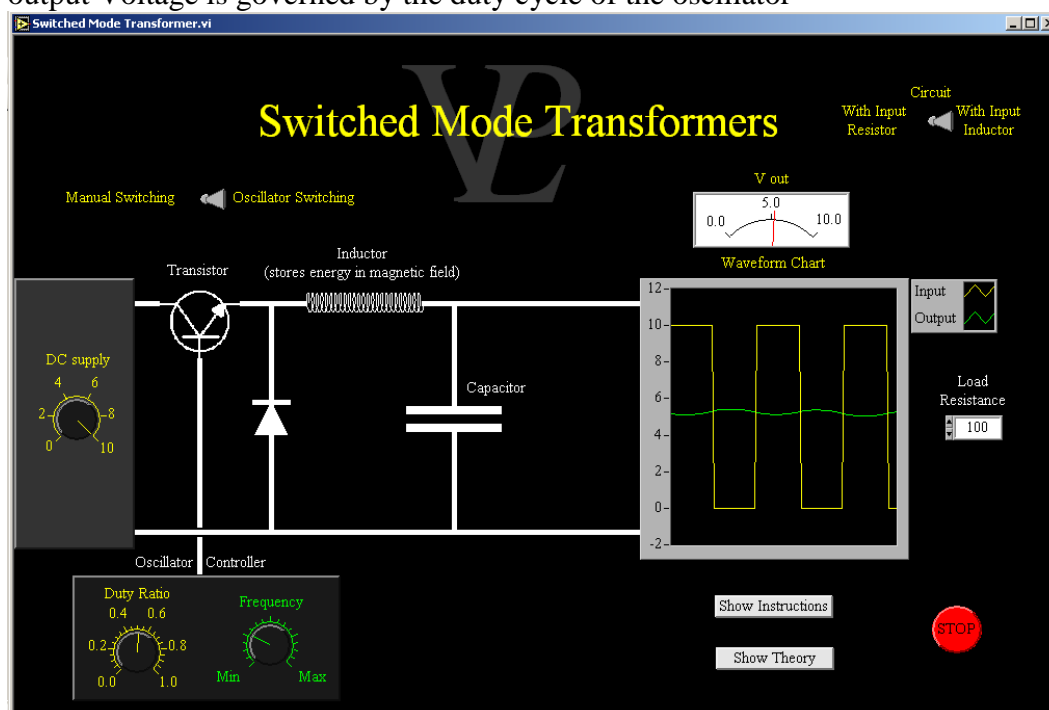
The moving coil galvanometer lies at the heart of all the 'old fashioned' Voltmeters and Ammeters. It is built a little like an electric motor, except that it has two spiral springs which hold the coil horizontally when no current is flowing through it. These same springs are used to connect to the coil so that an applied current can be made to circulate round it. If the current flows one way round, Fleming's left hand rule shows that the sides of the coil will experience equal but opposite forces (because the currents at the two ends of the coil are going in opposite directions), thus creating a couple which turns the coil (and attached needle) against the restraining forces of the springs. The larger the current, the further the coil will rotate before the spring bends enough to restrain it. If the current is applied the other way round, an opposite turning moment ensues.

Notice that the permanent magnets are concave, and that there is a cylindrical iron form inside the coil. This is to make the magnetic field be as radially symmetric as possible, so that the scale can also be as linear as possible.

8.14 Switched Mode Transformer

Basic/Advanced

This simulation explains the function of a switched mode transformer, and how the output Voltage is governed by the duty cycle of the oscillator



Switched mode transformers can be used on both AC and DC supplies. The principle consists of switching the input on and off very rapidly. The output voltage V_o is related to the input voltage V_i by the following equation. $V_o = D V_i$ where D is the duty ratio $D = t_{on}/(t_{on}+t_{off})$. Switched mode transformers use capacitors and inductors (not resistors) and this means that very little energy is wasted as heat. For switched mode transformers to be compact and lightweight, the inductors as well as the capacitors need to be very small. In order to achieve ripple free voltages they are switched at relatively high frequencies (>20 kHz).

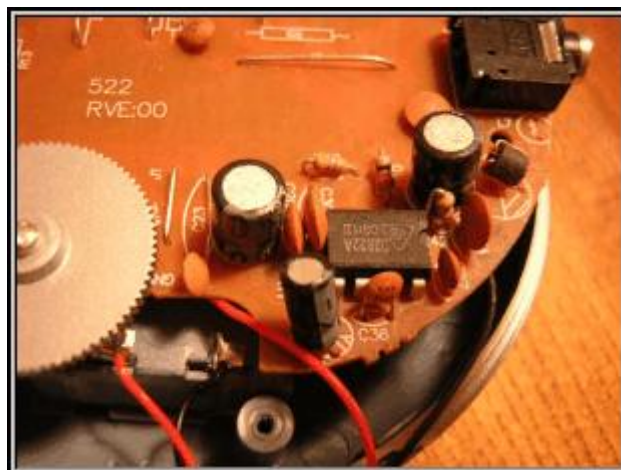
The back EMF E of an inductor is given by $E = -L \frac{dI_{in}}{dt}$ where I_{in} is the current flowing in to the capacitor from the source and L is the inductance. The rate of change of the capacitor Voltage V_c is given by $\frac{dV_c}{dt} = (I_{in} - I_{out})/C$.

When the transistor is switched on, the rise in the current flowing in to the capacitor is somewhat limited by the inductor so that the capacitor charges slowly. When the transistor is switched off, the current flowing in to the capacitor cannot drop to zero immediately because the collapsing magnetic field in the inductor induces a forward EMF which keeps the current flowing a while longer (in this instance the current is drawn through the forward biased diode). Depending on the Duty ratio, the transistor may be switched on again before the magnetic field collapses completely, and so the current has not dropped to zero.

The smoothed ripple in the current through the inductor is further smoothed by the capacitor so that the output voltage is essentially ripple free. This can be achieved if the oscillator frequency is made sufficiently high. The main advantages of switched mode transformers is that they are energy efficient, compact, lightweight and can convert DC or AC in to well regulated DC. A different configuration to the one shown in this simulation can even produce voltages that are higher than the input source!

CHAPTER 9

ELECTRONICS

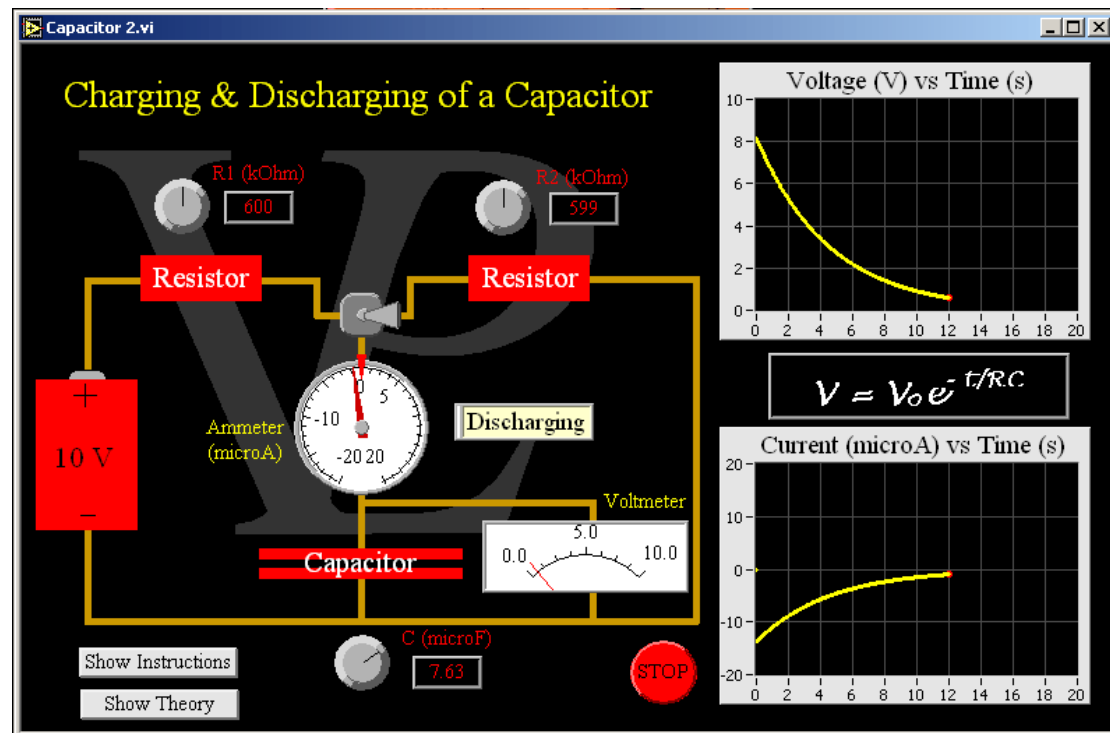


Electronic components are in nearly everything!
What does each component do?

9.1 Capacitor

Advanced

This simulation shows the charging and discharging of a capacitor through variable resistors. The size of the capacitor can also be varied. V and I graphs are plotted against time.



The time taken to charge a capacitor depends on the current flowing into the capacitor; and the current flowing into the capacitor depends on the resistance in the line and also on how charged the capacitor already is. When it is totally discharged, a large current can flow into it, but when it is nearly completely charged it is difficult to get any more charge into it, so the current will be small.

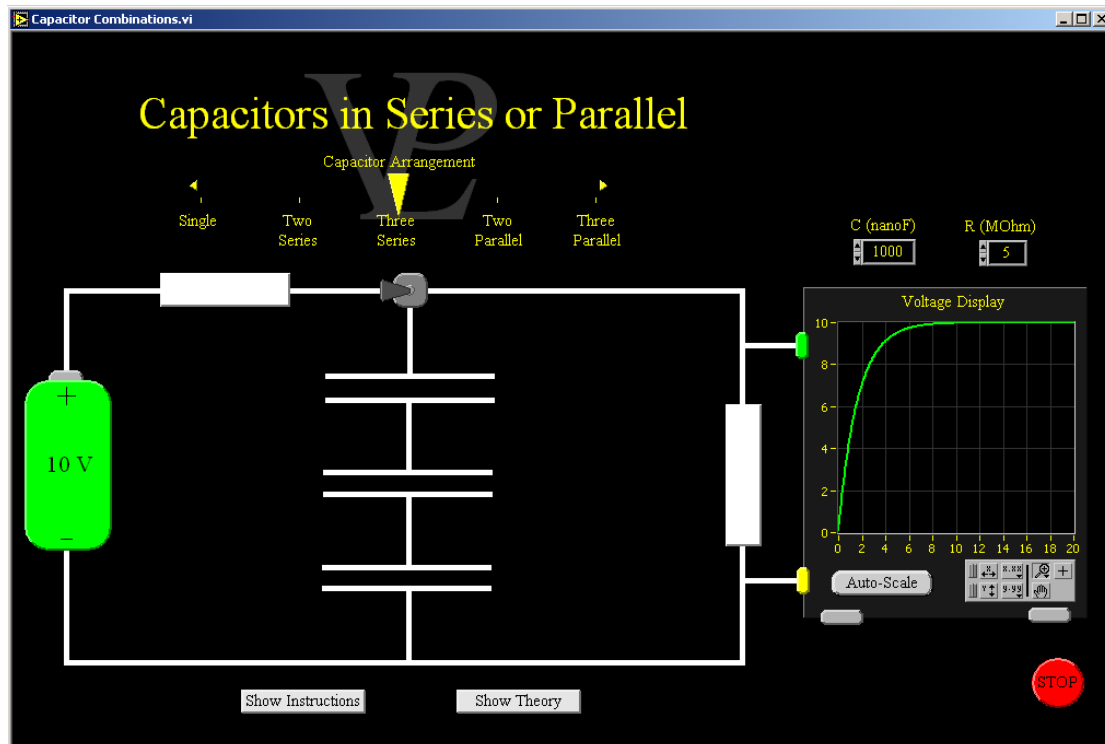
The time taken to discharge a capacitor depends on the size of the current flowing out of it. The larger the current, the sooner the capacitor discharges. The discharge current depends on the resistor through which it is discharging and also the state of charge of the capacitor.

When the capacitor is nearly full, the discharge current is large, but as the capacitor starts to get discharged, the current that flows gets smaller.

9.2 Capacitor Combinations

Advanced

This simulation shows what effect the arrangement of capacitors has on their overall capacitance.



Like resistors, capacitors can be connected together in series or in parallel. However their combined effect is the opposite to that expected from resistors:

When resistors are connected in series, the overall combined resistance increases. However, when capacitors are connected in series, their overall combined capacitance decreases.

The proof of these relationships is beyond the scope of this brief explanation, but the expressions governing combined capacitors are the following:

For capacitors in series: $1/C_{\text{total}} = 1/C_1 + 1/C_2 + 1/C_3 \dots$

For capacitors in parallel: $C_{\text{total}} = C_1 + C_2 + C_3 \dots$

(it is the opposite way round to the ways resistors combine!).

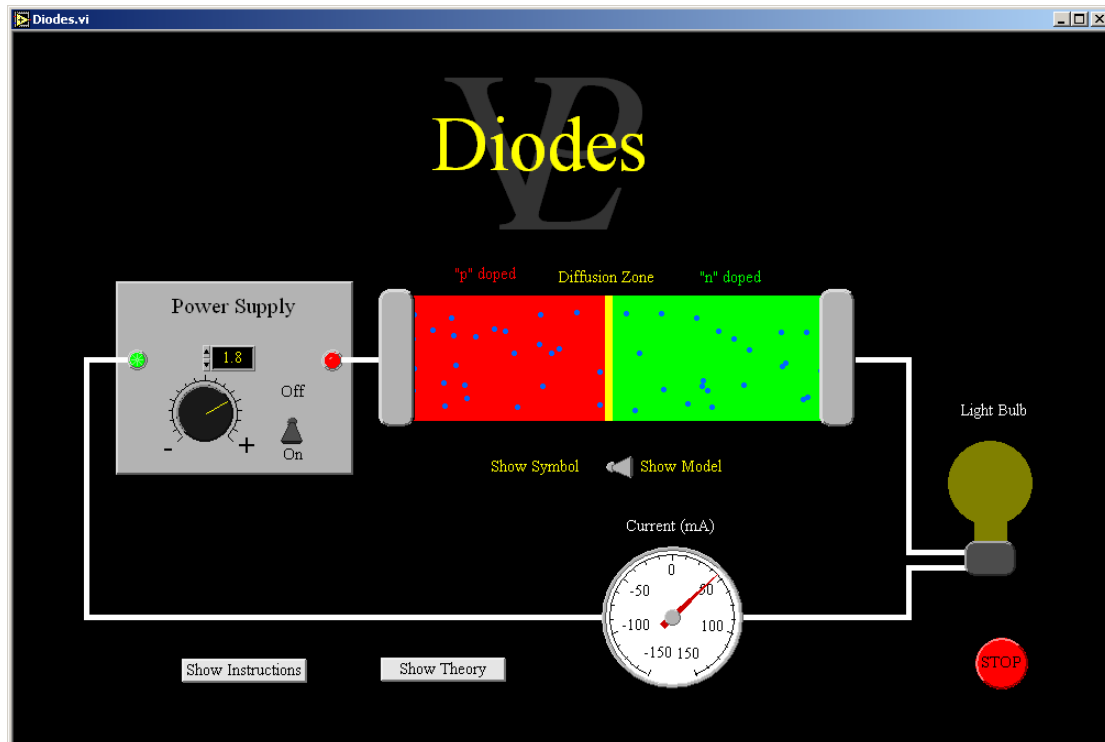
In parallel, capacitances simply add up, so it is easy to estimate what the overall capacitance will be.

In series it is a little more difficult to visualise the effect. The following short-summary can be useful to remember: When a number of different capacitors are connected in series, the overall capacitance will be smaller than the smallest of them. And when two equal capacitors are connected in series, the overall capacitance will be one half of that of a single capacitor.

9.3 Diodes

Advanced

This simulation shows the principle of the diode and how it follows from the construction of doped semiconductors. The effect of the depletion zone is shown.



In order to understand the principle of the diode it is necessary to first understand the nature of semiconductors (see that simulation first).

Diodes are electronic devices that conduct electrical current in one direction but not in the other. They are said to be 'polarised'.

Typical diodes are made by bonding a positively doped semiconductor on to a negatively doped semiconductor. At the junction between them some of the excess electrons from the 'n doped' (green) side diffuse into the 'p doped' (red) side creating a neutral diffusion zone (yellow) which is incapable of conducting electrical current.

If an external Voltage or electric field is applied across the junction in the forward direction, the electrons from the 'n doped' zone are pushed towards the diffusion zone making it narrower and narrower until electrons can jump across the diffusion zone straight in to the 'holes' of the 'p doped' semiconductor and so a current starts to flow.

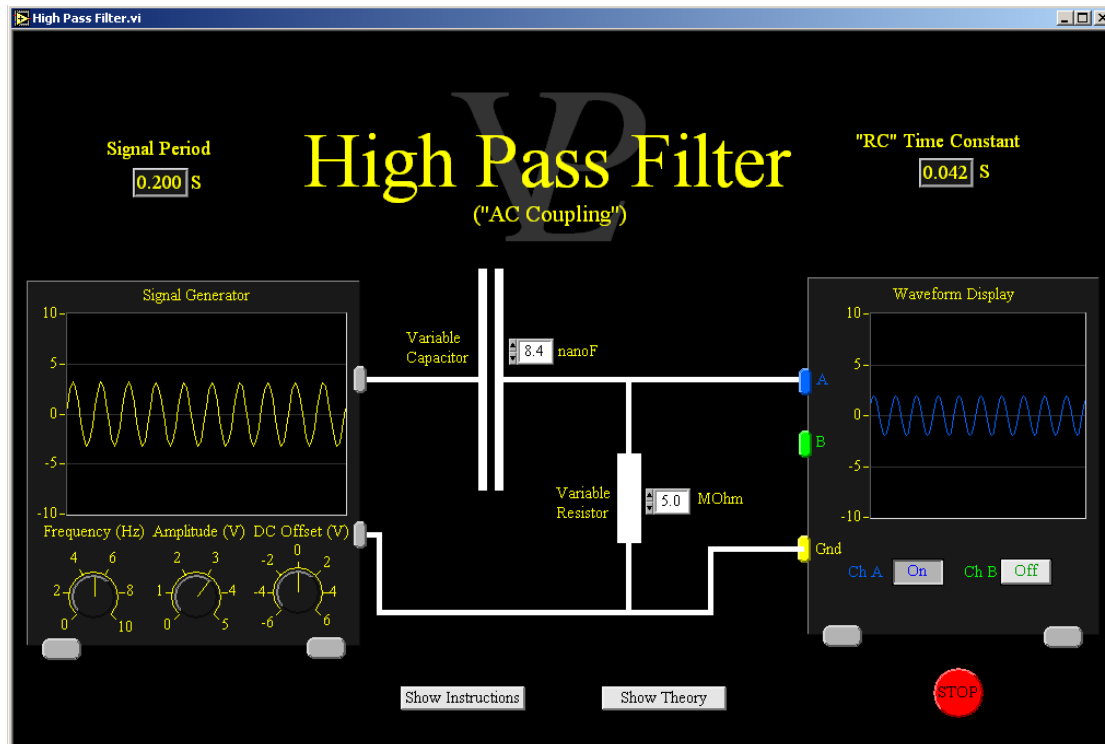
If a reverse Voltage is applied, electrons try to flow in the opposite way, but this only makes the diffusion zone wider, making it impossible for any current to flow. This is the property that makes diodes useful to 'rectify' alternating currents.

If the reverse Voltage is too large the Diode breaks down and goes 'open circuit'. That is the end of that diode - time to buy a new one!

9.4 High Pass Filter

Advanced

This simulation shows how it is possible to “AC Couple” circuits together so that only the high frequency components get through.



High Pass filters are simple circuits designed to reject unwanted low frequency components in a signal without hindering the passage of higher frequency components.

The unfiltered AC signal needs to pass through a capacitor before it can flow through the resistor. The impedance of capacitors to low frequencies is very high; this limits the current and so limits the Voltage that develops across the Resistor. If the capacitor is large, its impedance at a given frequency is smaller, allowing more varying current to flow through it; this increases the amplitude of the output. If the resistor is large, the small current flowing through it will nevertheless represent a larger voltage difference across it (Ohms Law); this also increases the output amplitude.

If the capacitor and resistor are both large, the transmitted signal will have significant amplitude even for low frequencies! Clearly the system needs to be designed to match the frequencies that are to be cut out. "High" and "Low" frequency are relative terms. They need to be compared to the "RC Time Constant" (the product of the Resistance times the Capacitance) in order to be able to know if they will pass or be attenuated.

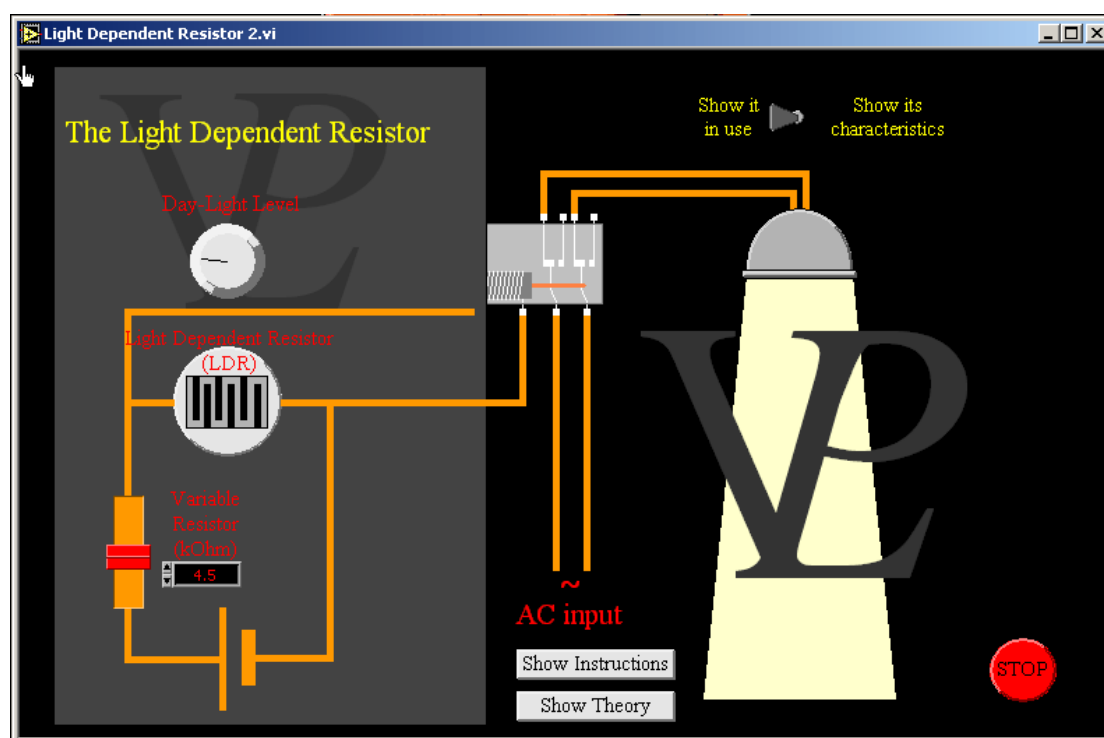
As an exercise, you might want to convince yourself that of the following: $1 \text{ Ohm} \times 1 \text{ Farad} = 1 \text{ Second}$!! (I find that amazing!)

Signals with periods around 10 times smaller than RC are nearly totally transmitted. Those with periods around 10 times larger than RC are nearly totally filtered out.

9.5 Light Dependent Resistor

Basic/Advanced

This simulation illustrates the principle and the use of a light dependent resistor. See how its resistance is affected by light intensity, and then connect it into a real circuit to operate an automatic lighting circuit where the switching threshold can be adjusted by means of a variable resistor



The light dependent resistor (LDR) is a device made out of semi-conducting material. Light makes its resistance decrease. Some students remind themselves of this using the letters LDR and making them stand for Light Decreases Resistance.

Explanation of the circuit:

The circuit is a potential divider in which the voltage from the battery is shared between the LDR and the variable resistor.

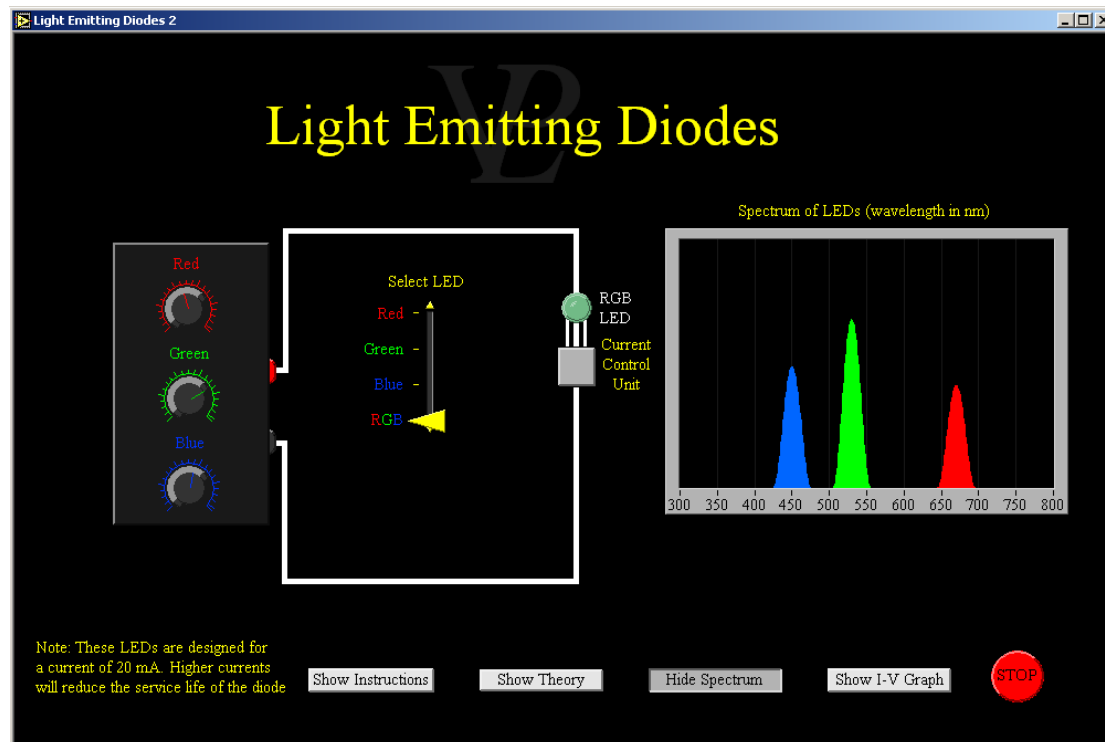
When it's light, the resistance of the LDR is low, so the LDR only gets a small share of the p.d. When it gets dark, the resistance of the LDR gets larger, giving it a larger share of the p.d. If this p.d. is large enough, it activates the relay and switches the light on.

Adjustment of the variable resistor changes the share of the p.d that the LDR is getting. This makes it possible to adjust the light level at which we wish the lamp to switch on.

9.6 Light Emitting Diodes

Advanced

This simulation illustrates the principle of the light emitting diode and shows why light is emitted as the electrons pass from one side to the other. It also shows how the voltage drop across the diode is related to the colour of the light emitted.



Light Emitting Diodes need to have a minimum potential difference across them before they can start to produce any light at all. The magnitude of the required potential difference depends on the colour of the LED. A photon is generated when an electron drops from a higher energy level in the n doped semiconductor to a lower energy state as it re-combines with a hole in the p doped semiconductor. This energy difference must be supplied by the external Voltage.

The energy difference in a red LED is smaller than that in a blue LED. Consequently a red LED requires a smaller external Voltage, but also produces a lower energy photon than the blue LED would produce.

Quantitatively we can say $e\Delta V = hf = hC/\lambda$ where:

e is the charge of an electron ΔV is the diode voltage

h is Planck's constant f is the frequency of the photon

C is the speed of light λ is the wavelength of the photon.

LEDs are fabricated to operate optimally at a particular current (normally a few tens of mA). Above a maximum permitted current the LED starts to get damaged. It is therefore important to limit the current in some way. If circuitry is available it is best to use a constant current source, but if that is not an option, a resistor should be fitted so that it will limit the maximum current.

The size of the resistance can be calculated from the following relationship:

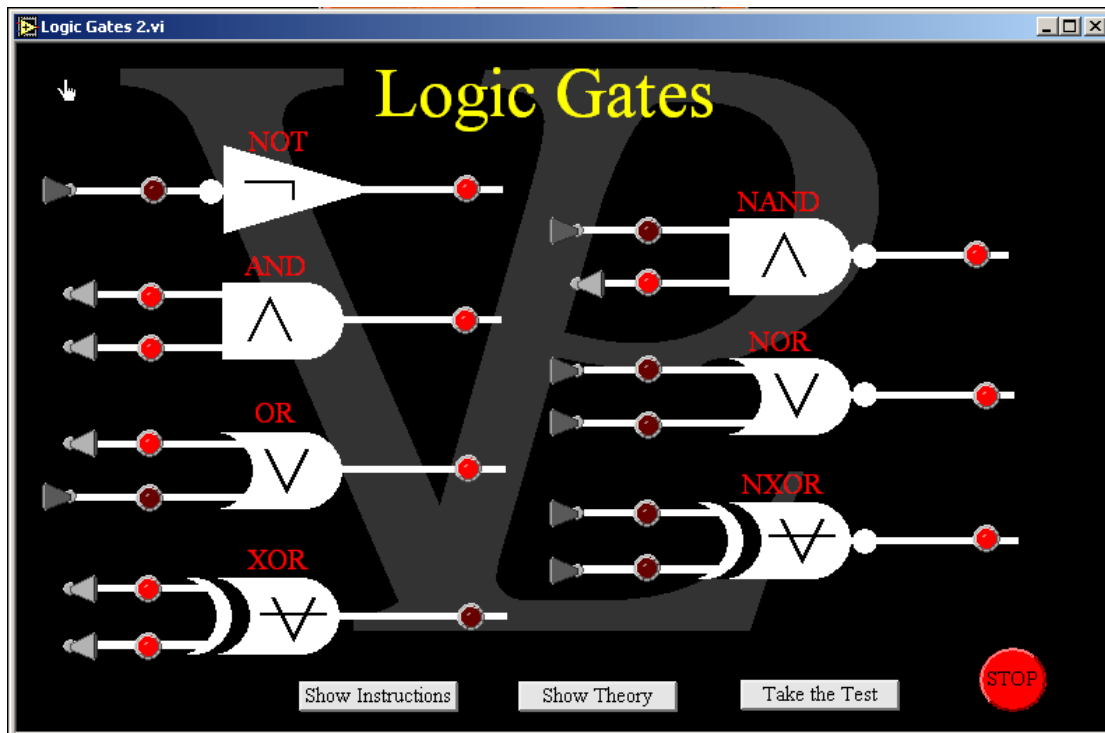
$$V_{app} = \Delta V + I_{max} R, \quad \text{or} \quad V_{app} = hC/e\lambda + I_{max} R \quad \text{Where:}$$

V_{app} is the total applied Voltage, I_{max} is the maximum recommended current and R is the series resistor to limit the current .

9.7 Logic Gates

Advanced

This simulation illustrates the principles of logic gates. Learn how the different types operate, and then take a test!



Logic gates are used to handle many types of conditions in circuits. For example: Switch engine on if the safety interlocks are in place and the start button is pressed.

Nearly all the gates shown here have two inputs. The outputs depend on the condition of the inputs. The simplest ones have names that make them easy to remember.

AND: The output will be high if input A AND input B are high.

OR: The output will be high if the input A OR the input B are high.

NOT: The output will be high if the input is NOT high.

XOR (exclusive OR): The output will be high if the input A OR the input B are high, excluding the case where both are high.

NAND (Not AND): This is the same as an AND gate followed by a NOT gate. The output will be high if input A AND input B are NOT high.

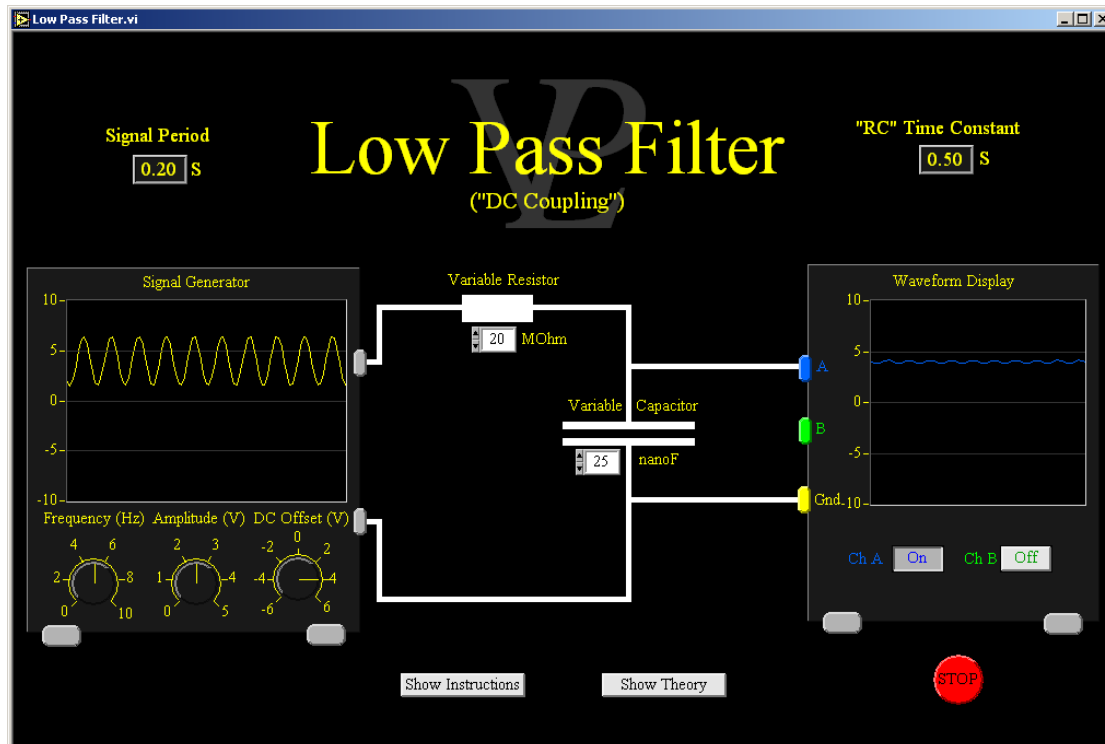
NOR (Not OR): This is the same as an OR gate followed by a Not gate. The output will be high if input A or input B is low, or if both are low.

NXOR (Not XOR): This is the same as a XOR gate followed by a Not gate. The output will be high if input A OR input B is low, but not if both are low.

9.8 Low Pass Filter

Advanced

This simulation shows how a resistor and a capacitor can be used to filter out high frequency components and only transmit the low frequency components.



Low Pass filters are simple circuits designed to reject unwanted high frequency components in a signal without hindering the passage of lower frequency components. Low pass filters are sometimes called "DC Coupling" because they allow DC Voltages through.

The unfiltered signal needs to pass through a resistor before it can charge the capacitor, this limits the current and so slows down the rate at which the capacitor voltage can change. The response of the Capacitor Voltage is therefore slowed down. If the resistor or the capacitor are large, the rates of charging and discharging will be much longer. This attenuates high frequency Voltage changes even more.

"High" and "Low" frequency are relative terms. They need to be compared to the "RC Time Constant" (the product of the Resistance times the Capacitance) in order to be able to know if they will pass or be attenuated.

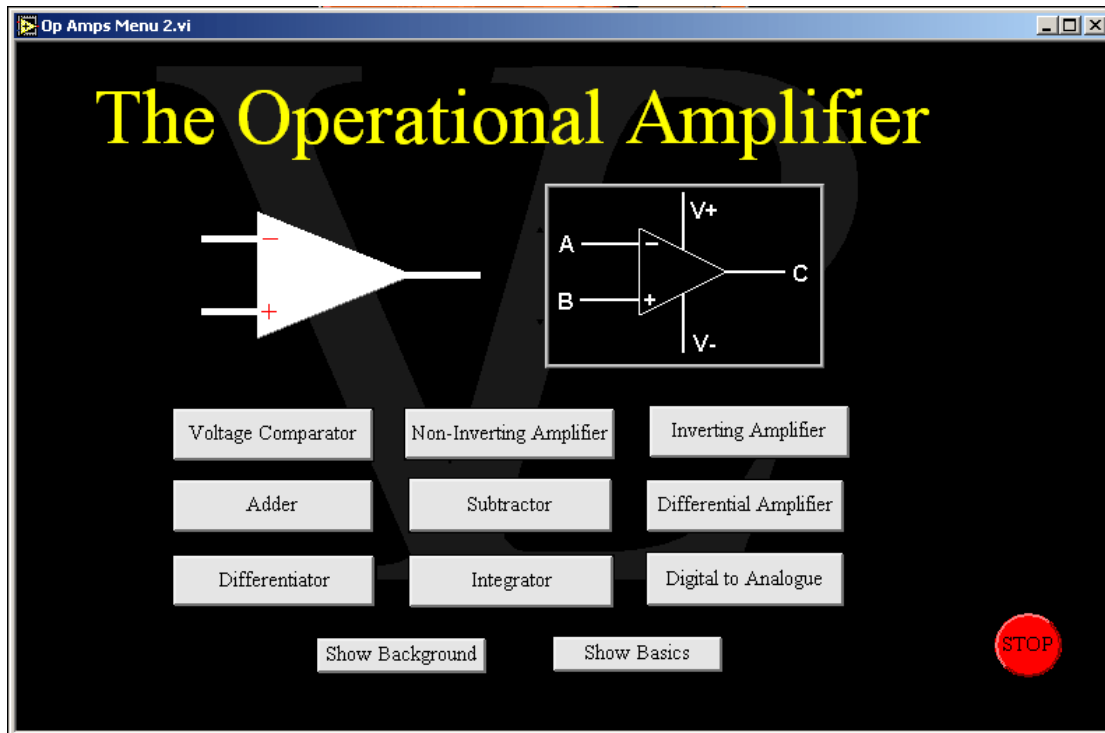
As an exercise, you might want to convince yourself that of the following: $1 \text{ Ohm} \times 1 \text{ Farad} = 1 \text{ Second}$!! (I find that amazing!)

Signals with periods around 10 times smaller than RC are nearly totally attenuated. Those with periods around 10 times larger than RC are passed through with nearly no attenuation.

9.9 Operational Amplifiers

Advanced

This comprehensive simulation shows nine different ways in which operational amplifiers may be used in order to achieve different functions. It starts with the simplest comparator and goes right up to the integrator.

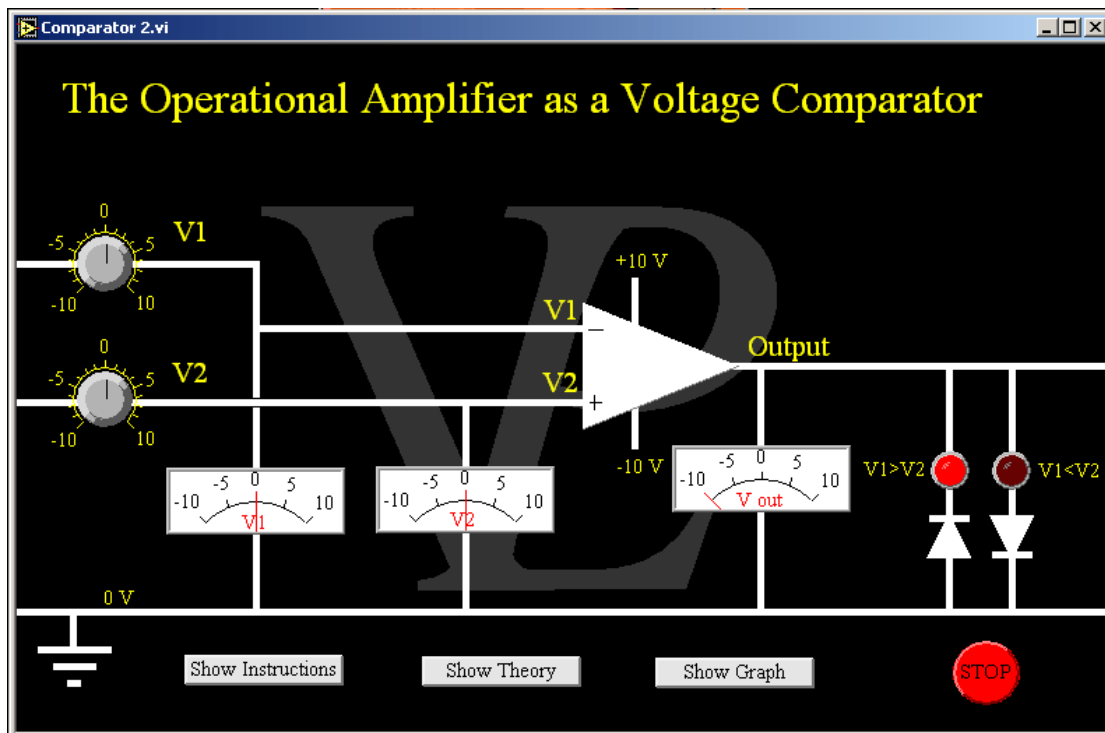


The operational amplifier is an electronic device which contains thousands of transistors back to back. Its gain can easily reach 100,000. However, it is seldom used in that way. In most applications 'feedback' is used in order to adjust the gain and obtain the desired behaviour.

Most circuits today use operational amplifiers rather than transistors because their performance is so much better. The reason they are called 'Operational Amplifiers' is that they are able to do several mathematical operations including adding, subtracting and even differentiating and integrating.

9.9-A Operational Amplifiers in a Voltage Comparator

Advanced



An operational amplifier contains approximately 2000 transistors inside it. The amplification is so large (typically 100000 times) that the output quickly swings from the maximum positive to the maximum negative.

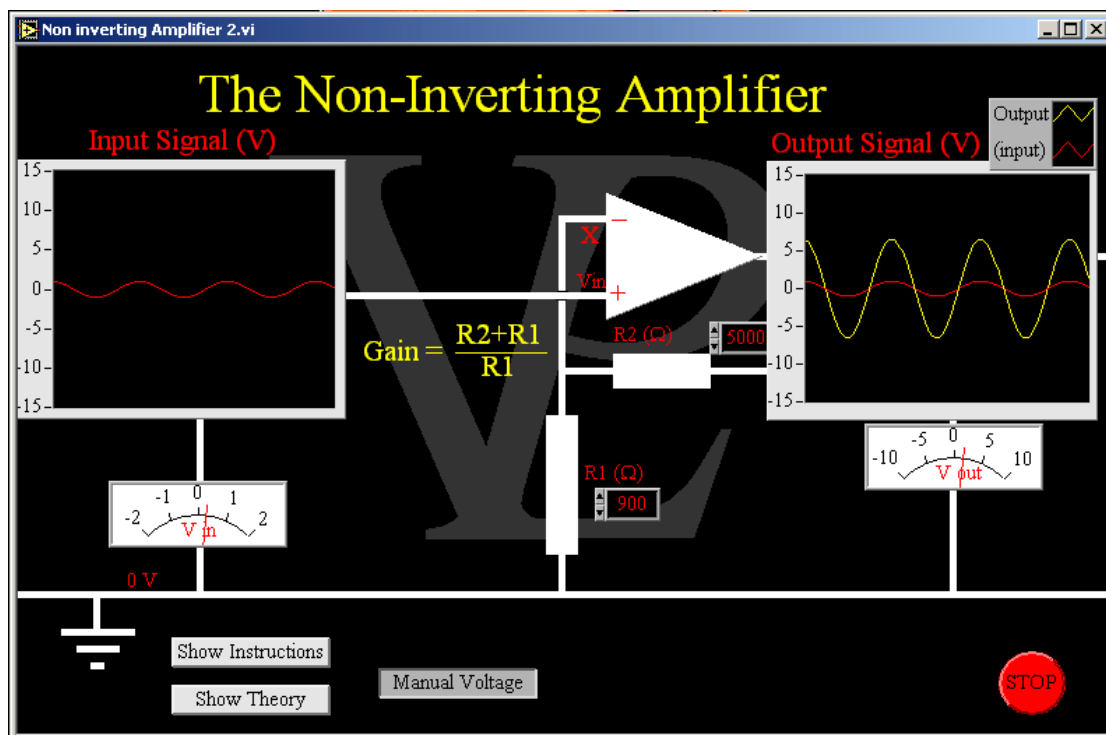
In this example there is no feedback. If V_1 is greater than V_2 , the output goes to -10, otherwise it is +10. This circuit is called a 'comparator' because it simply compares V_1 with V_2 .

The - input is called the inverting input, and the + input is called the non-inverting input.

The input resistances are effectively infinite (draw negligible current), and the typical output resistance is 100 Ohms

9.9-B Operational Amplifiers in a Non- Inverting Amplifier

Advanced



This operational amplifier is being used as a non-inverting amplifier whose gain is determined by the ratio $(R_1 + R_2)/R_1$.

Notice that the input voltage is connected to the non-inverting input.

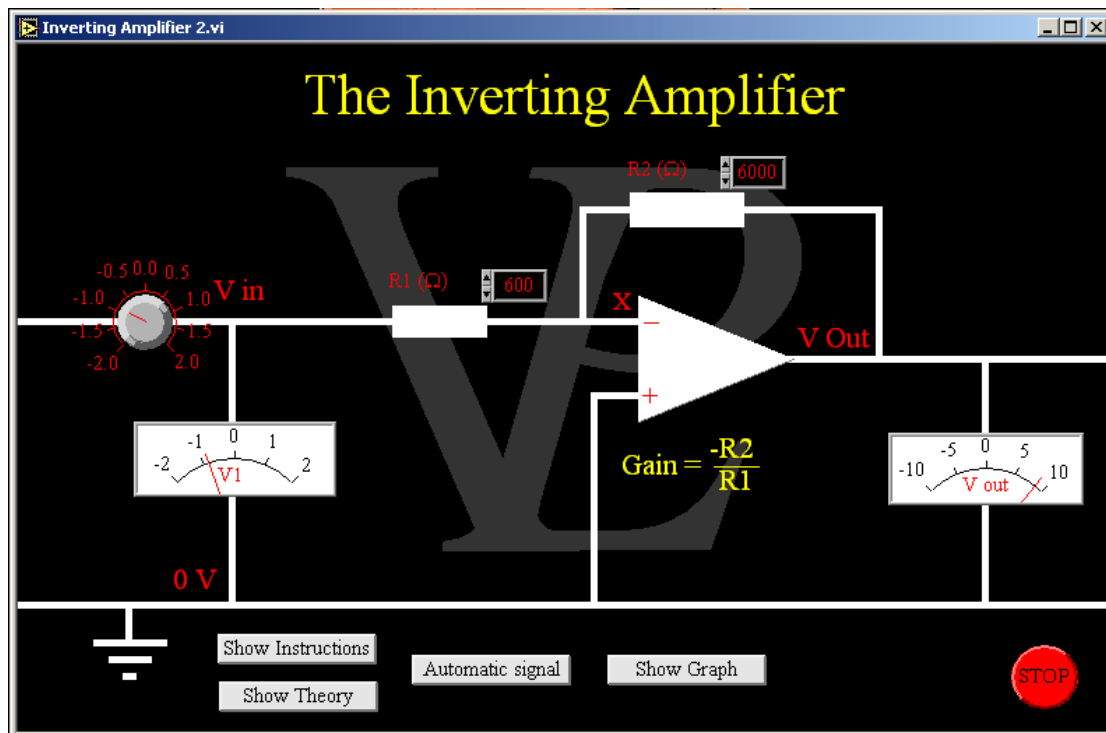
Part of the output is used to pull up the voltage at X until it matches that at the non-inverting input. This may sound complicated but it isn't.

Since no current can enter at X, the current through R_1 and R_2 is the same. Therefore $V_{out}/(R_1 + R_2) = V_{in}/R_1$ or $\text{Gain} = (R_1 + R_2)/R_1$

If the gain is too high, the output voltage is restricted by the supply (in this case 10 V), and signals get clipped.

9.9-C Operational Amplifiers in an Inverting Amplifier

Advanced



This operational amplifier is being used as an inverting amplifier whose gain is determined by the ratio $-R_2/R_1$.

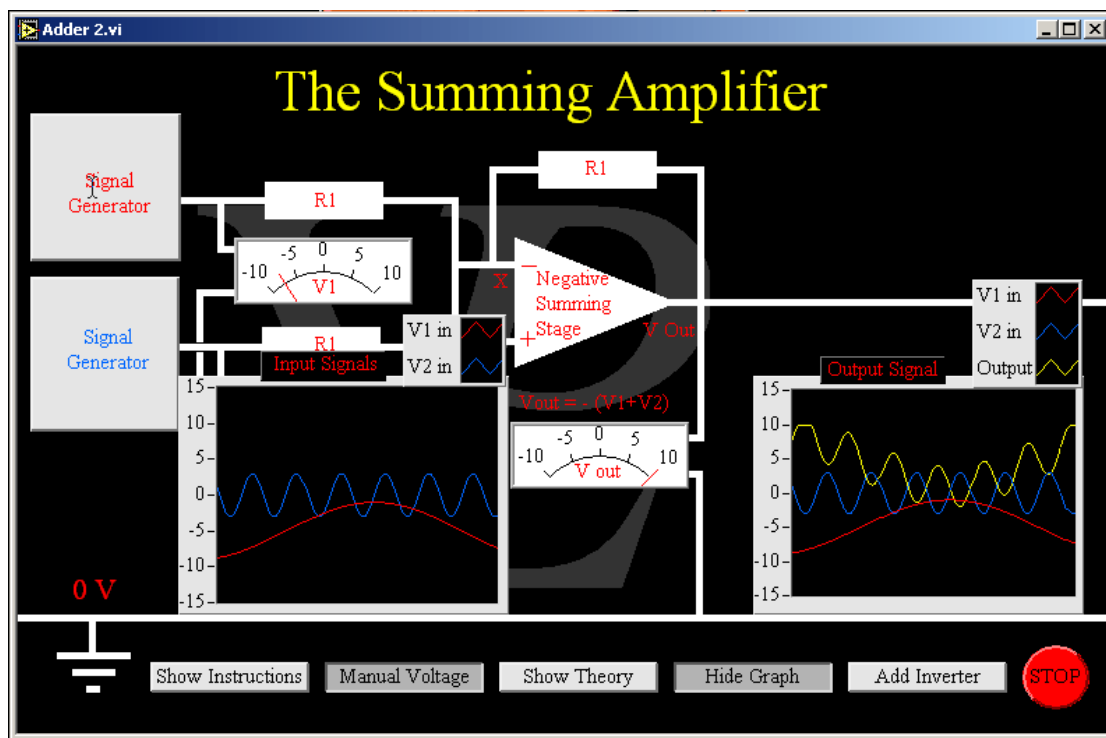
Notice that since the non-inverting input is connected to earth, the voltage at the inverting input is always be zero (a virtual earth). This arrangement behaves almost like a 'see-saw' pivoted at X but with unequal length arms. Vout goes up when Vin goes down (at the left hand side of R_1). Vout swings up and down more wildly because R_2 is normally larger than R_1 .

The potential divider made up by R_1 and R_2 provides the feedback that determines the gain. If the gain is too high, the output voltage is restricted by the supply (in this case 10 V), and signals get clipped. (Select 'signal' to see this clearly).

Although it is an inverting amplifier, in practice very often it does not matter (e.g. audio etc).

9.9-D Operational Amplifiers in an adding Amplifier

Advanced



This operational amplifier (op-amp) is being used as a summing amplifier.

Notice that the two input currents reach point X (which is a virtual earth) and that they cannot enter the op-amp here. Thus the sum of the currents must make its way through the top resistor to the output.

Point X behaves like the pivot of a see-saw; if positive currents come in, they cause the output voltage to go negative. This configuration actually gives the negative sum as an output.

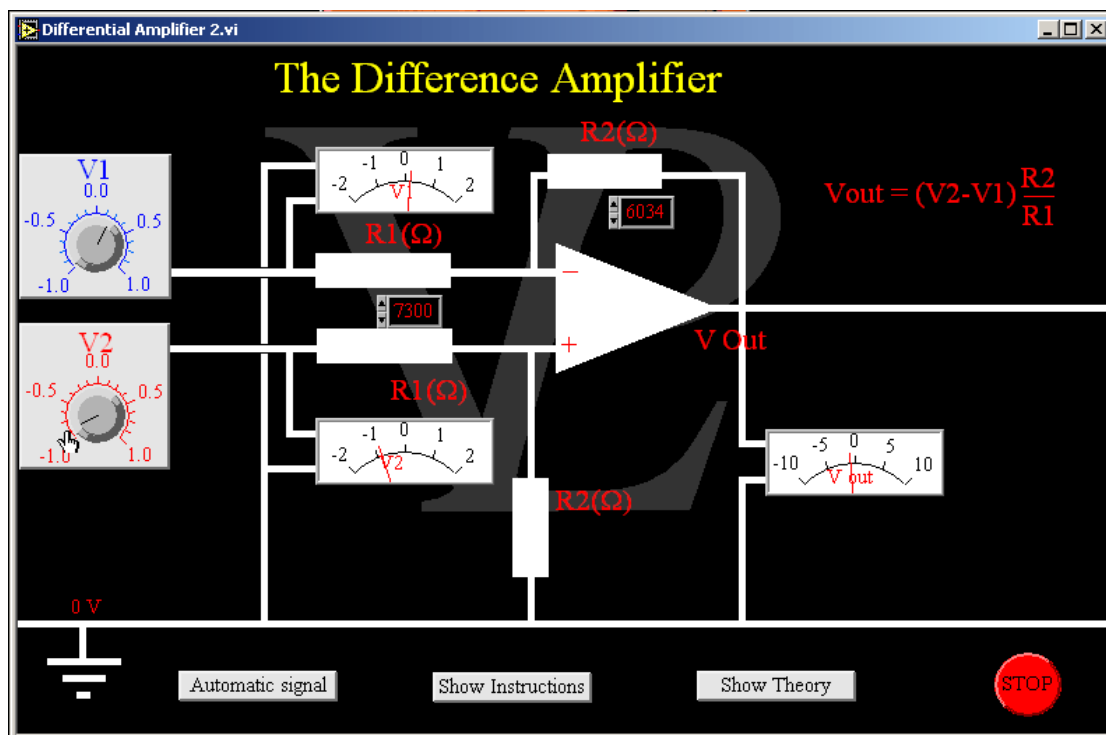
In order to get the sum positive again, it is necessary to use an inverting amplifier as a second stage.

Notice that the resistors in this example all have the same value, this gives equal weighting to the two inputs, and gives unit gain to the output.

Notice also that if the sum exceeds the source voltages which power the op-amp the output signal gets clipped.

9.9-E Operational Amplifiers in a Difference Amplifier

Advanced



This op-amp is being used as a difference amplifier.

Notice that the configuration only amplifies any differences that there might be between V_1 and V_2 .

This is very useful to clean up a signal that has come down a coaxial cable. Any noise that has superimposed itself on the signal will probably also be present in the screen. If the noise is common, it subtracts out.

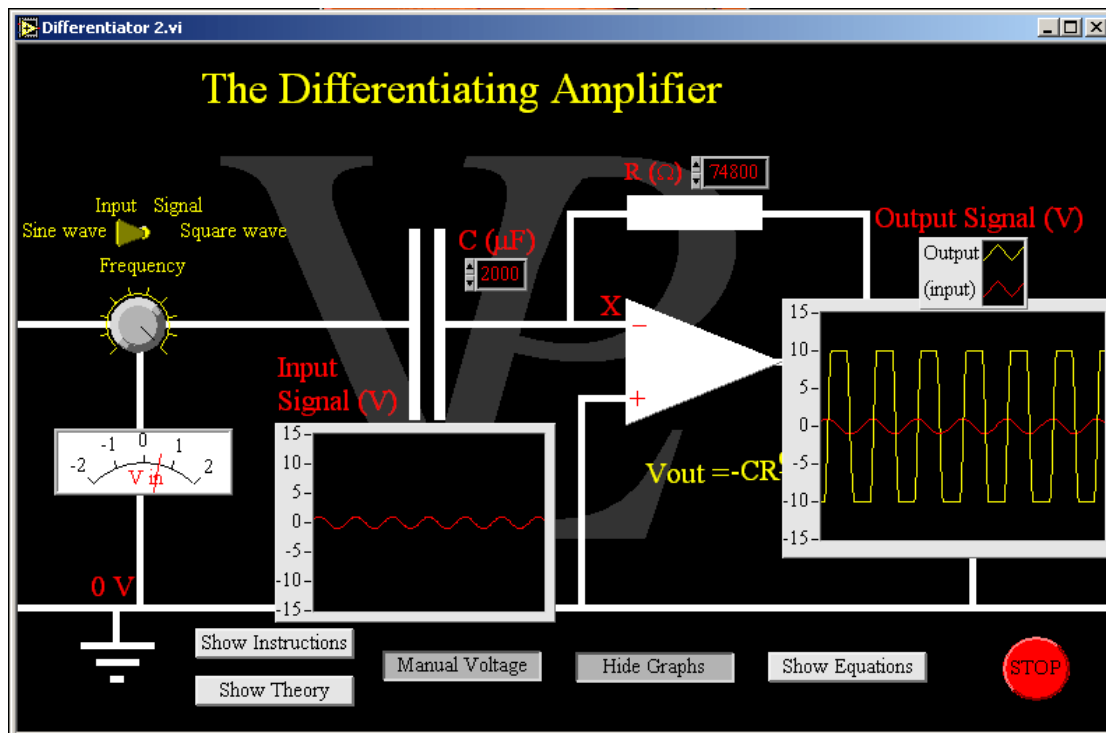
The difference between V_2 and V_1 is amplified by the ratio R_2/R_1

Notice that the two resistors labelled R_1 are equal in value, as are the two labelled R_2 . Click and drag on the two top resistors in order to vary their magnitude.

Notice also that if the sum exceeds the source voltages which power the op-amp the output signal gets clipped.

9.9-F Operational Amplifiers in a Differentiating Amplifier

Advanced



This operational amplifier is being used as a time differentiating amplifier whose gain is determined by the value of $-RC$.

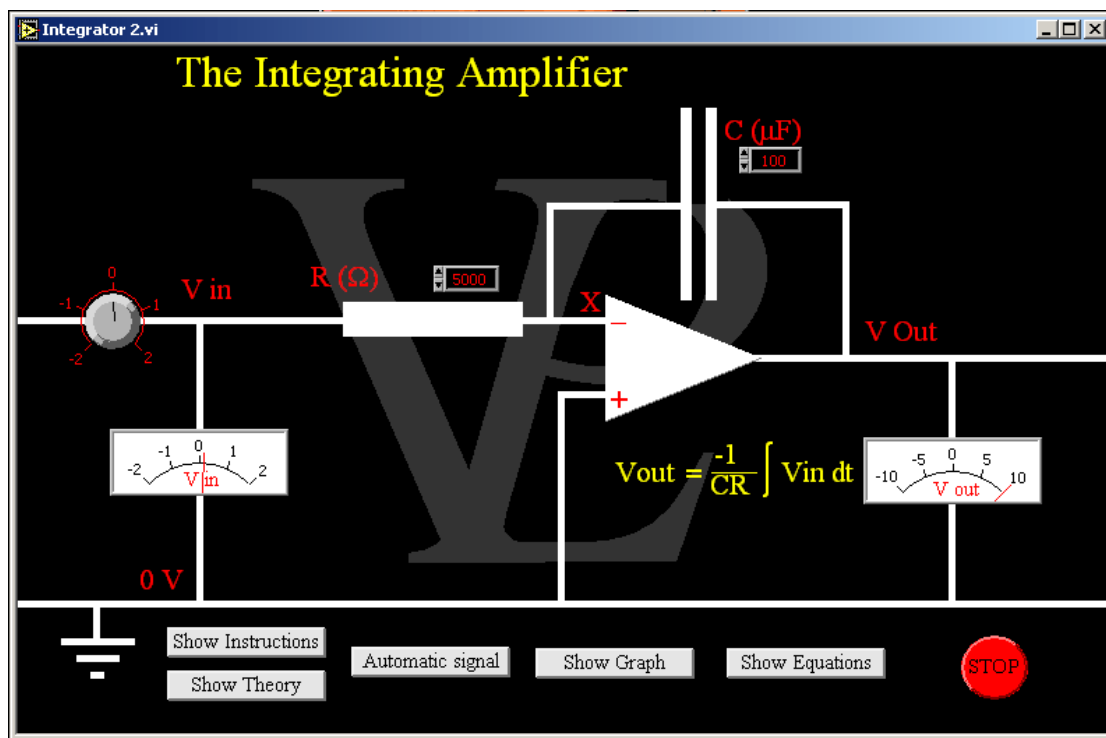
While the input voltage is constant (whatever value) no current will be flowing out the other side of the capacitor, so the output voltage will be the same as that at X, ie zero volts. However, when the input voltage is changing, a transient current will flow 'through' the capacitor, Since the current cannot enter the op-amp at X, so it must go or come through the resistor.

Detailed examination of the direction in which the currents need to flow will show that it is a negative differentiator.

The operation is easier to understand when the input is a square wave (large spikes where the gradient is $+\infty$ and $-\infty$), but notice the phase change when differentiating a sine wave.

9.9-G Operational Amplifiers in an Integrating Amplifier

Advanced



This operational amplifier is being used as an integrator amplifier whose gain is determined by the value of $1/RC$.

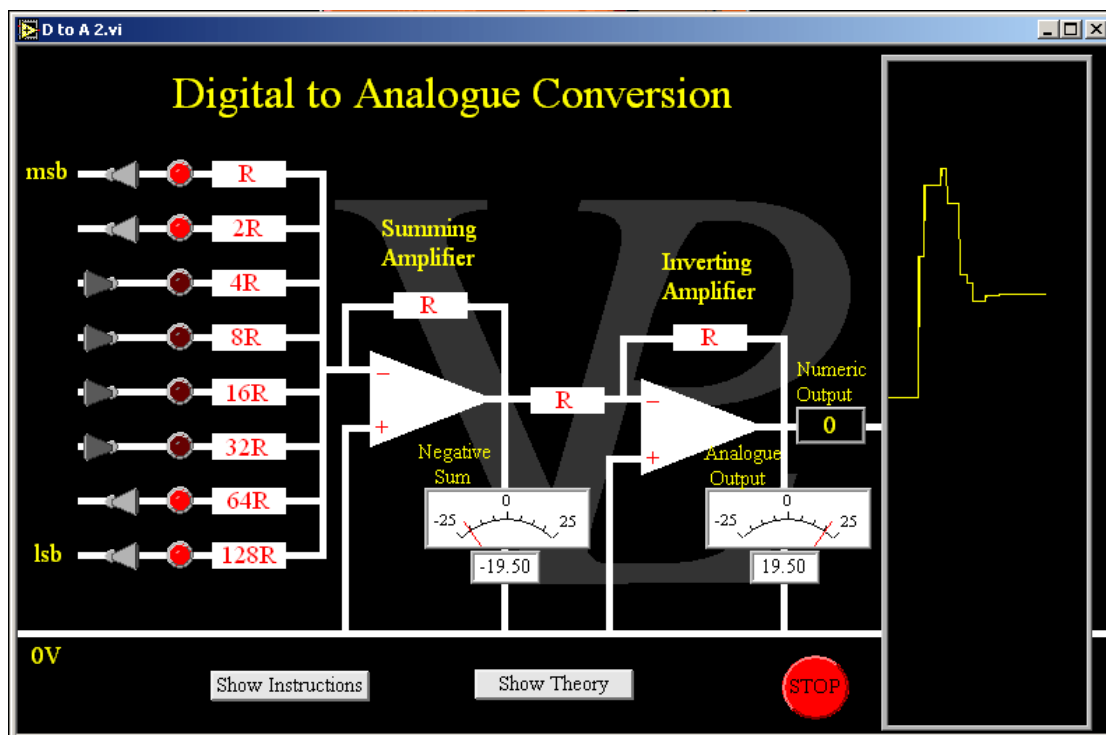
While the input voltage is positive, the current cannot enter the op-amp at X, so it must go to the capacitor.

The point X is still a 'virtual' earth, and since the left hand side of the capacitor is charging up, the right hand side of the capacitor is forced to go negative (it is a negative integrator).

Notice that as long as the input voltage is positive the output voltage will continue to creep downwards until it reaches the negative supply value. That is the limit of the integration.

9.9-H Operational Amplifiers in a Digital to Analogue Converter

Advanced



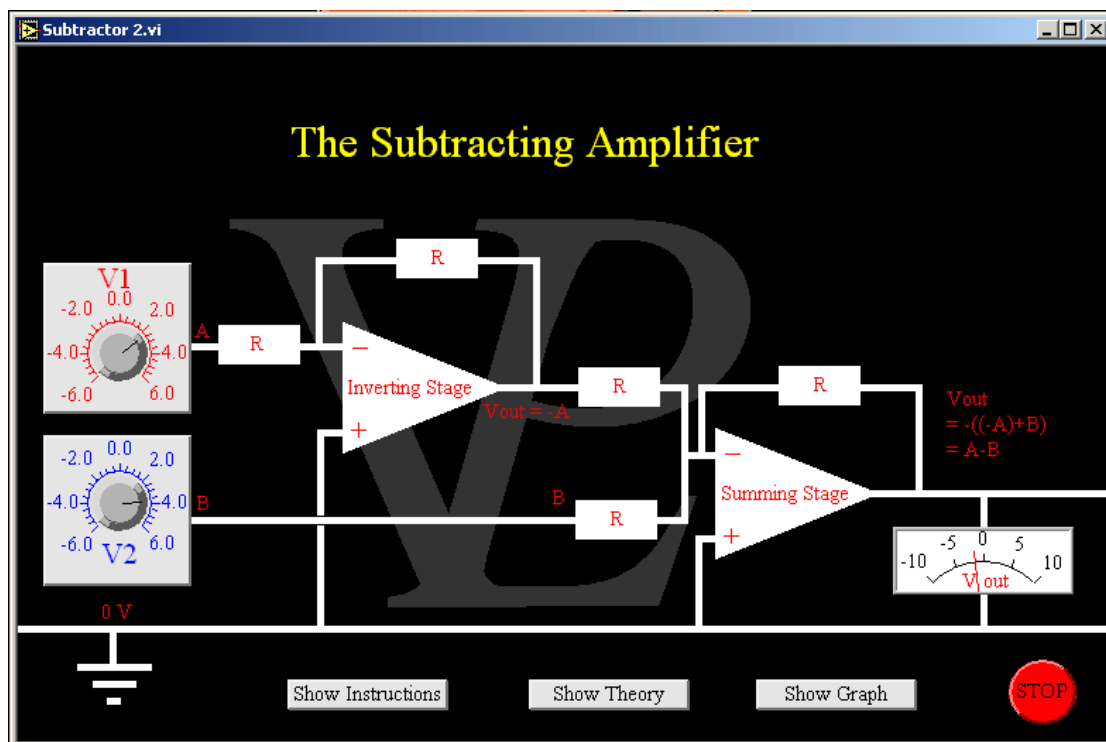
Digital to analogue conversion can be achieved using a summing amplifier.

Notice that the gain of the least significant bit (lsb) is 128 times smaller than that of the most significant bit (msb). This is achieved by choosing the ratio of the resistances.

A second (inverting) stage is required because the output of the summing amplifier is negative

The resolution (size of the lsb) in this example is 0.1 V

9.9-I Operational Amplifiers in a Subtracting Amplifier



This operational amplifier (op-amp) is being used as a subtracting amplifier.

Since it is easier to make unity gain amplifiers if they are inverting amplifiers, we will use this type.

First of all A is inverted.

B is then added to - A with a summing amplifier which is also an inverting one.

Notice that $-((-A)+B)$ is the same as $A-B$.

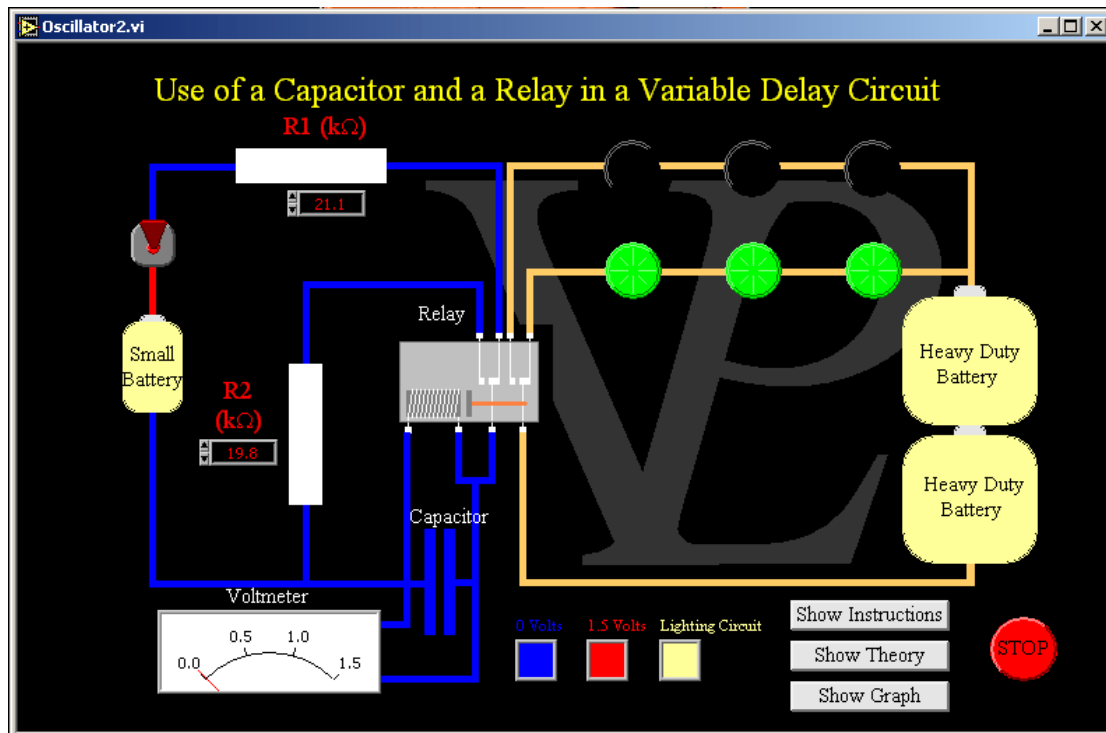
Notice that the resistors in this example all have the same value, this gives equal 'weight' to the two inputs, and gives unit gain to the output.

Notice also that if the difference exceeds the source voltages which power the op-amp the output signal gets clipped.

9.8 Oscillator

Advanced

This simulates an oscillating circuit using two resistors, a capacitor and a relay. The resistances can be altered in order to vary the 'on' and 'off' times.



The charging and discharging of the capacitor takes place via the two variable resistors.

A relay can be used so that a large current (the lighting circuit) can be switched 'on' and 'off' using a small current (from the little battery).

In this case the circuit has been devised so that when the relay switches on, the contact to the little battery is broken. The relay is then held energised for a little while longer with charge from the capacitor. When the capacitor discharges the relay releases the contacts, and the capacitor starts to charge again.

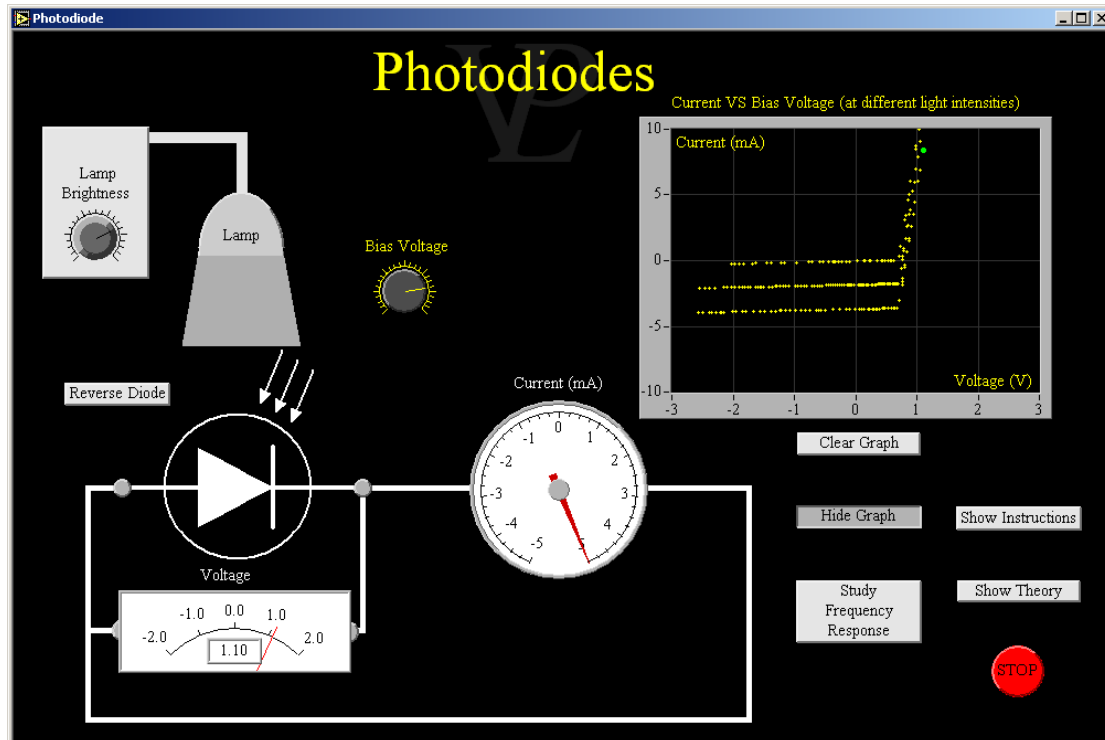
The second set of contacts on the right hand side of the relay is used to connect either the green or the red lights.

Notice that the voltage required to switch the relay on is far greater than the voltage required to hold the relay at the 'on' position.

9.11 Photodiodes

Basic/Advanced

This simulation permits the user to study the behaviour of a photodiode under different levels of illumination as well as different biases. It also studies the frequency response at different levels of reverse bias.



A full explanation of the photodiode is beyond the scope of this simulation. You will need to consult a textbook.

Briefly, when light falls on the photodiode it causes electrons and holes to be created in the depletion region near the junction between the n and p doped semiconductors. The electrons travel one way (towards the p doped side) and the holes travel the opposite way (towards the n doped side). This "photocurrent" flows in the opposite direction to the current that would normally be conducted by a diode.

When a photodiode is connected directly to a resistor (or other load) it is said to be operating like a photovoltaic cell; converting light energy into electrical energy. The voltage output of a photodiode is not at all linear with light intensity. To use a photodiode as a light intensity sensor it is necessary to bias the diode by applying a reverse voltage across it. The photocurrent response is then very linear with light intensity.

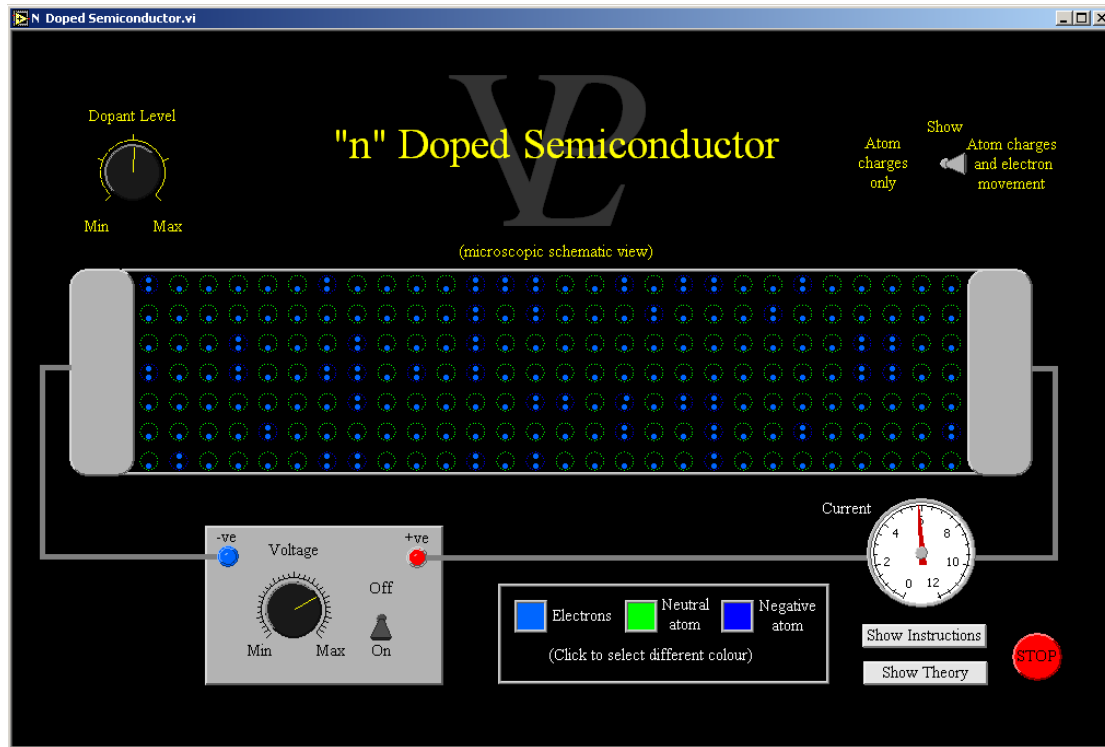
The response time of an unbiased photodiode is not very fast (rise times of the order of 1 microsecond). When faster response times are wanted (as in fibre-optics communications) the diodes are reverse biased. This increases the frequency response dramatically.

The sensitivity of photodiodes is also dependent on the wavelength of the light falling on it. Different materials perform better in visible, infrared and ultraviolet.

9.12 Semiconductors

Basic/Advanced

This simulation gives an introduction to “p” and “n” doped semiconductors and shows how charges travel through to form a current. The level of doping can also be adjusted to see what effect it has.



Semiconductors are materials that are neither insulators nor good conductors. Examples of these materials are Silicon and Germanium.

These materials can be melted and then impurities can be added to the melt before allowing it to solidify and re-crystallise. This process is called 'Doping'.

The dopant is called a 'donor' if it contributes a conduction electron or an 'acceptor' if it steals a conduction electron (leaving a positive 'hole'), giving rise to 'n type' and 'p type' semiconductors respectively.

In 'n type' semiconductors electricity is conducted via the donated electrons from the impurities. In 'p type' semiconductors electricity is conducted via the movement of 'holes'. Electrons travel in the opposite direction to the conventional current, and 'holes' travel in the same direction as the conventional current.

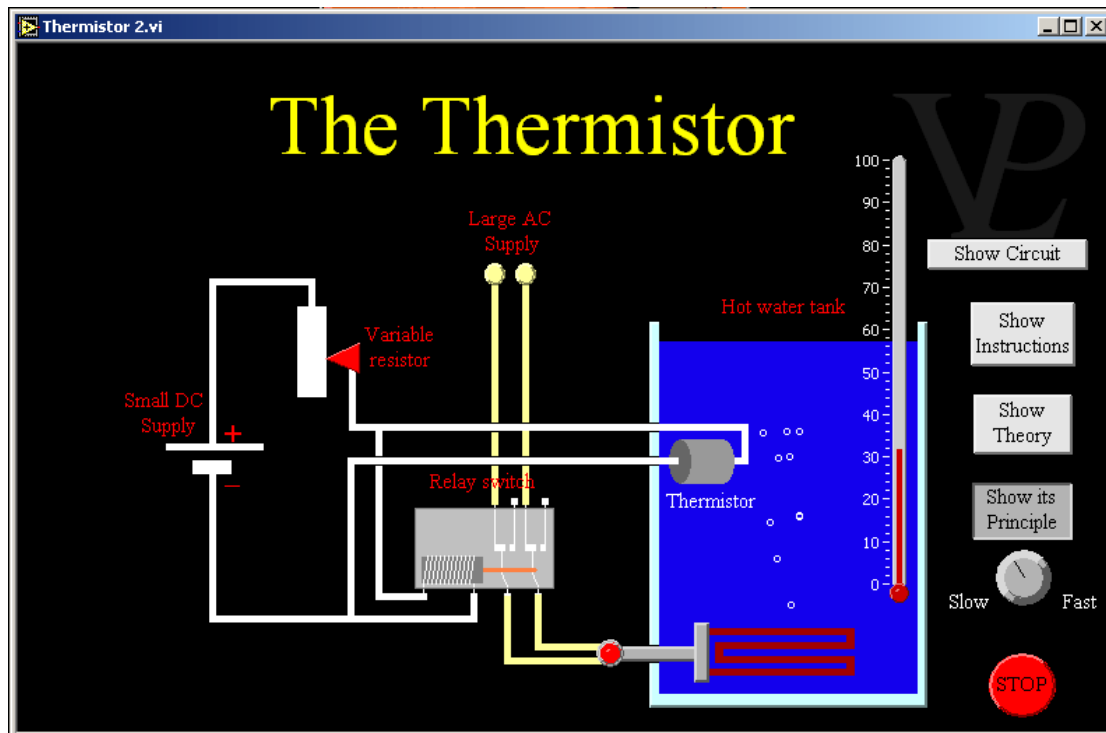
The conductivity of semiconductors can be altered externally by changes in Temperature, Electric field and Optical radiation, for this reason many transducers are made of semiconductors (photodiodes, thermistors, field effect transistors, etc.)

Bonding different types of semiconductors to each-other gives rise to many of the modern electronics components (diodes, transistors, operational amplifiers, etc.)

9.13 Thermistor

Basic/Advanced

This simulation shows the principle of a thermistor, and also shows how a thermistor may be used in a practical circuit to control the temperature of water.



The thermistor is a component which is made of semi-conducting material. Its ability to conduct electricity increases when it is heated.

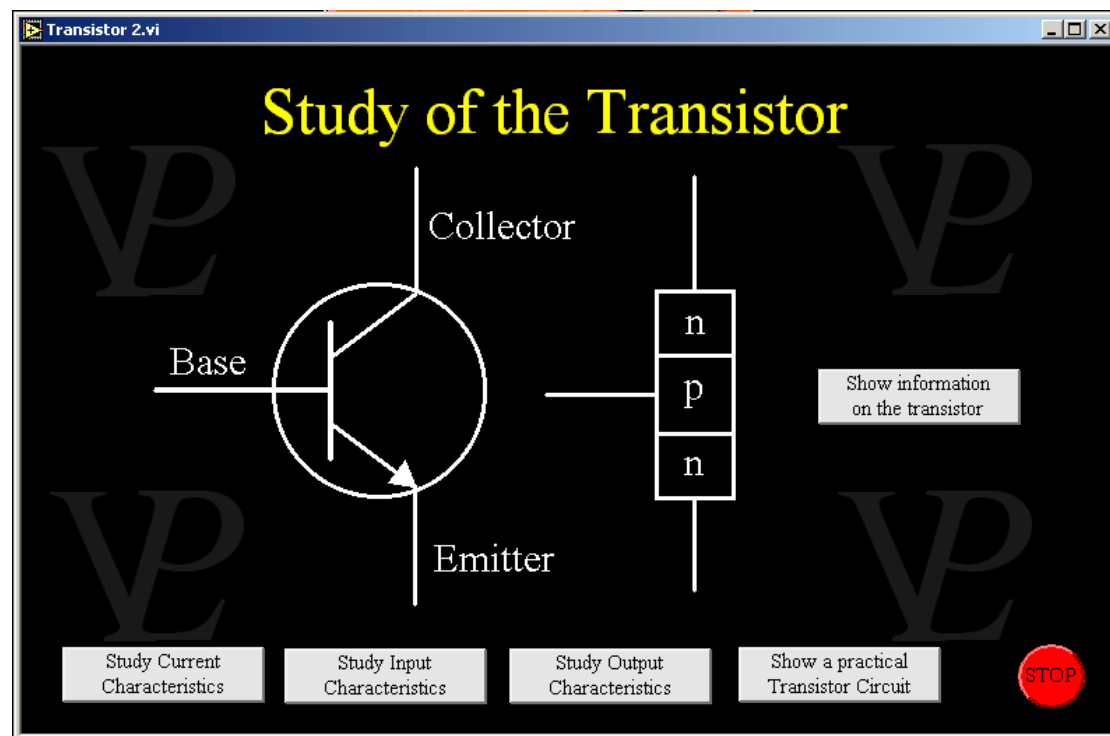
This happens because a semiconductor does not have many free electrons to carry the charge across. When the thermistor is heated, the thermal energy given to the atoms causes some of the bound electrons manage to break loose and so start to move and carry charge through the circuit.

This increase in the number of charge carries drastically reduces the resistance of the thermistor.

9.14 Transistor

Advanced

This programme shows the principle and characteristics of the common npn transistor. It contains 4 sub programs illustrating the input characteristics, the output characteristics, the transfer characteristics, and a simple circuit showing an AC coupled audio amplifier.



Transistors are the most important electronic devices today. They are used in many different applications because they act as simple amplifiers. They are very fast in their operation and last indefinitely.

A transistor is made of three pieces of semi-conducting material which are bonded together. The most common one (as shown here) is called an npn transistor.

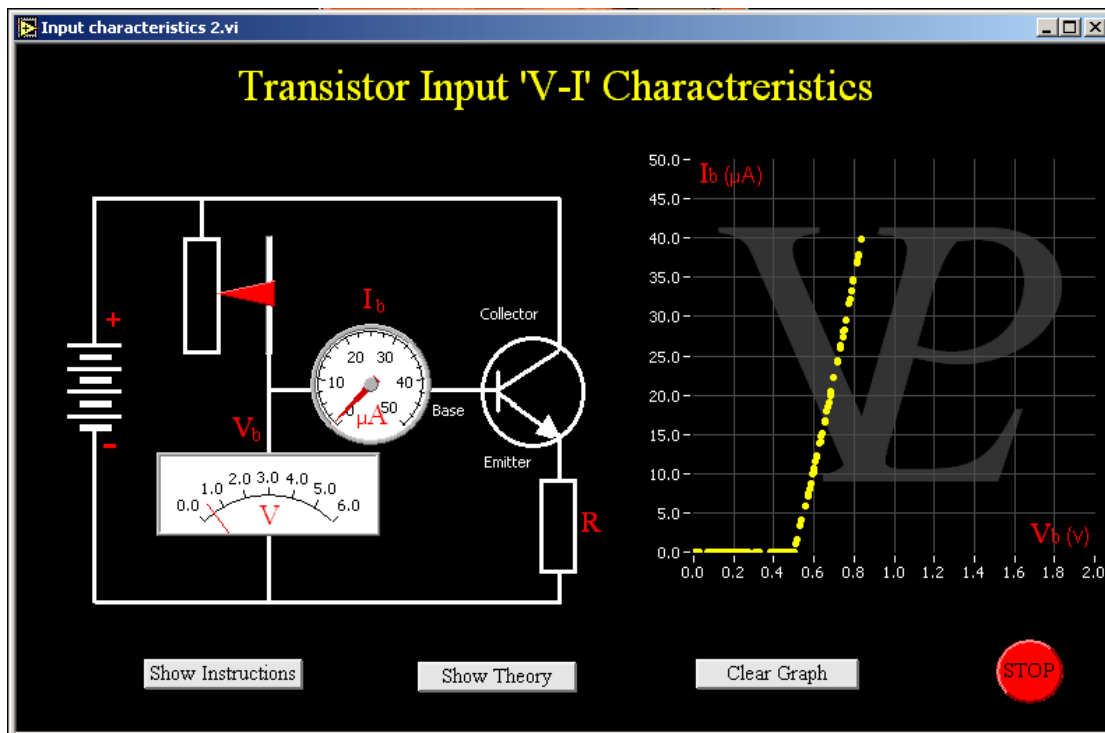
The n type semiconductor has impurities added to it so that it has a slight excess of electrons which can act as negative charge carriers.

The p type semiconductor has impurities added to it so that it has a slight shortage of electrons. This can be understood as having 'holes' of missing electrons. These holes are the main charge carriers which are positively charged because of the absence of the negative electron.

The three connections are called the collector, the base and the emitter. No current can flow from the collector to the base unless a small current is injected into the base. When this is done, the current that flows from the collector to the emitter is typically 1000 times larger than the current injected through the base.

9.14-A Input Characteristics of the Transistor

Advanced

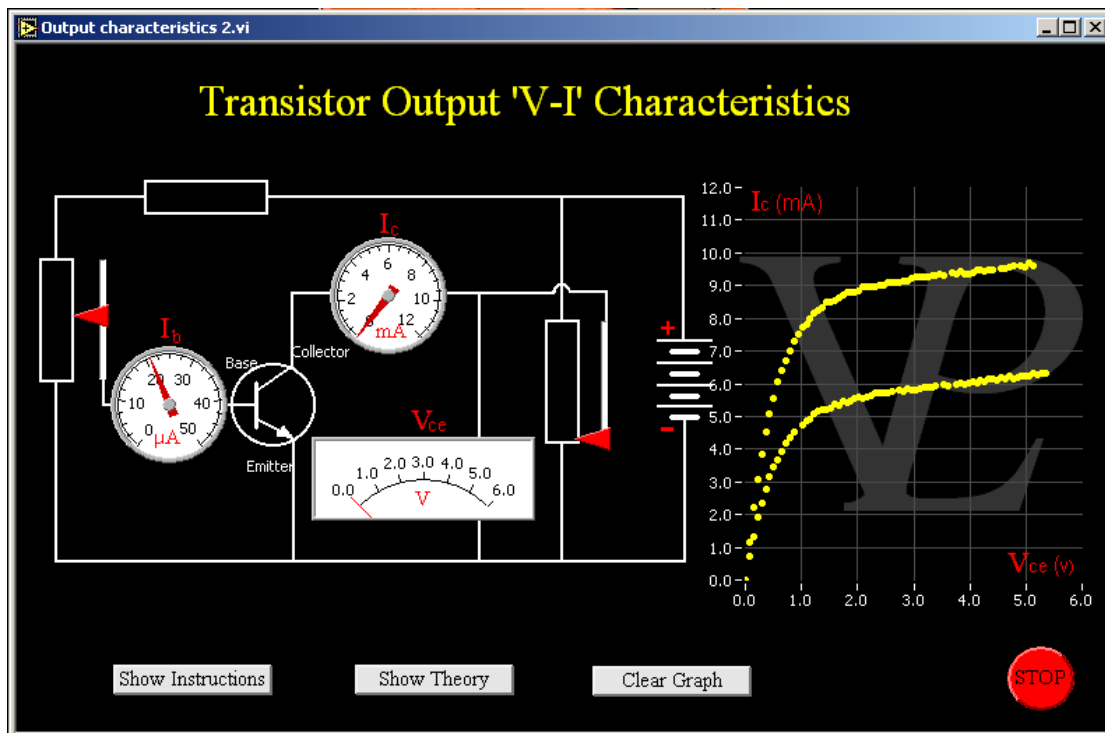


When a voltage is applied to the base of a transistor, no current flows towards the emitter until the base voltage reaches about 0.6 V (similar to a diode).

Above this voltage the base emitter current rises quite sharply. Note however that the resistance between the base and emitter is still very large (of the order of 1 MW)

9.14-B Output Characteristics of the Transistor

Advanced



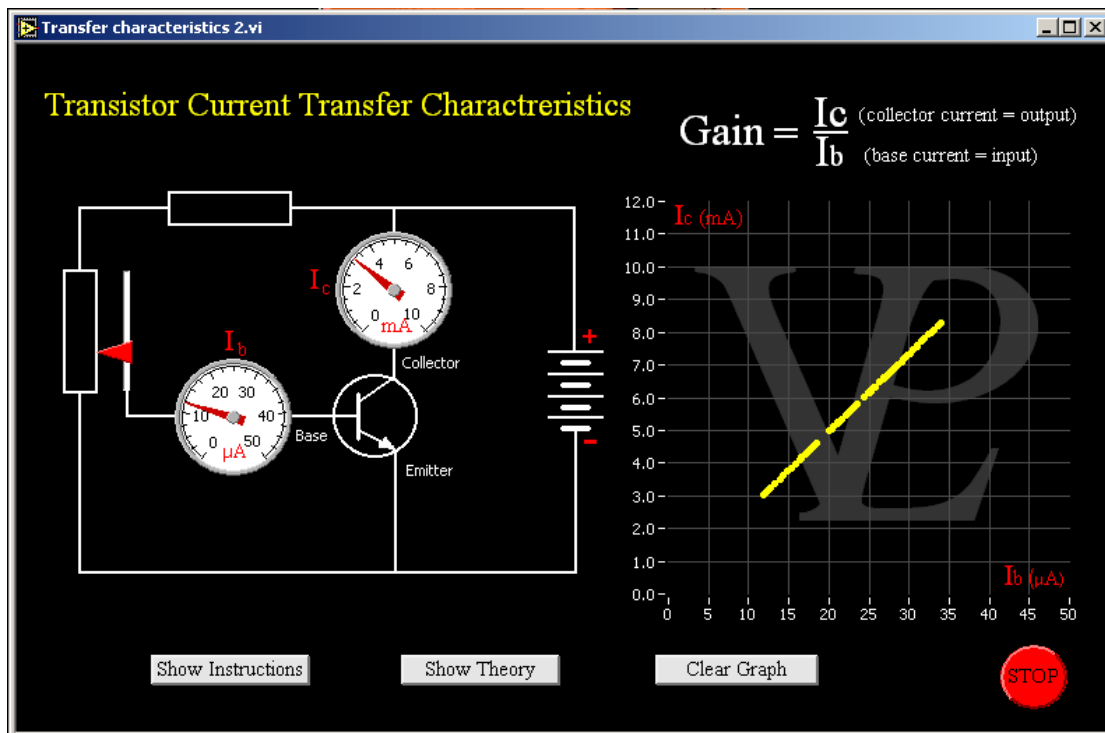
A small current flowing through the base towards the emitter (measured in micro-Amps) causes a much larger current to flow between the collector and the emitter (measured in milli-Amps).

The transistor acts as a current amplifier whose gain ($=I_c/I_b$) can be as large as 1000.

This is the main use of a transistor. It is a very efficient current amplifier which has many uses in nearly all electronic circuits.

9.14-C Current Transfer Characteristics of the Transistor

Advanced



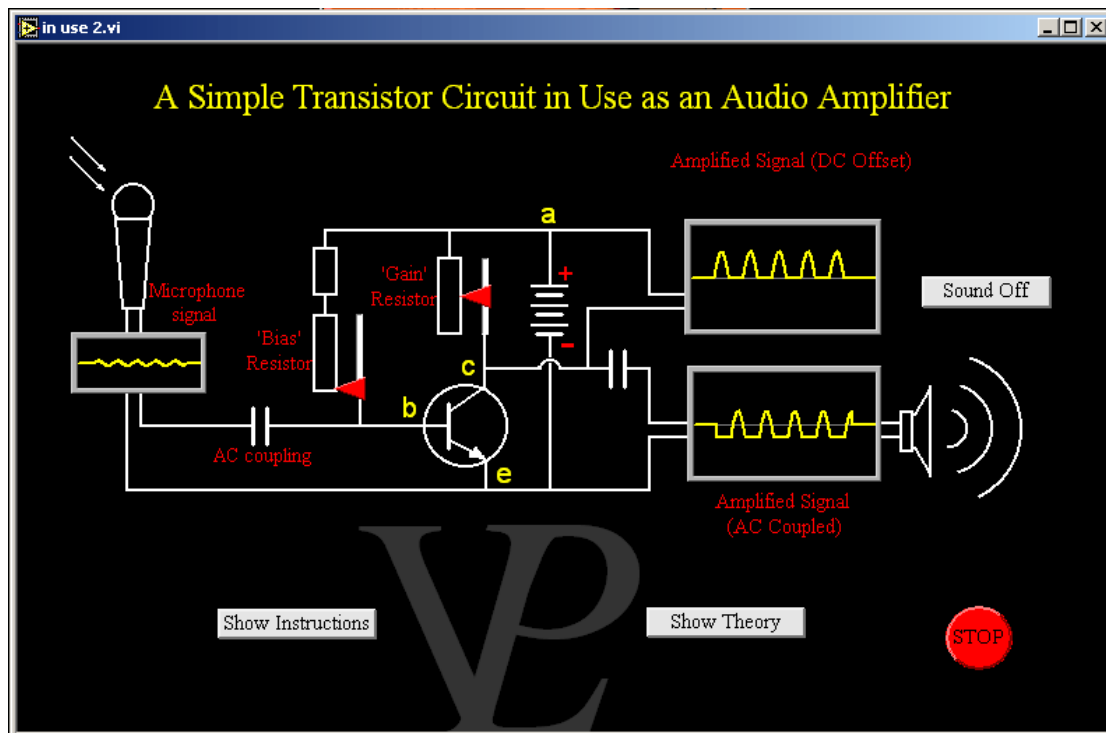
A small current flowing through the base towards the emitter (measured in micro-Amps) causes a much larger current to flow between the collector and the emitter (measured in milli-Amps).

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This is the main use of a transistor. It is a very efficient current amplifier which has many uses in nearly all electronic circuits.

9.14-D The Transistor as an Audio Amplifier

Advanced



When a positive signal from the microphone arrives at the base it causes the base voltage to increase a little, this increases the base-emitter current which causes a larger collector-emitter current to flow through the 'gain' resistor. This larger current makes larger voltages appear across a-c and c-e.

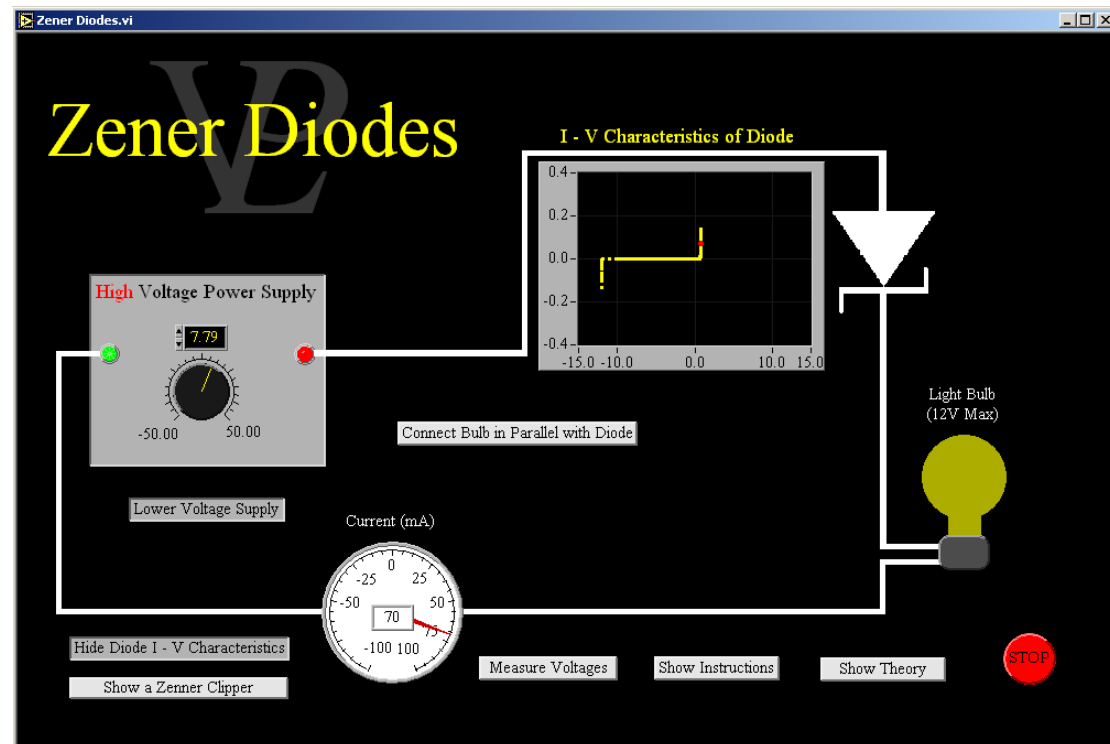
Notice however, that when a negative voltage comes from the microphone, no current can flow, and so no negative 'troughs' can be amplified. This distorts the signal from the microphone. To get round this problem, the base is 'biased' through the use of a bias resistor which pulls up the voltage of the base, such that a small current is always flowing through the transistor. The microphone is then AC coupled so that only varying signals get through. When a negative signal (or trough) comes, it momentarily lowers the voltage of the base, thus reducing the base current and the consequent collector current too. This causes the collector voltage to drop, and so the amplified trough appears on the output.

Notice that one of the outputs is in phase with the input, but has a large DC offset. The other is in anti-phase with the input, but because it is also AC coupled it does not have a DC offset.

9.15 Zener Diodes

Advanced

This simulation shows the difference between a normal diode (which can break-down if the reverse voltage is too high) and a Zener diode which does not. Its use as a DC voltage regulator is explained.



A Zener diode behaves much like a normal diode when the Voltage across it is positive. It also is similar when the Voltage is negative, but only up to a point. When the reverse Voltage reaches the "Zener Breakdown Voltage", the diode starts to conduct in the reverse direction but the Diode does not get broken!

The other interesting thing about Zener diodes is that if you try to exceed the reverse Voltage beyond the Zener value, the potential difference across it remains fairly stably at the Zener value! (It is necessary to make sure there is a resistor connected in series with it for this to happen).

This interesting feature of Zener diodes makes them useful as DC Voltage limiters or regulators. Zener diodes are more normally used in their reverse direction rather than their positive direction!

If two Zener diodes are connected in series, but pointing in opposite directions, and then energised with an AC current, the pair will clip an AC Voltage at an amplitude equal to the Zener Voltage (actually about 0.7 V higher than the Zener Voltage)

CHAPTER 10

ELECTROSTATICS

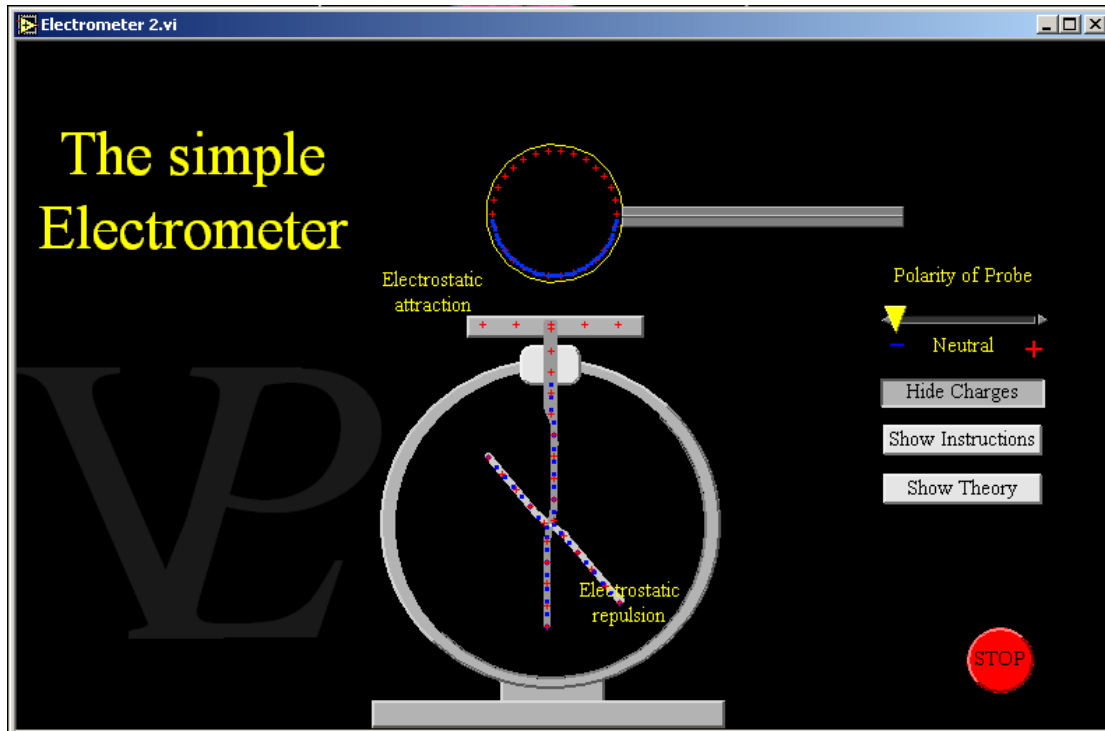


Electrostatics at work in my “thunderball” lamp.
What are electrostatic forces?

10.1 Electrometer

Basic/Advanced

This simulation shows the workings of an electrometer, and how it can be used to detect the presence of electric charge on a body.



The Electrometer is an instrument that can be used to measure the presence (and relative amount) of electrostatic charge.

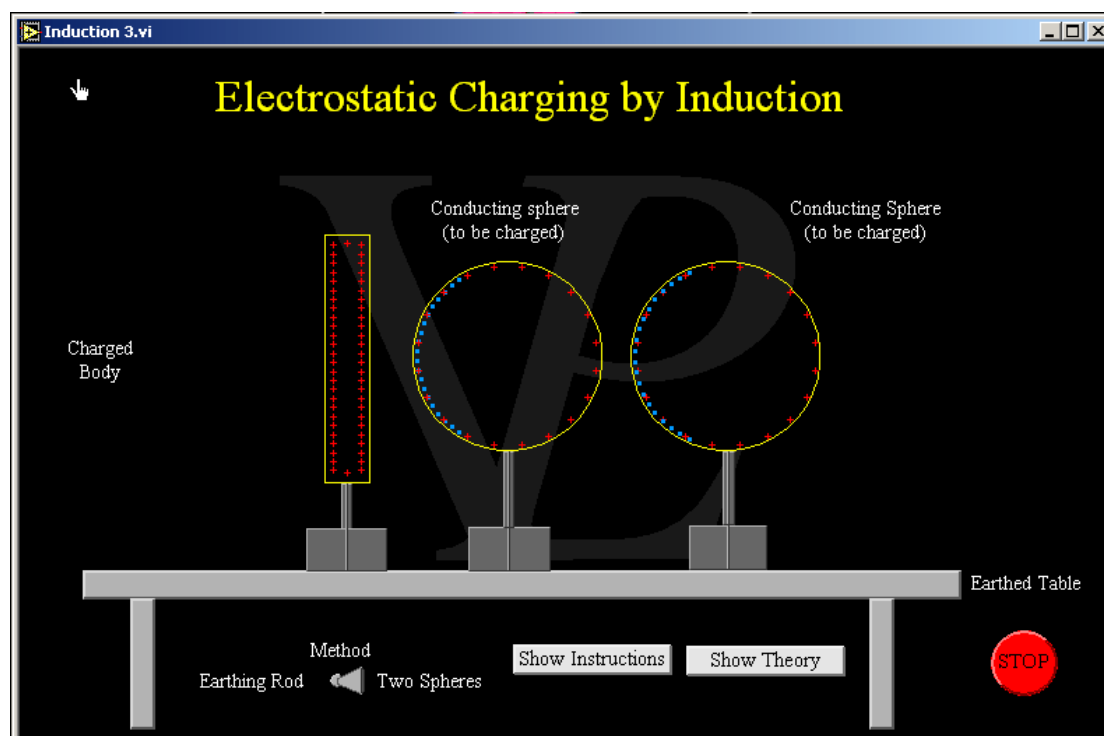
When a charged object approaches the top plate it attracts the opposite polarity to the top and repels like charges to the bottom. The pivoted rod starts to repel away from the fixed rod and swings away.

Note: Although greater charge causes the angle to increase, the relationship is not at all linear.

10.2 Electrostatic Induction

Basic/Advanced

This simulation shows two different ways of electrostatic charging by induction. The first uses two spheres, the second a single sphere and an earthed wire.



Electrostatic charging by induction can be achieved without even touching the spheres with the charged rod.

1 - Firstly the rod is charged by another method for example by friction. In this explanation we will assume the rod was charged negatively. A similar reasoning can be used to explain the positive case, except that positive charges are not free to move because they are trapped in the nucleus of the atoms.

2 - As the rod is brought near to the first sphere it repels the negative charges in the sphere away from it.

3 - a) When the earthing rod is brought to touch the opposite side of the sphere the negative charge flows down to earth.

b) When the right hand sphere is brought towards the first one, its negative charges are also repelled by the charges on the rod. When the two spheres touch, all the repelled negative charges move on to the right hand sphere.

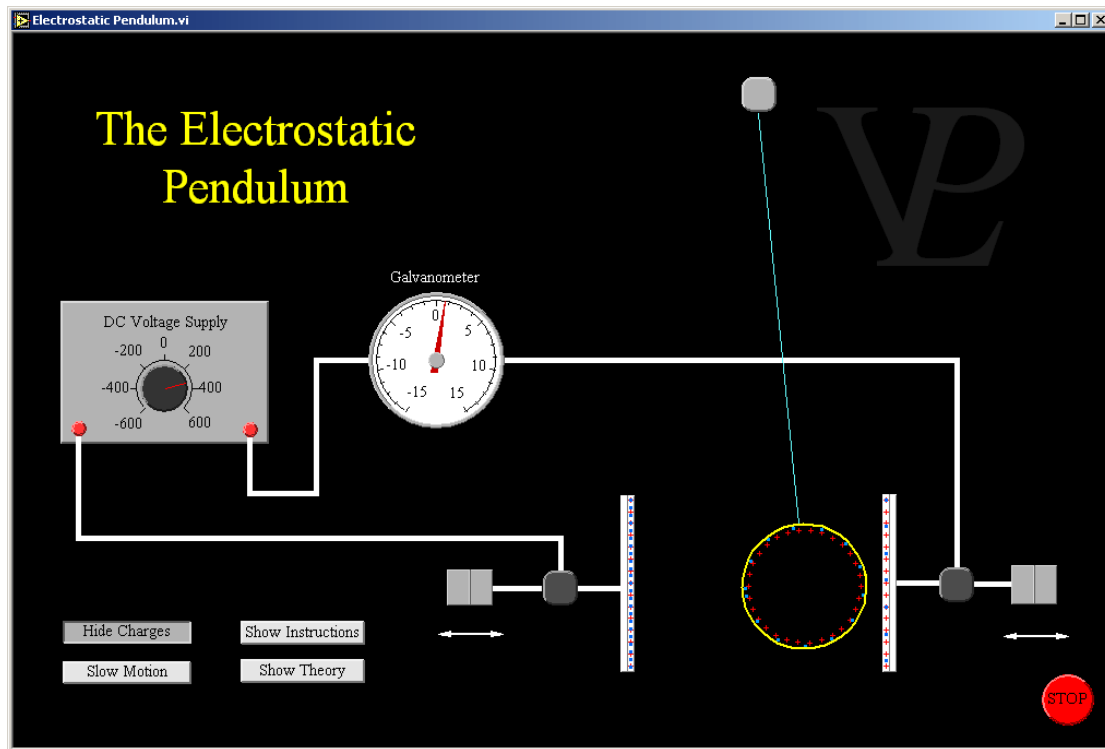
4 - Provided the sphere/rod or sphere/sphere are separated from each-other before the first charged rod is moved away, the charges will remain separated and the sphere(s) will remain charged.

5 - Note that none of the charge on the originally charged rod is used up. With care, a charged rod can be used to charge any number of spheres.

10.3 Electrostatic Pendulum

Advanced

This simulation shows how a suspended conducting sphere can be attracted to a pair of oppositely charged plates at either side of it. It also shows how the sphere can transport charge from one plate to the other, and so give rise to a small current.



The Electrostatic Pendulum is a simple experiment to demonstrate the transport of charge. It uses a conducting sphere on the end of an insulating string, hanging between two plates. When a significant DC voltage is applied across the plates it creates a strong electric field between them.

If the sphere is first given a little swing so that it comes in contact with one of the plates (swing it by touching the insulating string so that you don't get a shock!), it will charge up either positively or negatively (depending on which plate it touches). If it has just touched the positive plate, electrons will leave the sphere, leaving it positively charged.

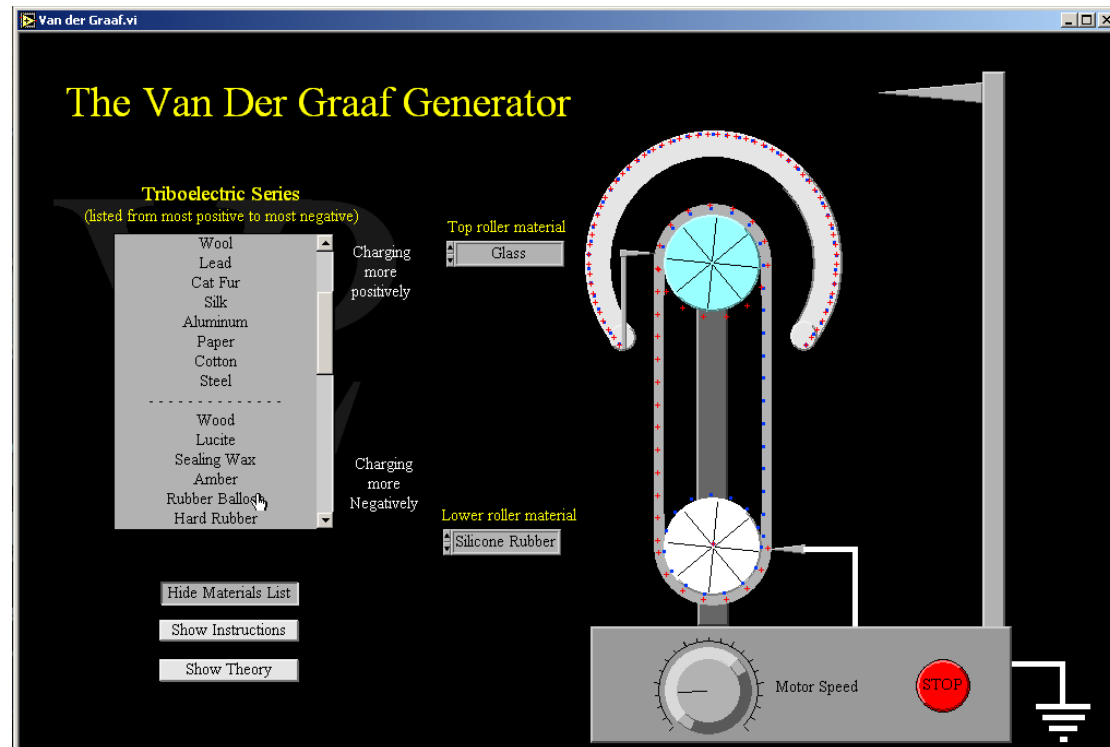
The electric field then will exert a force on the charged sphere pushing it towards the negative plate. As soon as it hits the negative plate, electrons will rush on to the sphere making it negatively charged. Now the electric field will push the negatively charged sphere in the opposite direction, and the ball will swing back until it touches the positive plate again, and the process will repeat endlessly.

If you are not happy with 'electric fields', then simply think of the electrostatic repulsion between a positive plate and a positively charged sphere, and the attraction between a positive sphere and a negative plate. Each time the sphere changes its charge, the attraction and repulsion change too.

10.4 Van Der Graaf

Basic/Advanced

This simulation explains how static electricity is created when two dis-similar materials are pressed together and then separated. It also explains the effects of sharp points. Study the effect of the materials of the top and bottom rollers.



A Van Der Graaf generator produces large potential differences, by separating charges when a rubber belt passes over two rollers. When two dis-similar materials are pressed together and then separated (or when they are rubbed together), one of them will try to steal electrons from the other. The effect is called tribo-electricity. The triboelectric series of materials is a 'pecking order' listing of the materials showing the ones which lose their electrons easily (charge positively) at the top of the list, and going down towards the ones that steal electrons strongly (charge negatively) at the bottom of the list.

The bottom roller material is normally chosen so that the bottom roller steals electrons from the belt (the belt charges up positively), and the top roller material is chosen so that it loses electrons to the belt. In this way the rubber belt will carry positive charges upwards, and negative charges downwards, doubling the rate at which the generator dome charges up.

Sharp points tend to discharge any charges that are close to their tips, because the electric field strength close to sharp points is very strong. The sharp point inside the dome removes any excess charge on the belt when it comes to the top, transferring the charge to the dome. The sharp points at the bottom remove any excess charge when the belt reaches the bottom and sends it to ground. As soon as charges reach the dome of the generator, they spread themselves out evenly over its external surface.

CHAPTER 11

ENERGY

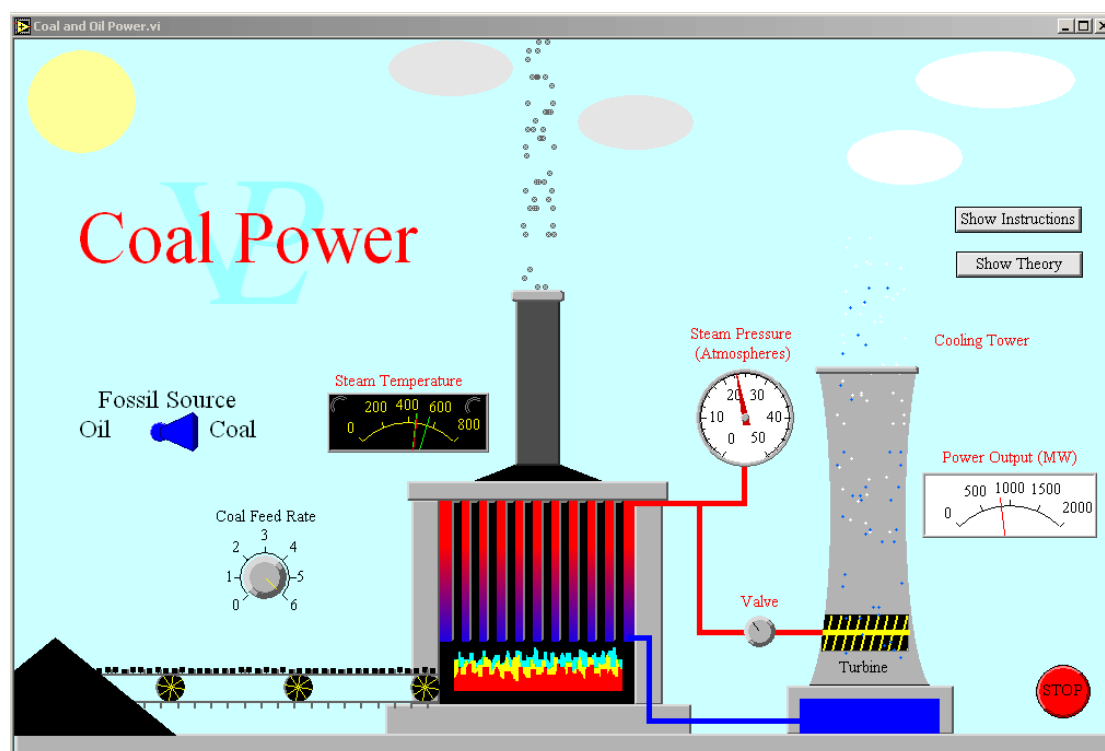


My favourite form of 'clean energy'!
What other sources of energy do you use?

11.1-A Coal and Oil

Basic/Advanced

This simulation shows the similarities in the basic construction of oil and coal powered stations. The power output is proportional to the rate of burning of fuel.

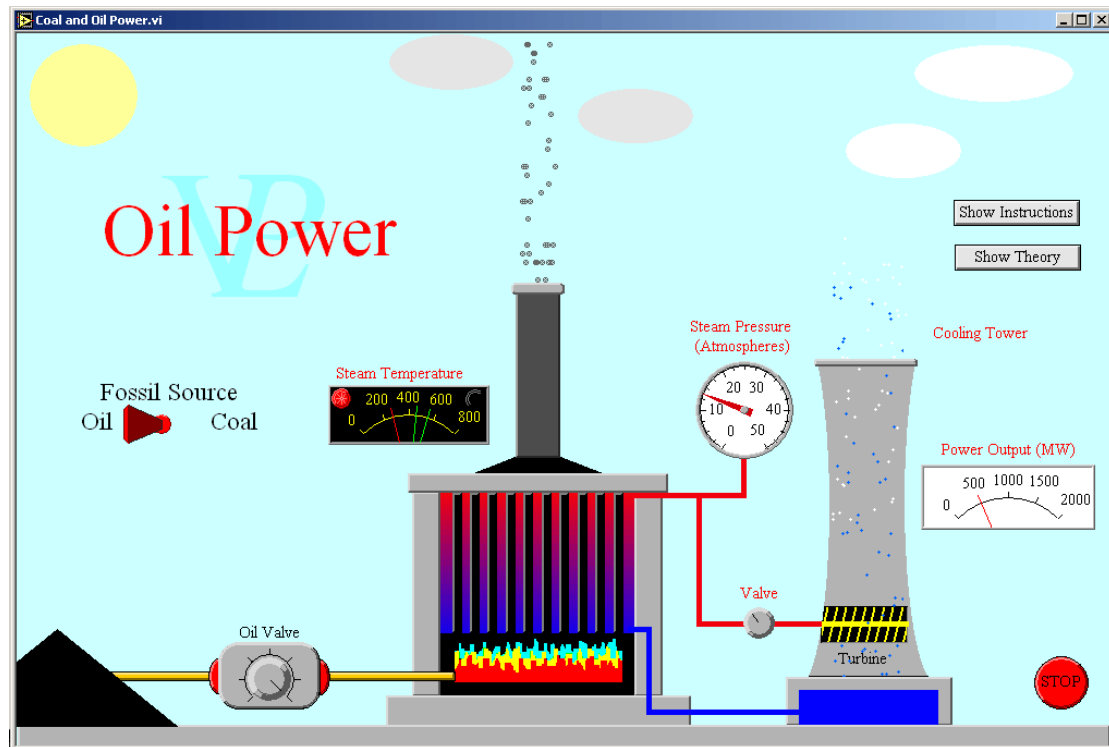


In the absence of 'natural catastrophes', vegetation dies on the surface of the Earth and rots away in such a way that it is not preserved. When floods and land-slides bury vegetation in water or mud so that air is excluded, the vegetation no longer rots. It is preserved (fossilised) and over a long time becomes coal, oil or gas. The amount of coal distributed around the whole world is vast, and is evidence of a global catastrophe which affected the entire world.

A lot of the energy that the vegetation received from the sun is stored in the chemical bonds of the wood and other material of the plants. This energy is still present in the chemical bonds of the coal and oil.

Fossil fuel powered stations use the energy stored in the chemical bonds of the fuel. The energy is released by burning the hydrocarbons in the presence of oxygen and converting them into water, carbon dioxide and heat. The heat is used to make steam, and the steam is used to drive a turbine connected to a giant generator to produce electricity.

11.1-B Oil Power



The world is carelessly using so much energy, that the levels of carbon dioxide are rising at an alarming rate and causing global warming. Burning coal also produces sulphur dioxide, nitrogen oxide and also small particles of soot which pollute the atmosphere and cause acid rain which kills both plant and animal life.

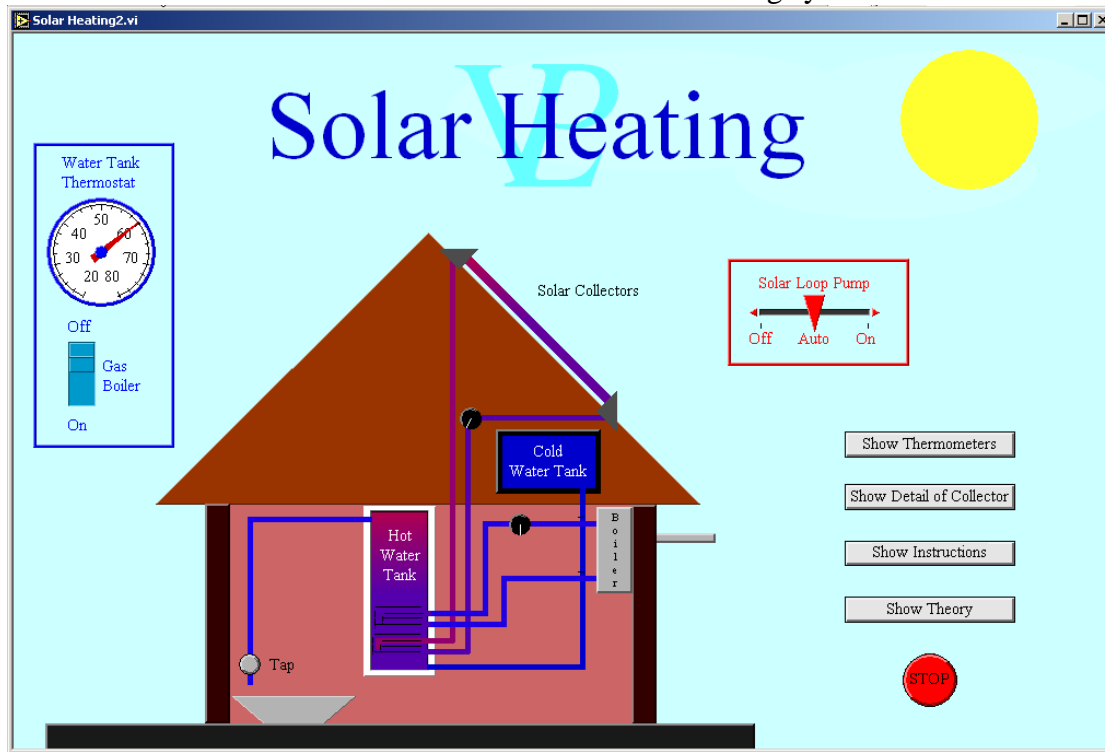
Just one coal power station burns the equivalent of 160 million trees per year! - and there are hundreds of coal power stations around the world!

In order to protect our planet, we need to use energy sensibly, and turn to renewable sources of energy (solar, wind, tidal, hydro), as well as invest in safe nuclear technology.

11.2 Domestic Solar Heating

Basic/Advanced

This simulation shows how a modern domestic solar heating system works.



Solar collectors are a very effective way of gathering heat from the sun in order to heat up water in an insulated tank. In countries that receive intense sunlight (near the equator) the collectors can be very simple; a darkened flat panel is sufficient. In places where the sunlight is less intense it may be necessary to use 'solar concentrators'. One of the designs is made up of evacuated glass tubes where the back half of the tube is aluminised so that it reflects light and heat towards a focus. A thinner darkened tube is placed at the focus so that it absorbs a concentrated amount of sunlight.

As soon as the collector is some 10 C warmer than the bottom of the insulated water tank, a pump starts to circulate the fluid from the collectors to a heat exchanger at the bottom of the tank. Here the fluid loses its heat to the water, and then returns to be heated again by the sun.

The fluid that is pumped round is normally ethylene-glycol (anti-freeze), so that it never freezes inside the glass tubes, where it might otherwise cause them to crack during a cold winter night.

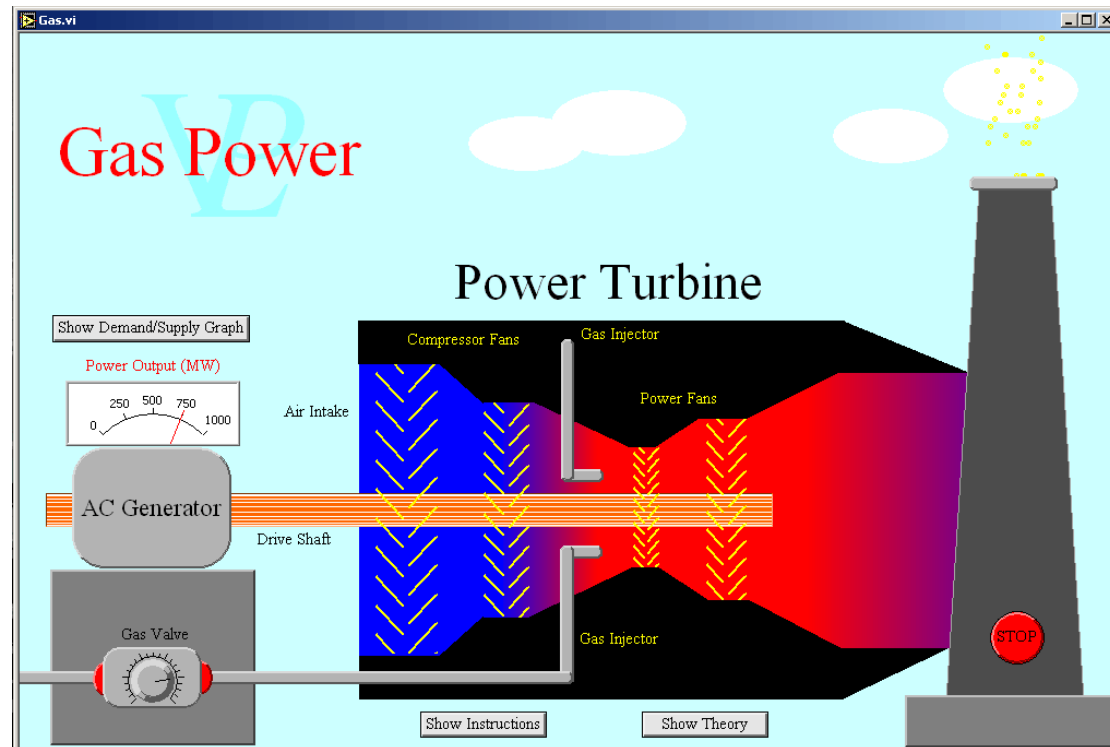
Even if the sun is shining directly on the collectors, their efficiency can range anywhere between 30% and 70% depending on factors such as: Outdoor temperature, Temperature of the water tank, Angle of the collector, etc.

The following figures are based on the system on the roof of my house: Around spring time in a temperate zone and with clear skies a 3 square meter collector can typically absorb some 750 Watts during the central 4 hours of the day. More in the summer, and less in the winter. Unless the weather is very good, a solar system will only heat the water up from around 15 C to 40 C, a gas boiler can be used at the end of the day to further heat the water up to around 65 C. On good summer days the collectors get up to 95 C and the tank gets up to 65 C without any help from the boiler!

11.3 Gas

Basic/Advanced

This simulation shows how the basic turbine in a gas powered station works. The user is challenged to control the power output to match the fluctuating demand for electricity.



When vegetation and animals die on the surface of the Earth they rot away emitting gasses (and horrible smells!) When floods and land-slides bury them under water or mud so that air is excluded, they no longer rot in the same way. Some of it becomes coal, some becomes oil, and some of the gasses emitted in the process become trapped underground. The energy stored in the chemical bonds of these life forms is still present in the chemical bonds of the "fossil fuels".

In a gas powered station the gas is burned directly inside a gas turbine (a complicated set of fans). Air is first compressed by the 'compressor fans' and then the gas is injected into high pressure air and burned. The rapid expansion of the gas causes the 'power fans' to rotate very fast. The drive shaft of the turbine system is connected to an AC Generator and so produces electricity. Gas powered stations can be turned high and low fairly quickly in order to respond to electricity demand.

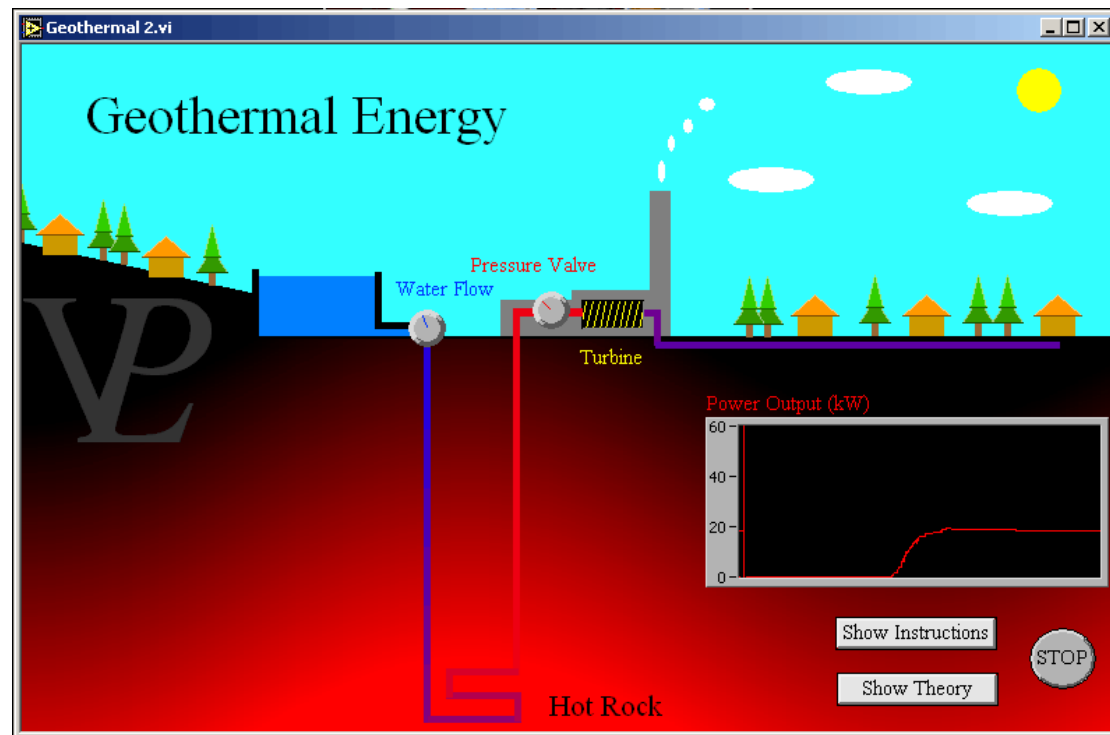
Gas power generation is cleaner than burning coal, however gas is still a non-renewable resource and does contribute to the increase of carbon dioxide in the atmosphere.

The best gas powered stations make use of the heat generated to heat nearby hospitals, swimming pools and houses (this is called combined heat and power). This increases the total efficiency of the station tremendously. However this requires the power station to be located close to the community, and people frequently object to this.

11.4 Geothermal Energy

Basic/Advanced

This simulation shows the principle of harnessing geothermal energy by converting water into steam that drives a turbine. Eventually the earth crust cools down and the scheme loses its viability, making it necessary to relocate!



Geothermal energy can only be used economically in places where the Earth's crust is thin so that the magma is closer to the surface making the rock very hot. This is generally true in areas where there is significant volcanic activity.

A deep bore is drilled into the earth, typically 1 or 2 km deep, and water is pumped down into it. The heat of the rocks turns this water into steam which rises through a separate bore.

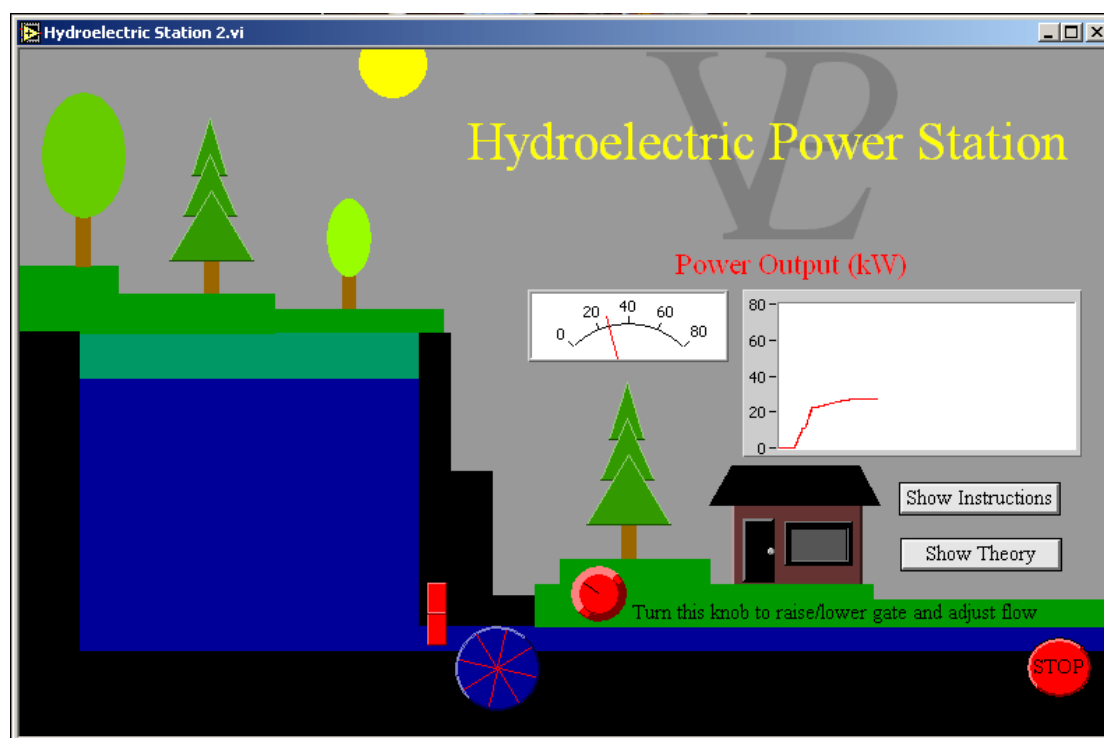
This steam can be used to drive a turbine for electricity generation and the left-over heat can be used to heat houses and green-houses.

One disadvantage is that after a prolonged period of time, of at least several years, the rock under the place where the geothermal plant has been installed may start to cool down. This reduces the power output, and in some cases makes the power station useless.

11.5 Hydroelectricity

Basic/Advanced

An artificial lake in the hills stores water. You have control over the sluice to adjust the amount of water you flow past the turbine. Manage the plant to try to ensure a relatively constant power output even through the weather is changeable!



In the UK, hydroelectricity is driven from lakes whose water is pumped up into the mountains when there is spare electrical capacity. The scheme works like a giant battery. When the demand exceeds the supply that the National Grid is able to provide, the valves are opened and the hydroelectric station can be fully operational within 10 seconds.

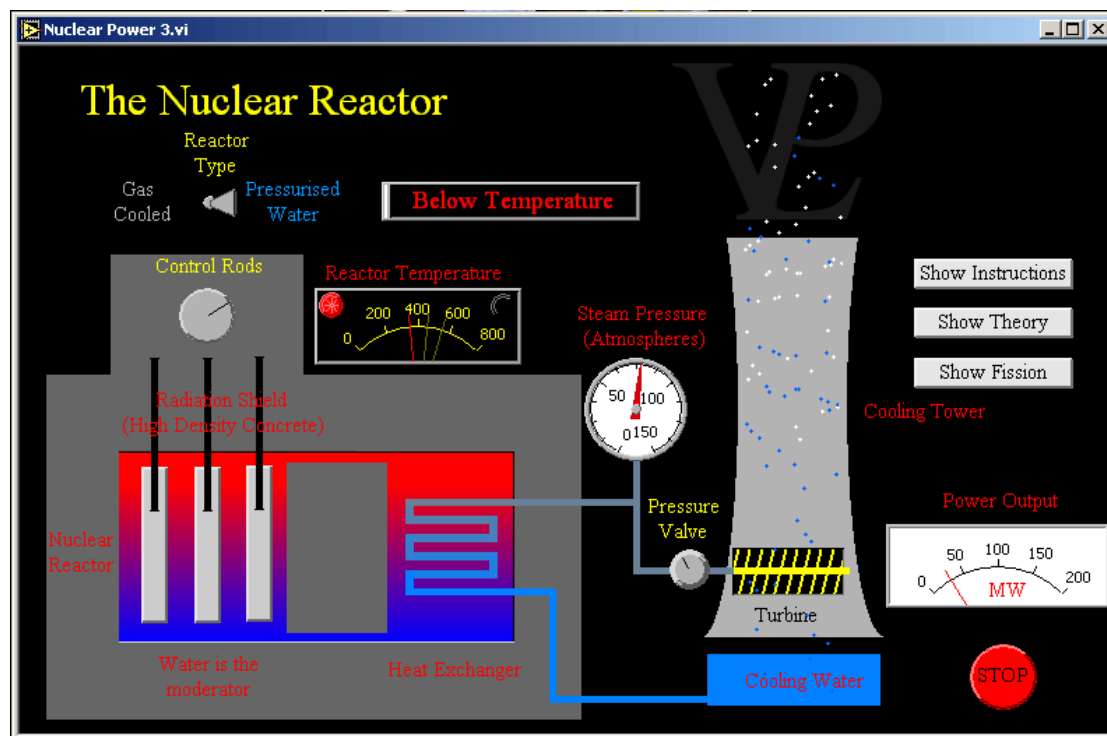
In countries which have large rivers which are maintained by heavy rainfall, such as China, India and Latin America, hydroelectricity is used as a source of energy which is indirectly fuelled by the sun which drives the weather systems. In these countries electricity becomes scarce when there are prolonged droughts.

The potential energy of the water ($PE = mgh$) is converted into kinetic energy ($KE = \frac{1}{2}mv^2$) as the water flows down the pipes. This moving water drives the turbines which convert it into electrical energy.

11.6 Nuclear Energy

Basic/Advanced

You are the new manager of Nuclear Power station! You can choose between water cooled or gas cooled reactors! Adjust the control rods and the pressure valve to the turbines in order to run the plant efficiently. If you allow it to overheat, safety procedures are imposed and you are fired!



At the core of a nuclear power station are the uranium fuel rods. This uranium is 'enriched' in that it has a high number of ^{235}U atoms compared to ^{238}U . The enriched uranium nucleus can disintegrate via fission spontaneously, and when it does this it splits up into two major fractions and 2 or 3 neutrons. In the process, some of the binding energy which held the original nucleus together is given off as heat. When the neutrons produced by the first disintegration hit other uranium nuclei, they cause them to split too. This can quickly start off a fast growing chain reaction, which if left to itself would become a nuclear bomb.

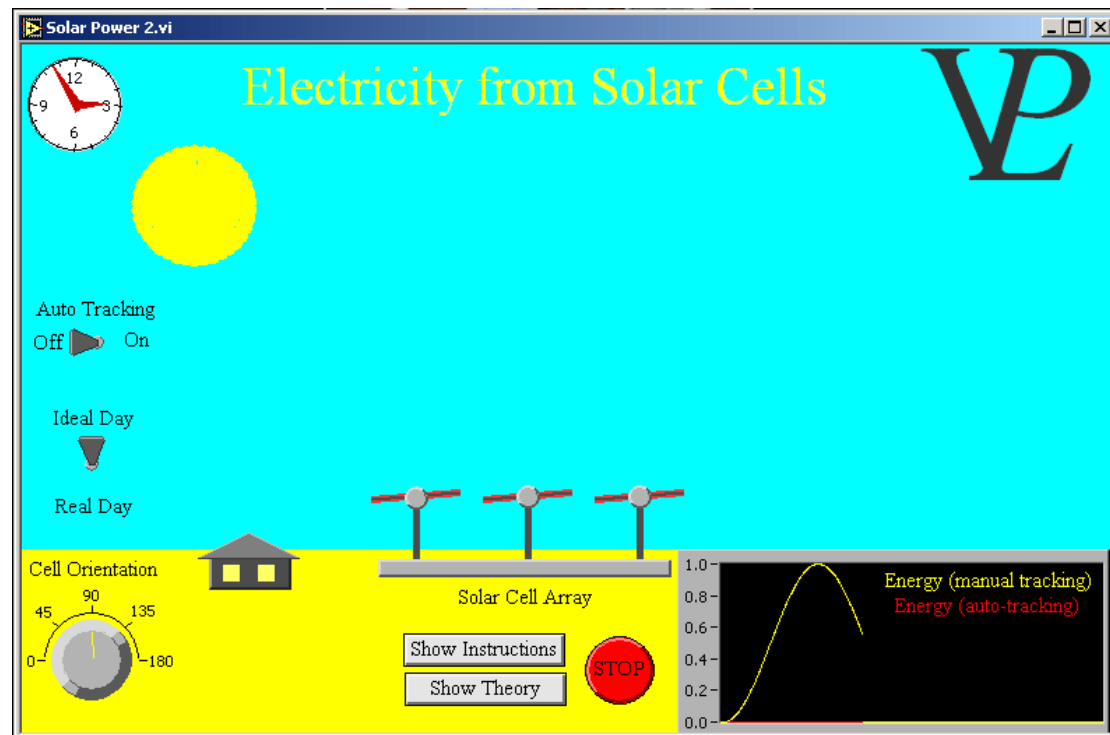
In order to slow down this chain reaction, control rods made of boron are used. These rods absorb neutrons and so slow the chain reaction down. If the control rods are fully inserted into the fuel rods, they absorb all the neutrons produced such that a chain reaction never gets started. This has the effect of shutting the reactor down.

When the rods are retracted from the fuel rods fewer neutrons are absorbed and the chain reaction starts to build up. Heat must be extracted from reactor core otherwise it will overheat and eventually melt down. Water or compressed carbon dioxide can be used in the primary heat exchanger to cool the core down. The secondary heat exchanger is used to convert water into steam, and the steam is used to drive a turbine which in turn drives a generator. Beyond the generator are the cooling towers which are used to cool the exhaust steam. Heat and water vapour escape from the top.

11.7 Solar Power

Basic/Advanced

Investigate how the power collected by solar cells changes throughout the day. Test the difference between fixed cells and auto-tracking solar cells can make. Notice the effect of cloud cover



Electricity can be produced using the sun and solar cells. Solar cells are made from semi-conducting material, which is fairly expensive to produce. In addition to that solar cells are very inefficient (around 3%). However, they are non-polluting and use a renewable energy source as they will keep on working while there is energy coming from the Sun. They are particularly useful in remote places where there is no access to power of any other forms. They are an ideal solution for space stations and satellites where they are used to recharge batteries.

The amount of power collected will depend several things:

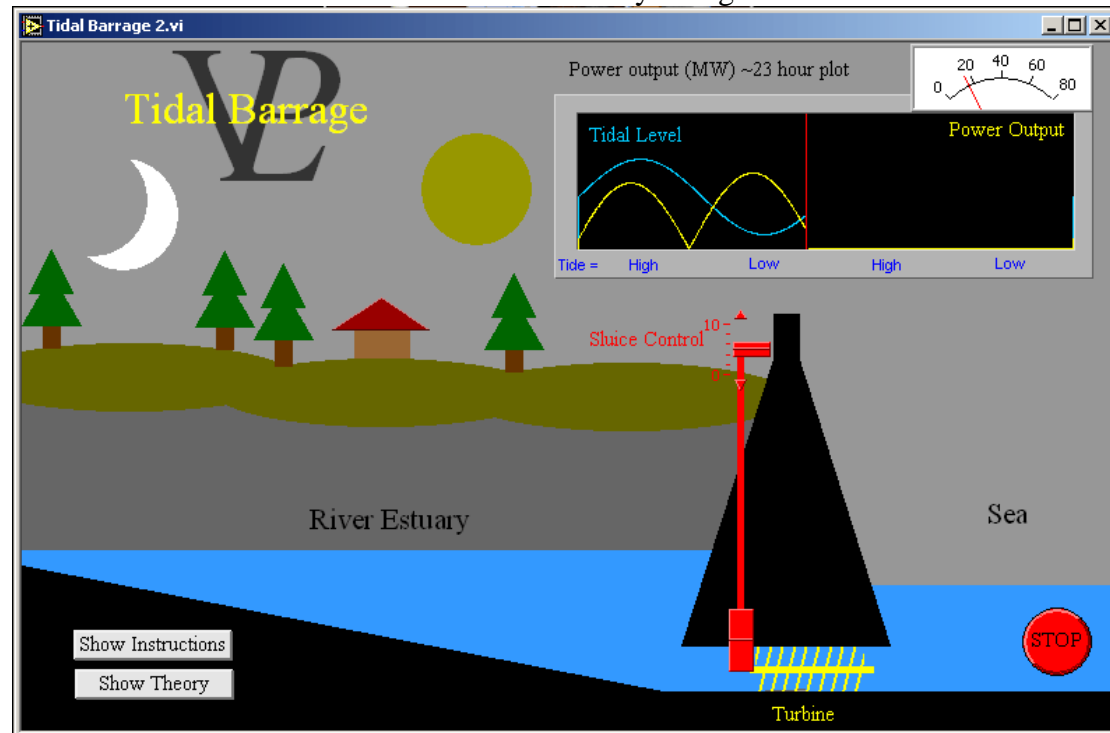
- 1 - How much atmosphere the radiation from the Sun must pass through before reaching the cells. (time of day, season of the year)
- 2 - The orientation of the solar cells. Are they facing the sun directly?
- 3 - The weather conditions.

Fixed solar cells are arranged so that they get the maximum at midday. If you live far North or South you will need to angle the cells towards the equator. Strictly speaking you also need to adjust them depending on the season.

11.8 Tidal Barrage

Basic/Advanced

Manage a Tidal Barrage to try to get the maximum overall energy from the tide. You will notice that however hard you try, there will always be two 'dead-times' in a complete tidal cycle. Since the tides are not synchronised with the day/night, these dead-times will come at different times of the day or night!



Tidal barrages can be built where there are large river estuaries in which large amounts of water can be trapped when the tide is high. If the water is kept until the tide has dropped considerably, then the water can be passed through a turbine and used to generate electricity.

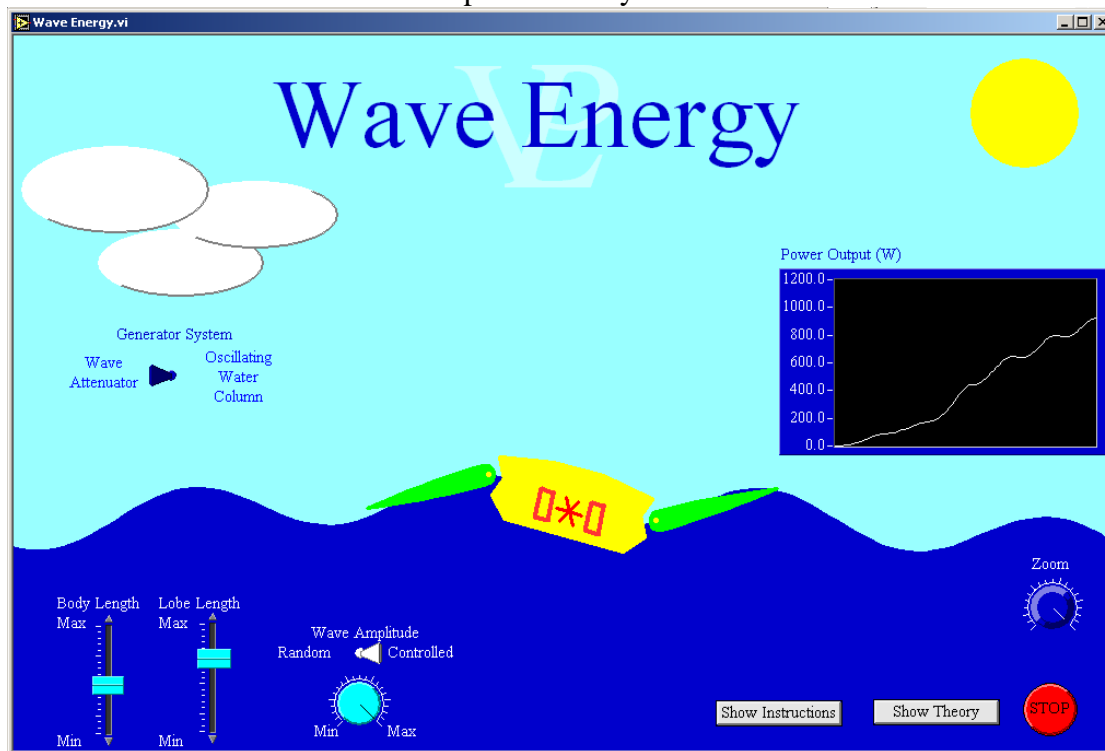
Notice that it is not possible to obtain a steady power generation, and that every 23 hours there are four times when the power output is zero. This is one of the disadvantages of tidal barrages. Since the tides are driven by the moon, the periods of peak power will not occur at the same times of day.

Other drawbacks are that they provide a hindrance to water based navigation as well as causing possible environmental damage to coastal life. Another serious consideration is that the river may eventually get silted up and the reservoir can get full of mud, making the system useless.

11.9 Wave Energy

Basic/Advanced

There are a number of different ways in which energy can be extracted from waves in the sea. This simulation shows two practical ways in which this is achieved.



Capturing wave energy efficiently opens up a potentially vast supply of renewable energy because the oceans are vast. However there are many practical factors that must be considered before placing the systems out to sea: How costly are the systems to produce? (in money and energy), How will the energy be transmitted back to land? (how long will the cables be), How consistently wavy is that site? (stormy/calm). What maintenance is needed? (can it be done out at sea?), What is their expected life service? (will it produce more energy in its service life that was used to make it in the first place!).

"Wave Attenuators" use the flexing motion of the waves to operate pumps that drive a generator to produce electricity. They need to be 'tuned' to a scale that matches the predominant wavelength of the waves. In the system shown here, maximum energy is generated when the lobes and the body length are approximately half a wavelength long. This ensures maximum torque as well as maximum rocking between the lobes and the body (shorter lobes may rock well, but have less torque!)

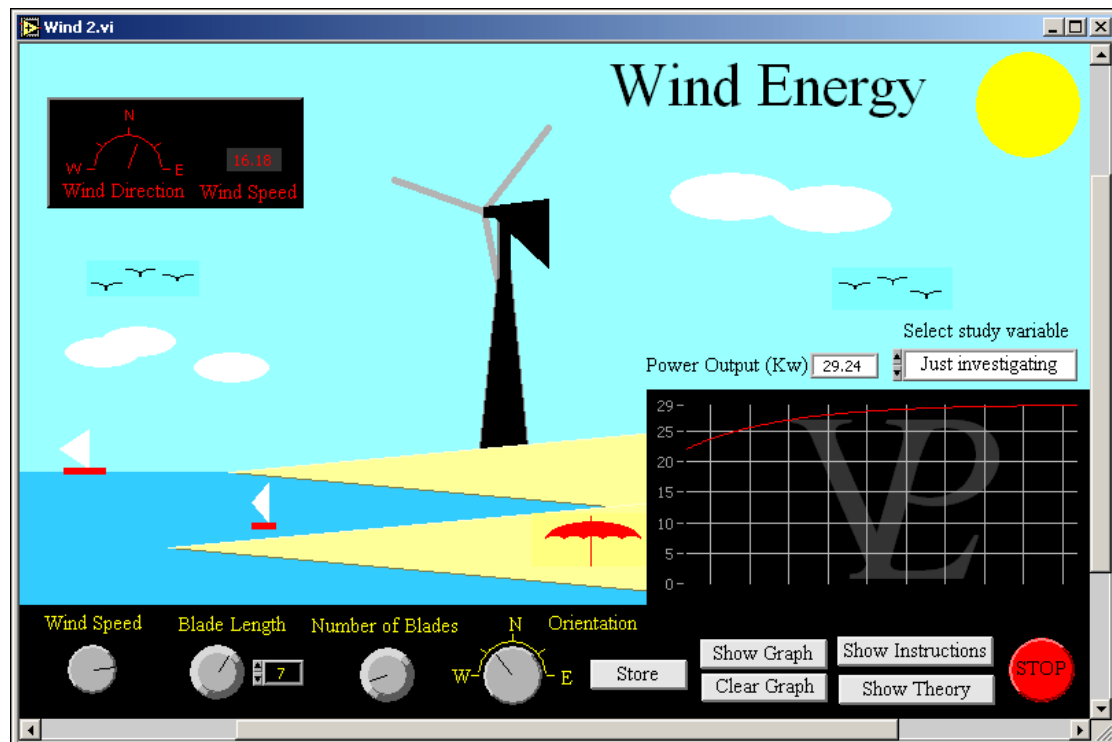
"Oscillating Water Columns" use the wave surface to pump air up and down through a funnel in which there is a fan that will drive a generator. The wider the skirt of the funnel, the more air will be displaced, However if the funnel skirt is exactly one wavelength wide, it will hardly pump at all, because the mean displacement over an entire wave is zero! The body length is adjusted so that it rocks as little as possible but rises and falls in antiphase with the water in the funnels. Practical systems have to be designed to fit the conditions where they are to be placed.

The energy generated can be transmitted back to land via electrical cables, or can be used to generate hydrogen on site which can either be stored for subsequent retrieval or can be piped to land for use in fuel cells.

11.10 Wind Energy

Basic/Advanced

Check the wind indicator to see where the wind is coming from. Adjust your wind turbine to face the wind. Investigate the effect of the size and number of the blades. Store your results and plot graphs. (In this simulation, you can even control the wind speed!)



The power output of a wind turbine is not related in a simple way to the wind velocity, length of blades or the number of blades. However, the following general observations can be made:

- 1 - Longer blades catch more wind, and also produce larger turning moments at the hub.
- 2 - More blades catch more wind, but also add to the weight and cost. If the number is increased too much, one blade will start to run in the wake of the preceding one and so the advantage does not increase as much as expected.
- 3 - In modern wind turbines, the angle of the blades can also be adjusted for different wind speeds in order to get the maximum power output.
- 4 - The magnetic field strength inside the generator can be adjusted in order to obtain different electrical power outputs even while the turbine is rotating at the same velocity.

CHAPTER 12

FLUIDS

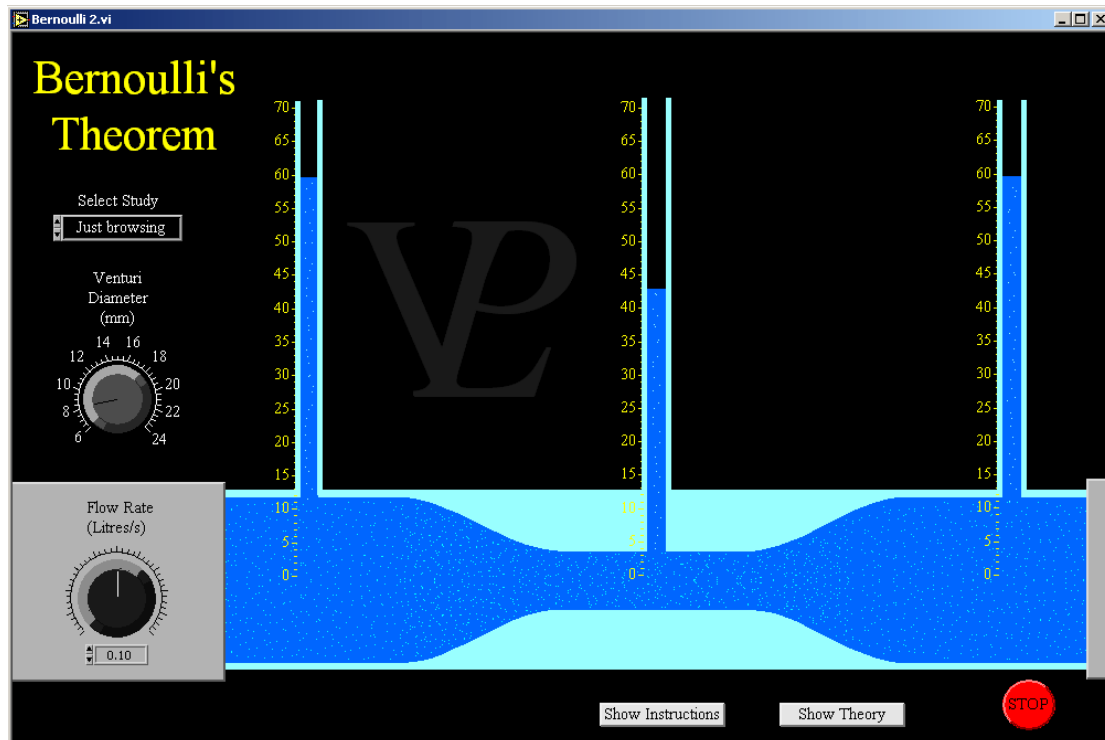


Hot and cold fluids flow all around my house.
How does pressure relate to flow?

12.1 Bernoulli

Advanced

This simulation shows how the pressure in a flowing fluid drops as the velocity increases. A venturi with differential manometers shows the differences in pressures.



Bernoulli studied how the pressure varied along flow lines and deduced a law on how the pressure would vary along it. His law is applicable when the fluid is incompressible, and its viscosity is low.

His findings can be summarised in an equation that bears his name.

$$p + \rho gh + \frac{\rho v^2}{2} = k \quad \text{where } p \text{ is the pressure, } \rho \text{ is the density, } g \text{ is gravity, } h \text{ is the}$$

height in the fluid and v is the velocity of the fluid and k is a constant. It is worth looking up a fuller explanation in a text book, the proof is quite interesting!

When fluids speed up and slow along their flow lines (as when flowing through a constriction), the local pressure is affected. This effect is used to help vapourise petrol inside a carburettor (petrol vapourises even faster at low pressures).

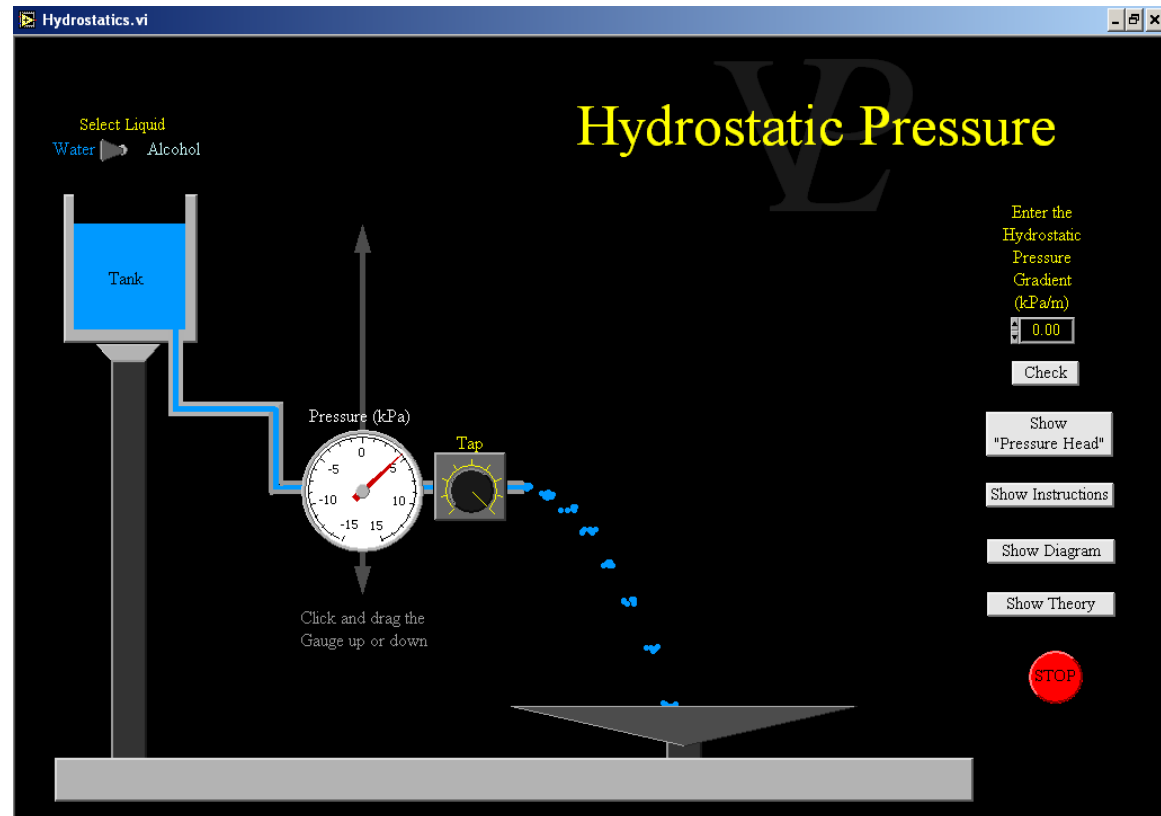
It also something ships need to take into account when moving a large boat in a narrow canal or lock gate. If the boat causes the displaced water to flow fast around the boat, its pressure will drop, and the boat will sink a little deeper into the water. If the lock is shallow it can cause the boat to touch the bottom. The effect can also be noticed when a fast moving boat goes past a boat that has been tied up at the side of the river; it will 'suck' the stationary towards it.

The effect can also be felt in a tall vehicle when another tall vehicle drives past it at high relative speed; the vehicles are temporarily drawn to each-other!

12.2 Hydrostatics

Advanced

This simulation shows the effect of the weight of stationary fluids over the fluid layers beneath them.



Hydrostatic Pressure is the pressure produced in liquids when they are stationary (hydrodynamics deals with fluids in motion, and their study is generally more complex). In Hydrostatics it is only the weight of the liquid (plus any additional pressure applied to the top surface of the liquid) that needs to be considered.

At any depth under the surface of a liquid, the layer beneath needs to support the total weight of all the liquid above it. Consider an imaginary cylinder of water with base A and height h ; its volume will be Ah , and its mass will be $Ah\rho$, where ρ is the density of the liquid. The weight that needs to be supported by the layer underneath it will be $Ah\rho g$ (where g is gravity). That weight acts over the entire bottom area of the imaginary cylinder we are considering. The pressure will be the Weight divided by that Area, so the pressure at the bottom will be $P = \rho gh$.

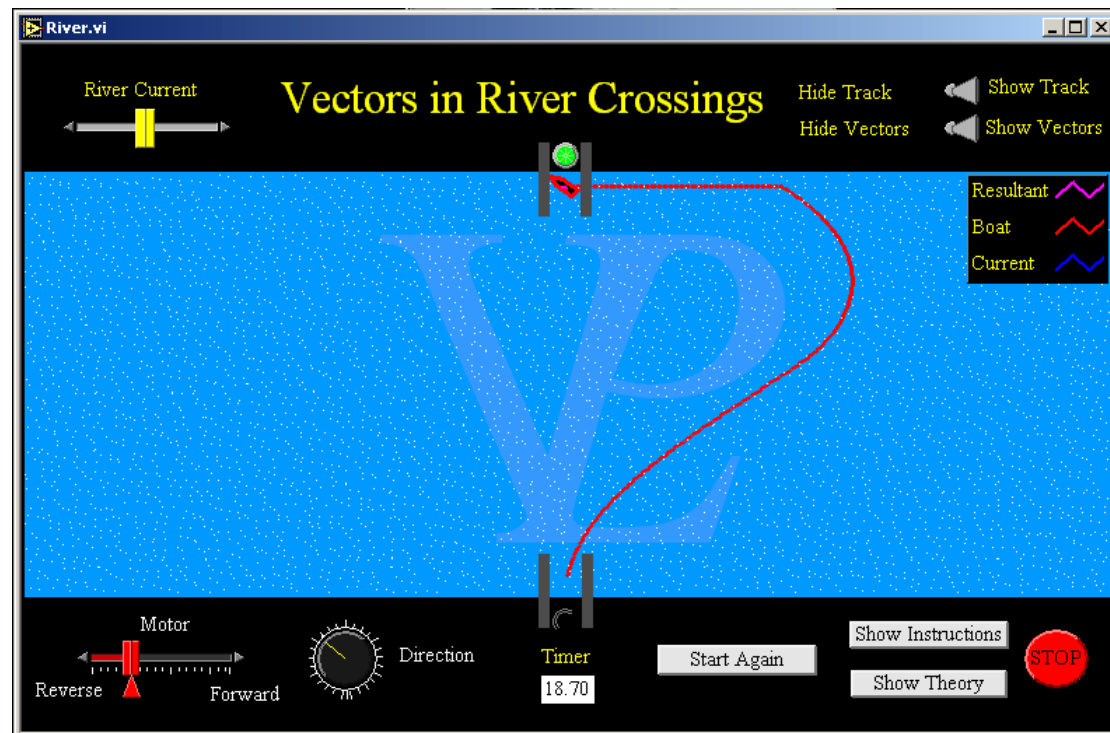
The pressure increases linearly as the depth increases. The pressure gradient is defined as $dP/dh = \rho g$. Submarines and divers can work out how far beneath the surface of the sea they are, simply by measuring the pressure: $h = P/\rho g$. Atmospheric pressure also increases the lower we go. At sea level it is approximately 100kPa (= 1 Atmosphere), and as you climb up a mountain or fly in an aeroplane, the pressure decreases the higher you go. However, atmospheric pressure gradient is not linear, because gasses are compressible, so the density does not remain uniform.

Fluids 12.3

12.3 River

Basic/Advanced

This simulation shows the ‘triangle of velocities’ at work in a practical way as a boat tries to traverse a fast flowing river. It also shows how velocity gradients across a river can make it tricky to steer in a straight line!



A motor boat navigating through a flowing river is a good illustration of how vectors add up to give a resultant.

Even if the boat is directed straight across the river, the flow of the water causes the overall trajectory of the boat to deviate down-stream.

Because of friction in water, the centre of a river flows faster than the water near the banks (assuming the river is also deepest in the middle).

It is possible to steer the boat partly up-stream in order to make the boat take a slightly more direct route across the river.

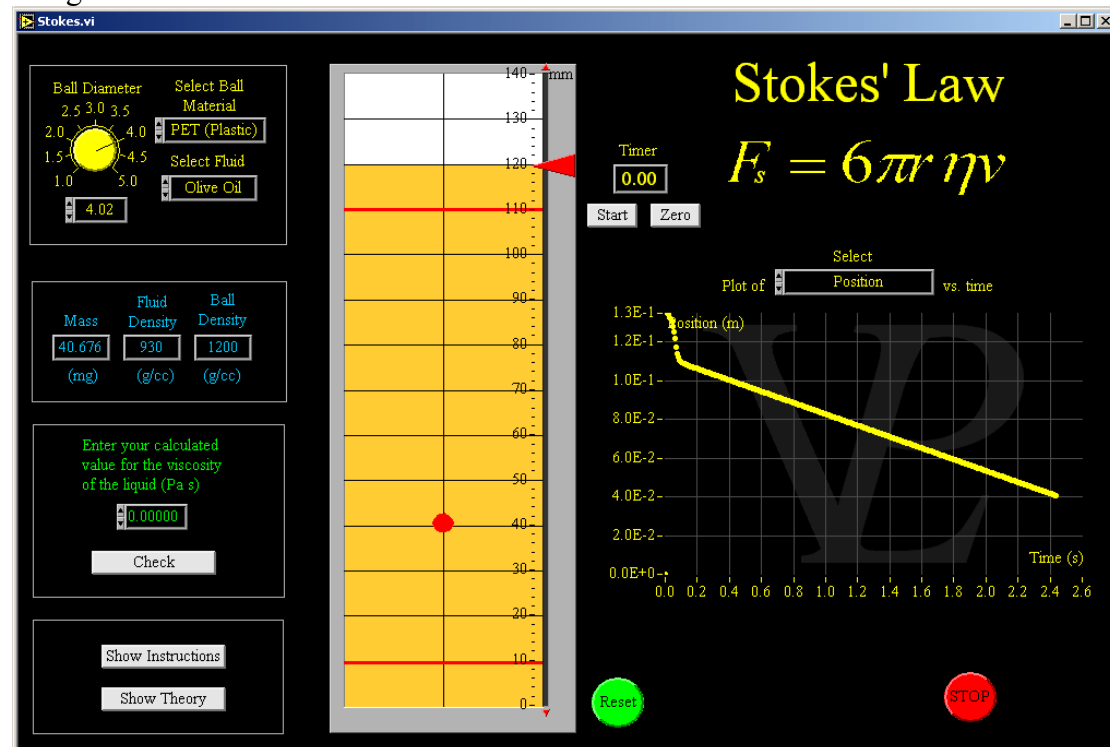
If the river is flowing at its maximum rate, it is not possible to cross the river in a straight line by simply steering up-stream!

It is nevertheless possible! See if you can use your ingenuity to get across during maximum flow!

12.4 Viscosity

Advanced

This simulation shows how viscous forces in a fluid cause balls falling through it to fall with a terminal velocity. Using balls of suitable radius and density makes it possible to carry out an experiment to measure the viscosity of four different fluids using Stokes' Law.



When an object falls through a fluid it will experience a drag force which will tend to slow it down. Fluids that offer appreciable drag are said to be viscous.

George Gabriel Stokes studied this effect, and the law is named in his honour as Stokes' Law.

The viscous force is always in the opposite direction to the velocity and is given by $F = 6 \pi r \eta v$ where r is the radius, v is the velocity and η is the viscosity measured in Pa s (Pascal seconds). When a ball is falling in a liquid, the downward force W due to its mass is $W = \frac{4}{3} (\pi r^3 \rho_1 g)$ where ρ_1 is the density of the ball and g is gravity.

The ball will also experience an upward force U due to upthrust following Archimedes principle. $U = \frac{4}{3} (\pi r^3 \rho_2 g)$ where ρ_2 is the density of the fluid.

When the ball is falling at constant velocity these forces are balanced. $W = F + U$
Substituting these we find $v = \frac{2}{9} r g (\rho_1 - \rho_2) / \eta$ or $\eta = \frac{2}{9} r g (\rho_1 - \rho_2) / v$

Notice however that if $\rho_1 < \rho_2$ the ball will float!

An easy way to measure the viscosity of some fluids is to drop a ball in it, wait until it reaches terminal velocity and then time its descent over a known length to measure its velocity. However it is necessary to choose the density and diameter of the ball carefully to make sure it will reach terminal velocity well before hitting the bottom of the tank!

CHAPTER 13

FORCES

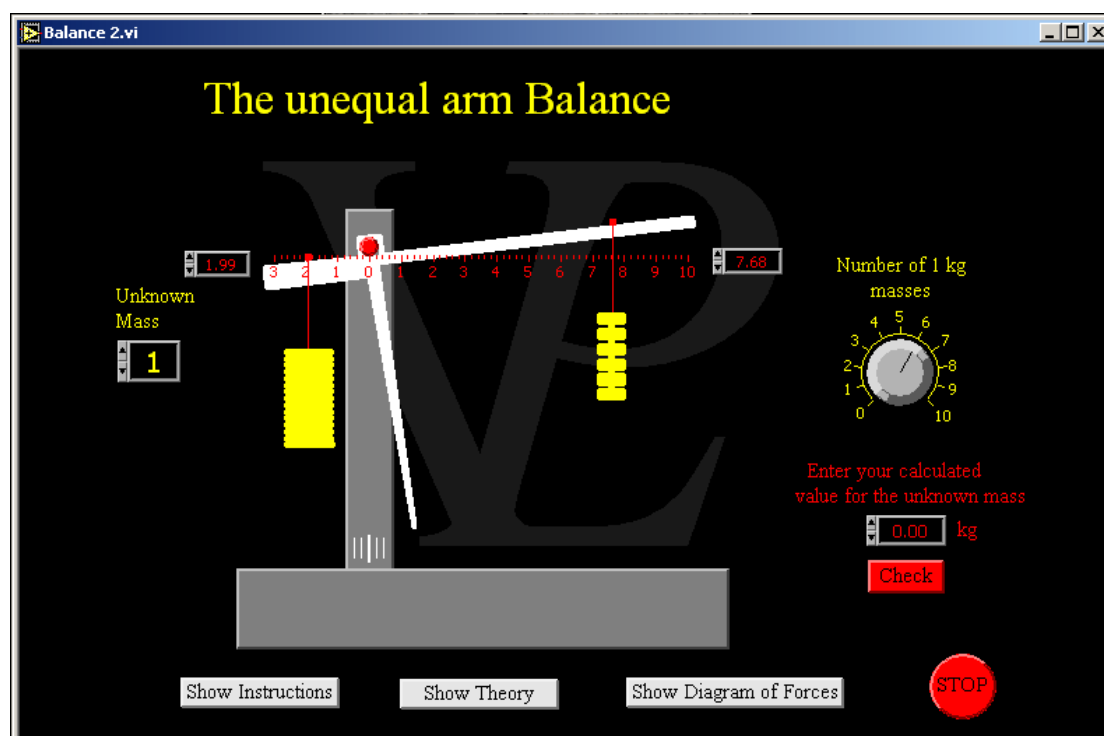


Some of the tools I use to exert forces.
What are forces, and what do they do?

13.1 Balance

Basic

In this program the pupil will learn to apply the principle of moments to find the mass of an unknown weight by using known weights and adjusting the length of a graduated arm. The program also checks the answers arrived at by the pupil.



A balance of this type uses the theory called 'moments of forces'. That is a bit of a strange name, but the explanation is not very complicated.

Moments are forces which cause things to rotate rather than to accelerate in a fixed direction. Wherever you have a pivot there is potential for rotation, so the theory applies.

The moment of a force is the product of the force multiplied by the perpendicular distance between the force and the pivot.

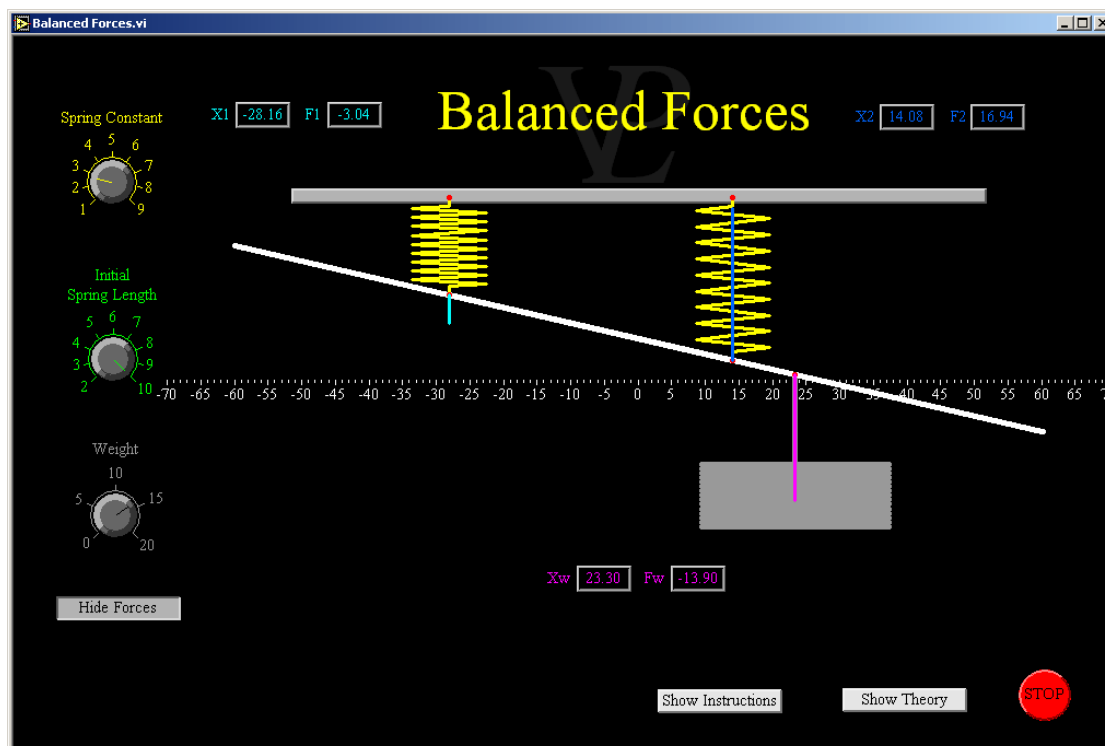
In this example the masses on the right hand side produce a clockwise moment, and the unknown mass on the left hand side produces an anti-clockwise moment.

When the clockwise moment is equal to the anticlockwise moment the balance is in equilibrium.

13.2 Balanced Forces

Basic/Advanced

This simulation shows two springs supporting a weight by means of a long bar. It can be used to visualise how equilibrium is established when forces are not co-linear.



When a system of forces is in equilibrium, there will be no resultant force, and no resultant moment.

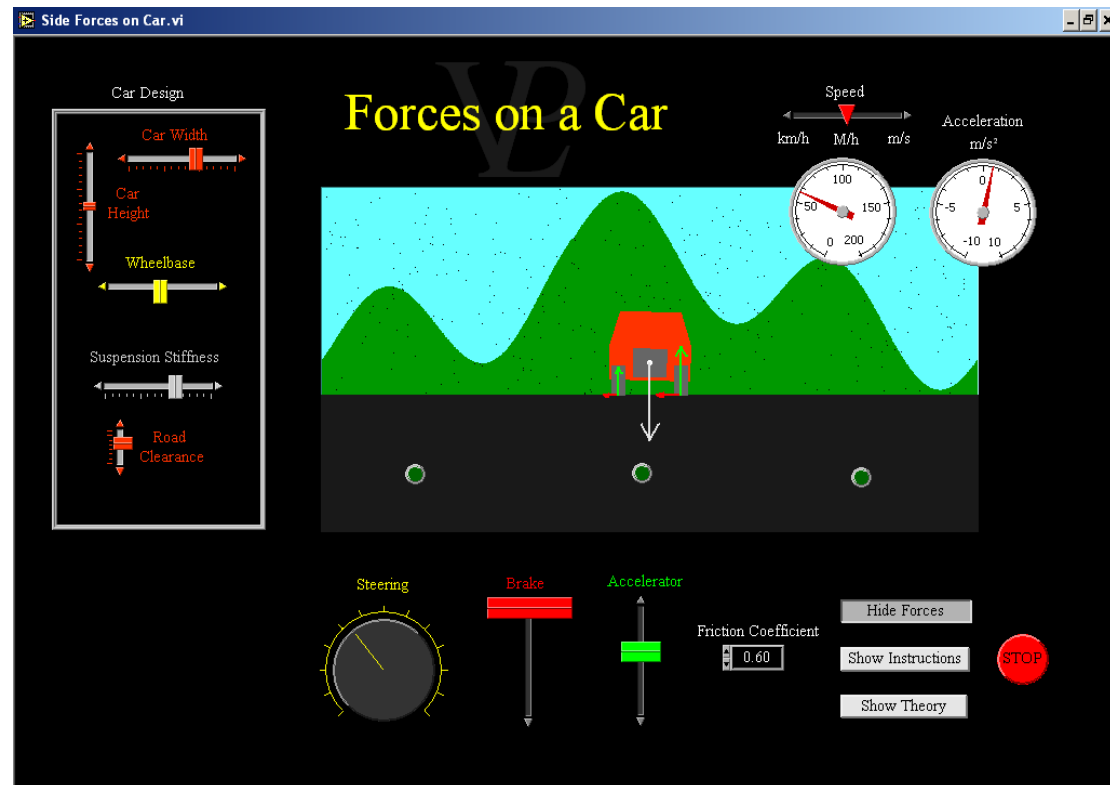
This means that the total upward force will be equal to the total downward force, the total forces to the right will be equal to the total forces to the left, and the total clockwise moment will be equal to the total anti-clockwise moment about any point in the system.

If this condition is not met, then something is going to accelerate and change the positions until it comes to rest in a way that the forces and moments are totally balanced.

13.3 Car Forces

Basic/Advanced

This simulation shows how unbalanced forces acting on a car cause it to accelerate, decelerate and change direction. It also shows how the distribution of forces affects the stability of the car.



The position of the engine in an unloaded vehicle affects the centre of gravity. Modern cars usually have the engine at the front, so the weight supported by the front wheels is greater than that supported by the back wheels. Partly for this reason, modern cars are also front-wheel-drive (the engine connects to the front wheels the back wheels simply roll). Heavy load vehicles (which are normally loaded on the back) are normally rear wheel driven.

The braking is achieved through all the wheels (front and back). However, the wheels supporting the greater weight will provide the better grip, and also the greater braking. When braking, the wheels provide a turning moment which attempts to rotate the car. The front wheels provide a counter moment and this adds to the weight that the front wheels support (and reduces the weight that the rear wheels support).

When accelerating hard, the turning moment of the wheels tends to lift the car at the front. In severe cases it may be possible to do a "wheelie" (lifting the front wheels off the road). If the car is front wheel drive, this limits the grip and the maximum acceleration. Rear wheel drive cars can continue to grip the road and accelerate even when the front ones are in the air! - but they cannot steer!

In all cases the road friction limits the maximum acceleration and braking that can be achieved. If the road is particularly slippery (snow, ice, mud) four-wheel drive cars

obtain better traction. However when it comes to braking they are no better than a normal car.

The height of the centre of gravity of the vehicle combined with the suspension stiffness determines the stability of the vehicle and also the rocking of the bodywork. Low centres of gravity make for stable cars, but these are no good when driving through deep mud or deep water.

Every design is a compromise. No design is optimum for all conditions; each type of vehicle is tuned for its most likely application.

When a car is driving in a straight line, the left hand wheels support the same weight as the right hand wheels. However, when a car is turning left, the road exerts needs to exert a centripetal force on the wheels directed towards the inside of the bend.

The centripetal $F_c = M v^2 / r$. Where M is the mass of the car, v is its speed and r is the radius of the bend (that is why a small radius bend at high speed requires such large centripetal forces!

This centripetal force produces a turning moment on the vehicle which tries to rotate the bodywork clockwise (when viewed from the rear). To maintain the balance the right hand wheels support a greater weight than the left hand ones and this maintains the balance when turning round a corner. A similar reasoning follows when turning right.

The wheels on the inside of a bend bear less weight than those on the outside of the bend. If a car is accelerating or braking heavily at the same time as turning a bend, the wheels on the inside of the bend will be the first ones to skid!

If the centre of gravity of the car is quite high and the bend in the road is sharp, the clockwise moment of the grip on the road may be greater than the anti-clockwise moment that the right hand wheels are able to provide. If this happens, the car will start to roll over clockwise and the left hand wheels (which are no longer bearing any weight) will lift in to the air!

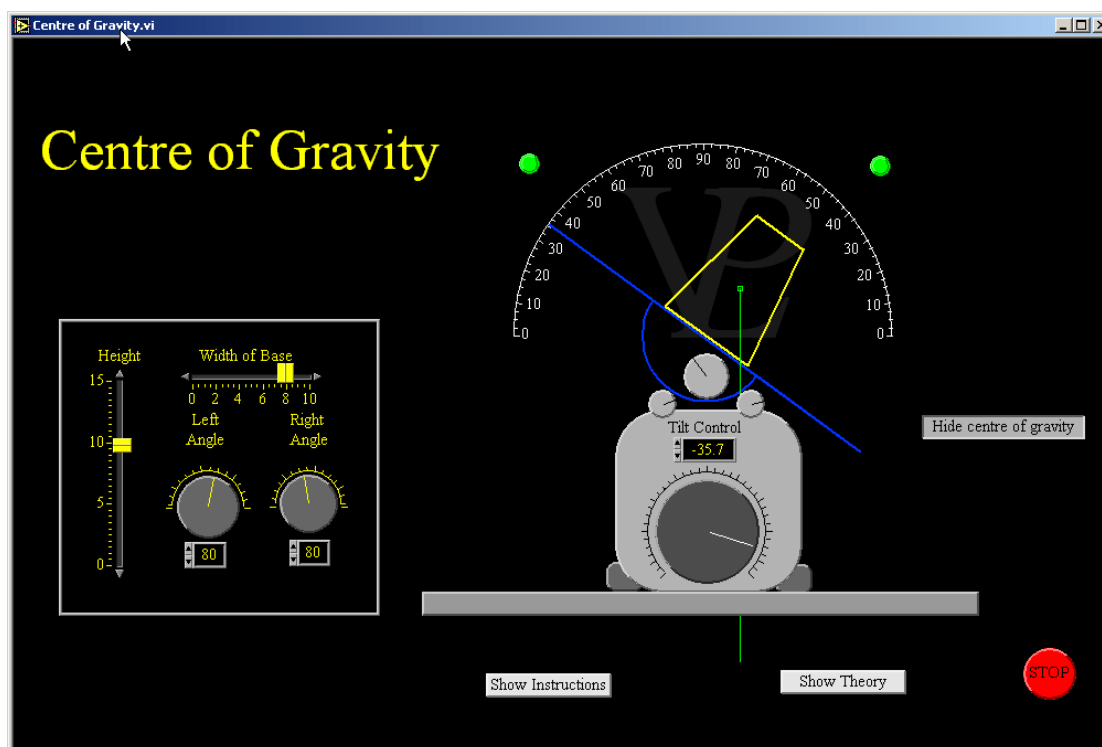
Cars that will need to make tight turns at high speeds must therefore be designed with very low centres of gravity. Their stability can be further improved wider wheelbase (think of a modern racing car).

However, racing cars are not very practical for carrying loads, and they are not easy to get in and out of! Typical family cars need to be designed with passenger comfort in mind as well as their safety. In normal circumstances a car should skid and slide sideways across a road instead of tipping over.

13.4 Centre of Gravity

Basic/Advanced

This simulation shows the position of the centre of gravity of a polygon of variable shape and dimensions. The user can then tilt the object over and note the point at which the object topples over.



The centre of gravity (or centre of mass) is the point where all the weight of the object seems to be acting through. It is a mathematical construction; it can sometimes even be located outside of the object itself!

When a book is mostly on top of a table it does not fall, but as you push it progressively off the edge of the table it reaches the point where it falls off the edge. That is because the centre of gravity of the book has just moved off the edge of the table. Clearly gravity is acting on both sides of the book (over the table and over the edge), but the book behaves as if it was acting at just one point, and if this point is over the edge, it will fall.

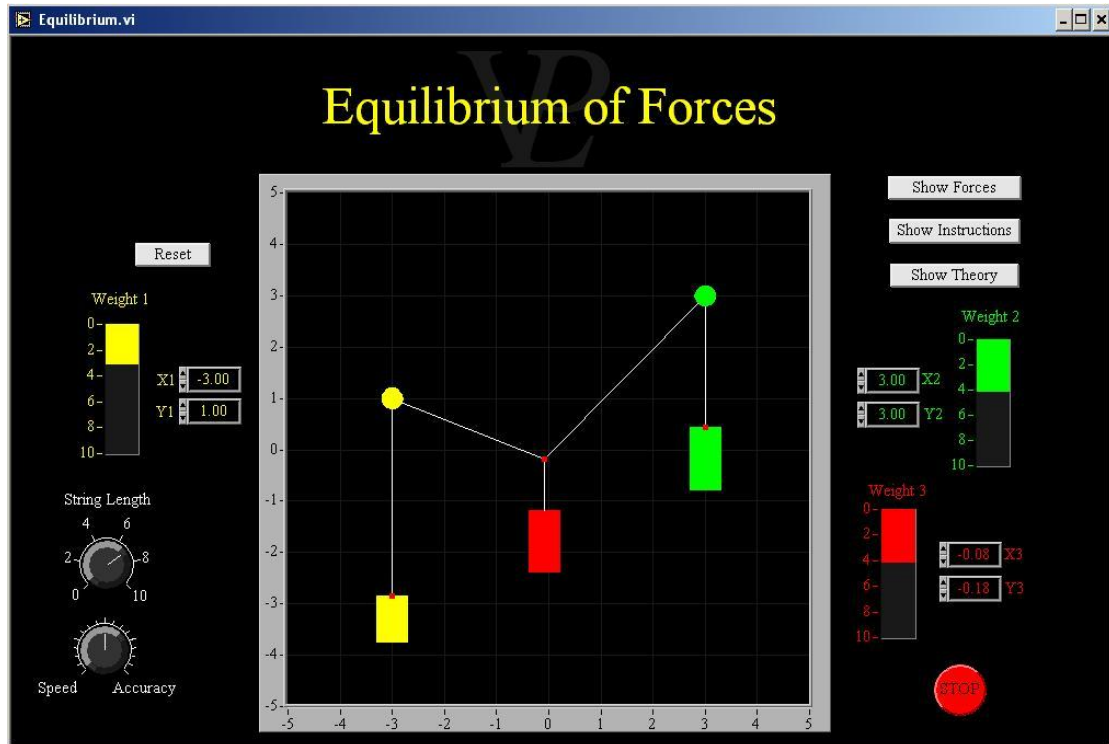
The stability of an object depends on the position of its centre of gravity and the size of its base. Provided the centre of gravity is located vertically above the base of the object it will not fall over.

When the object is tilted over it can reach the point where the centre of gravity is no longer above its edge. When this happens, the object topples over.

Broad based object which are short in height are the most stable, and tall objects with a narrow base are very unstable. Stability is an important consideration when designing all sorts of things from desk and floor lamps and furniture to cars, bridges and buildings.

13.5 Equilibrium

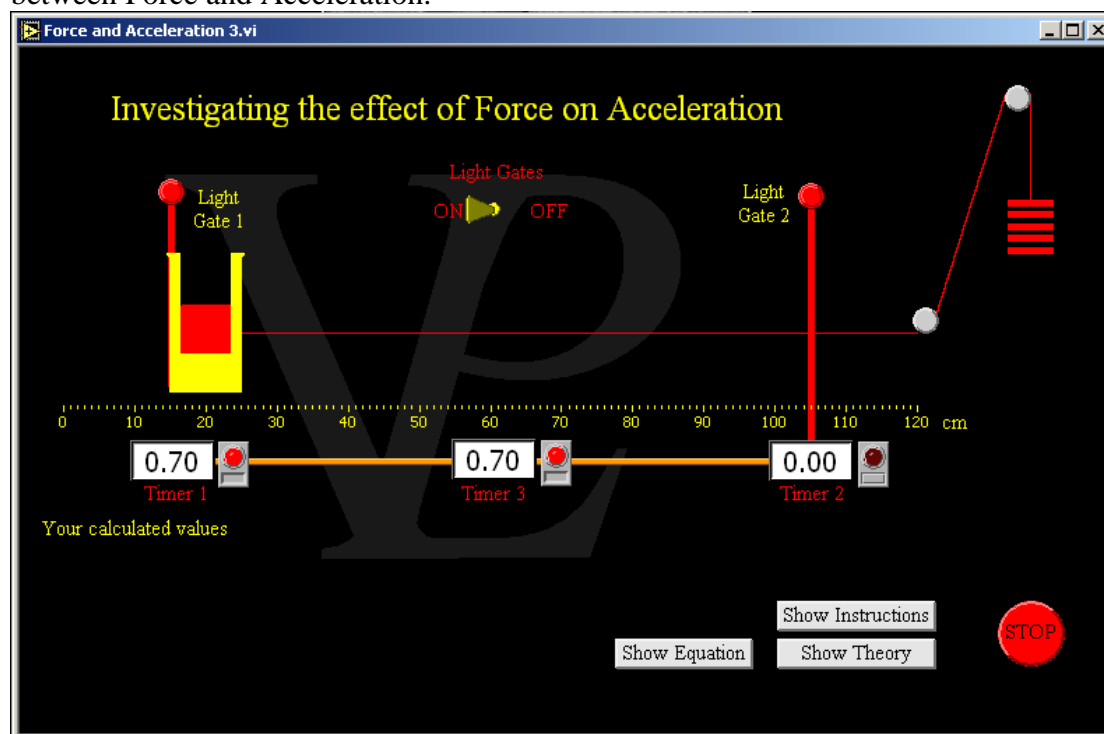
Basic/Advanced



13.6 Force and Acceleration

Basic/Advanced

In this simulation a trolley is caused to accelerate along a track by means of weights attached to a pulley. The acceleration is measured using two light gates. (Calculations need to be carried out). A graph can be plotted in order to investigate the relationship between Force and Acceleration.



Light gates are often used in science because they react much faster than humans with stop watches. Light gates 1 and 2 measure the total amount of time T_1 and T_2 during which the beam is broken. Stop clock 3 measures the time between when light gate 1 is first blocked and when light gate 2 is first blocked. T_3 is the time taken for the trolley to travel between the two light gates.

The vehicle is 10 cm long and it will block the beams while its whole length goes past the beam. The velocities V_1 and V_2 can be worked out to be 0.1m (the length of the trolley) divided by T_1 or T_2 (the time taken to travel 0.1 m).

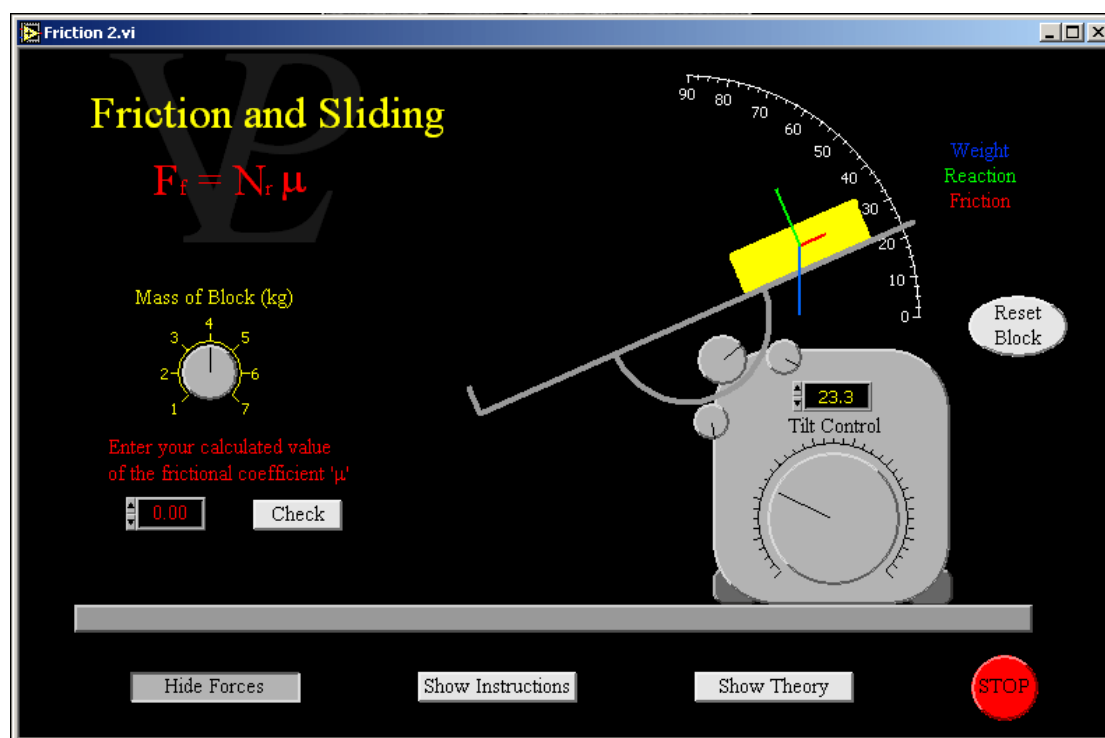
Acceleration is defined as the change in velocity divided by the time taken for the velocity to change. So the acceleration is equal to $(V_2 - V_1)/T_3$.

If Isaac Newton is right, then the acceleration should be proportional to the applied force. This means that the graph of force against acceleration should be a straight line. The equation relating acceleration (a), force (F) and mass (m) is $F=ma$. If we plot force on the Y axis, and the acceleration on the X axis then the gradient of the graph will be equal to m , the entire mass that is accelerating – the trolley, plus all the masses on the trolley, plus all the masses on the hanger.

13.7 Friction

Basic/Advanced

This simulation illustrates the effect of friction with a block on an inclined plane. The forces can be hidden or displayed and the angle table can be adjusted until the block just starts to slide. Calculations are also included.



The maximum frictional force present between two surfaces depends on two things:

- The properties of the atoms which make up the two materials, this will be a constant for the materials used.
- The force that is pressing the surfaces together, known as the normal force.

Frictional forces are always reactive, by this we mean they always try to oppose movement or attempted movement. When an object is not moving, nor about to move (an object resting on a flat surface), there is no frictional force.

The maximum frictional force F_f is numerically equal to the product of the normal force N_r and a frictional coefficient μ which is specific to the two materials in question. $F_f = N_r \mu$

In the case of an object that is about to slide, the normal force is given by $N_r = W \cos \theta$, where W is the weight of the object.

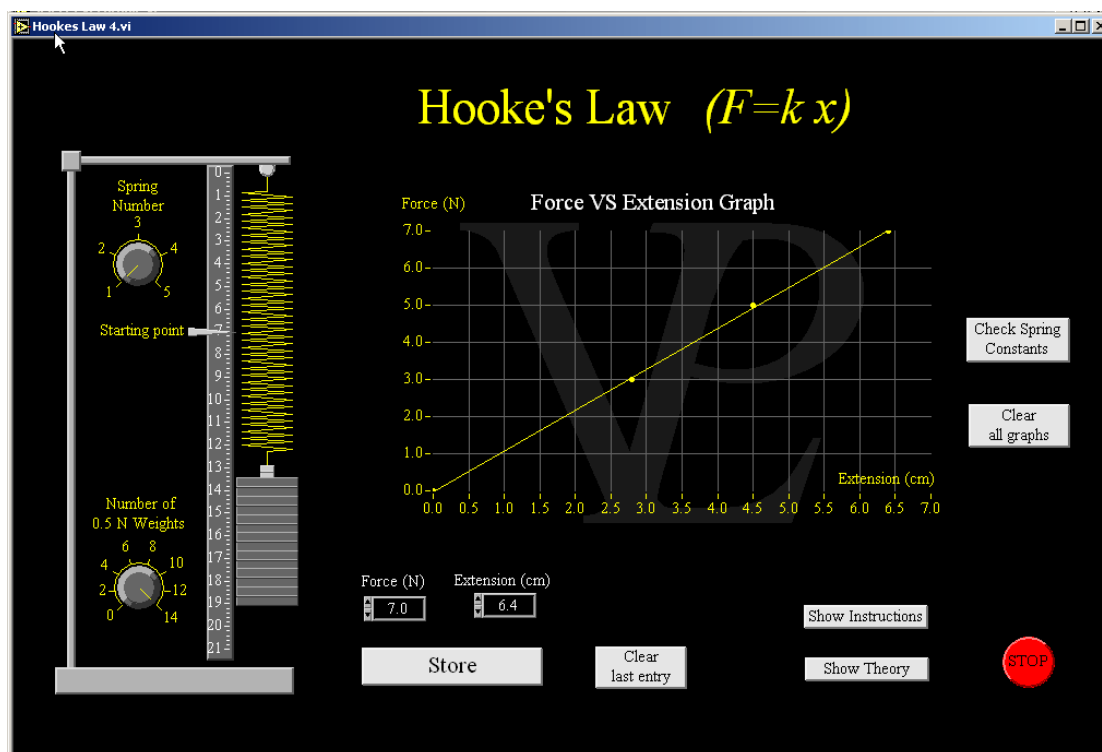
The component of the gravitational force parallel to the plane pushing the object down the plane is $F_{//} = W \sin \theta$

When $F_{//}$ is greater than the maximum frictional force the object starts to slide. When the forces just balance we can show $W \sin \theta = W \mu \cos \theta$. Cancelling W we find that $\mu = (\sin \theta / \cos \theta)$, So $\mu = \tan \theta$.

13.8 Hooke's Law

Basic

This simulation allows the pupil to measure and plot the extension of several springs as they are loaded by with a calibrated set of masses. From the graphs the pupils are able to determine the spring constant and ask the computer to check their answers.



Hooke's Law states that the extension (x) of a spring is proportional to the force (F) applied to it.

The equation that relates them is $F = kx$.

k is the spring constant.

In this simulation the units of this constant are Ncm^{-1} .

If a graph is plotted with Force on the Y axis and the Extension on the X axis, the gradient of the best fit line through the data will be the value of the spring constant k .

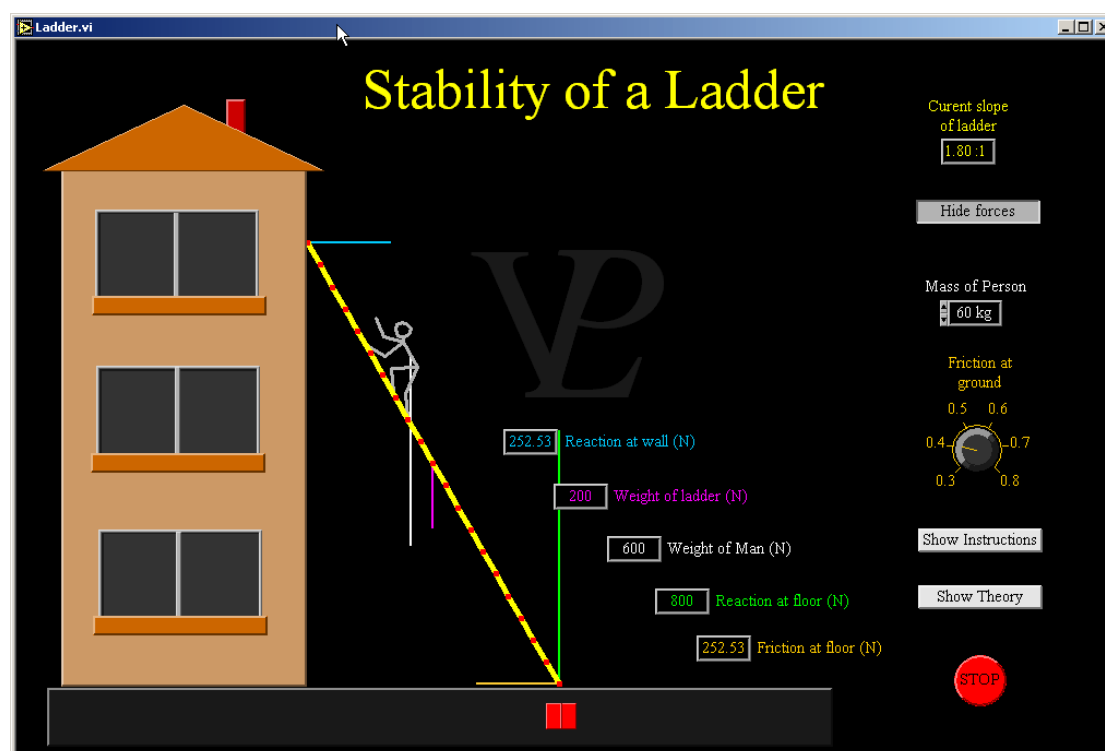
The stiffer springs will give a steeper slope, and less stiff springs a shallower slope.

The bigger your range of values of F and x , the better chance you have of calculating a reliable value of k from the graph.

13.9 Ladder

Advanced

This simulation was written to help to visualise the forces acting on a ladder as it leans up against a wall, and as a man climbs up the ladder. The angle of the ladder, the weight of the man and the friction at the floor can all be varied.



When a system of forces is in equilibrium, there will be no resultant force, and no resultant moment.

This means that the total upward force will be equal to the total downward force, the total forces to the right will be equal to the total forces to the left, and the total clockwise moment will be equal to the total anti-clockwise moment about any point in the system.

In a ladder, the total weight will always be matched by the reaction at the floor. However if the reaction at the wall becomes larger than the frictional force available at the foot of the ladder, it will begin to slide away from the wall.

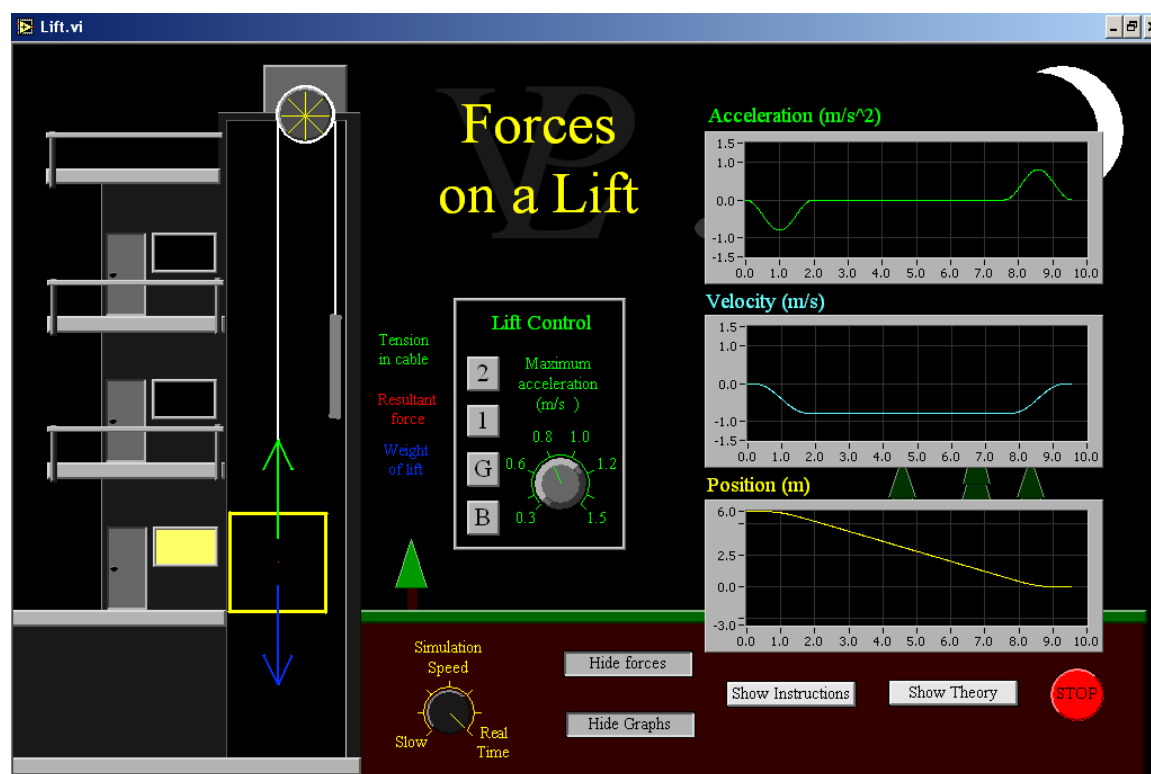
If the ladder is placed a little too vertical, then the weight of the person climbing it might produce a clockwise moment that is larger than the counter-clockwise moment of the weight of the ladder, and the ladder will fall away from the wall at the top!

Health and Safety recommend an angle somewhere between 4:1 and 3:1. However if the floor is slippery it may be necessary to tether the bottom of the ladder to the wall.

13.10 Lift ("Elevator")

Basic

This simulation shows how the forces acting on a lift combine to accelerate the lift up and down, and how when the resultant is zero the lift travels at constant velocity.



When a lift is stationary its weight W is exactly balanced by the tension T in the cable that is supporting the lift. The vector sum of W and T produces a zero resultant. To get the lift to go up, it is necessary to increase the tension so that $T > W$. This will produce a non-zero resultant force which is pointing upwards, causing an upward acceleration. The velocity of the lift continues to increase all the time that $T > W$.

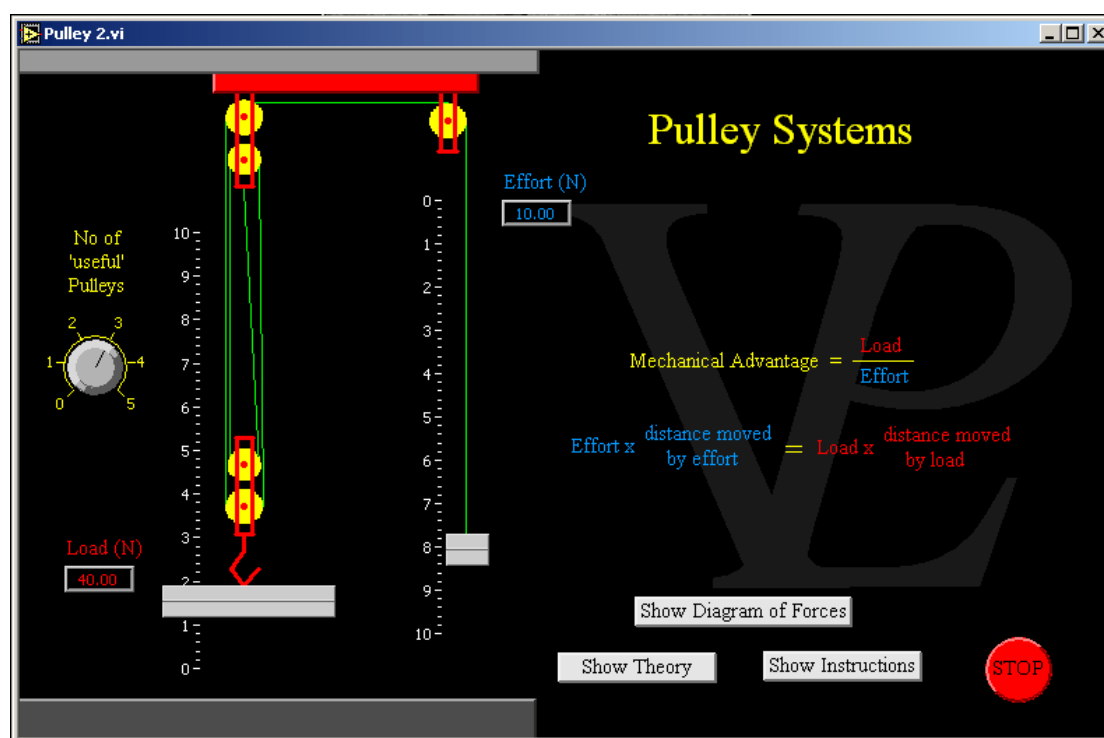
For the lift to rise at constant velocity it is necessary to reduce the tension again so that $T = W$. This will again produce a zero resultant, ensuring that the lift continues at constant velocity. To get the lift to stop it is necessary to decelerate it by reducing the tension so that $T < W$. This will produce a resultant force acting downwards which will accelerate the lift downwards until the velocity is zero. A lift accelerating upwards at 1 m/s will make the passengers feel 10% heavier (and 10% lighter if the lift is accelerating downwards). Notice that the lift will be accelerating downwards at the end of an upward journey! So for any journey on the lift a passenger will experience both an apparent increase and decrease of weight.

For a lift to be comfortable, it is important to increase the accelerations and decelerations gradually, otherwise the passengers will experience jerks. The maximum acceleration of the lift in this simulation can be adjusted by the user, but it will apply it and then reduce it back to zero in just under 2 seconds. Intelligent lift controllers will adjust their accelerations and maximum velocities to suit the length of the journeys they need to make.

13.11 Pulleys

Basic

This simulation allows the pupil to investigate the effect of using different numbers of pulleys in order to lift a given weight. A distinction is made between useful pulleys and pulleys which simply change the direction of the effort. The simulation shows how total energy is conserved.



Pulley systems are used in order to help lifting heavy weights, they give us what is known as a mechanical advantage.

A pulley system consists of wheels over which ropes can loop round. Ideally the wheels rotate freely so that the tension in the rope at either side of the pulley is the same.

Notice that the two permanent pulleys at the top are simply reversing the direction of the tension in the string, they are not giving any mechanical advantage.

Notice also that the middle rope in the pulley system can be attached at the top or bottom. This affects the number of ropes that are actually sharing the weight.

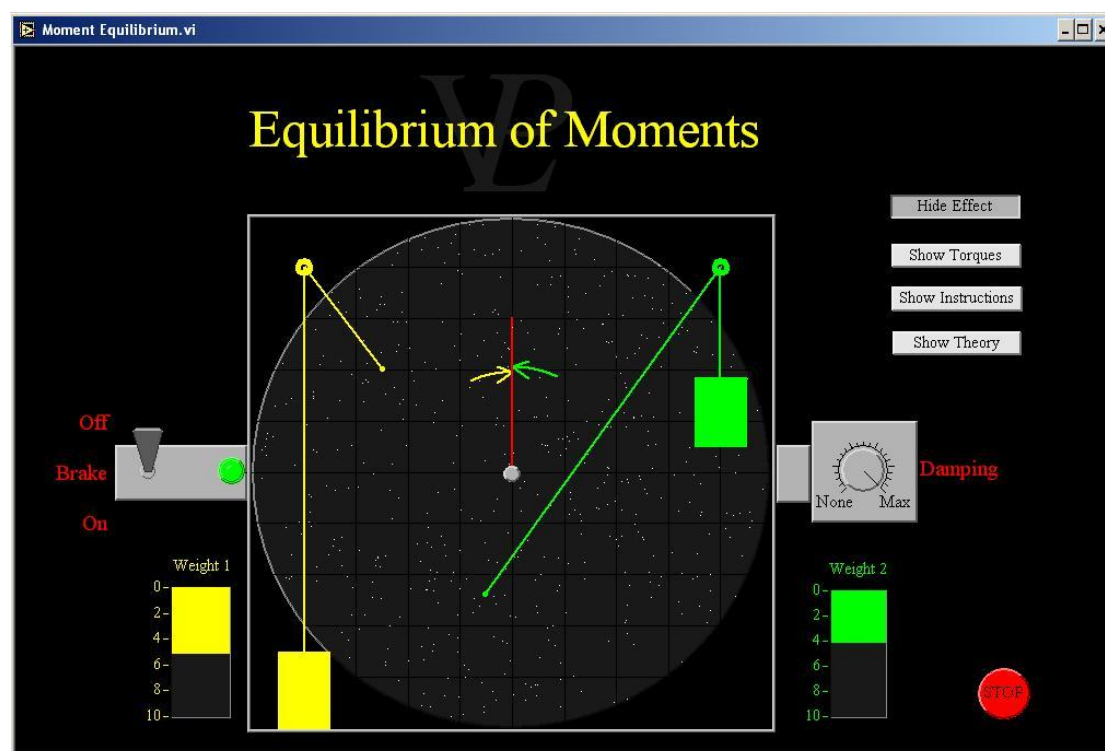
Counting the number of pulleys that seem to be helping can be a bit confusing; it is better simply to count the number of rope sections that are sharing the load.

The force needed to lift the weight will simply be the weight divided by the number of strings sharing that weight.

13.12 Rotational Equilibrium

Basic/Advanced

This simulation shows how there can only be rotational equilibrium if there is no resultant moment.



The "turning moment" of a force (sometimes simply called "torque" or "moment") is defined as the product of the force and its perpendicular distance to the pivot.

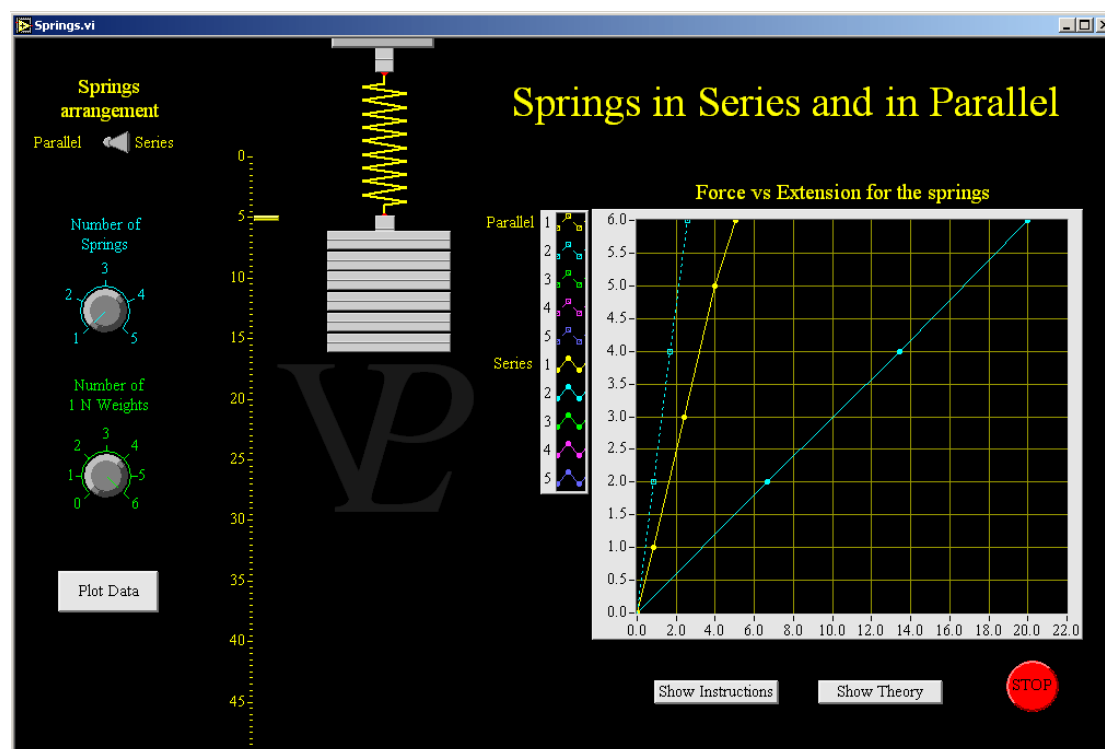
If the turning moments are not balanced (if the resultant moment is non-zero) then the object on which the moments are acting will start to rotate. The angular acceleration will depend on the magnitude of the resultant moment as well as on the angular inertia of the object (just as linear acceleration depends on the resultant force acting on a body and its inertial mass).

In this example two unbalanced moments cause the wheel to rotate, and eventually come to a stop and rotate backwards again. If there is no damping the oscillation will continue indefinitely. Normally there are frictional forces which will steal the energy and dampen the motion until the system finally comes to rest at an angular position where the clockwise moments are equal to the anti-clockwise moments (zero resultant moment).

13.13 Springs

Basic/Advanced

This simulation shows how springs combine in series and in parallel, and how the spring constant of the entire arrangement depends on the number and the arrangement used. It should be used as an extension on Hooke's Law.



When springs are combined either in 'Series' (one hanging from the other) or in 'Parallel' (side by side) they change the overall spring constant or 'stiffness' of the arrangement.

When arranged in Series, the extension is larger than that of an individual spring because each spring extends, and the extensions are added up. This makes the group have an overall lower spring constant. In these examples, where the individual springs all have the same constant k , the overall spring constant is given by: $K_{\text{series}} = k / n$ where n = is the number of springs.

In the case of parallel springs, the load is shared equally by each of the springs, and so the extension is smaller than it would be when using a single spring. The spring constant is given by: $K_{\text{parallel}} = n k$.

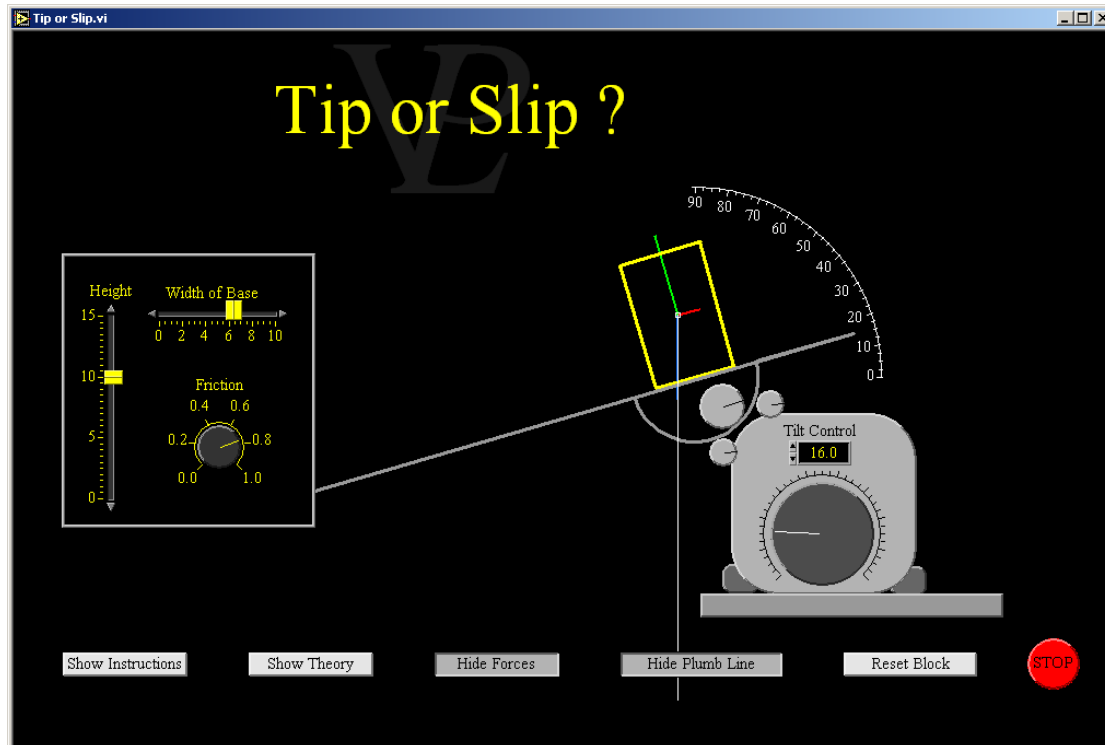
When the individual springs have different constants then their combinations are as follows: $1/K_{\text{series}} = 1/k_1 + 1/k_2 \dots + 1/k_n$ and $K_{\text{parallel}} = k_1 + k_2 \dots + k_n$

Notice that this is the opposite to how resistances combine in series or in parallel!

13.14 Tip or Slip

Basic/Advanced

This simulation shows what determines whether an object will slip or tip over what it is on an inclined plane. The shape of the object as well as the frictional coefficient can be varied.



Whether a block will tip before it slips, or slip before it tips depends on its shape as well as the frictional coefficient between the block and the table.

Not surprisingly, if the frictional coefficient is very low, and the centre of gravity is also low, the block is more likely to slide, and if the frictional coefficient is high, and the centre of gravity is high, the block is more likely to tip.

If $\tan \theta > \mu$ the block will start to slide.

If $\tan \theta > w/h$ the block will start to tip.
(where w = width, h = height)

So

If $w/h > \mu$ the block will slip, or

If $w/h < \mu$ the block will tip.

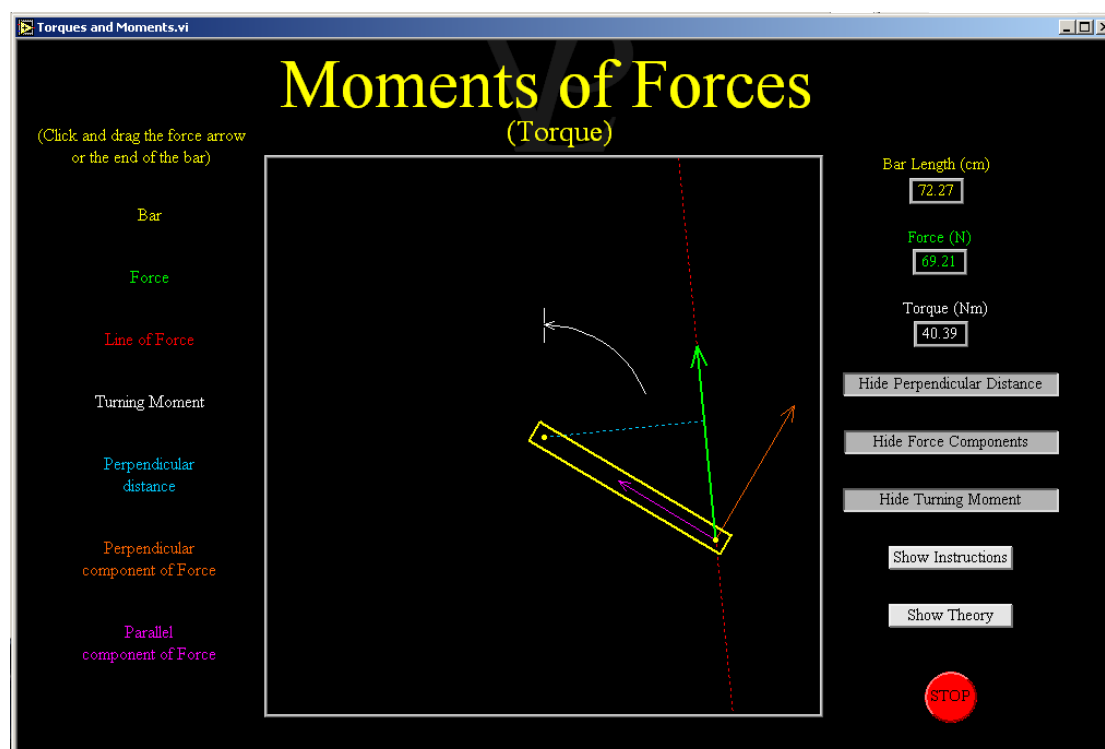
If $w/h = \mu$ the block will start to tip and slip at the same time!

Strictly speaking the frictional force and the normal force act at the interface, not at the centre of the block as shown in the diagram!

13.15 Torques and Moments

Basic/Advanced

This simulation helps the user to see what is meant by the 'perpendicular distance to the pivot', and so helps him to calculate turning moments correctly.



The "turning moment" of a force (sometimes simply called 'moment' or 'torque') is defined as the product of the force and the perpendicular distance to the pivot.

It is also possible to calculate the moment by first resolving the force into its two components: perpendicular to the bar and parallel to it. The Parallel component will be pointing either directly towards or directly away from the pivot, and so will have no turning effect. It is the perpendicular component that will have a turning effect.

Using moments it is possible to calculate loads and forces even in systems where there is no pivot! In equilibrium all clockwise moments are balanced by counter-clockwise moments. An 'imaginary' pivot can be placed anywhere inside or outside the object and the clockwise moments about this imaginary pivot will balance with the counter-clockwise ones if the system is in equilibrium!

Examples of balanced moments are everywhere: A ladder resting against a wall, a trestle table, the span of a bridge...

CHAPTER 14

GASES

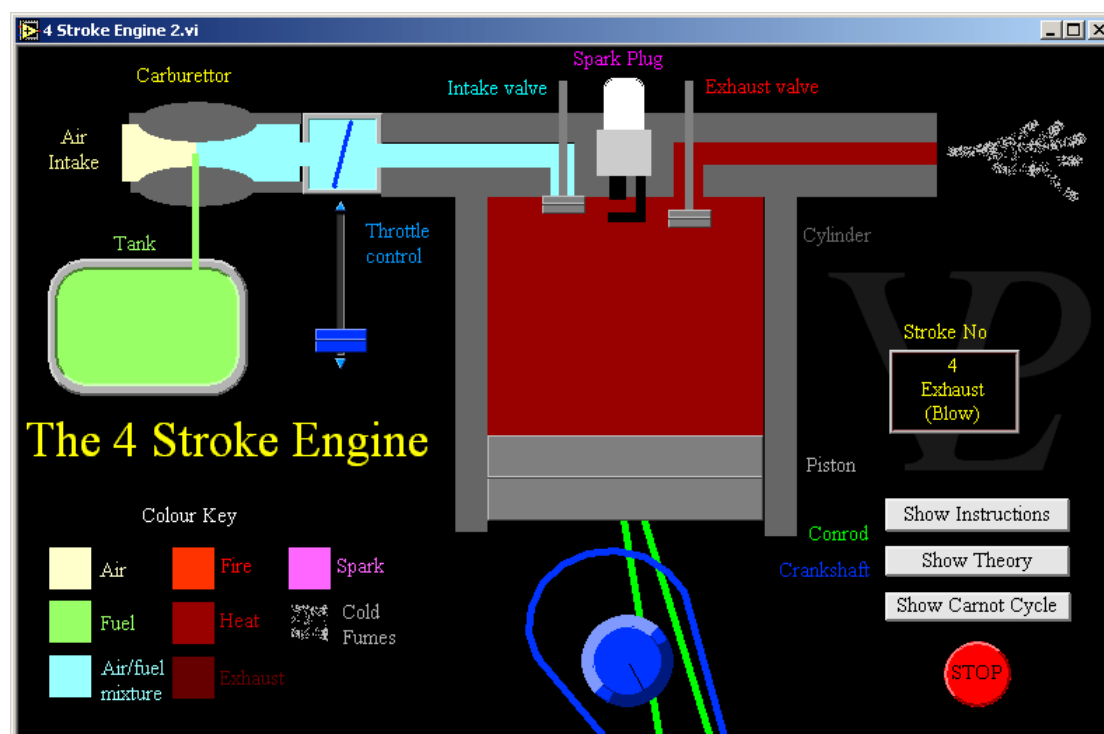


Car engines work by creating hot gases and letting them expand.
Why do hotter gases try to expand?

14.1 4 Stroke Engine

Advanced

See how a 4 Stroke Engine works in slow motion. Adjust the throttle to see how this affects the intake and so the power and velocity of the engine.



Whenever a gas is compressed rapidly it will heat up because work is being done on the gas. This type of compression is called an adiabatic compression. The compressions and expansions inside a 4 stroke engine are always adiabatic because they happen so fast. It takes work to compress a gas. The amount of work is the area under the P-V graph marked out by the curve. In an engine, this work is done by the electric starter motor of the car, and once it gets going, the flywheel stores kinetic energy and supplies it to the piston so that it can compress the gas.

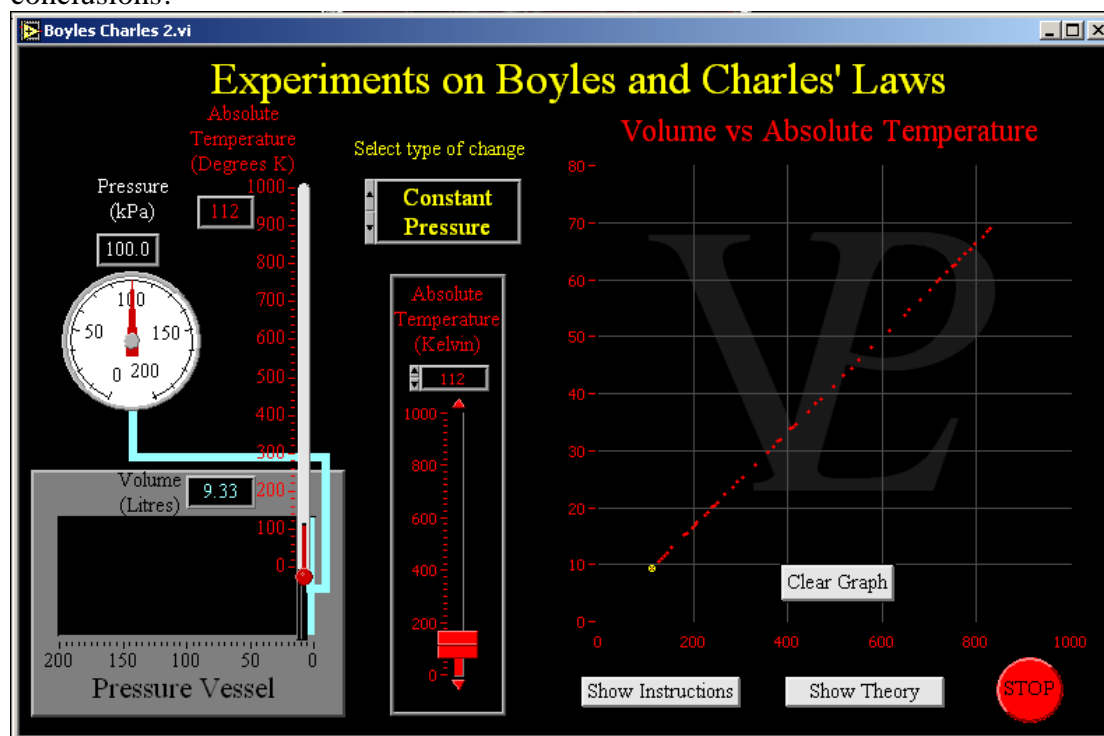
When heat is injected into the cylinder of the engine by burning the petrol vapour, the position occupied by the point on the P-V Graph suddenly jumps up to a much higher adiabatic curve. This much higher pressure drives the piston back down. At this point it is the gas that is doing the work, which is also equal to the area under the curve. However, since the curve is now much higher than the initial one, the area is also much larger. This means that the work carried out by the gas is greater than the work that was done to the gas in the first place. This means that there is a net energy output from the engine. This excess energy is what is used to spin the flywheel and also to drive the car.

When the throttle inside the carburettor is opened the air-fuel mixture can pass through it more rapidly, this gives the cylinder a chance to get more air and fuel into it before even starting the compression. This increased amount of mixture makes it a little harder for the flywheel to compress, but once it is compressed and ignited it produces much more energy on expanding. This way much more power is transmitted to the wheels and the car accelerates away rapidly.

14.2 Boyles Charles

Advanced

Investigate Boyles Law and Charles Law on a gas inside a closed container. Adjust the parameter and watch the isothermal or isobaric change being plotted on a graph. Chose what you want to plot along the X and Y axes, and reach your own conclusions!



To try and identify the patterns between the temperature and the volume of a gas it is helpful to plot graphs of the data you can collect.

As there are three variables, to make the graphs clear it is best to maintain one of the variables at a constant value.

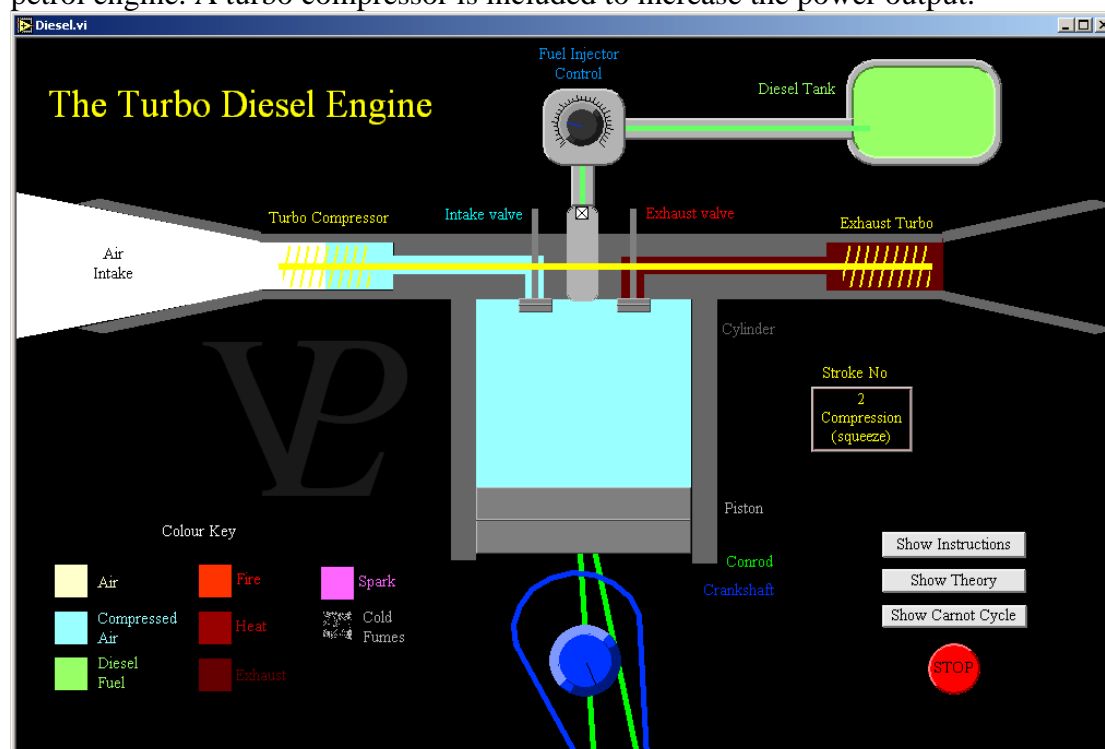
If we keep the temperature constant (isothermal change) we will discover Boyle's Law, namely that P is inversely proportional to V (or $PV = \text{constant}$).

If we keep the pressure constant (isobaric change) we will discover Charles' Law, namely that the volume of a gas is proportional to its absolute temperature (V proportional to T).

14.3 Diesel Engine

Advanced

See how a diesel engine works, and see the essential differences between it and a petrol engine. A turbo compressor is included to increase the power output.



Whenever a gas is compressed rapidly it will heat up because work is being done on the gas. This type of compression is called an adiabatic compression. The compressions and expansions inside a diesel engine are always adiabatic because they happen so fast. It takes work to compress a gas. The amount of work is the area under the P-V graph marked out by the curve. In an engine, this work is done by the electric starter motor of the car, and once it gets going, the flywheel stores kinetic energy and supplies it to the piston so that it can compress the gas.

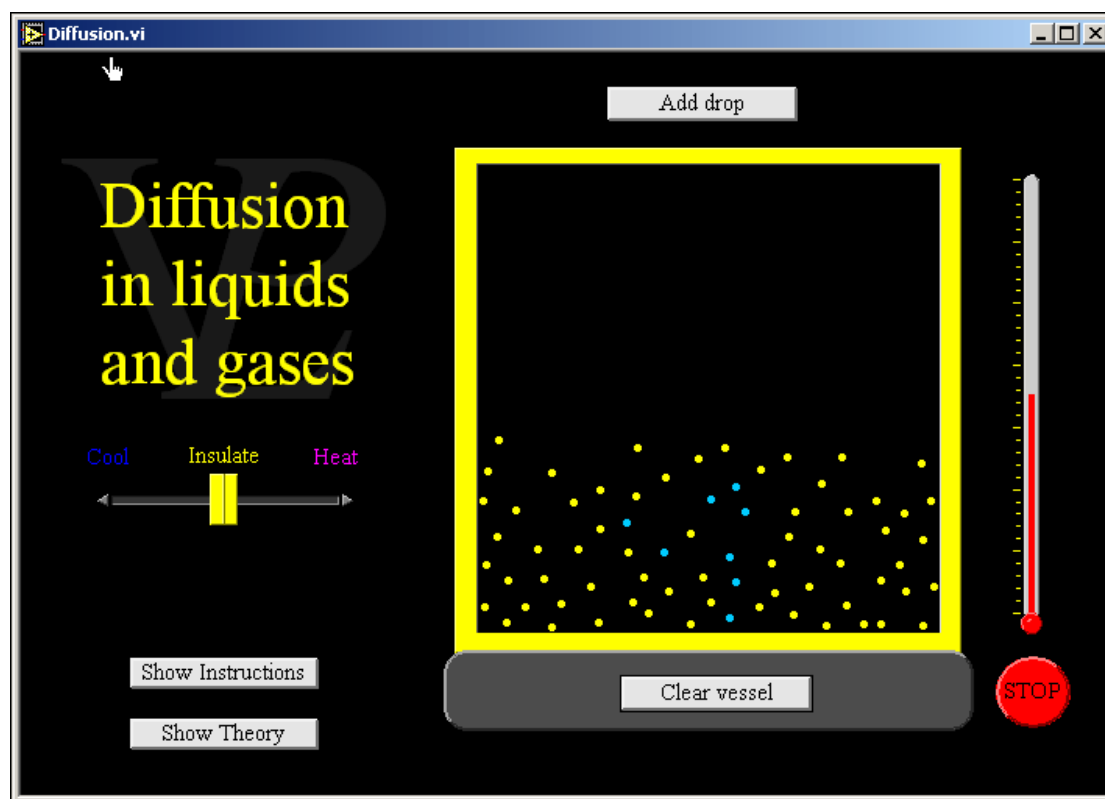
When diesel fuel is injected into a hot pressurised cylinder it burns rapidly without needing a spark to ignite it. On burning, it increases the temperature of the gas, the position occupied by the point on the P-V Graph suddenly jumps up to a much higher adiabatic curve. This much higher pressure drives the piston back down. At this point it is the gas that is doing the work, which is also equal to the area under the curve. However, since the curve is now much higher than the initial one, the area is also much larger. This means that the work carried out by the gas is greater than the work that was done to the gas in the first place. This means that there is a net energy output from the engine. This excess energy is what is used to spin the flywheel and also to drive the car.

When the injector increases the amount of fuel delivered to the engine it makes it burn hotter, and so deliver more power. An additional turbo pump which is driven by the exhaust gases is used to compress air at the intake in order to increase the power without having to make the cylinders still bigger.

14.4 Diffusion

Basic/Advanced

See how diffusion in gases and liquids is driven by collisions between molecules. See what effect temperature has on the speed of diffusion.



In a liquid, the molecules are jostling and bouncing off each-other all the time. In warmer liquids this motion is even more vigorous, and molecules can get past each-other and move around a little more freely.

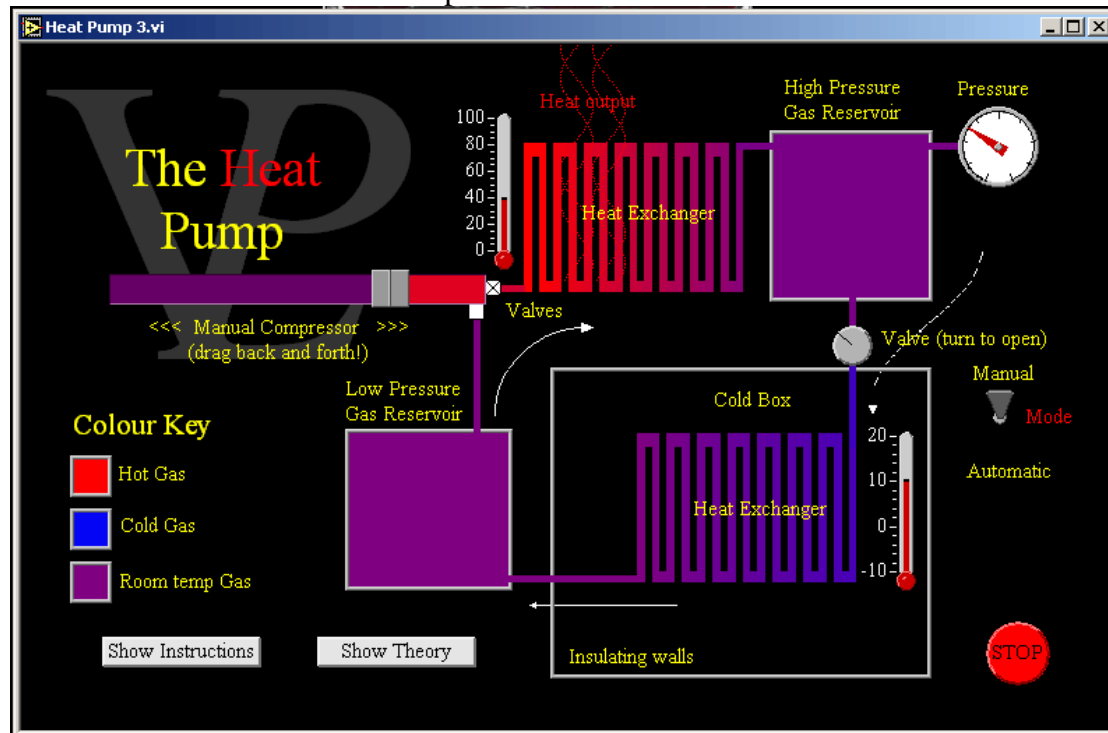
When a drop of say ink is added to the water, the molecules in the liquid will bounce off the molecules of the ink and gradually cause them to get mixed in to the bulk of the liquid and so dilute the ink. This process is called diffusion.

When the liquid is heated sufficiently to become a gas, the diffusion process happens even faster. This is how perfume gets from one end of a room to another in just a few seconds. Diffusion causes the concentrated molecules of perfume to be spread out roughly uniformly into all the air in the room.

14.5 Heat Pump

Advanced

Investigate how a heat pump works inside the refrigerator. See how compression leads to heating (which is wasted out the back) and expansion leads to cooling (the purpose of the machine). The pump works in both manual mode and automatic mode (where a thermostat is used to control the operation).



The function of the heat pump is based on adiabatic compressions and expansions. The compression that happens outside of the cool box (normally at the back of the refrigerator) produces some heat because work is being done on the gas and this increases its internal energy. That is why refrigerators are often warm round the back. This heat is lost to the air, and by the time the gas reaches the high pressure reservoir it is nearly back at room temperature.

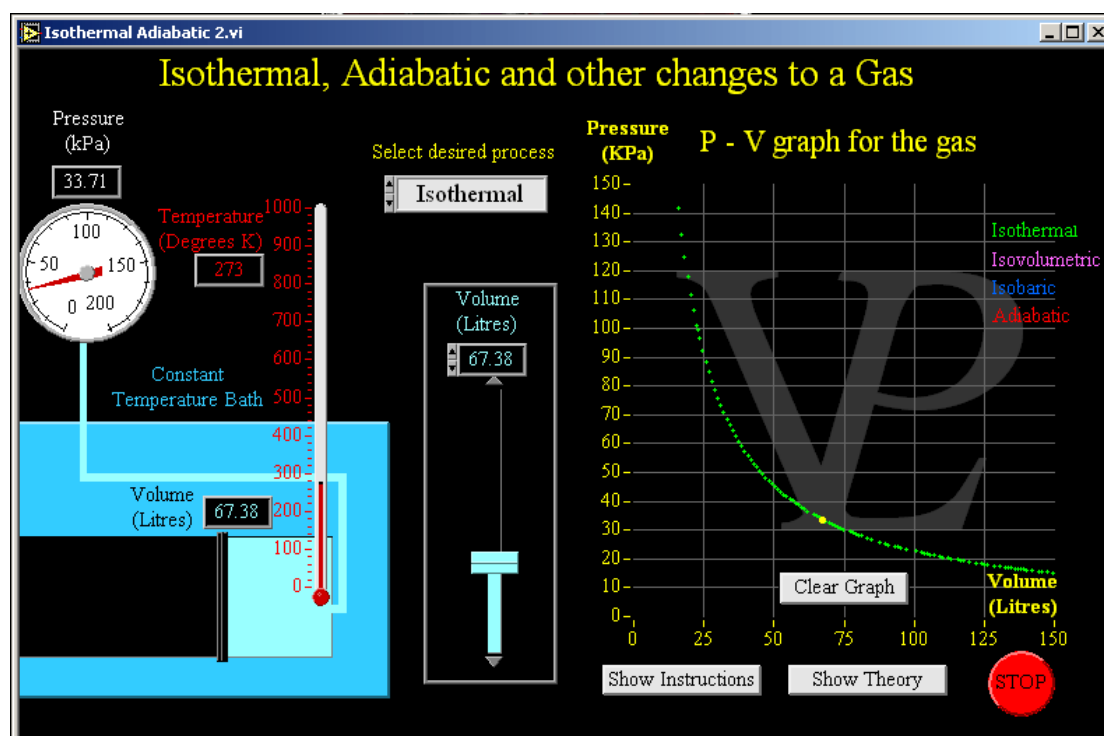
The adiabatic expansion which happens inside the cool box causes the gas to cool down because it is doing work by expanding; the gas does work at the expense of its internal energy. This is the cooling that we want in the refrigerator. The cold gas then slowly absorbs heat from the air inside the refrigerator, and the cold air absorbs heat from the food that is inside. In this way everything inside the refrigerator cools down. At this point the gas has warmed up a little and is now ready to come out of the cold box and be compressed again to repeat the loop endlessly.

The thermostat and a built-in thermocouple inside the refrigerator are continually compared. If the temperature is a little higher than the value set on the thermostat the valve is opened to allow more gas to undergo adiabatic expansion. When the temperature becomes a little lower than that set at the thermostat the valve shuts off. The compressor is operated by a pressure switch in the high pressure gas reservoir. If the pressure is below a certain level, the compressor is switched on. When the pressure is sufficiently high, the compressor is switched off.

14.6 Isothermal Adiabatic

Advanced

Investigate Isothermal and Adiabatic changes and see the curve that gets plotted as you vary the volume. If you artificially inject some heat (as in the internal combustion engine) you can see how the curve jumps to another locus.



The most usual graphical representation for changes in gases is the P-V graph. The reason for this is that the area under a P-V graph represents the work done.

An isothermal change is one in which the temperature remains constant during the expansion/contraction and as a consequence of this heat needs to enter or leave the gas. Isothermal changes need to be slow changes.

In Isovolumetric changes no work is done. Any change in temperature simply produces a change in pressure.

In Isobaric changes, the pressure remains constant. The gas expands as it is heated, and the work done is equal to the pressure multiplied by the change in volume ($W = P\Delta V$).

In Adiabatic changes no heat enters or leaves the gas. Any work done in expanding has to be carried out at the expense of its own internal energy, hence the gas cools down. Conversely, if the gas is compressed by an external force, the work done on the gas results in an increase of internal energy, hence the gas heats up.

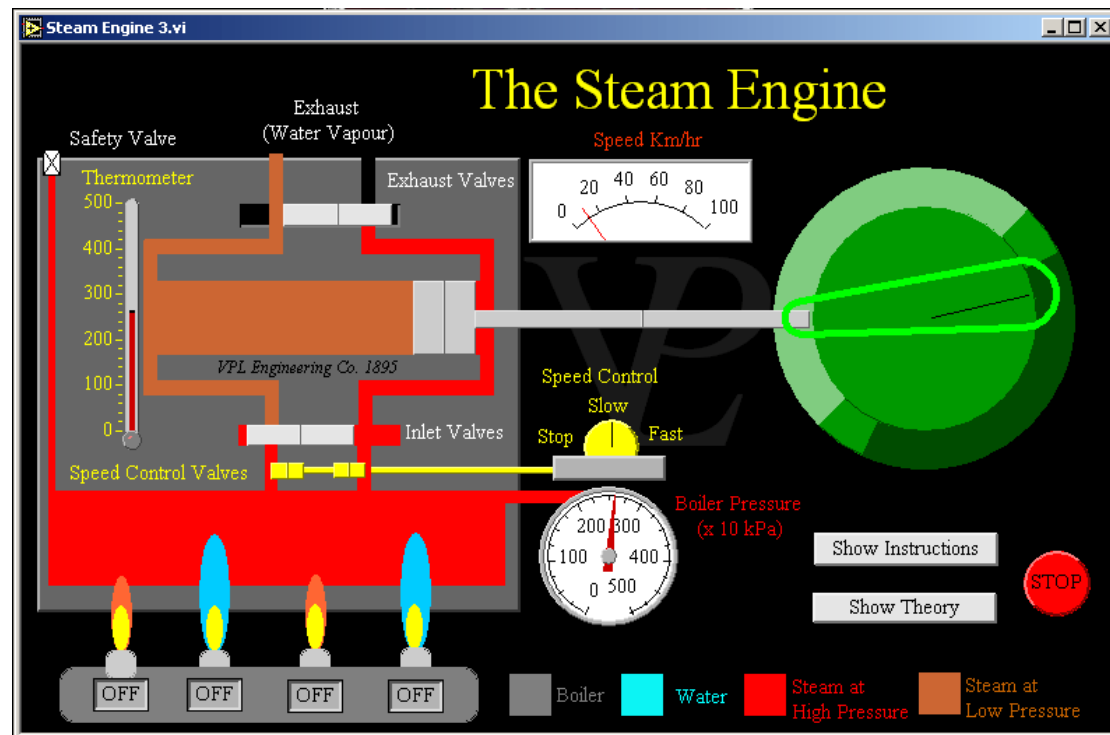
Adiabatic changes must be carried out rapidly so that there is little time for heat to enter or leave the gas. This is one of the reasons why the end of a bicycle pump gets warm when you pump up a tyre quickly.

Notice that in a P-V Graph Adiabatic curves are steeper than isothermal ones.

14.7 Steam Engine

Advanced

This modelled Steam Engine illustrates how heated water becomes high pressure steam which can be used to drive a reciprocating piston. When the piston is connected to a wheel, it can be used to drive any number of mechanical devices.



In a steam engine, the combustion (burning) takes place outside the cylinder in the furnace below the boiler. When the temperature exceeds 100°C , steam starts to form. As the temperature continues to rise, the pressure of the steam increases, and if the valves to the cylinder are opened by the locomotive engineer, the pressure pushes the piston out.

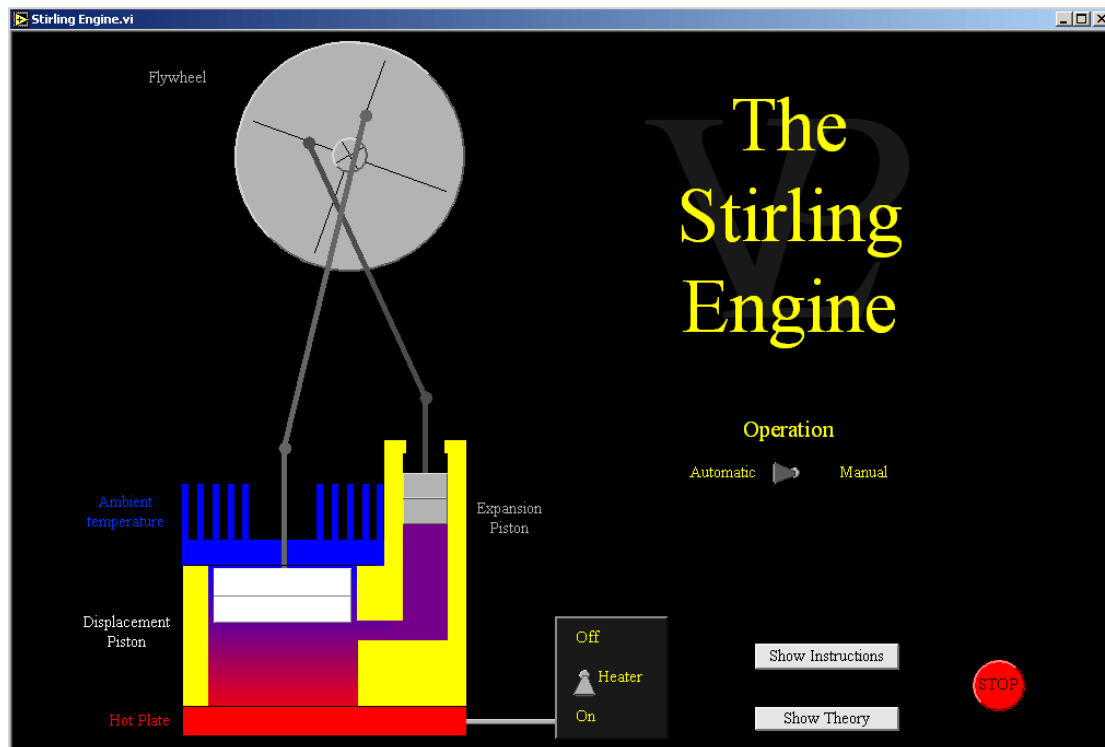
A clever system of valves driven by the engine itself opens and closes the intake and exhaust valves. Notice that the system both pushes and pulls the piston back and forth.

The maximum speed of the engine depends on the load and also on the heat of the flames under the boiler. If the pressure inside the boiler exceeds the maximum safe limit, the safety valve allows some of the pressure to escape.

14.8 The Stirling Engine

Advanced

See how this – the most simple of heat engines – forms the basis on which all other engines work. Operate the displacement piston manually to see the principle, and then add the flywheel to make it run automatically.



Reverend Robert Stirling invented the "Air Engine" (now called the Stirling Engine) in 1816. He proposed it as a safe alternative to a steam engine. It can operate at much lower temperatures and does not use such large pressures.

The engine needs a temperature difference between the hot side and the cold side. It has a loose fitting displacement piston which simply displaces the bulk of the air from the cool side to the hot side and back again. It is made of a thermally insulating material.

When the bulk of the air is in the hot side, it tries to expand and so increases the pressure. The pressure drives the pressure piston out and causes the flywheel to start turning. The flywheel then moves the displacement piston so that it drives the bulk of the air to the cool side. The air then cools and tries to contract. This reduction in pressure 'sucks' the pressure piston back down again, further driving the flywheel round.

The first Stirling engine was used to pump water out of mines. Model Stirling engines can operate from the heat of a hand at 38C! If a Stirling engine is driven by an external source of rotation (without applying heat to one side), it will act like a heat pump, making one side heat up and the other side cool down! Stirling engines have been used to refrigerate systems such as air conditioners.

CHAPTER 15

HEAT

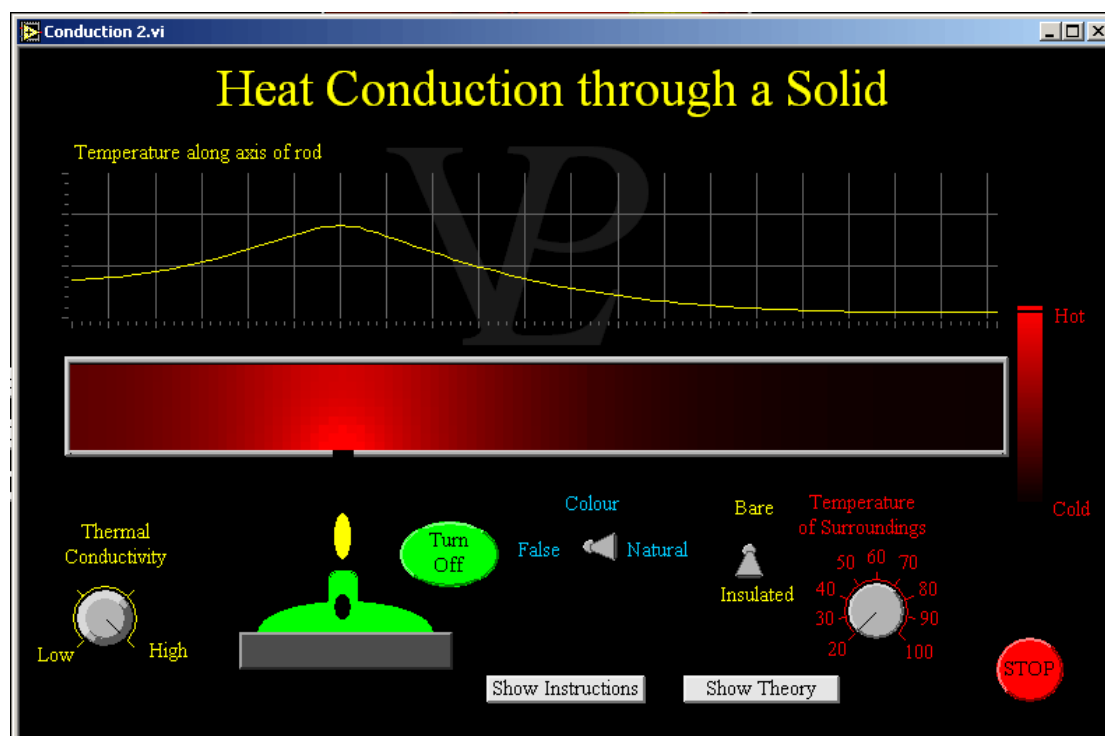


An obvious source of heat in my house.
What else does heat do?

15.1 Conduction

Basic/Advanced

Visualise how heat gets conducted along a solid rod. Alter the conductivity and see what difference it makes. Investigate the effect of insulation.



Heat energy is transported through solid materials in two ways:

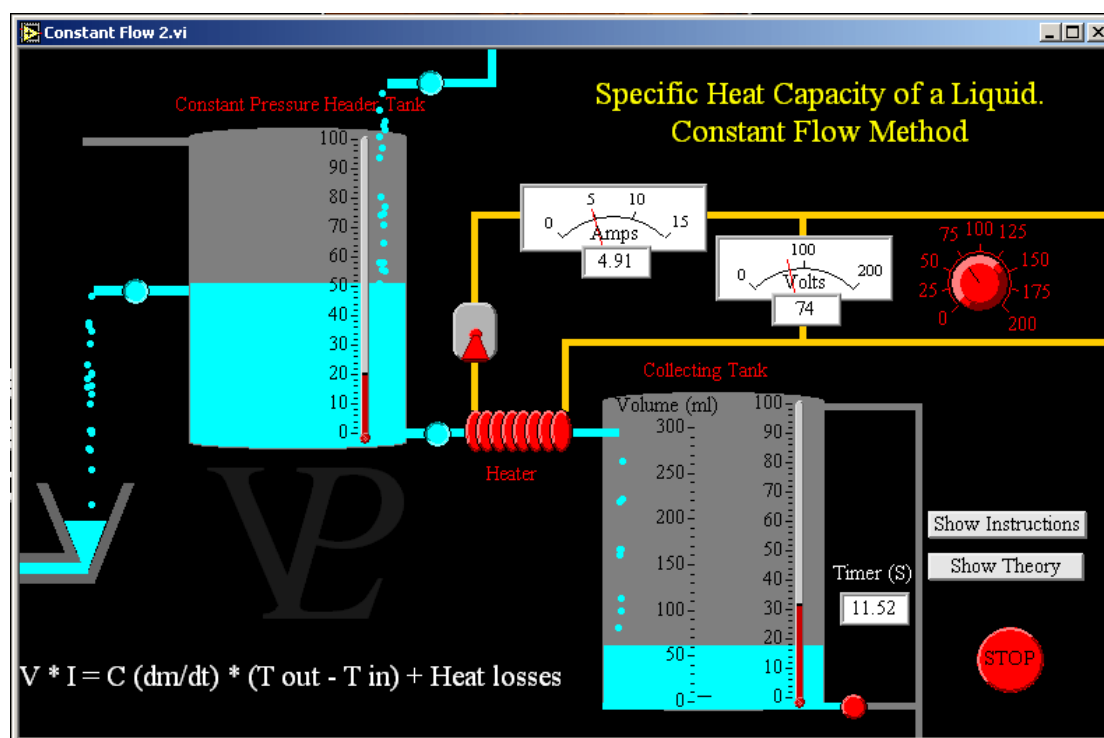
- 1 - Vibration of atoms is transmitted through to neighbouring atoms; this is a very slow process.
- 2 - Energetic electrons that are loosely bound to some atoms can rush away to other parts of the material and so transport some of the energy with them; this is a much faster process.

Normally materials that are good electrical conductors are also good heat conductors. Can you see why?

15.2 Constant Flow

Basic/Advanced

Carry out a virtual experiment to determine the specific heat capacity of water using the constant flow Constant Flow method. Change the flow rate and repeat experiment at the same temperature to cancel errors due to heat losses.



The constant flow method for measuring the specific heat capacity of liquids is a very practical method, as with care, it is possible to eliminate errors due to heat losses. The constant pressure header tank is used in order to ensure that the flow rate going through the heater is truly constant. Electrical heaters are also good because it is very easy to calculate the power that is being injected into the water.

Once the flows and temperatures settle down we can say

Power In = Heating rate + losses

In this example it may seem strange to speak of heating rate as the temperature has stabilised. Even so there is a heating rate because each second a certain amount of water is heating from T_{in} to T_{out} , so we say

$IV = C (dm/dt) * (T_{out} - T_{in}) + \text{Losses}$

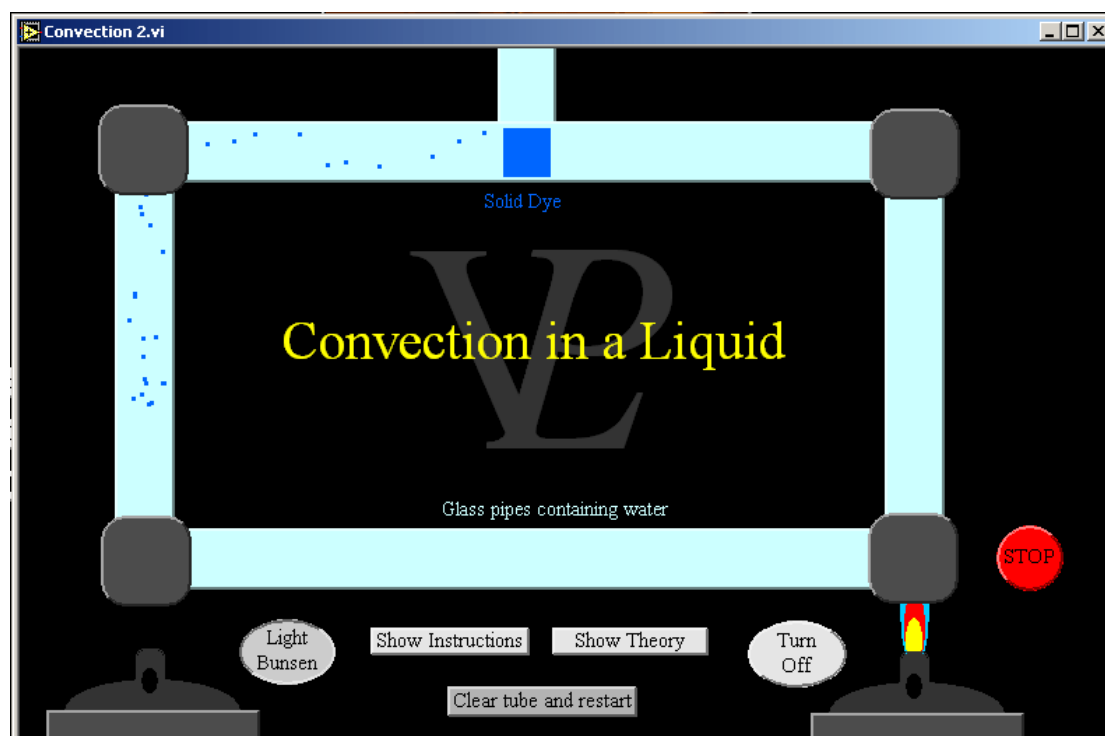
(Where C is the specific heat capacity, usually measured in joules per kilogram Kelvin)

Now for the clever bit: Notice that V , I , T_{in} and T_{out} can all be measured from the equipment. This leaves you with two unknowns namely C and the Heat Loss. If we can repeat the experiment with a different flow rate but keeping the same T_{in} and T_{out} , the heat losses will be the same. This way we obtain two simultaneous equations where the value of the heat loss is the same in both, allowing us to eliminate it.

15.3 Convection

Basic/Advanced

Heat one side or other of a closed rectangular pipe and watch the convection currents that are formed with the aid of a dye that slowly dissolves into the liquid.



Convection currents are driven by density changes.

When a liquid or gas (fluid) is heated it expands and so becomes less dense. Since it is less dense, it rises above the colder, denser liquid or gas. This is exactly the same thing that happens when a cork floats on water. The cork is less dense than the water and so it rises above it. This rise and fall of hot and cold fluids is called convection.

Another common example of convection is in a fire. The warm, less dense air created around the flames rises up the chimney and is replaced by cooler, denser air that is drawn in from around the fire. This movement of air is what causes the 'roaring' sound that you sometime hear from a fire.

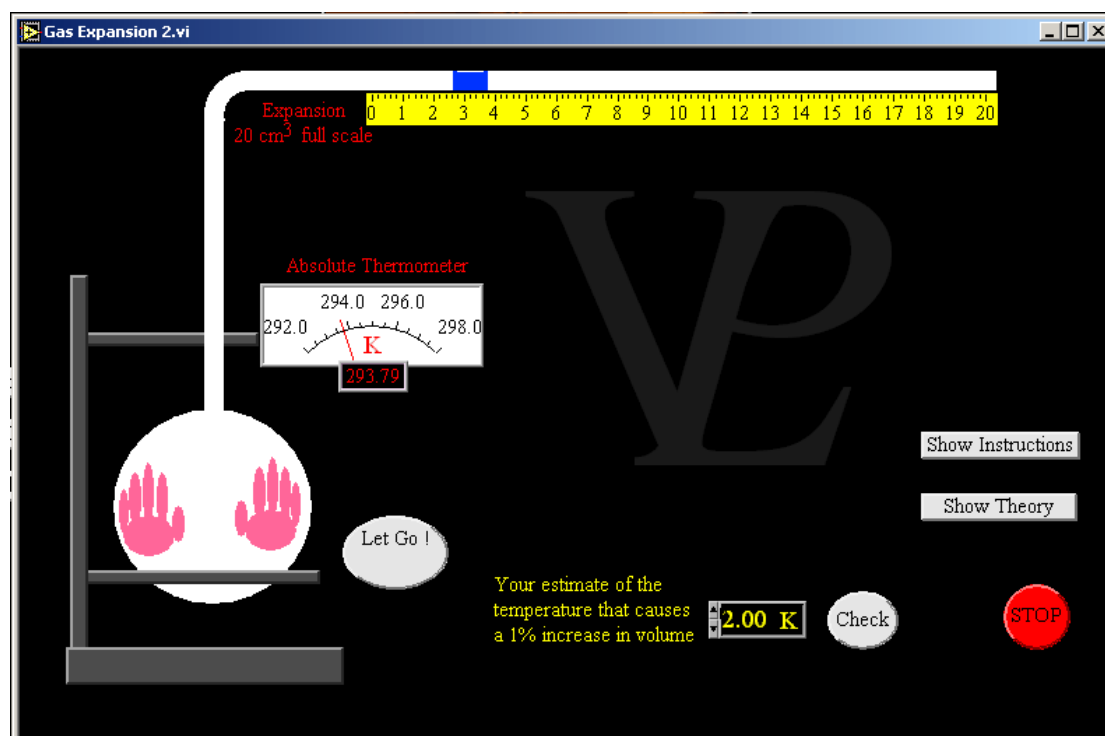
Convection is the driving force behind all weather patterns and is also the driving force behind plate tectonics which is the movement of the Earth's crust and can cause earthquakes.

To think about: What would happen to convection if gravity did not exist?!

15.4 Gas Expansion

Basic/Advanced

Watch how rapidly a gas expands even with a very small increase in temperature. Estimate what temperature increase is required to produce a 1% increase in volume.



All gases try to expand when they are heated, but because they are very compressible, they will only expand if the container allows them to. The pellet of tinted water in this tube moves easily, so the gas can expand at constant pressure.

Gases expand much more than liquids or solids. A rise in temperature of only 1°C makes a significant difference (heat from your hands is enough).

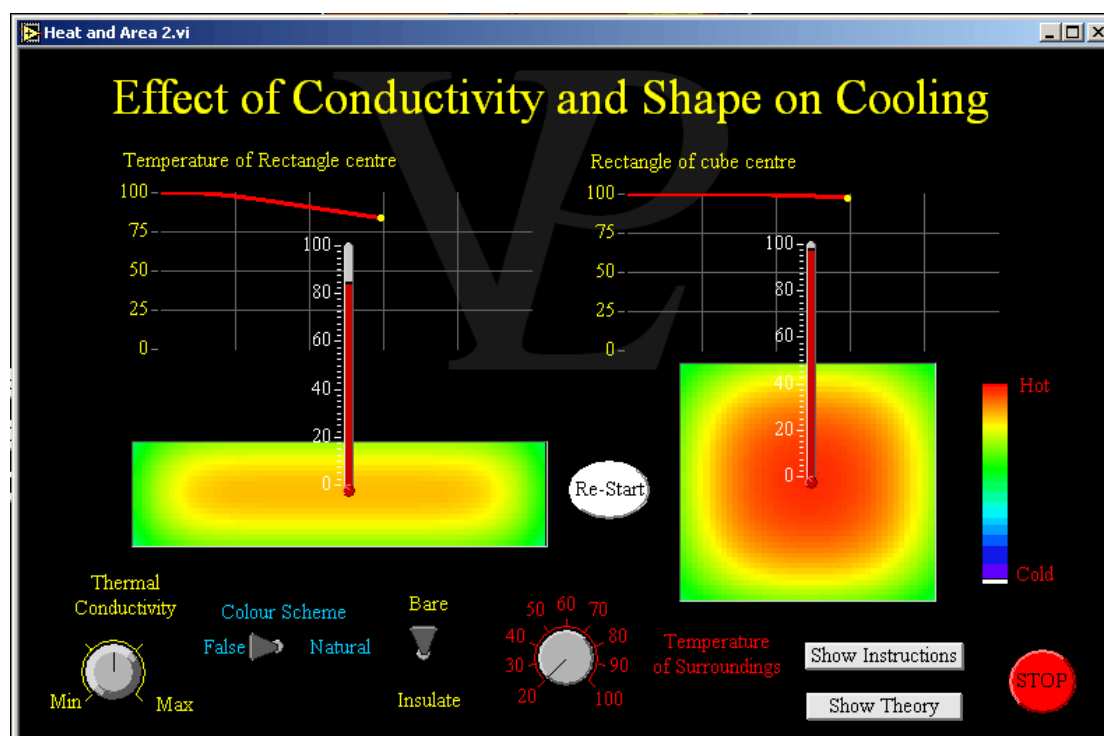
If you take an empty bottle, pour a little hot water into it do the lid up tight, and then shake the bottle so that the heat of the water warms the air up, you will notice how the bottle hisses when you open it.

The expansion of gases is linear with the absolute temperature.

15.5 Heat & Area

Basic/Advanced

This simulation shows how the shape of an object determines the rate at which its centre cools down. The user can change the conductivity of the material and the temperature of the surroundings.



The rate at which bodies cool down depend on the temperature of the surroundings, the size of their surface area, their thermal conductivity and whether they are insulated or not. (It also depends on their specific heat capacity, but that option is not being considered in this simulation.)

Notice how the rectangular object, which has a larger area to volume ratio, loses heat faster than the cube. For this reason 'heat sinks' and 'cooling fins' are always given large area to volume ratios. Small children and babies will get cold much quicker than adults because of their larger area to volume ratio.

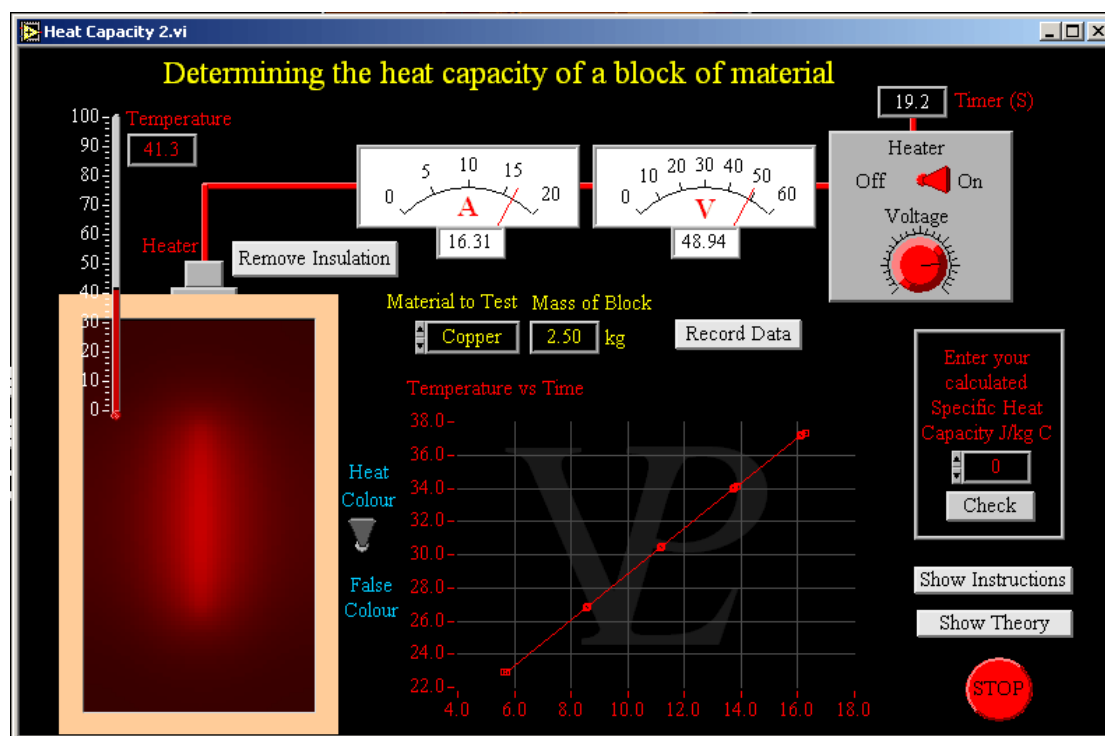
Notice also that the faster cooling rates are achieved when the surrounding temperature is lowest. It is rare for a car to overheat in winter, whereas in the summer car engines have to work harder to keep cool.

Insulating material reduces the cooling rates significantly. That is the reason we build insulation into houses, and also why polar bears have such thick fur.

15.6 Heat Capacity

Basic/Advanced

Determine the Specific Heat Capacity of a solid block of material. Heat it with an electric heater for a short time. Allow the temperature to stabilise and record it. Repeat the heating and stabilising steps until a graph is formed. Use it to calculate the result.



The heat input can be calculated by multiplying the electrical power and the time. Heat input = VIt , where t is the time for which the current flows through the heater.

This heat will increase the temperature of the block.

The heat capacity of the block is the amount of heat it takes to raise its temperature by one degree.

The specific heat capacity is the heat required to raise the temperature of one kilogram of the material by one degree.

The equation relating the heat input and the temperature rise of the block is

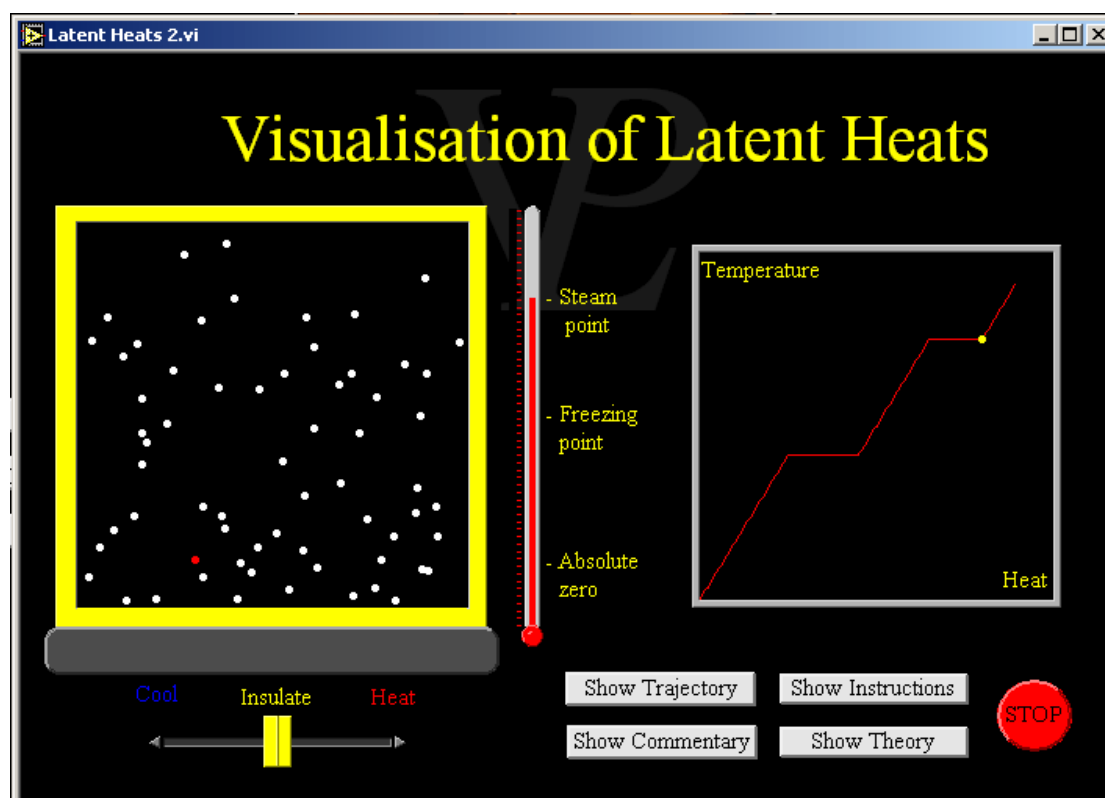
$$V I t = C m (T_{\text{final}} - T_{\text{initial}})$$

Note that $(T_{\text{final}} - T_{\text{initial}})/t$ is the gradient of the graph. Note also that each block of material has a different mass, so remember to take that into account.

15.7 Latent Heats

Basic/Advanced

This simulation shows what happens at the molecular level as a solid is given more and more energy. It goes through the 3 phases of matter, plotting the temperature against the energy input, with the temperature lingering at each phase change.



In a solid, any energy supplied to it causes the molecules to oscillate more about their mean position. Once the molecules have enough energy to break their bonds with their neighbouring molecules, they are free to move away from their original place. This is what happens when a solid melts. While a solid is melting, its temperature remains constant and will not increase until the last of the molecules have broken their bonds and the entire mass has melted.

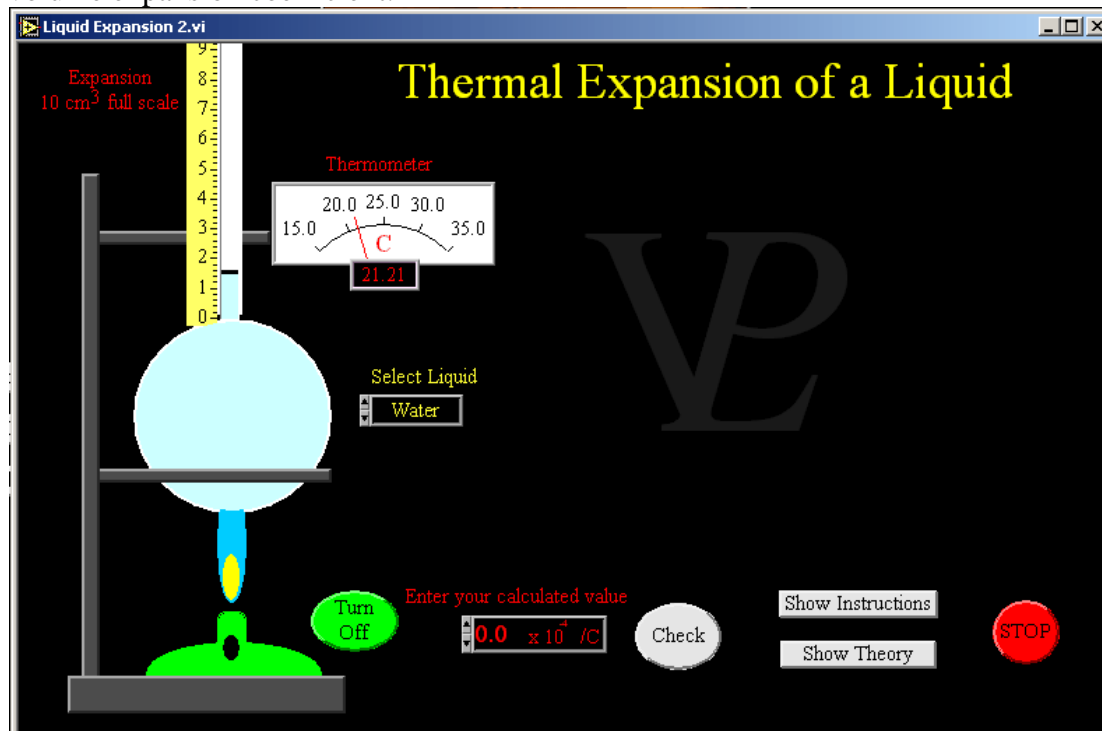
Once the entire solid has melted, any further energy supplied to the molecules causes them to move around faster. This increases the temperature of the liquid. If enough energy is supplied to the liquid, the molecules will eventually get enough energy to break away from the surface of the liquid entirely, and so become a gas. This is called evaporation. Evaporation can actually happen at lower temperatures, but happens most furiously at the boiling point. Any additional energy given to the liquid will simply cause more molecules to evaporate, and the temperature will not rise any further until the entire liquid has evaporated.

When the gas is allowed to cool down sufficiently, it will start to condense back into a liquid (this will happen at the same boiling point), and then ultimately back into a solid (at the same freezing point).

15.8 Liquid Expansion

Basic/Advanced

Heat a liquid inside a large spherical vessel and watch the liquid level rise inside the tube. From the rise in liquid level and the measured temperature rise, calculate the volume expansion coefficient.



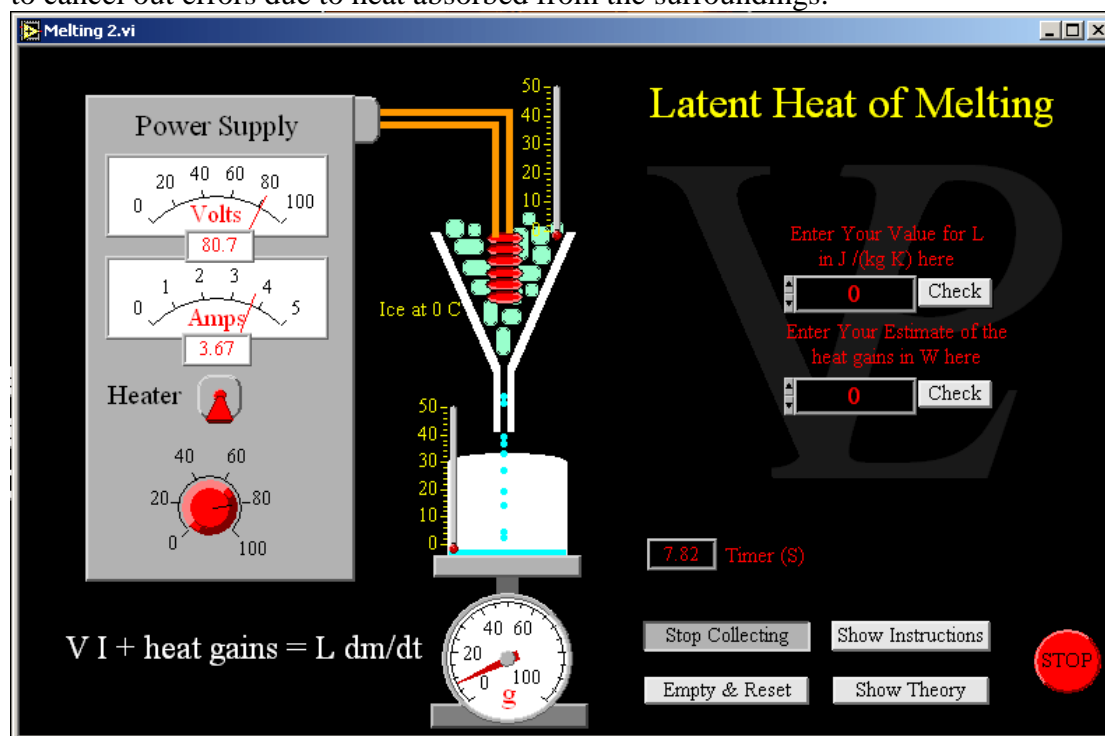
Although liquids expand much less than gases, they still expand far more than solids, so a tube with a narrow bore is enough to show the increase in the volume of a liquid in a bulb. Notice that the temperature rise only needs to be about 10 degrees for the effect to be noticed clearly. The increase in volume of a liquid is proportional to the original volume, and also to the increase in temperature. So we say $\Delta V = k V_i (T_f - T_i)$ or $V_f = V_i (1 + k (T_f - T_i))$ where: T_f and T_i = Final and Initial temperatures and k is the constant which relates them together.

Water is the most interesting and marvellous liquid. From about 4°C upwards it expands as the temperature increases as expected. However from 4°C downwards it also expands, this is unique behaviour. This means that it is possible for water below 4°C to float above warmer water beneath it. This may sound like a simple curiosity, but as we will see in a moment, it is a matter of life and death. As water freezes into ice it also expands a little further, which is why ice floats. Why is this so important? There is a process called evaporation whereby water turns into vapour. When this happens, the water left behind cools down further. If water contracted as it got colder, ice would be denser than water, and it would sink to the bottom of lakes and oceans. If no ice forms on the top surface of a lake, water is free to continue evaporating, and so the water would continue to cool down further until the entire lake was solid ice. This would be bad news for fish and other water life. Since land life is dependent upon water life, it would be bad news for us all. Fortunately water expands below 4°C, and ice floats. This serves to seal the top surface of water masses and so preserve the life deep beneath the ice. There are other characteristics of water that show it to be uniquely designed to sustain life.

15.9 Melting

Basic/Advanced

Melt some ice with the help of an electrical heater, and collect the water over a measured length of time. Calculate the power input from the voltage and current and so calculate the latent heat of fusion. Repeat the experiment at a different power rate to cancel out errors due to heat absorbed from the surroundings.



Electrical methods to measure the latent heat of melting of solids are the easiest because the heater can be controlled very accurately.

Notice that both the ice and the water collected below are at 0°C. The energy input from the heater (and the surroundings) is only being used to melt the ice, not to warm the water up. Heat in + gains = $L m$ where L is the latent heat and m is the mass melted (gains (or little g for short) is the heat gained from room)
 (Power \times time) + $g = L m$ or $V I t + g = L m$

Dividing both sides by t we get $(VI) + G = L (m/t)$. m/t could also be written as dm/dt , it is equal to the rate of melting. G is the rate of heat gained from room ($= g/t$) which should be roughly constant.

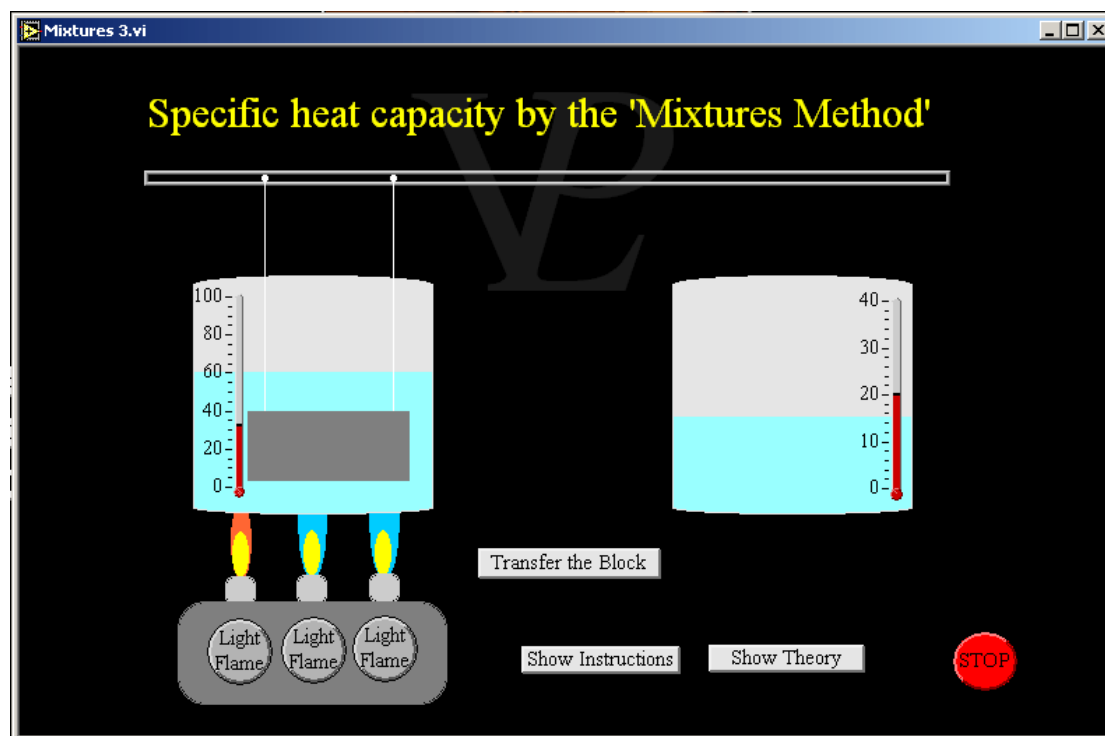
In this last equation we have two unknowns: L and G . We wish to find L but do not normally care about G . If we repeat the experiment twice, we can eliminate G and find L .

Better still: If we repeat the experiment for many different power inputs, we can plot a graph of Power (Y axis) against dm/dt (X axis). The gradient will be a more accurate value for L , and the intercept will be the negative of G .

15.10 Method of Mixtures

Basic/Advanced

Heat a block of unknown material in boiling water. Transfer it to a calorimeter which contains water at room temperature. Note the rise in temperature, wait for temperatures to stabilise, and calculate the specific heat capacity of the block!



The 'Method of Mixtures' works on the principle that the heat lost by the block will be equal to the heat gained by the liquid in the second calorimeter (conservation of energy). If we know the mass of the block, and also the mass and the specific heat of the liquid, we can calculate the specific heat capacity of the block.

This treatment ignores the heat capacity of the calorimeter, which should be small compared to that of two litres of water.

Heat lost by block = Heat gained by water

$$M_b C_b (T_{bi} - T_f) = M_w C_w (T_f - T_{wi})$$

Where: M_b = Mass of block (here 2kg), C_b = Specific heat capacity of block

M_w = Mass of water (here 2 kg (= 2 litres)),

C_w = Specific heat capacity of water = (4200 J/(kg K))

T_{bi} = Starting temperature of block (heat until 100°C)

T_f = Final temperature. T_i = Initial temperature of liquid (in this case 20°C)

The experiment works best if heat losses are minimised, so ideally:

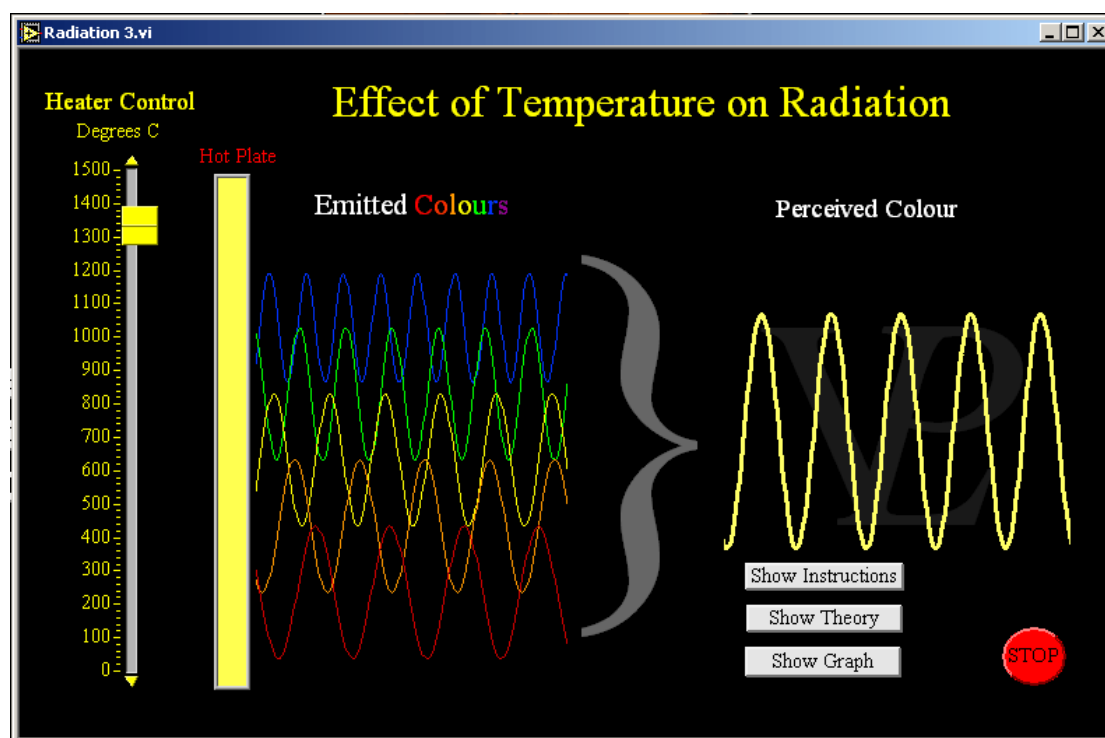
- 1 - Transfer the block as rapidly as possible.
- 2 - Insulate the second calorimeter.

Notice that the same experiment can be used to find the specific heat capacity of the liquid instead. In that case you would need to know the specific heat capacity of the block instead.

15.11 Radiation

Basic/Advanced

Notice the perceived colour change as a hot plate warms up. Visualise the shortening of the wavelength as well as the increase in intensity. See an introduction to Wien's displacement law.



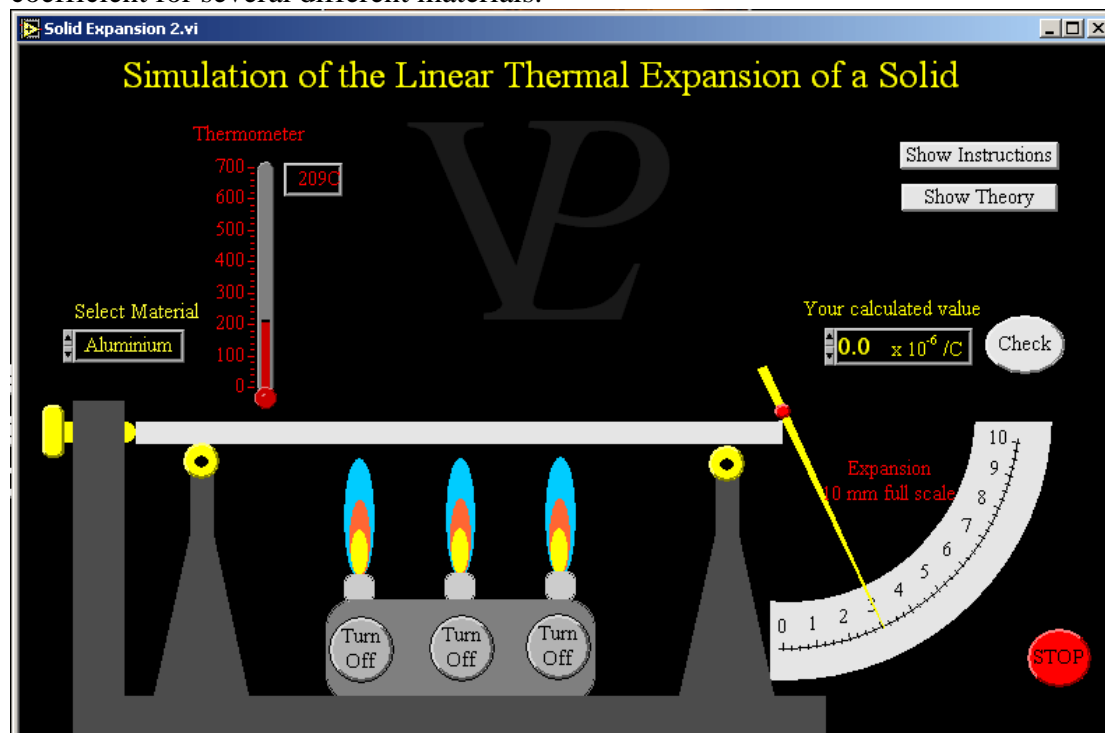
Notice the change in wavelength as the plate gets hotter although the speed of light remains the same.

- 1 - Warm objects emit only in the infrared, long invisible wavelengths.
- 2 - Hot objects emit in the infrared and also in the red, the longest visible wavelength.
- 3 - Very hot objects emit well into the visible and that makes them look 'white hot'
- 4 - The graph displayed here shows how the energy over the wavelengths is distributed as an object gets hotter. The vast majority of the energy is emitted in the infra-red.

15.12 Solid Expansion

Basic/Advanced

Heat a metal rod with the aid of Bunsen burners, note the rise in temperature and also the expansion as magnified by a simple dial gauge. Calculate the linear expansion coefficient for several different materials.



Most materials expand when heated. In real life the expansion occurs in all three dimensions. Here we are only concerned with the length.

The extension of a rod is proportional to the original length; a longer bar will extend more than a shorter one. The extension is also proportional the increase in temperature; a larger temperature rise causes it to extend more than a smaller temperature rise.

So we say

$$\text{extension} = \alpha L_i (T_f - T_i) \quad \text{or}$$

$$L_f = L_i (1 + \alpha (T_f - T_i))$$

Where L_i = Initial length

L_f = Final length

T_i = Initial temperature

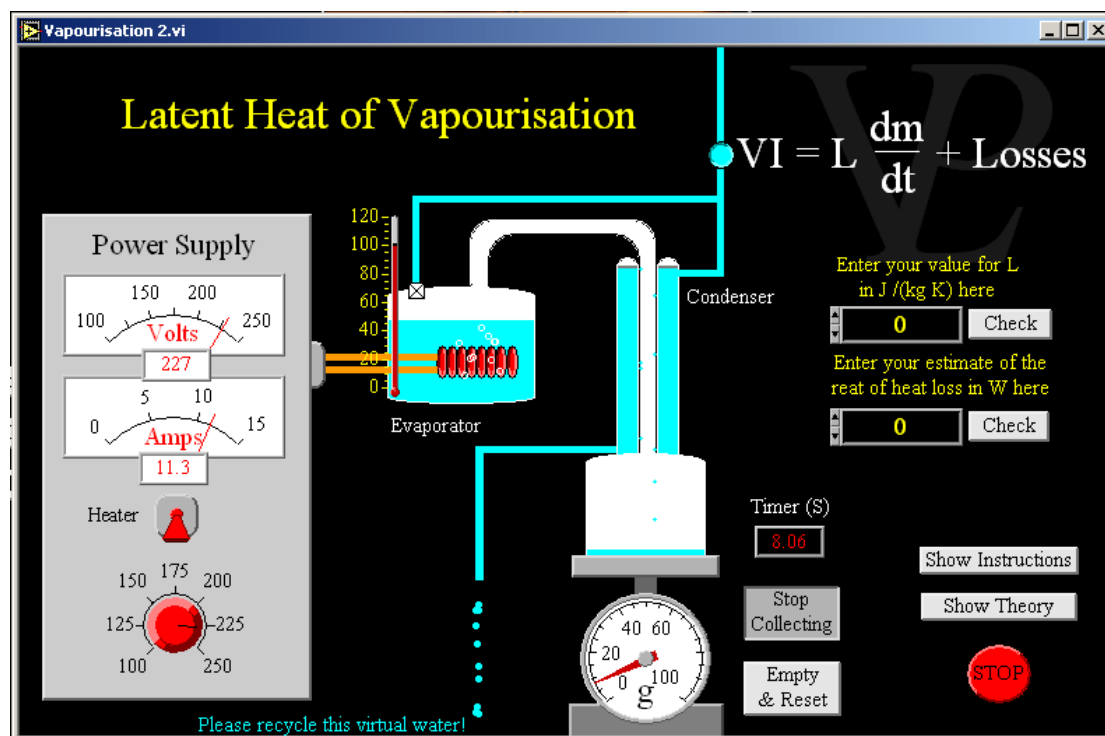
T_f = Final temperature

α = Expansion coefficient

15.13 Vapourisation

Basic/Advanced

Vapourise water with an electric heater, condense the steam and measure the rate at which the water is being condensed. Use this information to calculate the latent heat of vapourisation.



Once the water has reached 100°C, any further energy supplied will do two things: vapourise water, and get lost to the surroundings. So we say:

Energy In = Energy to vapourise + Losses

Or

Energy In = (L m) + Losses

where m = mass of water vapourised, and

L = Specific Latent Heat of vapourisation

Differentiating with respect to time (or, if you don't like differentiation, dividing through by time) we get

Power in = (L (dm/dt)) + Power losses

Or

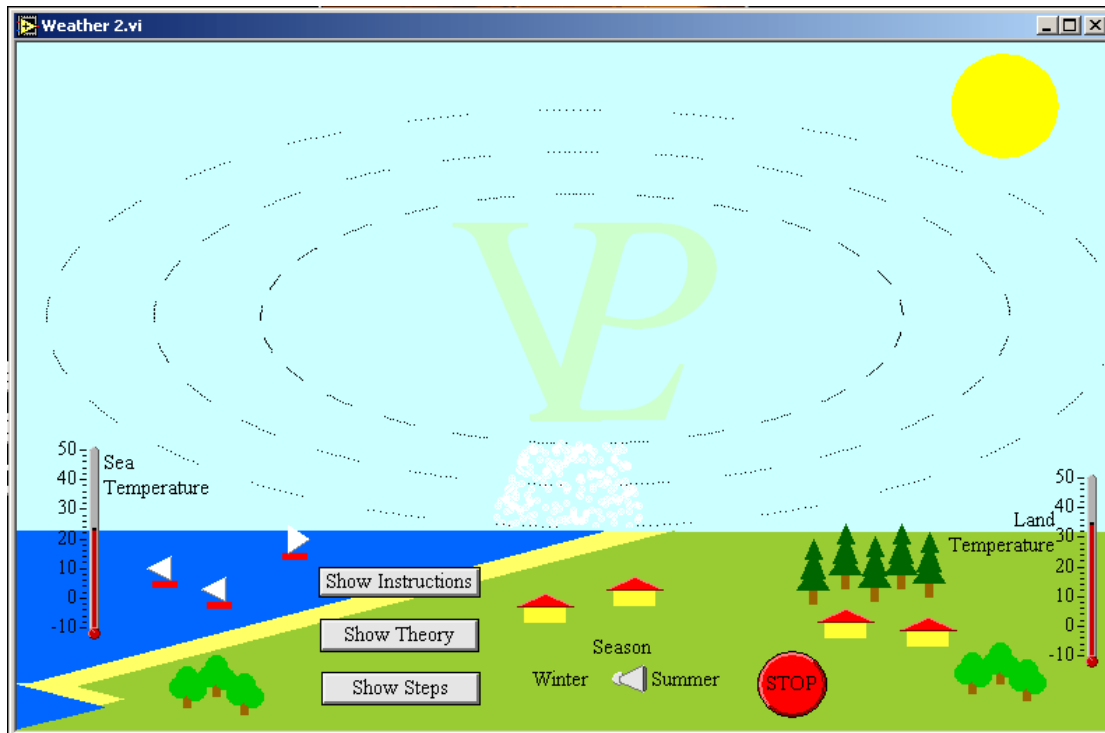
V I = (L (dm/dt)) + Power losses

The power losses will remain approximately constant regardless of the power at which you are running the heater because the boiler will still be at 100°C. So if several different power levels and evaporation rates are obtained and plotted on a graph (Y = power rate and X = dm/dt) it is possible to calculate the Latent Heat of Vapourisation from the gradient of the graph, and the intercept will reveal what the heat losses of the system are.

15.14 Weather

Basic/Advanced

This program simulates a weather system driven by convection currents due to the differential heating of land and water. It is set in South India, where the 'Monsoon' winds dominate the weather system.



All of the weather patterns on Earth are driven by the sun. The energy from the sun heats the land and the sea at different rates because the specific heat capacity of water is larger than that of land.

Generally land heats up faster than sea, but also cools down quicker. In the summer the land will be warmer than the sea, and in the winter the land will be colder than the sea.

These differences in temperature cause convection currents of air which will always rise above the warmer surface and sink down on the colder surface.

The convection loops of air will pick up water vapour from the sea when they blow over the water. When the air later starts to rise and to cool, it will reach a point where the water vapour will condense out as droplets, and cause it to rain. If this rain lands upon land, it causes the surface to cool down a little, but it will have very little effect on the temperature of the sea.

'Greenhouse gases' released into the atmosphere as a consequence of burning fossil fuels affect how easily the land and the sea can cool down. This in turn affects the convection currents responsible for the weather.

CHAPTER 16

KINEMATICS



Kinematics is the study of objects in motion.
This one is quite unpredictable!

16.1 Ballistic Trolley

Advanced

This simulation shows how the vertical and horizontal motions of projectiles are completely independent.



Projectile motion becomes much easier to understand if it is split into two separate motions. In the absence of air resistance the horizontal component of the velocity is constant (in this case, equal to the velocity of the trolley).

The vertical velocity is a motion that starts with a positive velocity, but which is continually decelerated by gravity until it stops and reverses direction falling back down to the trolley.

When the two motions are combined it gives rise to a trajectory called a 'parabola'. There are many different shapes of parabola, but they all have the same characteristic.

A stationary observer can see the trajectory of the ball as a parabola, however from the point of view of an observer sitting on the trolley, the ball simply goes up and comes down (as if the trolley were not moving!) This is like a child playing with a ball inside a car that is travelling along the motorway.

When air resistance becomes significant (at high speeds, or where the ball is very light), the air drag will reduce the horizontal velocity of the ball. (imagine a child throwing a ball vertically up through the sun-roof of a car while it is travelling fast!). In this case the ball will not fall back inside the cannon (or the hands of the child!)

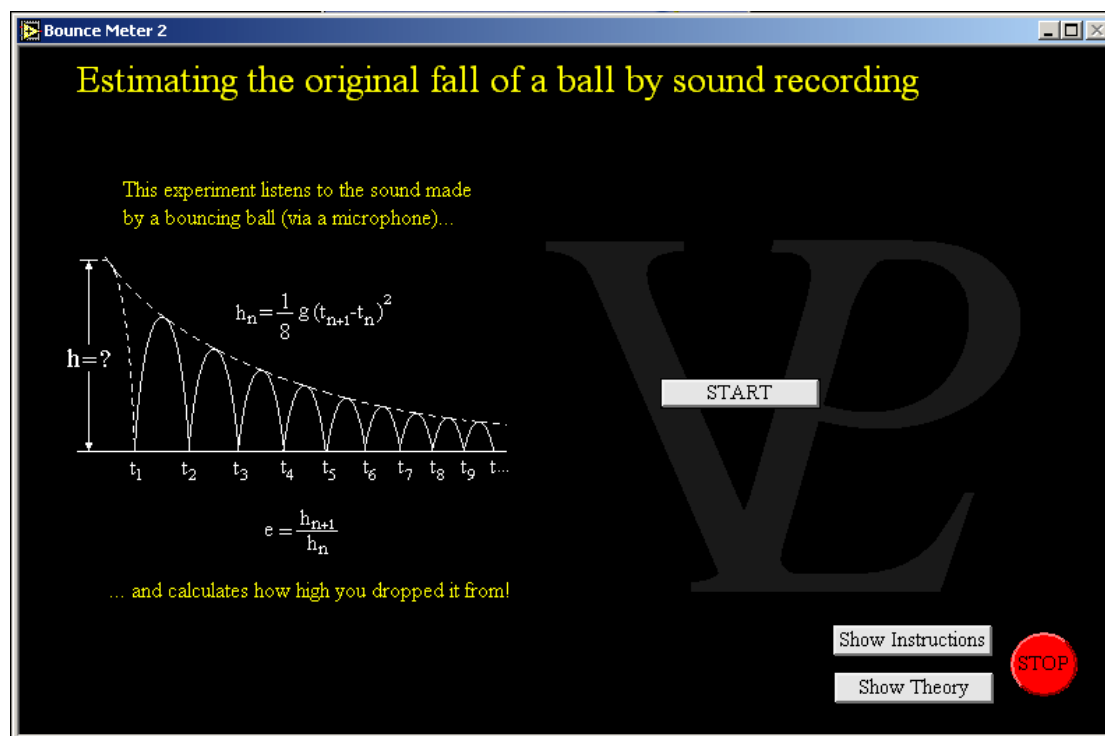
Challenge: See if you can slow the trolley down after launching the hollow ball so that you can still catch it back inside the cannon!

Kinematics 16.2

16.2 Bounce meter

Advanced

This interesting experiment can calculate the height from which you drop a ball! The only requirement is that the ball bounces several times. A microphone is required to listen for the times at which the ball hits the table or floor.



In the absence of air resistance, the height to which an object rises when projected vertically up in the air can be calculated if we know how long it remained in the air.

We use $s = u t + \frac{1}{2} a t^2$ to calculate how long it takes for the object to fall from its maximum height, and we remember that it takes an object as long to travel from the ground to the top of its trajectory as it will take for it to fall to the ground again.

For the falling part of the trajectory $u = 0$, so $s = \frac{1}{2} g (t \text{ fall})^2$. However, the computer records the time between impacts, so the $t \text{ record} = 2 (t \text{ fall})$ so $s = \frac{1}{2} g (t \text{ record}/2)^2$ or $s = \frac{1}{8} g (t \text{ record})^2$. So using this equation we calculate the heights of as many rebounds as possible.

In this simulation the elasticity 'e' is defined as the ratio of the rebound height to the previous height. $e = h(n+1) / h(n)$. In a perfectly elastic rebound $e = 1$, but in the real world e is probably no better than 0.9 even for very bouncy balls.

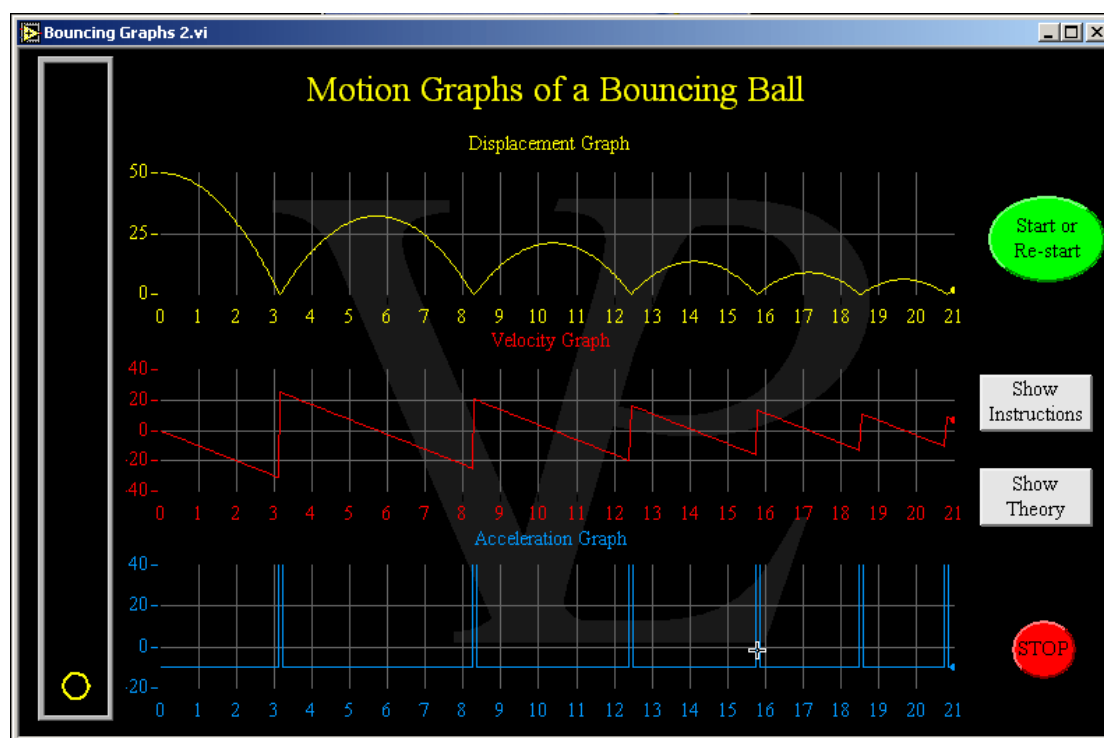
Using a suitable number of bounces it is possible to get a good average value for e. Then, having calculated the height of the first rebound, we use the value of e to guess what the initial height was.

The larger the number of rebounds that can be recorded, the better the estimate of the original height will be.

16.3 Bouncing graphs

Advanced

This simulation shows a ball bouncing and plots the displacement, velocity and acceleration graphs so that the users can see the relationship between them clearly. It is designed to help the user to interpret the three types of graph.



Note: air resistance is ignored in this simulation, a fair approximation at low velocities.

There are some important things to notice in the graphs:

- 1 - While the ball is in the air it only has gravity acting upon it. Consequently:
 - a) The acceleration graph is constant, always at -9.81 m s^{-2}
 - b) The velocity graph has a constant negative slope
 - c) The displacement graph always has a downward curve
- 2 - The velocity alternates between positive (going up) and negative (going down), going through zero when the ball is at its maximum height.
- 3 - There is a large positive acceleration each time the ball hits the ground, but this only lasts a very short time (as long as the ball is in contact with the ground). The softer the ball, the longer the period of contact is.

16.4 Falling Target

Basic/Advanced

This simulation illustrates the fact that even if a target starts to fall at the same time that a bullet leaves the end of a rifle, the bullet will still hit it!



When aiming at a target which starts to fall just as the rifle is fired interesting things happen. Intuitively you may feel that you ought to aim a little below the target. However, gravity will affect the bullet as well as the target, so the net effect is that no compensation is necessary.

This is true whether the target is level with the rifle or if it is above or below. The easiest case to understand is the one where the target and the rifle are level with each other.

The horizontal velocity of the bullet is constant (ignoring air resistance) and the vertical component of its velocity is accelerated downwards due gravity. The vertical velocity (and position) of the target at all times is the same as that of the bullet, so because they both fall together, the bullet will still hit the target.

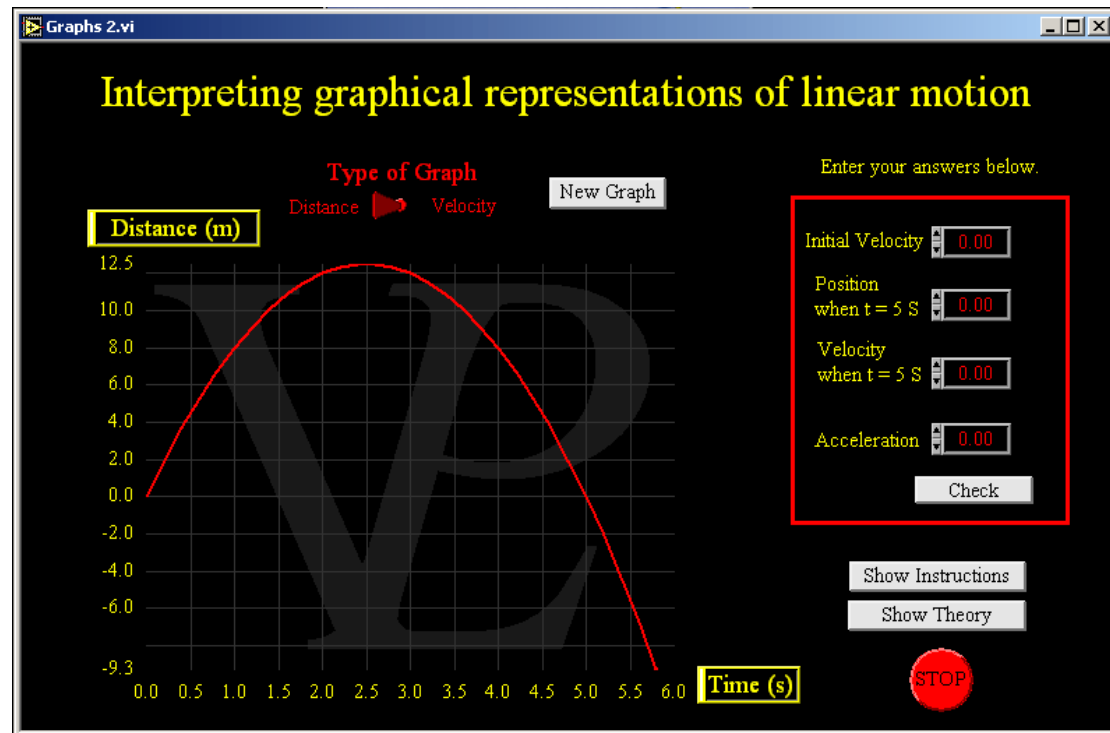
The reasoning is a little more complex in the case where the target is higher or lower than the rifle, but the overall effect is the same. The vertical component of the velocity of the bullet is modified by gravity in such a way that it still hits the target!

Kinematics 16.5

16.5 Graphs

Basic/Advanced

Learn to read information from distance-time and velocity-time graphs. Check your interpretations against the computer.



Learning to interpret motion graphs is an important skill in physics.

The most important step is to read the Y axis carefully. Is it a velocity graph or a displacement graph?

If it is a displacement graph, then:

- a) Distances travelled can be read directly
- b) The slope represents the velocity.

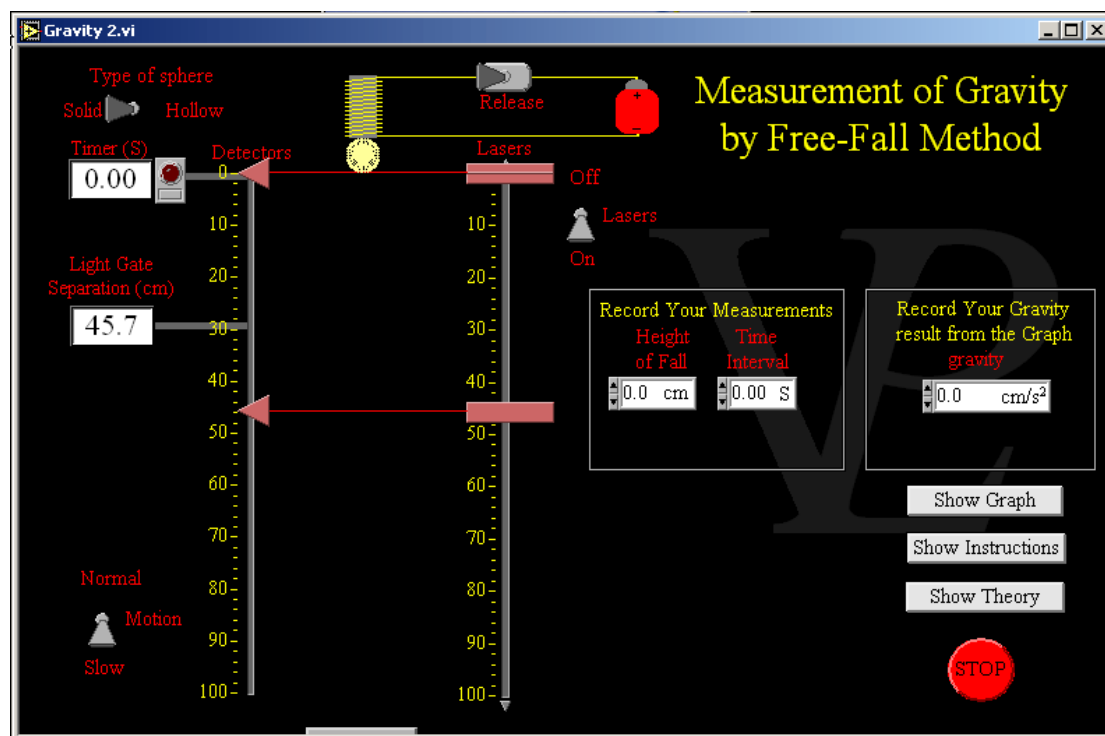
If it is a velocity graph, then:

- a) The velocity can be read directly
- b) Its slope represents the acceleration
- c) The area under the graph represents the distance travelled.

16.6 Gravity

Advanced

Measure gravity with the aid of a free-fall experiment using light gates. Drop the ball from different heights and obtain a graph from which g can be calculated. (Slow motion can be selected)



The electromagnet is made to hold the sphere up just above the first light gate. When the electromagnet is de-energised the sphere falls, blocking off the first light beam and starting the clock. When it goes past the second light gate the clock is stopped. If the acceleration is uniform, we can use the equation $s = ut + \frac{1}{2}at^2$. To make it easier for ourselves we make sure the first laser is positioned right at the top. Then we can say $u = 0$ so the equation reduces to $s = \frac{1}{2}at^2$. Where $a = g$ the acceleration of gravity.

A graph where s is plotted against t^2 will yield a straight line, and the gradient of that line will be exactly $\frac{1}{2}g$.

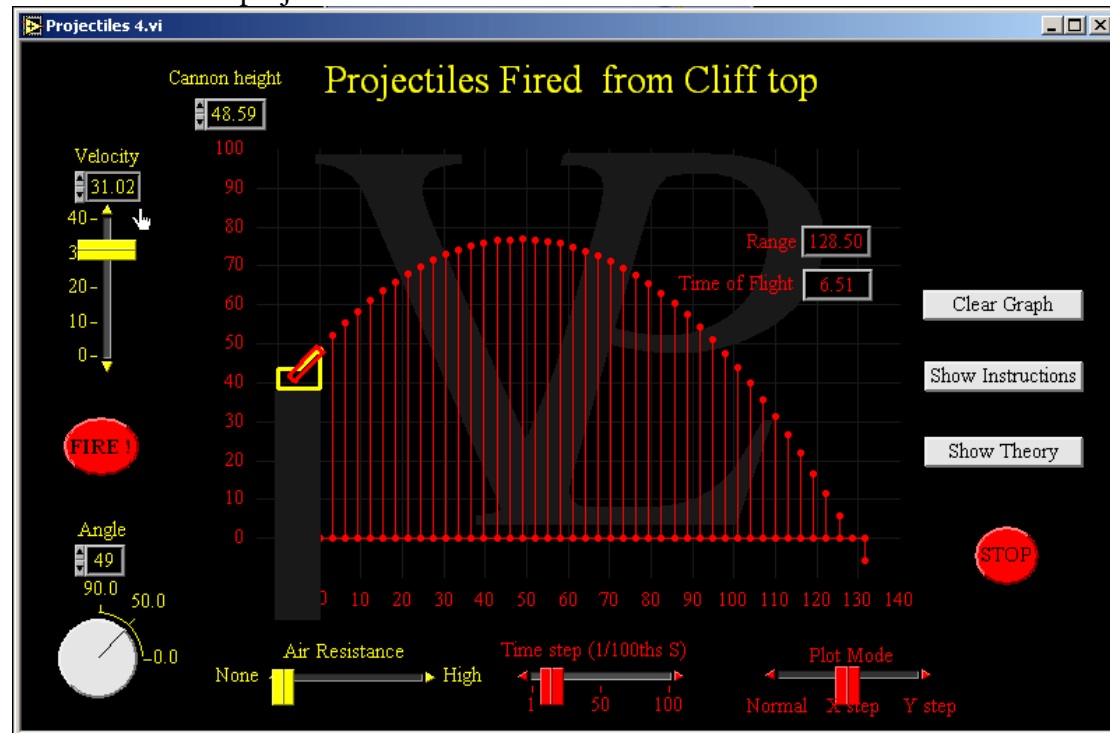
Notice that this will not be the case if the first light gate is moved down a bit, as u will no longer be zero.

If air resistance becomes significant (as in the case of a hollow sphere), then it will slow the fall. The slope of the line will start to reduce and the gradient will no longer represent $\frac{1}{2}g$. The fall tends towards terminal velocity where the acceleration is zero.

16.7 Projectiles

Advanced

Fire a projectile from the side of a cliff and adjust the initial velocity and angle in order to investigate the effect on the range. Visualise the constant horizontal component to the velocity and the accelerated vertical component. See how air resistance affects projectiles



Projectile motion may seem very complicated to begin with, but if you consider the motion as made up of two different components - vertical and horizontal - then it is much easier to understand.

The horizontal component of the velocity is $U_{\text{horiz}} = U \cos \theta$ and remains constant throughout the entire trajectory, because gravity does not affect the horizontal acceleration. Horizontally we can say $S_{\text{horiz}} = U \cos \theta t$ and $V_{\text{horiz}} = U \cos \theta$ throughout the entire trajectory.

Vertically, the motion is an accelerated (or decelerated) motion because gravity (g) is acting in the vertical plane. The vertical component of the initial velocity is $U_{\text{vert}} = U \sin \theta$ and after firing $V_{\text{vert}} = U \sin \theta - gt$ and $S_{\text{vert}} = U \sin \theta t + \frac{1}{2}gt^2$

The time at which the maximum height is reached will happen when $V_{\text{vert}} = 0$, $t_{\text{max}} = U \sin \theta / g$. This time can be used to calculate the maximum height achieved.

If a projectile is fired from the ground, its total time of flight will be exactly twice the time it took to get to the top of its trajectory $t_{\text{total}} = 2 t_{\text{max}}$. We can calculate the range of the projectile by multiplying t_{total} by the constant horizontal velocity.

$$\text{Range} = U_{\text{horiz}} t_{\text{total}} \quad \text{Range} = (U \cos \theta) 2(U \sin \theta / g) \quad \text{Range} = 2U^2 (\cos \theta \sin \theta) / g.$$

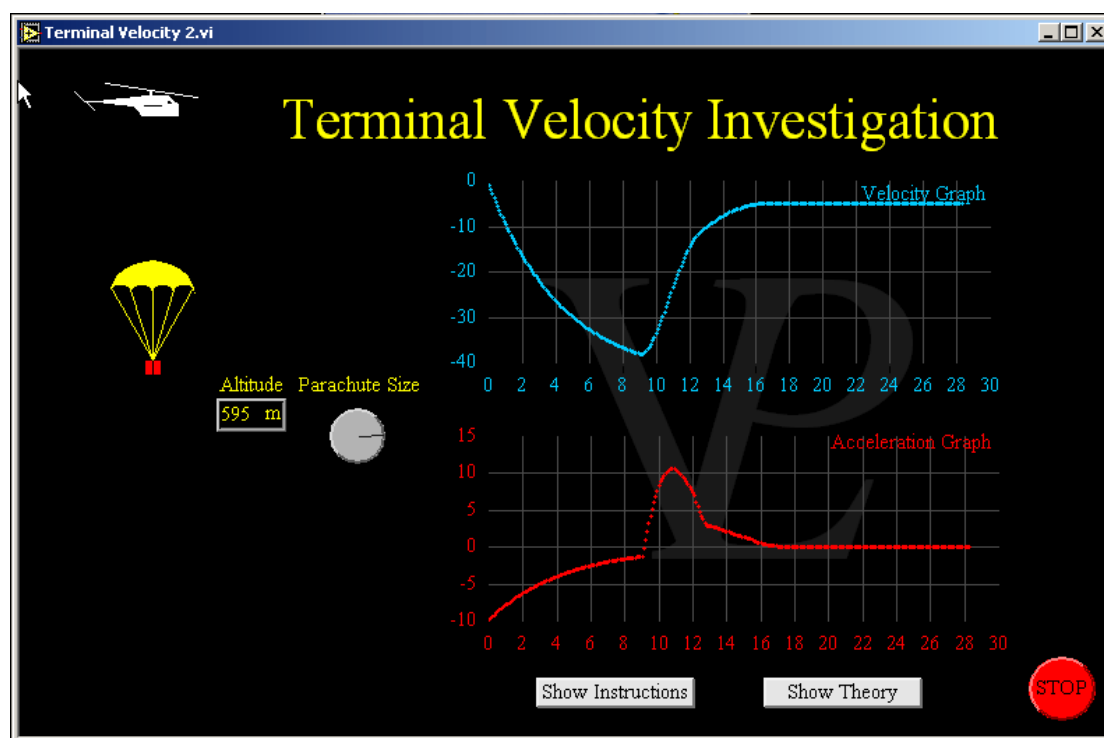
These are based on the starting point and finishing point being on the same vertical level so the range will be affected if the projectile is fired from the top of a cliff.

The theory of projectile motion becomes much more complicated when air resistance needs to be taken into consideration. Briefly, both the vertical and horizontal motions become decelerated, but at a non uniform rate. The deceleration depends on the velocity.

16.8 Terminal Velocity

Basic/Advanced

See how the terminal velocity of a parcel is affected by the size of parachute attached to it. Graphs of velocity and acceleration are plotted as the parcel falls. Experiment with different size parachutes!



The rate at which objects fall on the moon is completely independent of their size and density because there is no air to cause any friction. Objects will simply continue accelerating until they hit the surface of the moon with very large forces which is why you see so many craters on the moon. Thankfully on Earth we do have an atmosphere. The air presents some resistance to objects moving through it. This resistance increases with the size of the object and also with its speed.

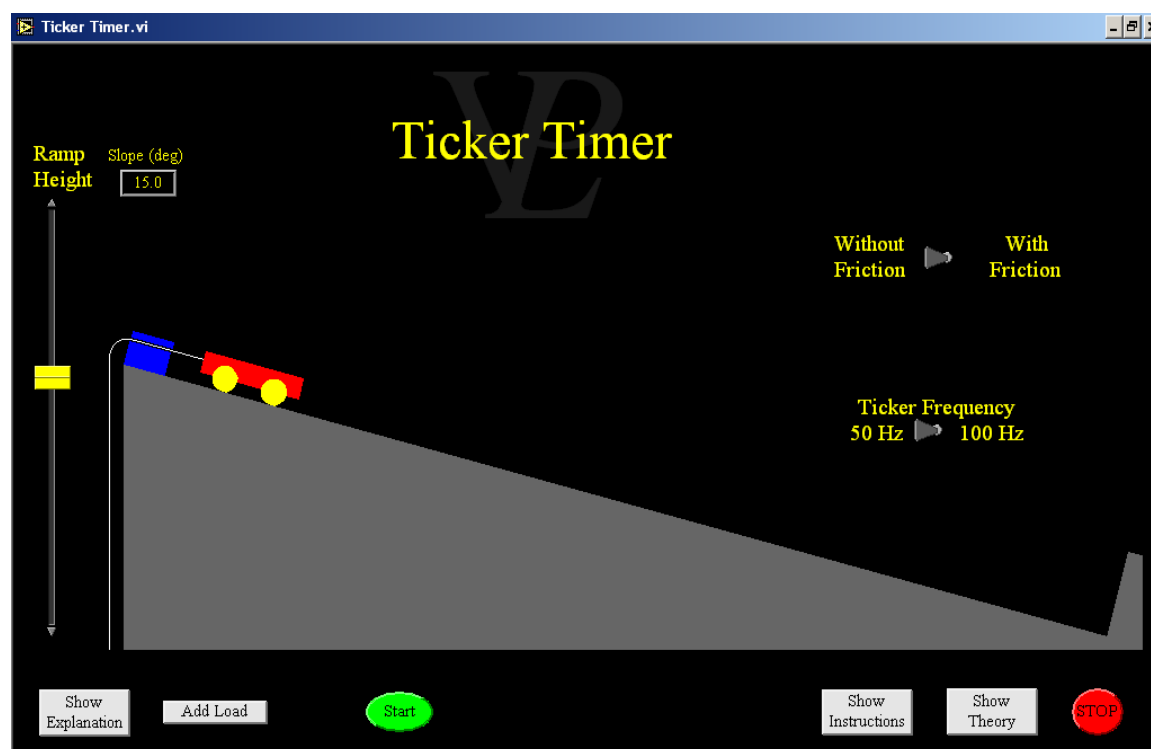
As the speed of a falling object increases, at some point the retarding force due to air resistance will match the gravitational force pulling the object down. At this point the object will not be able to accelerate any further; it will travel at constant velocity. We say it has reached 'terminal velocity'. It is possible to change the terminal velocity of an object by changing its size whilst keeping its weight constant. Parachutes increase the overall size of an object, and this causes a greater air resistance (drag) force. When the parachute opens, the object will slow down until the drag decreases to the point where it is equal with the gravitational force at which point terminal velocity will have been reached. The greater the surface area of the parachutes, the lower the terminal velocity reached.

It is not only falling objects which can reach terminal velocity. If you ride your bicycle and let yourself roll down a long hill, eventually you will stop accelerating and travel at constant velocity. You can increase your terminal velocity by crouching down so that your effective size is smaller, or you can decrease your terminal velocity by opening your coat and sitting very upright.

16.9 Ticker Timer

Basic/Advanced

This simulation shows how a ticker timer can be used to measure the velocity and acceleration of a trolley.



A Ticker timer is an electromagnetically activated tapper which can pinch a paper tape at set intervals. The modelled one can operate at either mains frequency (50 Hz), or twice mains frequency (100 Hz).

When the special paper tape is pinched lightly it darkens, marking the position of the paper within the jaws of the ticker timer.

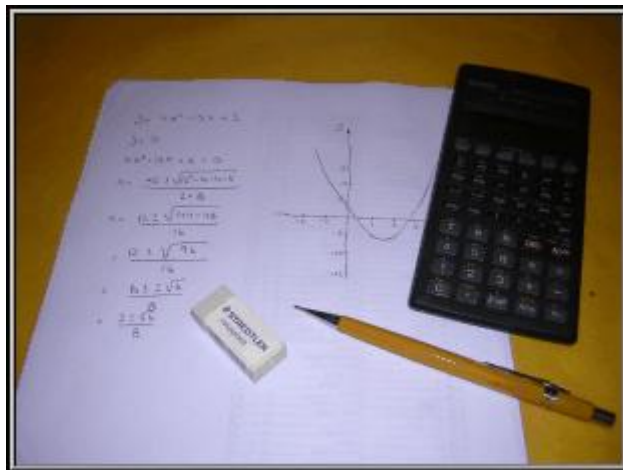
The space between any two consecutive spots will be the distance travelled in 0.02 s (if operating at 50 Hz). So the speed of the trolley in mm/s can be calculated as the distance between spots in mm divided by 0.02 s.

If the trolley moves at constant velocity, the space between consecutive spots will be constant, but if the trolley is accelerating, there will be an increase in the separation of the spots.

The "Show Explanation" buttons show how accelerations and velocities are calculated.

CHAPTER 17

MATHEMATICS

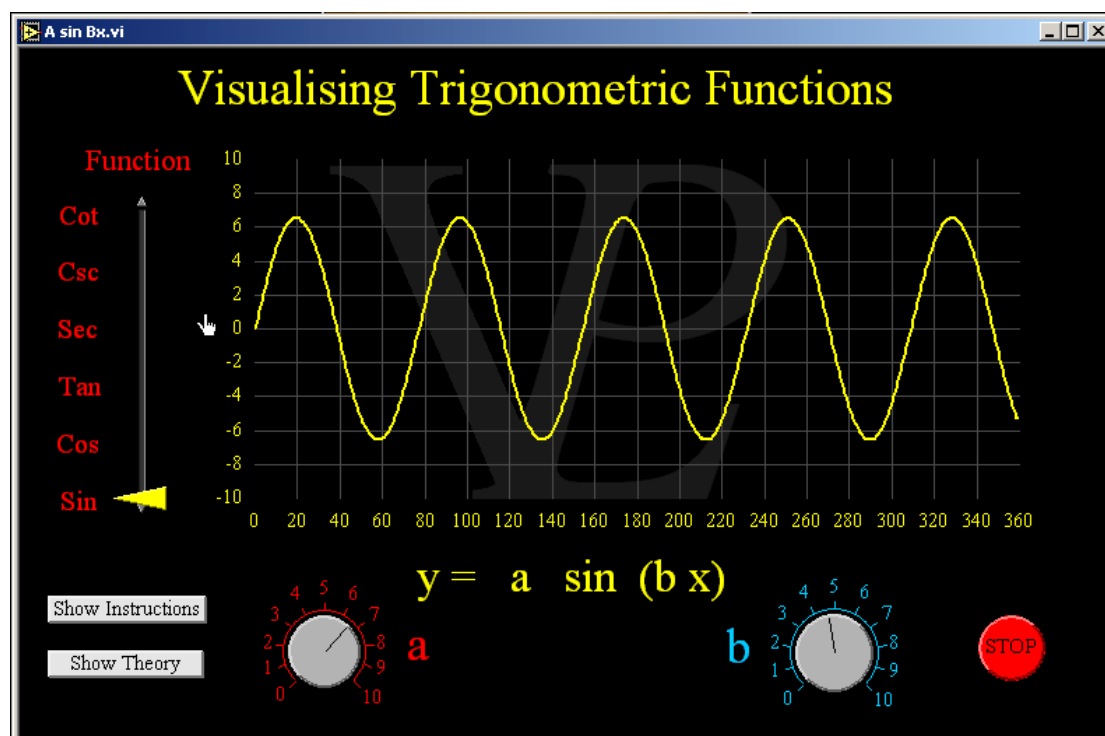


Mathematics can be very difficult, but it is very useful.
How would science manage without it?

17.1 A sin Bx

Basic/Advanced

Plot an equation of the form $A \sin Bx$. Visualise what A and B do to the shape of the locus



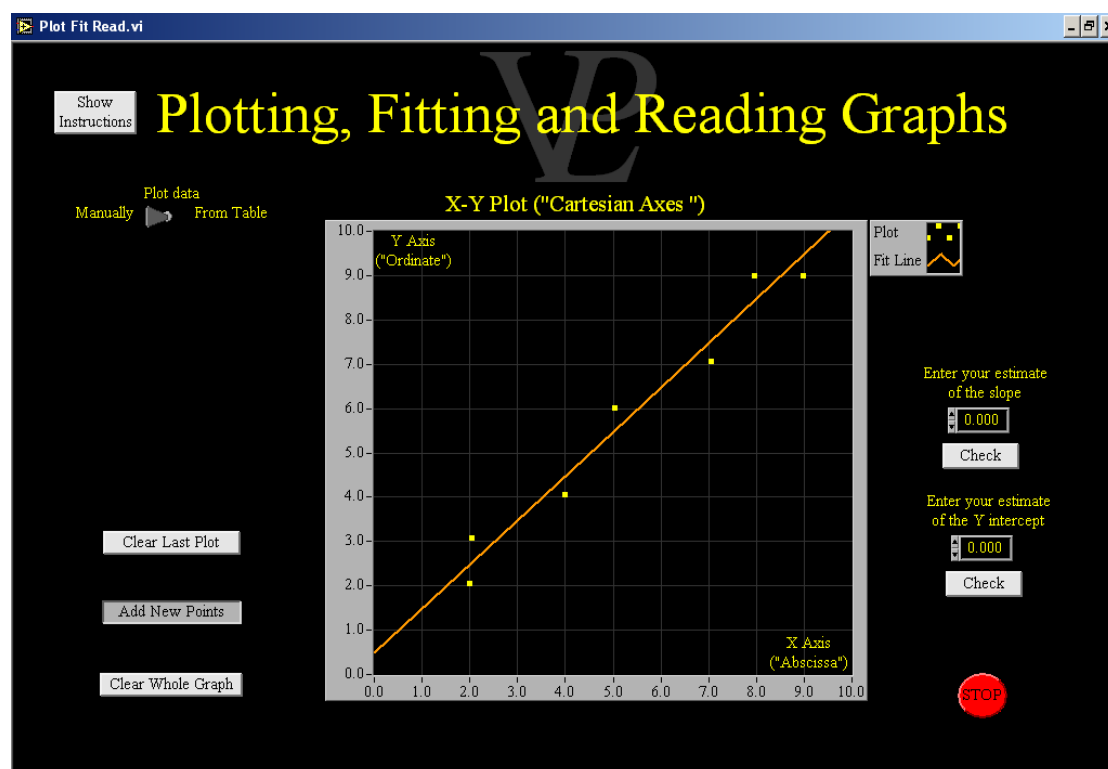
Trigonometric functions have many applications in mathematics and physics. They are used to handle problems ranging from simple triangles to musical signal manipulations.

To see how the different functions relate to the lengths of the sides of a right angled triangle, see the simulation called 'Sin Cos Tan'.

17.2 Graph Plot Read

Basic

This program enables the student to practice fitting lines of best fit to data and then reading the slopes and intercepts.

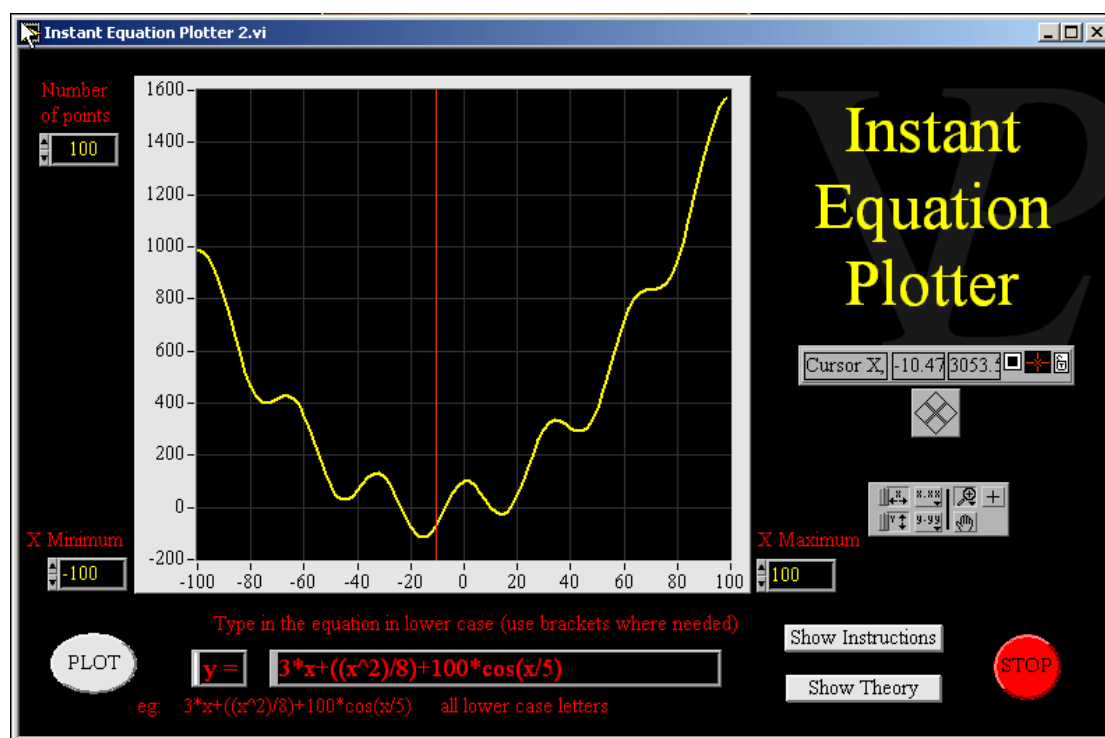


- 1 - Set the size of the graph display by over-typing the numbers at the origin and at the extremes of the X and Y axes
 - 2 - Click on the graph where you want each point to be placed.
 - 3 - If you make a mistake with a point, click on the "Clear Last Plot" button to remove the last point you plotted.
 - 4 - When you have completed all the point you wish to plot, click the "Add/Adjust Fit Line" button.
 - 5 - Click and drag the mid point of the line until it lies near the centre of your plotted data.
 - 6 - Click and drag the left or right hand side of the line to adjust its slope until it best fits the plotted data.
 - 7 - Repeat steps 5 and 6 until you are satisfied that the line is an accurate fit to your data.
 - 8 - Read the scales of the graph carefully and calculate the slope of the line of best fit.
 - 9 - Enter your calculated values into the fields on the right hand side and press "Check" to see if you have got it right (correct if within 2%)
- There is your challenge!

17.3 Instant equation plotter

Basic/Advanced

Type the equation in the box, select the X max and X min limits and the graph will be plotted. This enables students to visualise what shape any given equation will produce.



Learning to visualise what graphs will look like is an important skill which is applicable in a wide range of disciplines.

Try some of the following:

$$y = 5 \cos(0.1x) \times \sin(0.1x)$$

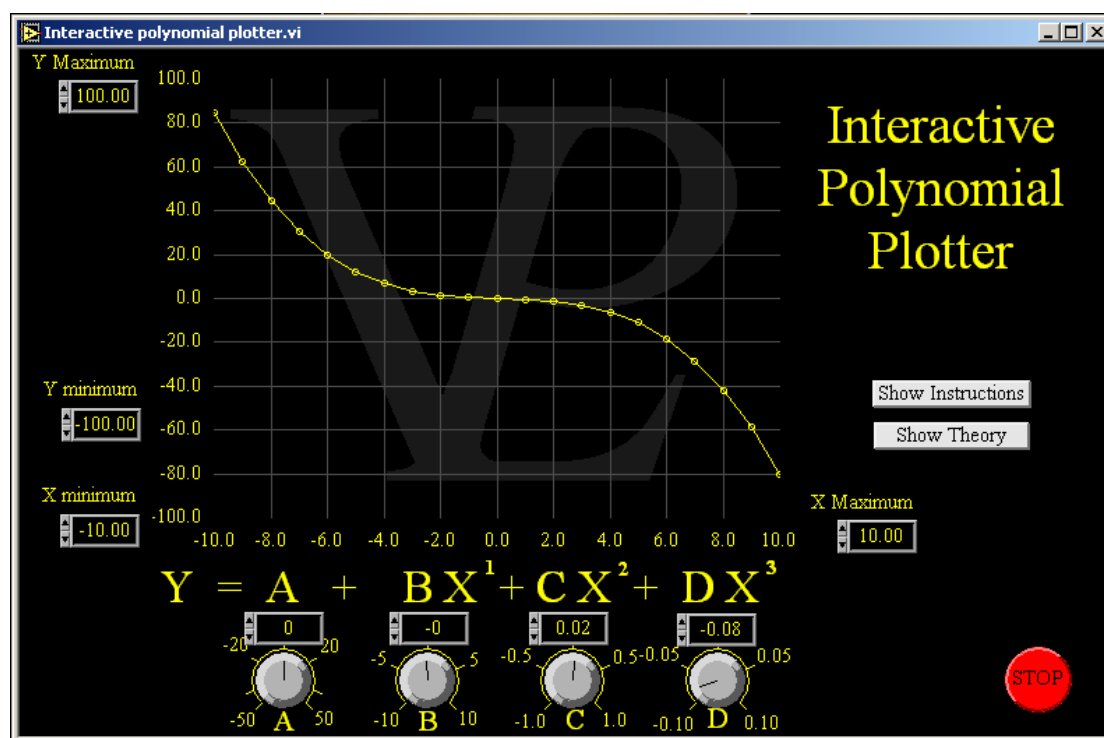
$$y = 10 \sin x \times e$$

$$y = 0.00001x - 0.01x + 0.01x - 0.1x$$

17.4 Interactive polynomial plotter

Basic/Advanced

This program allows the student to get immediate feedback on the effect of coefficients in a normal polynomial. The values of the coefficients can be controlled using sliders.



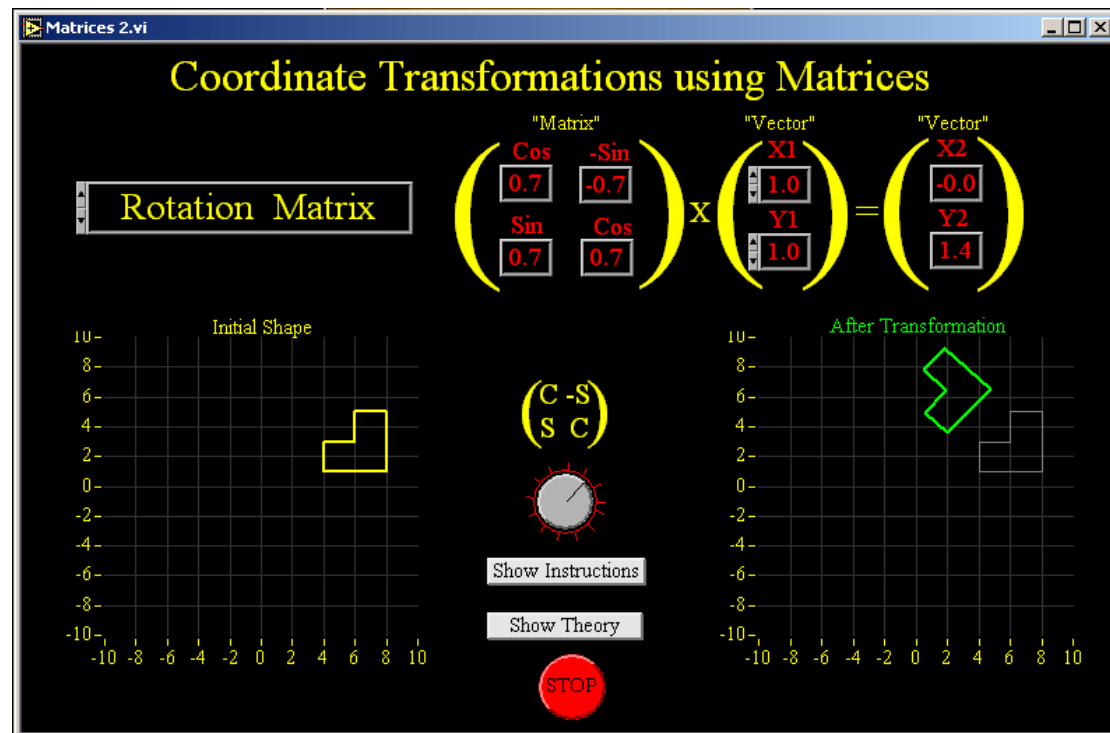
Learning to visualise what graphs will look like is an important skill which is applicable in a wide range of disciplines.

This interactive polynomial plotter should show you that the signs and values of the coefficients of the higher orders are the ones that dominate the shape well away from the origin, and the coefficients of the lower orders (and especially the constant) dominate the shape for values of x that are smaller than 1.

17.5 Matrices

Advanced

This program shows one use of matrices in transforming the coordinates of a polygon in the Cartesian space. Several transformations are given, including a user definable one.



Matrices are a mathematical tool that is used to solve certain types of mathematical problems. Two of the most important ones are transforming coordinates in 2D, 3D and even nD space, and also solving n simultaneous equations with n unknowns.

Vectors contain only one column of coordinates, but have as many rows as the number of the dimensions of the space being used. The column contains the x, y, z,... coordinates of the vector in question. In the examples shown here, the matrix is a 2 by 2 matrix and the vector is a 1 by 2 vector, we are working in 2 dimensional space.

Matrices have rows and columns of numbers. A matrix needs to have as many columns as the number dimensions it is going to represent.

The way in which the computation is carried out is as follows. Note that a normal text editor cannot produce brackets that span several lines. Here the brackets are composed of 3 superimposed smaller brackets.

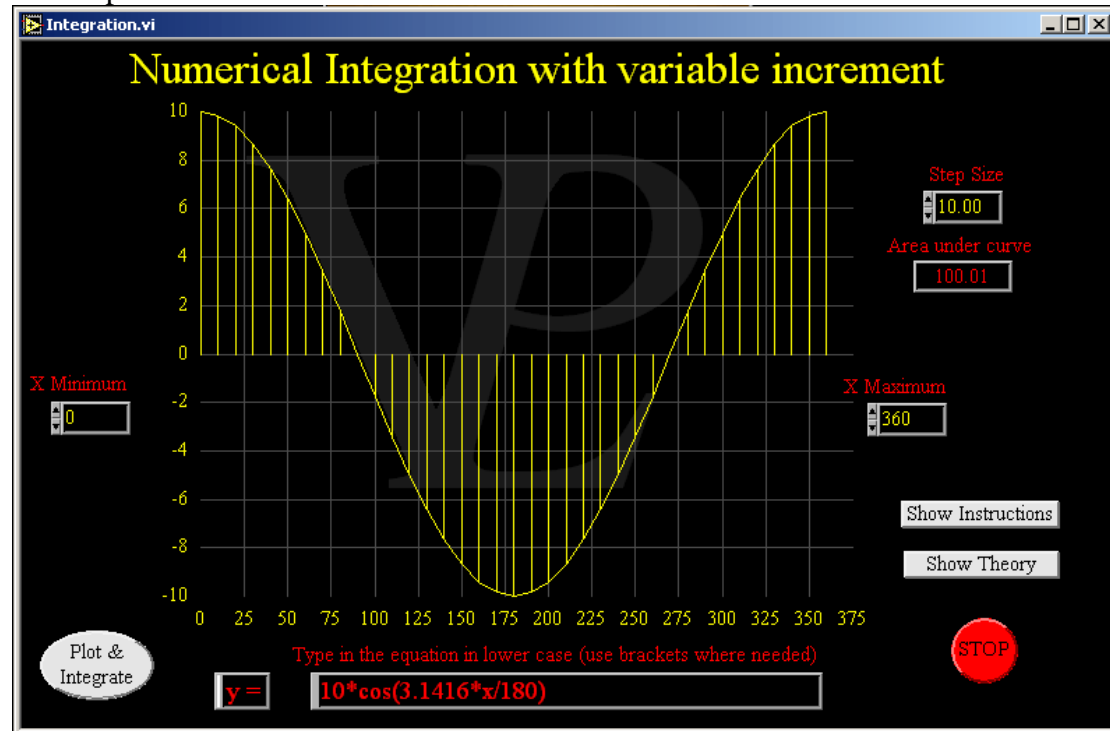
$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \times \begin{pmatrix} e \\ f \end{pmatrix} = \begin{pmatrix} g \\ h \end{pmatrix} \quad \begin{matrix} (a \times e) + (b \times f) = g \text{ and} \\ (c \times e) + (d \times f) = h. \end{matrix}$$

You will see from the choice of matrices available in this program, the values of a, b, c and d determine what type of matrix it is, and what function it serves (rotation, reflection, etc).

17.6 Numerical integration

Basic/Advanced

This program carries out Numerical Integration under the curve of any equation given. The effect of step size can be studied, and integrations under standard functions can be compared.



Numerical integration is a way of finding the area under a curve when it cannot be calculated analytically because it can become difficult.

The method consists of:

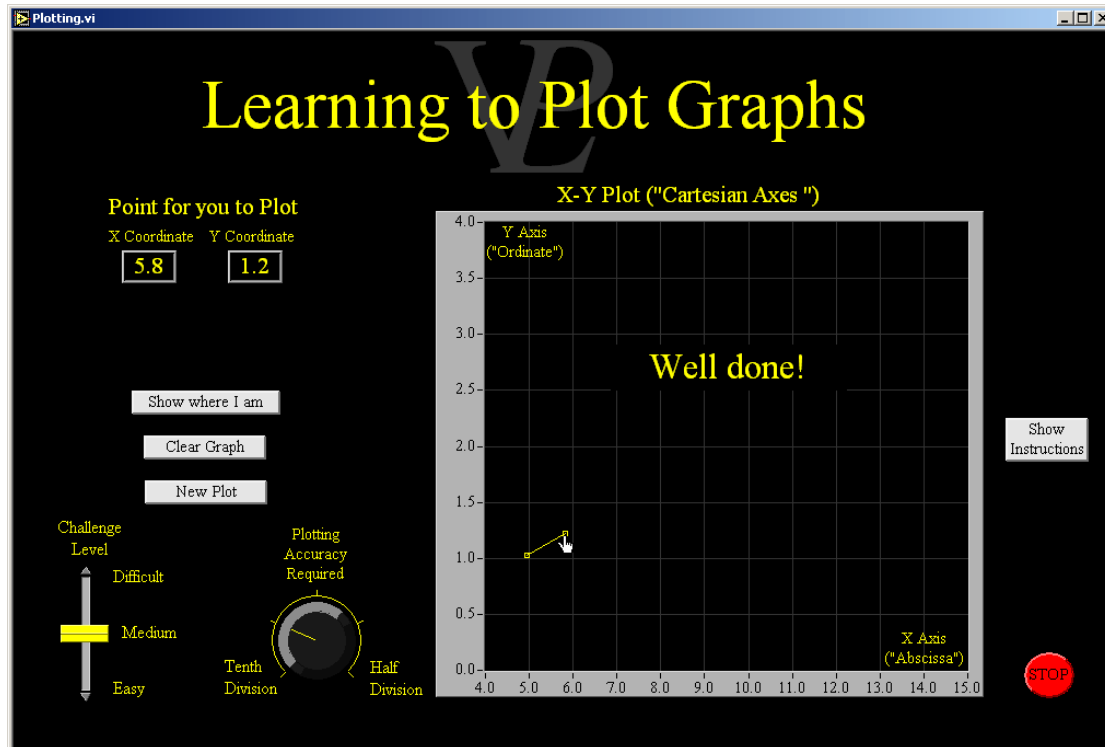
- 1 - Dividing up the shape into small vertical strips
- 2 - Calculating the area of each strip assuming it to be rectangular
- 3 - Adding all the areas of all the strips together.

The narrower we make the strips, the better the approximation becomes. Depending on how accurate we need the result to be, we can decide how narrow the strips need to be made.

17.7 Plotting

Basic

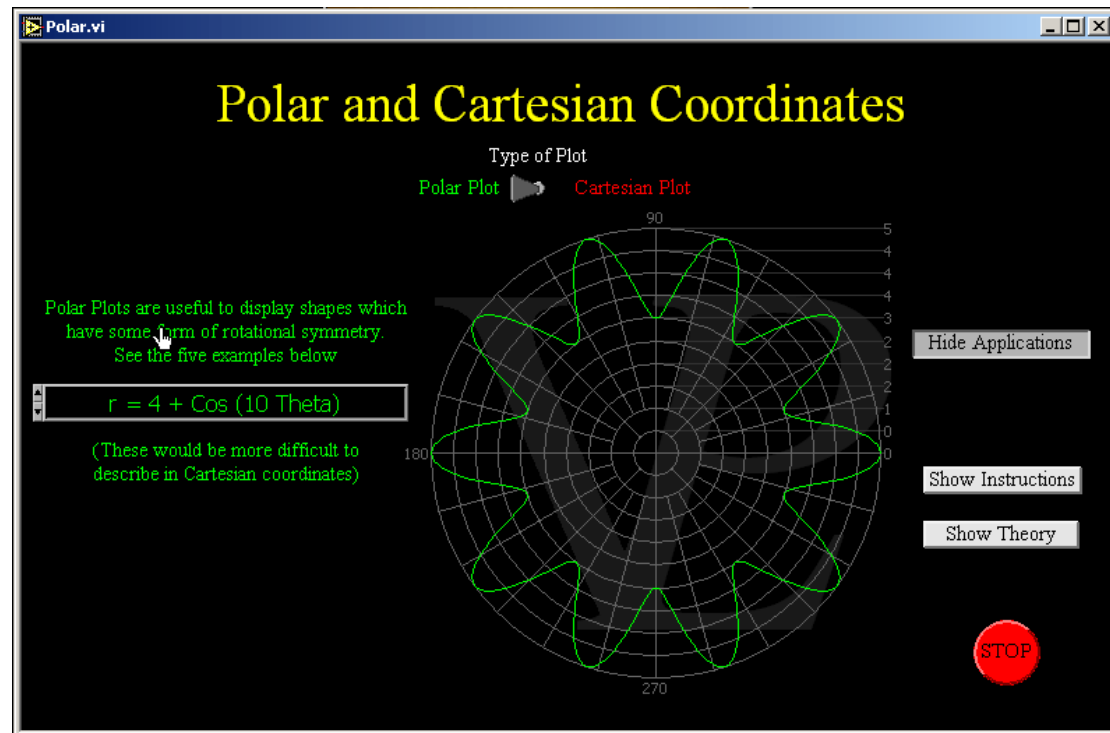
Test your skills at plotting graphs at three different levels of difficulty



17.8 Polar Coordinates

Advanced

This program illustrates the use of polar coordinates (as compared with Cartesian coordinates). It shows why they are useful and gives some typical applications.



There are a number of different ways to plot information graphically. Perhaps the most common one is the Cartesian system with which you will already be familiar.

For some applications, the Cartesian system is not suitable, or at least becomes very complicated to use. This is why we sometimes use a globe rather than a flat map.

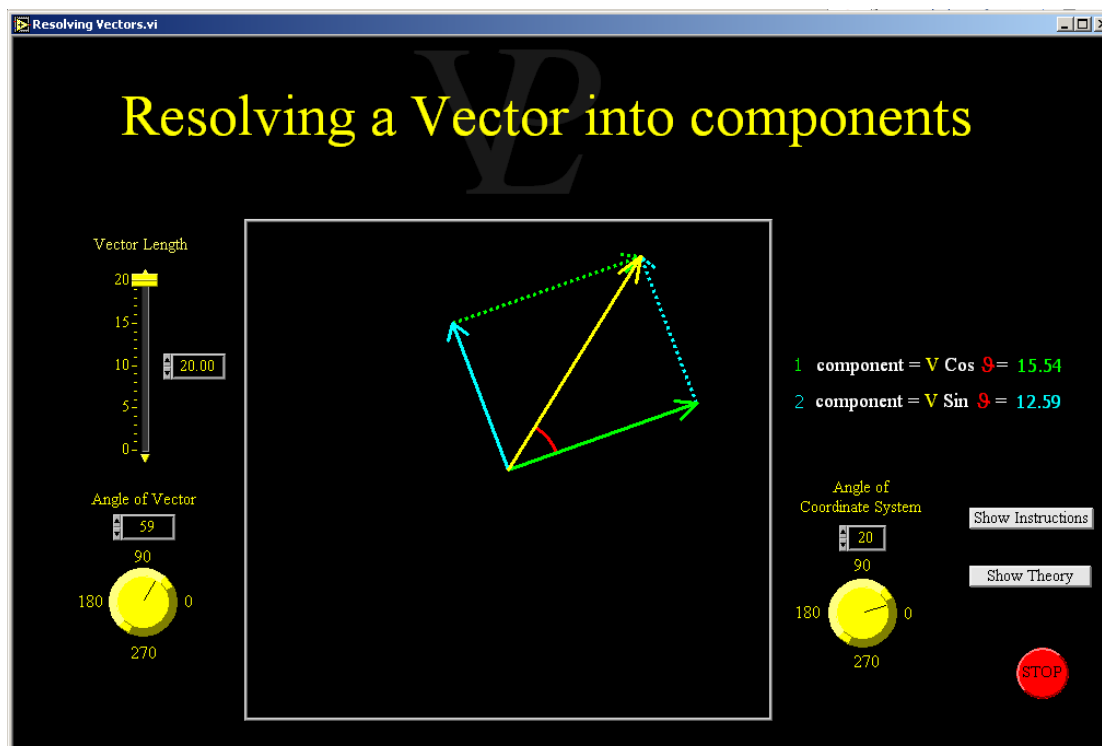
One possible alternative is the polar plot. In this system we define the distance and direction of a point instead of its x and y coordinates.

This system makes it possible to generate very interesting shapes with fairly simple equations.

17.9 Resolving Vectors

Advanced

This simulation enables the user to see how forces can be resolved into two perpendicular components.



Any vector can be made up of the sum of two vectors which are perpendicular to each other.

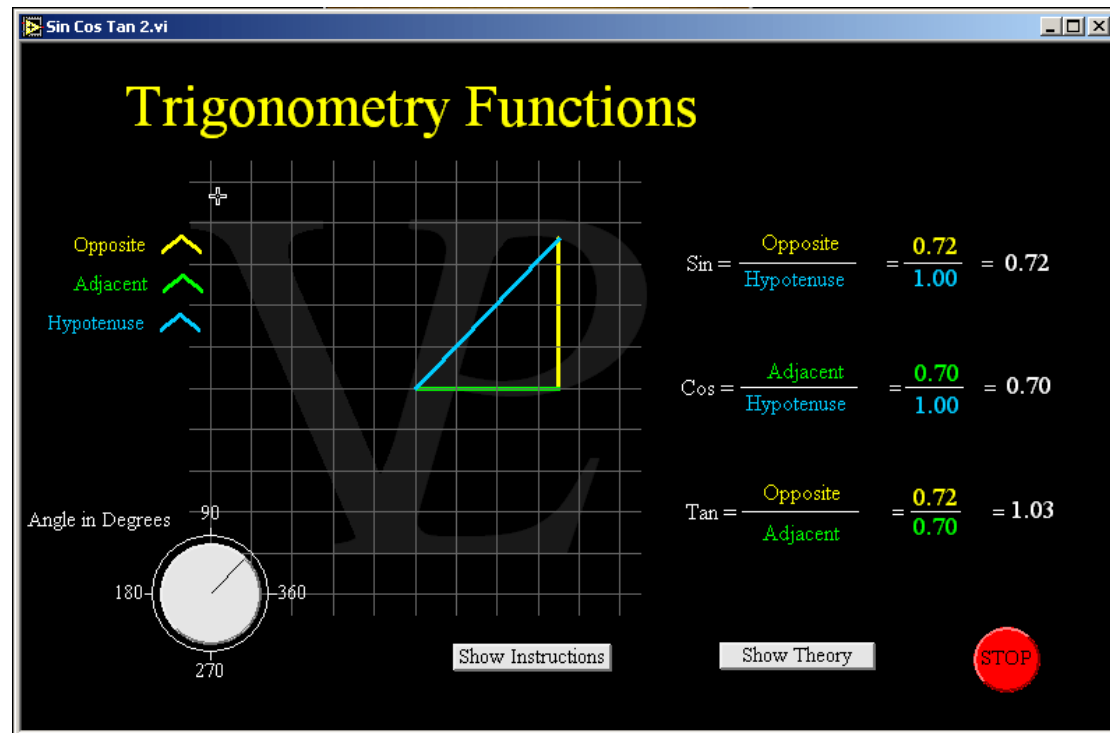
This process is called "resolving" a vector into two components. Vectors are commonly resolved into their vertical and horizontal components. This is convenient when trying to balance the forces acting on an object. If the object is in equilibrium, the sum of all the vertical components will be zero, and so will the sum of all the horizontal components.

Sometimes it is more useful to resolve a vector into components which are not horizontal and vertical, but into directions which are parallel to a surface and perpendicular to it. A good example of this is when trying to find the forces acting on a block resting on an inclined surface. See the simulation on Friction in the Forces chapter.

17.10 Sin Cos Tan

Basic/Advanced

This simple program shows how Sin, Cos, and Tan derive from a vector on Cartesian axes.



The Sine of an angle (sin) is defined as the ratio of the length of the side opposite to the angle to the length of the hypotenuse.

The Cosine of an angle (cos) is defined as the ratio of the length of the adjacent side to the length of the hypotenuse.

The Tangent of an angle (tan) is defined as the ratio of the length of the side opposite to the angle to that adjacent to it.

Notice that there is always one right angle in these triangles.

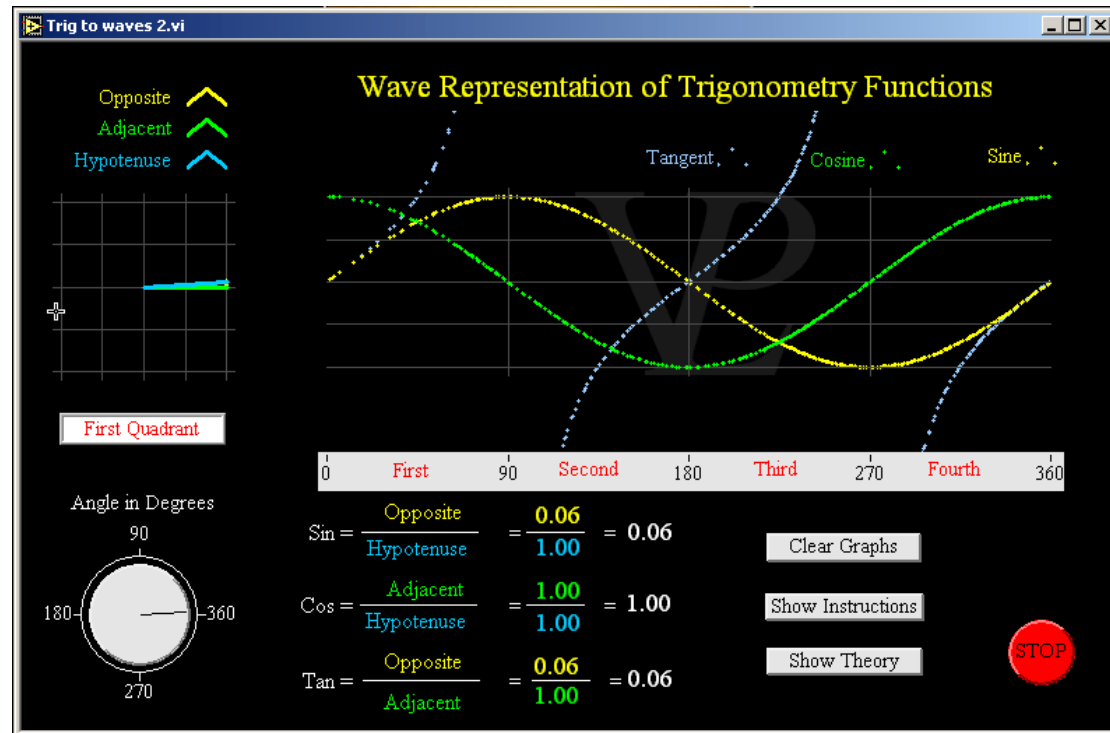
Notice also, that the sign of the lengths is also important. Lengths above the X axis are positive (below are negative), and lengths to the right of the Y axis are positive (to the left are negative). The length of the hypotenuse is defined to always be positive.

Following this sign convention, you will see why sometimes the sin, cos and tan can sometimes be negative. Interestingly, when both the adjacent and opposite sides are negative, the tan of the angle will still be positive. Can you see why?

17.11 Trigonometry to Waves

Basic/Advanced

This program shows how Sin, Cos and Tan can be plotted as waves on a graph.



This programme was used to illustrate the relationship between sin, cos and tan, (which may seem to be related only to triangles) to sine waves and cosine waves. (tan waves are not usually thought of as waves).

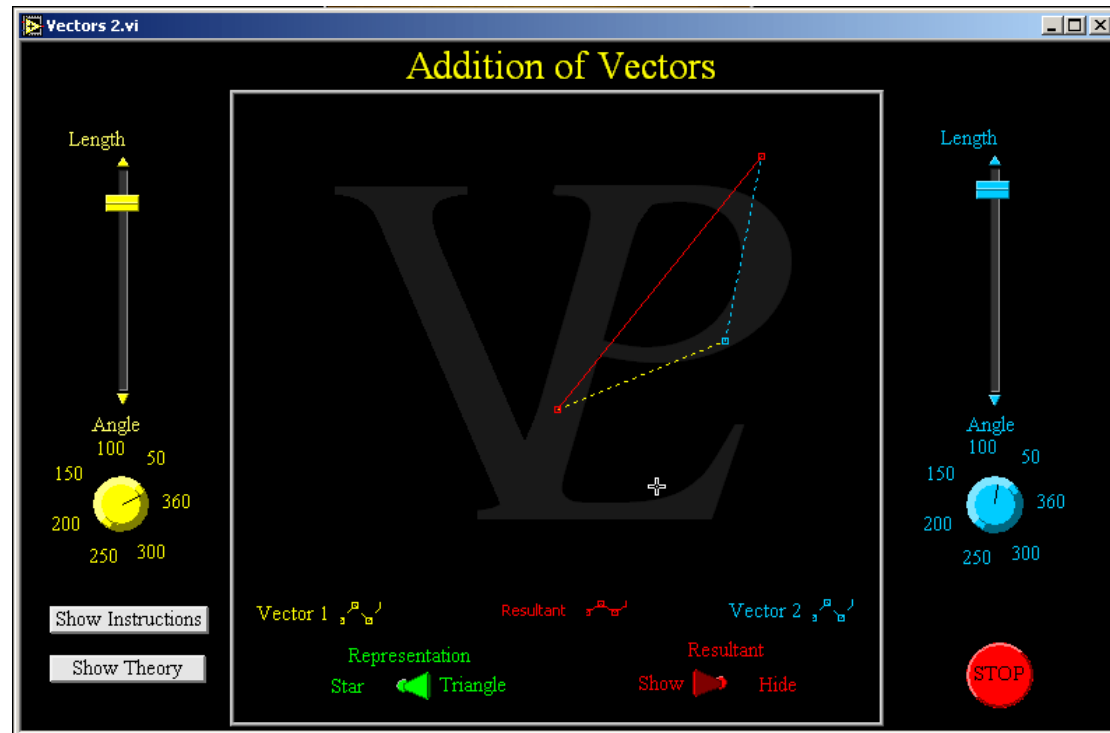
Notice that the sine wave and the cosine wave seem to be very similar, except that they are out of step with each other. We say there is a phase difference between them. See if you can convince yourself that their phase difference is 90 degrees.

More challenging: See if you can work out which is ahead of the other.

17.12 Vectors

Basic/Advanced

This program shows how two vectors can be combined in order to obtain a resultant.



Vector addition is an important skill in physics. It is used to combine forces, velocities and directions. Addition of vectors is a fairly easy thing to do graphically.

Draw the first vector, making sure that its length represents its numerical quantity (e.g. 10 cm represents 10 N), and its direction follow the angle required by the particular problem you are trying to solve.

Draw the second vector, starting from where the first vector ended. Use the same scale as for the first vector.

To find out the resultant of the vectors, draw a vector that starts from the beginning of the first vector and finished where the second vector finished. Measure its length and convert the units back using the same scale.

To subtract vector B from A, first reverse the direction of B (obtain $-B$), and then add $(-B)$ to A.

If you need to add three or more vectors, simply keep on adding them by starting the third where the second ended, and starting the fourth where third

CHAPTER 18

MATTER

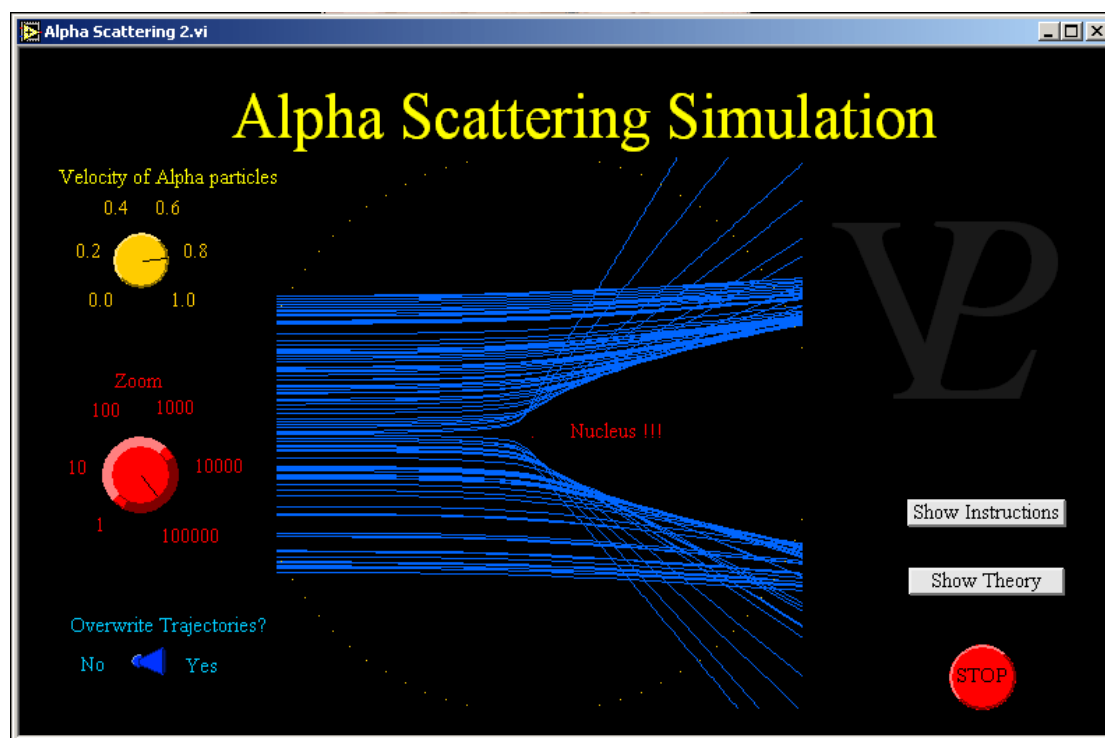


It may be easy to measure matter.
But what on earth is it?

18.1 Alpha Scattering

Advanced

This simulation shows how Alpha particles can be scattered from a gold foil. Zooming in to the gold foil reveals the presence of atoms within it. Zooming further in begins to reveal the presence of the nucleus. Investigate the effect of the initial speed of the Alpha particles.



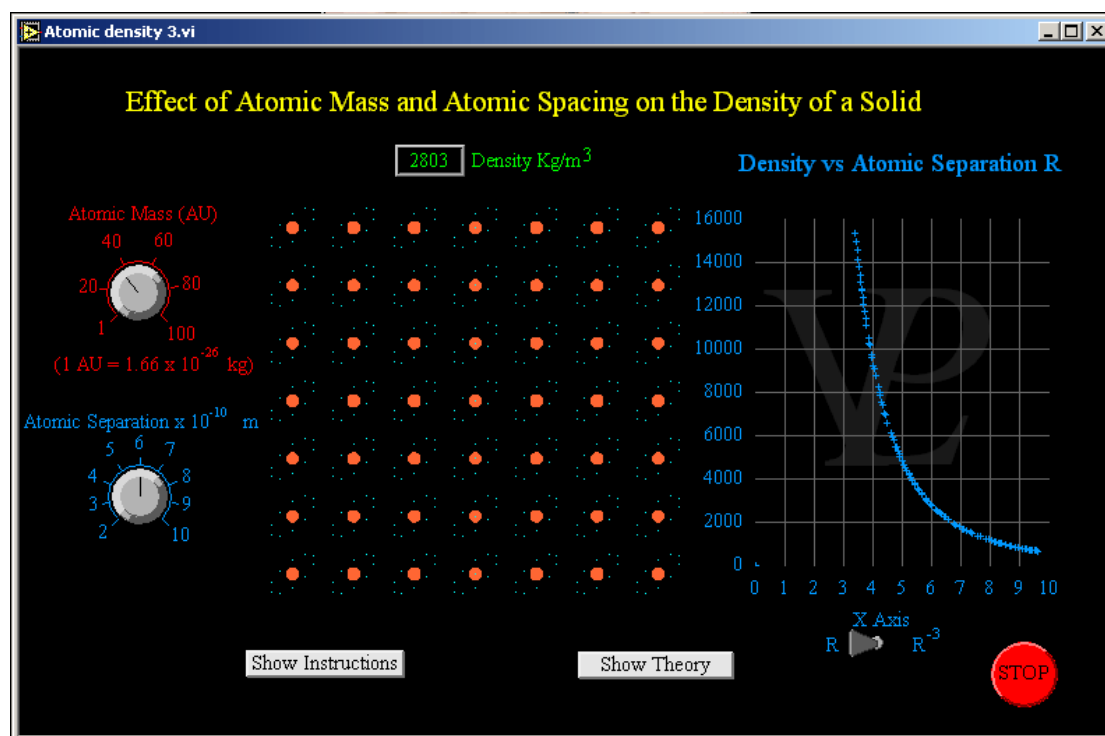
In this simulation, instead of giving you the theory, it is more instructive for you to discover it for yourself. Follow this list of guiding questions to help you to discover how Rutherford was led to the conclusion that atoms have a massive nucleus.

- 1 - Why can alpha particles fly right through a gold film?
- 2 - Why can't complete atoms deflect the alpha particles?
- 3 - Why do some alpha particles get deviated so strongly?
- 4 - How do we know a nucleus is so much smaller than an atom?
- 5 - Which alpha particles are deflected most: fast ones or slow ones?

18.2 Atomic Density

Basic/Advanced

This simple simulation shows how density can be affected by the mass of the atoms making up the solid and interatomic spacing.



The density of a material depends on the separation between the atoms and the mass of the atoms of the material.

Since most inter-atomic spacing is very similar, the main factor affecting the density is the atomic masses of the elements which make up the solid.

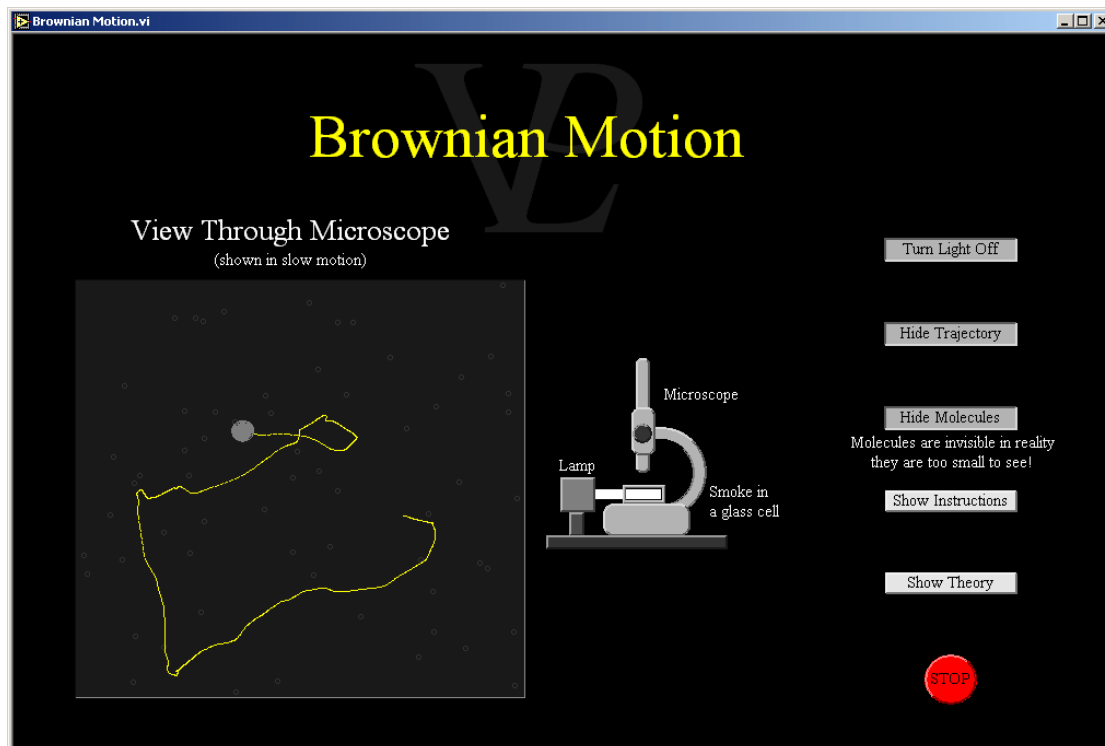
Some crystal lattices are arranged in such a way that the mean inter-atomic spacing is larger. This causes the density of the solid to be a little lower.

Interestingly, the density of nearly all materials reduces with temperature. Can you see why this might happen?

18.3 Brownian Motion

Basic

See a smoke particle doing its 'random walk', and wonder at the possible causes. Click a button to reveal the invisible molecules colliding against the smoke particle.



One of the most compelling pieces of evidence for the existence of molecules is the fact that smoke particles in air are seen to move around in a random walk with small jerky movements. We call this type of movement "Brownian motion" in honour of the botanist Robert Brown.

Brownian motion can also be observed with small particles suspended in water.

The movement of the small smoke particle that we observe is the result of many collisions of molecules against it. Since molecules are hitting it from all sides, we only see the effect of the small imbalance of collisions which give rise to the change in the velocity of the smoke particle.

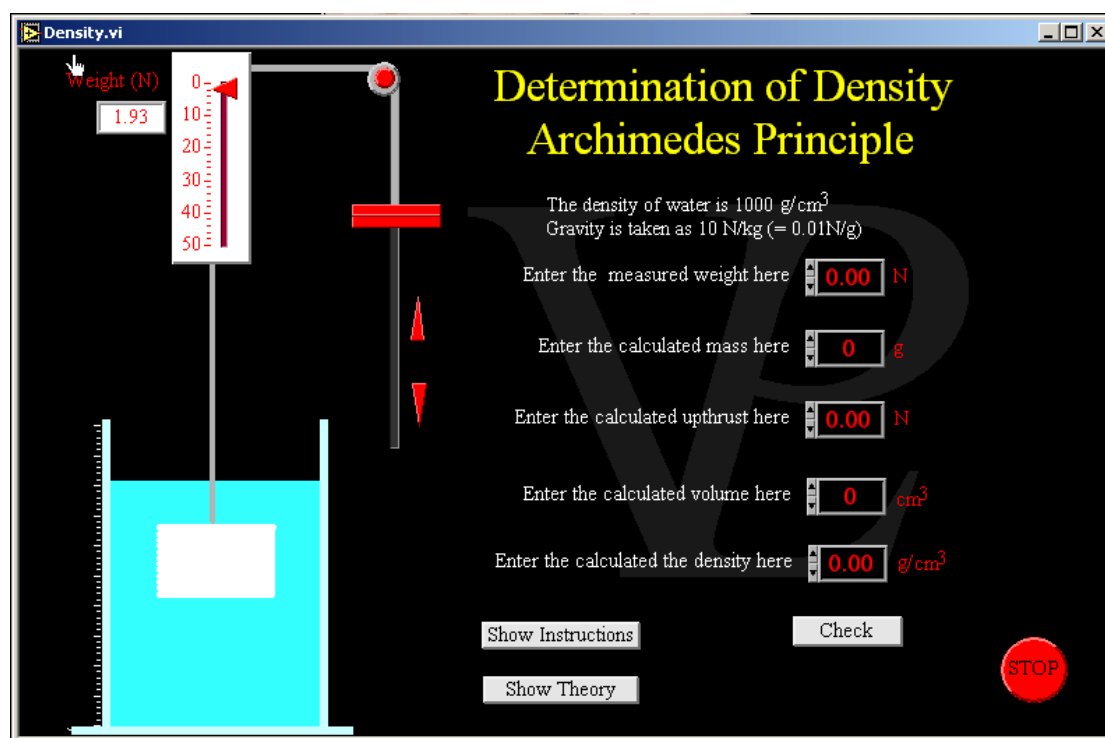
Smoke particles are much larger than the invisible molecules that are knocking it around, therefore the molecules must be moving very fast in order to 'pack enough punch' to get something that is much bigger to move around like that.

At room temperature, molecules are typically travelling at around 1000 miles per hour!

18.4 Density

Basic

This simple simulation prompts the student to calculate the density of a block of material by making use of Archimedes' Principle. The simulation allows the pupil to weigh an object in air and also when submerged in water.



Archimedes discovered that a body submerged under water experiences an apparent loss of weight or upthrust that is equal to the weight of the water it displaces.

The weight of the object is measured with the object completely outside of the water.

The mass in grams is obtained by dividing the weight by the force of gravity, 0.01N/g.

The upthrust is the difference between the body's weight in air and its weight when submerged under water.

The volume of the object is calculated from the upthrust because we know that since the density of water is 1 g/cubic cm, each cubic centimetre of displaced water produces an upthrust of 0.01N

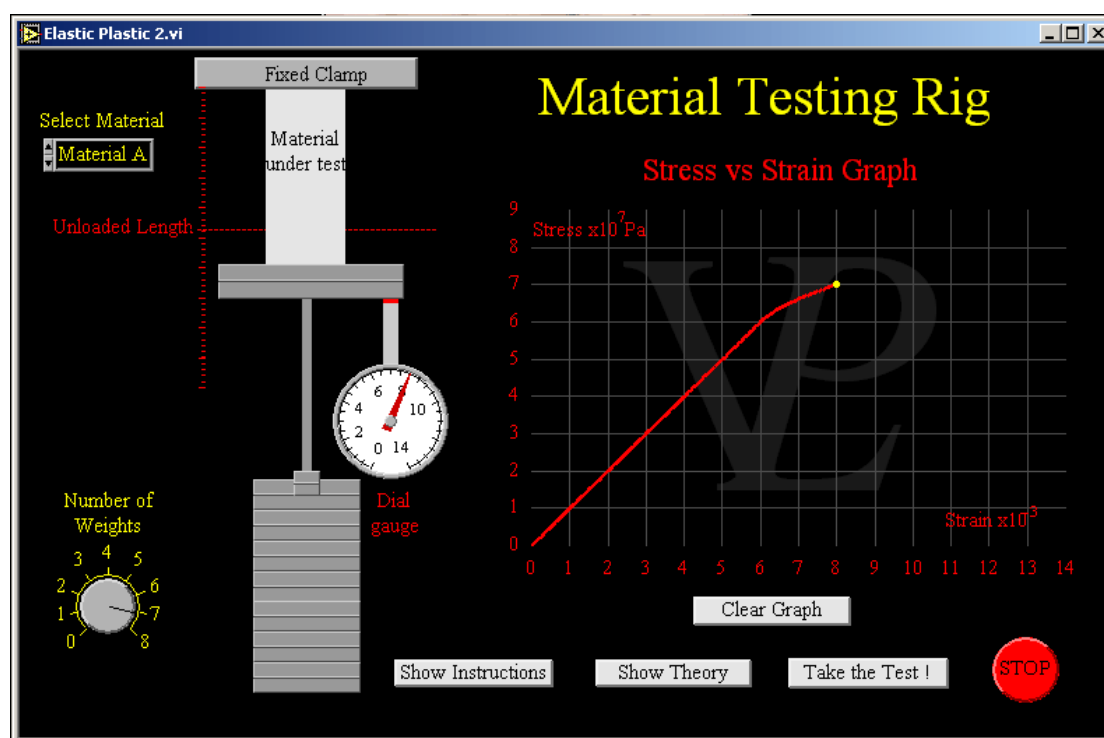
The density is calculated by dividing the mass of the object by its volume.

In this way Archimedes was able to check if the crown that had been made for the king was real gold or not.

18.5 Elastic Plastic

Advanced

This simulation allows the pupil to investigate the different stress/strain relationships of 4 different materials. The concepts of ductile and brittle, breaking stress and breaking strain are shown clearly. Graphs are produced from which pupils should be able to read information to be tested by the computer



Before we chose a material to build a bridge or some other structure, it is important that we know the characteristics of materials (strength, elasticity, ductility, etc). Test machines like the one shown here are used to stress materials and see how they deform.

Stress is defined as the force per unit area to which a material is subjected. Its units are the same as those for pressure, the Pascal (Pa) where $1\text{Pa} = 1\text{Nm}^{-2}$.

Strain is defined as the extension divided by the original length. It is a dimensionless quantity.

The Young's Modulus (or the Elasticity Modulus) is defined as the ratio of the stress to the strain. Here it can be read from the slope of the graph during its linear region where the strain is proportional to the strain. It has the same units as stress.

The yield point is the point at which the strain starts to increase more rapidly. The relationship is no longer linear.

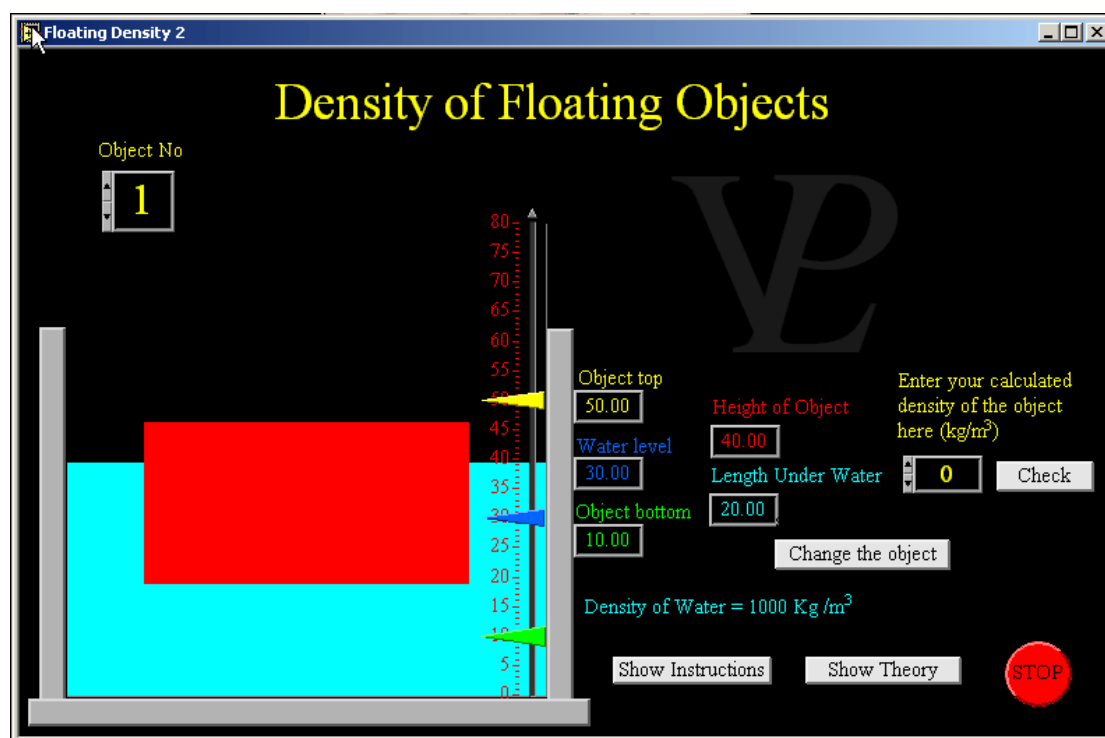
If a material only has a proportional region and then breaks, it is said to be a brittle material. They do not give you any warning that they are about to fail.

If a material has a large plastic region where the strain is no longer proportional to the stress, it is said to be a ductile material.

18.6 Floating

Basic

This simulation prompts the student to calculate the density of a block of material which floats. This is achieved by measuring what proportion of the block lays under-water.



From Archimedes Principle, we know that a body which is either partially or totally submerged in a fluid will experience an apparent loss of weight (upthrust) which is equal to the weight of the water that it displaces. While the weight of the amount of water that has been displaced is less than the weight of the object, the object will continue to sink.

At some point the weight of the displaced water will be equal to the weight of the object. This is the equilibrium condition. However, since the object had some downward momentum (and some of the water had an upward momentum), the object will sink a little further. When the weight of the displaced water is greater than the weight of the object, the excess upthrust will push the object up again. Eventually it will settle down.

In equilibrium:

Downward Force = Upward Force, so Weight of Object = Weight of displaced water

$M_o g = M_w g$, so $V_o \rho_o g = V_w r_w g$, so $H A \rho_o g = L_u A \rho_w g$, so $H \rho_o = L_u \rho_w$, so

$\rho_o = (L_u / H) \rho_w$

The letters have the following meanings:

M_o = Mass of object, M_w = Mass of displaced water, V_o = Volume of object

V_w = Volume of displaced water, ρ_o = Density of object, ρ_w = Density of water

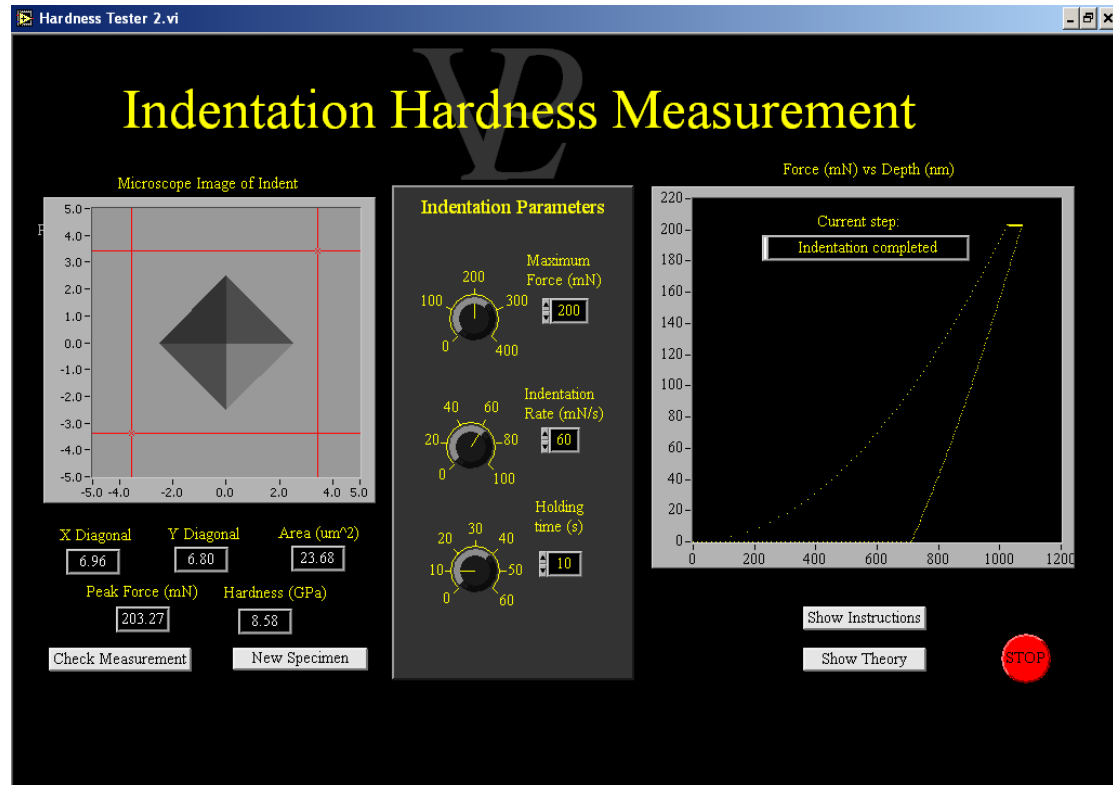
H = Height of object, L_u = Length of object under water,

A = cross sectional area of object, g = Gravity

18.7 Hardness

Advanced

This simulation shows how a typical instrumented hardness tester works



Hardness is a measure of how easy or difficult it is to dent or scratch any material. If a big dent can be made with a small force, the material is "soft" (e.g. lead), and if even large force makes a small dent in a material, it is "hard" (e.g. diamond). Generally indenters are made of diamond so that they can indent most other materials without getting damaged themselves.

There are a number of different measures of hardness through indentation. There are also a number of different shape indenters. The most common are the following: Vickers (4 sided pyramid), Berkovich (3 sided pyramid), Rockwell (conical with spherical tip).

The common factor of all measures of hardness is that they all involve the ratio of the force (in N or kg force) to the area of the indent made (in square metres). This means that hardness has the same units as pressure (Pascals). Since the numbers are quite large, hardness is usually quoted in GPa.

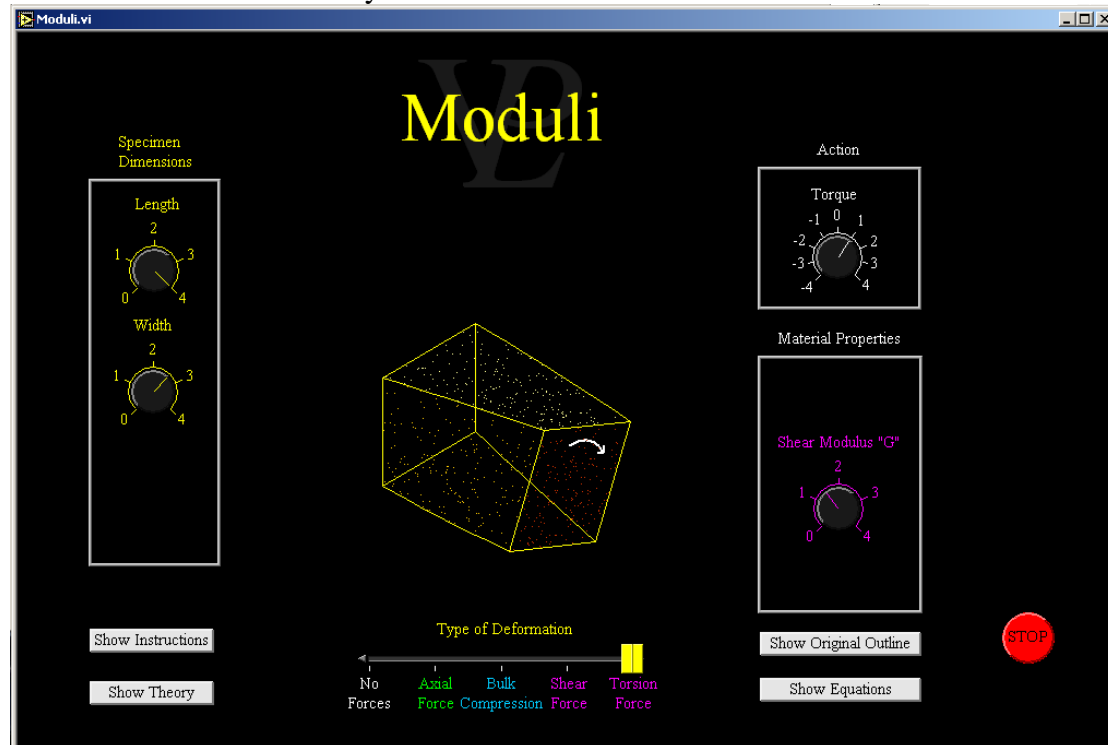
If the shape of the indenter is known accurately it is possible to calculate the area of contact by knowing how far the indenter has penetrated in to the material. Capacitance transducers or Linear Voltage Displacement Transducers can be used to measure the penetration depth and Piezoelectric Transducers or fine motor controlled stages can be used to apply the forces.

The area of the indent is approximately calculated from the residual depth of the indent (the depth at which the indenter lifts away from the material after the indent has been made). Vickers and Berkovich indenters are designed so that the area of contact is approximately 24.5 times the square of the depth.

18.8 Moduli

Advanced

This simulation shows how the deformation of materials depend on the applied forces and their moduli of elasticity.



Uniaxial Strain: When an object is acted upon by a uniaxial tensile or compressive force, it stretches or shrinks along that axis by an amount that is proportional to its original length, and inversely proportional to its cross sectional area and its "Elasticity Modulus" E . As a consequence of this stretching/shrinking, the object will normally contract/expand in its transverse dimensions. The ratio of the lateral strain to its longitudinal strain is a constant known as the "Poisson Ratio".

Bulk Compression: The "Bulk Modulus" K is a related constant that describes how the volume of a material will change when external pressure is applied to it. Volume will always decrease with increasing pressure.

Shear Strain: Shear strain occurs when a force is applied that is parallel to the cross sectional area of the specimen. The angle by which the material shears is inversely proportional to the "Shear Modulus" G and the cross sectional area, and proportional to the shear force.

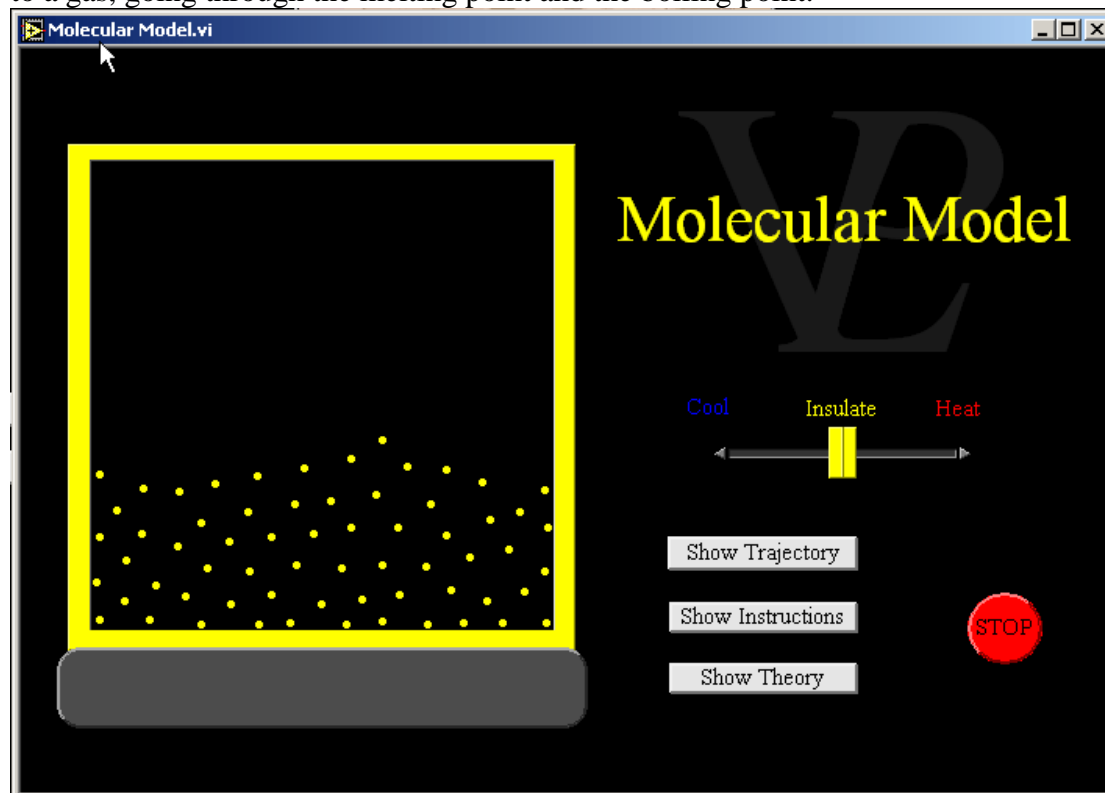
Torsional Strain: Torsional Strain is a special case of shear strain. The principle is the same except that the applied force is now a Torque, and a geometric factor J - the "Torsion Factor" - needs to be calculated. Generally the twist angle is inversely proportional to the cross sectional area and the Shear Modulus, and proportional to its length and the Torque applied.

There are equations which relate the different moduli to each other. In all cases a higher modulus represents a stiffer material, better able to resist deformation. In real life, deformations normally combine: shear strain and bending often go together, and bending results in a combination of tension and compression over different parts of the specimen.

18.9 Molecular Model

Advanced

Visualise the motion of molecules as the phase changes from solid to liquid and then to a gas, going through the melting point and the boiling point.



In a solid, any energy supplied to it causes the molecules to oscillate more wildly about their mean position. Once the molecules have enough energy to break their bonds with their neighbouring molecules, they are free to move away from their original place. This is what happens when a solid melts.

Once the entire solid has melted, any further energy supplied to the molecules causes them to move around faster.

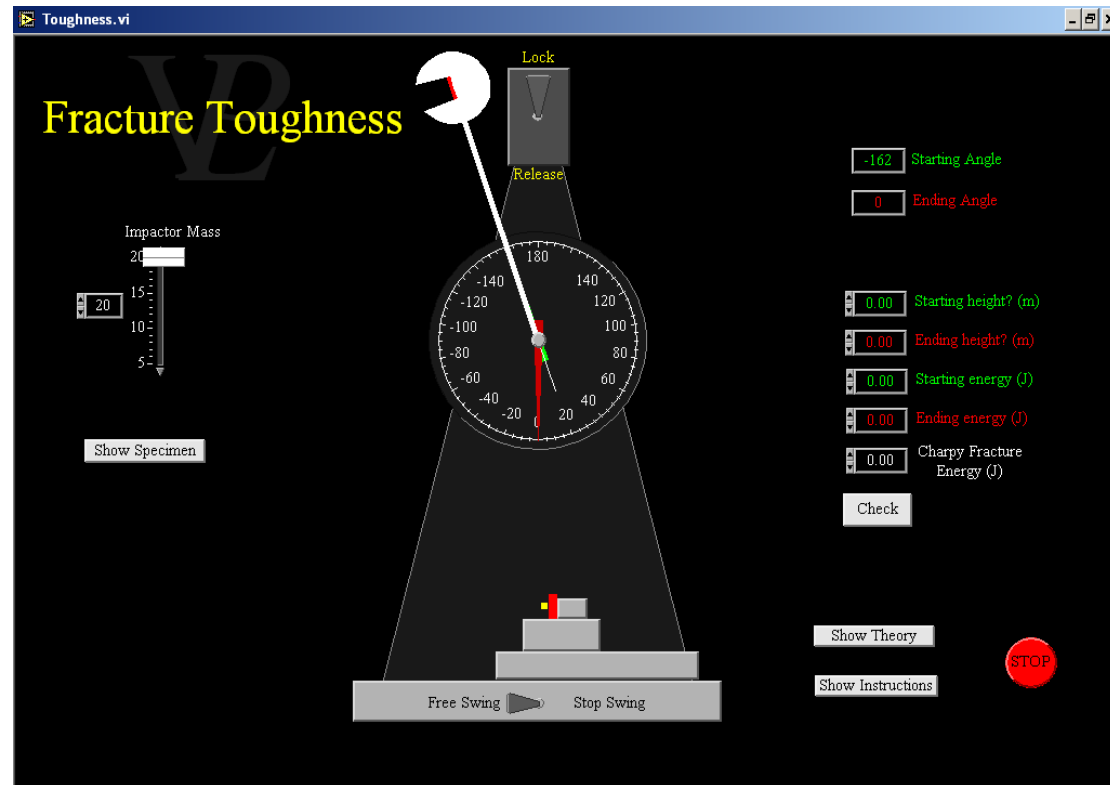
If enough energy is supplied to the liquid, the molecules will eventually get enough energy to break away from the surface of the liquid entirely, and so become a gas. This is called evaporation. Evaporation can actually happen at lower temperatures, but happens most furiously at the boiling point.

When the gas is allowed to cool down sufficiently, it will start to condense back into a liquid, and then ultimately back into a solid.

18.10 Toughness

Advanced

This simulation shows how a Charpy test is used to calculate the toughness of a material specimen by looking at the energy required to break it.



The toughness of a material is a measure of how difficult it is to fracture or crack it. Toughness is the opposite of brittleness. Before materials can be used for many applications, it is necessary to know how tough they are, because this determines how they will respond to an impact. There are a number of different measures of toughness (with different units!). The measurement method illustrated in this simulation is the "Charpy Test". The Charpy Value has units of energy (Joules).

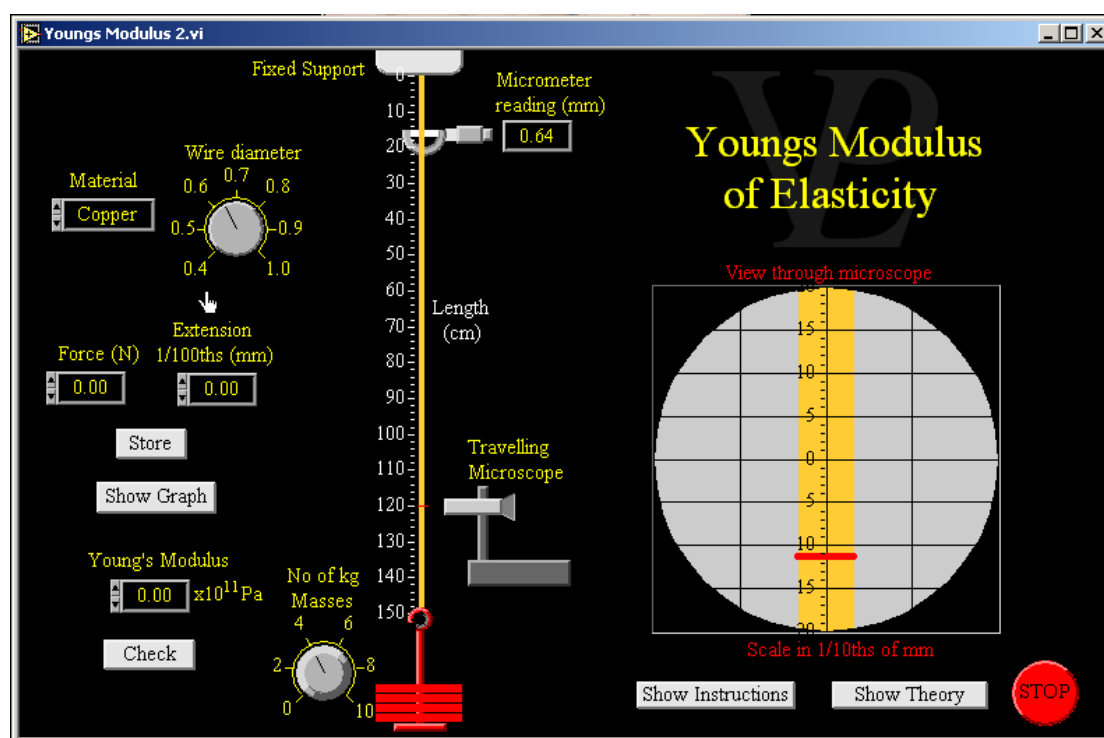
In simple terms, the technique measures the energy stolen from the oscillation of a heavy pendulum when it strikes a specially prepared sample of material. The initial energy in the oscillation is calculated from the gravitational potential energy at the start (the height from which the pendulum is dropped). The final energy of the pendulum is measured from the maximum height to which the pendulum will rise after having broken the material specimen at the bottom of the swing (in practice, both of these are calculate from angles).

The toughness of materials is affected by temperature. At lower temperatures materials tend to become more brittle; at higher temperatures materials tend to become more ductile (and harder to fracture). The change is somewhat gradual, but the centre of the temperature range at which the change is noted is called the Ductile-Brittle Transition Temperature (DBTT)

18.11 Young's Modulus

Advanced

This is a fairly sophisticated simulation which mimics a travelling microscope looking at the extension of wires of different material and diameter as they are loaded. Measurements are recorded, a graph is plotted and from that the Young's Modulus can be calculated and compared with the values stored in the computer.



The Young's modulus or modulus of elasticity (E) is defined as the stress divided by the strain. $E = \text{Stress} / \text{Strain}$

The stress is the weight hung on the wire divided by the cross-sectional area of the wire. $\text{Stress} = \text{Force} / \text{Cross-sectional area}$

The strain is the extension of the wire divided by its original length (120 cm).

$\text{Strain} = \text{extension} / \text{original length}$

Combining these equations together we get $E = (\text{Force} / \text{area}) (\text{extension} / \text{length})$

Rearranging this equation we get

$E = (\text{length} / \text{area}) (\text{Force} / \text{extension})$, or $E = (\text{length} / \text{area}) \text{gradient}$.

CHAPTER 19

MEASUREMENTS

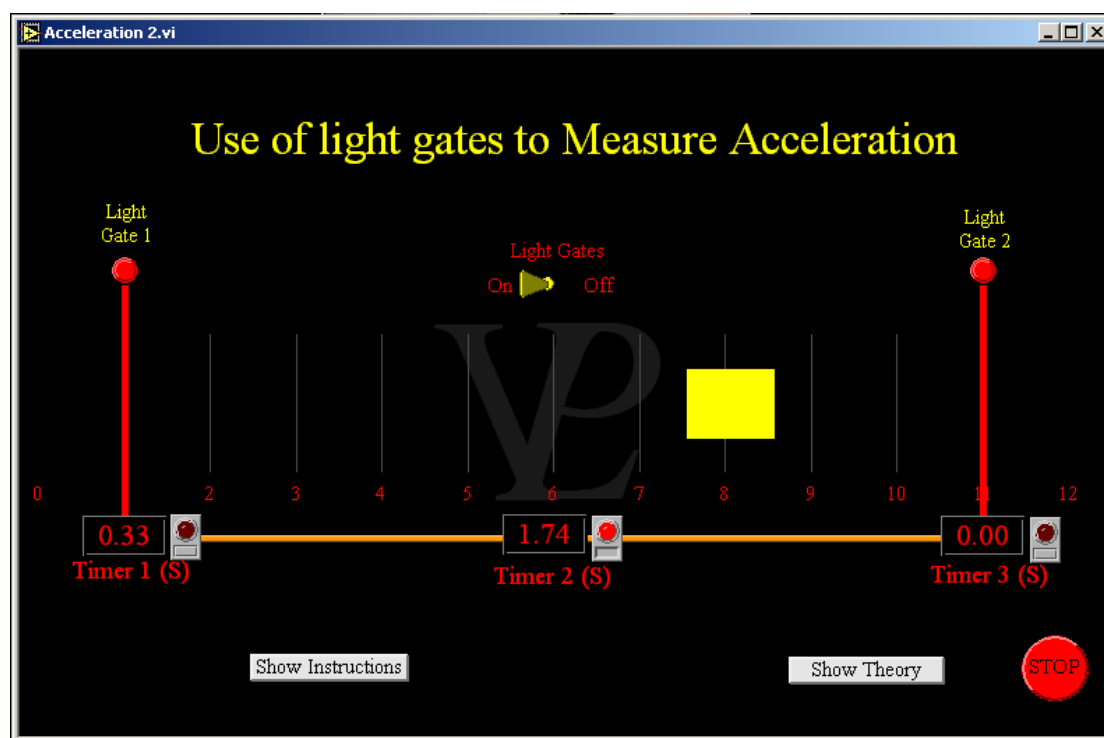


“All science is measurement, but not all measurement is science”
Why do we need to measure things?

19.1 Acceleration Measurements

Basic

This simple simulation tests the pupil's ability to calculate the acceleration of a trolley that goes past two light gates connected to three clocks. The pupils calculated answers can be checked against the computer calculated value.



Acceleration is defined as the change of velocity with time. Mathematically we can say $\text{Acceleration} = (V_{\text{final}} - V_{\text{initial}}) / \text{Elapsed time}$, simplified as $a = (V_f - V_i) / t_2$

To make the calculations easy the vehicle is 1 m long and it will block the beam while its whole length goes past the beam. So the velocity in each case will be $1\text{m}/\text{time}$, where t is the time measured by that stop-clock. So

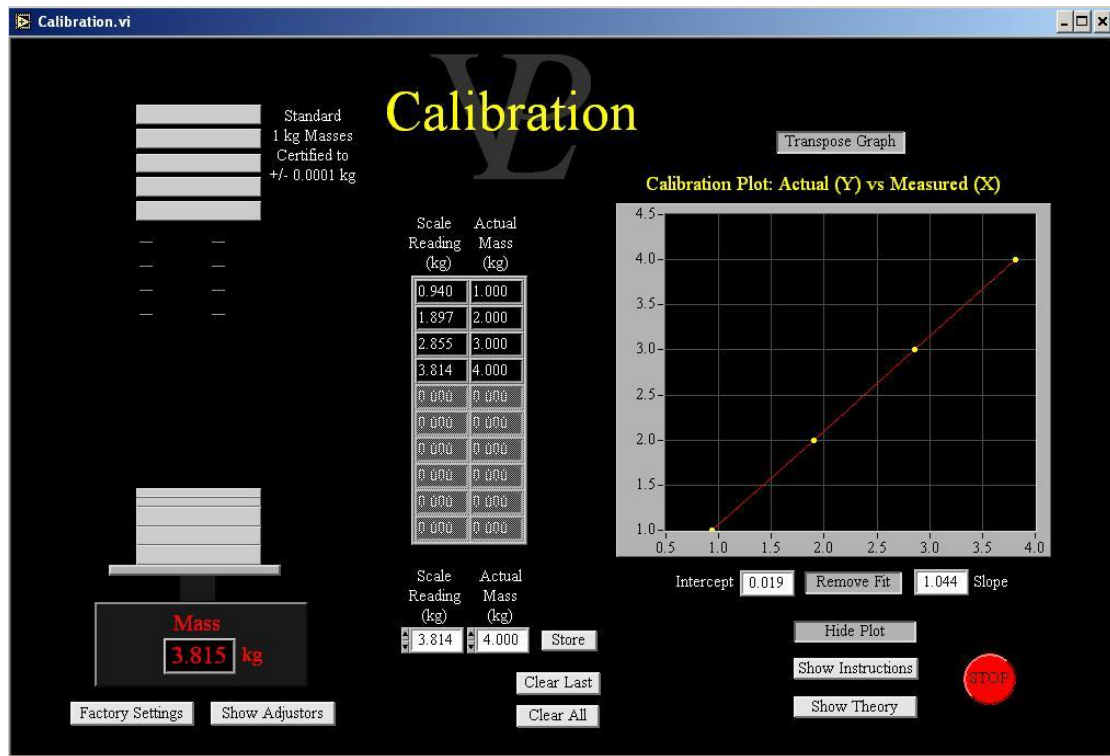
$$V_i = 1/t_1 \text{ and } V_f = 1/t_3$$

The central clock measures the time interval between breaking light beam 1 and light beam 2, and therefore the time taken to change from velocity 1 to velocity 2. That elapsed time is t_2 .

The acceleration is therefore given by $a = ((1/t_3) - (1/t_1)) / t_2$, or $a = (t_1 - t_3) / (t_1 t_2 t_3)$.

19.2 Calibration

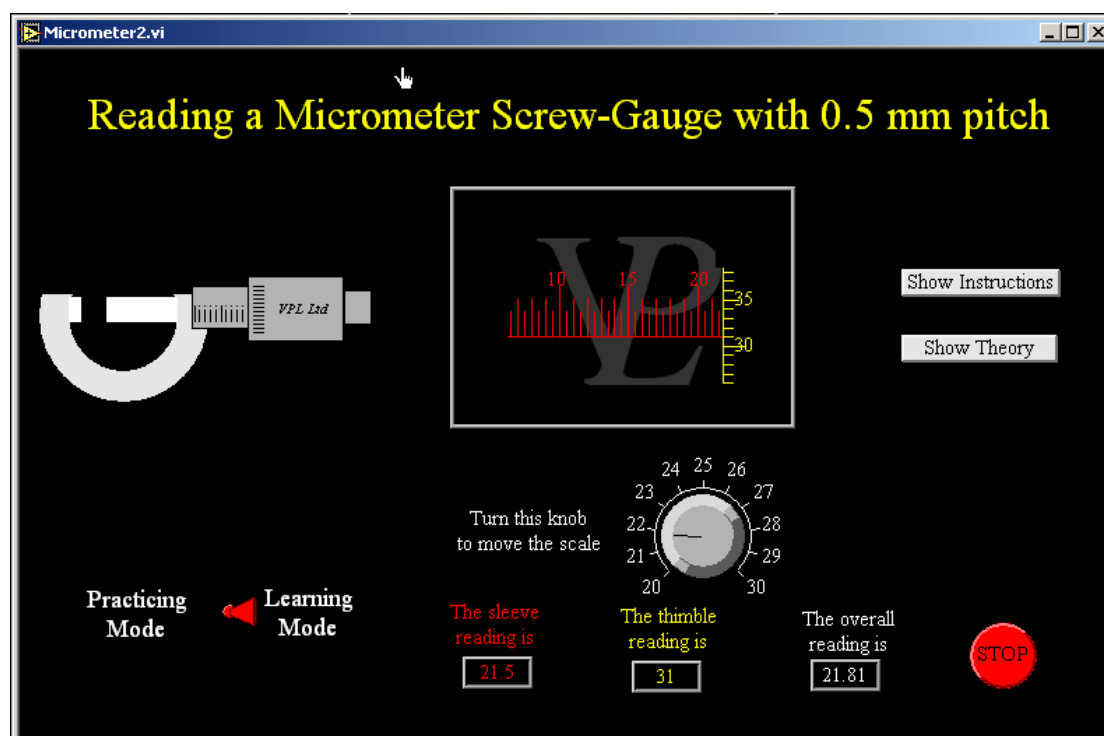
Basic



19.3 Micrometer

Basic

This simulation illustrates the operation of a Micrometer. It runs in two modes: learning and practicing. The pupil can compare his reading with that of the computer in order to check that he has read it correctly.



A Micrometer is used to measure the external dimensions of objects which are about 3 cm or smaller. It looks a little like a G Clamp, but should never be used like one.

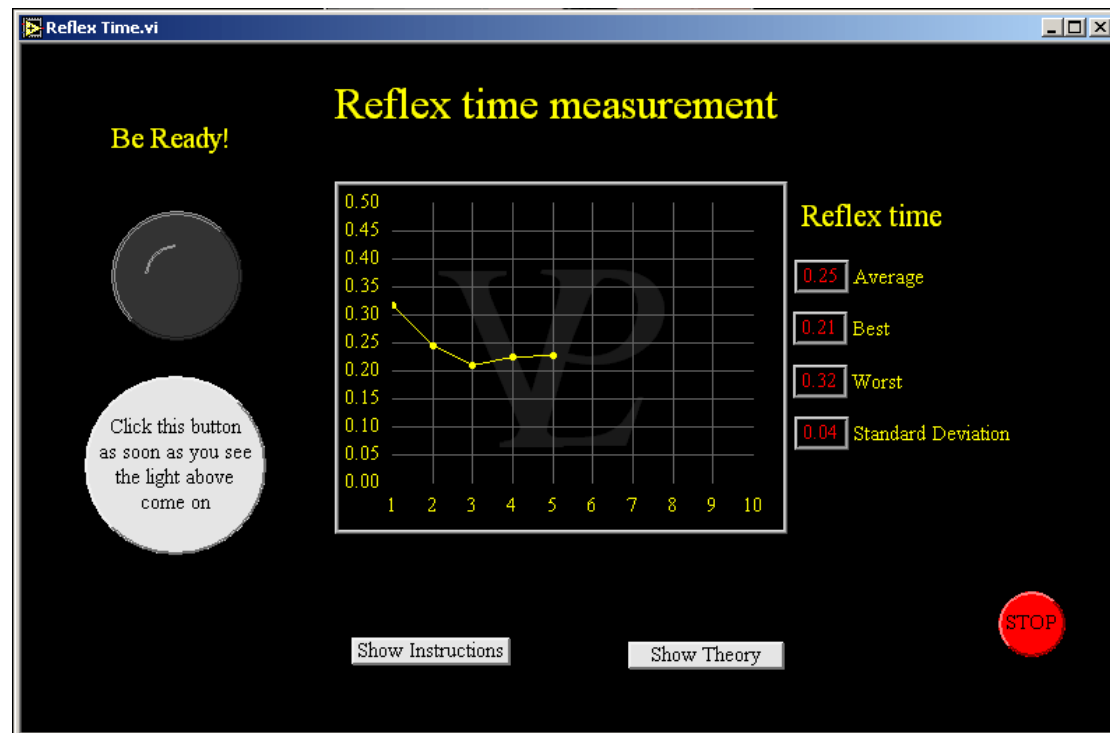
The object to be measured should be placed in the gap between the anvil and the spindle. At the opposite end there is a little ratchet with which the thimble should be rotated. The ratchet ensures that the thread is not over-tightened.

The sleeve has a ruler engraved on it which reads to the nearest half millimetre. The thimble also has a 'circular ruler' engraved on it. This reads to the nearest 1/100th of a millimetre.

19.4 Reflex time

Basic

This program offers the user the opportunity to test his reflex time 10 times. It plots out the response times and calculates the average. It tells the user how far his car would have travelled on the motorway before he even reacted!



There is nothing magic behind this simulation.

What is really interesting is what is going on behind your eyes. It takes a while for your brain to receive the message from your eyes, and then it also takes a while for your brain to send the message down to your fingers.

0.2 seconds: Very good

0.3 seconds: Average

0.4 seconds: hmm

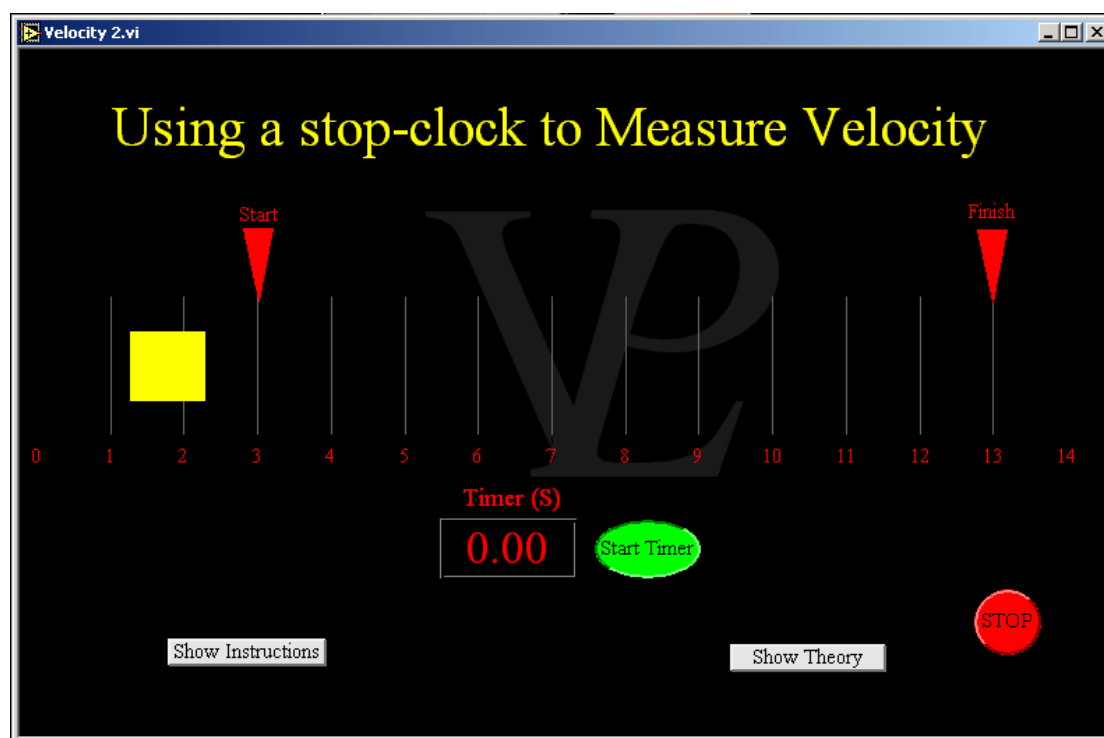
0.5 seconds or above: You've got a problem (or you are asleep!)

Many things can slow down your reflexes including tiredness, illness and drugs.

19.5 Velocity Measurements

Basic

This simple simulation tests the pupil's ability to calculate the velocity of a trolley that goes past two light gates connected to a clock. The calculated result can be checked against the computer calculated value.



The velocity of an object is defined as the distance it travels divided by the time it takes to travel that distance. $\text{Velocity} = \text{distance}/\text{time}$.

The distances are often fairly easy to measure accurately because we can take a long time about it and do it carefully. However, the time can sometimes be difficult because we have a reflex or reaction time, the time that it takes us to react to something happening.

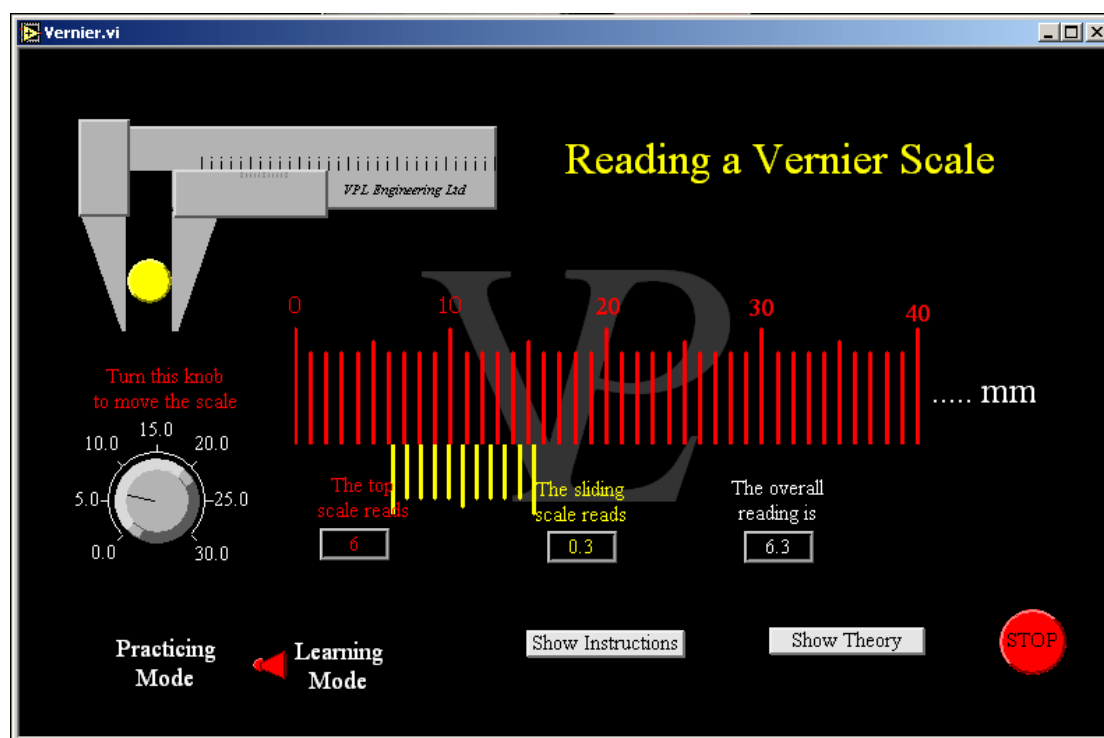
One way to try to reduce the error introduced by our reflex time is to try to make sure that the initial timing method is similar to the final timing mechanism. That way the errors at the start and end will be similar and tend to cancel out.

In this example we try to reduce errors due to reflex time by allowing the vehicle to start moving before starting the timer. In this way it is possible to anticipate the starting with the same degree of accuracy as we anticipate the ending time.

19.6 Vernier Callipers

Basic

This simulation illustrates the operation of a Vernier Calliper. It runs in two modes: learning and practicing. The pupil can compare his reading with that of the computer in order to check that he has read it correctly.



This instrument is called Vernier callipers (yes plural - like scissors). It is used to measure the dimensions of objects up to 15 cm in length.

The clever bit is the little scale that slides along. Its divisions are 9/10ths of the size of the main scale, look carefully to convince yourself.

To measure something:

1 - Count along the red (main) scale until you reach the first line of the yellow (sliding scale). That gives you the integer number of millimetres.

2 - Count along the yellow (sliding) scale starting ZERO, one, two... until you find the line that best lines up with the line on the red scale.

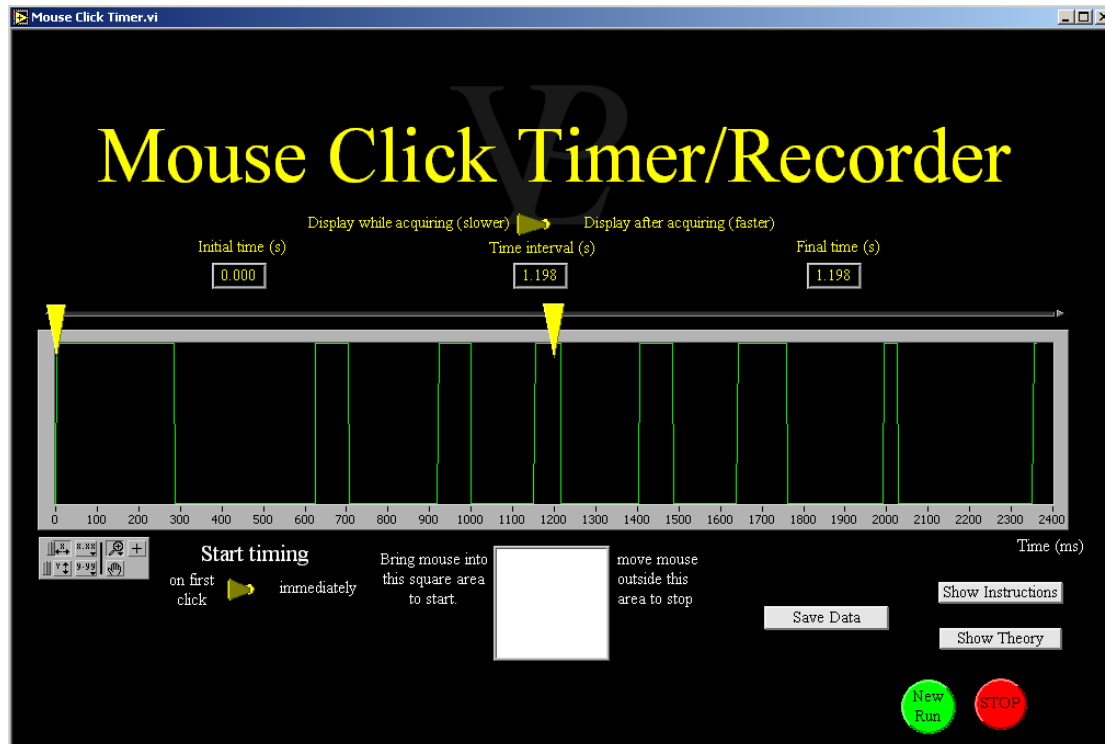
The number of the yellow (sliding) line that best lines up is the number of 1/10ths of millimetres.

Real Vernier callipers can be used to measure external and internal diameters and flats, and also the depth of holes too.

19.7 Mouse Click Timer

Advanced

This program records the times at which the mouse buttons are clicked and produces a graphical output of the record. The data can then be saved to a file for separate analysis. This program was produced for use with a modified mouse; where the buttons have been removed and replaced with either Light Dependent Resistors or Reed Switches. The system can then be used as a low cost 'light gates' system or magnet operated timer.



Build your own Low Cost Light Gates (or Reed Switch timer) System

Light gates can be used to time events with far better precision than a human can achieve. If a normal computer mouse is 'sacrificed' it is possible to convert it into a low cost light gate system.

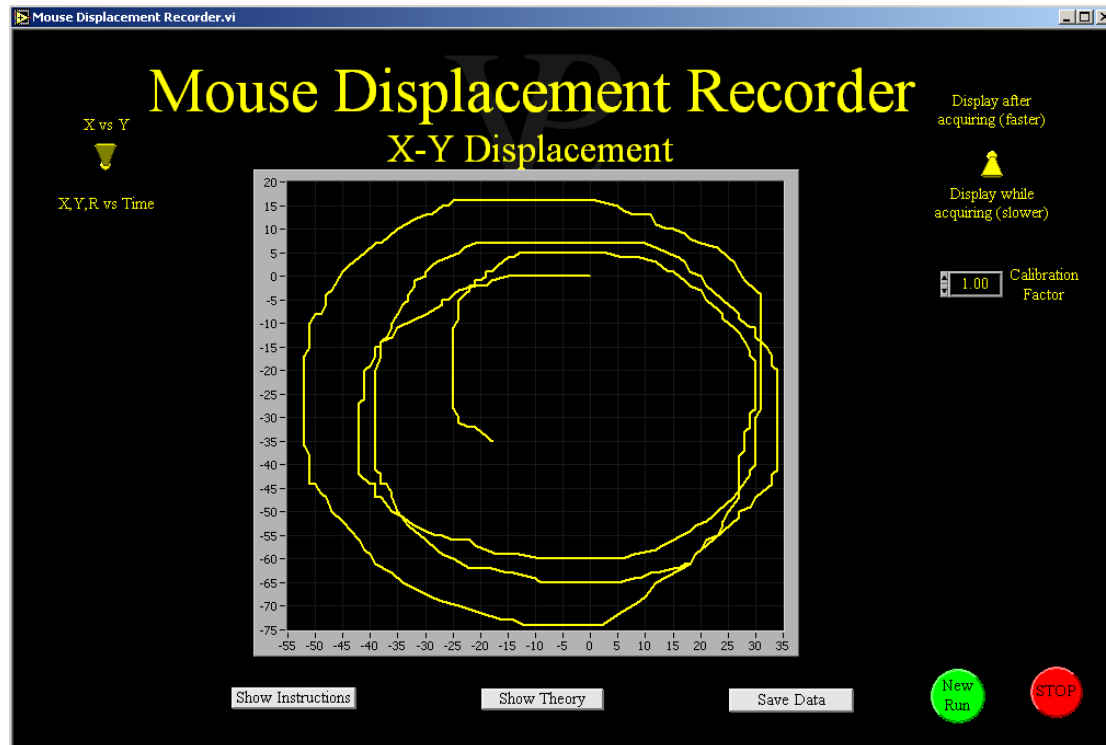
To achieve this you need to de-solder the two microswitches that are operated by the mouse buttons. In their place solder a pair of leads leading to light dependent resistors. In this way the 'mouse buttons' can be operated by light beams being broken. (When light shines on the LDRs, their resistance drops dramatically, and the computer interprets this to be a mouse click).

The timing of a modified mouse will not be perfect as it is complicated by delays in the computer reading the mouse, and on the exact timing of the loop in this computer program. Nevertheless, it should be possible to obtain timing results with timing errors which are in the region of 10 ms or less.

19.8 Mouse Displacement recorder

Advanced

This program can be used as a cheap position data-logger! It records both X and Y and displays them as an X-Y graph or as a function of time. It is possible to export the data to an external file for further analysis.



This program works best with a cordless optical mouse, although it is possible to get it to work with a normal corded mouse provided the cord is long enough to reach the range you want to record.

Note that it is possible to install two mice at the same time (or if working from a laptop computer, you can use the touch pad and an optical mouse).

The important thing is to ensure that the mouse stays in close enough proximity to a flat surface so that it can remain active throughout the recording period.

If the mouse is being towed along by a trolley this should be quite easy to achieve, but if the mouse is swinging from a pendulum it may be necessary to place a vertical surface parallel to the plane of the pendulum and make the pendulum slide against it as the pendulum swings.

The range of travel of the mouse can be changed by adjusting its sensitivity (You can change the sensitivity, range and performance of the mouse by going through Start - Control panel - Pointer options - Pointer speed (drag it to the left - minimum) and Deselect "enhance pointer precision").

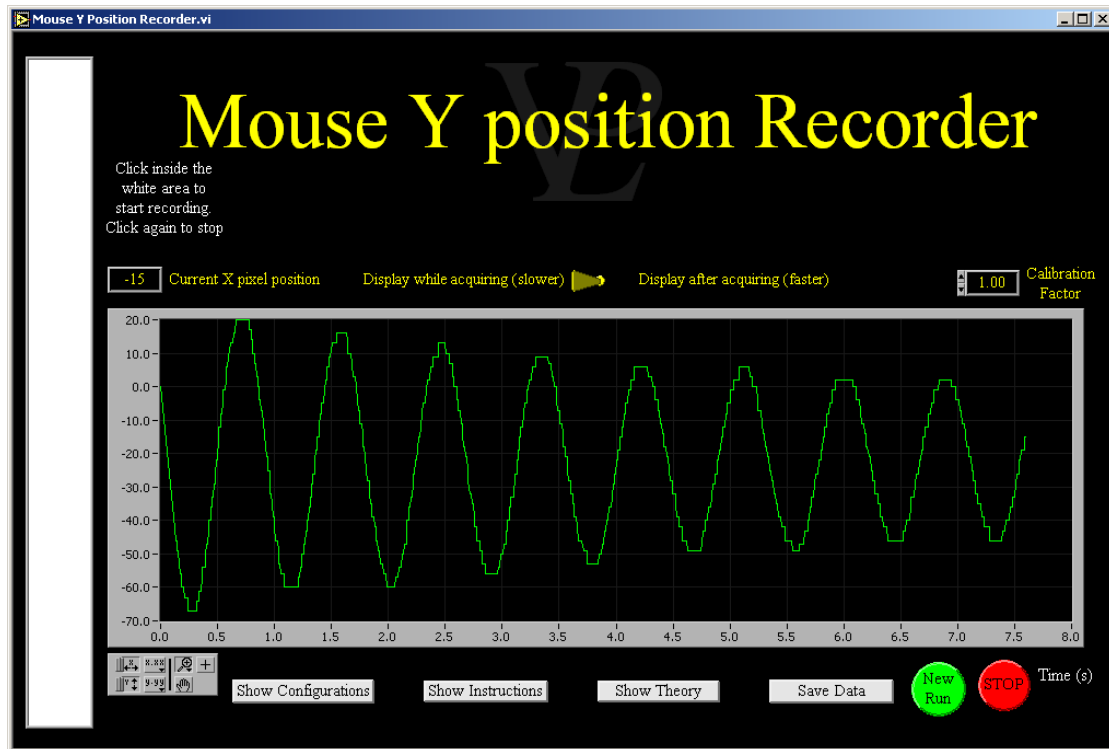
Note that there is a tradeoff between range and resolution. There are approximately 1000 bits of resolution in X and 650 in Y. If you reduce the mouse sensitivity to a minimum, the range will be large, but the minimum step size will also be larger. Conversely, if you want maximum resolution, increase the mouse sensitivity to a maximum, but note that the maximum range will be reduced.

With a few trials it is possible to find a suitable compromise. Enjoy!

19.10&11 Mouse X position recorder

Advanced

These two programs record and display the position of the X or Y coordinates of the mouse. They were written to be used as low cost data loggers of the position encoders of a ball driven mouse. The data recorded can be exported to a file to be analysed by the user in the form of a spreadsheet. Instructions are given on how to modify the mouse.



Build your own Low Cost Data Logger!

If a normal computer mouse (with a tracking ball) is 'sacrificed' it is possible to convert it into a low cost position, force or angle data logger.

To achieve this you need to remove the ball and open up the mouse so that the spindle of the X or Y rotating wheel is exposed. Loop a thread around the spindle and add a small weight to tension the thread as shown in one of the diagrams. It should then be possible to pull the other end of the thread out and it should pull itself back under the action of the small weight.

You can now attach the free end of the thread to the bob of a pendulum (for example) and use this program to monitor the position of the bob as it swings back and forth. You could also attach a heavier weight to the end of the thread and let it fall under gravity. The graph should record its acceleration. (Note that the thread around the spindle will provide a little friction)

Investigate how it could be used to measure force or angle. Happy experimenting!

CHAPTER 20

MEASUREMENT UNCERTAINTY

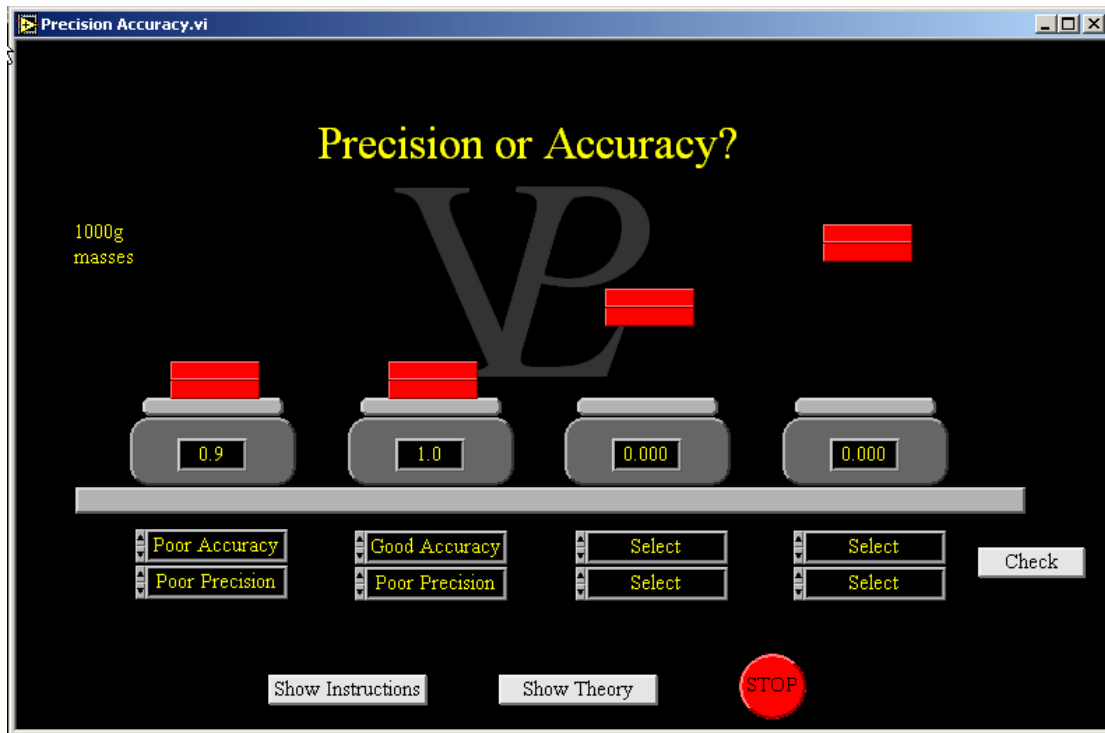


All measurements have some degree of uncertainty in them.
How do uncertainties affect science?

20.1 Precision Accuracy

Advanced

This simulation teaches the difference between precision and accuracy in order to help in the understanding of uncertainty.



Precision is the number of significant figures to which a quantity is measured. This is sometimes also referred to as 'sensitivity' or 'resolution'.

Accuracy is how close the measurement is to the actual true value it should be.

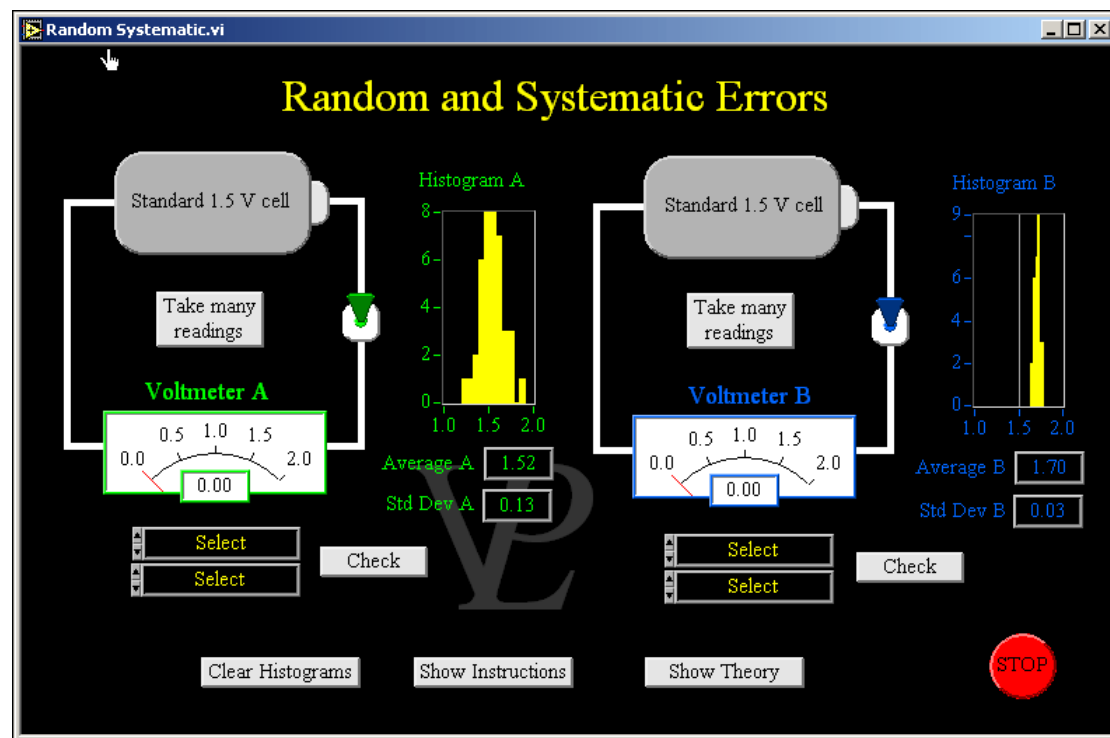
There are other factors that determine how useful a measurement result actually is, such as 'repeatability'; how much the value varies when the measurement is repeated.

These ideas lead toward uncertainty in measurement. Find out more about it using the other simulations in this chapter.

20.2 Random Systematic

Advanced

This simulation shows how measurement errors can be introduced either by random sources or by systematic faults with the equipment. It shows how histograms of repeat measurements of a known quantity can be used to identify the magnitude of each of the error types.



Random errors are those that cause the measurement value to change nearly every time a fresh measurement is made. The causes can be many; friction, vibration, electromagnetic interference...

The best way to reduce the effect of random errors is to take many repeat measurements and average the result. The Standard Deviation of the measurement is a measure of the random error in a measurement.

Systematic errors are those that cause the measurement to be consistently wrong by the same amount. For example a voltmeter may always read 1 Volt lower than it should.

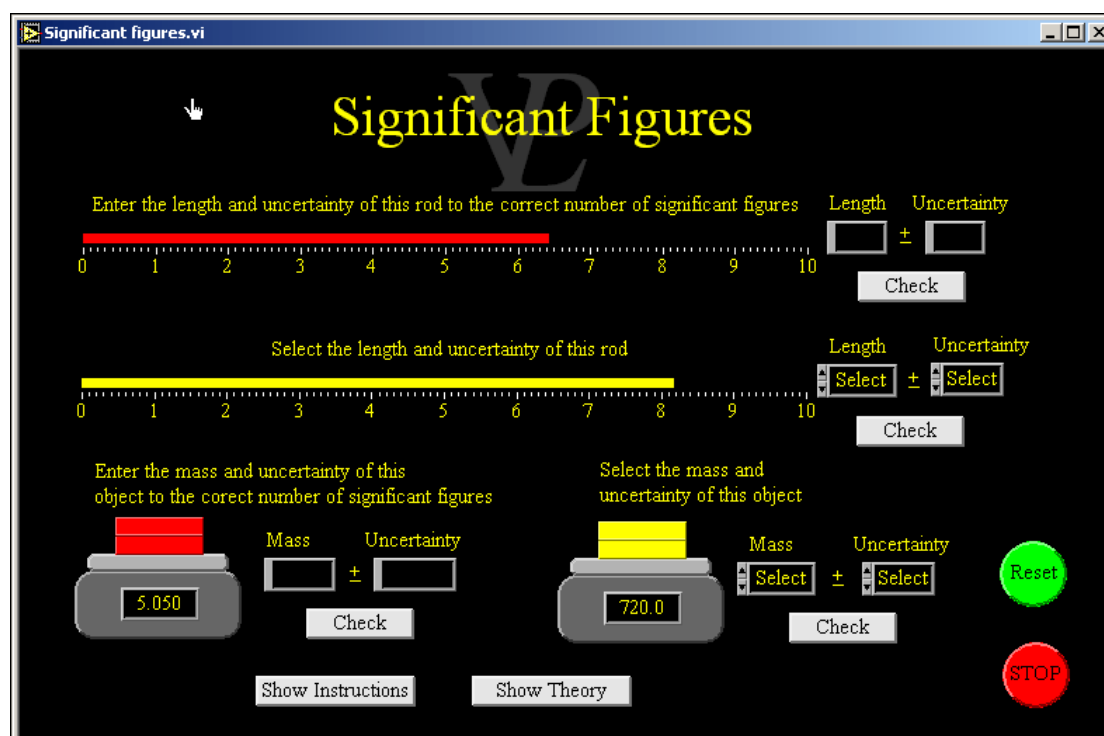
Systematic errors cannot be corrected by taking many repeat measurements and averaging, because each repeat measurement will be consistently wrong by the same amount, and so the average will also be wrong. Systematic errors must be corrected by adding or subtracting an offset and by multiplying by a scaling factor as necessary.

Often there is a combination of random and systematic errors in an instrument. The random part can be reduced by averaging, and the systematic by offset and scaling.

20.3 Significant Figures

Advanced

This simulation teaches the user to justify the number of significant figures used when recording a measurement. The precision is limited either by random variability or by limitations in the resolution of the scale or equipment used.



The number of figures with which a number is recorded is very significant. Mathematically we say $7.0 = 7$ but in physics this is no longer true!

7.0 means that we know it is not 6.9 or 7.1, whereas 7 means we only know it is not 6 or 8. So recording 7.0 represents better, more precise knowledge than 7 that is why we write it down with more significant figures.

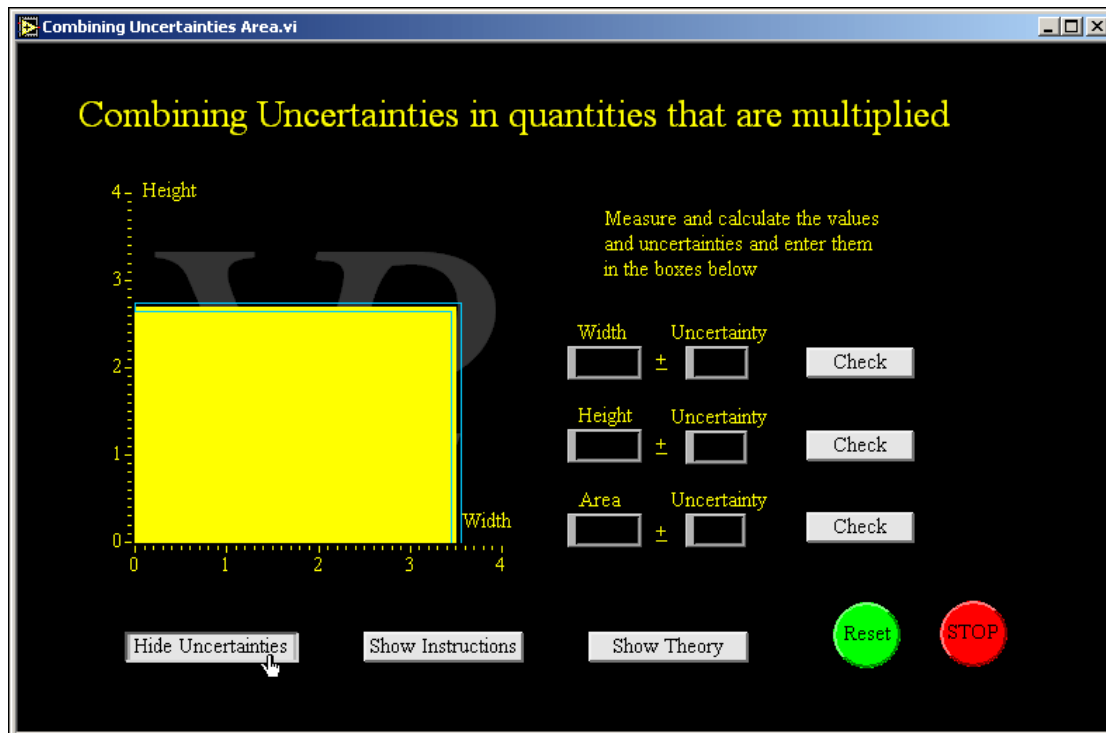
Generally the uncertainty in the measurement or knowledge of a quantity is + or - half the last recorded place. For example if an instrument gives a stable reading of 37.3 the uncertainty is 0.05 (the instrument is rounding to the nearest 0.1). When reading a ruler we generally round to the nearest millimetre, so the uncertainty is 0.5 mm.

When a reading is not stable it becomes more difficult! It is necessary to see what the variation range is, and what the mean of the variation is. The uncertainty will generally be half the total range.

20.4 Uncertainty in Area

Advanced

This simulation teaches how uncertainties in linear dimensions combine to give an overall uncertainty in the calculation of an area.



Frequently it is necessary to calculate the uncertainty in a quantity that is not measured directly, but is calculated from two or more other quantities. For example an area calculated from length and height.

To calculate the uncertainty of the area it is necessary to add the fractional uncertainties together and multiply them by the calculated area.

Fractional uncertainty in Height = (h/H)

Fractional uncertainty in Width = (w/W)

Total fractional uncertainty = $(h/H) + (w/W)$

Total uncertainty = $W \times H ((h/H) + (w/W))$

Where W = Width, w = uncertainty in width

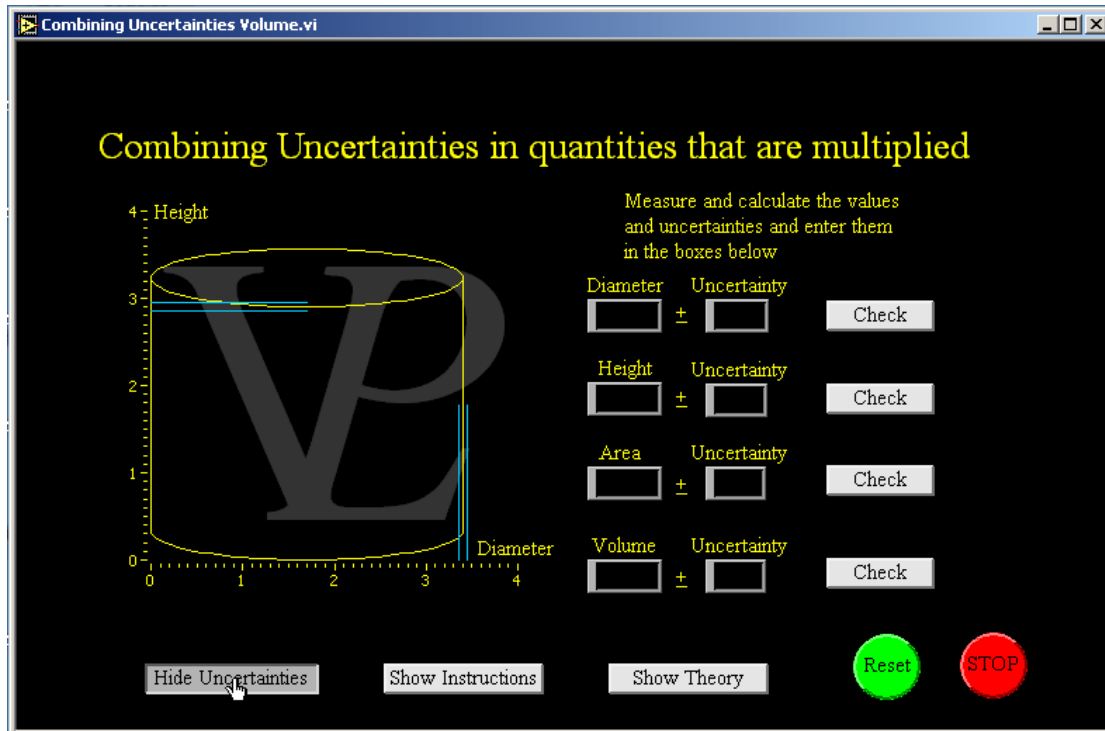
H = Height, h = uncertainty in height

Another way to calculate the total uncertainty is to add the individual percentage uncertainties first and then calculate the percentage of the final result. Mathematically this is equivalent.

20.5 Uncertainty in Volume

Advanced

This simulation teaches how uncertainties in length and diameter combine to give an overall uncertainty in the calculation of a volume



Before trying to understand this theory, make sure you have understood the "Combining Uncertainties Area" simulation. The volume of a cylinder is calculated from its diameter and its height.

The area is πr^2 or $\pi \times (D/2)^2 = (\pi/4) D D$. Notice that the uncertainty in the diameter contributes twice to the uncertainty of the area because the diameter is squared. So the overall fractional uncertainty is the sum of the fractional uncertainty in height and twice the fractional uncertainty in volume. To get the overall uncertainty in volume we multiply the volume by the overall fractional uncertainty.

Fractional uncertainty in Height = (h/H)

Fractional uncertainty in Width = (d/D)

Fractional uncertainty in Area = $(d/D) 2$

Total fractional uncertainty = $(h/H) + 2 (d/D)$

Total uncertainty = $H \times (\pi/4) \times D^2 ((h/H)+2(d/D))$

Where D = Diameter, d = uncertainty in D , H = Height, h = uncertainty in H

Another way to calculate the total uncertainty is to add the individual percentage uncertainties first and then calculate the percentage of the final result. Mathematically this is equivalent.

Note: Sometimes it is necessary to calculate the uncertainties first before being able to decide the correct number of decimal places to which a quantity should be recorded. Generally uncertainties are rounded to the nearest significant figure.

CHAPTER 21

OPTICS

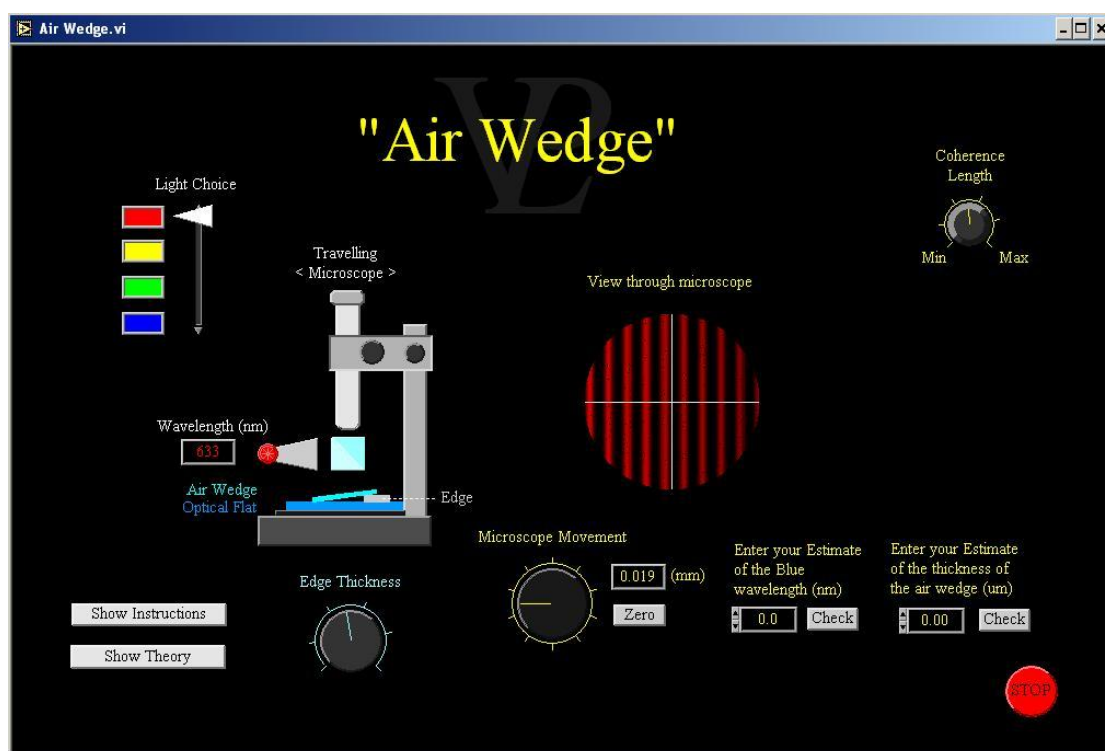


Lenses are the main components of many optical instruments.
What do they do, and how do they do it?

21.1 Air Wedge

Advanced

See how parallel interference fringes are produced by a very narrow wedge of air between two optical flats. See how the coherence length of the source affects the fringe contrast.



To understand the air wedge it is necessary to be familiar with the principles of constructive and destructive interference in waves and the concept of optical path difference.

When two glass slides are superimposed on each other but trapping a very thin piece of foil on one side, light from above that reflects from the top of the bottom slide will interfere with light that reflects from the bottom of the top piece of glass.

When twice the thickness of the air gap is a multiple of the wavelength of the light used, a dark destructive interference fringe will be formed. (remember that there is a 180 degree phase change on reflecting from a higher refractive index surface, but not when reflecting of an interface with a lower refractive index).

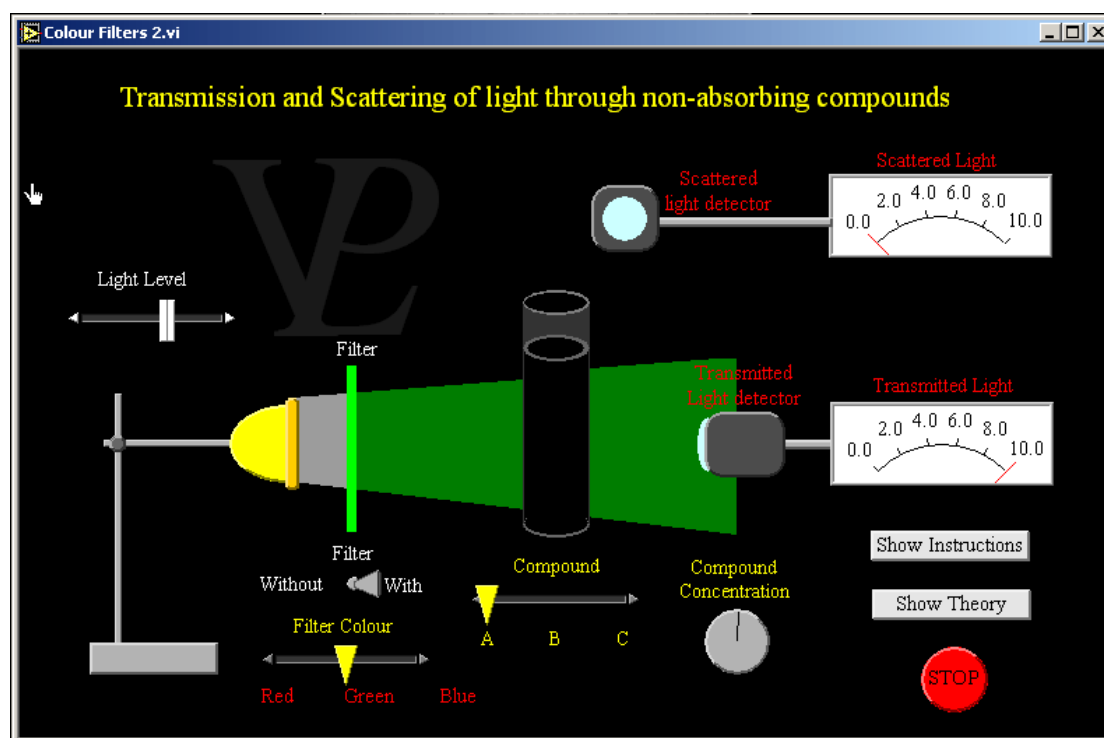
When twice the gap is $(n+1/2)$ times the wavelength, then a bright fringe will be seen.

Counting the fringes is a way of measuring the thickness of very thin foils. It can also be used as a way of comparing wavelengths.

21.2 Colour Filters

Advanced

This simulation shows how colour filters may be used to study and measure the scattering and transmission of coloured light from various compounds. The scattering is a measure of the concentration of the compounds.



Some compounds absorb light, others do not. But even if they do not absorb light, they can still reduce the amount of light they transmit by scattering part of the original light. They can absorb it, and then re-emit it in another direction.

The amount of light scattered depends on the concentration of the compound doing the scattering. The colour that is scattered depends on the compound, on the difference in electronic energy levels of the atoms making up the gas.

Generally the transmitted light tends to be of different colour from the scattered light. For example, if blue is scattered, then orange light is transmitted, hence the colour of sunsets. (white - blue = orange, white - green = pink, white - red = light blue.)

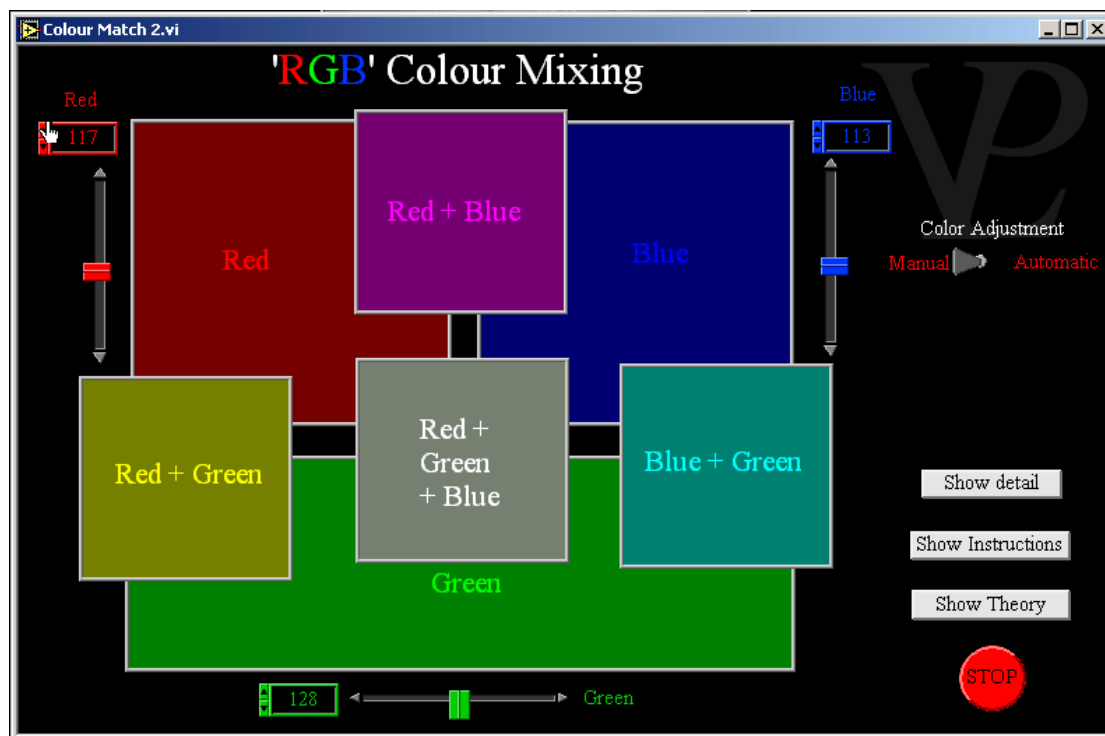
Notice that a compound that only scatters one colour allows the other colours to pass through (it does not scatter the others). If you shine red light on something that scatters blue, nothing is scattered and the light passes straight through.

If you know what colour your compound scatters, and you are trying to measure its concentration, then it is best to filter the light to that precise wavelength. This reduces the noise on the signal detected by cutting out the background light.

21.3 Colour Match

Basic

This simulation shows how Red, Green and Blue (RGB) combine to form all the colours possible on a monitor. If a good magnifying glass is used, the colour pixels on the monitor can be seen, otherwise select 'show detail' to see an enlarged part of the screen.



Although the eye can see all the visible colours of the spectrum from red to violet, what is actually going on in the eye and brain processing is different from what you might expect.

The eye only detects three primary colours; red, green and blue. It is most sensitive to green, which is in the middle of the visible spectrum. When the eye sees other colours like say yellow, it is actually seeing roughly equal amounts of red and green.

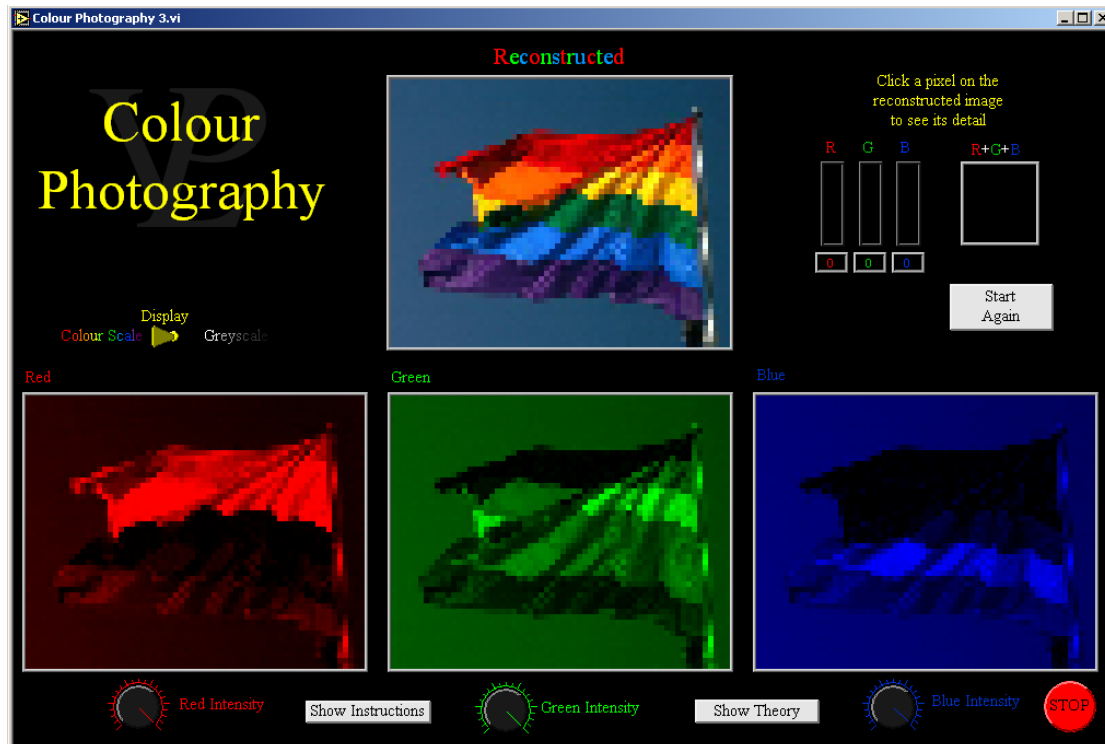
When the eye detects a varying ratio of the three primary colours, the stimulus is converted in the brain to give a perception of colours.

If you have a fairly high power magnifying glass, take a look at the different parts of the screen. You may be surprised at what you see!

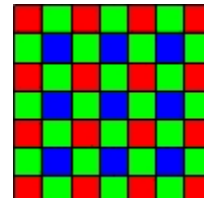
21.4 Colour Photography

Basic

This simulation shows how a digital colour camera works. It allows the user to reconstruct his image and adjust its final colour balance.



The raw image is filtered so that separate Red, Green and Blue images can be captured. Historically this can be done with beam-splitters followed by filters. In practice an array of small pixel sized filters such as that shown here is placed in front of each of the photosensitive pixels.



In this way three photographs can be captured; each records the light intensity of its particular colour.

Whereas in a black and white digital image each pixel has a single light intensity value, each pixel of a colour digital image has three values (red, green and blue).

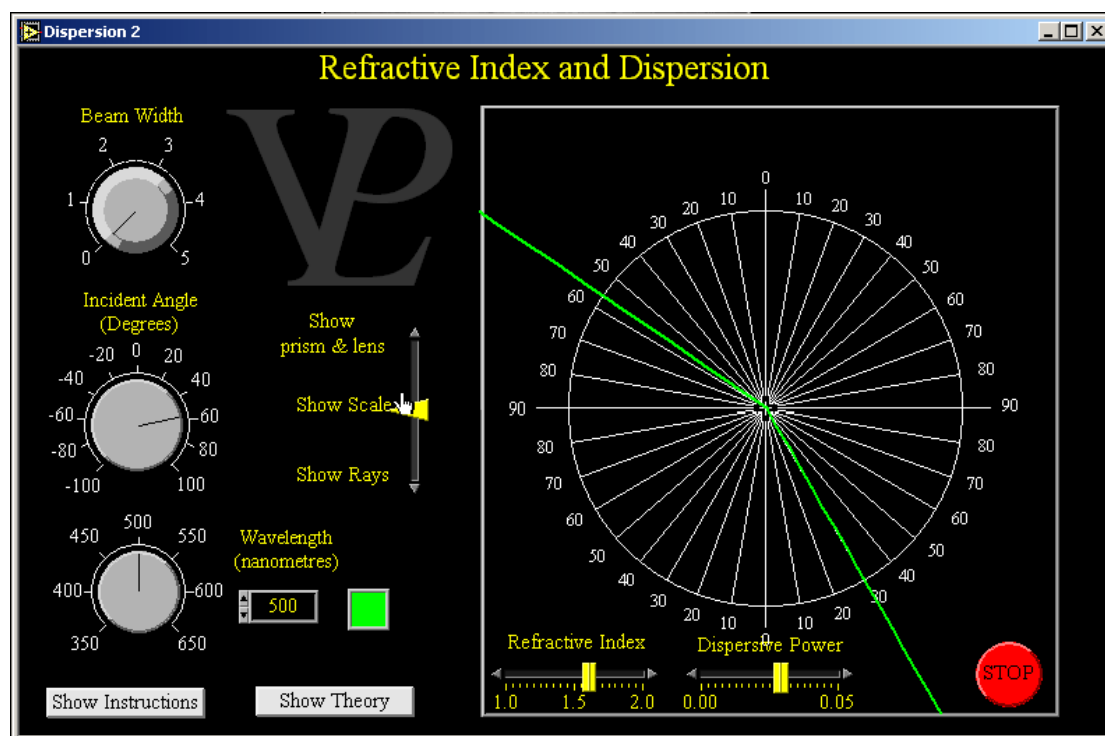
When it comes to reproducing the image, the screens of computers, cameras and video projectors all have red green and blue pixels which can be activated at different intensities. If the pixels are close enough together (so that they eye cannot resolve them as separate) the eye-brain interprets the combination of red-green-blue combination as a colour!

Once a digital colour image has been captured it is possible to artificially enhance or reduce the contributions from the red, green and blue to change the tone of the picture. Enhancing the red makes the image "warmer". Enhancing the blue makes it look 'colder'.

21.5 Dispersion

Basic

This simulation shows how lights of different colours are refracted by different amounts when they encounter a refractive index boundary, giving rise to Dispersion.



There is a separate simulation designed to deal with refraction. See that one before you study this one.

The refractive index of a medium is not the same for every colour. For this reason different colours get refracted by a different amount, this is called dispersion.

If the incident ray is a mixture of colours, they will disperse into a rainbow pattern called a "spectrum". Notice that the red is refracted by the least amount and violet the most.

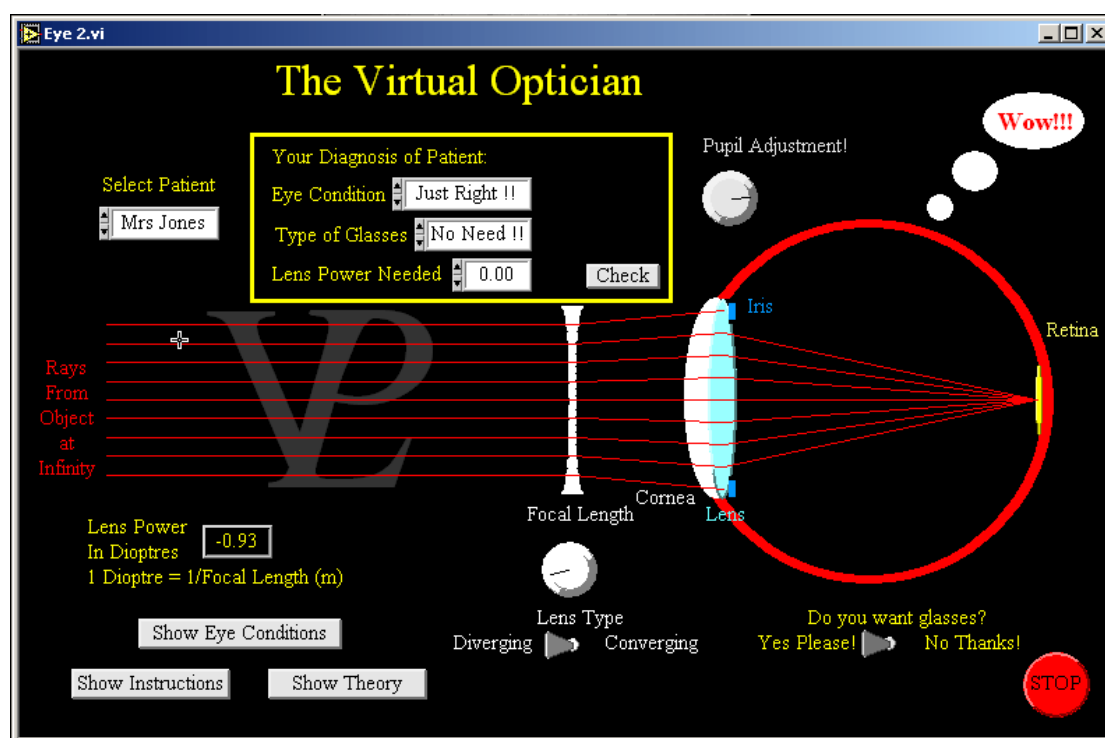
In a lens, dispersion produces different focii for different colours. This gives rise to "Chromatic Aberration". Cameras, telescopes and microscopes would produce terrible images if this chromatic aberration was not corrected.

Although different types of glass have different powers of dispersion, you cannot get glass with a zero power. This means that it is not possible to make a lens made of a single piece of glass which is free of chromatic aberration.. The only way round the problem is to make doublet or even triplet lenses out of two or three different types of glass with different dispersions, so that one corrects for the dispersion introduced by the other.

21.6 Eye

Basic

In this simulation, several patients with different eye conditions come to you to have their vision checked and, if necessary, corrected. You must diagnose the problem, choose the right type of lens, and adjust the power of the lens for perfect focussing on the retina.



When the muscles surrounding the lens in the eye are not able to focus the image on to the retina sufficiently well, things start to look blurry. It is time to visit the optician.

If object that are close up are OK, but those at a distance are blurry, we say the person is short sighted. If it is the other way round, we say he is long sighted. Normally people become long sighted as they get older. You can tell by the way they hold pieces of paper at arms length in order to read them.

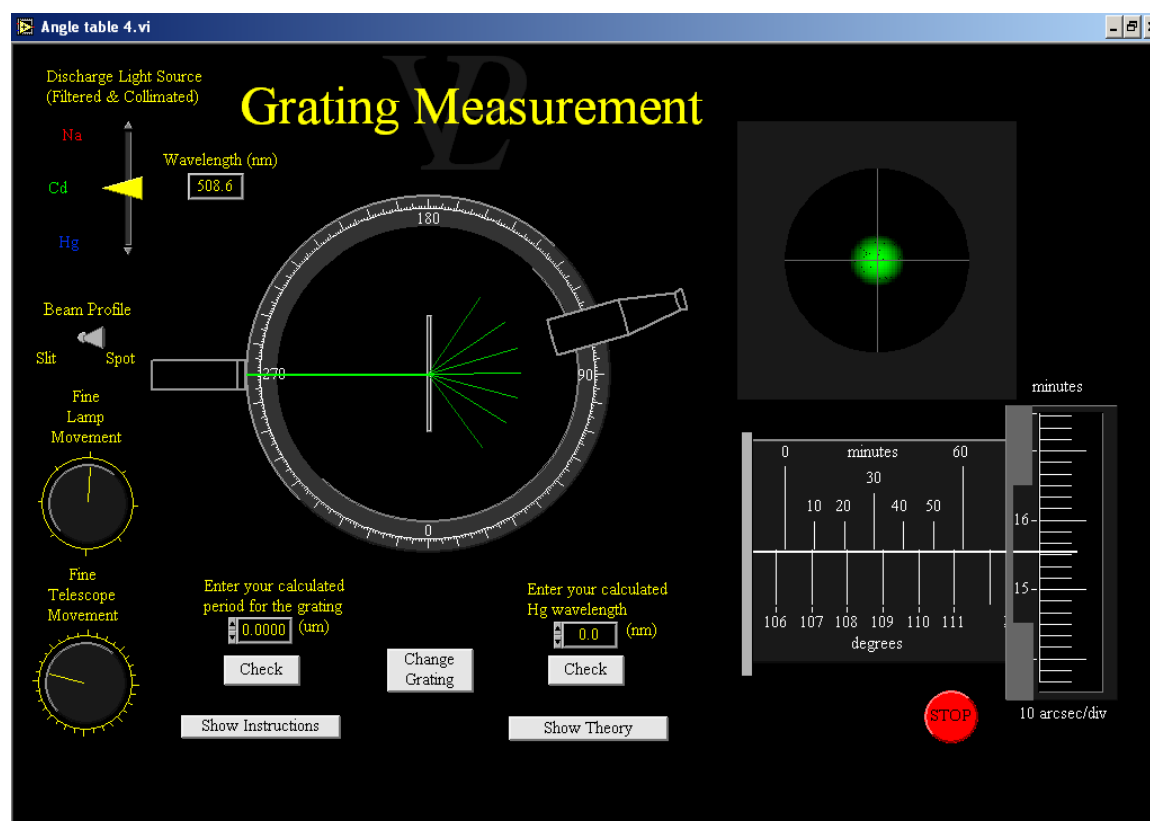
To correct for long-sightedness, you need a converging lens, and for short-sightedness you need a diverging lens. The power of lenses is measured in 'dioptres'. One dioptre is the power of a lens which has a focal length of 1 metre. ($\text{Power} = 1 / \text{focal length}$).

When glasses are not available, there are some simple steps you can take to make things a little better. Reading things in brighter light can help because it makes the pupil contract tightly; this makes the eye approximate to a pin-hole camera which needs no focussing. Even when a person needs glasses fairly badly, if he looks through a hole which is about 1 mm in diameter, he will see things in focus.

21.7 Grating Measurement

Advanced

This comprehensive simulation is a good virtual experiment. The user has to position diffracted order on a cross hair and read a micrometer scale.



An angle table is a brilliant tool for measuring diffracted orders from a grating. In most angle tables both the light source and the telescope can be rotated. Ideally the grating is positioned perfectly perpendicular to the laser beam. In this case $d \sin \theta = n \lambda$ (eq 1) where d is the period of the grating, θ is the angle of the diffracted order

n is the diffracted order (negative or positive integers), λ is the wavelength.

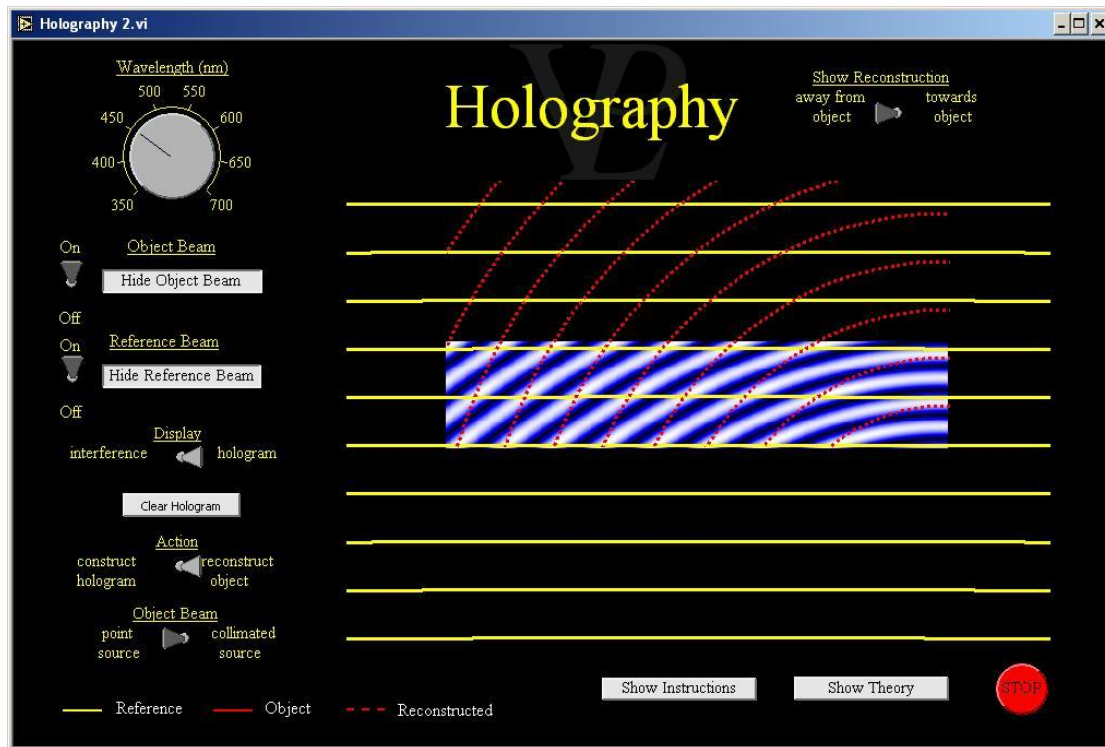
However, since in practice one can never guarantee that the grating will be positioned perfectly perpendicular to the light beam the expression needs to be changed to $d \sin \theta + d \sin \alpha = n \lambda$ (eq 2) where α is the small angle between the normal to the grating and the incident beam. Although α remains constant during the whole experiment (provided we don't move the grating or the laser!), that does not mean that all the values of α are shifted by a constant offset. Larger angles are shifted more than smaller ones. So for greatest accuracy two possible methods can be followed: Equation 2 can be re-arranged to $n = d/\lambda \sin \theta + d/\lambda \sin \alpha$ (eq 3).

By measuring several diffracted orders, and plotting n along the Y axis and $\sin \theta$ along the X axis, it is possible to obtain a straight line where the slope is equal to d/λ , since λ is known, d can be calculated. Another benefit of this graphical method is that the scatter of the results on the graph will also give a measure of the uncertainties in the determination of the period of the grating.

21.8 Holography

Advanced

See how a reference beam and an object beam interfere inside a photographic emulsion to produce a holographic fringes which can then be used to reconstruct the object beam.



A Hologram is a spatial record of the interference pattern between two waveforms. When two coherent waves overlap (that is two waves having the same frequency and with a fixed phase relationship between them) they produce a wave pattern where nodes and antinodes hold a fixed position.

Recording a Hologram: If photographic emulsion is placed in the region where the beams are interfering, it will record a series of fringes at the locations where the light intensity is highest. These fringes are the basis of the hologram.

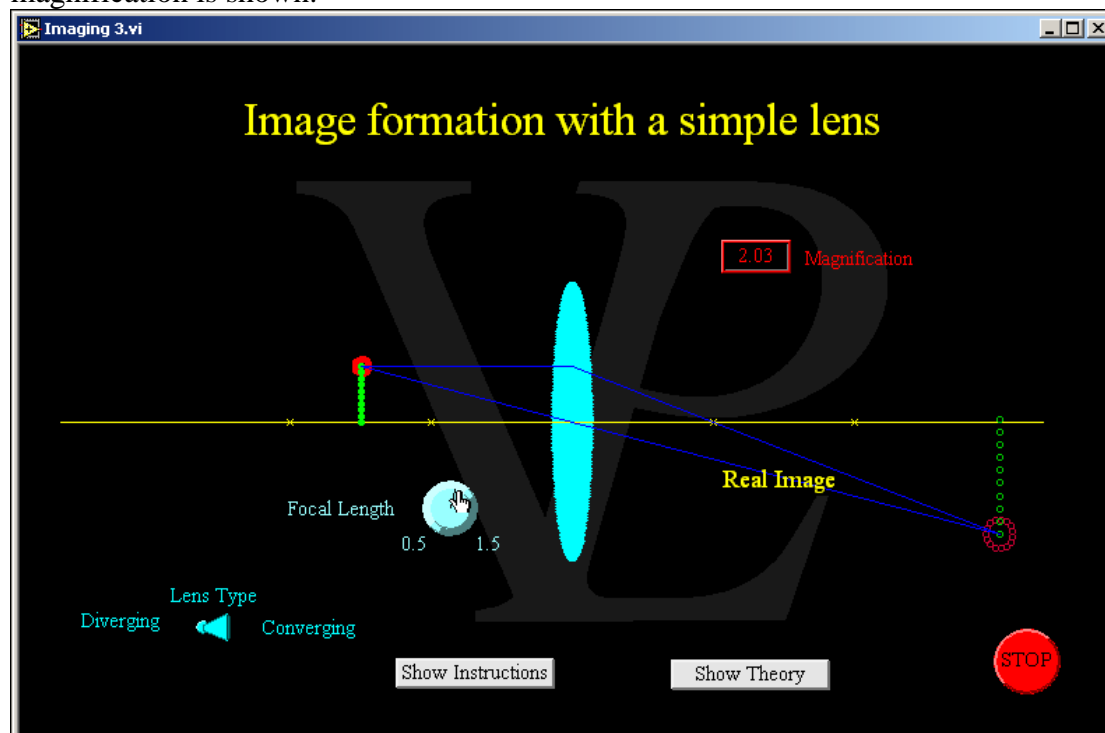
Once the hologram has been exposed and developed, the direction of the reference beam is reversed, and the positions of the fringes in the hologram become scattering centres from which secondary wavelets are produced. The wavelets scatter in such a way that their resultant (the sum of all the individual wavelets) produces a wavefront that heads back towards the position where the object was. In the opposite direction, the wavelets also add up to produce a wavefront that looks like it originated from the object (although the object is no longer there).

Normal holograms only look sharp when viewed with monochromatic light of the same wavelength as they were recorded. Good quality holograms can be made by exposing the photographic emulsion to three different colours at the same time (Red Green and Blue). Each colour produces its own interference pattern. When reconstructing, the object appears to be in true colour (although it actually is the addition of only 3 colours).

21.9 Imaging

Basic

This simulation shows how and where images form when the position of the object or power of the lens is varied. Real and virtual images are formed and the magnification is shown.



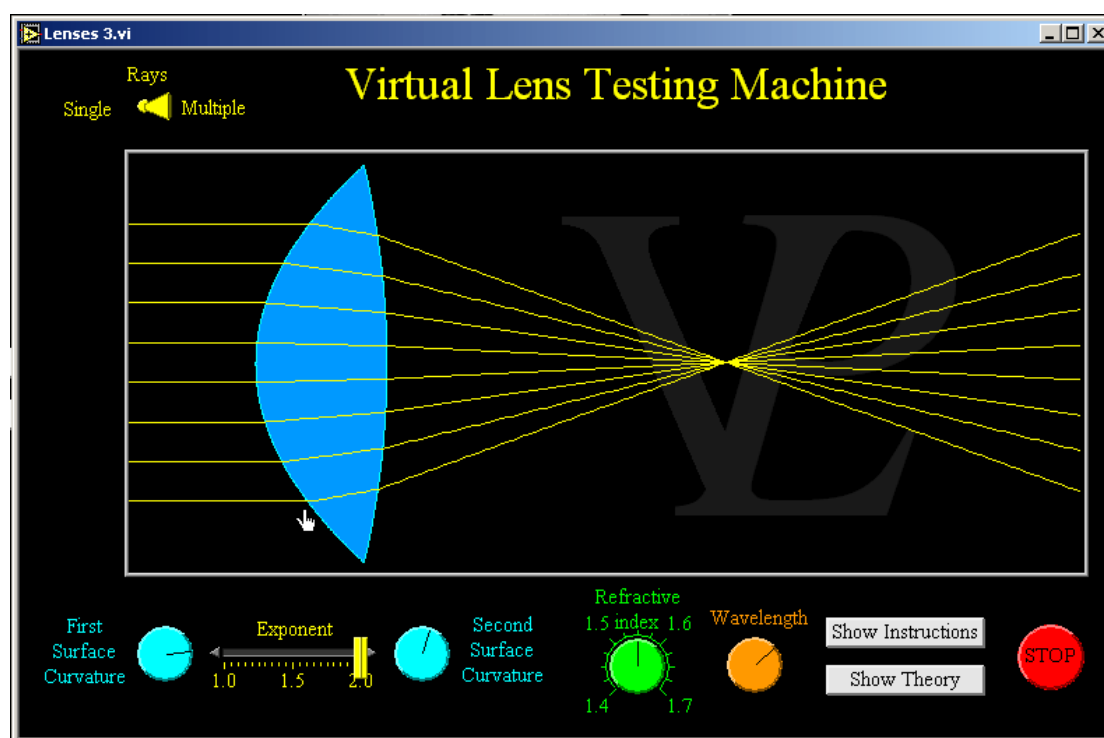
Lenses are normally used to form images. Sometimes the images are real and other times they are virtual. In real images, the light rays actually go through the image, if you were to place a piece of paper there, you would see the image projected on it. They are inverted (upside-down) with respect to the object. In virtual images, the light rays only appear to be coming from the image. Virtual images do not project on to a piece of paper. Virtual images are also upright - the same way up as the object. There are three main rules which the rays obey:

- 1 - Rays which run parallel to the axis on the left hand side of the lens will go through the focus on the opposite side.
 - 2 - Rays which go through the focus on the left hand side of the lens will go parallel to the axis on the opposite side of the lens.
 - 3 - Rays which go through the centre of the lens will pass through without being bent.
- Diverging lenses always produce virtual images which are de-magnified
 Converging lenses are in many ways more interesting than diverging ones; everything depends on the position X of the object compared to the focal length f :
- a) if $X < f$, it will produce a magnified virtual image behind the object.
 - b) if $X = f$ the image will never form, it will be at infinity.
 - c) if $X > f$ the lens it will produce a real image located at the other side of the lens.
 - d) if $f < X < 2f$ the image will be magnified.
 - e) if $X = 2f$ the image will be exactly the same size as the object.
 - f) if $X > 2f$ real images get formed, but they are de-magnified.

21.10 Lenses

Basic

This is a virtual lens testing machine. The effect of surface curvatures on the focal length can be seen in real time, and if the lenses are significantly curved, spherical aberration begins to present itself. Chromatic aberration can also be noted if the colour of the rays is changed. Converging and diverging lenses can be modelled.



Lens design is quite a complicated science. The basic concepts are explained here.

Lenses that are fatter in the middle are converging lenses, and those that are thinner in the middle are diverging. The curvature of the surfaces of a lens determines its focal length. As a general rule very curved lenses have shorter focal lengths.

The refractive index of the glass used also determines the focal length, but the range of refractive indices available for glass is quite small, so it is necessary to work on the surface curvature.

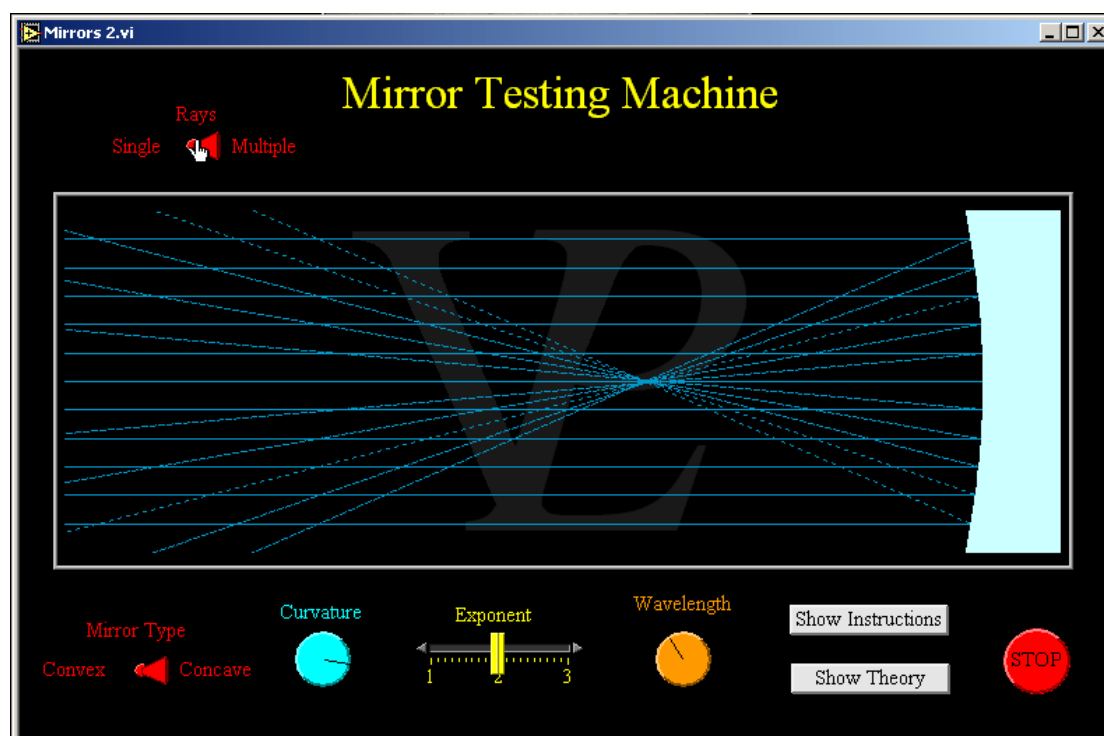
When lenses do not manage to focus all the rays into a small spot they are said to have 'spherical aberration'. In order to get lenses with a very small spherical aberration it is necessary to share the bending of the rays roughly equally between the front surface and the back one.

Years ago the lens curvature had to be polished by hand. Fortunately today there are computer controlled lathes which are able to turn a lens to any given shape you want. Ray-tracing programs, which are far more sophisticated than this one, are used to model the required shape of the lenses before they are actually made.

21.11 Mirrors

Basic

Parabolic mirrors are tested with this simulation, showing how the curvature affects the focal length. If the shape is changed from being parabolic (i.e. not an x^2 function) bad aberrations ensue.



Mirrors may seem second rate compared to lenses however they have a very real advantage over lenses. They do not suffer from chromatic aberration. This is because the rays never enter the material of the mirror; they are simply reflected from its surface.

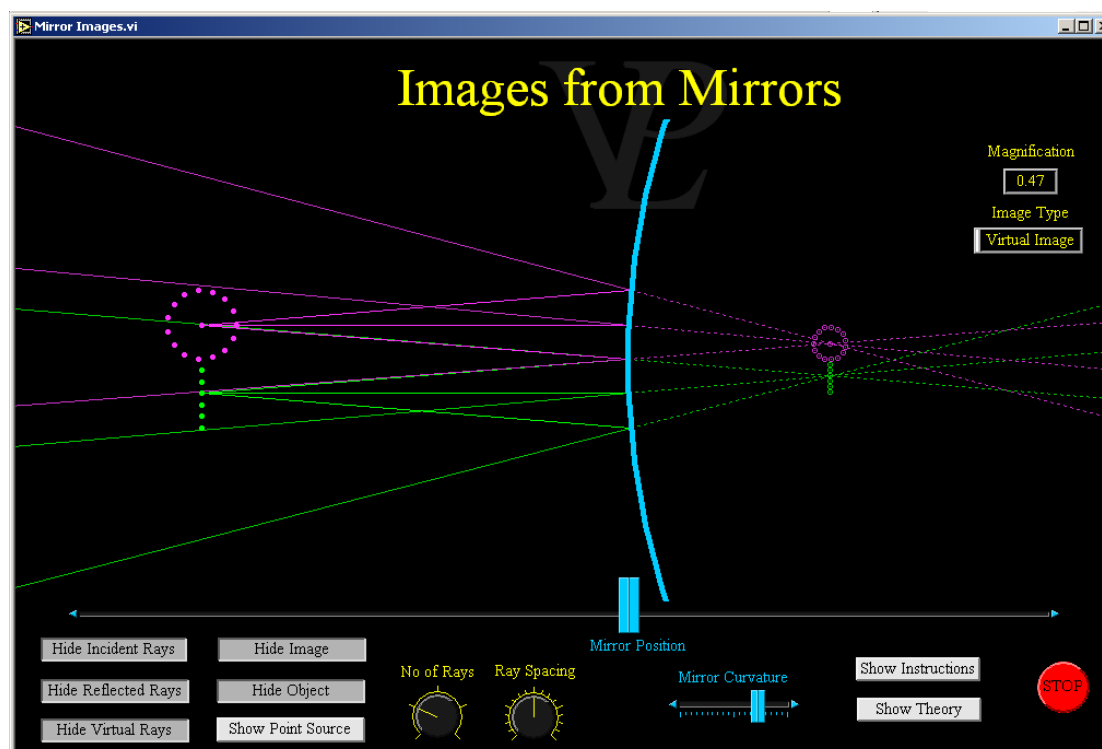
Mirrors can still suffer from spherical aberration, and for that reason the shape of the surface must be polished very carefully.

If the surface of the mirror follows the equation $y = c x^e$, spherical aberration is zero when $e = 2$. i.e. when the shape is a parabola. This is where the term parabolic mirrors comes from!

Parabolic mirrors are used in searchlights and telescopes. Some of the larger ones are 50m in diameter!

21.12 Mirror Images**Advanced**

This simulation shows how mirrors create images when the rays reflect from them.

**Flat Mirrors:**

Flat mirrors produce "virtual images" which appear to be behind the mirror at the same distance behind as the object is in front. Mirror images appear laterally inverted (left to right) but are still upright.

Convex Mirrors:

When mirrors are convex, the image is still virtual, but reduced in size and lies closer to the mirror than the object is to the mirror.

Concave Mirrors:

When the mirror is concave, and the object is close to the mirror (less than F - the focal length) the image will be virtual but enlarged.

When the object is exactly $1F$ away from the mirror, no image is formed. The reflected rays are parallel and said to be "collimated"

When the object is somewhere between $1F$ and $2F$ the image is real and magnified.

When the object is exactly $2F$ away from the mirror, the image is equal in size to the object.

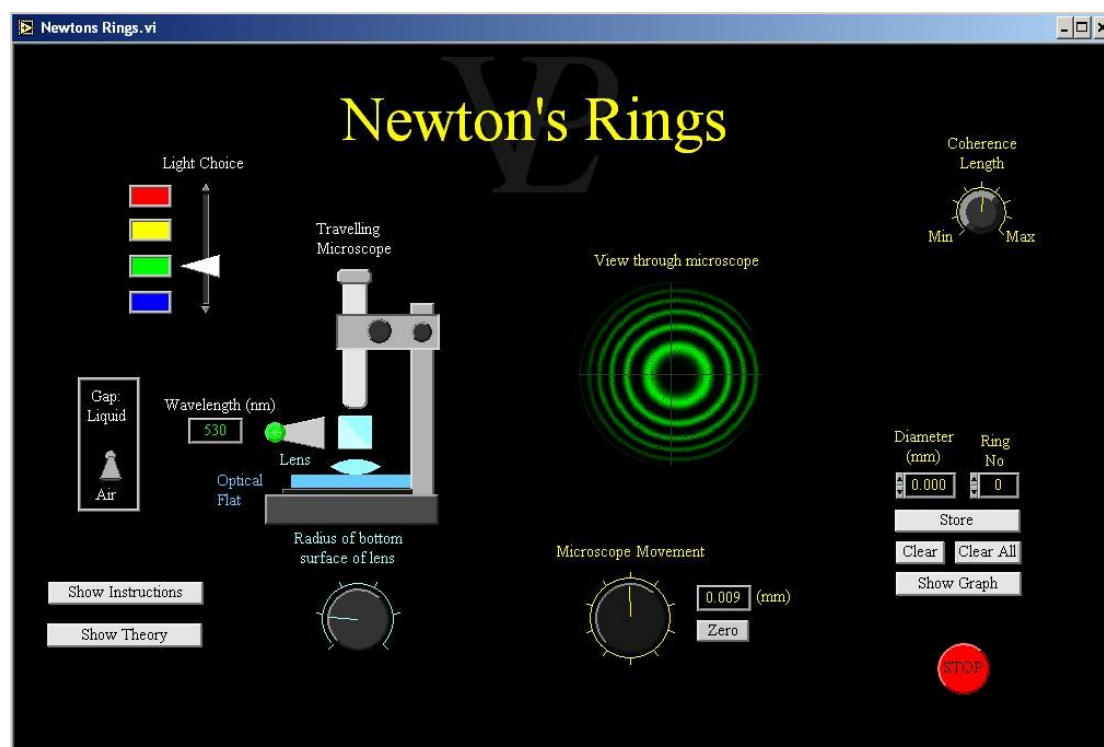
When the object is more than $2F$ away from the mirror the image is de-magnified (smaller than the object).

Images from curved mirrors that are not parabolic can suffer from "spherical aberration". Rays that are significantly off axis can result in distorted images due to "Coma" (this aberration is noticeable in this simulation)

21.13 Newton's Rings

Advanced

This is a 2D version of the “air wedge”; it much nicer to look at! – It can also be used to measure the curvature of a lens surface.



To understand the Newton's rings it is better to start with the “air wedge” simulation.

When a lens is placed on top of an optical flat and illuminated with a monochromatic light from above, light reflecting from the bottom surface of the lens will interfere with light reflecting from the top surface of the optical flat.

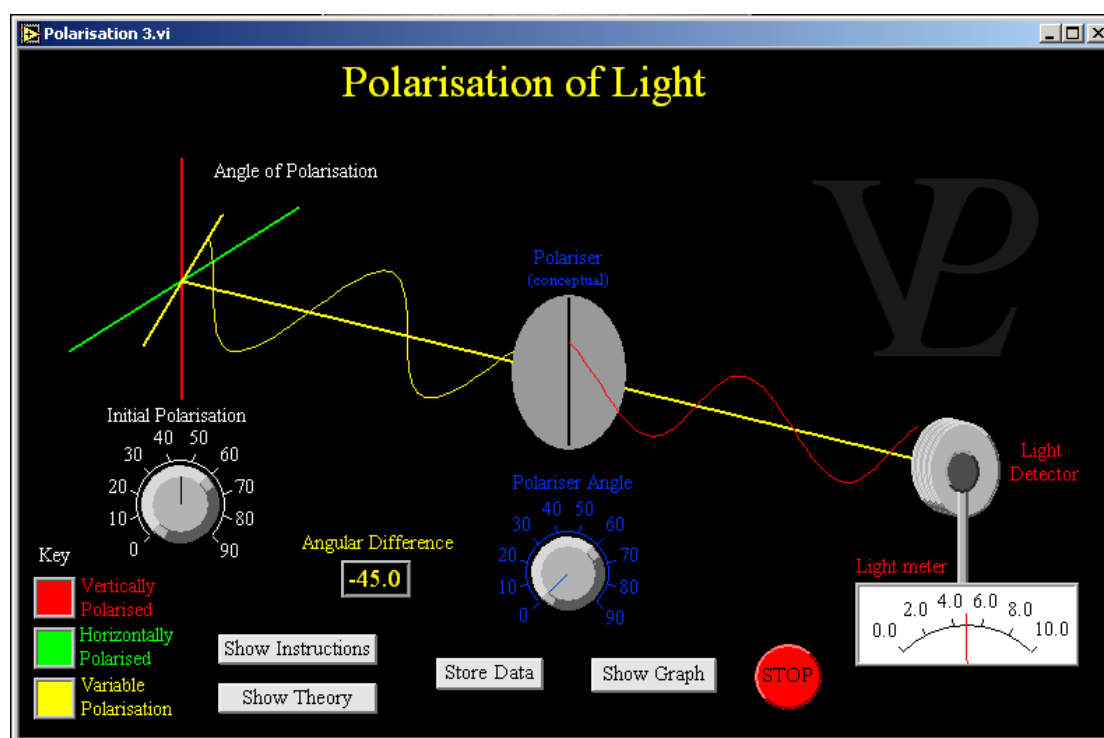
Dark fringes will occur whenever twice the gap is an exact multiple of the wavelength being used.

Measuring the radius of the annular fringes it is possible to build up information on the curvature of the lens.

21.14 Polarisation

Advanced

In this simulation a polarizer can be rotated in front of polarised light and a detector measures the intensity of the transmitted light. If sufficient data is obtained a graph showing the \cos^2 relationship is obtained.



Light waves can be polarised, that means that the disturbance can be limited to one plane. When a piece of polaroid is placed in front of normal light it polarises the light. Light can also be polarised through reflection and through scattering. This is why skiers sometimes wear polarised goggles to reduce the glare from the light reflected off the snow.

If the piece of polaroid is rotated in front of a polarised ray of light, it causes a variation in the intensity of the light that gets through. Notice that what matters is the relative angle between the original polarisation and the second 'polariser'. The polarisation of the light wave that gets through takes on the polarisation of the last polariser it got through.

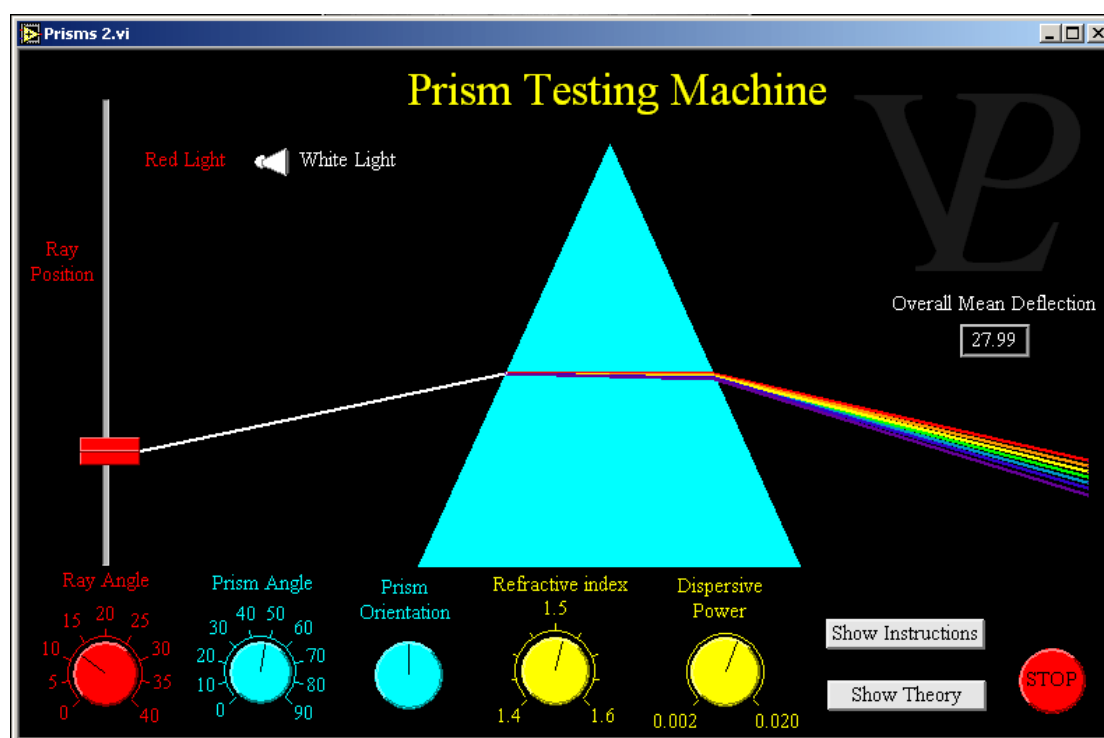
The amplitude of the transmitted wave is proportional to the cosine of the relative angle. If the angle is 90 degrees, the light is extinguished completely.

Since the amplitude is proportional to $\cos\theta$, the intensity is proportional to $\cos^2\theta$.

21.15 Prisms

Basic

In this simulation, a ray of light of variable colour is made to shine onto a face of a Prism of variable angle and refractive index. The refraction at each of the faces is shown and the overall deviation is noted. If white light is selected, the typical prismatic dispersion of colours is shown.



Prism is the name given to a family of optical components where the surfaces are flat, but the sides are not parallel to each other. Prisms come with many different angles, but the two most common are the 45 degree one (45° , 45° , 90°) and the 60 degree one (60° , 60° , 60°).

Sometimes hollow prisms are made of three sheets of thin glass so that they can be filled with liquids so that their refractive can be studied.

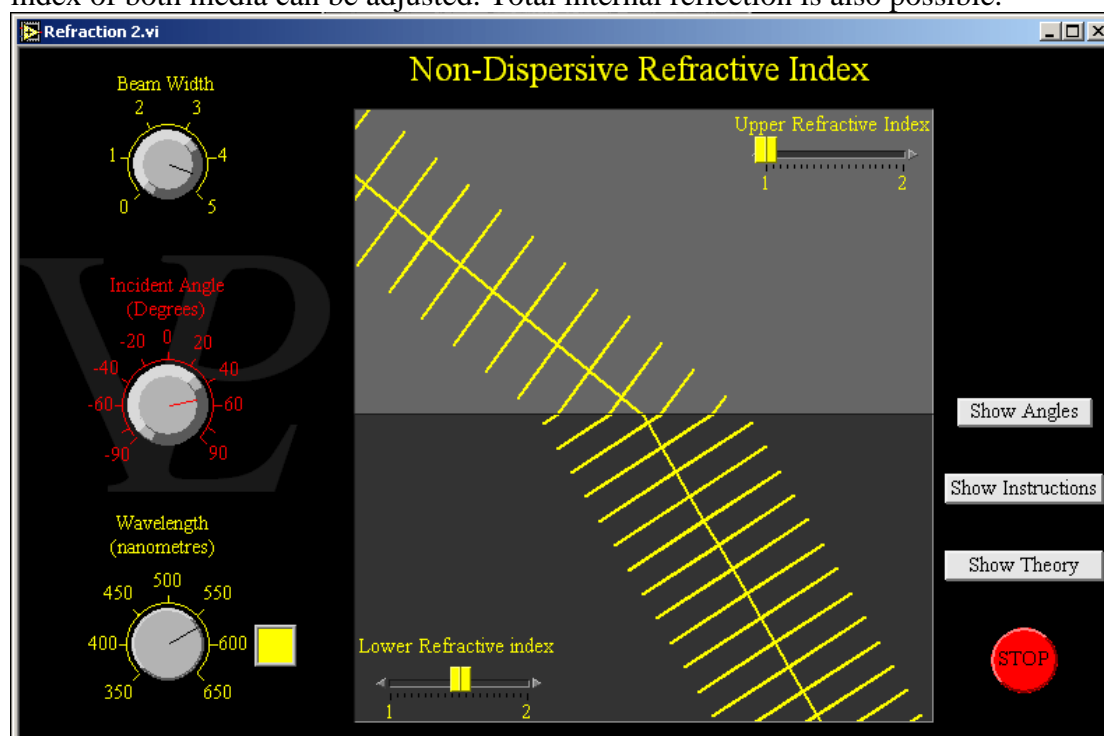
One of the most common uses of prisms in schools is to show that white light can be separated into its constituent colours. This relies on dispersion; the fact that the refractive index is slightly different for different colours.

The most common application of prisms in optical equipment is as ray benders in things like binoculars and periscopes. Prisms are better than mirrors in these cases because they can be used in 'total internal reflection' so that no light intensity is lost.

21.16 Refraction

Basic

This simulation shows how refraction at the boundary of a medium comes as a consequence of the slowing down of the light as it enters the medium. The refractive index of both media can be adjusted. Total internal reflection is also possible.



The speed of light depends on the medium through which it is travelling. It travels fastest through a vacuum, only slightly slower through air, and about 30% slower through glass or water. The 'refractive index' (symbol 'n') of a material like glass or water is defined as the ratio of the speed of light in a vacuum to the speed of light in the material. $n = c/v$, where c = the speed of light in vacuum and v = speed of light in the material.

As a consequence of this change of speed, when a light ray travel from air into water (or glass) the wavelength gets shortened and the ray gets deviated (or bent) towards the line which is perpendicular (or normal) to the interface. Think of a car that drives off a paved road, and lets its right hand wheels go on a soft sandy verge. The extra drag on that side causes the car to swerve to the right.

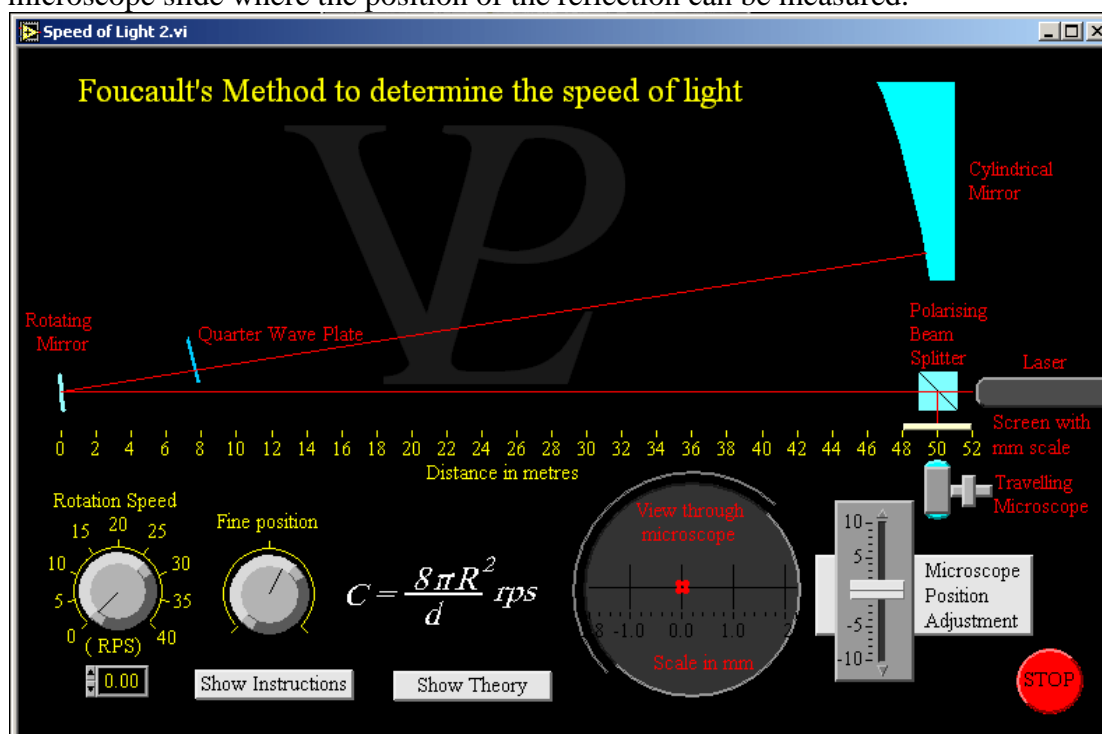
The amount of bending depends on how much the light is slowed down by. The ratio of the sine of the incident angle to the sine of the refracted angle is also equal to the refractive index n . $n = \sin(i)/\sin(r)$ where i = incident angle, r = refracted angle. Note that these angles are measured to the normal of the interface, and not to the interface itself.

When a light ray travels from a medium which has a higher refractive index to one that has a lower refractive index, the ray gets bent away from the normal. If the incident angle is above a certain critical angle the ray is reflected instead. This is called total internal reflection.

21.16 Speed of light

Advanced

This virtual experiment allows the student to measure the speed of light using the rotating mirror method. A laser beam is reflected back and made to shine upon a microscope slide where the position of the reflection can be measured.



This is a modified version of Foucault's method although he did not have a laser. The laser beam is passed through a polarising beam-splitter which allows one polarisation through and reflects the other. The laser is rotated such that the outgoing beam is totally transmitted. The laser then proceeds towards the rotating mirror. From there it is reflected on to the cylindrical mirror (nearly flat), whose curvature is centred at the axis of the rotating mirror. The beam therefore retraces its path back towards the rotating mirror. As the mirror is rotating by the time it gets back it finds the mirror in a slightly different position. The beam therefore reflects back toward the polarising beam-splitter along a path that is slightly different.

In its double journey to the mirror and back the beam will have passed twice through the quarter wave plate. The plane of polarisation will be perpendicular to what it was before. So the return beam is deflected by the polarising beam-splitter, and shines onto a small screen. A microscope is used to observe where the light spot hits the screen. Knowing how far the beam has travelled and the speed of rotation of the mirror, it is possible to calculate the speed of light C .

The radius of the cylindrical mirror is 50 m, and is denoted R and the beam travels there and back, a total of $2R$ ($=100$ m). The time taken (dt) will be $dt = 2R/C$ so $C = 2R/dt$. In that time, the mirror will have rotated by a small angle α (α , in radians) which is calculated $\alpha = \omega \times dt$ so $dt = \alpha/\omega$ where ω is the angular velocity $\omega = 2\pi$ RPS (RPS = number of revolutions per second). The angle by which the beam is diverted will be equal to 2α , so the displacement D of the spot as seen by the microscope is given by $D = 2\alpha R$ so $\alpha = D/2R$. Substituting we get $C = 8\pi R$ RPS/ D .

CHAPTER 22

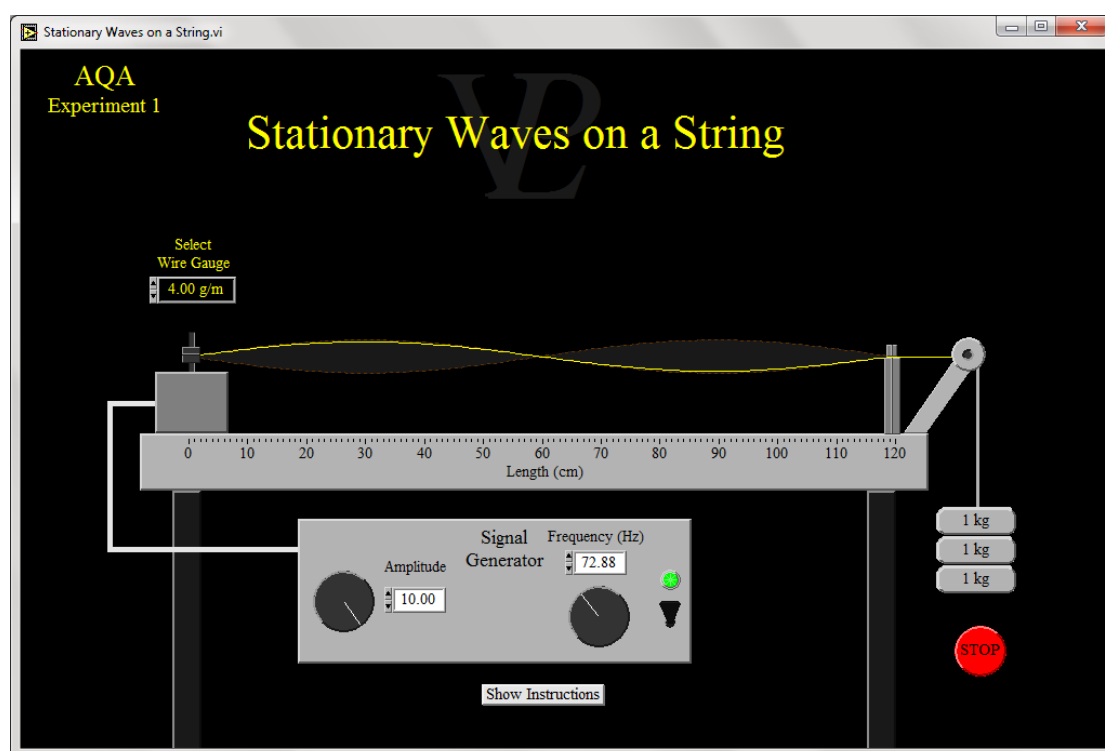
PRACTICALS



Preparing for set practical experiments without having any equipment!

22.1 AQA Experiment 1. Stationary waves on a string.

Advanced



This simulation is designed to help students prepare for AQA set practical No1

Investigation into the variation of the frequency of stationary waves on a string with length, tension and mass per unit length of the string

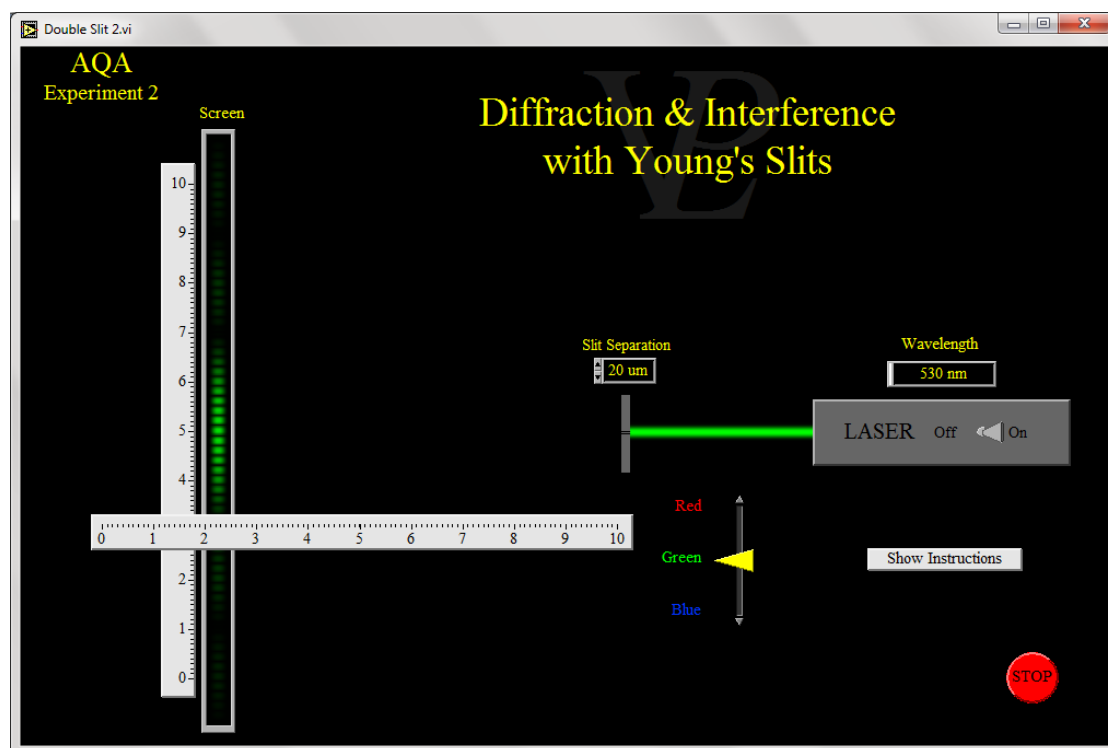
Simulation Instructions:

- 1 - You can change the amplitude and frequency of the signal generator using the two knobs (or type the frequency in the field)
- 2 - You can select the wire gauge by clicking inside the field
- 3 - You can change the length of the wire by clicking on the bridge and dragging it sideways.
- 4 - You can change the weights providing the tension by clicking on the masses and dragging up or down.

The experimental procedure, the recording of data, and the plotting and analysis are left up to the student to devise.

22.2 AQA Experiment 2. Double Slit Interference

Advanced



This simulation is designed to help students prepare for AQA set practical No 2.

Investigation of interference in Young's slit experiment and diffraction by a diffraction grating.

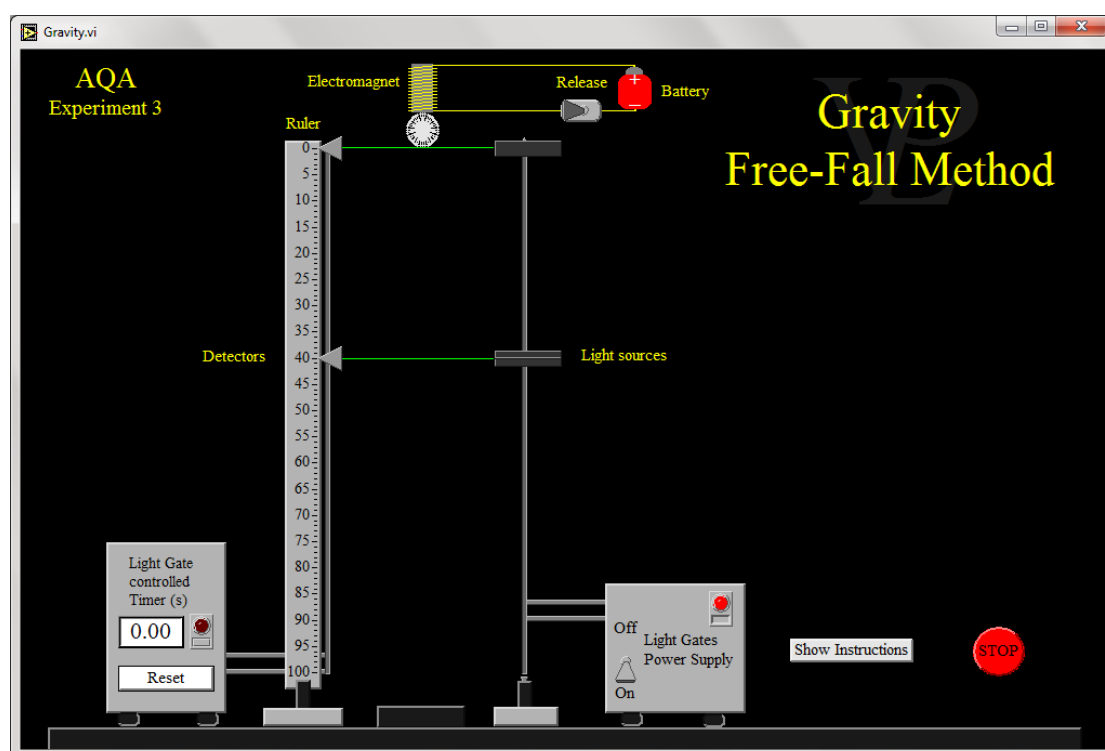
Simulation Instructions:

- 1 - Turn the laser ON using the switch on the right hand side
- 2 - Select the slit separation by clicking inside the field
- 3 - Select the Laser wavelength to be used using the yellow vertical slider.
- 4 - The two rulers show units in cm.
- 5 - Click on the bottom part of the screen and drag it left or right to change its distance from the slits.
- 6 - Carry out whatever measurements you need in order to work out what the approximate slit separation is in the unknown pair.
- 7 - Carry out whatever measurements you need in order to work out the unknown blue wavelength is.
- 8 - Estimate what your uncertainty is likely to be for both 6 and 7.

The experimental procedure, the recording of data, and the plotting and analysis are left up to the student to devise.

22.3 AQA Experiment 3. Gravity by free-fall method

Advanced



This simulation is designed to help students prepare for AQA set practical No 3.

Determination of g by a free-fall method

Simulation Instructions:

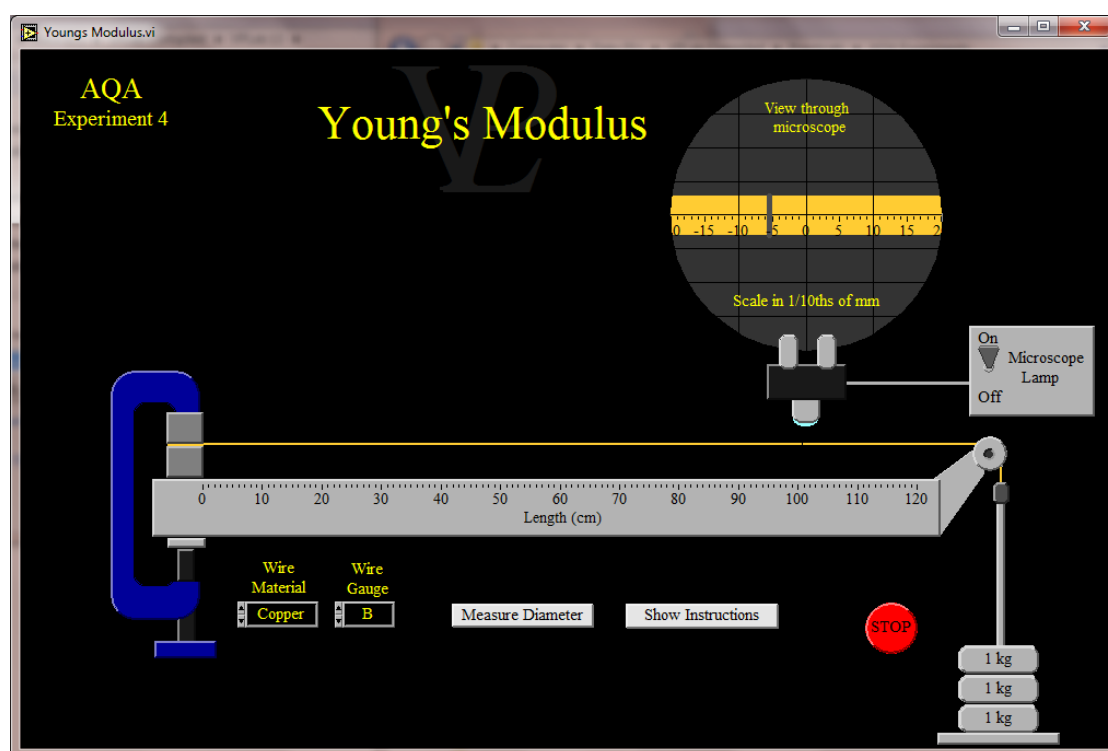
Using the equipment available, measure the acceleration due to gravity

- 1 - The switch on the electromagnet circuit releases the steel ball
- 2 - The reset button on the light gates timer also replaces the steel ball
- 3 - The light gates power supply must be switched on for them to detect the passing of the ball and trigger the timer.
- 4 - The light gates can be dragged up or down to any desired position (click on the light sources)

The experimental procedure, the recording of data, and the plotting and analysis in order to calculate the value of gravity are left up to the student to devise.

22.4 AQA Experiment 4. Young's Modulus by Extension

Advanced



This simulation is designed to help students prepare for AQA set practical No 4.

Determination of the Young Modulus by a simple method

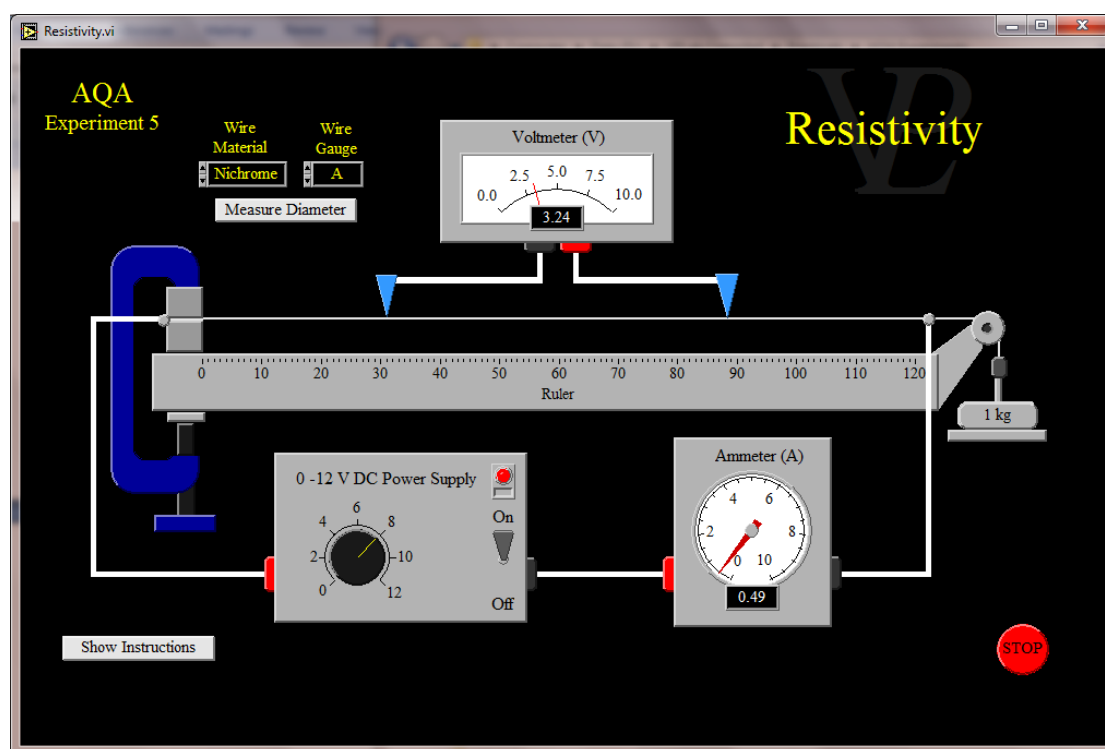
Simulation Instructions:

- 1 - Add or remove 1 kg masses on the right hand side by clicking on the masses and dragging up or down
- 2 - You can select the wire material and gauge by clicking inside the fields
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Switch the microscope ON to see how the wire extends as you load it. Record the extensions for different weights.

The experimental procedure, the recording of data, and the plotting and analysis required to calculate the Young's modulus of the material selected are left up to the student to devise.

22.5 AQA Experiment 5. Resistivity of Wire Samples

Advanced



This simulation is designed to help students prepare for AQA set practical No 5.

Determination of the resistivity of a wire using a micrometer screw gauge, ammeter and voltmeter.

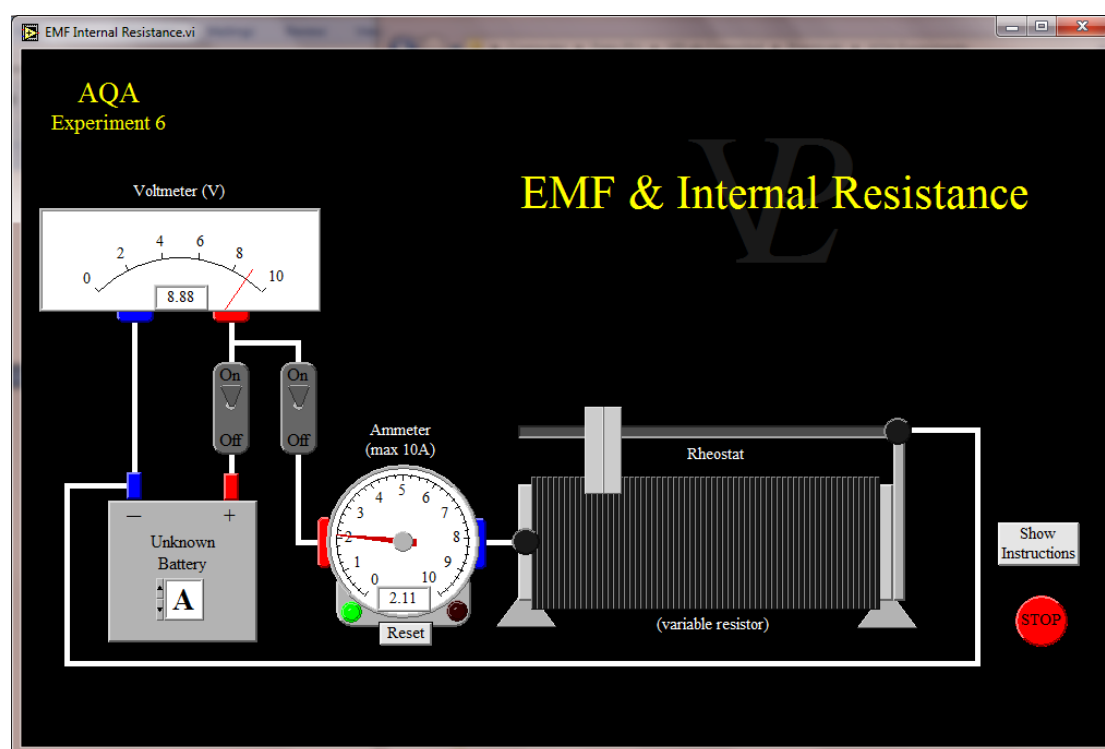
Simulation Instructions:

- 1 - Select the material you want to test by clicking in the field
- 2 - Select a suitable wire diameter by clicking in the field (A is the thinnest)
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Make sure the knob is turned down to zero before switching the power supply ON. If you drive a current of more than 10 A, the circuit breaker will trip and switch the power supply Off automatically.

The experimental procedure, the recording of data, and the plotting and analysis required to calculate the resistivity of the material selected are left up to the student to devise.

22.6 AQA Experiment 6. EMF and Internal Resistance

Advanced



This simulation is designed to help students prepare for AQA set practical No 6.

Investigation of emf and internal resistance of electric cells and batteries by measuring the variation of the terminal pd of the cell with current in it.

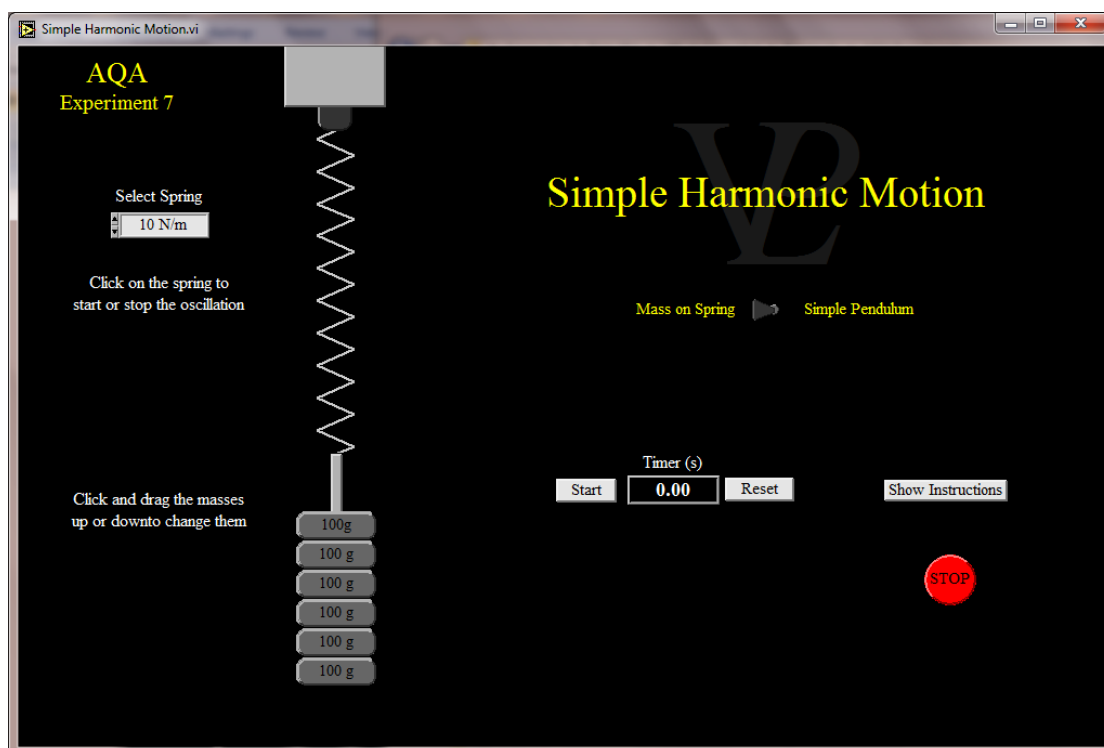
Simulation Instructions:

- 1 - Select the battery whose EMF and internal resistance you want to measure (A to D) by clicking inside the field in the battery.
- 2 - Toggle the switches to close the circuit to suit your needs
- 3 - Click on the rheostat slider and drag it left or right to change its resistance
- 4 - The maximum current the ammeter can cope with is 10 A. If the current exceeds that, the red light will show. Increase the resistance and press the reset button to get it working again.

The experimental procedure, the recording of data, and the plotting and analysis required to calculate the EMF of the battery and its internal resistance are left up to the student to devise.

22.7 AQA Experiment 7. Simple Harmonic Motion

Advanced



This simulation is designed to help students prepare for AQA set practical No 7.

Investigation into simple harmonic motion using a mass-spring system and a simple pendulum

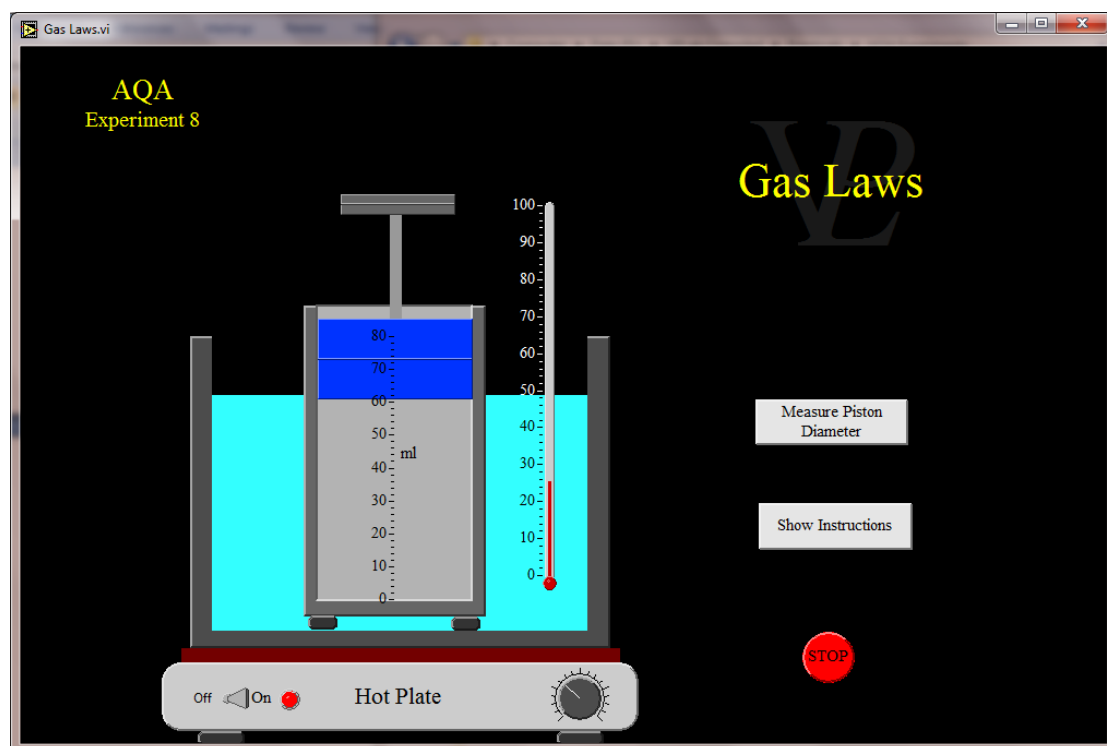
Simulation Instructions:

- 1 - Decide whether you want to study a mass on a spring or a pendulum, and use the horizontal toggle switch to select it.
- 2 - The oscillations are started and stopped by clicking near the top of the string or spring.
- 3 - The mass or the length of the pendulum are changed by clicking and dragging the mass or the pendulum up or down.
- 4 - The spring stiffness can be changed by clicking inside the field and selecting one of the options presented.
- 5 - Make sure you 'get into the rhythm' of the oscillations first, and then time an adequate number of oscillations so that you reduce errors due to reaction time.
- 6 - Use the stop-watch to obtain your timings.

The experimental procedure, the recording of data, and the plotting and analysis required to calculate the dependence of the period of oscillation are left up to the student to devise.

22.8 AQA Experiment 8. Charles and Boyle's Gas Laws

Advanced



This simulation is designed to help students prepare for AQA set practical No 8.

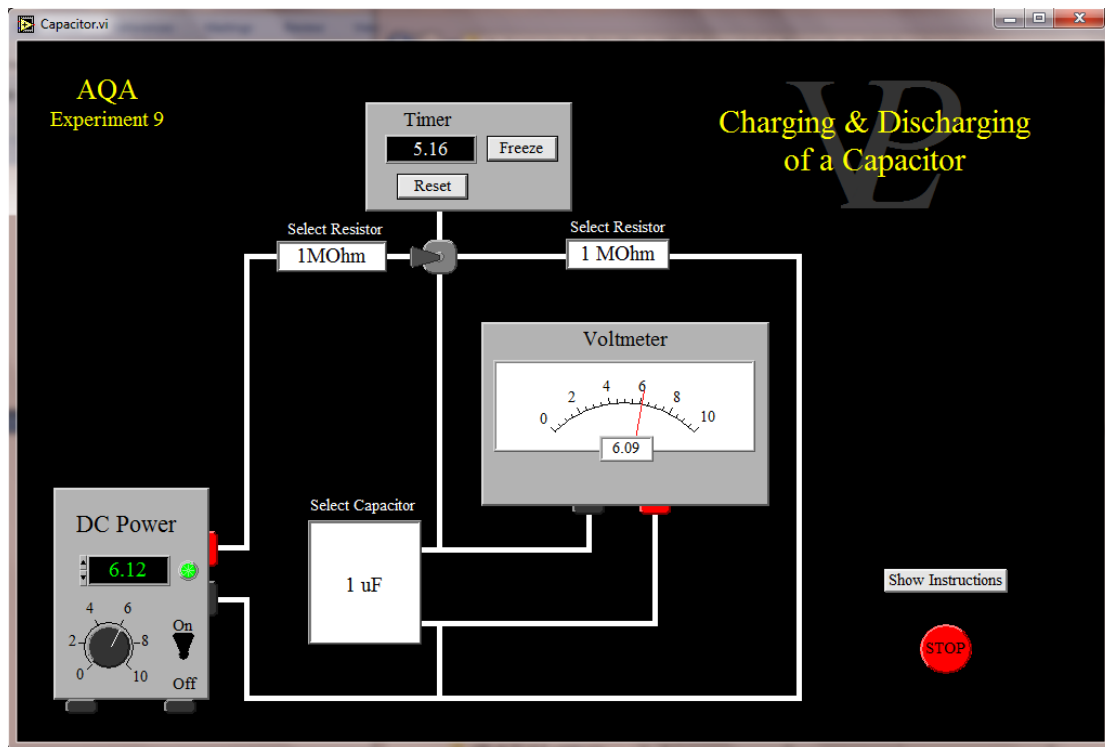
Investigation of Boyle's (constant temperature) law and Charles's (constant pressure) law for a gas

Simulation Instructions:

- 1 - The frictionless piston can move up and down inside the measuring cylinder. The volume of the gas is shown in the scale in millilitres. The starting volume is 60 millilitres.
- 2 - Exert pressure on the piston by adding 2 kg masses on top of the plunger above the piston; do this by clicking on it and dragging upwards or downwards.
- 3 - You can measure the diameter of the frictionless piston by pressing the "Measure Piston Diameter" button. Measure it several times.
- 4 - Wait until piston stops moving before taking a reading of the volume. The pressure is calculated from the mass and the piston face area.

The water bath maintains a steady temperature as you vary the pressure. However, if you want to carry out an experiment at constant pressure instead, remove all the masses from the plunger first.

22.9 AQA Experiment 9. Capacitor Charging and Discharging Advanced



This simulation is designed to help students prepare for AQA set practical No 9.

Investigation of the charge and discharge of capacitors

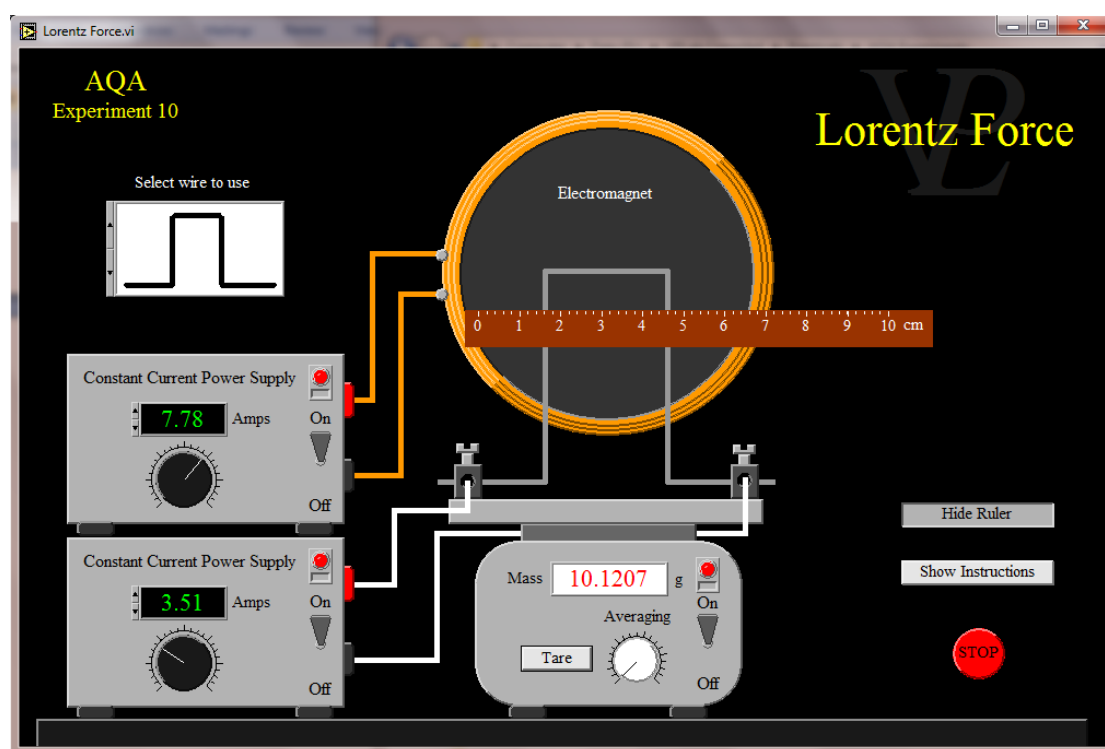
Simulation Instructions:

- 1 - Switch on the power supply, and set any desired voltage.
- 2 - Click inside the resistors and select the values you want them to have.
- 3 - Click on the capacitor and select the value you want it to have.
- 4 - Toggle the central switch in order to start the charging or discharging of the capacitor. Notice that the timer starts automatically when you toggle this switch.
- 5 - Carry out an experiment to determine the effect of the resistance and capacitance on the charging and discharging time constant

The experimental procedure, the recording of data, and the plotting and analysis required to determine the effect are left up to the student to devise.

22.10 AQA Experiment 10. Lorentz Force on Conductors

Advanced



This simulation is designed to help students prepare for AQA set practical No 10.

Investigation the relationship between the force, magnetic flux density, current and length of wire using a top pan balance

Simulation Instructions:

- 1 - Choose the wire you want to use by clicking in the field and selecting
- 2 - Press the "Show Ruler" button to display a ruler with which you can measure the length of the wire in the magnetic field. Click near the 5 cm position and drag the ruler left or right to position it.
- 3 - Switch the digital balance ON
- 4 - Switch the current supply to the electromagnet ON, and increase the current to a suitable level.

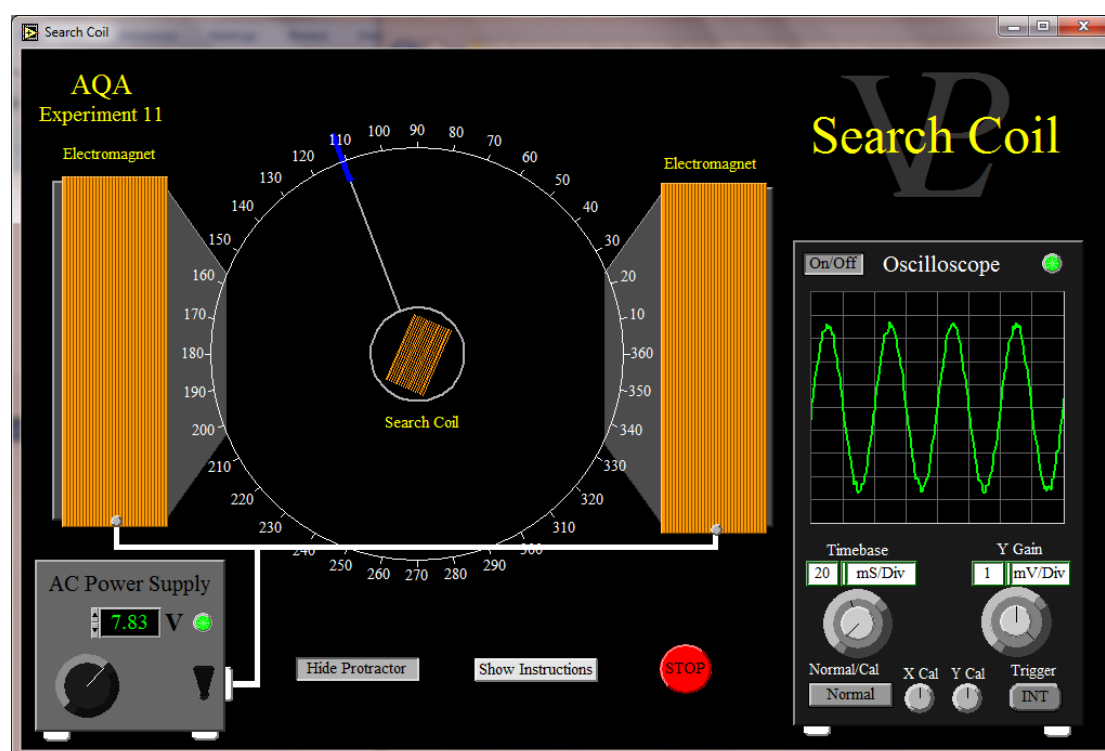
Note: The electromagnet produces a magnetic field of approximately 0.011 Tesla per Ampere flowing through it.

- 5 - Switch the current supply to the test wire ON, and increase the current.
- 6 - Check that the digital balance is displaying a change in measured mass when you change any of the currents.
- 7 - The "Tare" button on the digital balance resets the reading to zero.
- 8 - The "Averaging" knob increases the integration time of the balance to reduce random variations in the display.

The experimental procedure, the recording of data, and the plotting and analysis required to calculate the resistivity of the material you select are left up to the student to devise.

22.11 AQA Experiment 11. Search Coil in Magnetic Field

Advanced



This simulation is designed to help students prepare for AQA set practical No 11.

Investigate the effect on magnetic flux linkage by varying the angle using a search coil and oscilloscope

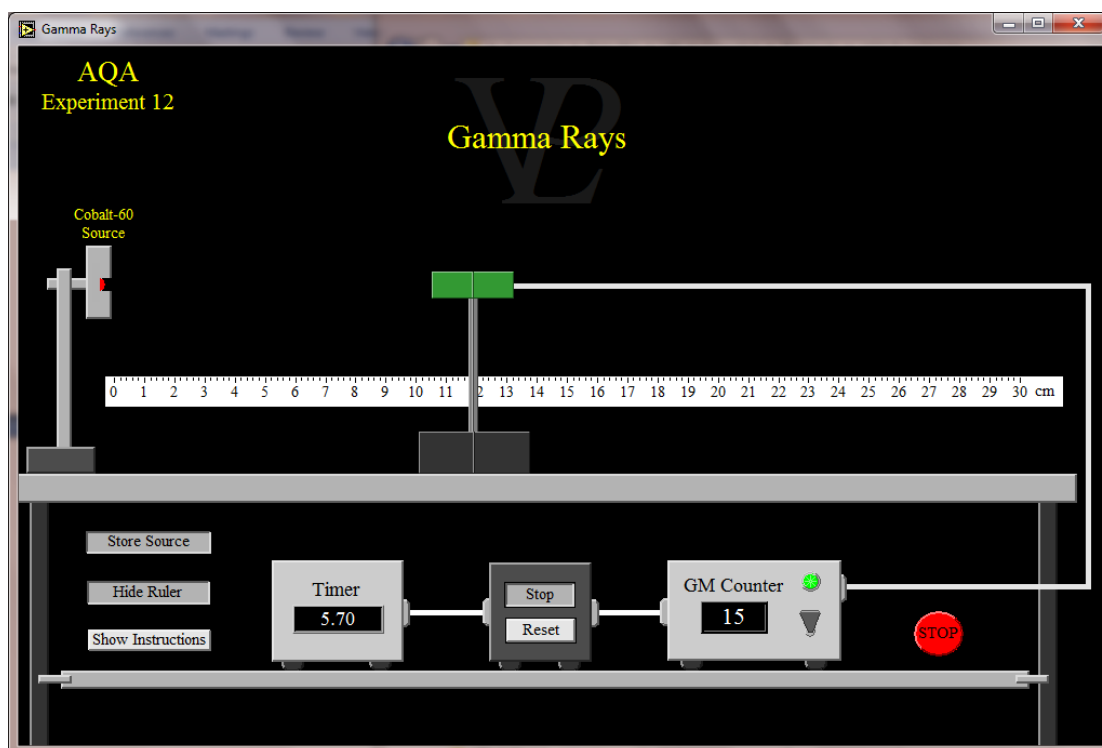
Simulation Instructions:

- 1 - Switch the AC Power supply ON.
- 2 - Switch the Oscilloscope ON.
- 3 - Increase the voltage to the electromagnets to around 10V.
- 4 - Adjust the Y Gain on the oscilloscope until a suitable display of the voltage from the search coil is obtained.
- 5 - Click and drag the blue handle of the search coil left or right in order to rotate it.
- 6 - Press the "Show Protractor" button to help you measure the angle of rotation.

The experimental procedure, the recording of data and the plotting and of a graph to demonstrate the angular dependence of the search coil voltage are left up to the student to devise.

22.12 AQA Experiment 12. Gamma Rays Inverse Square

Advanced



This simulation is designed to help students prepare for AQA set practical No 12.

Investigation of the inverse-square law for gamma rays

Simulation Instructions:

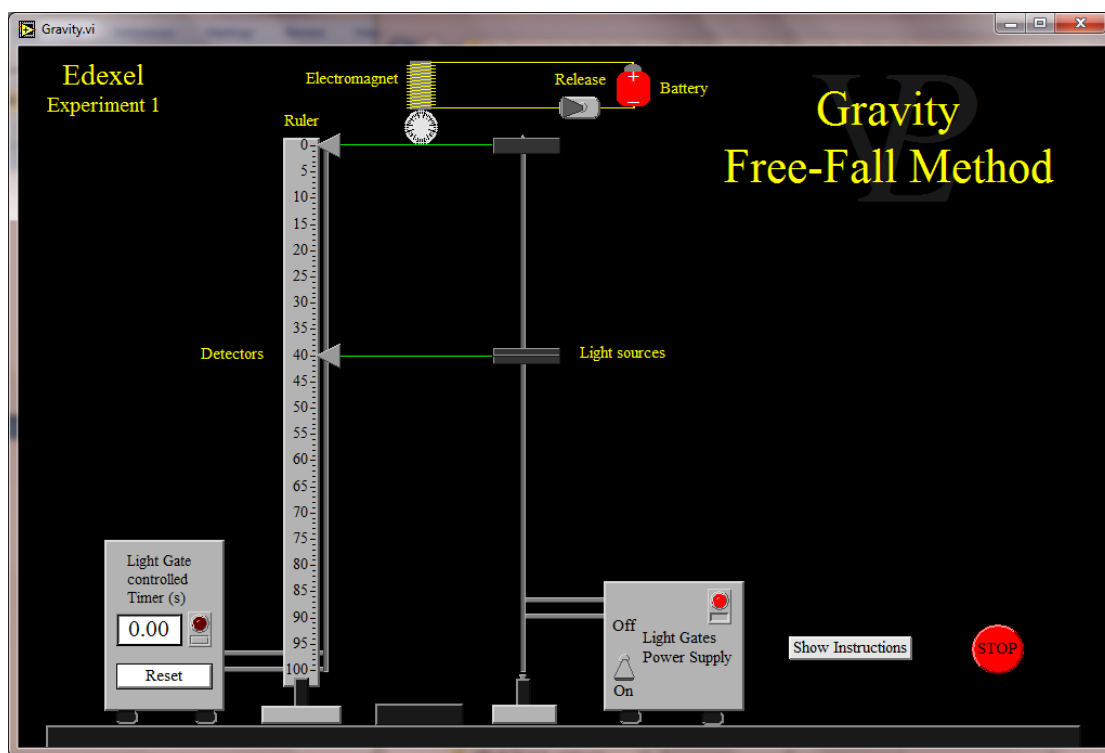
- 1 - Read warning on radioactive source, and when ready, click the "Open Box" button.
- 2 - Switch the G-M counter ON
- 3 - Slide the Geiger-Muller tube along the table by clicking and dragging its base left or right.
- 4 - Start the timer and counter by clicking the "Start" button. The "Reset" button clears both the timer and the counter
- 5 - Click the "Show Ruler" button to display a ruler

Note: The active part of the G-M tube is situated roughly at its centre, not at its front.

The experimental procedure, the recording of data, and the plotting and analysis required to verify the inverse square relationship are left up to the student to devise.

22.13 Edexcel Experiment 1. Acceleration of Free Fall

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 1

Determine the acceleration of a freely falling object

Simulation Instructions:

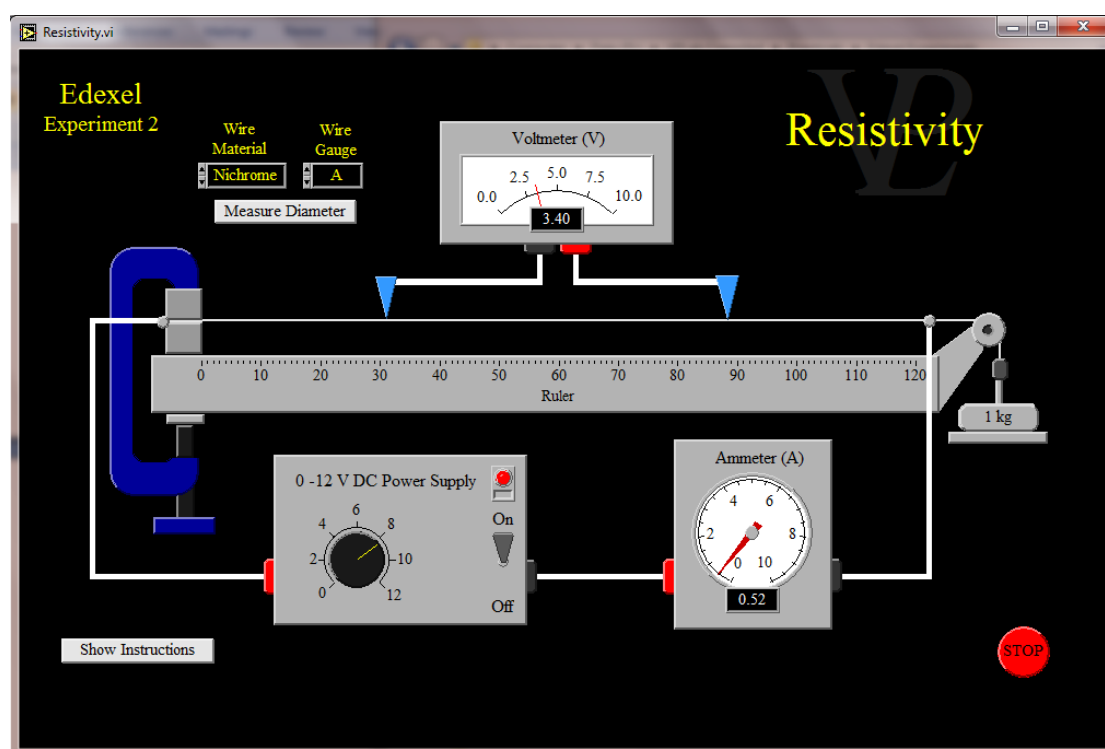
Use the equipment available to measure the acceleration due to gravity

- 1 - The switch on the electromagnet circuit releases the steel ball
- 2 - The reset button on the light gates timer also replaces the steel ball
- 3 - The light gates power supply must be switched on for them to detect the passing of the ball and trigger the timer.
- 4 - The light gates can be dragged up or down to any desired position (click on the light sources)

The student is left to devise the experimental procedure, the recording of the data, the plotting of graphs and the calculation of gravity.

22.14 Edexcel Experiment 2. Resistivity

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 2

Determine the electrical resistivity of a material

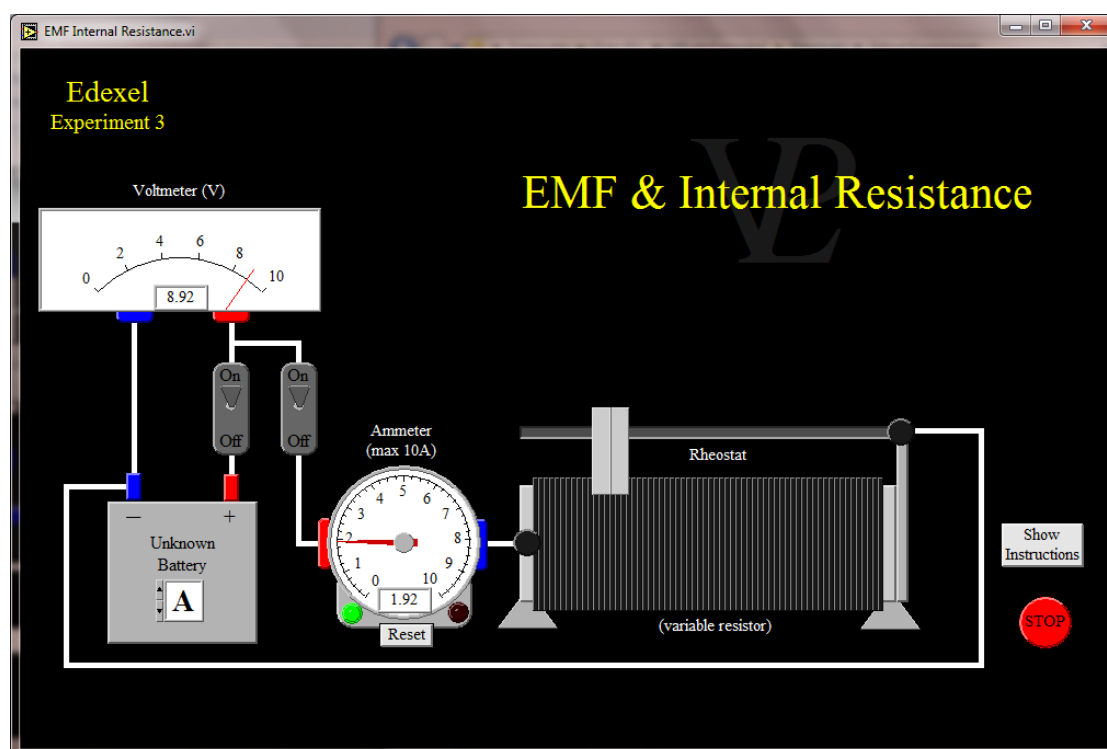
Simulation Instructions:

- 1 - Select the material you want to test by clicking in the field
- 2 - Select a suitable wire diameter by clicking in the field (A is the thinnest)
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Make sure the knob is turned down to zero before switching the power supply ON. If you drive a current of more than 10 A, the circuit breaker will trip and switch the power supply Off automatically.

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis required to calculate the resistivity of the material selected

22.15 Edexcel Experiment 3. EMF and Internal Resistance

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 3.

Determine the e.m.f. and internal resistance of an electrical cell

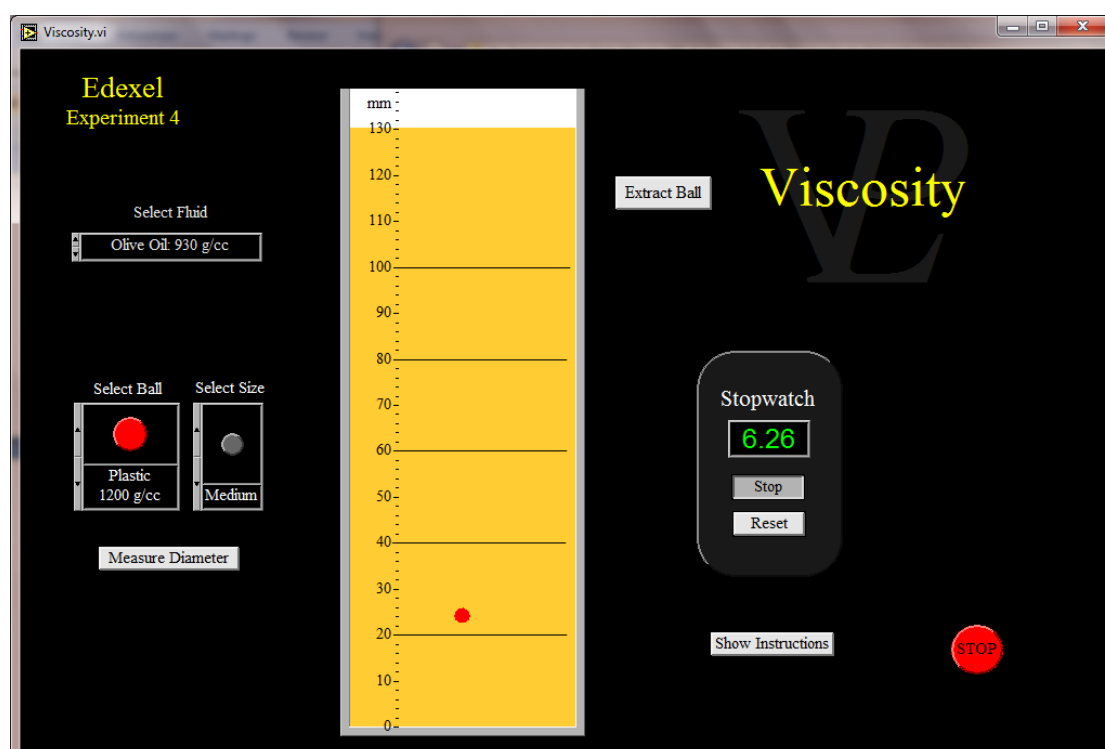
Simulation Instructions:

- 1 - Select the battery whose EMF and internal resistance you want to measure (A to D) by clicking inside the field in the battery.
- 2 - Toggle the switches to close the circuit to suit your needs
- 3 - Click on the rheostat slider and drag it left or right to change its resistance
- 4 - The maximum current the ammeter can cope with is 10 A. If the current exceeds that, the red light will show. Increase the resistance and press the reset button to get it working again.

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis required to calculate the EMF of the battery and its internal resistance.

22.16 Edexcel Experiment 4. Viscosity by Falling Ball

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 4

Use a falling-ball method to determine the viscosity of a liquid

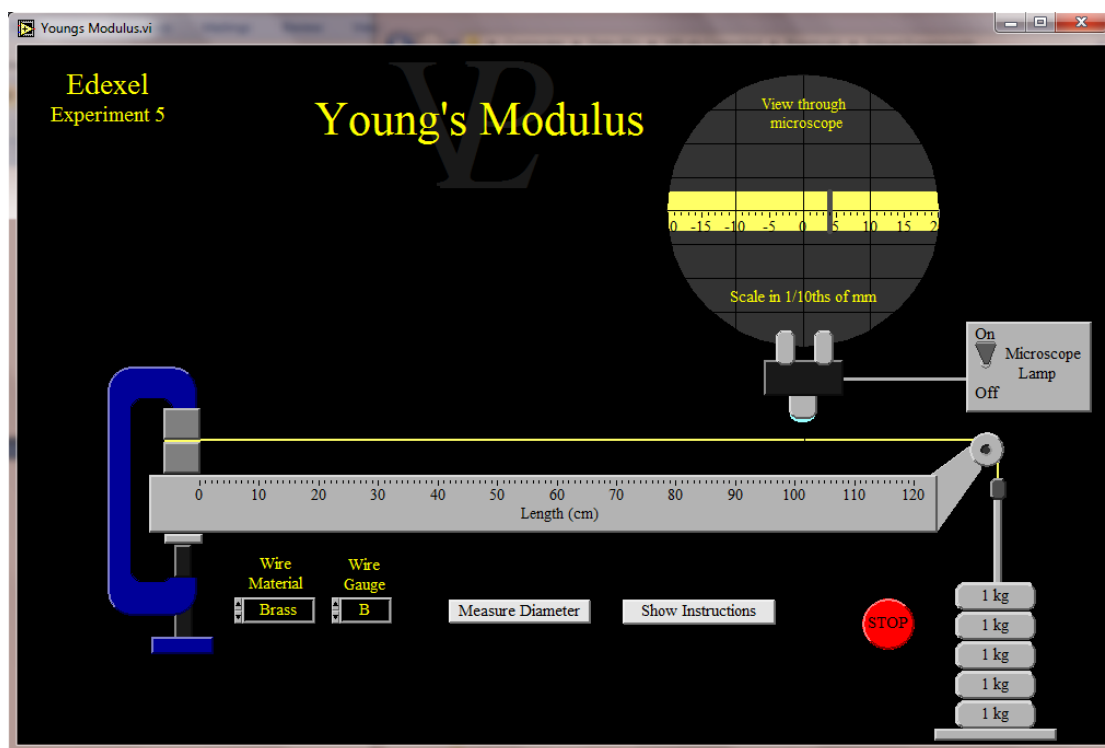
Simulation Instructions:

- 1 - Select the fluid you want to test
- 2 - Select the material of the ball you want to use
- 3 - Select the size of the ball you want to use
- 4 - Measure its diameter using the micrometer
- 5 - Drop the ball and use the stopwatch to measure the terminal velocity of ball.

The student is left to devise the experimental procedure, the required measurements, and the subsequent analysis necessary to calculate the viscosity of the liquids.

22.17 Edexcel Experiment 5. Young's Modulus

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 5.

Determine the Young modulus of a material

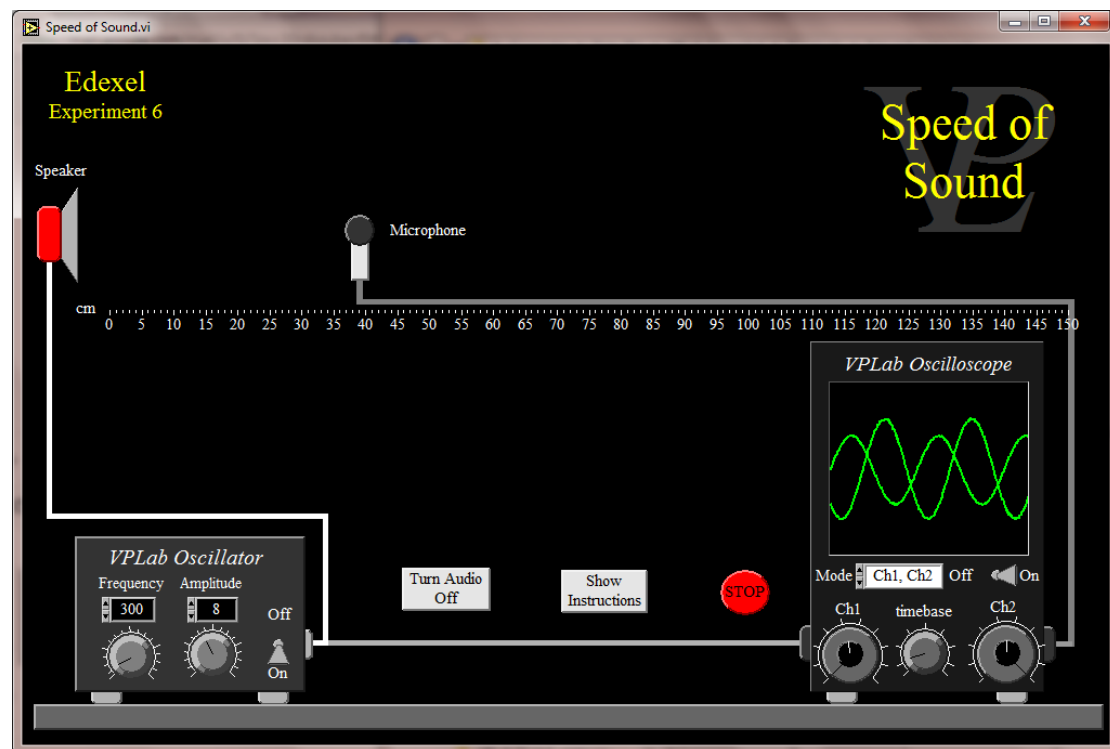
Simulation Instructions:

- 1 - Add or remove 1 kg masses on the right hand side by clicking on the masses and dragging up or down
- 2 - You can select the wire material and gauge by clicking inside the fields
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Switch the microscope ON to see how the wire extends as you load it. Record the extensions for different weights.

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis required to calculate the Young's modulus of the material selected.

22.18 Edexcel Experiment 6. Speed of Sound

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 6

Determine the speed of sound in air using a 2-beam oscilloscope, signal generator, speaker and microphone

Simulation Instructions:

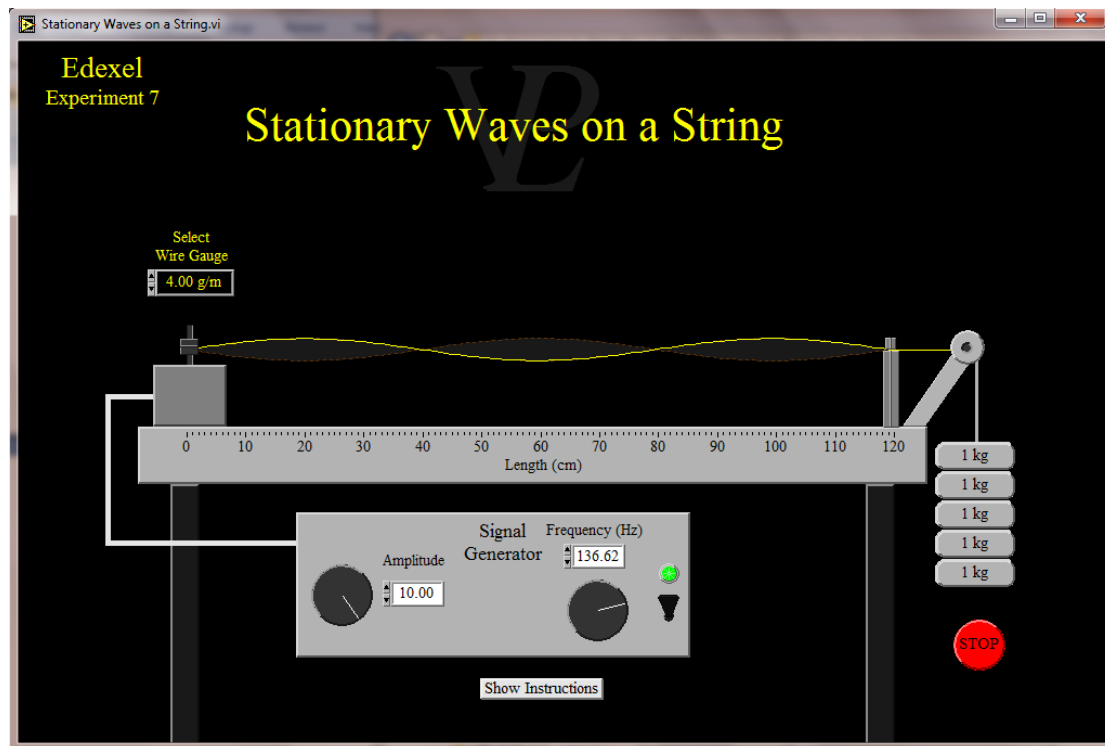
You are preparing for an experiment to measure the speed of sound using a signal generator, a speaker, a microphone and a dual beam oscilloscope.

- 1 - Switch the signal generator ON, and vary the amplitude and frequency using the knobs
- 2 - Switch the oscilloscope ON, and select the mode which you think will be most useful to you
- 3 - You can adjust the Gains of both channels using the outer (lighter) knobs, and the Offset using the inner (darker) knobs.
- 4 - The timebase is adjusted using the middle knob.
- 5 - Click and drag the microphone left or right.

The student is left to work out which measurements he/she considers most useful to generate a plot from which he/she will be able to calculate the speed of sound.

22.19 Edexcel Experiment 7. Vibrating Strings

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 7

Investigate the effects of length, tension and mass per unit length on the frequency of a vibrating string or wire

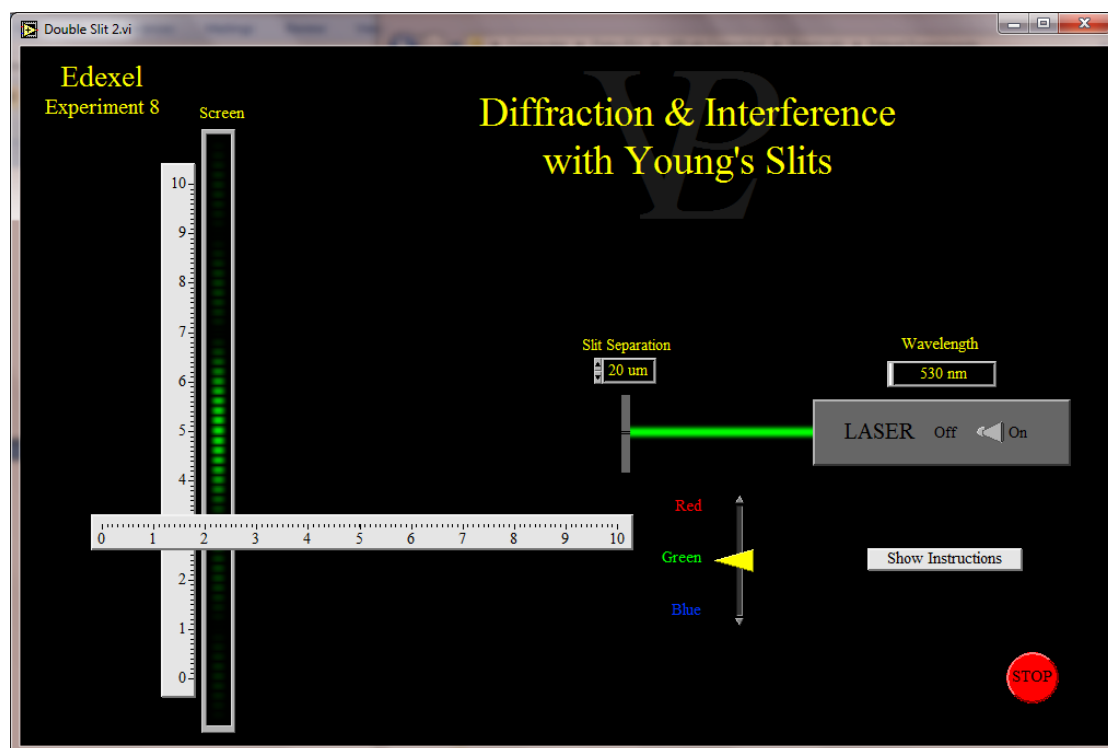
Simulation Instructions:

- 1 - You can change the amplitude and frequency of the signal generator using the two knobs (or type the frequency in the field)
- 2 - You can select the wire gauge by clicking inside the field
- 3 - You can change the length of the wire by clicking on the bridge and dragging it sideways.
- 4 - You can change the weights providing the tension by clicking on the masses and dragging up or down.

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis of results.

22.20 Edexcel Experiment 8. Wavelength by Diffraction

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 8

Determine the wavelength of light from a laser or other light source using a diffraction grating

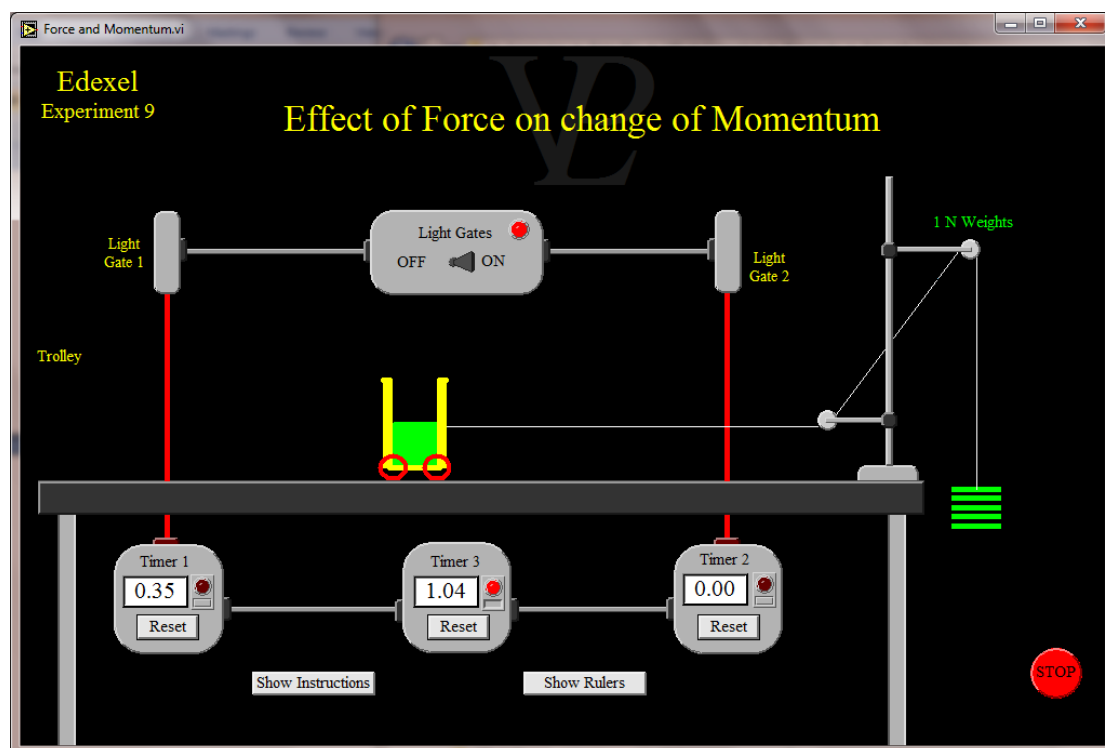
Simulation Instructions:

- 1 - Turn the laser ON using the switch on the right hand side
- 2 - Select the slit separation by clicking inside the field
- 3 - Select the Laser wavelength to be used using the yellow vertical slider.
- 4 - The two rulers show units in cm.
- 5 - Click on the bottom part of the screen and drag it left or right to change its distance from the slits.
- 6 - Carry out whatever measurements you need in order to work out what the approximate slit separation is in the unknown pair.
- 7 - Carry out whatever measurements you need in order to work out the unknown blue wavelength is.
- 8 - Estimate what your uncertainty is likely to be for both 6 and 7.

The student is left to devise the experimental procedure to be followed, the data which should be recorded and the analysis of results.

22.21 Edexcel Experiment 9. Force and Momentum

Advanced



This simulation was designed to help students prepare for Edexcel practical experiment No 9

Investigate the relationship between the force exerted on an object and its change of momentum

Simulation Instructions:

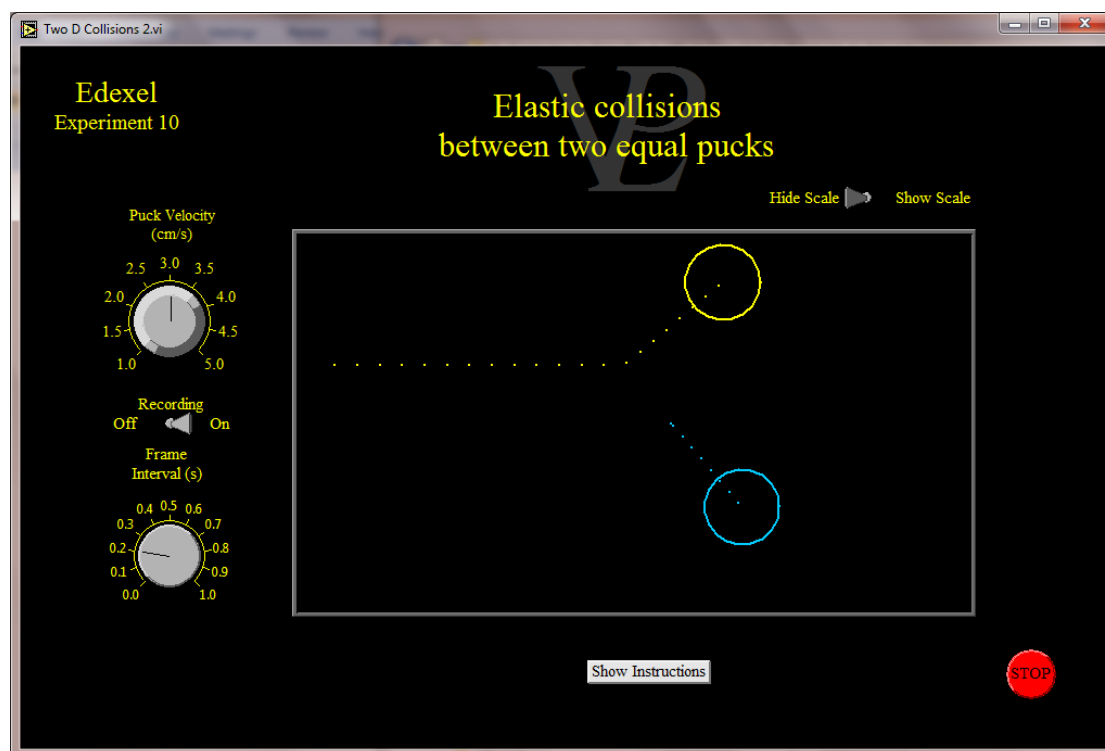
You are preparing for a practical experiment to investigate the relationship between Force and change of Momentum.

- 1 - The light gates are switched on at the top, and the timers respond to broken light beams.
- 2 - Click on the weights at the right hand side and drag up or down to change the number of 1 N weights used to pull the trolley. Notice that the total number of masses is kept constant: they are either on the mass hanger, or on the trolley.
- 3 - Press the green "Release" button to unclamp the pulley and so let the tension through to the trolley.
- 4 - Press the "Show Rulers" button to display rulers with which you can measure the length of the trolley, and the separation of the light gates.
- 5 - Reset each of the timers by pressing its button.
- 6 - Press the green "Reset" button to move the trolley back to the starting position.

The student is left to devise the experiment and take whatever measurements he/she think are necessary, followed by the analysis of the measurements and the conclusions.

22.22 Edexcel Experiment 10. Collisions

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 10

Use ICT to analyse collisions between small spheres, e.g. ball bearings on a table top

Simulation Instructions:

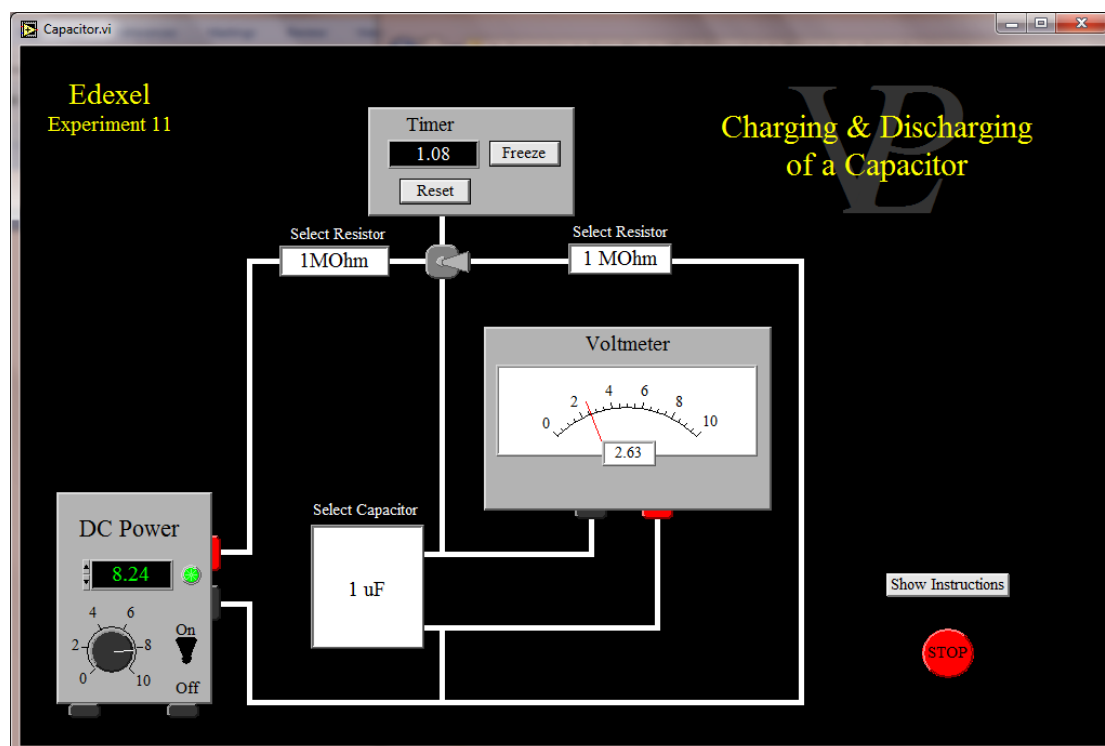
You are preparing for a practical experiment investigating collisions in 2 dimensions.

- 1 - Adjust the initial velocity of the yellow puck using the knob on the top left.
- 2 - Click and drag the yellow puck Up or Down to change its position.
- 3 - Press the green GO button at the bottom left to set the yellow puck into motion.
- 4 - To run again, press the green Reset button at the bottom right.
- 5 - If you want to record the positions of the pucks, toggle the Recording switch to ON, and set the recording interval with the knob below.
- 6 - To display a cm scale to help you with your measurements, toggle the switch at the top right hand side.

The student is left to devise the design of the experiment, what initial settings to use, what to record, and how analyse the results.

22.23 Edexcel Experiment 11. Capacitors

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 11

Use an oscilloscope or data logger to display and analyse the potential difference (p.d.) across a capacitor as it charges and discharges through a resistor

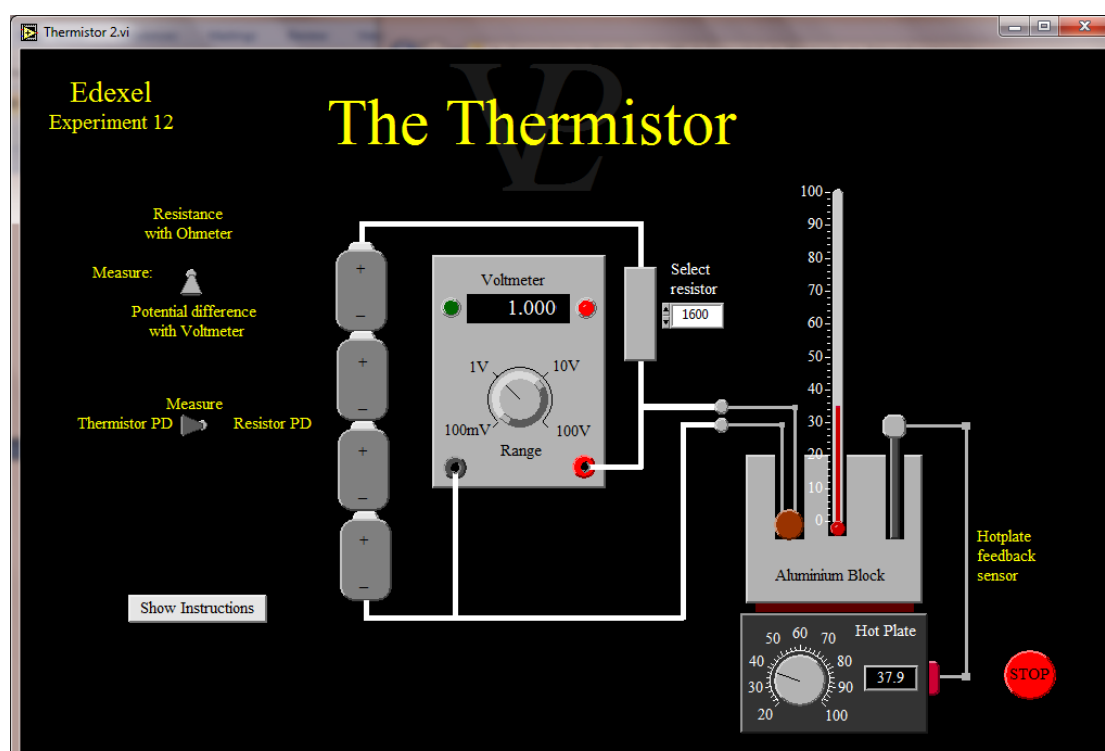
Simulation Instructions:

- 1 - Switch on the power supply, and set any desired voltage.
- 2 - Click inside the resistors and select the values you want them to have.
- 3 - Click on the capacitor and select the value you want it to have.
- 4 - Toggle the central switch in order to start the charging or discharging of the capacitor. Notice that the timer starts automatically when you toggle this switch.
- 5 - Carry out an experiment to determine the effect of the resistance and capacitance on the charging and discharging time constant

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis required to determine the effect.

22.24 Edexcel Experiment 12. Thermistors

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 12

Calibrate a thermistor in a potential divider circuit as a thermostat

Simulation Instructions:

You are preparing for a practical experiment where you will be relating the temperature to the voltages across a potential divider containing a resistor and a thermistor. The circuits can be used either as a thermometer or as a thermostat to drive a relay switch and so control a heater.

The relay will energise ON when a voltage greater or equal to 3V is applied to it.

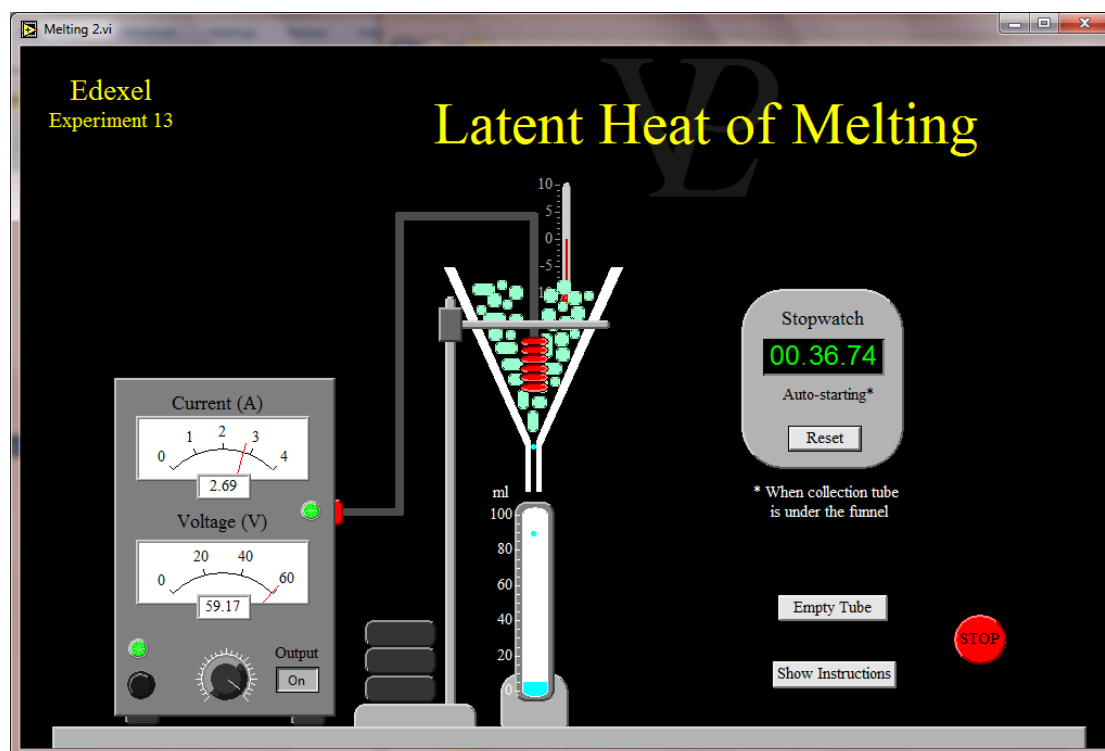
Carry out an experiment to find what value resistor would be best suited to switch the resistor ON when the temperature drops below 65 C. Draw a diagram showing where you would connect the relay switch.

- 1 - Use the vertical toggle switch to choose whether to measure the resistance of the thermistor with an Ohmmeter or the voltages across either of the components.
- 2 - Use the horizontal toggle switch to select which of the potential differences you want to measure.
- 3 - Turn the knob on the hot plate to set the temperature at which you want the aluminium block settle.
- 4 - Click inside the Select Resistor field and select the value of the fixed resistor you would like to use to obtain an output which you can best relate to the temperature range between 20 and 100 C.

The student is left to decide which resistor to select, what measurements to make and how to plot and analyse the data.

22.25 Edexcel Experiment 13. Latent Heat

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 13

Determine the specific latent heat of a phase change

Simulation Instructions:

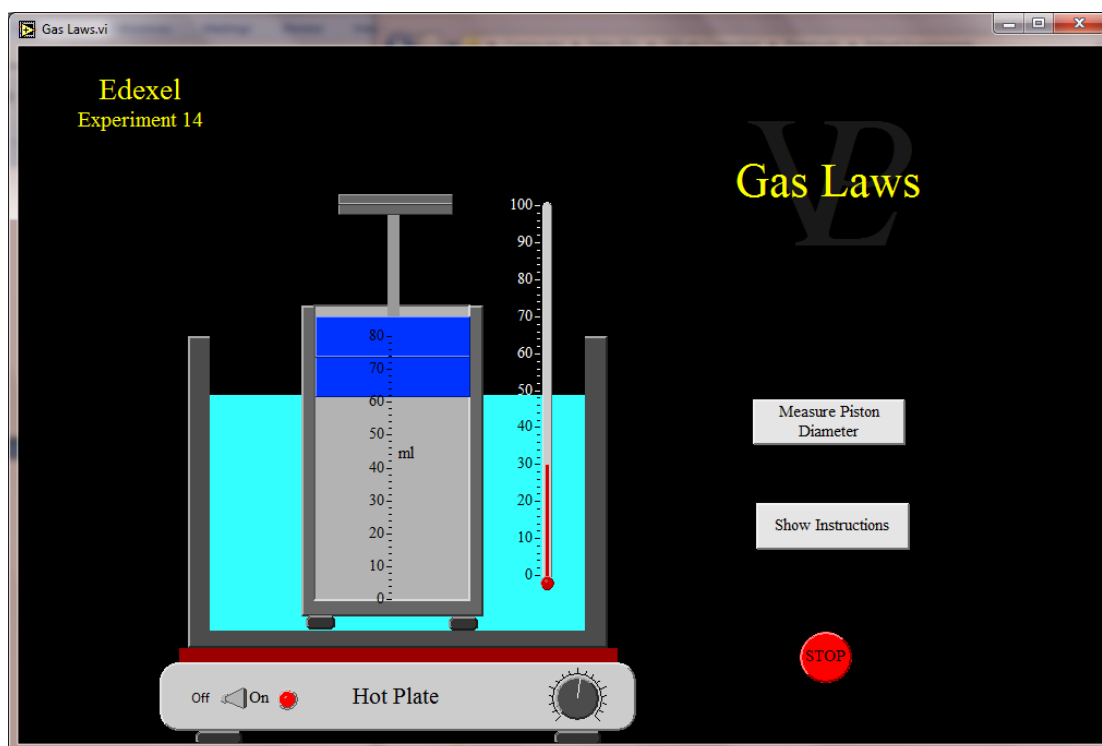
You are preparing to carry out a practical experiment to determine the latent heat of freezing.

- 1 - Notice that left to itself the ice will melt and water will drip out of the funnel
 - 2 - The rate of melting can be increased if a heater element inserted in the ice funnel is powered up.
 - 3 - The collection tube can be clicked and dragged to sit under the funnel and so collect the drips.
 - 4 - When the collection tube is in place, the stopwatch will start automatically. When it is dragged out again the stopwatch will stop.
- Additional challenge: It should also be possible to calculate the rate of heat gain from the surroundings. See if you can do it!

The student is left to devise the experimental procedure, the measurements to record and the analysis.

22.26 Edexcel Experiment 14. Gas Laws

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 14

Investigate the relationship between pressure and volume of a gas at fixed temperature

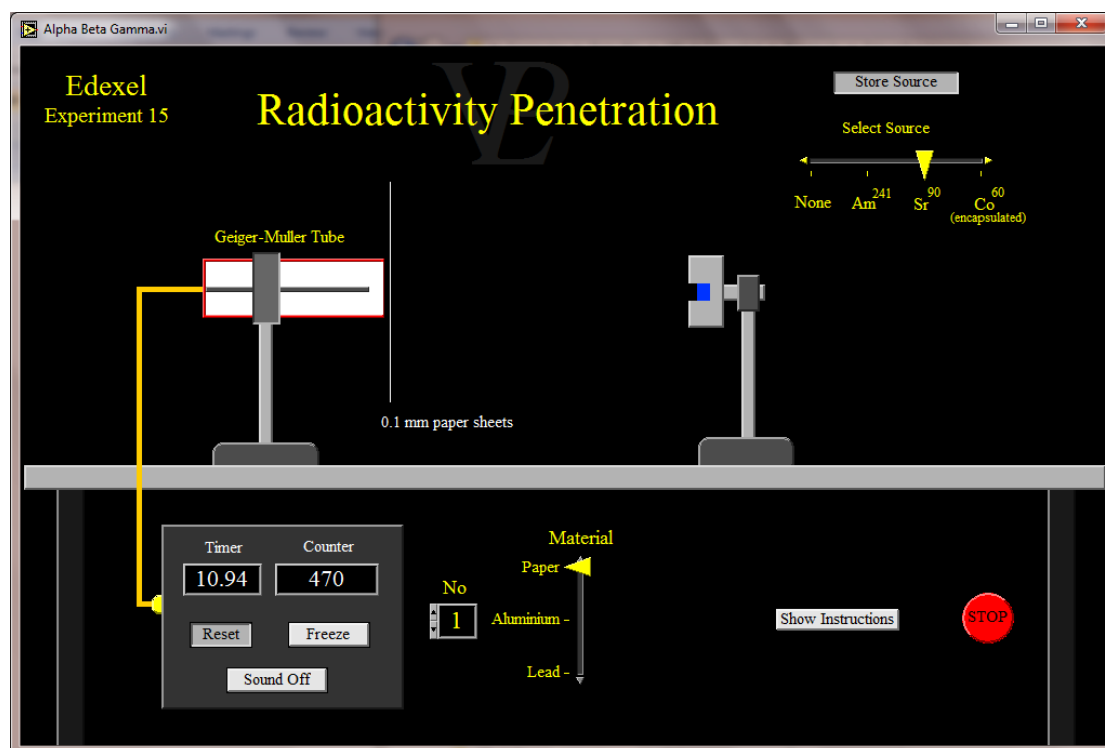
Simulation Instructions:

- 1 - The frictionless piston can move up and down inside the measuring cylinder. The volume of the gas is shown in the scale in millilitres. The starting volume is 60 millilitres.
- 2 - Exert pressure on the piston by adding 2 kg masses on top of the plunger above the piston; do this by clicking on it and dragging upwards or downwards.
- 3 - You can measure the diameter of the frictionless piston by pressing the "Measure Piston Diameter" button. Measure it several times.
- 4 - Wait until piston stops moving before taking a reading of the volume. The pressure is calculated from the mass and the piston face area.
The water bath maintains a steady temperature as you vary the pressure. However, if you want to carry out an experiment at constant pressure instead, remove all the masses from the plunger first.
- 5 - Switch the thermostatically controlled hot plate on and set the temperature to say 1/6th of the range. Wait until piston stops moving before taking a reading
- 6 - Increase the temperature and take more readings.

The student is left to devise the experimental procedure, the recording of data, and the plotting and analysis required to calculate the Young's modulus of the material selected.

22.27 Edexcel Experiment 15. Alpha, Beta, Gamma

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 15

Investigate the absorption of gamma radiation by lead

Simulation Instructions:

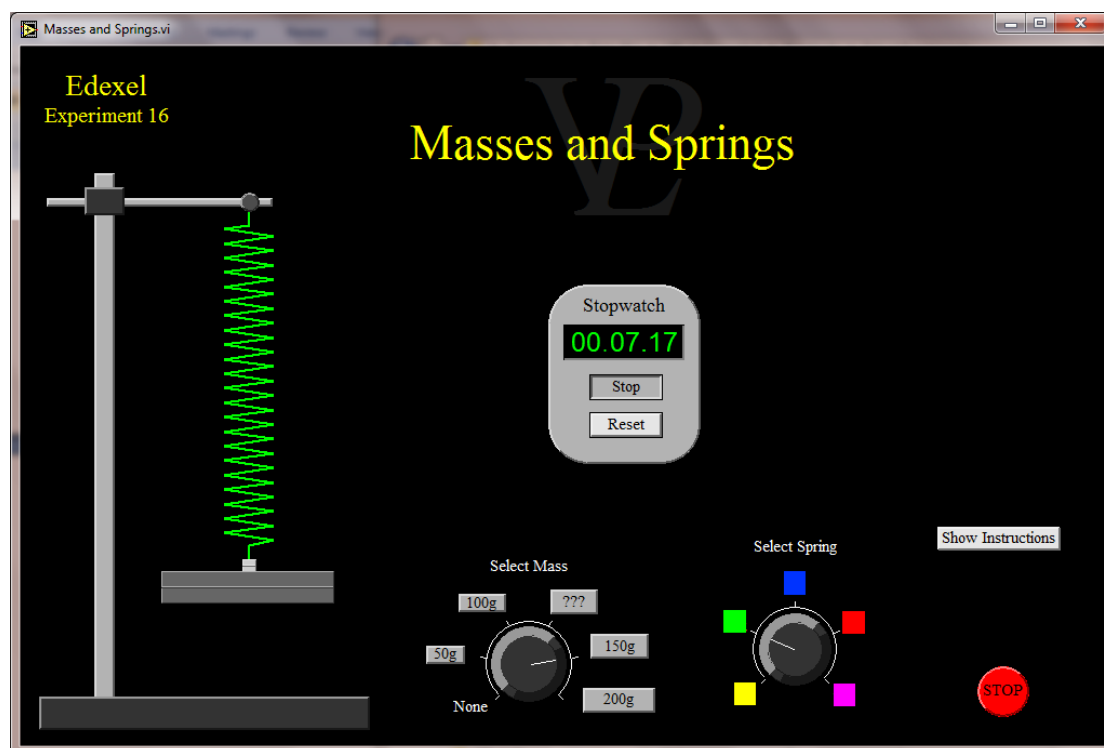
You are preparing for a practical experiment investigating the attenuation of radioactive particles by different materials. There are 3 different sources you can use.

- 1 - The counter/timer automatically starts counting when you press Start. Press freeze to read the display. Press Reset to start again.
- 2 - There is some background radiation that should be taken into consideration
- 3 - Open the box by pressing the button and select the source you want to investigate.
- 4 - Click and drag the base of the stand which holds the source to the left or right in order to change its position.
- 5 - Select the material of the sheets you want to use to absorb the radiation using the vertical slider.
- 6 - Change the number of absorbing sheets by clicking inside the field and typing the number.

The student is left to devise the experimental procedure, the measurements to take, how long to time for and the subsequent analysis.

22.28 Edexcel Experiment 16. Masses and Springs

Advanced



This simulation is designed to help students prepare for Edexcel practical experiment No 16

Determine the value of an unknown mass using the resonant frequencies of the oscillation of known masses

Simulation Instructions:

You are preparing for a practical experiment where you will try to deduce the value of an unknown mass by measuring the period with which it oscillates when hanging on a spring. Several different springs and some known masses are also given for you to use.

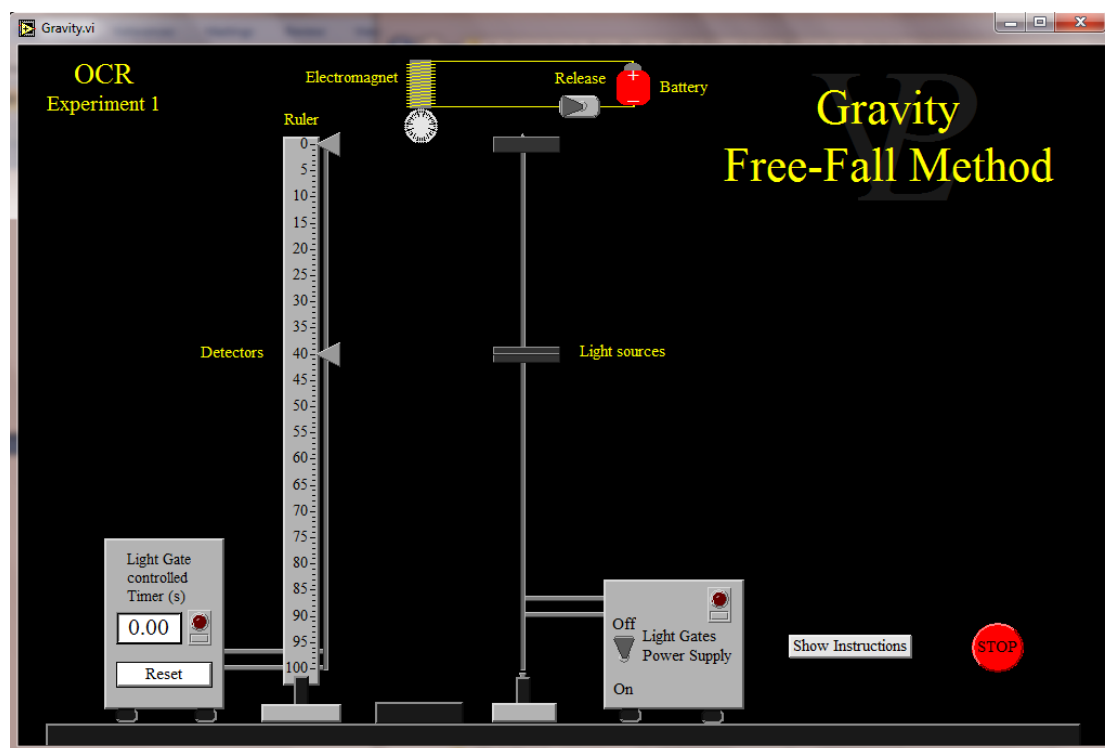
- 1 - Select the spring you want to use with the right hand knob.
- 2 - Select the mass you want to hang using the left hand knob.
- 3 - Use the stop-watch to help to measure the period of oscillation.

Note: The unknown Mass No 3 is changed each time the program is started. So if you abort and re-start the program previous measurements made with Mass No 3 will not be valid.

The student is left to devise the experimental procedure to follow, the measurements to record and the analysis needed to deduce the unknown mass.

22.29 OCR Experiment 1. Gravity by Free Fall method

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 1

Acceleration of free fall

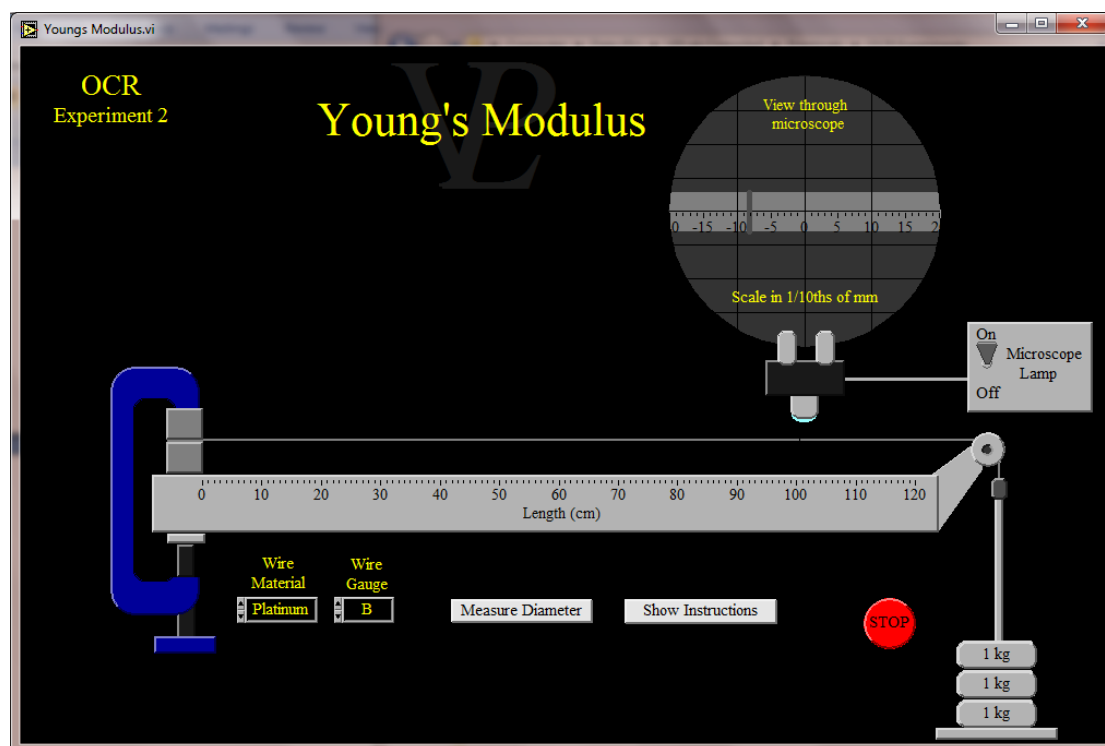
Simulation Instructions:

- 1 - The switch on the electromagnet circuit releases the steel ball
- 2 - The reset button on the light gates timer also replaces the steel ball
- 3 - The light gates power supply must be switched on for them to detect the passing of the ball and trigger the timer.
- 4 - The light gates can be dragged up or down to any desired position (click on the light sources)

The student is to devise the experimental procedure to be followed, the recording of the data, the plotting of graphs and the calculation of gravity.

22.30 OCR Experiment 2. Young's Modulus by Extension

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 2

Determining Young's Modulus for a metal

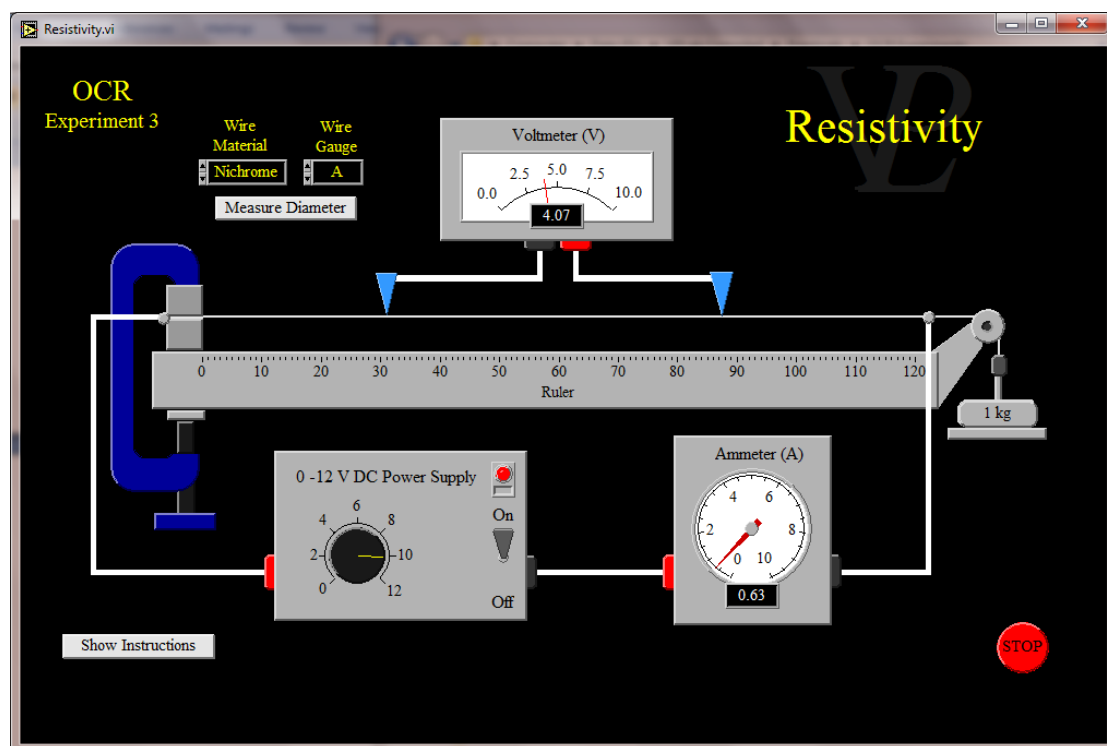
Simulation Instructions:

- 1 - Add or remove 1 kg masses on the right hand side by clicking on the masses and dragging up or down
- 2 - You can select the wire material and gauge by clicking inside the fields
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Switch the microscope ON to see how the wire extends as you load it. Record the extensions for different weights.

The student is to devise the experimental procedure to be followed the recording of data, and the plotting and analysis required to calculate the Young's modulus of the material selected.

22.31 OCR Experiment 3. Resistivity of Metals

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 3

Determining the resistivity/conductivity of a metal

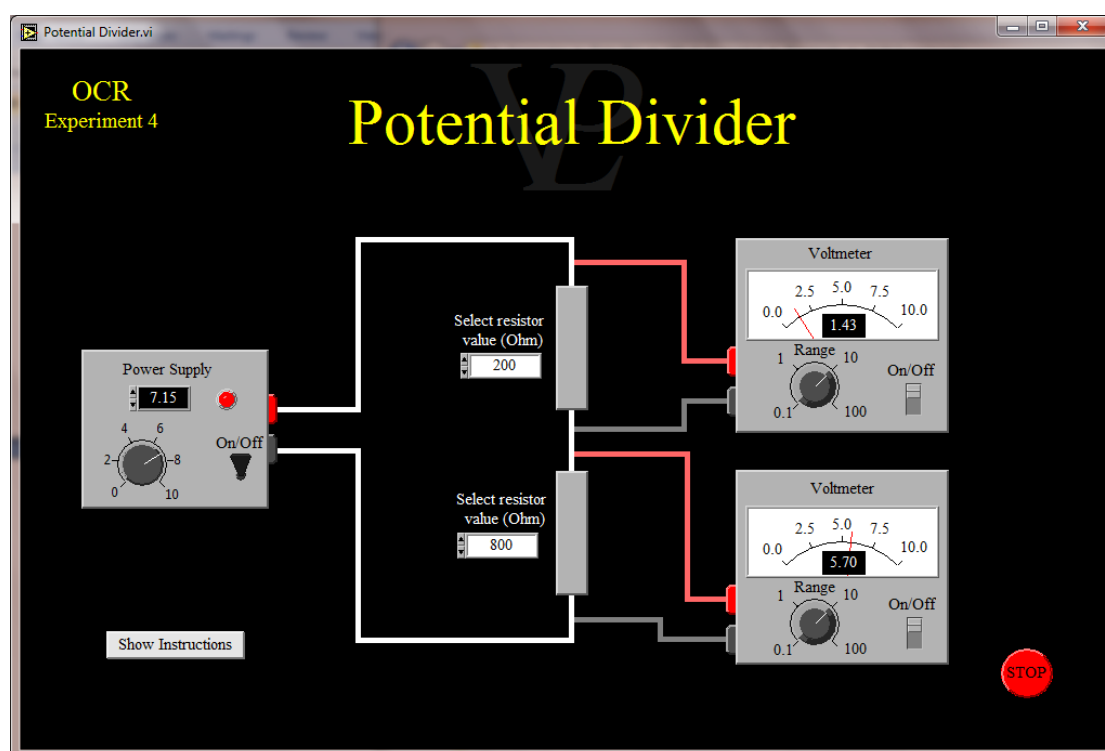
Simulation Instructions:

- 1 - Select the material you want to test by clicking in the field
- 2 - Select a suitable wire diameter by clicking in the field (A is the thinnest)
- 3 - You can measure the diameter of the wire by clicking the "Measure Diameter" button and then reading the micrometer. Take a few repeat measurements.
- 4 - Make sure the knob is turned down to zero before switching the power supply ON. If you drive a current of more than 10 A, the circuit breaker will trip and switch the power supply Off automatically.

The student is to devise the experimental procedure to be followed the recording of data, and the plotting and analysis required to calculate the resistivity of the material you selected.

22.32 OCR Experiment 4. Potential Divider Circuits

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 4

Investigation of potential divider circuits

Simulation Instructions:

You will be investigating the behaviour of a potential divider. You are provided with a power supply, a range of fixed resistors, and two voltmeters.

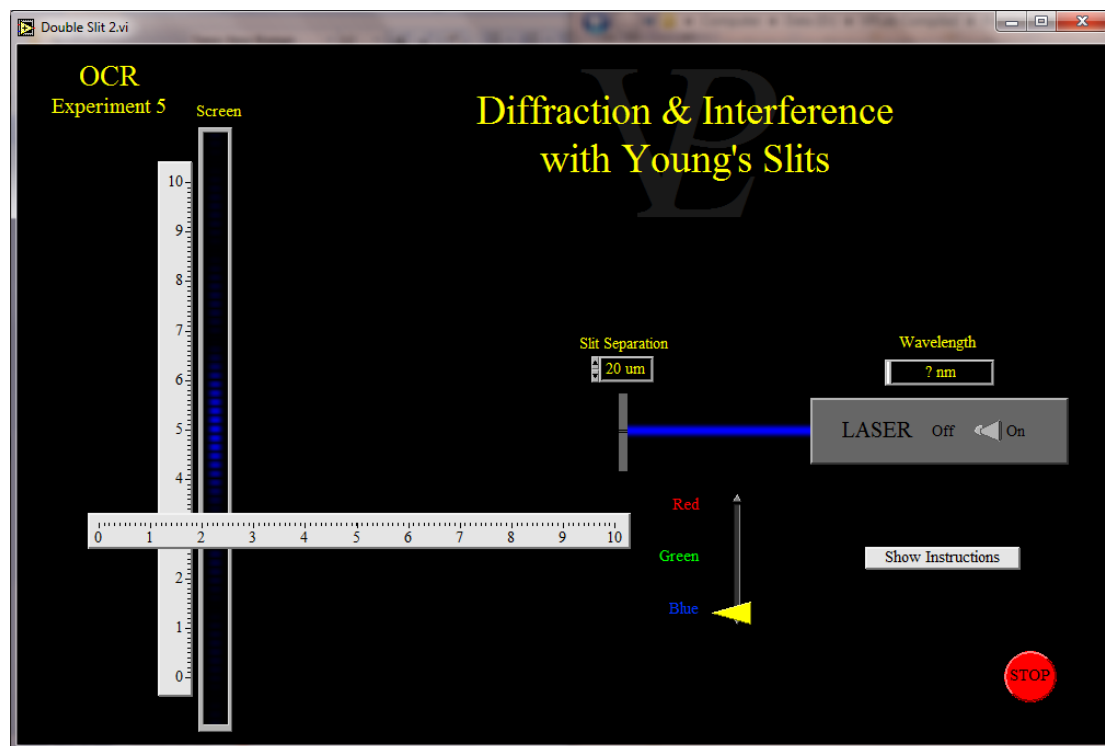
- 1 - Switch the power supply On by clicking on the toggle switch.
- 2 - Switch the two voltmeters ON by clicking on the slider switch
- 3 - Adjust the voltage by turning the knob on the power supply.
- 4 - Click inside the field to the left of the resistors and select the value resistor you want to use. Notice that the first value is unknown.
- 5 - The range of the voltmeters can be changed using the knob below the display.

Challenge: Once you have worked out the properties of a potential divider, see if you can use it to work out the values of the two unknown resistors.

The student is to devise the experimental procedure to be followed: What combination of resistors to select, what measurements to make and how to analyse the data obtained in order to show the properties of a potential divider.

22.33 OCR Experiment 5. Wavelength by Young's Slits

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 5

Determination of the wavelength of light and sound by two source superposition with a double-slit and diffraction grating

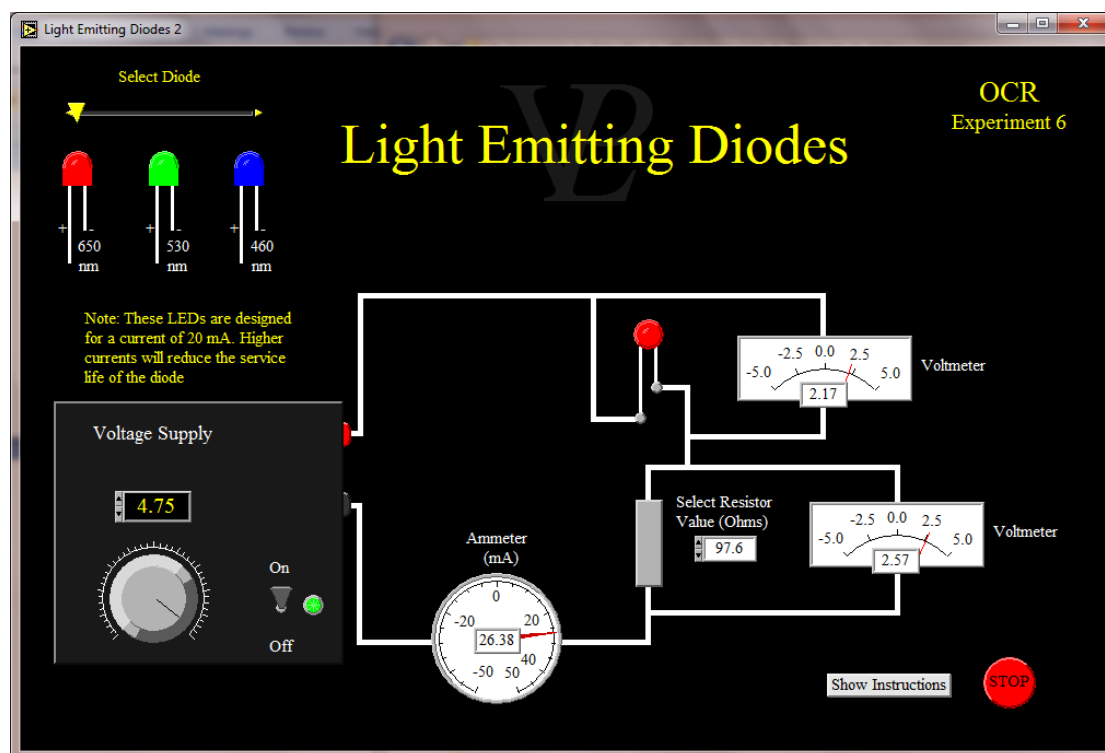
Simulation Instructions:

- 1 - Turn the laser ON using the switch on the right hand side
- 2 - Select the slit separation by clicking inside the field.
- 3 - Select the Laser wavelength to be used using the yellow vertical slider.
- 4 - The two rulers show units in cm.
- 5 - Click on the bottom part of the screen and drag it left or right to change its distance from the slits.
- 6 - Carry out whatever measurements you need in order to work out what the approximate slit separation is in the unknown pair.
- 7 - Carry out whatever measurements you need in order to work out the unknown blue wavelength is.
- 8 - Estimate what your uncertainty is likely to be for both 6 and 7.

The student is to devise the experimental procedure to be followed.

22.34 OCR Experiment 6. Planck Constant by LEDs

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 6

Determination of Planck's constant using LEDs

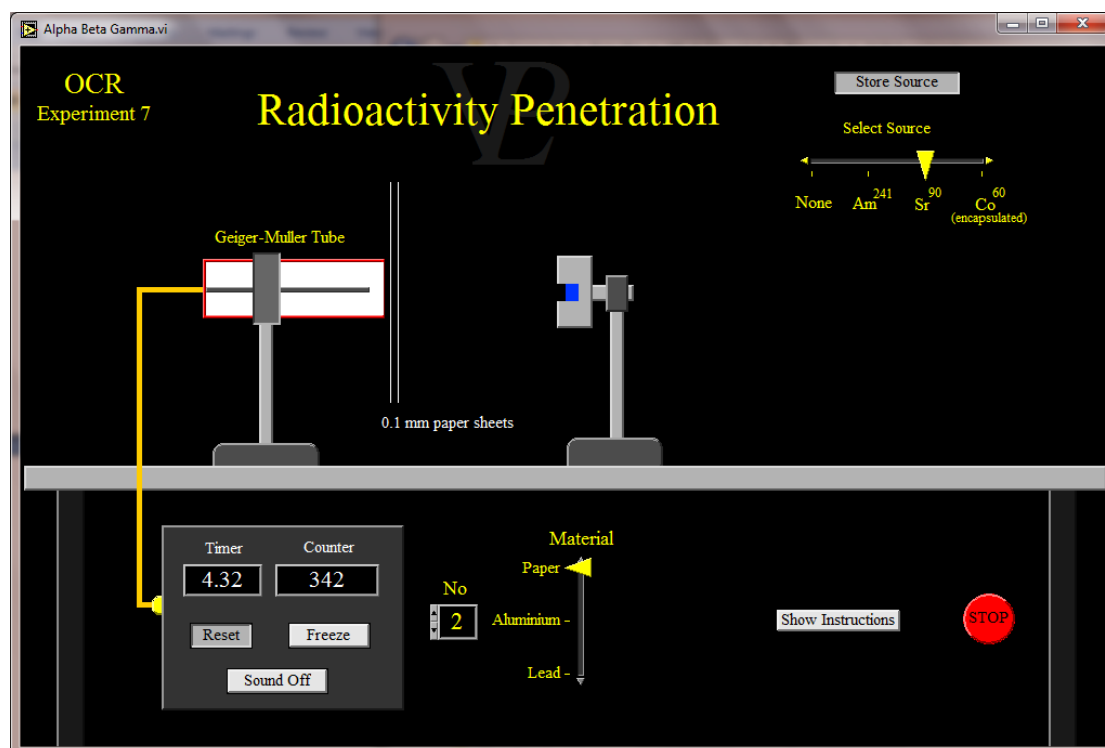
Simulation Instructions:

- 1 - Select the colour diode you want to use with the slider at the top right hand side.
- 2 - Select the current limiting resistor you wish to use by clicking in the field at the top right hand side.
- 3 - Switch the power supply ON, and increase the voltage gradually using the knob.
- 4 - Investigate what happens when the voltage is negative instead.
- 5 - Carry out whatever experiment you think you need to do and record any required data so that you can plot any necessary graphs and calculate an estimate of Planck's constant.

The student is to devise the experimental procedure to be followed.

22.35 OCR Experiment 7. Absorption of Alpha, Beta, Gamma

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 7

Absorption of alpha or beta or gamma radiation

Simulation Instructions:

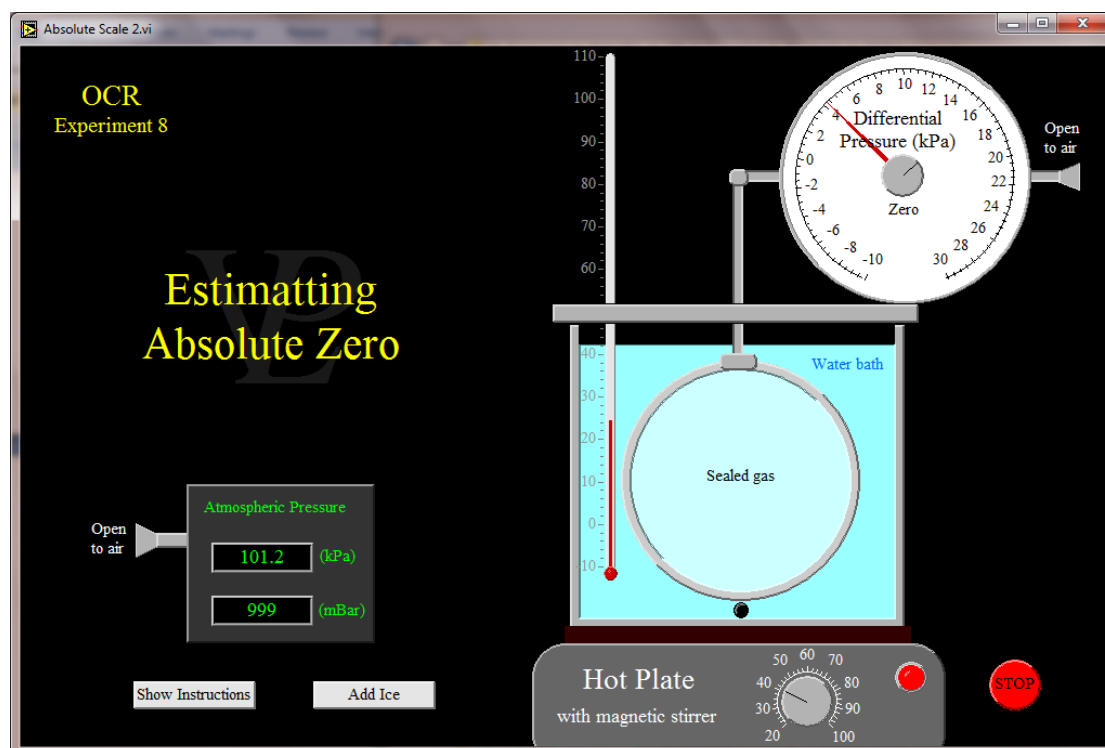
Investigating the attenuation of radioactive particles by different materials. There are 3 different sources you can use.

- 1 - The counter/timer automatically starts counting when you press Start. Press freeze to read the display. Press Reset to start again.
- 2 - There is some background radiation that should be taken into consideration
- 3 - Open the box by pressing the button and select the source you want to investigate.
- 4 - Click and drag the base of the stand which holds the source to the left or right in order to change its position.
- 5 - Select the material of the sheets you want to use to absorb the radiation using the vertical slider.
- 6 - Change the number of absorbing sheets by clicking inside the field and typing the number.

The student is to devise the experimental procedure to be followed, the measurements to take, how long to time for and the subsequent analysis.

22.36 OCR Experiment 8. Absolute Zero Estimation

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 8

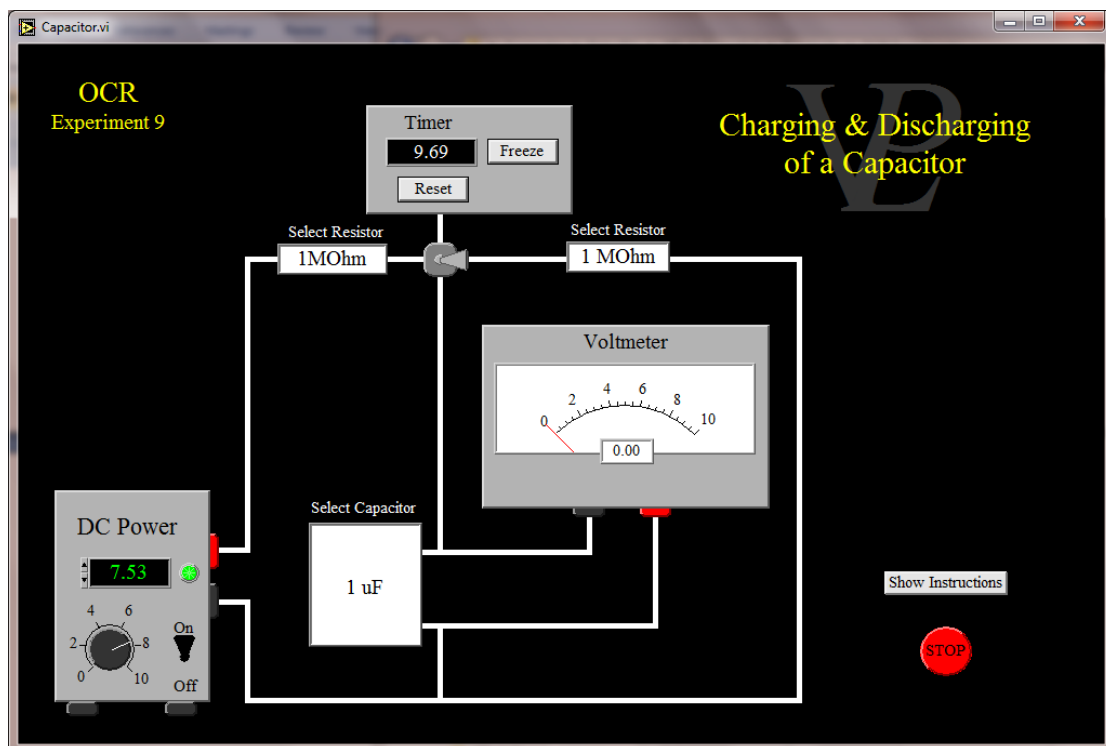
Determining an estimate of absolute zero using variation of gas temperature with pressure

Simulation Instructions:

You are preparing for a practical experiment in which you will try to estimate the value of absolute zero. You are provided with a thermometer, a barometer to measure atmospheric pressure as well as a differential pressure gauge fitted to a sealed gas container in a water bath.

- 1 - You can adjust the differential pressure zero point using the central knob.
- 2 - A magnetic stirrer is fitted to equalise the temperature throughout the bath.
- 3 - Press the Add Ice button to reduce the temperature of the bath down to around 0 C.
- 4 - Press the Remove Ice button to take out the ice before heating the water bath.
- 5 - The temperature of the water bath can be adjusted using the knob on the hot plate.

The student is to devise the experimental procedure to be followed what measurements to make, what graph to plot and what analysis to make.

22.37 OCR Experiment 9. Capacitor Charging and Discharging Advanced

This simulation was designed to help students prepare for OCR set practical experiment No 9

Determining time constant using the gradient of $\ln V$ or $\ln I$ -time graph

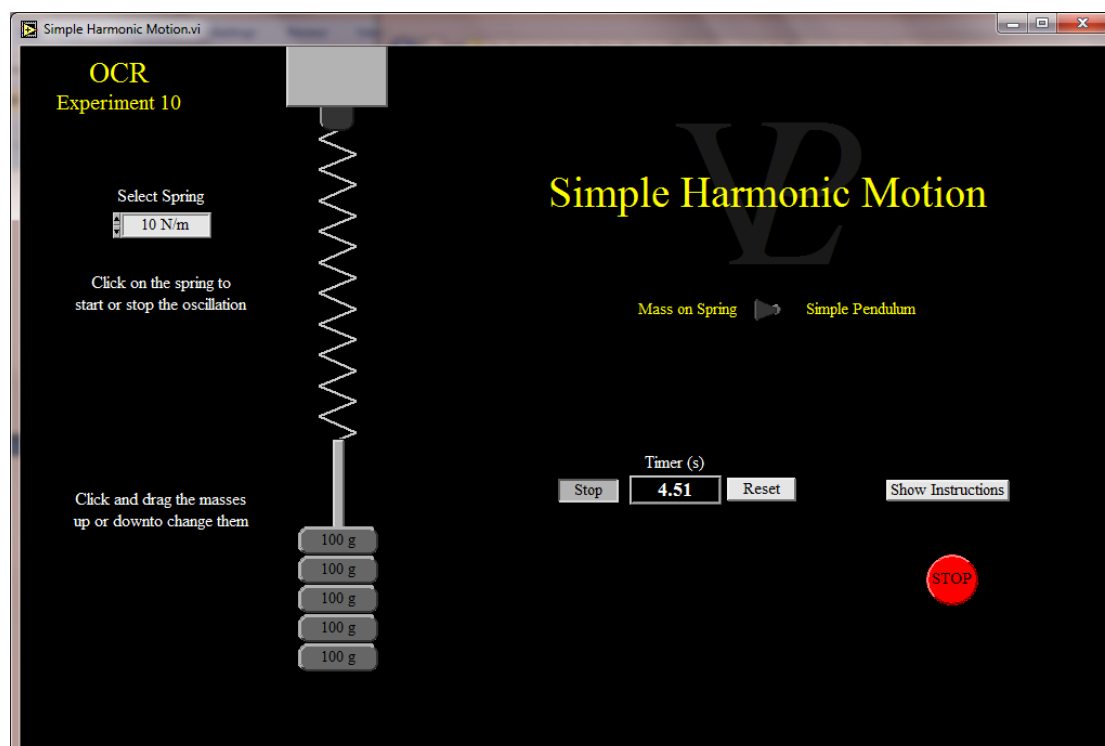
Simulation Instructions:

- 1 - Switch on the power supply, and set any desired voltage.
- 2 - Click inside the resistors and select the values you want them to have.
- 3 - Click on the capacitor and select the value you want it to have.
- 4 - Toggle the central switch in order to start the charging or discharging of the capacitor. Notice that the timer starts automatically when you toggle this switch.
- 5 - Carry out an experiment to determine the effect of the resistance and capacitance on the charging and discharging time constant

The student is to devise the experimental procedure to be followed, the recording of data, and the plotting and analysis required to determine the time constant.

22.38 OCR Experiment 10. Factors affecting SHM

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 10

Investigating the factors affecting the period of a simple harmonic oscillator

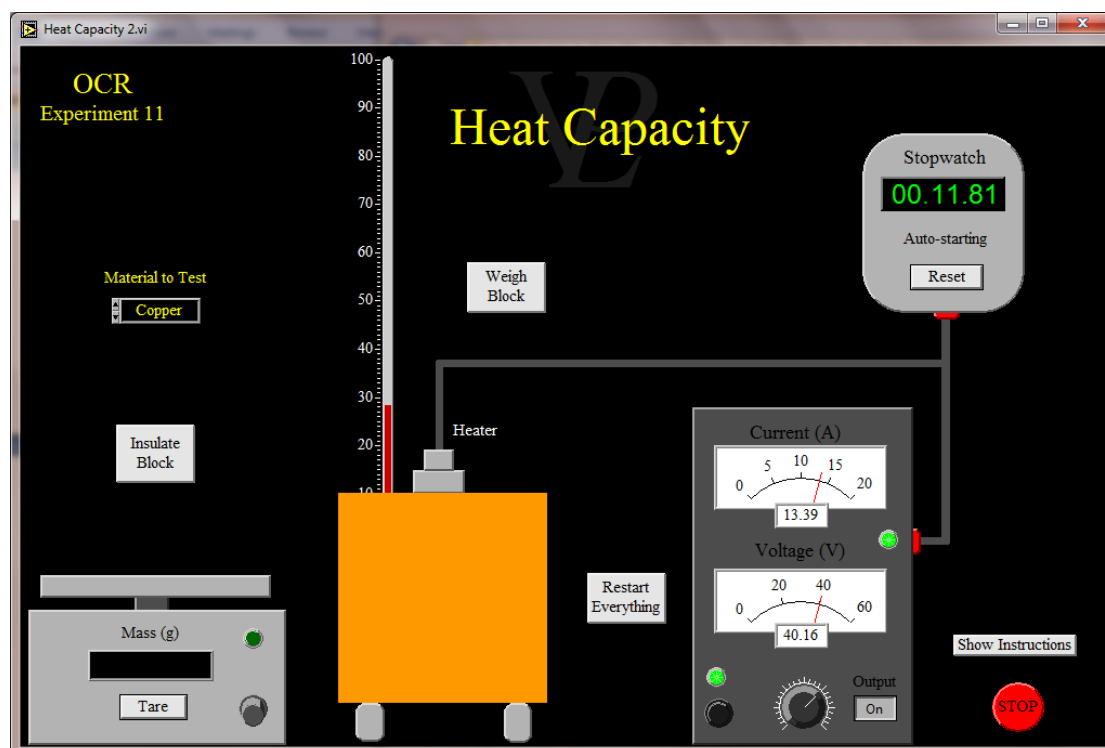
Simulation Instructions:

- 1 - Decide whether you want to study a mass on a spring or a pendulum, and use the horizontal toggle switch to select it.
- 2 - The oscillations are started and stopped by clicking near the top of the string or spring.
- 3 - The mass or the length of the pendulum are changed by clicking and dragging the mass or the pendulum up or down.
- 4 - The spring stiffness can be changed by clicking inside the field and selecting one of the options presented.
- 5 - Make sure you 'get into the rhythm' of the oscillations first, and then time an adequate number of oscillations so that you reduce errors due to reaction time.
- 6 - Use the stop-watch to obtain your timings.

The student is to devise the experimental procedure to be followed, the recording of data, and the plotting and analysis required to calculate the dependence of the period of oscillation.

22.39 OCR Experiment 11. Specific Heat Capacity

Advanced



This simulation was designed to help students prepare for OCR set practical experiment No 11

Determination of the specific heat capacity of a material

Simulation Instructions:

- 1 - Select the material you want to test (click inside the central yellow box and select one of the 5 materials)
- 2 - Switch the balance on, and press the Tare button to zero the display. Press the Weigh Block button to transfer the block to the scales.
- 3 - Press the Return Block to put the block of material back in its place with the heater inserted inside it.
- 4 - Switch the Power supply On, and adjust the voltage output with the knob. By default, the Output button will be Off.
- 5 - Press the Output Button so that it displays On. At that same time the current starts flowing, the stopwatch will start timing and the heater will start to heat up the block.
- 6 - Press the Output button again to stop the current output, and the stop-clock will automatically stop timing.
- 7 - Allow some time for the heat to be conducted through the block so that the temperature becomes uniform.
- 8 - Press the Insulate Block button to investigate the effect of insulating the block.

The student is to devise the experimental procedure to be followed, the choice of material, what procedure to follow, what measurements to take, what graphs to plot, and how to analyse the results.

CHAPTER 23

PRESSURE

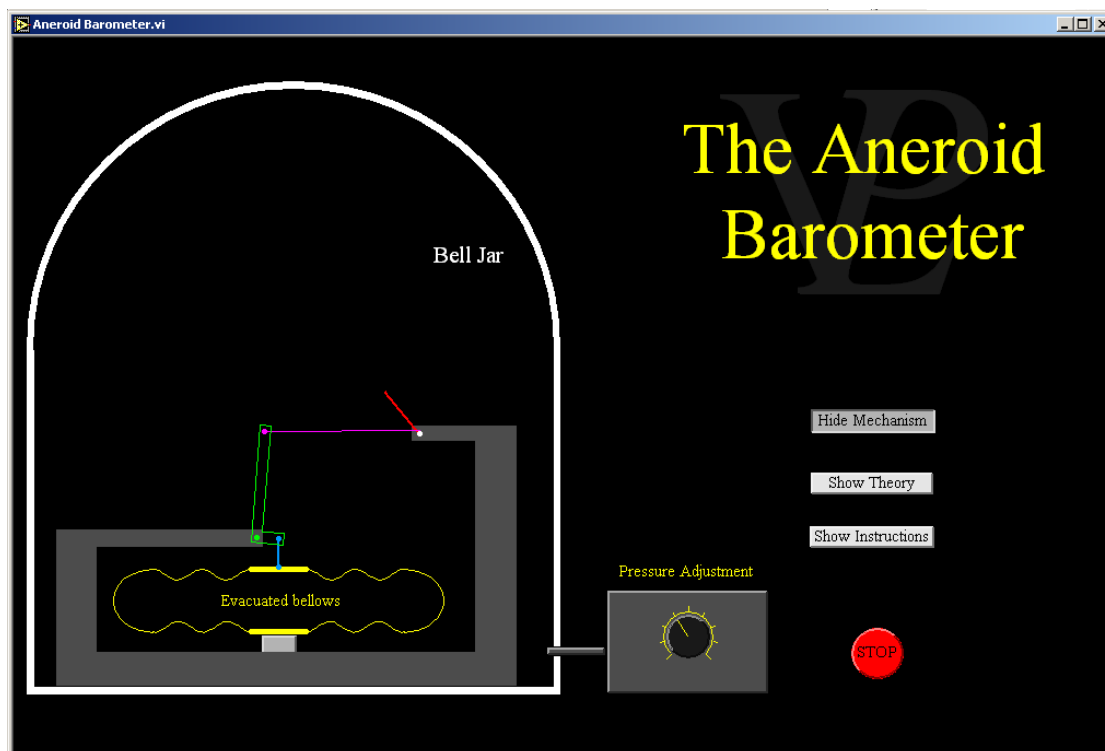


The right pressure in bike tyres makes a big difference to the ride.
What is pressure and how do we measure it?

23.1 Aneroid Barometer

Basic

This simulation shows how the internal components of an aneroid barometer work together to move a needle when the atmospheric pressure changes.



Traditional Barometers consist of a long inverted test-tube full of mercury, with the open end submerged in a beaker full of mercury which is open to the atmosphere.

Since mercury vapour is a health hazard, and these barometers were heavy and cumbersome, the Aneroid barometer was invented. This barometer has an evacuated capsule made of thin metal, so thin that changes in atmospheric pressure can change its shape! The changes are so small that they cannot be seen by eye. It is therefore necessary to amplify the movement using the principle of levers as well as that of a thin string wrapped round a very thin spindle. These two amplification devices make it possible to see the effect of the pressure changes.

Note: In this simulation the change in shape of the capsule has been greatly exaggerated!

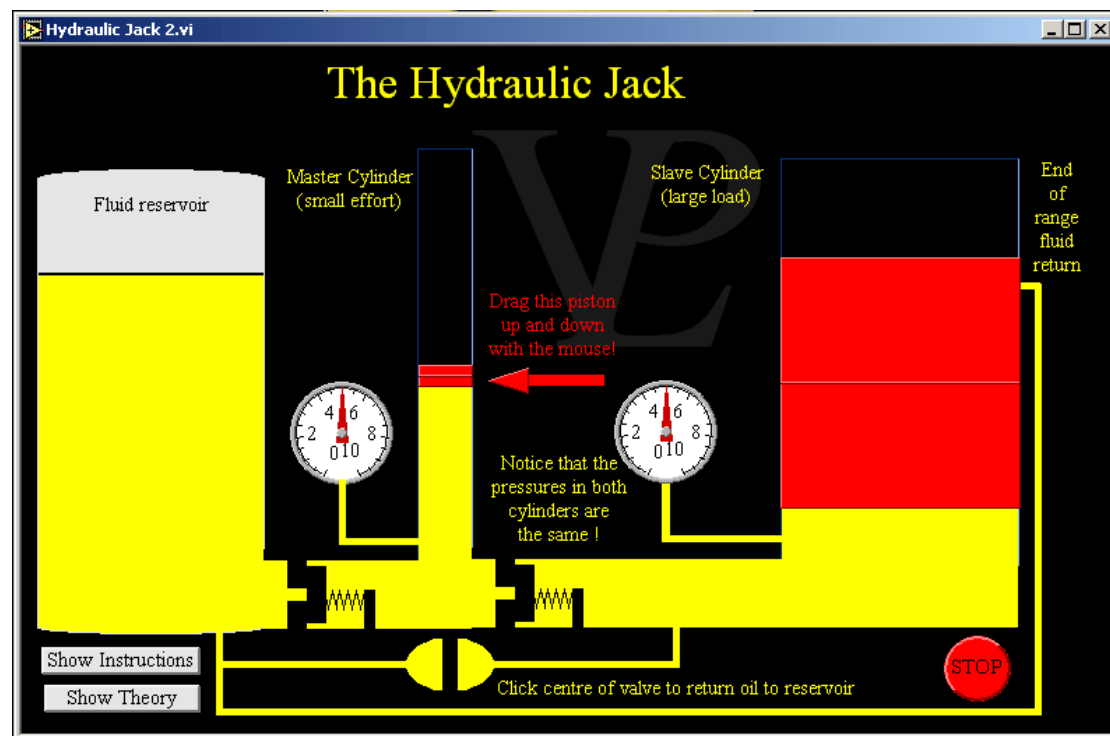
Atmospheric pressure falls as altitude increases because there is a smaller weight of air pressing down on the barometer. Barometers are therefore used in aviation, but it is important to know what the pressure is at ground level in order to know how close (vertically) you are to the runway!

Barometers are also useful indicators of weather changes. High pressure normally indicates dry weather and low pressure indicates rain.

23.2 Hydraulic Jack

Basic

The Hydraulic Jack simulation shows how when the piston of the master cylinder is pumped, oil flows past non-return valves and pushes the piston of the slave cylinder up. Pressure gauges show how the pressures in both cylinders are the same, and yet the force multiplication is achieved.



The master cylinder has a small diameter d and hence a small cross-sectional area a . The force f that is applied to the master piston produces a pressure p which is equal to f/a .

The slave cylinder has a large diameter D and hence a large cross-sectional area A . The load on the slave piston is F and it exerts pressure P on the oil beneath it which is equal to F/A .

Since the pressures of the oil in the two arms are equal, $p = P$.

$$f/a = F/A \quad \text{so} \quad F = f(A/a)$$

Now

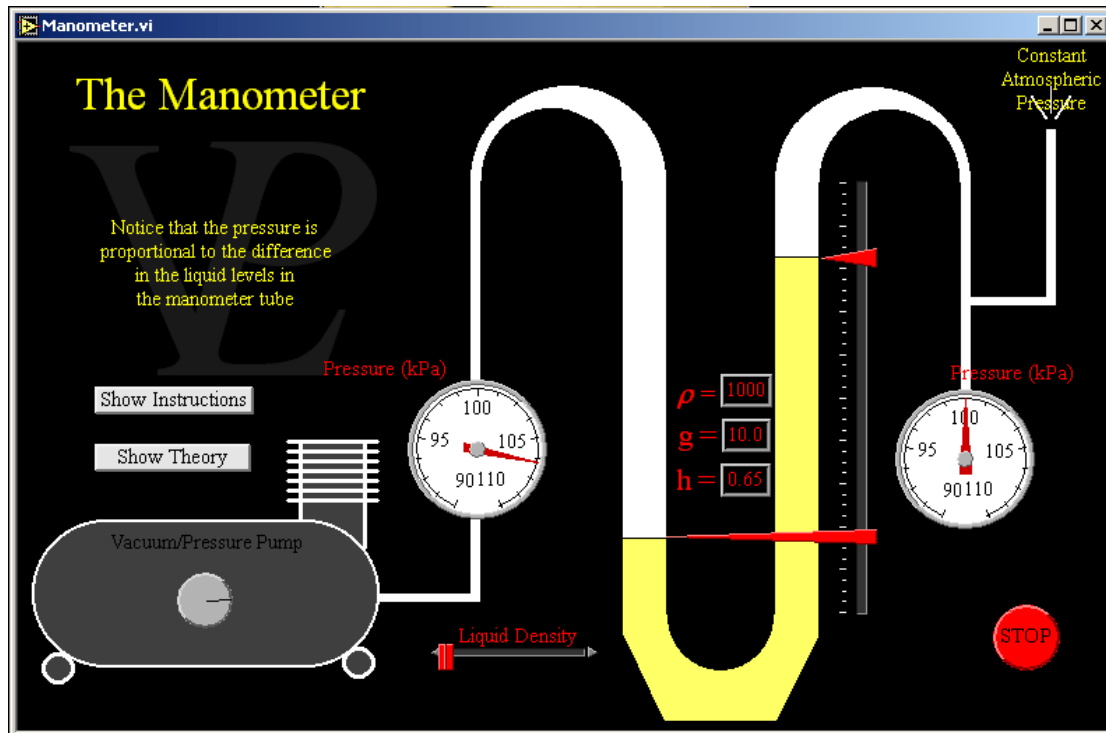
$$A/a = (D/d)^2 \quad \text{so} \quad F = f(D/d)^2$$

This means that even if the diameter D is 5 times larger than d , F can be 25 times larger than f . That is why a weak man can lift a two tonne truck with a jack.

23.3 Manometer

Basic

A simple U tube manometer is simulated to show how increased or reduced pressure in one side causes the levels to rise or fall relative to each other. The density of the liquid in the tube can also be changed.



The pressure below the surface of a liquid increases the deeper you go. This happens because of the added weight of liquid pressing down on the lower surface.

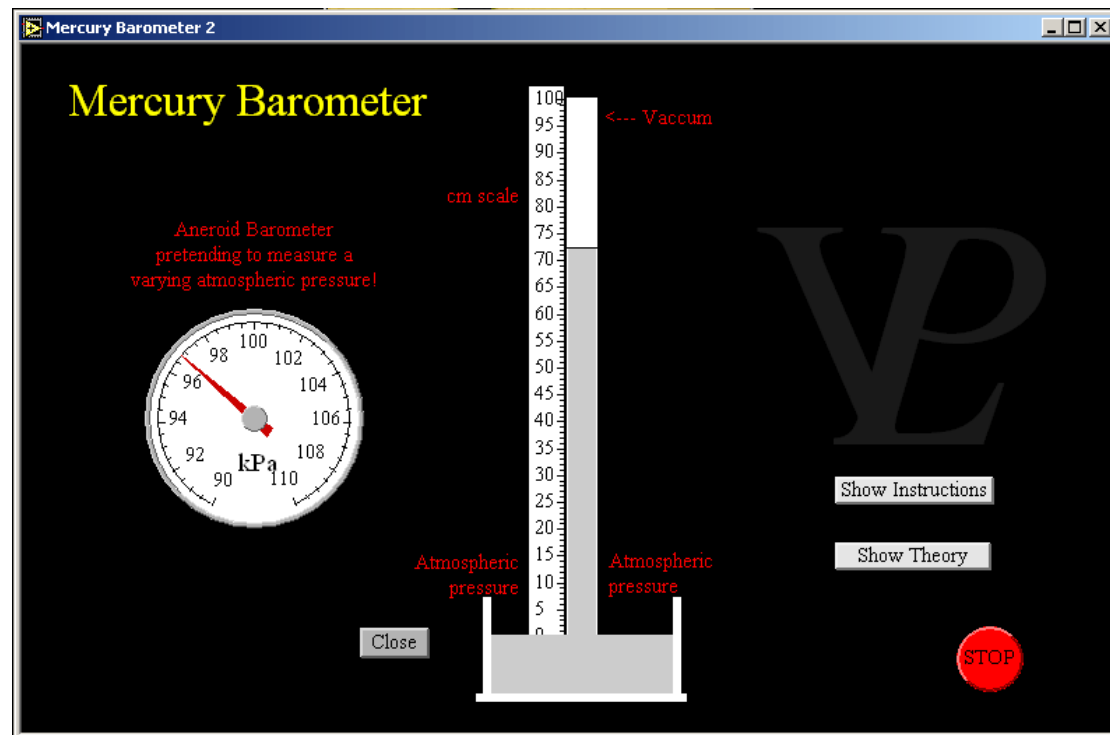
In a manometer or U Tube, the pressure difference between the sides causes a change in liquid surface levels.

The pressure difference P is given by the equation $P = \rho gh$,
 where ρ is the density
 g is the acceleration due to gravity
 h is the difference in liquid levels

23.4 Mercury Barometer

Basic

This simple simulation shows how a Mercury Barometer is made. It illustrates how the atmospheric pressure on the surface of the free mercury supports the weight of the mercury column.



The mercury barometer was the first type of system devised to measure atmospheric pressure.

The weight of the mercury causes the mercury level to fall until the level at which atmospheric pressure is strong enough to support the weight of the mercury column.

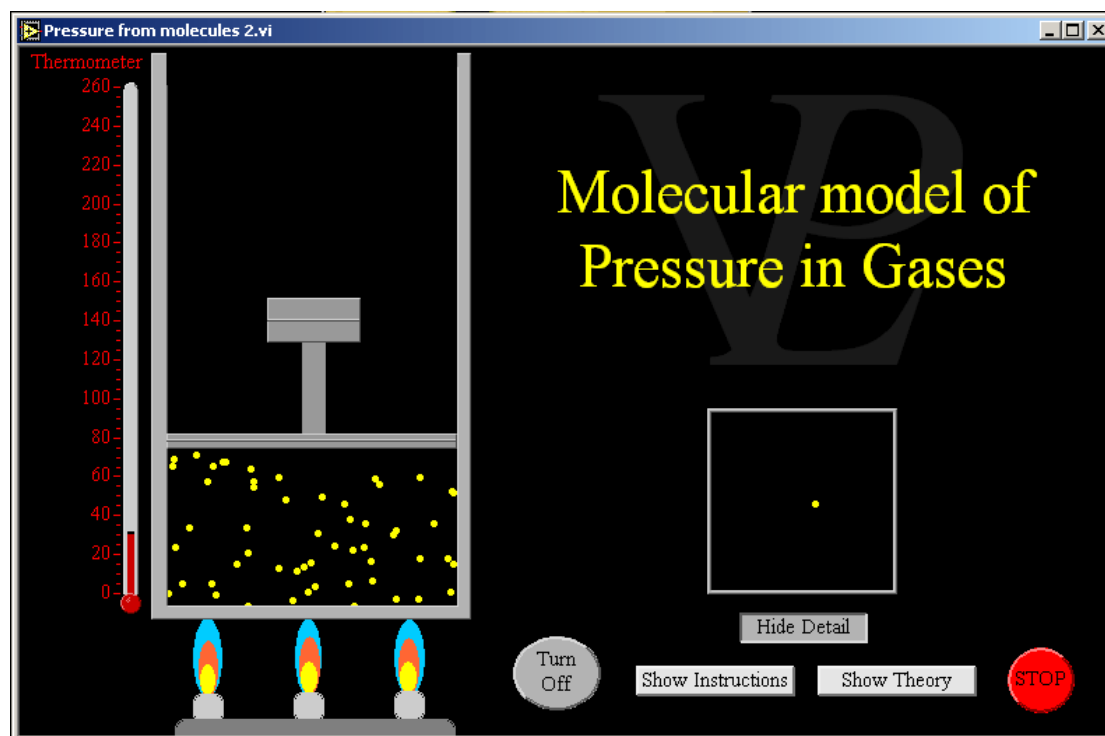
Notice that when the atmospheric pressure is high, the length of the mercury column increases, and when the atmospheric pressure falls the mercury level also falls.

If the tube is closed again with the rubber stopper at the bottom, the atmospheric pressure can no longer reach the mercury; the level remains stationary, as the pressure is now supplied by the rubber stopper. A question to check that you really understand what is going on. What will the height of the mercury in the column be if the diameter of the column is twice a large?

23.5 Pressure from Molecules

Advanced

This simulation helps to visualise how pressure is exerted by molecules striking the walls of the container which encloses them. It helps in understanding the effect of temperature on pressure.



The explanation is best given as a progressive list of events:

- 1 - When gas molecules strike the side of the container they bounce back off it.
- 2 - As a consequence of this, they experience a change of momentum.
- 3 - This change of momentum requires a force which the wall must have exerted on the molecule.
- 4 - Since 'action and reaction' are equal and opposite, the molecule must have exerted a force on the wall too.
- 5 - If all the microscopic forces due to the billions of molecules are added up, they can exert a considerable force.
- 6 - This average force is spread out over the entire area of the container walls to create a pressure.
- 7 - When the temperature rises, the velocity of the molecules increases such that they strike the walls harder and also more frequently. This increase in velocity causes a corresponding increase in momentum and thus increases the pressure.

Note that in this case, the pressure does not actually increase. It is at a little above atmospheric; just enough to support the weight of the mass resting on the piston. The reason the pressure does not increase is because the volume has increased, and so, although the molecules are striking harder, they are actually striking less frequently, because their round-trip distance has increased. The effect of the increased momentum and the longer round trip time cancel out. If the volume were to remain constant then the pressure would increase as expected.

CHAPTER 24

QUANTUM

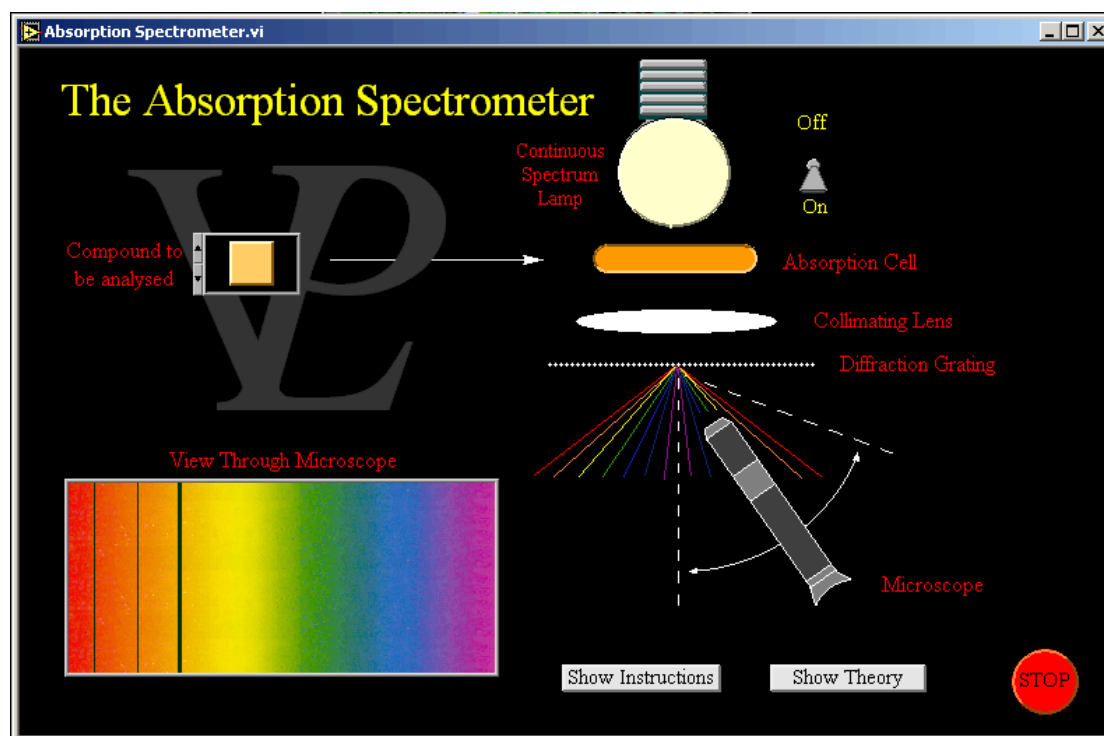


Crooke's radiometer is a household curiosity.
How does it work?

24.1 Absorption Spectrometer

Advanced

A continuous spectrum source is made to shine through glass cells containing different gases. Then the spectrum is studied through a diffraction grating and a microscope, particular lines are found to be missing from the spectrum. The gas can be changed giving rise to different dark lines.



When a gas is placed in front of a light source which is emitting a continuous spectrum, the atoms of the gas will absorb particular wavelengths which match the energy transitions present in the atoms.

In time, the atoms will de-excite, and another photon of the same colour will be emitted, however, it is unlikely that the photon will be emitted in the same direction as the original one, it looks like all the photons of that particular colour have been 'stolen' from the continuous spectrum. This gives rise to an 'absorption spectrum'.

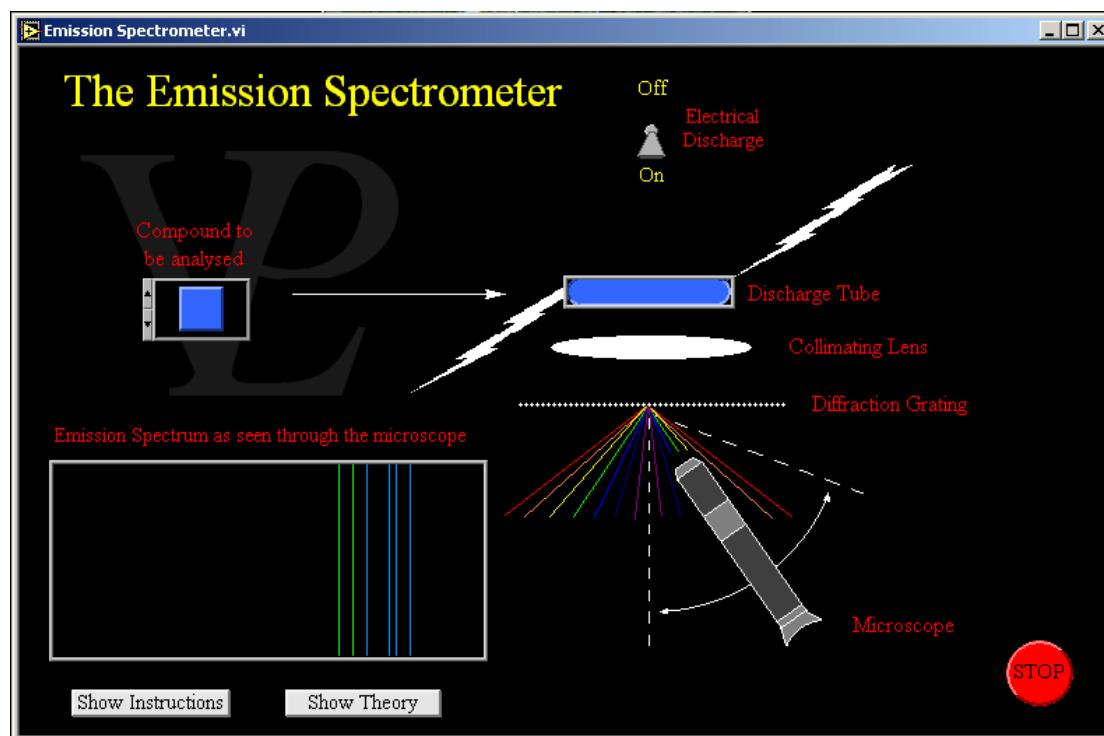
As with the emission spectrum, the lines in the absorption spectrum are characteristic of the atoms which are present. For a particular atom, the 'dark lines' in the absorption spectrum are present in exactly the same positions as the bright lines in the emission spectrum.

Fraunhofer noticed some dark lines in the spectrum coming from the Sun. The lines occur in exactly the same places as the emission lines for helium. That is how we know that there is a lot of helium present in the corona of the Sun.

24.2 Emission Spectrometer

Advanced

Gases in glass discharge tubes are excited when connected to high voltages. The light emitted from the discharge is studied with a microscope after it is diffracted through a grating. The spectrum reveals certain coloured lines which are unique to the gas used.



When an electrical discharge is passed through a low pressure gas lamp it excites gas atoms into a higher energy state. These atoms then become de-excited and as the electrons fall back into their ground level and give off light of particular wavelengths. Collectively they form a line spectrum.

The lens is used to collect light and pass it on to the grating. The grating separates the different colours by diffraction.

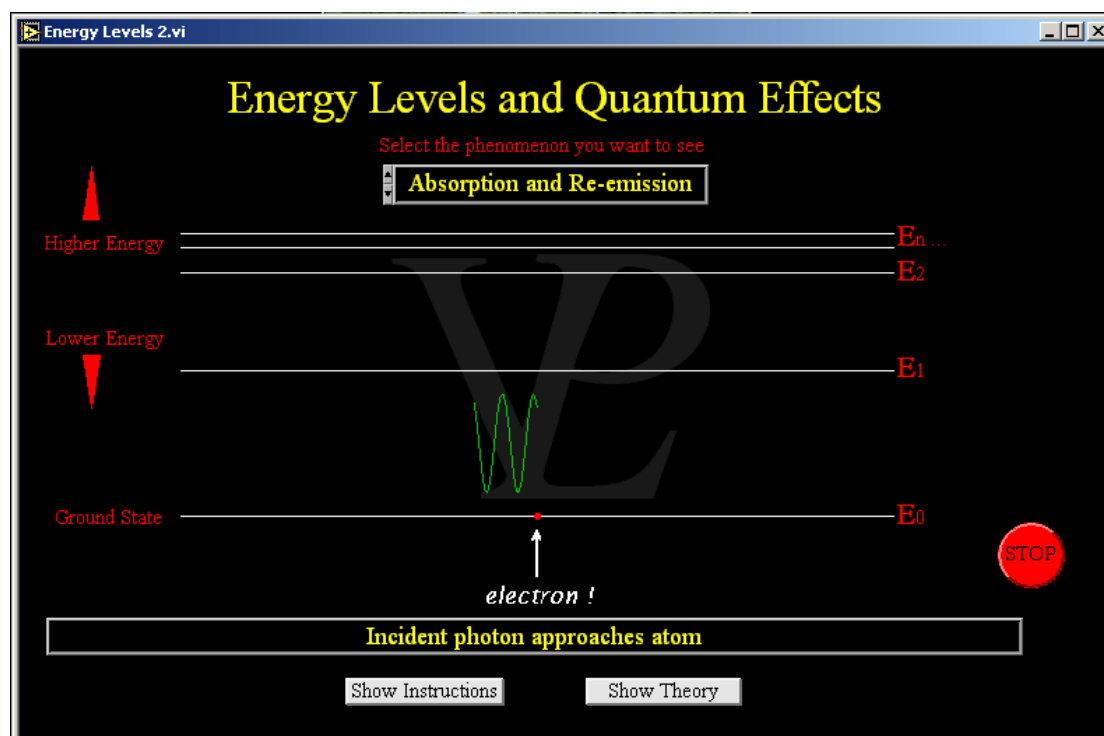
These wavelengths are characteristic of the particular gas. By studying the line spectrum of a mixture of gases it is possible to determine the different gases present. This technique is called gas chromatography and is a powerful tool for analytical chemistry.

Fluorescent and neon tubes contain a mixture of gases in order to obtain a particular overall colour.

24.3 Energy Levels

Advanced

This simple simulation illustrates the following quantum phenomena: Light absorption and re-emission, phosphorescence, Fluorescence, Laser, and Ionisation



Many interesting effects which you know about in real life are determined by electron energy levels at the atomic level!

Absorption and re-emission of electrons may not seem that exciting but they are very important. A photon is absorbed by the atom, and the electron is excited to a higher energy level, only to fall back down again and re-emit a photon again. This new photon can go in any direction, not necessarily the same direction as the first photon. This effect is responsible for the blue skies and also the red sunsets. The atmosphere absorbs blue photons and then re-emits them in other directions.

Phosphorescence is a little more interesting. A photon is absorbed by an atom, and the excited electron can remain on the higher energy level for quite some time. The energy level is called a 'meta-stable' level. Eventually the electron will fall again and give off a new photon in the process. This is how glow in the dark paints work! You need to leave them under a light source for a while so that they can absorb the energy as the electrons are raised to higher energy levels. This energy is then released over time gradually as they fall back down to their original level.

Fluorescence is also quite interesting, an energetic photon (often violet or UV) is absorbed by an atom but the photon is so energetic that the electron can jump up two or more energy levels. Then when the excited electron falls down again, it falls in stages, giving off two photons with lower energies and thus longer wavelengths. This

effect is responsible for the colour of the high visibility paints and coats that maintenance men wear on the motorways.

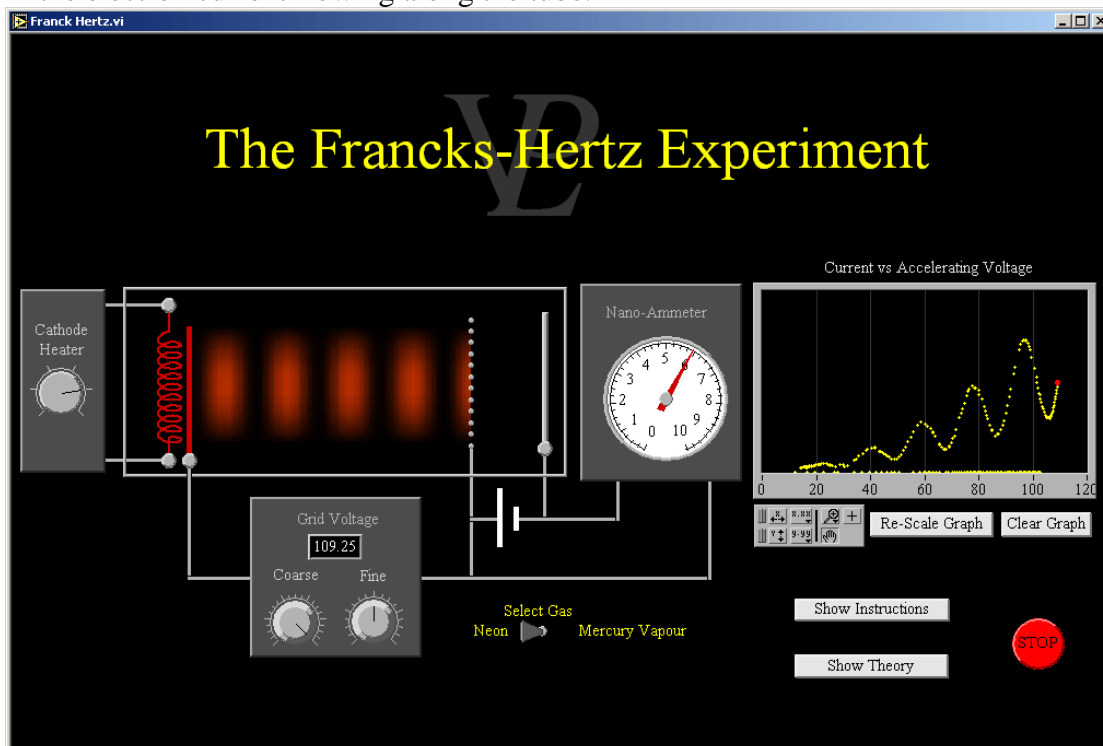
The Laser is also an interesting effect. First an electron needs to be excited to a higher level which is at least two higher than the ground state. It then falls down on to a meta-stable level and stays there for a while. If a photon comes along which has the exact wavelength or frequency as that which would be emitted if the electron were to fall down, it will stimulate the electron to fall down. When this happens you end up with two photons, and the interesting thing is that the photon produced will travel in exactly the same direction and have the same phase as the photon that stimulated it. That is where laser got its name: Light Amplification through the Stimulated Emission of Radiation.

Ionisation happens when the incoming photon has so much energy that it kicks the electron right out of the atom. It need never return although another electron from somewhere else will eventually come and fill the place.

24.4 The Franck-Hertz Experiment

Advanced

See how electrons accelerated in a low pressure neon atmosphere lose energy in discrete steps causing the gas to glow. See how this effect correlates to a regular drop in the electron current flowing along the tube.



In 1914 James Franck and Gustav Hertz carried out an experiment which was one of the earliest confirmations of the quantised nature of energy. A small amount of mercury is put in to a glass tube containing a cathode, a grid and a collecting anode. To vapourise some of the mercury, it is heated up to about 180 C. When the cathode is heated, it starts to release electrons through thermionic emission. These electrons are accelerated towards a grid which is held at a variable positive voltage with respect to the cathode. The anode is held at a slightly lower potential than the grid (typically 1.5 V) so that only electrons above this energy threshold can reach the anode.

Franck and Hertz noticed that the electron current collected by the anode did not increase continually with accelerating voltage. At periodic voltage increments, the current decreased to a local minimum. The current drop is not abrupt because the electrons have a spread of energy due to their thermal distribution arising from the heated cathode.

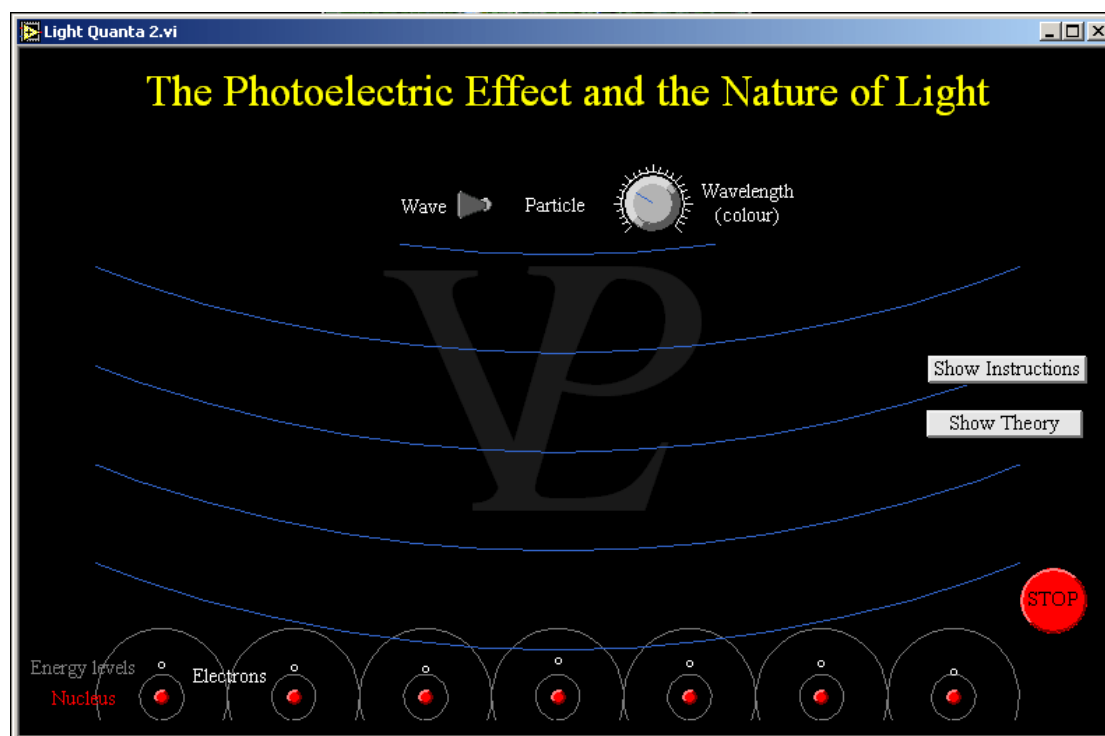
The interpretation of this observation is that at particular accelerating voltages the electrons have acquired sufficient energy to excite a mercury atom to a higher energy state. When this happens, the electron loses some of its kinetic energy and hence slows down (reducing the current). If the electron is still inside the accelerating electric field, it may again accelerate, and if the field is strong enough it may gain enough kinetic energy to excite another mercury atom before reaching the grid.

When mercury vapour is replaced with neon gas, similar behaviour is noted but the voltage intervals are larger. An additional interesting phenomenon is noted: The gas starts to glow at regular spatial intervals! This glow arises from the fact that the neon atoms that have just been excited by the electrons, then de-excite in several steps, giving rise to visible radiation lines between yellow and red.

24.5 Light Quanta

Advanced

This simulation illustrates how the wave model of light could not explain the instantaneous ejection of electrons from metal surfaces. Switching over to the quantum or particular model of light illustrates how there is sufficient energy to cause the immediate ejection of electrons.



With the discovery of diffraction phenomena with light, the wave nature of light was clearly established. The old corpuscular theory of light as proposed by Newton was finally discarded. However, the discovery of the photoelectric effect challenged the whole understanding of the nature of light all over again!

The photoelectric effect is the name given to an observed phenomenon in which light shining on a clean metal surface causes electrons to jump off. The following observations are key:

- 1 - The effect takes place instantaneously
- 2 - If the wavelength is too long, no electrons are emitted however intense the light. This means that weak violet light can do what intense red light can't.
- 3 - The kinetic energy of the emitted electrons is higher for shorter wavelengths.

The wave model of light did not fit well with these observations for the following reasons:

- 1 - A wave model would require time for the uniformly radiated energy to be absorbed equally by thousands of atoms to reach the point where they could become ionised
- 2 - In the wave model, the wavelength did not determine the energy of the wave, it was the amplitude and the intensity that related to the energy.

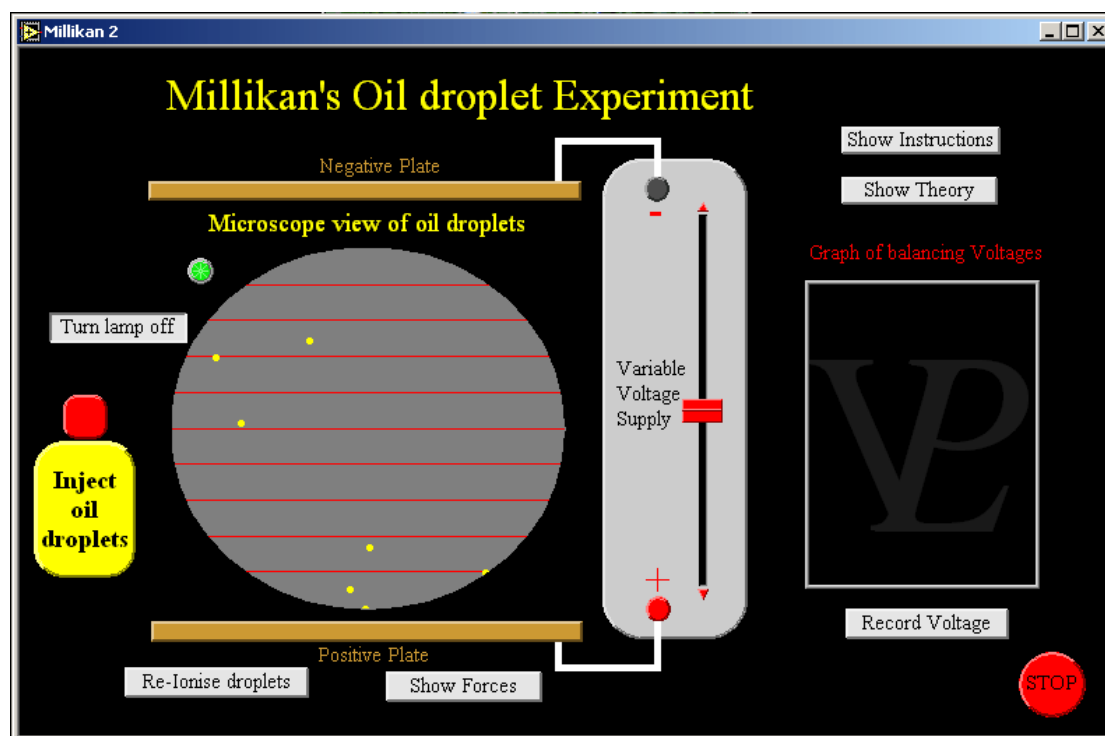
3 - The wave model could not explain how a weak violet light could apparently pack more energy than an intense red light.

The particle model of light called the 'quantisation' of light sees light as carried by photons. Each photon carries an energy which is inversely proportional to its wavelength (or proportional to its frequency). Light is not spread out uniformly over all the atoms, but photons strike individual atoms delivering all their energy to a single electron. In this way the first electron can be ejected instantaneously. A red photon simply does not have enough energy to kick an electron out of its atom, so however many red photons strike different atoms nothing happens. Photons with higher 'frequency' kick the electrons harder, so when they are emitted they fly off at greater speeds. It seems strange to talk of photons as having a 'frequency' particularly as that is wave model terminology, but we still do so. We now talk of light as having wave particle duality - a dual nature. If we are truly honest then we don't exactly know what it is and these are just models that work and explain what we have observed and do know.

24.6 Millikan's Experiment

Advanced

Droplets are injected between two flat electrodes and are viewed through a microscope. The potential difference across the electrodes is adjusted until any particular droplet ceases to fall under gravity. Re-ionise the droplet with a radioactive source. Record the balancing voltages and interpret the evidence.



Just the action of spraying oil droplets from a spray can is enough to cause some of them to become slightly charged. Millikan was able to change the charging on the droplets by radiating them with alpha particles from a radioactive source.

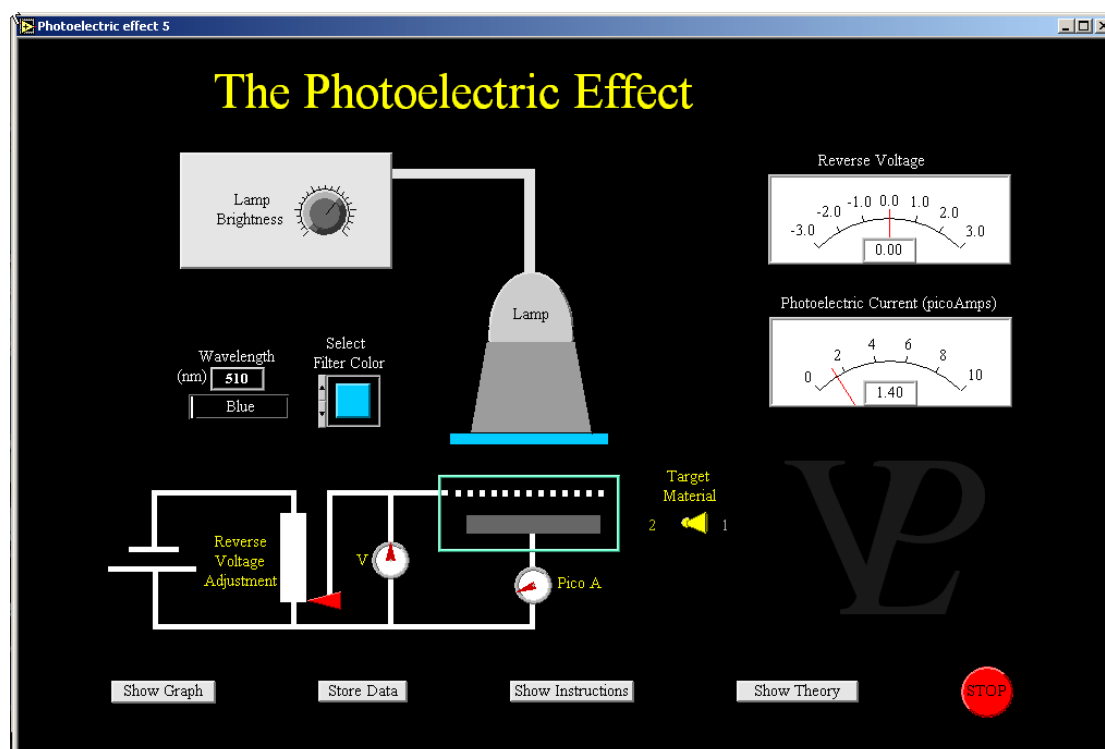
Millikan noticed that the voltages needed to balance the droplets came in discreet jumps. This led him to the belief that charge must also come in discrete amounts.

This is a difficult experiment to carry out even when simulated. It was even harder to do the real thing where the heat of the lamp produced small convection currents!

24.7 Photoelectric Effect

Advanced

Different colour filters are used to change the wavelength of the light shining on a metallic surface. A reverse voltage is applied to an electrode in order to just cut the photoelectric current to zero. The voltage and wavelength are plotted and from the graph, a value for Plank's constant is obtained. Two materials are available.



A complete explanation of the photoelectric effect is beyond the scope of this simulation. You will need to consult a textbook for a fuller explanation.

Briefly, when light falls on a metallic surface causes electrons to be emitted from the metal. The energy with which these electrons are ejected depends on the wavelength (or frequency) of the incident light, and not on the intensity of the light. This was a very surprising thing when discovered.

If the wavelength of the light is longer than a certain amount (i.e. if the frequency is below a certain 'threshold frequency') then no electrons are emitted however intense the incident radiation.

Above that threshold frequency, the energy of the emitted electron increases as the frequency is increased further.

In this way it was discovered that weak ultra-violet light has more energy than strong visible light. This opened the way for the discovery of the quantisation of energy. It also showed that the energy of light is proportional to the frequency (or inversely proportional to its wavelength). The constant of proportionality is known as Plank's constant.

CHAPTER 25

RADIOACTIVITY

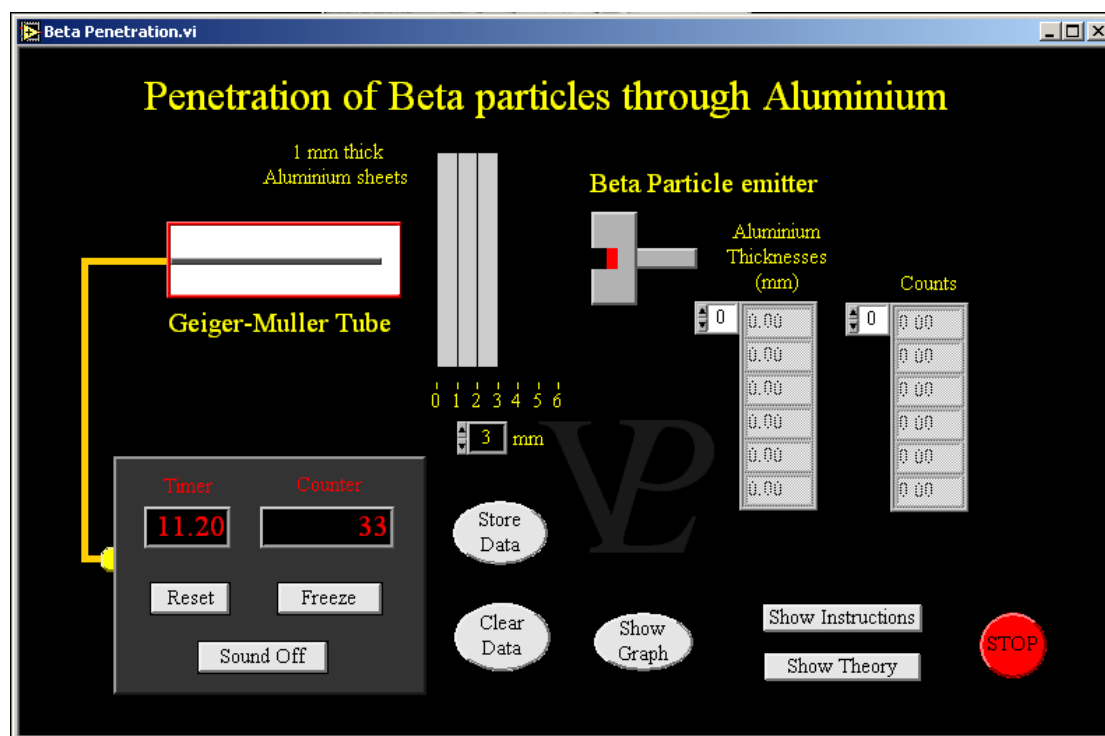


Smoke alarms have radioactive sources inside them.
What is radioactivity and what does it do?

25.1 Beta Penetration

Basic/Advanced

This simulation is designed to show how sheets of aluminium absorb beta particles, preventing them from reaching the Geiger-Muller tube. Time the number of counts for a few minutes, change the number of aluminium sheets, and store the data so that it can be displayed on a graph.



Beta particles are very high energy electrons. They are energetic enough to fly through an aluminium sheet. However, some of them do interact with the aluminium atoms and so they get absorbed.

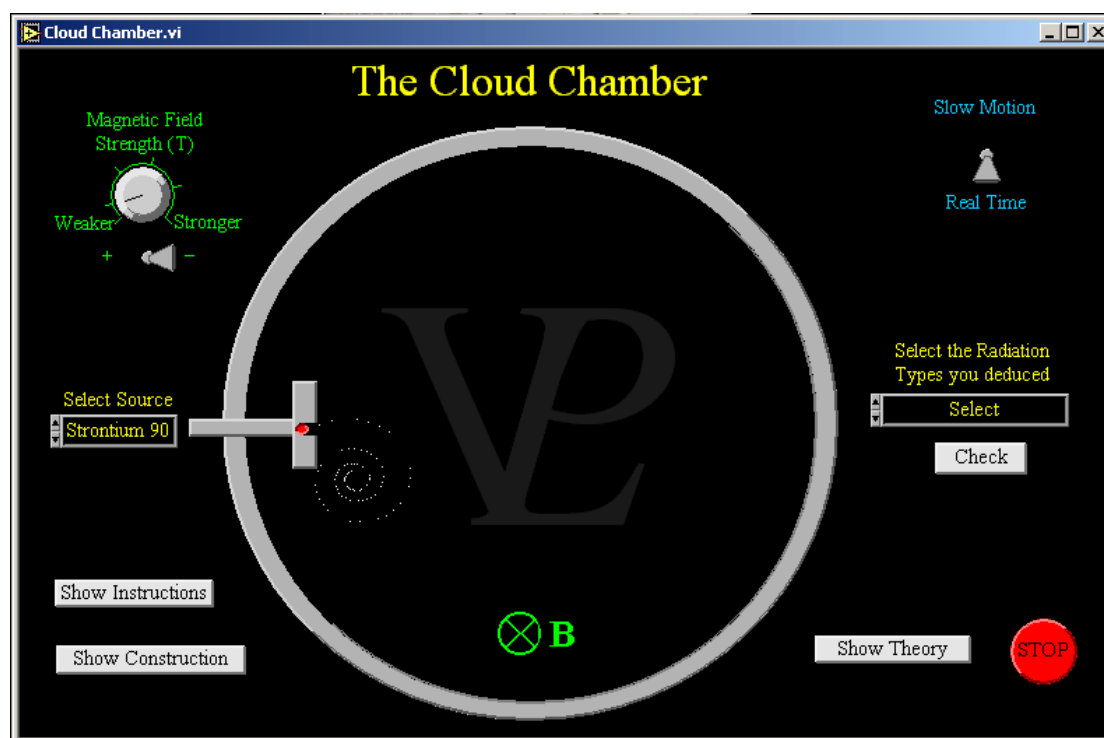
The probability of beta particles interacting with the aluminium atoms increases as the thickness of the aluminium increases. By the time the aluminium is 6 mm thick 99.999% of the beta particles will be absorbed.

The rate at which beta particles are transmitted through aluminium drops off exponentially with the thickness. Lead is even better at stopping beta particles.

25.2 Cloud Chamber

Advanced

This simulation shows the workings of a cloud chamber, and the typical tracks produced by the three different types of particle. It also invites the user to deduce for himself the types of radiation coming from different sources.



A cloud chamber is an enclosure which contains a saturated vapour, one which is just ready to condense into droplets. When an ionising particle goes past it causes condensation to form along its path, leaving a small streak of droplets in its wake.

Alpha particles are very ionising, making very thick tracks. Since they are also very heavy, they are only slightly deflected by very strong magnetic fields.

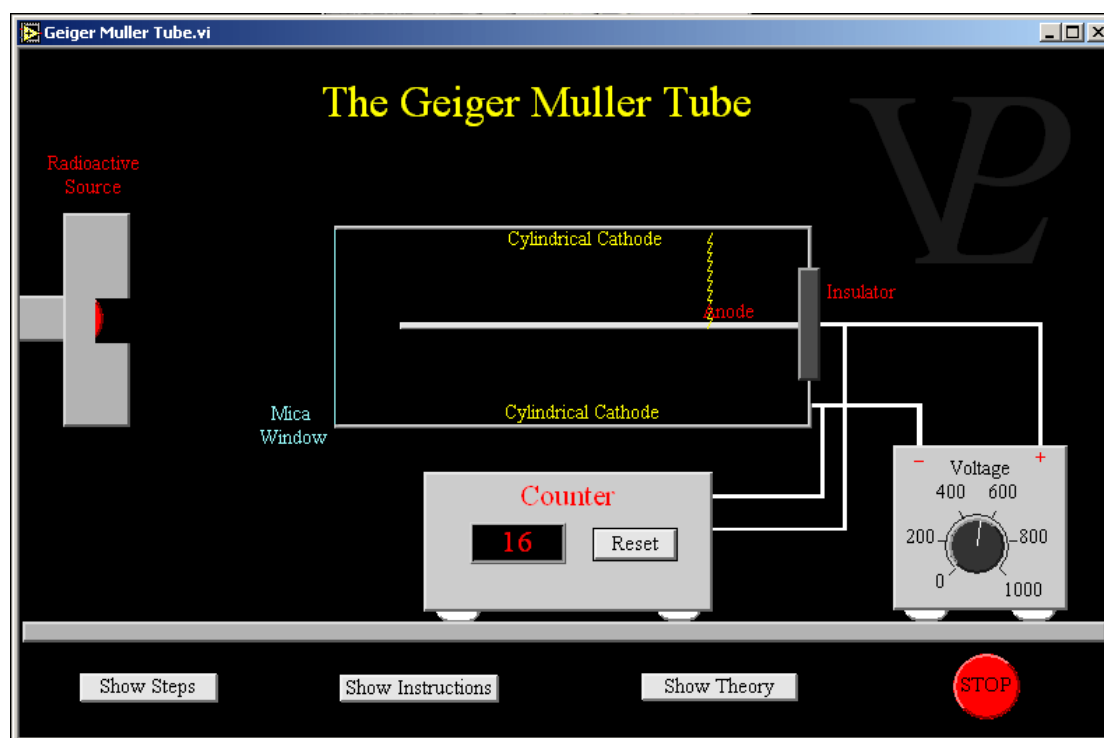
Beta particles are weaker ionisers, making weaker tracks. Since they are light particles they are deflected quite readily even by weak magnetic fields. Note that alpha and beta particles are deflected in opposite directions both obeying Fleming's left hand rule.

Gamma rays are very weakly ionising, but very penetrating. They do not make a solid track, but simply a series of wisps as they travel through. They are not deflected by magnetic fields because they have no charge.

25.3 Geiger Muller Tube

Basic/Advanced

This simulation shows the internal structure and workings of a Geiger Muller tube. The voltage between the anode and cathode may be adjusted to see what effect it has on the sparks produced (and counted) by box attached to it.



A Geiger Muller tube is a device which measures the presence of radioactivity. It makes use of the ionising effect of radioactive particles.

A tube containing a neutral gas is contained in a small cylinder which has a thin mica window through which radioactive particles can easily pass. In the centre of the cylinder there is a thin electrode which is made positive with respect to the outside. No current flows through the gas because it has no free charge carriers.

When a radioactive particle comes in, it ionises a few atoms. These ions are then accelerated by the electric field and when they pick up enough speed they in turn ionise other atoms in the gas. This gives rise to an avalanche of ions which constitute a small current. This small current is noted by a counter which increments each time it senses a small spark.

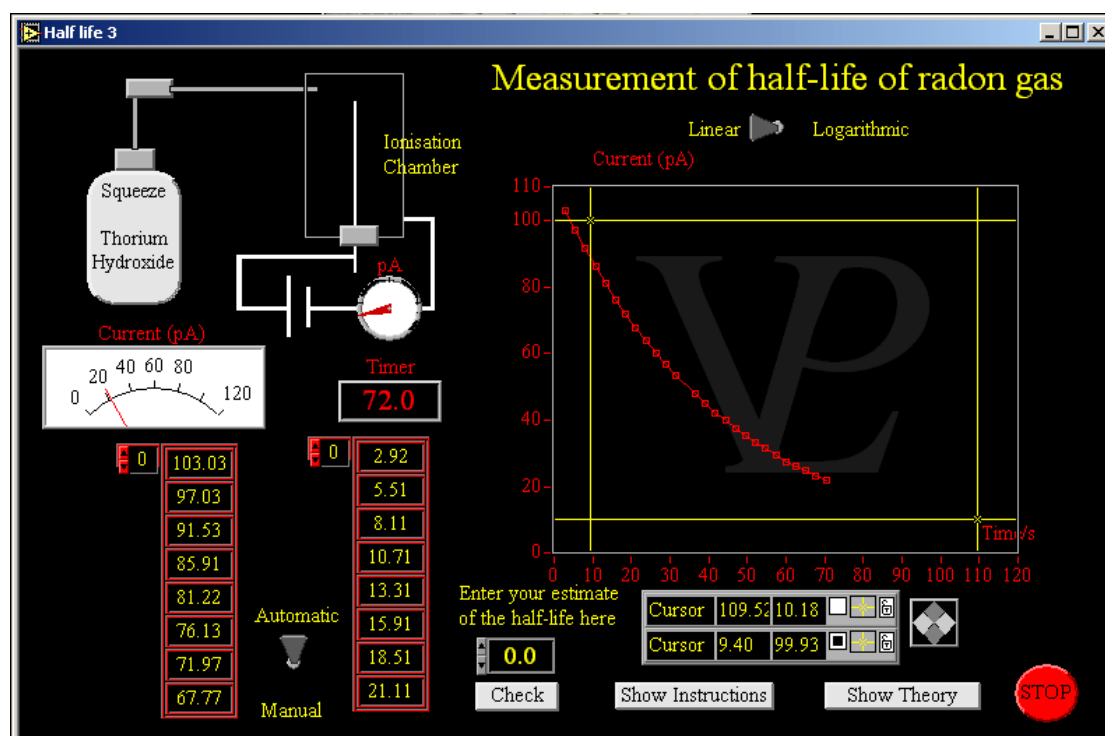
If the voltage on the central electrode is too low, the field is not strong enough to produce an avalanche. If it is too high, it will break down the gas, and a continuous spark will be created. If the voltage is just right which depends on size and geometry, it will only produce a spark when ionising radiation gets inside it and thus work properly.

See if you can find out at what voltage that happens in this simulation.

25.4 Half Life

Basic/Advanced

The ionisation current in a chamber containing radon gas is measured as time progresses. The student can record the value of the current at various time intervals. When enough data has been gathered, the graph will enable the student to determine the half life of the radioactive decay. The student can then compare the value he obtained with that known by the computer.



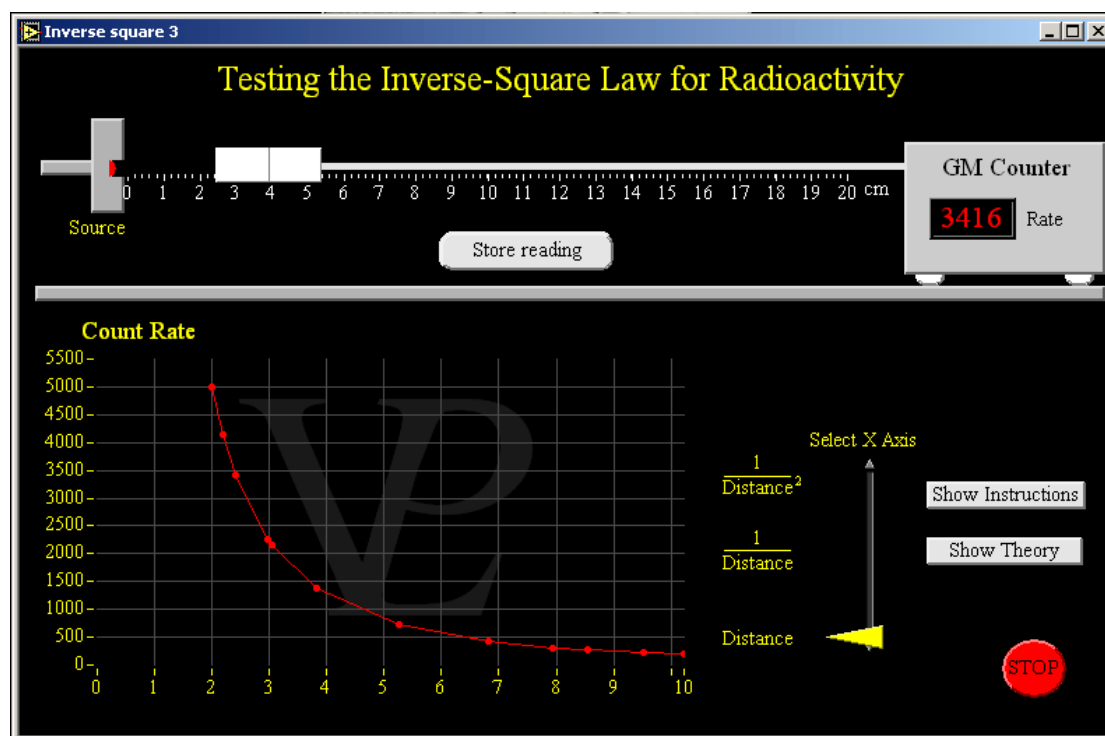
Thorium hydroxide is a compound that is found in many building materials. It gradually gives off radon gas which is radioactive.

It is possible for radon concentrations to build up in large old houses or basements that are not ventilated. Some houses have to have vents and air circulation pumps placed underneath them to remove the radon.

25.5 Inverse Square Law

Advanced

This simulation enables the student to measure the activity of a radioactive source at different distances from it. As the graph is plotted, the student then has the option of plotting the count rate against various different quantities on the X axis, in order to investigate the inverse square relationship.



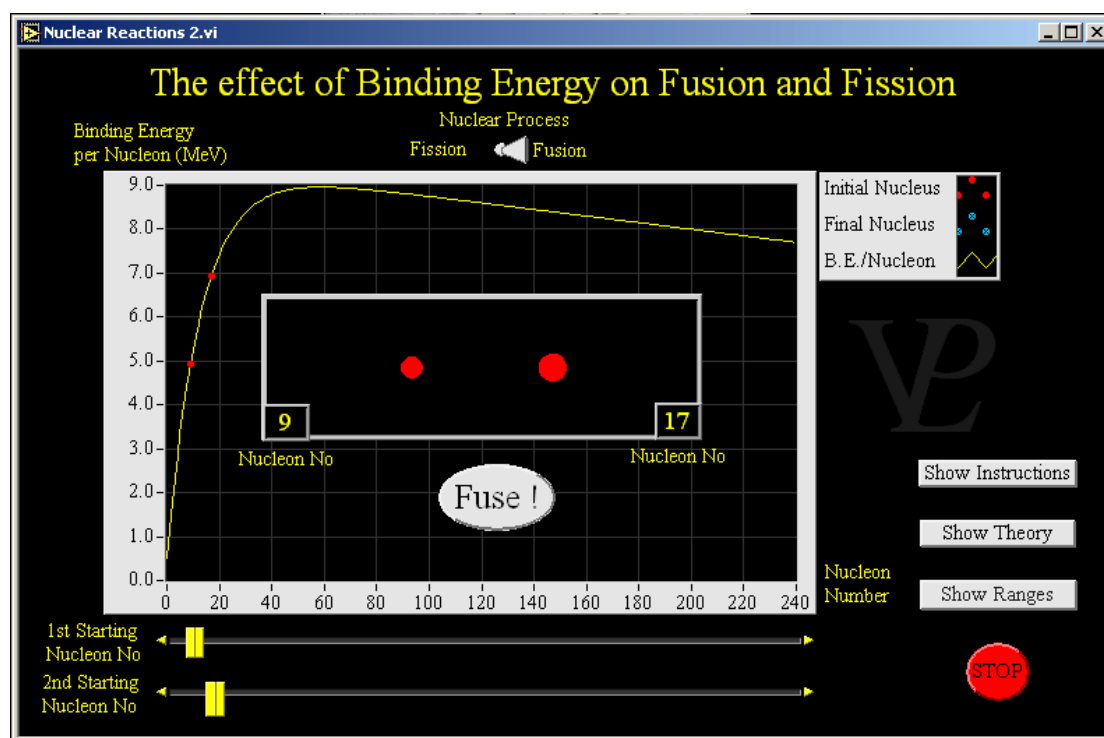
Many relationships in physics follow an 'inverse square law'. Examples of this are light intensity, gravity, sound, electric field strength. Whenever the property that is being studied spreads out radially in 3 dimensions, the strength of it will follow an inverse square law because it needs to spread uniformly over the surface of a theoretical sphere.

The surface area of a sphere increases as the square of the distance so the strength of the effect will be inversely proportional to the square of the distance to the source.

25.6 Nuclear Reactions

Advanced

This simulation shows how nuclear fusion and fission take place. It shows the graph of the binding energy per nucleon and how when nuclear reactions take place, there is a change in total binding energy. The energy released is calculated and displayed.



The yellow curve shown on the graph shows the binding energy per nucleon. You can think of this as the energy debt into which nucleons get when they decide to 'live together'. Different arrangements get them into higher 'debts'. Notice that the ones in the greatest 'debt' are those with a nucleon number around 60. If we can 'persuade' nucleons living in different arrangements to move closer to 60, they will get into a deeper energy debt and the energy difference will be released as heat.

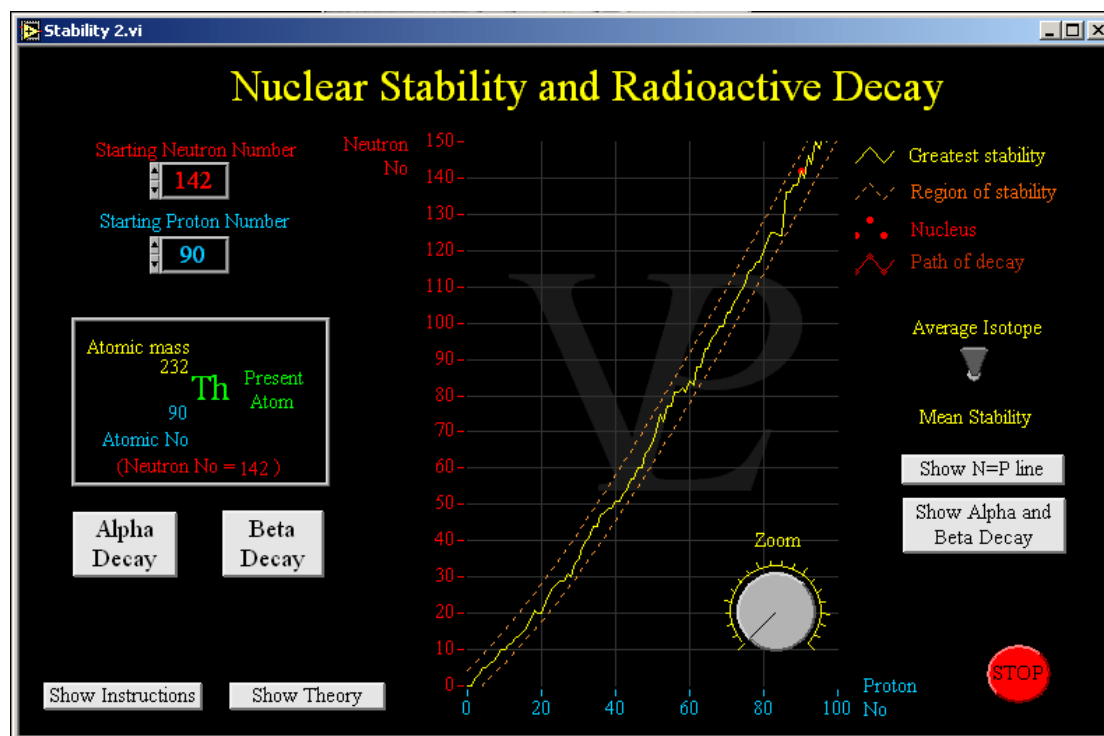
Fusion is the process whereby two smaller nuclei are pressed together tightly and so combine to form a single larger nucleus. If the latter nucleus has a larger binding energy per nucleon, the process releases the additional binding energy as heat.

Fission is the process whereby a single large nucleus is split into two roughly equal but smaller nuclei. If the latter nuclei have larger binding energies per nucleon than the 'parent' nucleus, the process releases the additional binding energy as heat.

25.7 Nuclear Stability

Advanced

This simulation shows the graph of the 'stability line' for all the elements in the periodic table. It shows how Alpha and Beta decays can move a nucleus closer (natural) or further away (artificial) from this line of stability.



The most common stable isotopes of the elements are arranged along a curve which starts with a gradient of 1 (number of protons = number of neutrons) and gradually gets steeper.

Isotopes which are some distance away from this line of stability are unstable, and they are likely to decay by either alpha or beta emissions.

Alpha emission causes both the coordinates to fall by 2. (Down Left x 2)

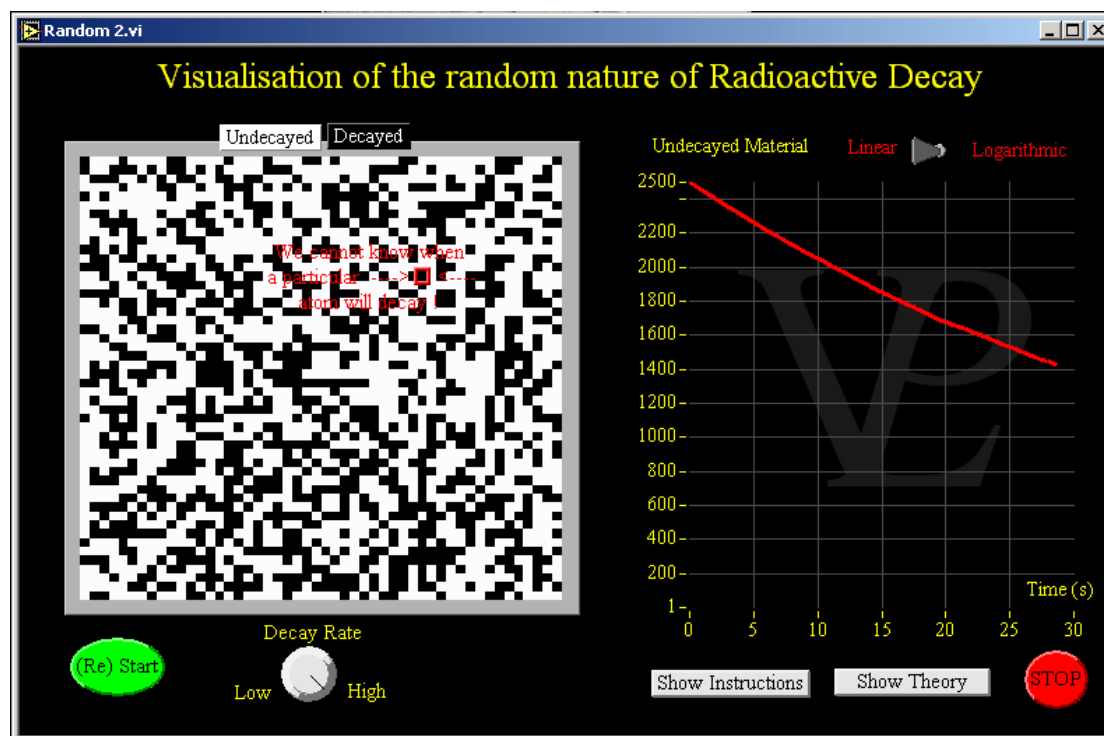
Beta emission causes the proton number to increase by 1 and the neutron number to fall by 1. (Down Right x 1)

Decays will keep on happening until the nucleus finds a more stable arrangement.

25.8 Random Decay

Basic/Advanced

This simple simulation is designed to show that radioactive decay is a random process, and whilst the overall behaviour of a large number of atoms can be predicted reasonably well, it is impossible to predict when any particular atom will decay.



Exponential decays are interesting relationships that occur in a number of processes. Some examples are as follows:

- 1 - The rate at which water level drops when a tap at the bottom of a water tank is opened as long as it is not being re-filled
- 2 - The voltage across a battery or a capacitor as it discharges through a resistor
- 3 - The decay of radioactive materials.

Whenever the rate of 'something' depends on the present amount of that 'something' the relationship will be an exponential. In the example of the water tank, the rate at which the water level drops depends on how high that level is. The higher the level, the greater the pressure at the bottom, and the faster the water pushes through the tap.

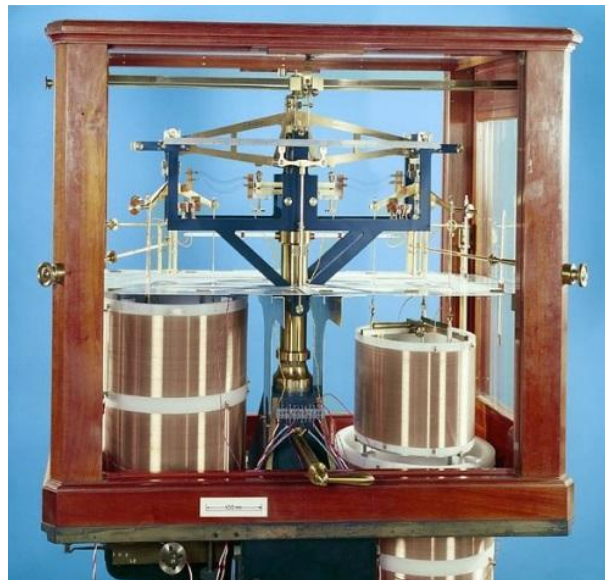
Mathematically we say $dQ/dt = -kQ$ where Q is the quantity we are measuring t is the time (so dQ/dt is the rate) k is the rate constant. Notice the negative sign.

The solution to this equation is $Q_t = Q_i e^{-kt}$ (you will need to consult a mathematics textbook for the proof of this) Where Q_i is the starting value of Q , Q_t is the value at a subsequent time t is the constant k has units s^{-1} .

The 'half life' T is the time it takes for half the initial amount to decay. It is given by $T = \ln(2)/k$ (you might just be able to prove this for yourself by letting $Q_t = Q_i/2$).

CHAPTER 26

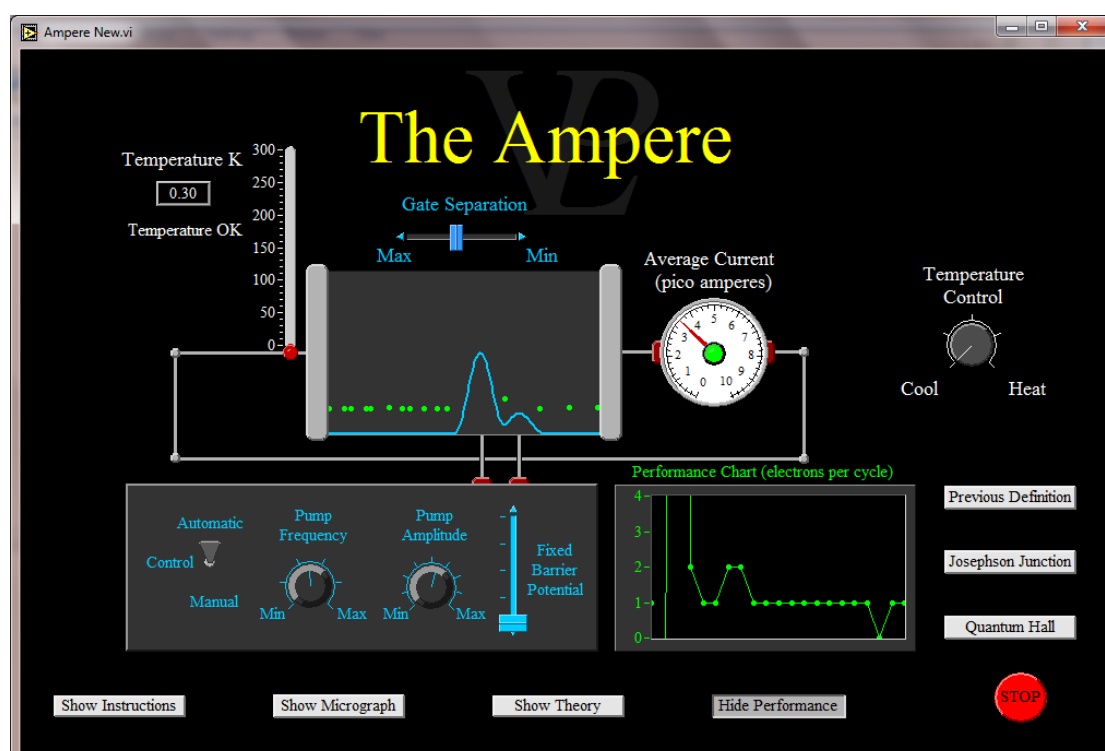
S.I. UNITS



Most measurements in physics need units in which to be expressed.
How are these units defined, and how are they realized?

26.1 Ampere

Advanced



The new definition of the ampere relies on the charge of the electron being defined to be $1.6021766208 \times 10^{-19}$ coulombs. This means that an ampere is achieved when $6.241509129 \times 10^{18}$ electrons flow past a point in a conductor in 1 second.

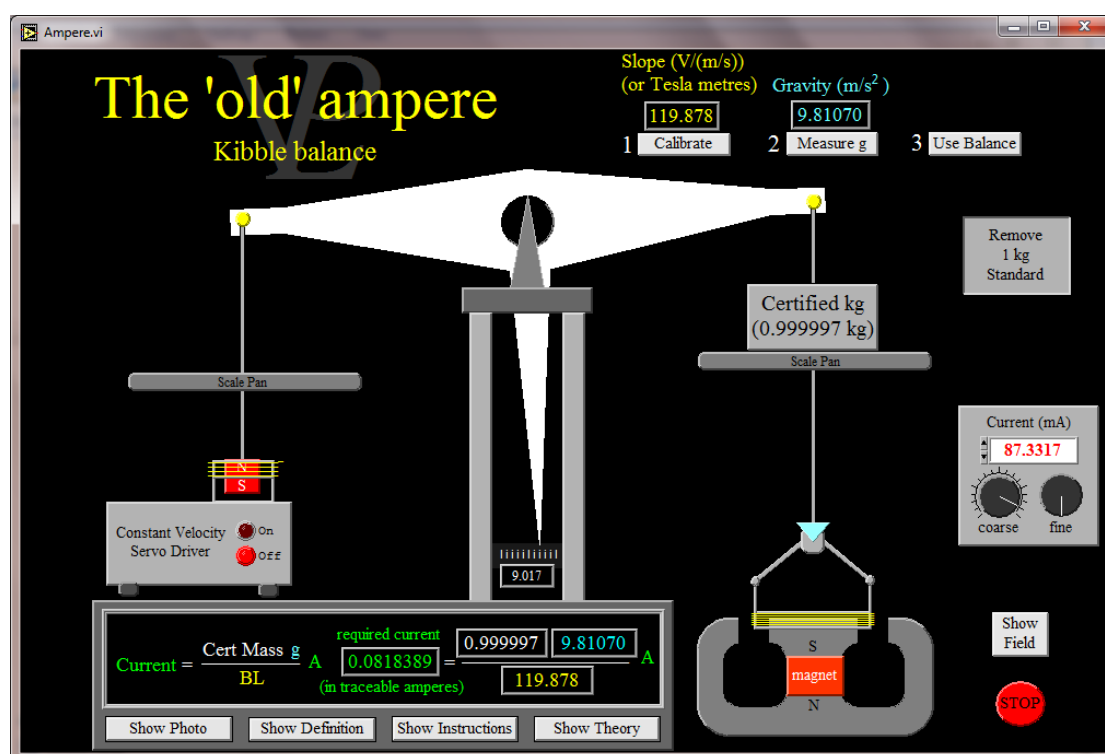
Single electron pumps consist of two gates: a variable potential G1 and a fixed potential G2. These are designed in such a way that they only trap one electron at a time. The potential of G1 is reduced so that low energy electrons can flow into the gap between the gates. The potential of G1 is then increased in such a way that the electron is now trapped between the gates. The increase in potential is adjusted in such a way that even if two electrons had entered the between the gates, one of them will be ejected back out. The other one remains trapped until the G1 potential increases enough to lift the electron over G2 and so push it towards the electron collector.

$6.241509129 \times 10^{18}$ is a very large number. Even pumping an electron every nanosecond (a pumping frequency of 1 GHz, which is a typical electron pump frequency realised at the National Physical Laboratory) it only generates a current of around 150 pA. However, this does not present a fundamental problem for a primary standard, as instruments called cryogenic current comparators can scale current by many orders of magnitude without significant loss of accuracy.

The best pumps can transport electrons reliably, making only about ten mistakes in a billion! However, faster pumping (to increase the current) causes the reliability to drop dramatically. Ongoing research at the National Physical Laboratory is discovering new ways of making pumps work accurately at higher pumping frequencies. In the meantime the realisation of the ampere is normally carried out using Ohm's Law, where the resistance is realised by the quantum Hall effect, and the voltage by the Josephson Junction.

26.2 The "Old Ampere"

Advanced



The unit of current is named in honour of the French scientist Andre Marie Ampere (1775-1836). The definition of the ampere (unit symbol A) is "the constant current which if flowing through two parallel conductors of infinite length and negligible cross-sectional area placed 1 metre apart in a vacuum will produce a force of 0.0000002 newtons per metre of their length"

We can approximate this definition using the force between current carrying coils of known dimensions, but the limits on how well this can be implemented were reached by the 1960s. The Kibble balance, developed at NPL and now familiar for its role in the redefinition of the kilogram is an evolution of these earlier current balances that removed the need to measure exact coil geometry. If we wanted to realize the ampere directly from its definition today, the Kibble balance would be the experiment of choice. In practice, the international adoption of voltage and resistance standards based on the quantum Hall and Josephson effects means that current is usually realized from these standards and Ohm's law.

A Kibble balance equates electrical and mechanical power (the electrical power applied to a coil operating inside a uniform magnetic field to the mechanical power used to lift a kilogram at constant velocity against gravity).

Formally we write $I V = m g v$ where

I is the current we are trying to realize in amperes

V is a voltage we need to measure

m is a kilogram mass that is traceable to the present artefact definition

g is the local value of gravity (which is measured through interferometry) and

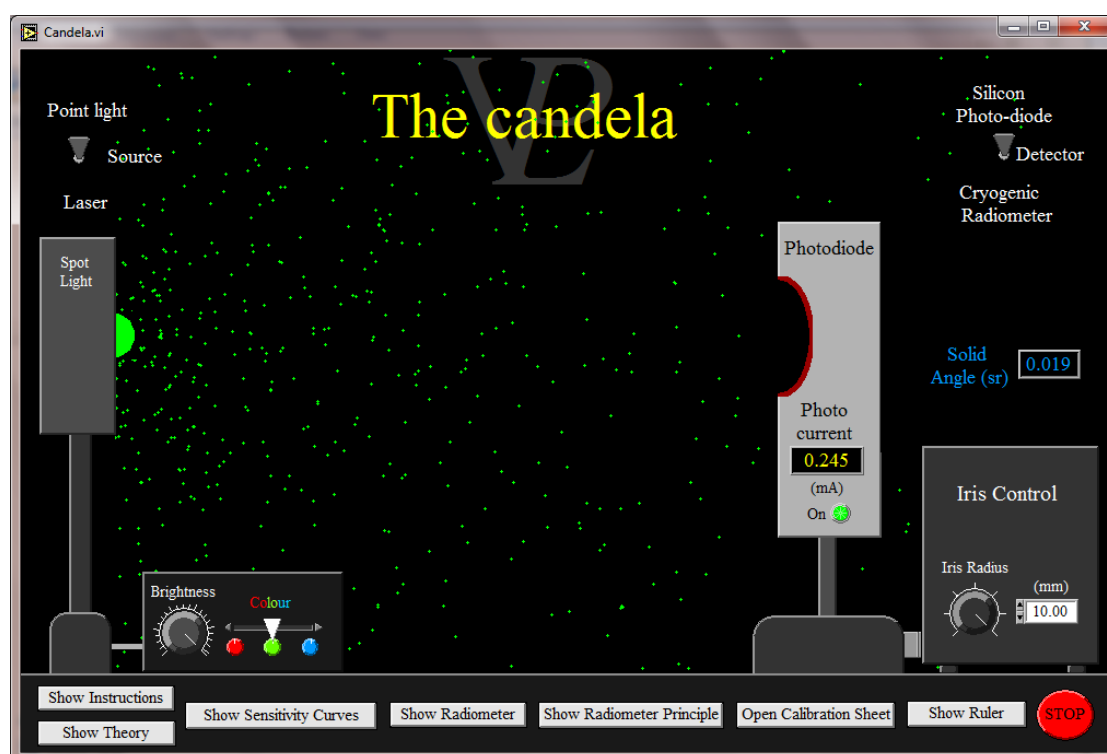
v is the constant velocity at which the kg will be made to rise against gravity - measured through interferometry.

As we can see from this equation, the Kibble balance on its own doesn't realise the ampere as we need to measure a voltage (which is not part of the ampere definition). What we can do is combine this with another electrical realization experiment, known as a Thompson-Lampard calculable capacitor. The description of this is beyond the scope of this simulation, but it gives us a resistance in ohms derived from c (the speed of light) and ϵ_0 (the permittivity of vacuum) both of which have defined fixed values. We can use this known resistance to eliminate the voltage and get to the ampere. Note that the realized ampere does depend on the artefact kilogram, as expected from its mechanical definition.

The situation with the ampere will become much simpler with the anticipated redefinition to use the elementary charge, e , without reference to mechanical units. Researchers at NPL and other laboratories are developing devices called 'electron pumps', which could realise an ampere standard by controlled transport of single electrons. Alternatively, the redefined ampere could still be realised by combining the existing standards for voltage and resistance, the Josephson junction and the quantum Hall effect respectively. The new definition is expected to be internationally ratified in 2018, and this will make it possible to realize the ampere without employing a Kibble balance.

26.3 The Candela

Advanced



The efficiency with which we can see a light source depends both on its intensity and the wavelengths at which it is emitting. The response of the human eye peaks around the yellow-green, which is fortunate, because that is where the peak output of the sunlight reaching the Earth is!

Finding out the wavelength sensitivity of the eye $V(\lambda)$ was not an easy thing to do. Extensive experimental work involving many laboratories and over 200 different people's eyes (of different ages 18-60, of both sexes!) was carried out to obtain the "Photopic Curve" or "standard eye response" $V(\lambda)$ in 1928. Incidentally, when it comes to eye response, there is no such thing as a standard person; as our eyes age, even the colour of our lenses yellows a little! So in reality, every person sees colours slightly differently.

In 1979, the candela was defined as "The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 watts per steradian". (540×10^{12} Hz corresponds to a wavelength of 555 nm, it is yellow-green)

A cryogenic radiometer compares the heating power of laser light with that of an inbuilt electrical heater. The detector is cooled to around 10 K so that it is not 'swamped' by the heat of the surroundings, and it is operated in a vacuum so that it is not heated by air molecules striking the detector. The temperature of the radiometer is measured when the laser light is falling on it, and then the laser is switched off and the detector is heated electrically up to that same temperature. This allows the optical power in the laser beam to be measured by equating it with the electrical power from

the heater. This can be repeated for a number of different laser powers and wavelengths. The uncertainty in the cryogenic radiometer response is around 0.001%.

Once the powers of the laser have been measured, they can be used in turn to calibrate the sensitivity of a silicon photodiode (a photodiode produces a small current (I_p) when light shines upon it, the sensitivity S can be expressed in mA/mW, or A/W, and is also a function of wavelength $S(\lambda)$). The photodiode is therefore calibrated with several lasers at different wavelengths, and its response $S(\lambda)$ is interpolated over the visible spectrum. A variable diameter iris in front of it can be used to set the solid angle Ω from which it is receiving the light.

The Luminous Intensity of a small monochromatic light source emitting at a wavelength can then be measured in candelas (cd) as

Luminous Intensity in cd = $K_m [I_p / S(\lambda)] \times V(\lambda) / \Omega$ where

K_m = maximum spectral luminous efficacy of radiation, defined to be 683 lm / W

I_p = photodiode current (mA)

$S(\lambda)$ = wavelength dependent sensitivity of the photodiode (mA/mW)

$V(\lambda)$ = standard eye response (weighting factor), and

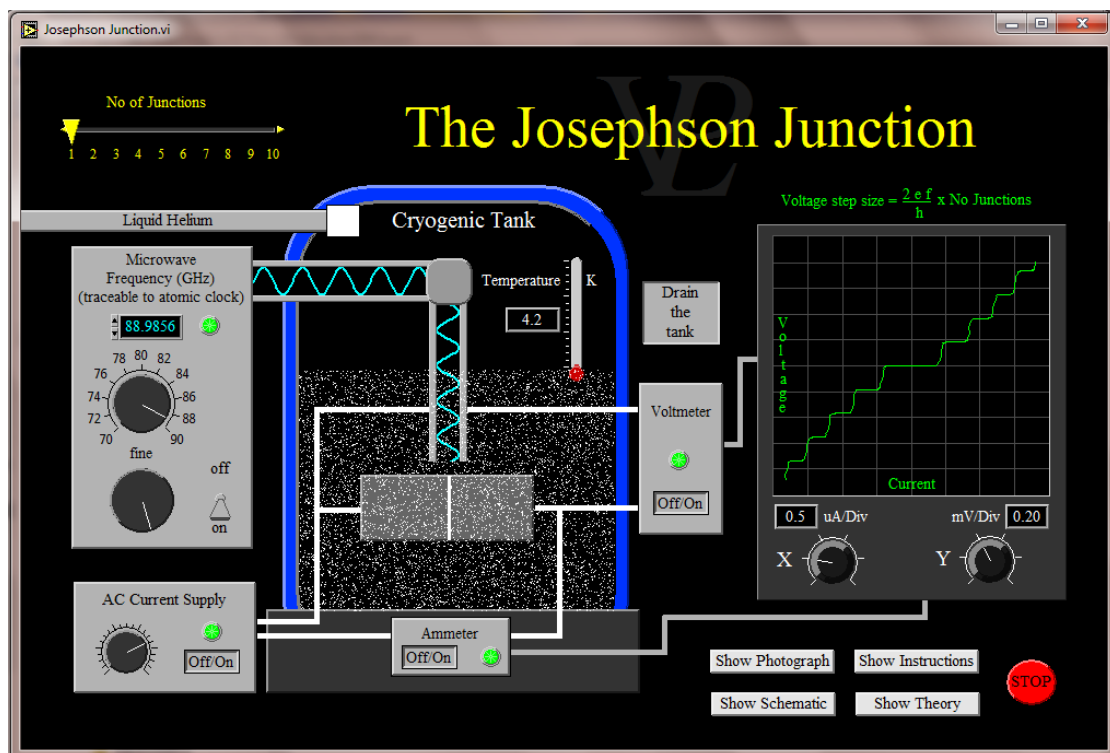
Ω = solid angle subtended by the iris at the source.

If the light source emits at many different wavelengths, as is usually the case, then the luminous intensity is found by adding together the luminous intensities of all the elemental wavelengths. In practice, measurement errors are minimised by using a filter in front of the photodiode to modify the response to be close to the standard eye response function. The photodiode and filter combination is called a "photometer", and it is the sensitivity of the complete photometer, not just the photodiode, that is used to calculate the luminous intensity.

A best measurement uncertainty of around 0.2% can be achieved when the calibrated photometer is used to measure the luminous intensity of specially-designed light sources.

26.4 The Josephson Junction

Advanced



When two electrodes are separated by a very thin barrier (an oxide, or another metal for example) it is possible to drive a small current through the barrier; it behaves just like a resistor. However if the junction is cooled down to very low temperatures (typically below 9 K) interesting things start to happen.

The first is that if a small current is made to flow it will not develop any potential difference across the junction. This can be demonstrated by driving a small alternating current through the junction and plotting the current and Voltage on the X and Y axes of an oscilloscope respectively. The plot obtained shows that the Voltage is exactly zero until a critical current is reached, above which the Voltage rises linearly with the applied current (as if it were a normal resistor)

A more interesting thing happens when additionally microwaves are made to impinge upon the junction: suddenly Voltage “steps” appear in what otherwise would have been the smooth slope of the resistance graph! The Voltage increment between steps is precisely equal for all steps. Experimentally it is found that the size of the Voltage steps (V_j) is related to the frequency (f) of the microwaves applied to the junction.

The surprising thing is that the factor that relates them is exactly $h/2e$ where e is the charge on the electron and h is the Planck constant.

It should be noted that the reciprocal of $h/2e$ is named the Josephson constant (K_j). In mathematical form we say $V_j = h f / 2e$ or $V_j = f / K_j$

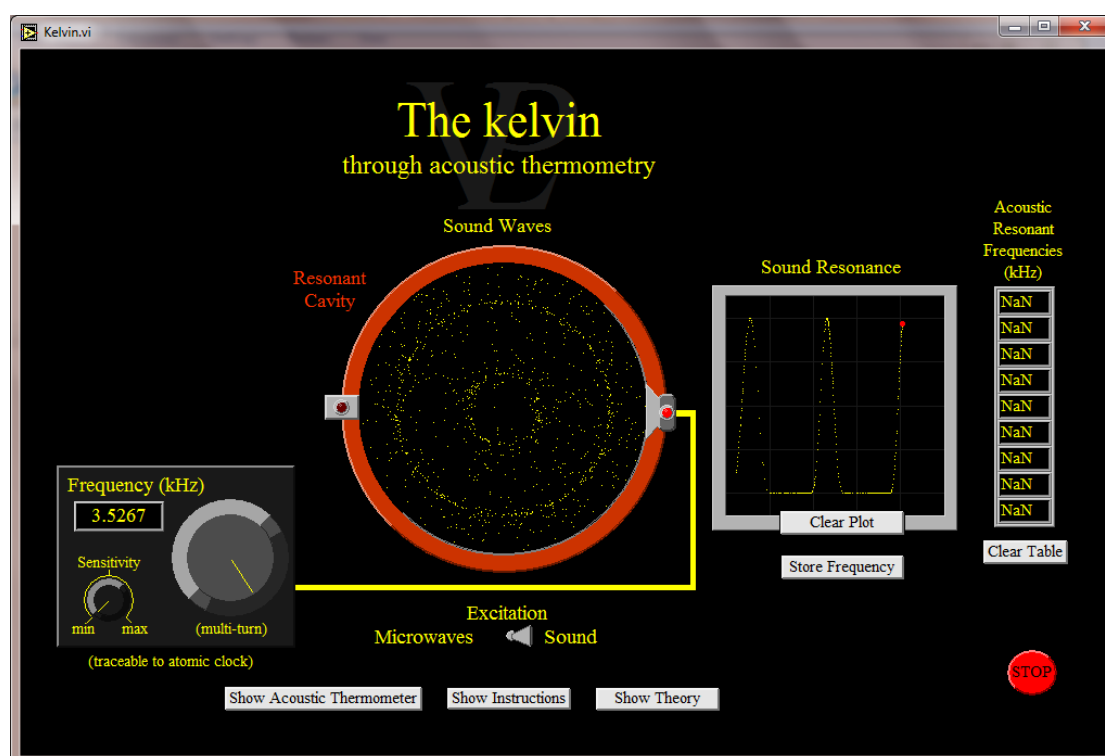
Since the frequency is now traceable to the atomic clock, this means that the Voltage steps V_j can be made traceable to fundamental constants (Caesium atom, charge on

the electron and Planck constant). This makes it possible to make a Voltage reference standard that is not dependent on any particular physical device.

Unfortunately each Voltage step is very small, so to get a Voltage step of approximately 1 V in magnitude it is necessary to make several thousand Josephson junctions and connect them in series. This is a manufacturing challenge, but it has been achieved.

26.5 The Kelvin

Advanced



In the new definition of the kelvin, we are abandoning the idea of special reference temperatures ("fixed points"). Temperature will be determined absolutely in terms of molecular energy using basic physical principles.

Of the many possible ways to work out the temperature, the most accurate involves the measurement of the speed of sound in a gas, as this is directly proportional to the average molecular speed. An acoustic thermometer works out the temperature from the speed of sound in a gas.

In the same way that the speed of a transverse wave on a string can be calculated by measuring its wavelength and the frequency at which it resonates, so the speed of sound can be worked out by measuring the acoustic resonances inside a spherical cavity of known diameter.

For a string of length L , a series of resonances occur at frequencies given by $F(i) = v \cdot i / (2L)$ where i is an integer). Resonance occurs when a multiple of the wavelength just matches the length of the string. So by measuring the resonant frequencies $F(i)$ on a string of known length it is possible to work out the speed of a wave on the string. Alternatively, if the speed of the wave were known, then measuring the resonant frequencies $F(i)$ would allow us to work out the length of the string.

For a spherical cavity, a series of acoustic resonances occur at frequencies at which the wavelength just matches the diameter of the cavity. The mathematics is more complex than for waves on a string, but the principle is exactly the same.

Firstly it is necessary to measure the dimensions of the resonant cavity with low uncertainty. At the National Physical Laboratory of the UK this is done by finding the

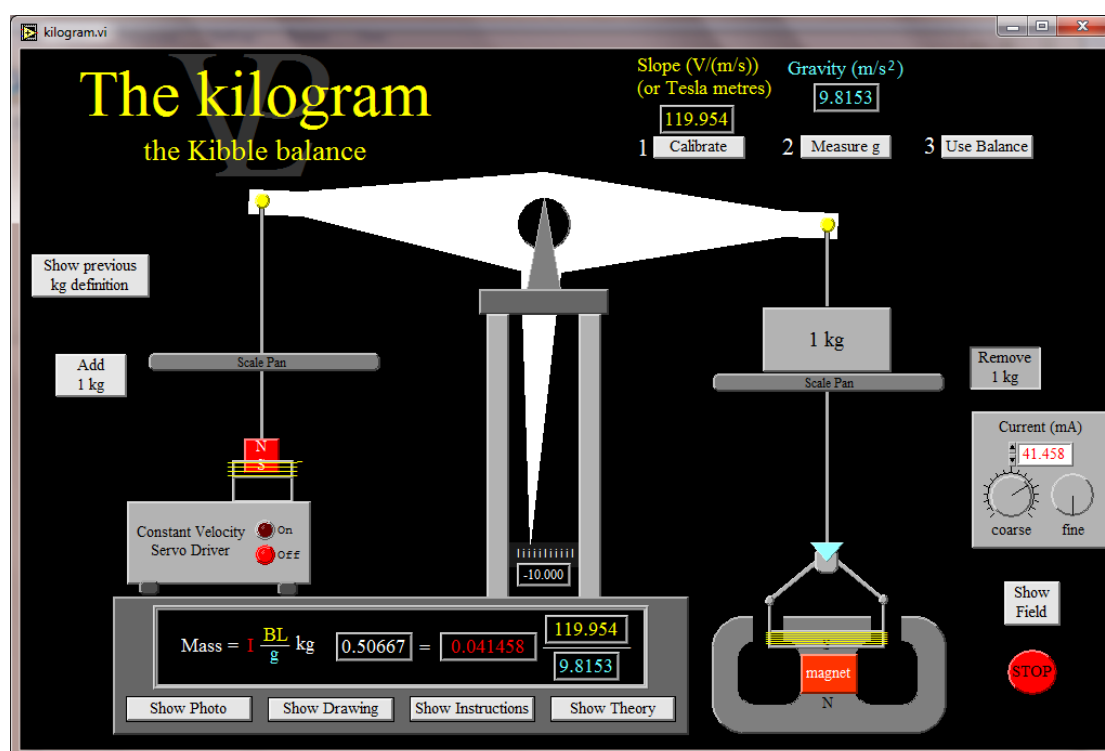
microwave frequencies at which the cavity resonates. The microwave generator frequencies are traceable to the atomic clock, and the speed of electromagnetic waves is a physical constant, so from these two it is possible to calculate the cavity dimensions. This can be repeated for different resonant modes in order to obtain good confidence in the cavity dimensions.

Once we know the cavity dimensions, we excite acoustic resonances inside the same cavity, and from the resonant frequencies we can calculate the speed of sound in the gas. This could be any gas, or even a mixture of gases. However, if we make sure the gas is a high purity monatomic gas (like argon or helium) the relationship linking the speed of sound to its temperature is $\frac{3}{5}mv^2 = kT$ where v is the speed of sound, m is the mass of an argon atom, k is the Boltzmann constant, and T is the absolute temperature.

In this way it is possible to make an absolute temperature measurement which relies entirely on physical constants and known material properties. It is different from a normal thermometer such as an electrical thermometer because once the Boltzmann constant has been defined it does not need to be calibrated against another thermometer.

26.6 The Kilogram

Advanced



The kilogram is the last of the SI units that relies on a 'physical artefact' standard. It is defined as the mass of the international prototype of the kilogram held at the Bureau International des Poids et Mesures (BIPM). This dependence on a physical object that could get damaged, or change over long periods of time is not satisfactory.

To find an alternative definition of the unit of mass it is necessary to be able to define mass in terms of fundamental or atomic constants in a similar way to the existing definitions of the metre and the second. This can be done by defining it in terms of the metre, the second and a fixed value of the Planck constant.

A definition is not useful unless there is a way of measuring mass in terms of it. This is achieved using an instrument now named the Kibble balance, after the late Dr Bryan Kibble who invented it in 1975 at the National Physical Laboratory in the UK. It was originally named the moving-coil watt balance because it related electrical and mechanical power using a moving coil. The international community subsequently renamed the balance in his honour.

The Kibble balance operates in two phases. The first phase balances the gravitational force mg acting on an unknown mass m with an electromagnetic force BIL generated by an electrical current I flowing in a coil of length L in a strong magnetic flux density B . This gives $mg = BIL$ (1), where g is the local acceleration due to gravity. Current and gravity can be measured independently, but the product BL is difficult to measure directly and has to be determined in the second phase of the experiment.

When a wire moves perpendicularly across magnetic field lines, a voltage is induced across it. Following Faraday's law we write

$V = BLv$ (2), where V is the induced voltage, BL has the same meaning as above, and v is the velocity of the perpendicular movement.

By combining equations 1 and 2 we can eliminate the product BL , without accurate knowledge of either B or L , to obtain $mgv = IV$ which is an expression of the equality of virtual mechanical and electrical power. Electrical power can be related to the Planck constant and the second using the Josephson and Quantum Hall effects. Both g and v can be measured, in terms of the metre and the second, using laser interferometers. The local acceleration due to gravity is measured by dropping a cube corner reflector, which forms one arm of a laser interferometer, in vacuum.

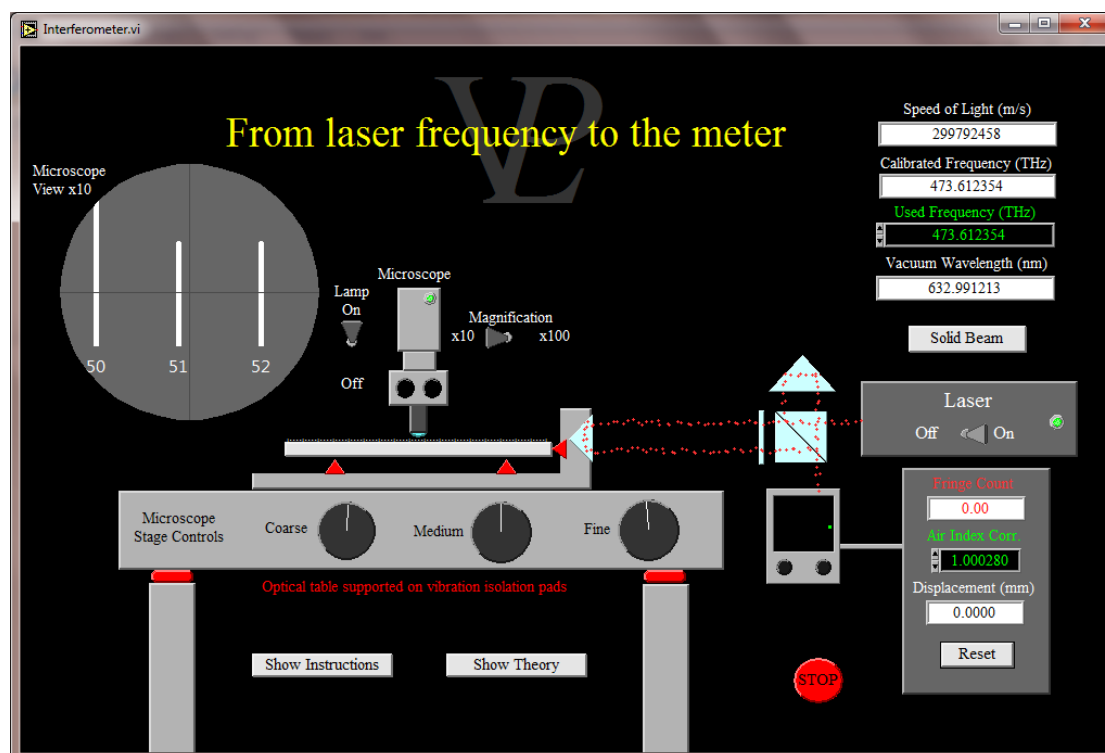
In the present case the mass to be measured is placed on the same side of the balance as the velocity measuring interferometer, the coil and the magnet. If it is placed on the other arm small differences in length between the two arms, caused by inevitable imperfections in manufacture, would make the measurement inaccurate.

It is important to know the acceleration due to gravity very close to the centre of mass of the kilogram mass. If there are large masses near the laboratory (massive walls, sloping landscapes) this can be difficult to arrange as an appreciable gravitational gradient may exist across the room!

For best precision, the entire balance is placed in a vacuum. This eliminates errors arising from the upthrust of the atmosphere on the kg mass which changes with atmospheric density caused by weather phenomena. It also eliminates the effect of the refractive index of air, simplifying the calculation of the velocity from the wavelength of the laser used in the interferometer.

26.7 The Metre

Advanced



The conception of the metre started sometime around 1791, when the French National Assembly decided that the unit of length should be one ten billionth (that is $1/10\,000\,000\,000$) part of one quarter of the polar quadrant going through Dunkirk and Barcelona. This was a difficult surveying job to do, but in 1799 a platinum 'end bar' was produced; it was known as the "Metre des Archives" and was the master standard for the metric system. It took some persuasion to encourage people to adopt this new measurement unit, and only by being rigorously enforced in 1837 did its usage start to increase. By 1870 it was widely used in Europe.

The Bureau International des Poids et Mesures (BIPM) in Sevres made copies of this metre in platinum-iridium in 1889. Copy No 6 became the International Prototype Metre, and participating nations were given a copy for themselves.

Between 1892 and 1940 efforts were made to find a natural length standard which was not related to a man-made artefact. Wavelengths of the light from various lamps were suggested and in 1960, the metre was defined as "the length equal to $1\,650\,763.73$ wavelengths in the vacuum radiation of krypton-86". From this date onwards the International Prototype Metre was replaced.

With the increased precision achievable from atomic clocks, in 1983 the metre was re-defined as "the length travelled by light in a vacuum during a time interval of $1/299\,792\,458$ of a second". Iodine stabilised helium-neon lasers were built that have a reproducibility of better than 3 parts in a hundred thousand million (3 parts in 10^{11}). More recently a system capable of producing a "femtosecond comb" of optical frequencies has been devised which is based on a mode-locked laser with a variable repetition rate frequency. The repetition frequency is adjusted such that of the many

different frequencies (and colours) produced, two of them are an octave apart (one has twice the frequency of the other).

Use is made of a non-linear optic medium in order to double the frequency of the lower one, and these two are now made to interfere with each-other. The beating frequency between the two makes it possible to deduce the offset frequency of the "femtosecond comb". Knowing this and the repetition rate frequency it is possible to calculate the frequencies of each of the 'teeth' of the comb.

Notice that to measure beat frequencies accurately it is necessary to have a high-precision clock! Fortunately the Caesium clock is highly stable, and it is used to calibrate a 10 MHz reference signal from which other instruments can derive their timings.

Laser Interferometers are a direct way to go from a traceable laser frequency (or known wavelength) to a traceable length. Normally it is laser frequencies that are calibrated rather than wavelengths because the wavelength can change if the refractive index of air changes due to temperature, pressure, humidity, etc.

For best precision it is important to measure the refractive index of the ambient air using a gas refractometer, but if this is not possible, then the refractive index of the air can be calculated fairly accurately from measurements of temperature, pressure and humidity.

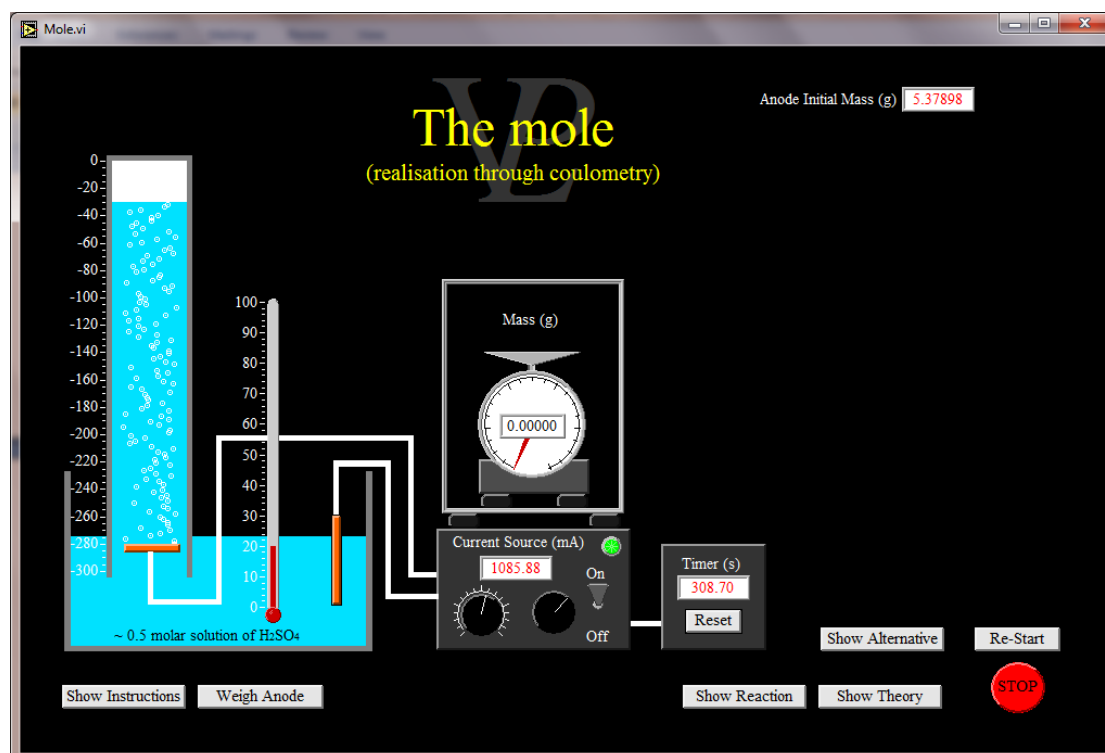
An interferometer makes use of a wave property known as "interference" (see the "Wave Interference" simulation in the "Waves" chapter of the Virtual Physical Laboratory). Coherent waves with different phases can interact with each other producing either constructive or destructive interference. If the light beam from the laser is split in two, and half of it is made to travel a fixed length path, but the other is made to travel a path that has a changing length, then when the two light beams are brought together again, the phase difference between them will cause the resultant light beam to vary in intensity going through Maxima and Minima ("fringes") every time that the optical path length difference between the two beams changes by one complete wavelength.

An electronic counter keeps track of the number of fringes and if it is given the frequency of the laser and the refractive index of the medium it can scale these counts into distances. In many interferometer systems (such as the one simulated here) the optical path length difference is twice the distance moved because the beam has to travel there and back.

It should be noted that a single interferometer signal cannot distinguish the direction in which it is counting (upwards or downwards), so a useful trick is to design a system with two interferometers outputs arranged to be 90 degrees out of phase with each other. If connected to the X and Y inputs of an oscilloscope the signals from the two interferometers plot a circle, and the direction of rotation (clockwise or counter-clockwise) informs the counter as to the direction in which the moving arm of the interferometer is moving. This technique is called "reversible fringe counting" or "quadrature counting". The best systems are also able to sub-divide integer fringes by calculating the angle which the plotted point makes with the origin of the oscilloscope.

26.8 The Mole

Advanced



The mole is one of the base units of the International System of units (SI).

A mole is the amount of substance containing as many elementary entities as there are atoms in exactly 0.012 kilograms (or 12 grams) of carbon-12, where the carbon-12 atoms are unbound, at rest and in their ground state.

The mole is used to describe a practical quantity of material and is the link between the microscopic and macroscopic worlds, used to scale phenomena from the atomic up to 'relevant' sizes.

As a result of the definition, the mole contains a defined number of entities, usually atoms or molecules. This number is the Avogadro constant (N_A).

The current measured value for N_A is: $6.022\,141\,79\,(\pm 30) \times 10^{23} \text{ mol}^{-1}$

This number is a dauntingly large figure: in grains of sand it would cover the United Kingdom to a depth of about 40 centimetres! There are about this number of human cells on Earth.

How do we know the magnitude of this number? There are a number of ways, Coulometry, as simulated here, is one of them. In this experiment the Avogadro number is traceable via the kilogram, the ampere and the second.

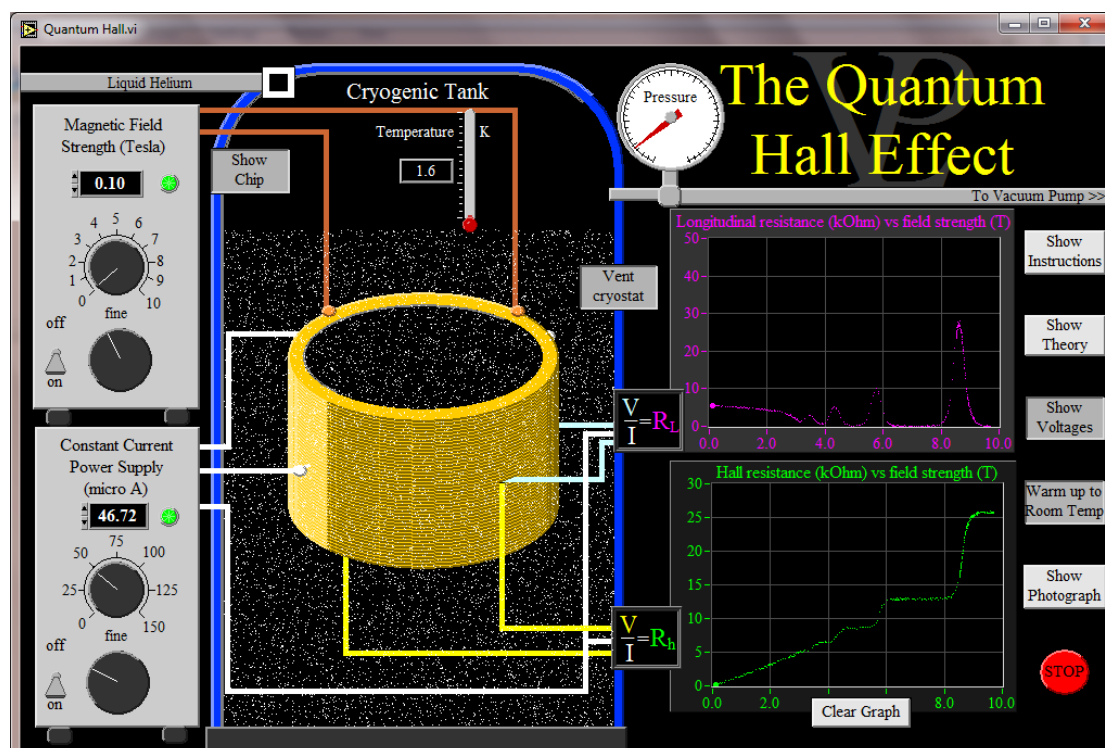
Another method being explored currently involves making a silicon sphere (as spherical as possible) and then weighing it to obtain its mass and so calculate how many moles it represents. The number of atoms present in the sphere can be calculated fairly accurately by measuring its volume and measuring the lattice spacing of silicon with X-ray crystallography.

The mass is traceable to the kilogram, and the atomic spacing is measured through diffraction experiments and is traceable to the metre. In this way it is possible to obtain a traceable value for the Avogadro number.

It is anticipated that in the near future, the Avogadro Number, together with the Planck constant, the Boltzmann constant and the charge on the electron will be defined, and the mol, the kilogram, the ampere and the kelvin will then be derived from these constants.

26.9 The Quantum Hall Effect

Advanced



The Hall effect was discovered by Edwin Hall in 1879, and in 1975 Ando, Matsumoto and Uemura predicted that Hall conductance might be quantised (but they did not actually believe it would be!). However, in 1980 Klaus von Klitzing discovered that the Hall conductance is exactly quantised. A satisfactory explanation of the theory behind this effect is beyond the scope of this simulation and requires a fair amount of study to begin to understand. Researchers working in the field for decades are still not 100% confident of their understanding of the effect, so don't feel bad if you don't either!

The main things to understand are as follows: Quantum effects are by their very nature small, any effects present in every-day life are totally swamped by the thermal energies. To begin to detect this quantisation three things are necessary:

- 1 - Very low temperatures (< 4 K)
- 2 - A two dimensional conductor (very thin in one dimension)
- 3 - Strong magnetic fields (~ 8 T - about 100,000 times stronger than the Earth's magnetic field!)

Achieving each of these is experimentally and technologically challenging!

When these conditions are met, we begin to see that electrons are actually quantum objects; that is, they cannot take on any energy they like, but must only exist in certain allowed energy levels.

Applying a strong magnetic field perpendicularly to a 2D conductor forces electrons to orbit around in small circles in the plane of the conductor. The circumference of these orbits is quantised. That means that the orbits will have discrete energy levels called Landau levels. The energy gap between Landau levels gets bigger as the magnetic field strength is increased. As the field is increased still further, the energy

gaps finally become large enough for us to notice the phenomena that happen when electrons start jumping from one allowed energy level to the next one.

One consequence of this quantised behaviour of electrons is that under these conditions the electrical resistance of this special 2D conductor ceases to vary linearly but starts to show some marked steps. In the forward direction the resistance alternates between being nearly zero, to suddenly increasing sharply, and then returning to very near zero! In the direction perpendicular to the applied current the "Hall resistance" shows some pronounced steps of varying height which occur at exactly the same field strengths at which the longitudinal resistance exhibited those peaks!

The "plateaus" in the Hall resistance happen at very repeatable values. Their values are all integer sub-multiples of h/e where h is the Planck constant and e is the charge on the electron (both universal constants). This ratio has been named the von Klitzing constant (R_k). $R_k = 25812.807459$ Ohms. These quantum resistance steps are called the "Integer Quantum Hall Effect" and occur at R_k , $R_k/2$, $R_k/3$, $R_k/4$... R_k/i (where i is an integer) until the steps get so small that they are difficult to distinguish experimentally.

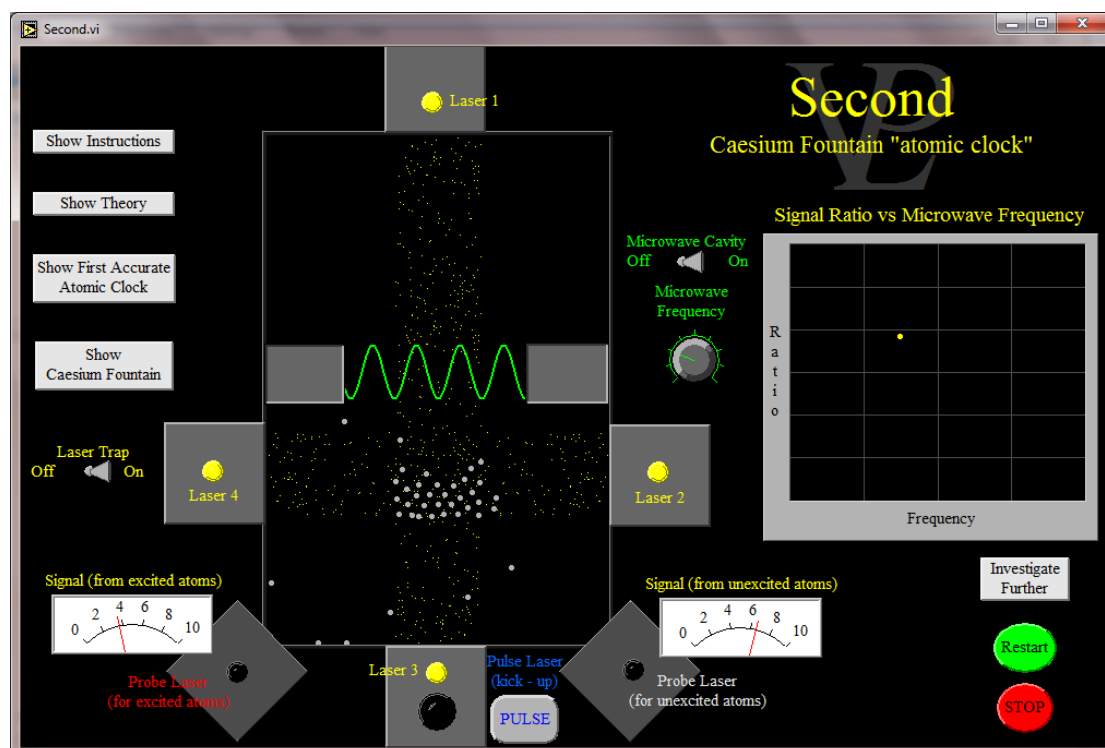
It has also been shown that these same value steps occur with a range of different 2D materials and even materials with imperfections.

More recently the effect has also been seen when using graphene as the 2D conductor. The consequence of all this is that the electrical unit of resistance can now be traced to a combination of two universal constants, and not to a man-made physical resistor in a standards laboratory!

With the recent discovery of graphene (a very thin lattice of carbon atoms, making it effectively two dimensional) it has been possible to reduce the very demanding experimental requirements. A temperature of 4.2 K is sufficient (so no vacuum pump is necessary), and a magnetic field strength of 5 T or less is adequate.

26.10 The Second

Advanced



Energy levels in an atom have very definite levels, and in order to excite an atom from its ground state to a higher energy level, they need to be stimulated by a photon with a very precise energy. The first accurate atomic clock was built by Louis Essen and Jack Parry at the National Physical Laboratory, UK.

The hyperfine energy transitions of Caesium atoms correspond to a very specific frequency in the microwave region of the electromagnetic spectrum. The Caesium fountain now supersedes Essen and Parry's clock; it first traps the atoms in a laser trap which is tuned to slow down the atoms until they have nearly no kinetic energy left (= are very cold!)

The atoms are then kicked upwards into a microwave cavity by means of a laser. The cavity is tuned as carefully as possible so as to excite the atoms as they pass through. After passing through the cavity the atoms enter an open space where they are free from electrical and magnetic influences, and experience 'weightlessness' because they are effectively in free fall. The absence of external fields is important because these would alter the energy levels in the Caesium atoms.

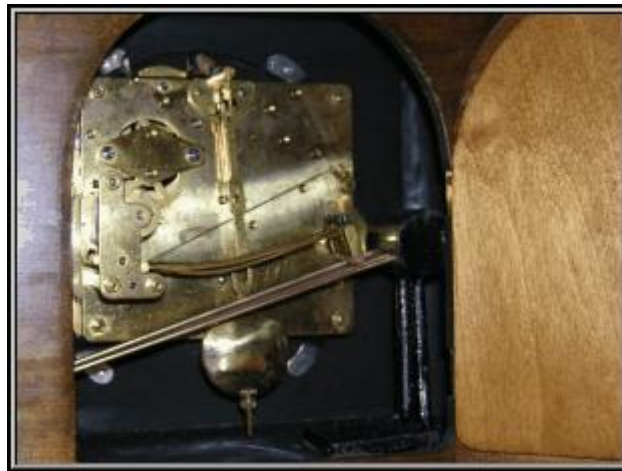
It is possible to probe Caesium atoms with a laser and deduce whether the atoms are excited or in their ground state. The number of atoms that were excited depends on how closely the frequency of the microwave cavity was matched to the natural 'resonant' frequency of the atoms. The frequency of the microwave cavity is constantly adjusted in order to maximize the number of excited Caesium atoms.

The second is now defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of

the Caesium 133 atom at rest and approaching absolute zero. This means that the second is now related to a physical constant in the universe, and in principle any laboratory can realize the second without having to calibrate it against another clock. In practice there are a number of atomic clocks around the world and regular inter-comparisons are carried out.

CHAPTER 27

SIMPLE HARMONIC MOTION

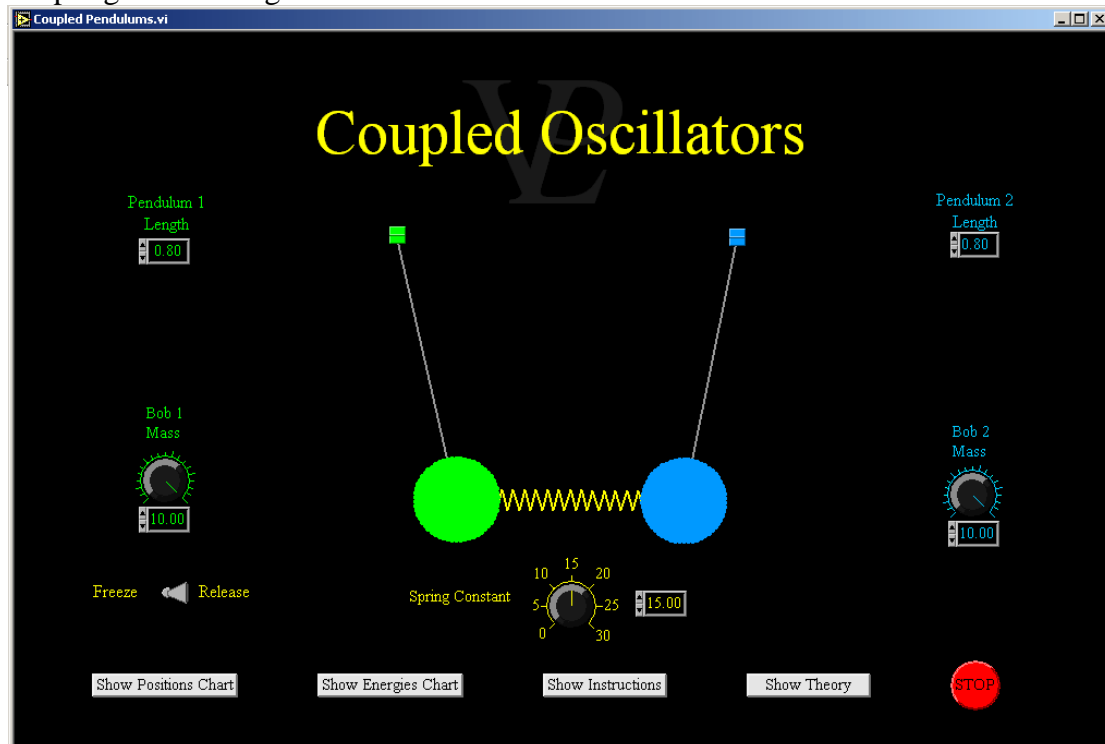


My grandfather's clock has a pendulum swinging inside it.
What other types of motion are 'simple harmonic'?

27.1 Coupled Pendulums

Advanced

Study the motion of a pair of pendulums when they are coupled with a spring. Vary the pendulum length and mass and also the spring constant to see how this affects the coupling of the energies.



The theory of coupled oscillators is quite involved. It is included in the Virtual Physical Laboratory simply as something to play with!

You will notice that the extent to which the energy couples back and forth between one pendulum through the spring to the other pendulum depends on how close the natural frequencies of the pendulums are matched and the value of the spring constants.

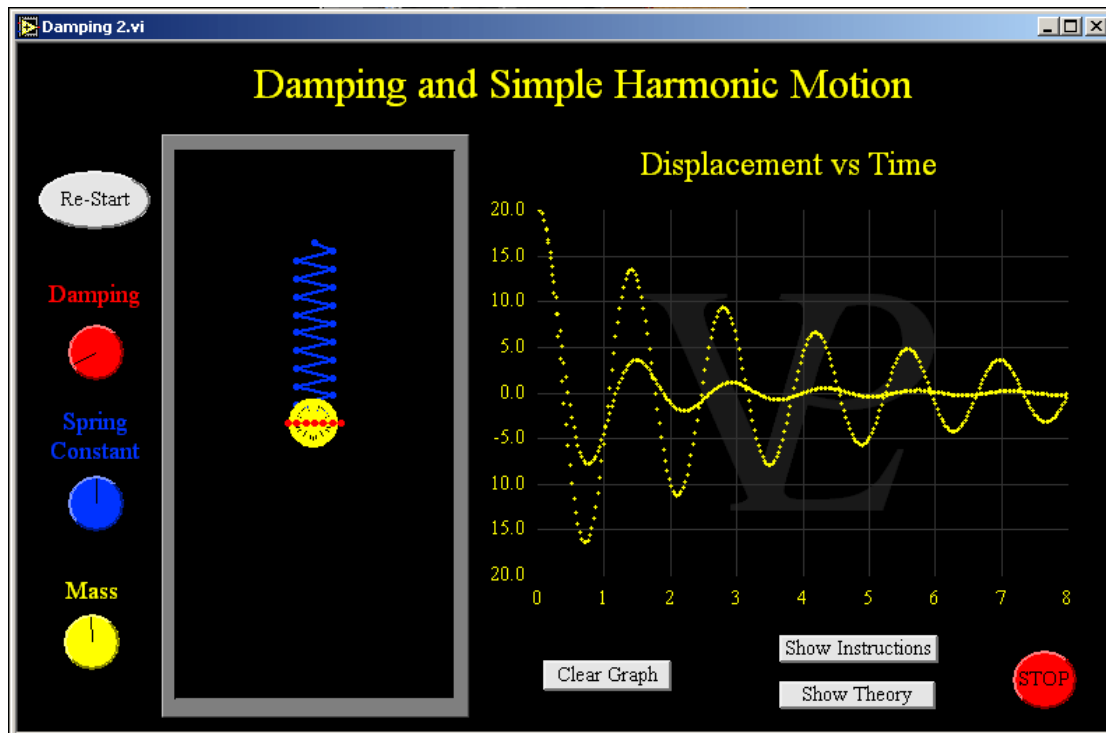
There is also the effect of the masses of the pendulums. Pendulums that are fairly well matched in mass will exchange energy quite well (one of them might nearly come to a total standstill while the other is oscillating at maximum amplitude). However pendulums that are very mismatched in mass will never come to a standstill before the energy of the system is totally lost through damping.

Notice also that (apart from damping) the energy in the total system is constant. The sum of the kinetic, gravitational potential and elastic energies is constant even though the amount of each varies continuously.

27.2 Damping

Advanced

This simulation allows the student to investigate the effect of damping on a simple oscillating system. The concept of critical damping is also introduced.



There are many mechanical and electrical systems that use oscillators. Musical instruments, radio and TV transmitters and receivers, suspension in cars...

In some cases we want to have as little damping as possible such as music and radio but in practice it is never possible to reduce the damping to zero.

In others systems we want very high damping such as in car suspension. However, if we damp the system too much, it becomes rigid and offers no suspension at all.

In cars it is desirable to have what is called critical damping, that is an oscillation where the system returns back to rest in the shortest possible time.

27.3 Hoop Resonance

Advanced

See what happens when a hoop of spring wire is driven at different frequencies. Notice the different (quantised) frequencies at which it will resonate, and how they are determined by the wavelength to perimeter ratio.



Most mechanical systems respond to vibrations. If their internal damping is low, they can be made to resonate at one (or more than one) frequency.

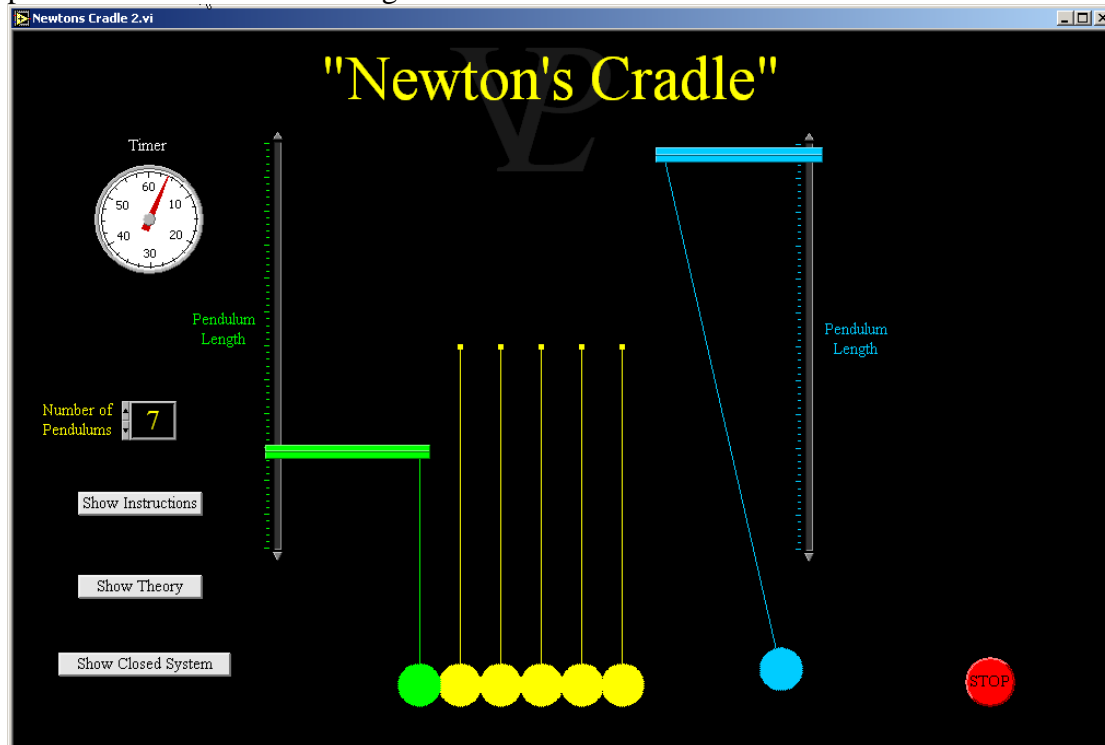
A wire or spring hoop can be made to resonate at a number of different frequencies. The shape of the excitation pattern (where the nodes and antinodes get formed) is such that there will always be an integer number of half-wavelengths going round the hoop when it is in resonance.

In a spring hoop, the stiffness of the spring will affect the frequencies at which it will resonate.

The patterns can be thought of as resembling the allowed energy levels for electrons in an atom. Just as only certain frequencies resonate in the spring hoop, so in an atom only discrete frequencies will produce a stable 'orbit'. These discrete frequencies give rise to the quantised energy levels 'permitted' in an atom.

27.4 Newton's Cradle**Advanced**

This simulation makes it possible to play with a series of pendulums that crash in to each other. See how momentum is conserved, and what happens when the extreme pendulums have different lengths.



The theory behind "Newton's Cradle" is quite interesting. The two main principles on which the behaviour is based are conservation of momentum (which always happens) and conservation of energy (which only happens in perfectly elastic collisions).

When the first pendulum collides with the next one, it transfers its momentum (and energy) to the next one, which in turn transfers it to the next one, until the final ball receives it and swings away. It will swing away until its kinetic energy is converted to potential energy. At this point the ball will stop and then swing back towards all the others, its potential energy is converted back into kinetic energy. and the process repeats itself.

It is interesting to consider the following:

1 - Why does the system eventually stop?

There are a number of reasons why the energy is lost: a) The collisions are not perfectly elastic, so the balls heat up very slightly, b) some of the energy is lost in sound, c) there is air resistance, d) some energy is used in continually bending the threads that support the pendulums.

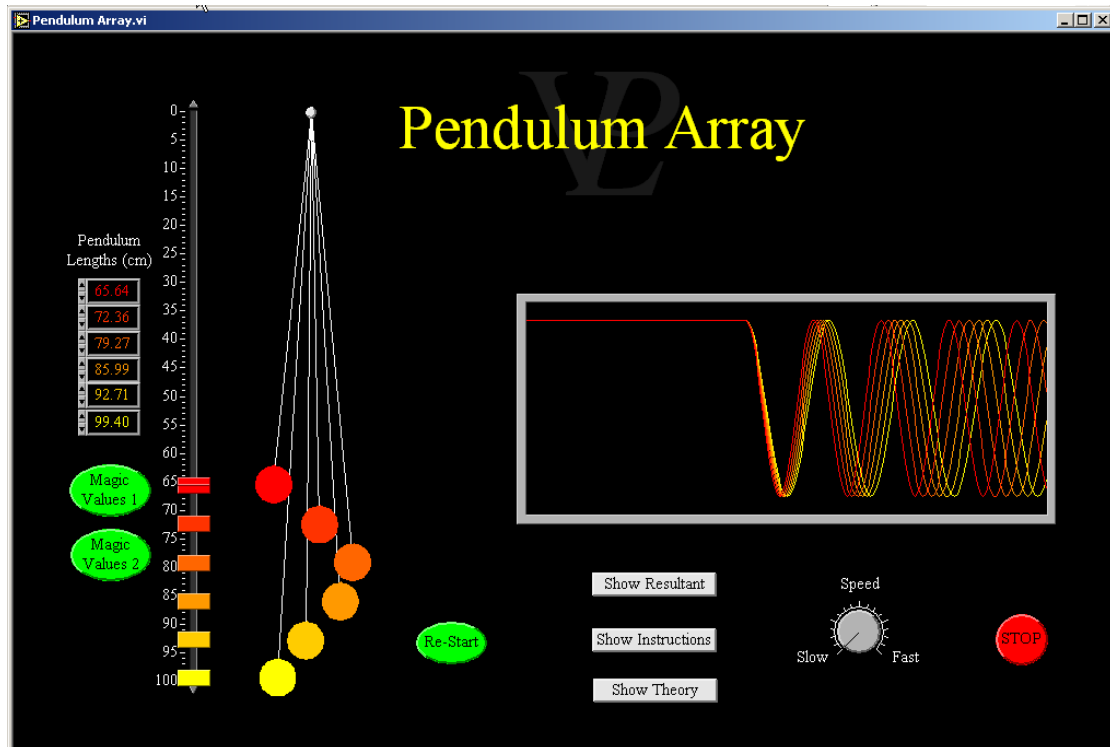
2 - When the right hand side ball reaches its maximum amplitude (and stops before swinging back) the momentum is zero. What has happened to the principle of the conservation of momentum?!

Momentum is only conserved in a closed system when no external forces act upon it. The thread of the final bob exerts a retarding force on the pendulum and so momentarily brings it to a stand still before accelerating it back towards the others. However the thread is also exerting a force on the cradle, so if the entire cradle were resting on frictionless bearings it would be noted that the cradle itself would be moving in such a way that the total momentum is always a constant.

27.5 Pendulum Array

Advanced

This simulation shows how pendulums can beat together. If the lengths are chosen in a special way they can be made to come into phase at predetermined times.



Oscillators with different frequencies or time periods will gradually get out of step with each other. Given enough time they will also get back into step at some point... but it may be a very long time!

The frequency at which two pendulums with frequencies F_1 and F_2 will get back in to step (the "beat frequency") is simply the difference between their frequencies. So we say $F_b = F_1 - F_2$

When there are more than 2 pendulums the picture gets a bit more complicated! However, if the difference between F_3 and F_2 is the same as the difference between F_2 and F_1 , then the frequency of the beats will be the same.

In the very special cases where $F_2 - F_1 = F_3 - F_2 =$

$F_4 - F_3 = \dots = F_{n+1} - F_n$ the frequency of the beats will be the same as the frequency of the beats between F_1 and F_2 .

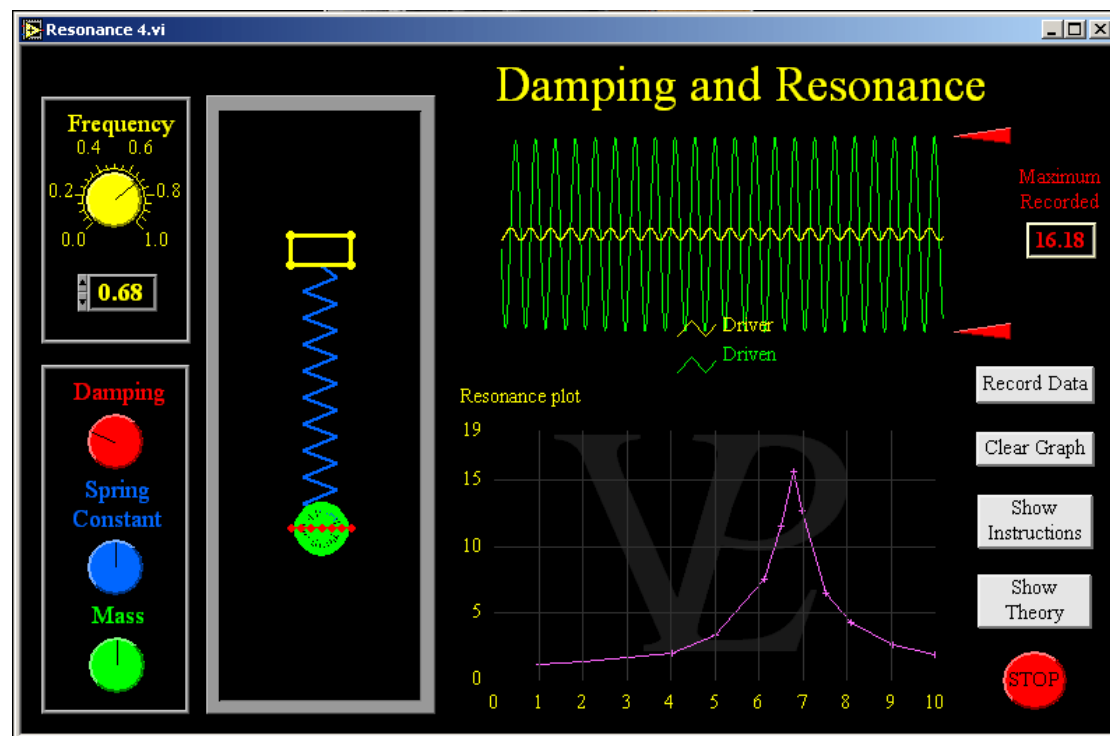
Two special cases have been worked out for you "Magic Values 1" and "Magic Values 2". See if you can work out some magic values for yourself using the fact that

$$F = \frac{1}{2\pi} \sqrt{\frac{g}{L}}$$

27.6 Resonance

Advanced

A resonating system is driven by an oscillator whose frequency can be controlled precisely. As the driver frequency approaches the natural frequency of the system; the amplitude of the oscillation will increase dramatically. The amplitudes can be stored at different frequencies to obtain a resonance curve. Study the effect of damping.



The characteristic resonance curve of a system tells us a lot about the behaviour of the system. A resonance curve which has a very sharp peak tells us that the damping is very small. If it has a very rounded peak, the damping is quite large.

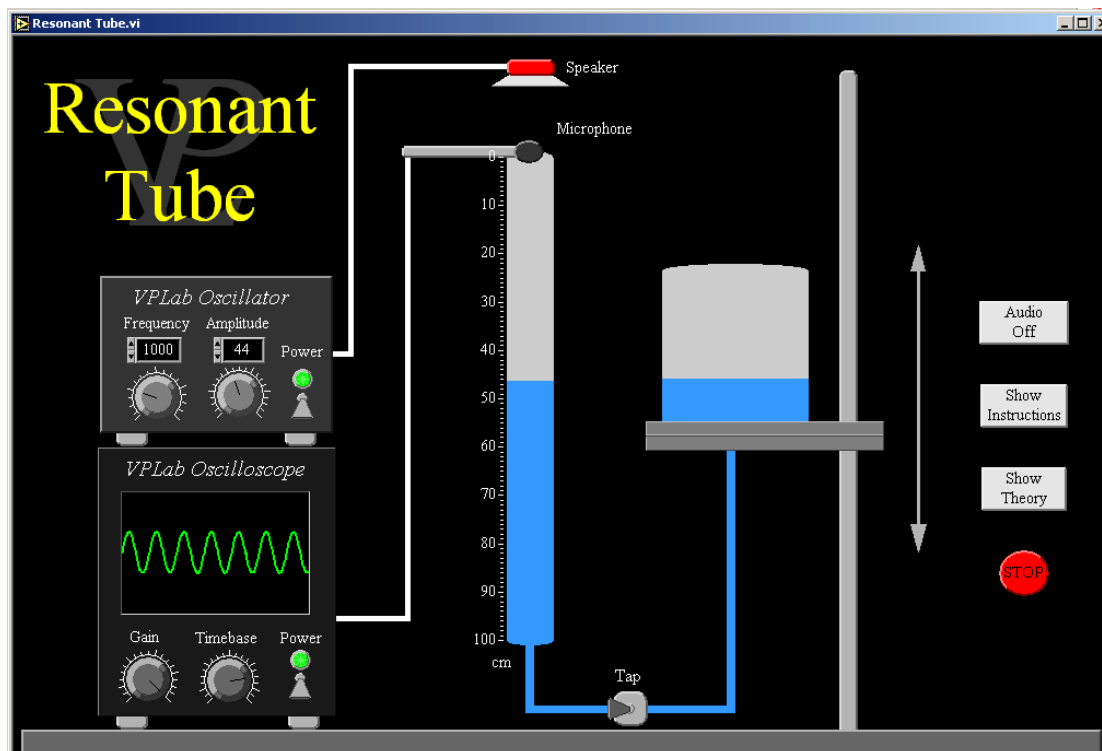
At very low frequencies, all curves should tend towards the $(0, 1)$ point, and at very high frequencies they all tend towards the $(f, 0)$ point, where f is the high frequency at which it is being driven.

The level of damping has very little effect on the natural frequency of the resonance, but it does affect its amplitude drastically.

27.7 Resonant Tube

Advanced

Study resonance effects in an open tube with a variable water level. See and hear the change in amplitude when the water level is at exactly the right place for resonance. Determine the speed of sound with this method.



Sound travelling downwards from the speaker will enter the tube and be reflected from the surface of the water at the bottom of the tube. When the reflected wave superimposes on the incident wave they will interfere with each-other.

If the length of the tube is just right for the frequency that is being used, the air column will resonate with a standing wave pattern that has a node at the water surface and an antinode at the open end. This resonance will add to the loudness of the sound that can be heard.

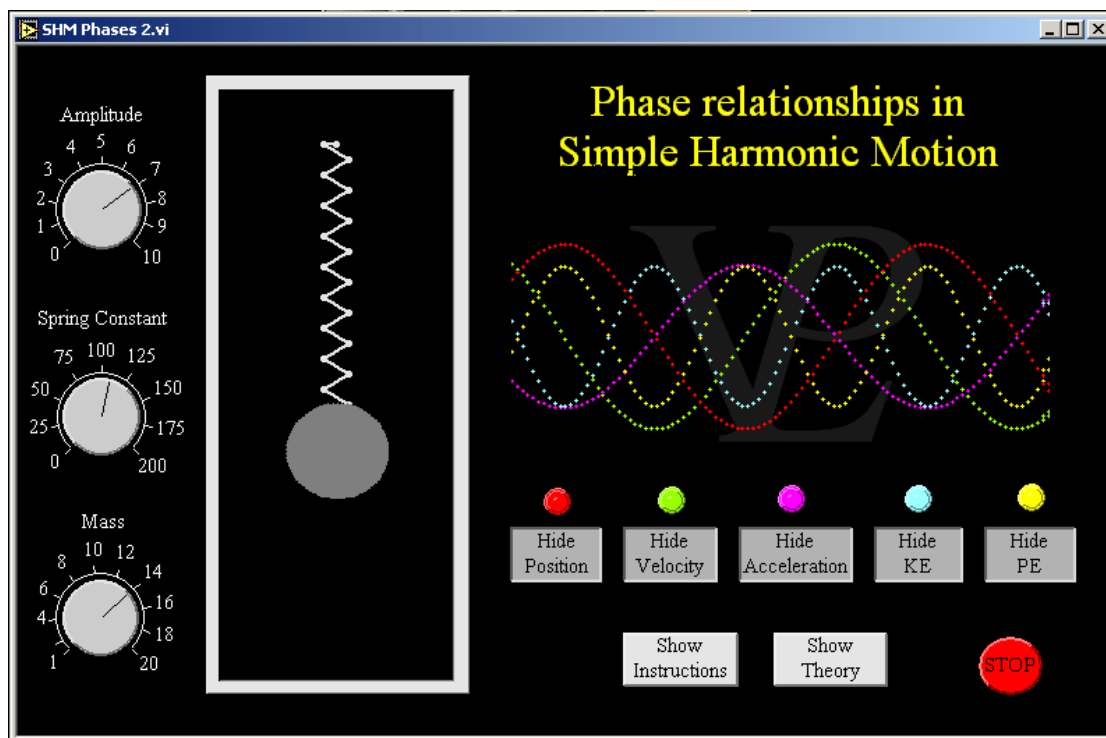
Depending on the frequency that is being used, there may be a number of different lengths which will resonate. Plotting these on a graph (Y = position, and X = position No) yields a graph whose slope is exactly half the wavelength. In this way it should be possible to obtain a more precise value for the speed of sound.

To see more on the theory of the resonant tube see the simulation called 'pipes'.

27.8 SHM Phases

Advanced

This simulation shows the phase relationships between the displacement and the velocity, acceleration, kinetic energy, and potential energy in Simple Harmonic Motion. Showing how the velocity and displacement are in phase quadrature, and the KE and PE are in antiphase with each-other and at twice the frequency.



Whenever there is a possible energy interchange between two different forms such as kinetic and potential or electric and magnetic then there is the possibility of setting up an oscillation.

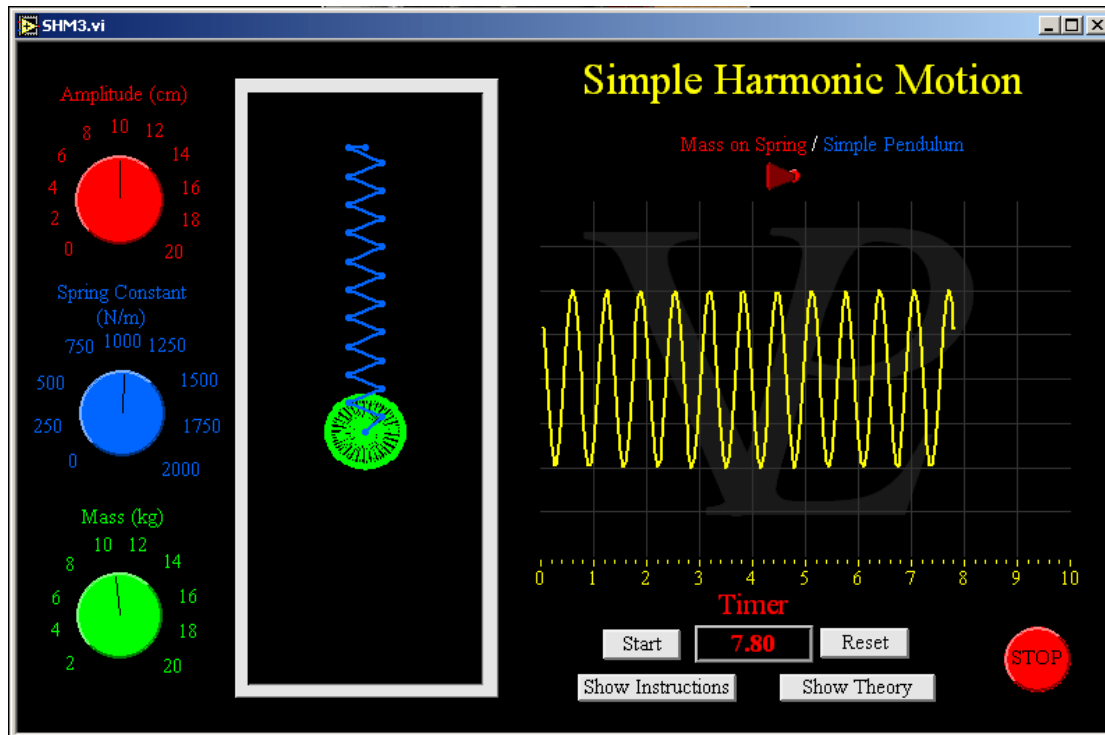
One of the most straightforward examples to imagine is a simple pendulum where the energy is changing from gravitational potential energy at the top of the swing to kinetic energy at the bottom of the swing. All the time the total amount of energy remains constant.

In the special case where the magnitude of the restoring force is proportional to the displacement and acts in the opposite direction to the displacement then the oscillation is said to be simple harmonic motion. When plotted the displacement, velocity and acceleration over time are all sinusoidal in shape. The acceleration will be in anti-phase with the displacement.

27.9 SHM

Advanced

The effect of length, mass and amplitude on the frequency of a simple pendulum can be investigated as well as the effect of the spring constant and mass on the frequency of mass on a spring.



In simple harmonic motion, the period is the name given for the time taken to complete one complete oscillation. It is often given the symbol T .

Generally the things that increase the inertia of the system lengthen the period, and those that increase the forces or stiffen the system shorten the period.

Some things increase both the stiffness and the inertia at the same time. When this happens, the net effect is that they do not seem to affect the period at all.

See if you can find out which ones do affect the period and which do not.

CHAPTER 28

SOUND

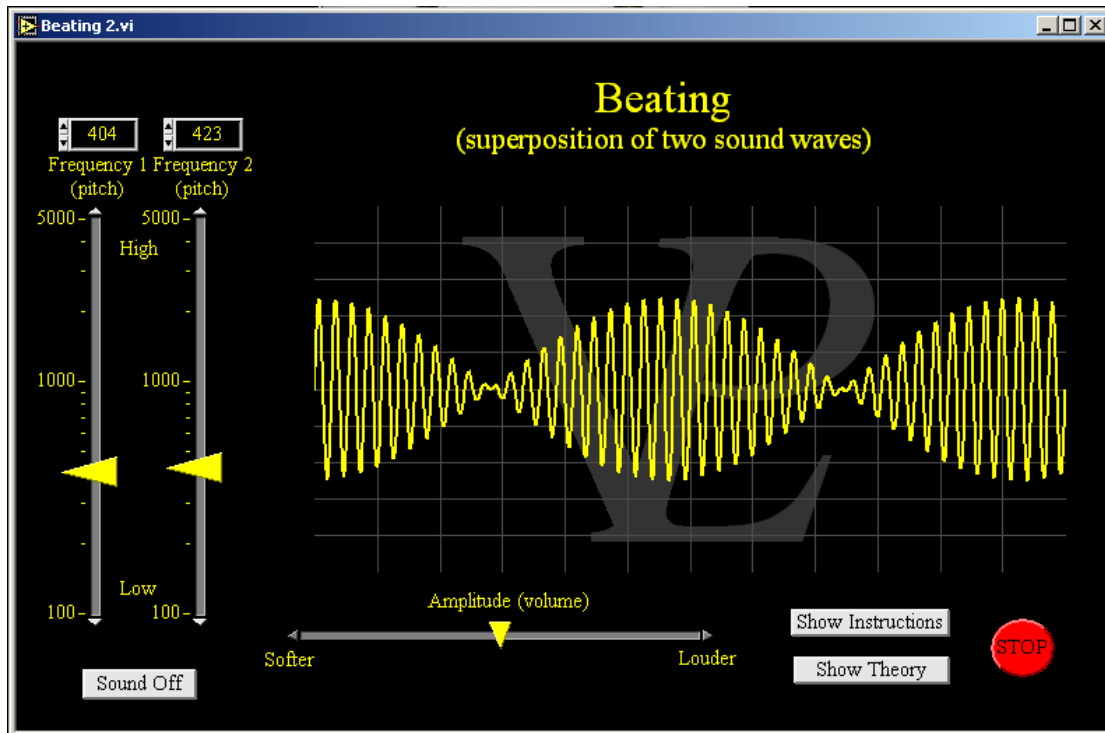


Wonderful sources of sound (if played well!)
What makes instruments sound different from each other?

28.1 Beating

Advanced

See and hear the effect of two sound waves of similar frequency interfering with each other. It will be noted that as the difference between the frequencies increases, the frequency of the beat also increases.



If your computer has speakers you should be able to hear the sounds when using this simulation.

When two similar but not identical frequencies are played together, a pattern of beats is heard.

The frequency of the beats is given by $f_b = f_1 - f_2$

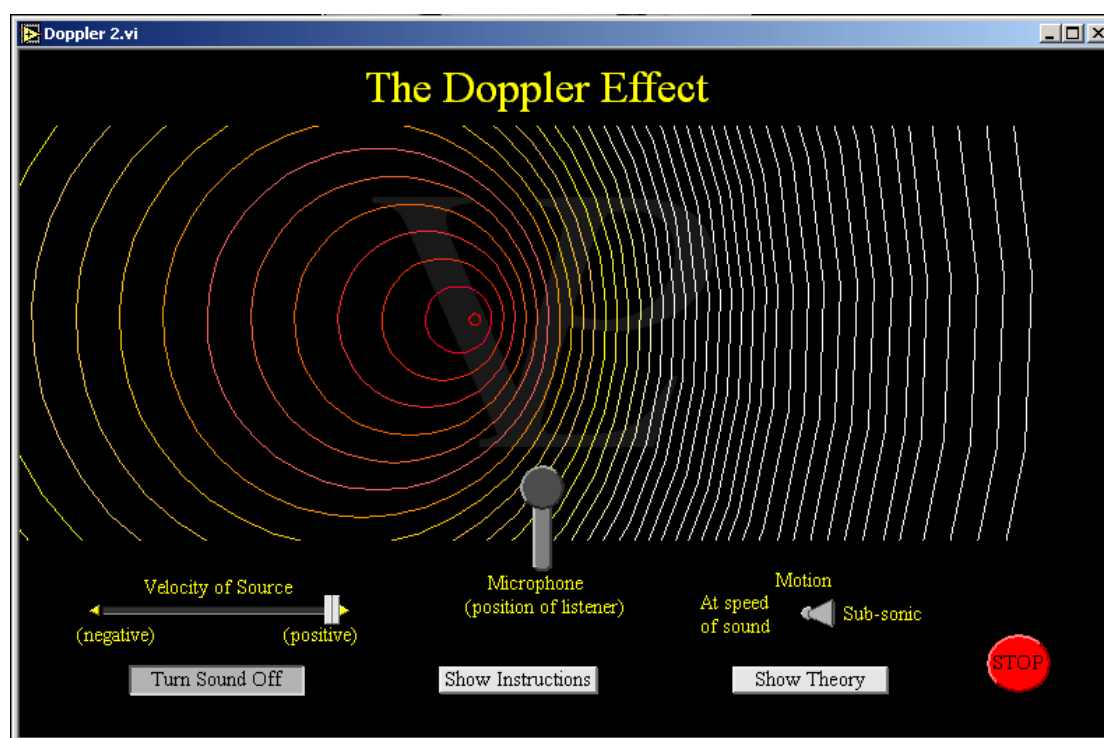
The frequency of the note is given by $f_n = (f_1 + f_2)/2$

This phenomenon may be heard when two instruments are close, but not exactly in tune, it may also be heard when two turbines on a jet are not rotating at exactly the same speed.

28.2 Doppler

Advanced

The effect of movement on a source of sound is investigated in this simulation. Sound waves get 'bunched up' or 'spread out' depending on the direction of the movement. The simulation is visual as well as audio. The simulation also explains the bang heard when travelling at the speed of sound!



The Doppler Effect is the name given to the change of frequency in the sound heard when the source or the listener is moving relative to each-other. In this simulation, only the source moves.

1 - When the source moves towards the listener, the wavelength gets shorter and since the speed of sound is constant, the perceived frequency increases.

2 - When the source moves away from the listener the wavelength gets longer and so the frequency perceived by the listener decreases.

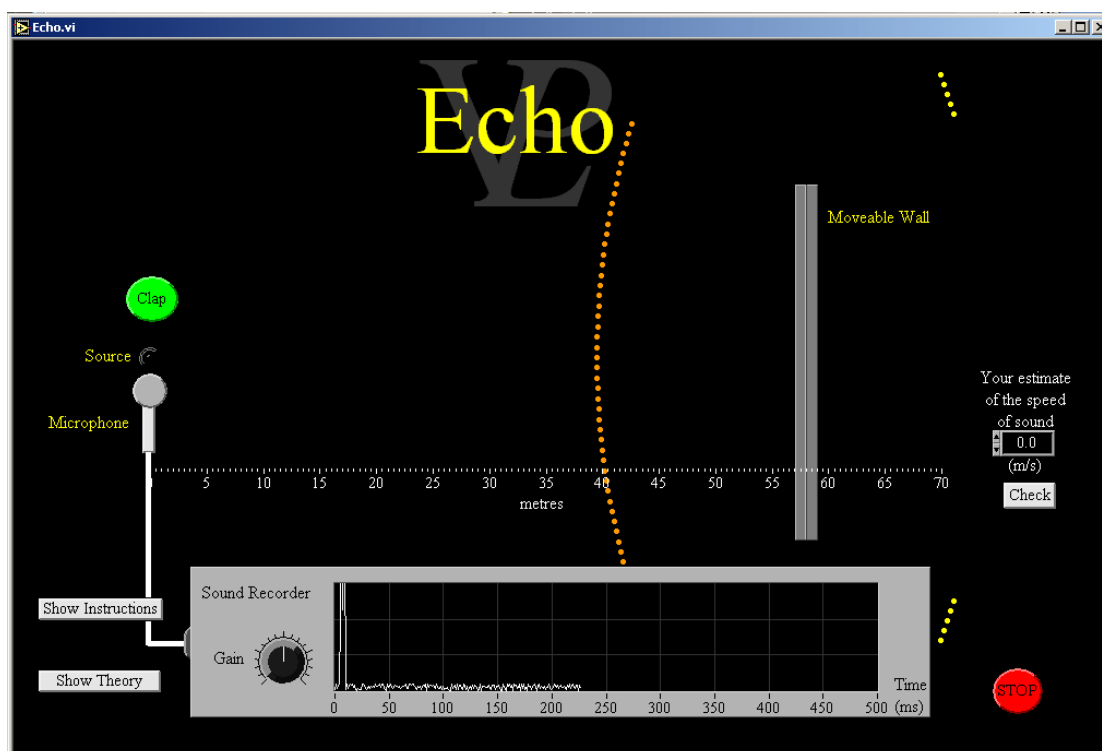
If the source moves at exactly the speed of sound, the source moves along with the sound it has just produced. The waves get completely 'bunched up'. When they finally reach the listener, he hears a loud bang.

Note that the Doppler effect also happens to light waves, except that the speeds required are much higher since the speed of light is so large. Colours are seen to be red shifted to a longer wavelength if they come from an object that is moving away or blue shifted to a shorter wavelength if they come from an object which is approaching the observer.

28.3 Echo

Basic

See how an echo is produced. Use a virtual microphone and a signal recorder to measure the speed of sound.



Sound is a longitudinal wave that travels away from the source in all directions. When it encounters a hard surface it can bounce back from it. In the special case where the surface is not only hard, but also fairly flat, the reflected sound wave can reproduce the original sound reasonably well. This reflected sound is called an "echo". Sounds normally bounce off many surfaces, but if the surfaces are not reasonably flat, or if there are many surfaces at different distances and angles it becomes very difficult to hear a clear echo.

The time between the original bang and its echo can be used to calculate the speed of sound, remembering that the total distance travelled is twice the distance between the source and the wall. $\text{Speed of sound} = \text{distance} \times 2 / \text{time for echo}$

In a large sports hall that has not been treated for acoustic damping it is possible to hear several echoes that bounce off different walls at different distances.

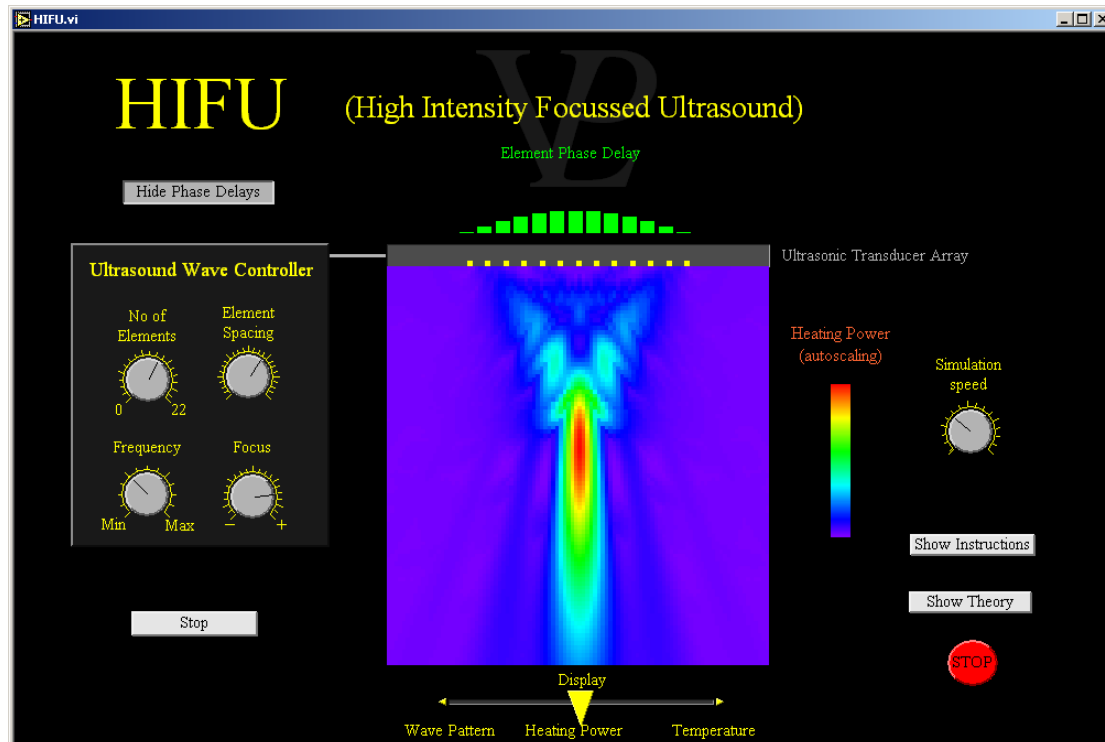
In a "reverberation chamber" (a special room with very flat parallel walls and ceilings) the echo of a loud clap can continue for several seconds as the sound bounces back and forth many times.

An "anechoic chamber" is exactly the opposite; it has walls which are covered in cones of foam so that the sound is absorbed immediately.

28.4 HIFU

Advanced

This simulation shows how it is possible to focus continuous ultrasonic waves to produce heating and so kill undesired cells inside the body without opening the body.



High Intensity Focussed Ultrasound (HIFU) is a new medical technique in which ultrasound is focused inside the body used to produce kill tumours.

This technique is a fairly recent development. It consists in sending a continuous ultrasound beam that is focused at a particular depth below the skin producing localised heating. If the temperature is raised to some 65 C and maintained for a few seconds, this is enough to destroy the cells in the focused area. This medical procedure is quick, relatively cheap and does not carry the health and safety restrictions of radiotherapy, however it also produces some collateral damage to the region around the focus.

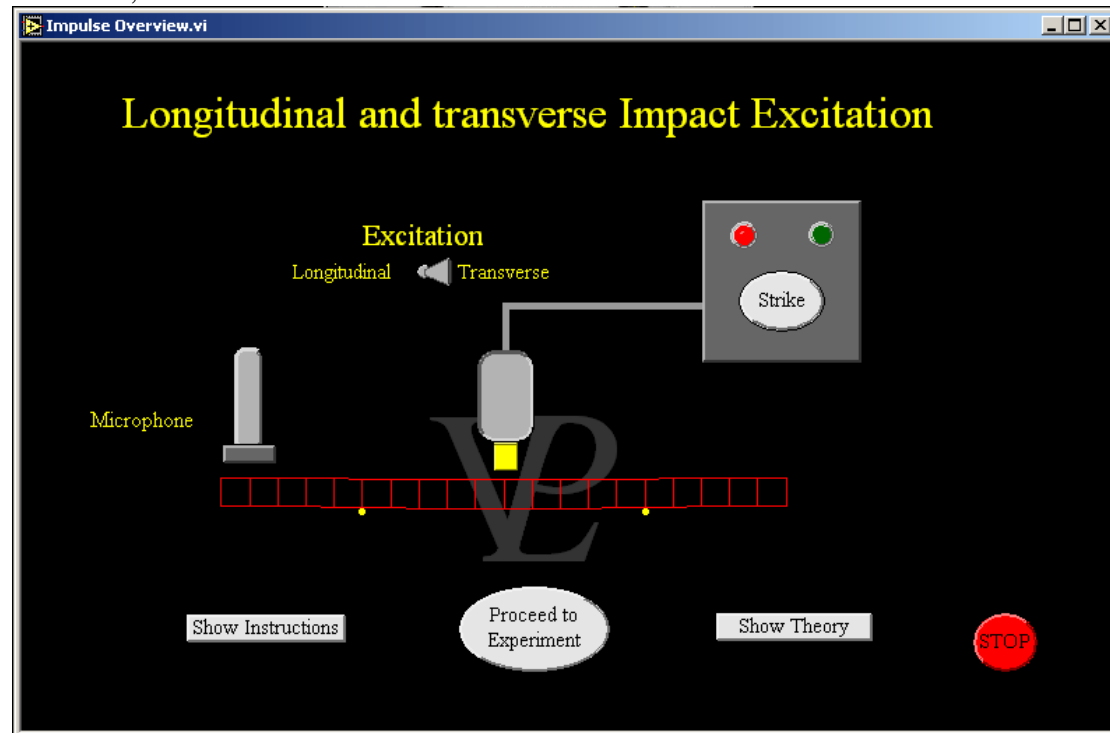
It differs from Lithotripsy in that the ultrasound waves are continuous instead of pulsed. The aim in HIFU is to produce heating, not shock.

The technique is 'non-invasive' as it does not involve cutting the body open, but it does carry the risk of some collateral damage. The skin immediately in contact with the transducers as well as the region around the focus can suffer some damage. However this is less severe than a full operation, is much cheaper and minimises the risk of external infection.

28.5 Impulse Excitation

Advanced

This experiment allows the user to obtain a fairly accurate measurement of the Young's Modulus of elasticity of a metal rod. The method consists in measuring the frequency of the ringing made when the rod is struck. It ties together the chapters of materials, waves and sound!



The longitudinal excitation is mathematically much simpler to understand than the transverse excitation. The velocity of sound through a solid is determined by its density and its modulus. The equation relating them is $v = (E/\rho)^{-1/2}$. (1) where E is the modulus and ρ is the density.

When a bar is supported in the middle and struck inwards at one end, the oscillation will form antinodes at both ends and a node in the middle. From your knowledge of waves you will remember that $v = f \lambda$. (2) where f is the frequency and λ is the wavelength. In the fundamental oscillation mode $\lambda = 2L$. (3) where L is the length of the bar or rod being tested. Substituting 2 and 3 into equation 1 we find that $E = 4 \rho (Lf)^2$. (4)

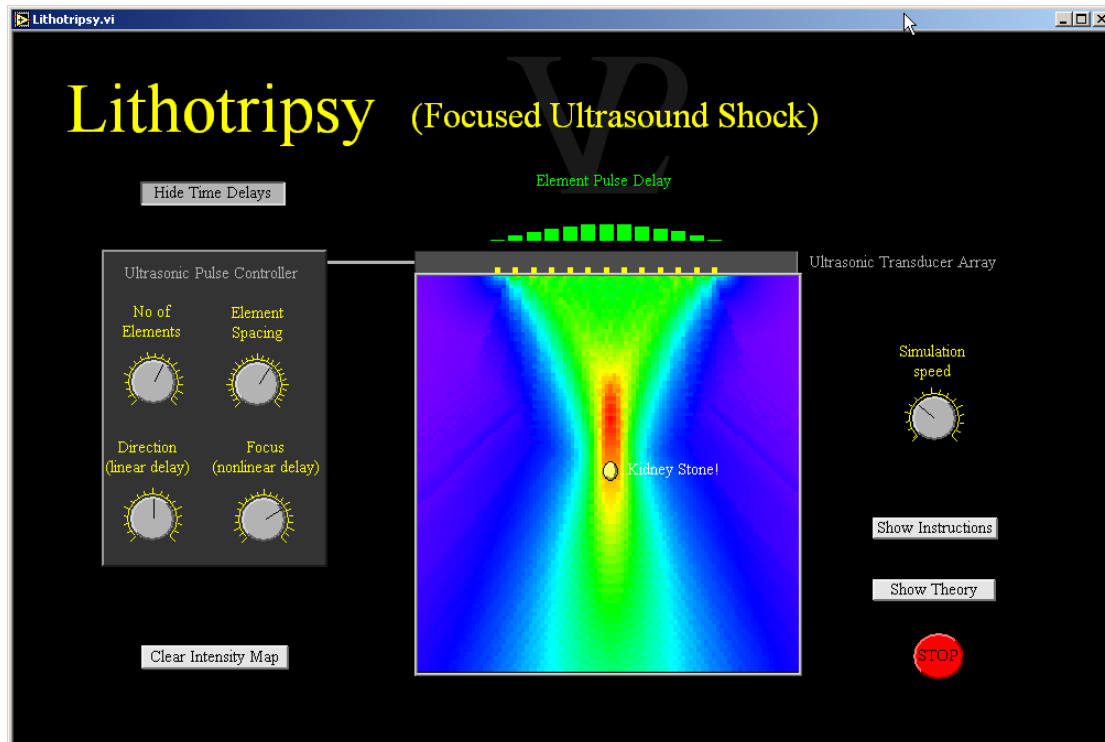
The transverse excitation mode is simple to understand qualitatively, but quite complicated mathematically. The frequency at which a transverse wave will propagate down the bar depends on the modulus, the mass and the exact dimensions of the bar. If the bar is supported approximately at the $1/4$ and $3/4$ positions they will become nodes whilst the middle and both ends will be antinodes.

The equation that relates the modulus to the parameters of the bar is a complicated one. The one given here is only an approximate one which works when $L \gg W > T$. L is the length, W is the width and T is the thickness. The bar must be resting on its wide side with its thickness in the Z direction. $E = 0.9465 L^3 M f^2 / (W T^3)$. (5) Note that M must be in g, and L, W and T must be in mm for this expression to be valid.

28.6 Lithotripsy

Advanced

This simulation shows how focused ultrasonic shocks can be used to shatter calcifications in the human body.



Lithotripsy is the name given to the technique by which kidney or gall stones are shattered in situ so that the body can get rid of them without further medical intervention.

Ultrasonic waves cannot be focused by conventional lenses. The way to focus them is by manufacturing a resultant wave with the desired wavefront curvature so that it will focus at the right place. The wavefront can be designed by firing different elements of a composite transducer at different times.

When ultrasonic pulses are focused their intensity increases significantly and can even cause a shock, which if repeated enough times, can cause calcium corpuscles inside a body to shatter into smaller pieces.

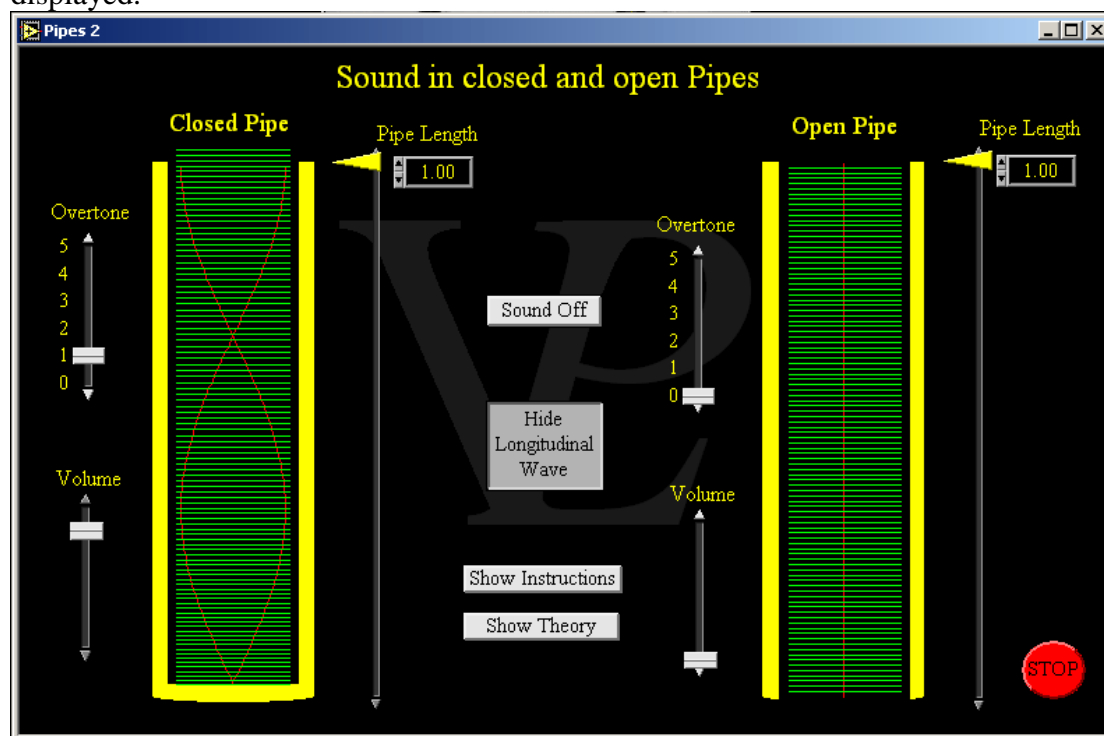
The technique is 'non-invasive' as it does not involve cutting the body open, but it does carry the risk of some collateral damage. The skin immediately in contact with the transducers as well as the region around the stone can suffer some damage. However this is less severe than a full operation, is much cheaper and minimises the risk of external infection.

Another technique involving focused ultrasound is known as HIFU (High Intensity Focused Ultrasound) - See the HIFU simulation. This technique is a more recent development. It uses a continuous ultrasound beam that is focused in order to produce heat to kill unwanted cells.

28.7 Pipes

Advanced

Sound waves in open and closed pipes can be investigated both audibly and visually. The position of nodes and antinodes will be noted as the fundamental and overtones are played. The longitudinal waves as well as the transverse representation may be displayed.



Several instruments such as flutes, saxophones, organs produce their sound by creating a resonating column of air inside them.

Columns of air form nodes whenever they encounter a closed end and antinodes when they meet an open end.

The position of the nodes and antinodes is what determines the frequency of the sound produced. The easiest way to raise the frequency of the resonating column is by using a shorter pipe. Church organs have many pipes of different lengths. In a flute the way that the effective length of the pipe is changed is by blocking and unblocking the holes along its side.

Another way to obtain a higher frequency is to blow harder in order to excite higher harmonics or overtones.

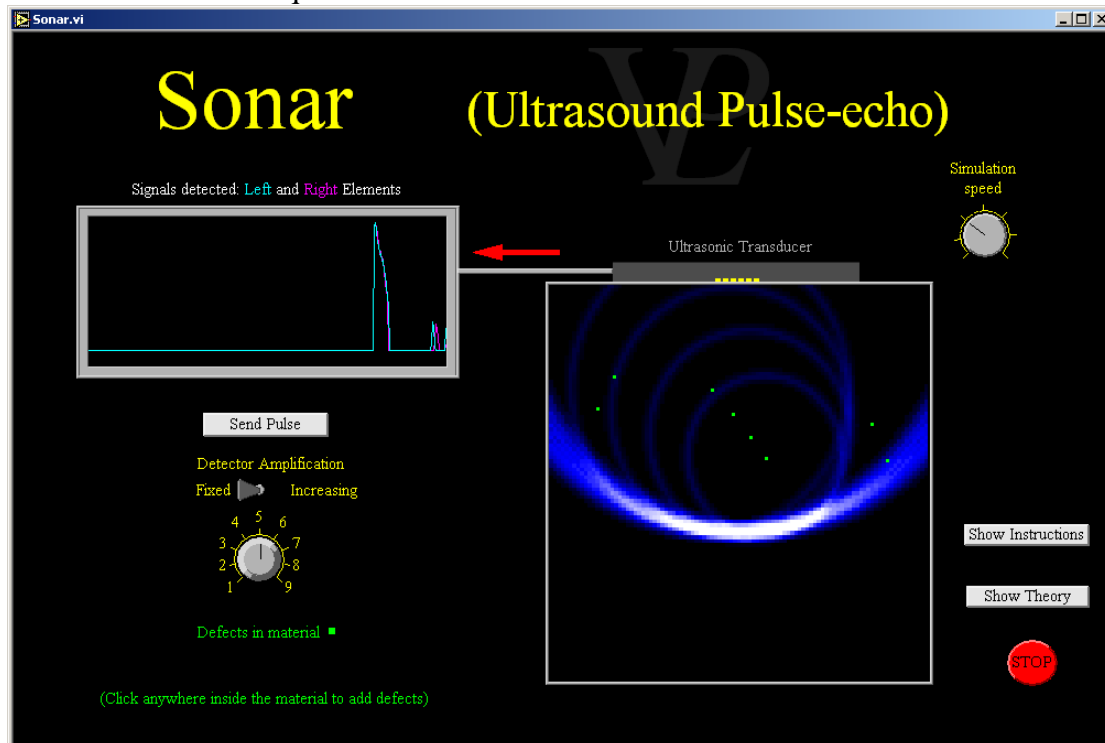
Open and closed pipes have different overtones. If the lowest frequency is f_c , a closed pipe can produce $f_c, 3f_c, 5f_c, \dots$ (only the odd numbered harmonics). For an open pipe, if the lowest frequency is f_o , it can produce $f_o, 2f_o, 3f_o, 4f_o, \dots$ (all the harmonics).

The advantage of a closed pipe is that for a given length of pipe, its lowest frequency is lower than the lowest frequency of an open pipe ($f_o = 2f_c$) making it possible to get very low notes out of a relatively short pipe.

28.8 Sonar

Advanced

This simulation shows how sound reflections can be used to detect the position of defects in a solid or liquid.



Ultrasound refers to sound waves with frequencies so high that they cannot be heard by humans (>20 kHz). Typical ultrasonic frequencies range between 400kHz and 4MHz. The "Sonar" family of applications all consist in sending a sharp burst of ultrasound (normally with a piezoelectric transducer) and then to 'listen' for any sound reflected back.

The sound reflected back is normally very weak, so it needs very high amplification. The longer the delay between the outgoing pulse and the reflection, the deeper into the material the defect is located. The location of the defect can be further located by looking at the differences in the reflected pulse as detected by the different elements of the transducer.

Ultrasound can be used as an imaging technique in a number of ways:

"Sonar" - The simplest mode simply measures the depth of seas and rivers. More developed systems can produce depth maps as images of the bottom of lakes, riverbeds, etc. Sonar can also be used to locate sunken ships. Less glamorous but more frequently Sonar is used to detect the presence of fish at a given depth below the boat.

"Ultrasound Scan" - Ultrasonic waves are weakly reflected from boundaries between regions of slightly different density. In this way "Pulse-Echo" to detect defects in materials or boundaries of differing densities in human bodies. In this way unborn babies as well as anomalous growths can be studied non-invasively.

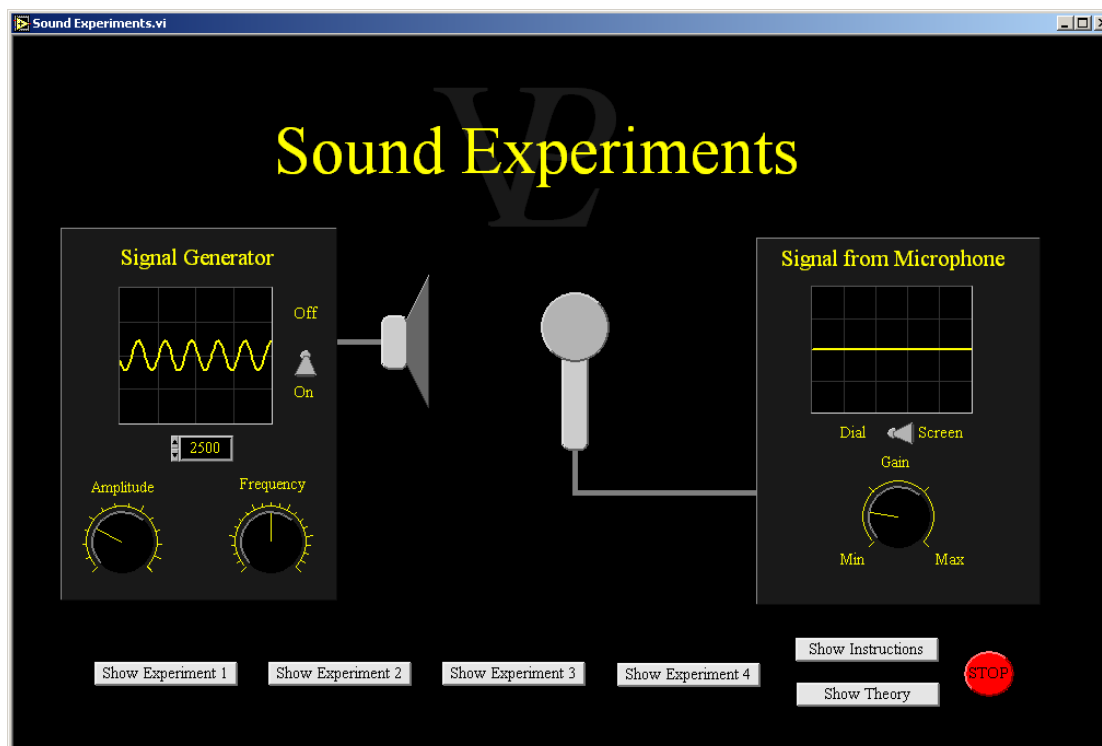
Engineers use this to detect defects in welds and melts of metal.

The overall direction in which the pulse is sent out can be steered by introducing a small time delay between the pulses sent by the different elements of the ultrasonic probe. It is possible to scan (and focus) the ultrasonic waves in a raster pattern in order to map out larger areas.

28.9 Sound Experiments

Advanced

To do these experiments you will need at least one microphone. There are four experiments you can try out.



The principles of superposition of sound waves can be studied in the waves chapter of the Virtual Physical Laboratory.

These sound experiments make it possible to use your computer as the source and recorder of sound interference patterns.

The standing wave pattern of experiment 1 makes it possible to calculate the speed of sound. You need one speaker and one hard board to reflect sound.

The standing wave pattern of experiment 2 makes it possible to calculate the speed of sound. You need two speakers.

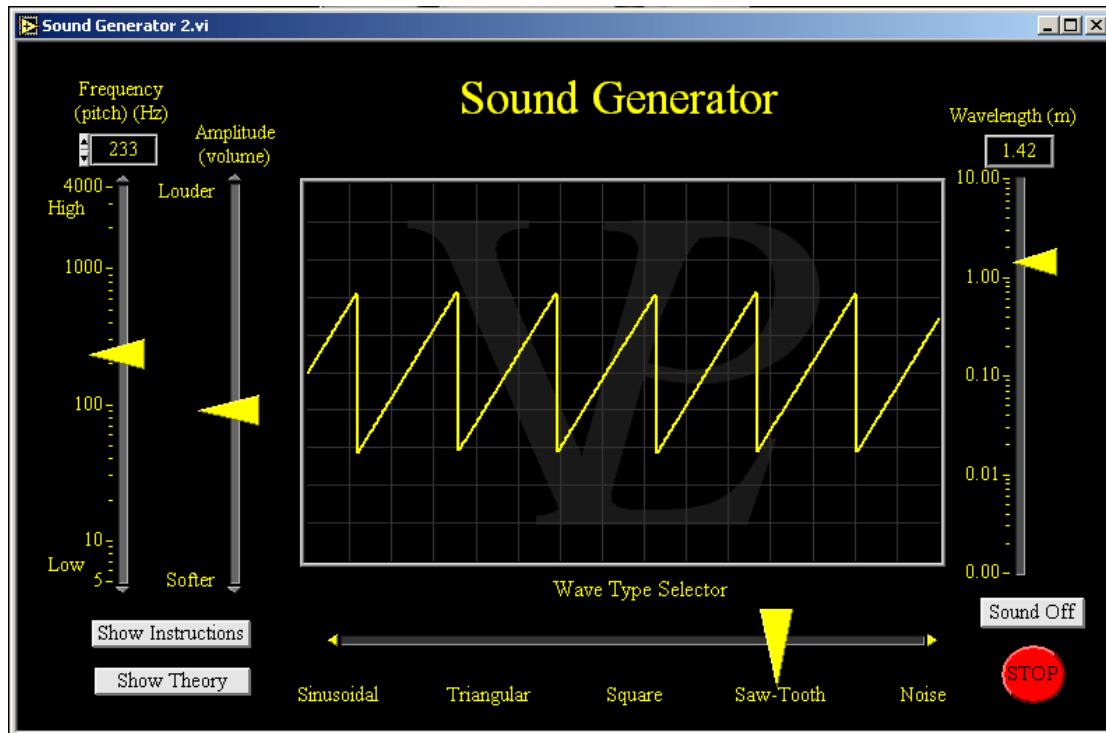
The "Youngs Slits" pattern of experiment 3 makes it possible to map out the pattern of maxima and minima and see how it is affected by speaker separation.

The phase relationship investigation of experiment 4 makes it possible to see how the separation of the microphones can pick up two positions that are in phase (maximum contribution from both microphones) or in anti-phase (where the signal of one microphone nearly cancels out the signal from the other one). This experiment can also be used to calculate the speed of sound.

28.10 Sound Generator

Basic/Advanced

A simple sound generator is displayed where the amplitude and frequency can be adjusted. See the inverse relationship between frequency and wavelength. Hear the difference between sinusoidal, triangular, saw tooth and square waves.



The amplitude of a sound signal determines its loudness, and the frequency determines its pitch.

If we change the frequency of a sound, we automatically change its wavelength.

The equation relating the frequency, the wavelength and the velocity of sound is

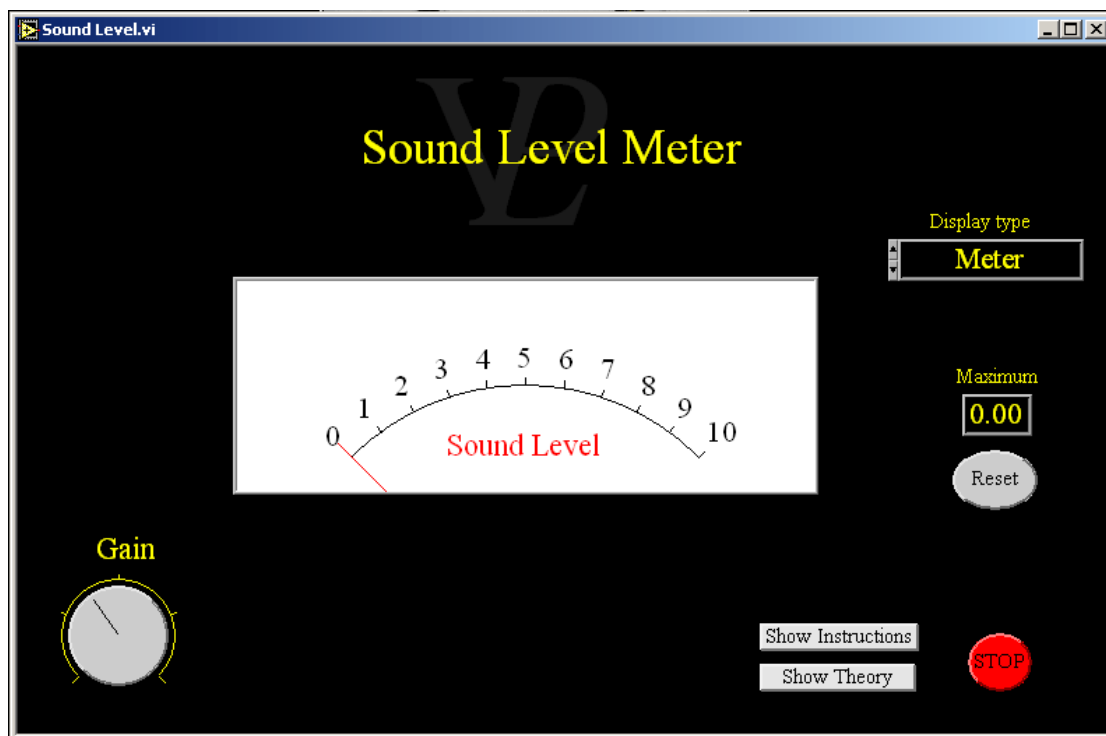
Velocity = frequency \times wavelength.

The speed of sound in air is roughly equal to 330 ms^{-1} , but it depends on temperature, pressure and humidity.

28.11 Sound Level

Basic

This program simply records the sound level (volume) and displays it in arbitrary adjustable units in a variety of ways. It can be used as a means to investigate the inverse square relationship of sound intensity with distance in a real experiment. (Microphone required)



Sound intensity is measured in 'decibels' which is a logarithmic scale!

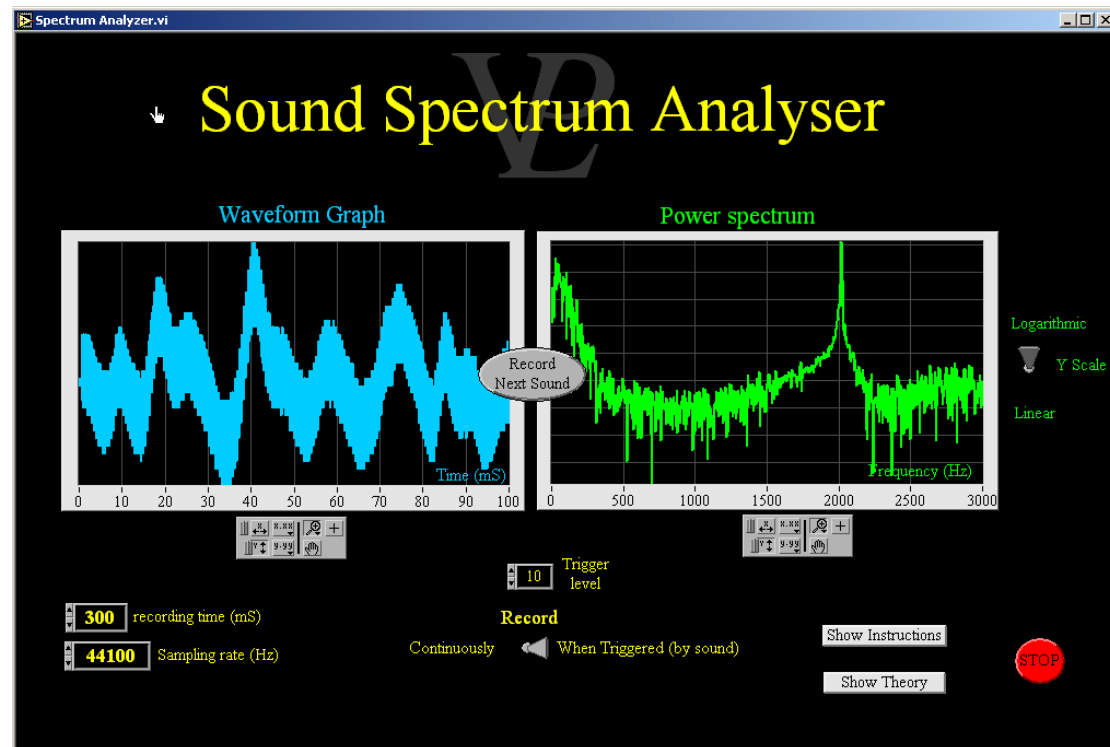
The signal recorded by this program cannot be easily converted into decibels because this recording is dependent on the quality and response of the microphone!

This program simply records the present sound level and also the maximum sound level achieved.

28.12 Spectrum Analyser

Advanced

This program records a sound signal obtained from a microphone, and analyses the spectrum and displays a graph. It can be used to measure the frequency of sound signals originating from plucked strings, resonating columns of air, tuning forks, etc.



This program samples the sound as recorded by the microphone at the rate selected in 'Sampling rate' either 11025, 22050, or 44100 Hz. For most audible sounds of interest 11025 is plenty as this represents a lot of data. Thus the recording time should be kept reasonably short, typically 100 ms. If you record at higher rates then the quality will be better but the data file larger.

After the sound has been recorded the program calculates the frequencies present in the sound by carrying out a Fourier transform. To find out more about this you will need to consult a mathematics text book.

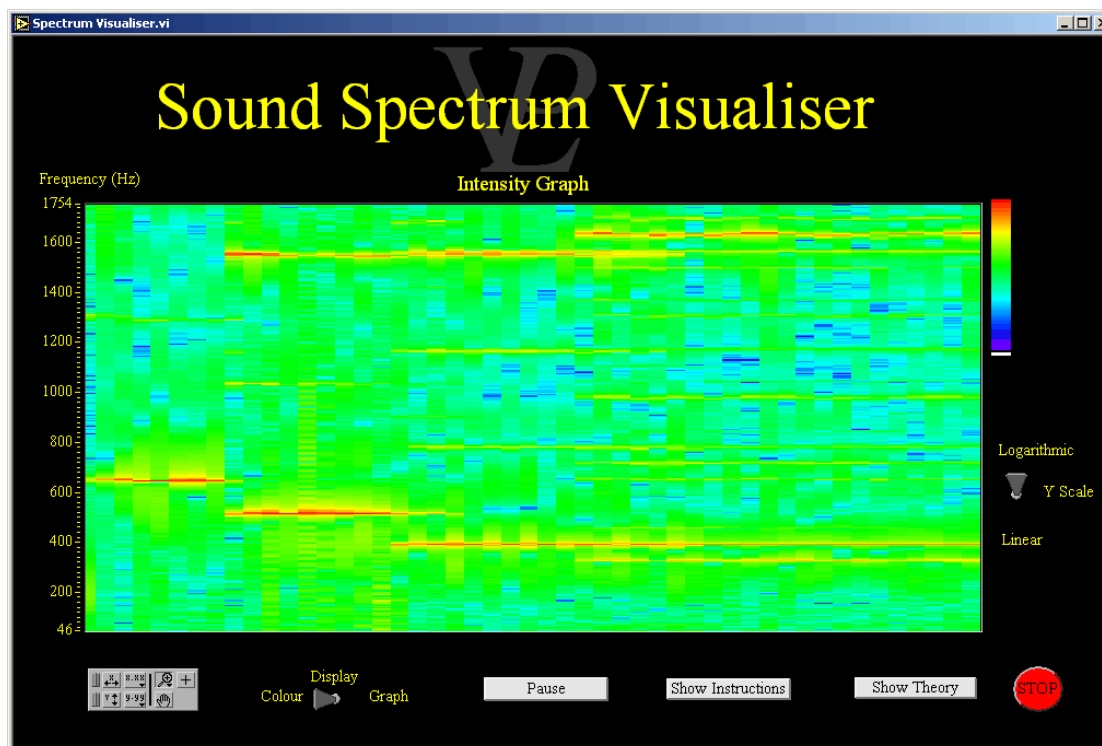
The precision with which the frequencies can be identified is governed by the sampling rate and the recording time. For best precision, increase both of these. You will be able to see how well the program resolves the frequencies by how narrow the peak is displayed.

You may often notice two or three peaks being displayed even though you thought you were only humming one note. That is because our voices and most instruments also produce what are known as harmonics at twice, three and sometimes more times the fundamental frequency. It is the relative strength of the harmonics that gives different instruments their distinctive sound quality.

28.13 Spectrum Visualiser

Advanced

This is a colourful scrolling spectrum display. It is ideal for use with instruments to see the harmonics as the notes change. A microphone is needed.



This program samples the sound as recorded by the microphone. It can manage to resolve frequencies up to around 15 kHz.

The two different modes of display serve to show the frequency composition of the sound being recorded.

Many instruments produce many different overtones and harmonics. If you sing a steady note you may often notice two or three peaks being displayed even though you thought you were only humming one note. That is because our voices and most instruments also produce harmonics at twice, three and sometimes more times the fundamental frequency. It is the relative strength of the harmonics that gives different instruments their distinctive sound quality.

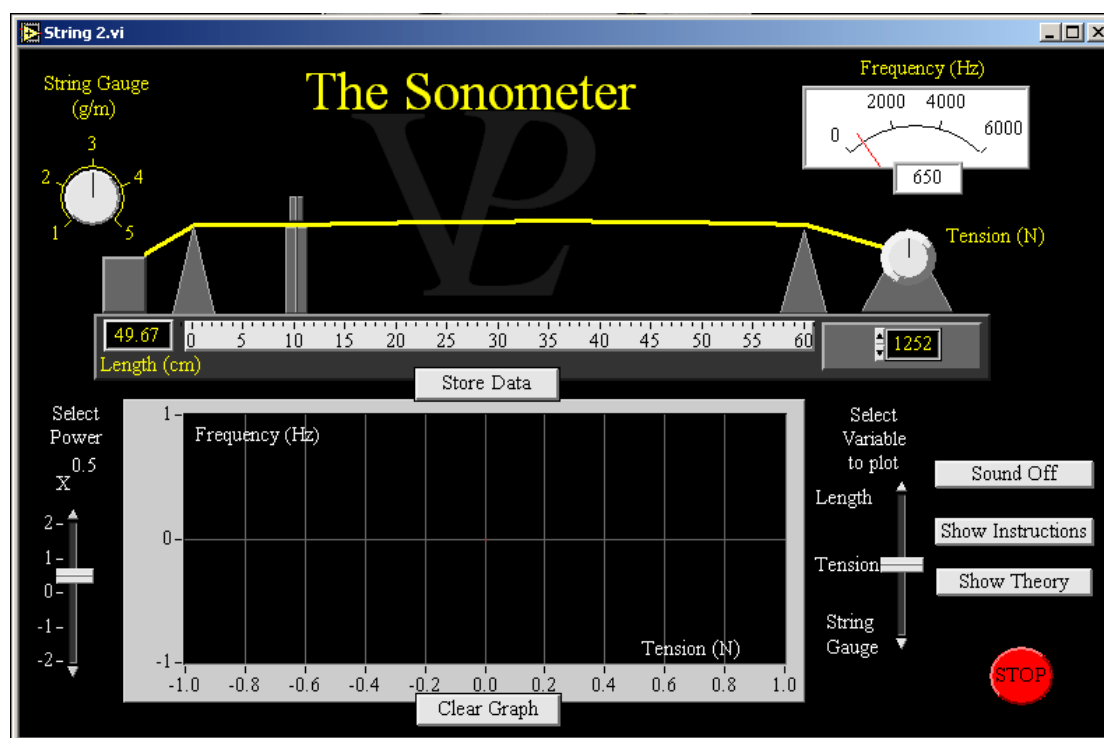
Instruments like trumpets produce a small number of harmonics when played softly (typically 4 or 5), but when they are played loudly they produce many more harmonics (well over 20!).

See what else you can discover by playing your instrument in to this spectrum visualiser!

28.14 String

Advanced

This simulation allow the student to investigate the relationship between the frequency of oscillation of a stretched string and its tension, length and thickness (strictly- its mass per unit length).



The frequency at which a tight string will vibrate depends on its length, tension, and its thickness (or more accurately, on its mass per unit length).

The velocity with which a transverse wave travels down a tight wire is given by:
 $v = (T/M)^{0.5}$.(1) where T is the tension in Newtons, M is the mass per unit length in kg/m.

When the string is plucked it will oscillate with a node at each end and an antinode in the middle. This means that the wavelength will be equal to twice the length of the string. wavelength = 2L . (2) where L is the length of the string

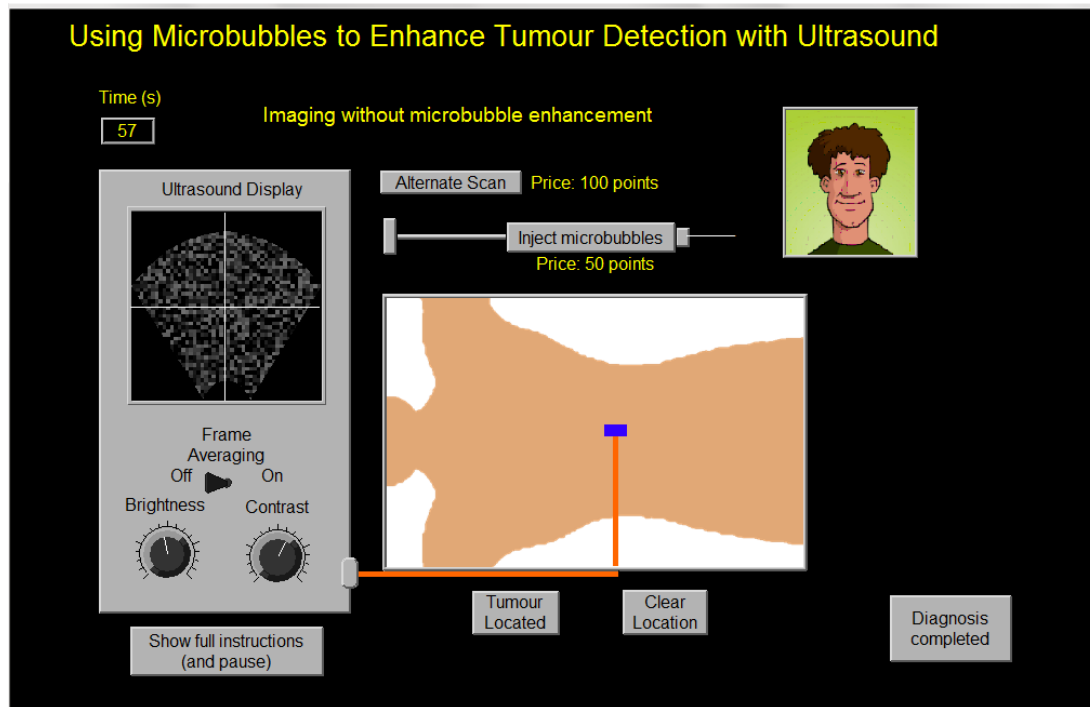
But we also know that $v = \text{frequency} \times \text{wavelength}$ (3) Rearranging (2) and (3) we find that $f = v/2L$ (4) and substituting from (1) we find that $v = \frac{1}{2}L(T/M)^{0.5}$.(5)

When tuning a guitar or a violin, the tension of the strings is adjusted with the keys at the far end of the guitar. When playing a guitar or a violin the different note frequencies are obtained by changing the length of the string. This is done by sliding a finger along its length and squeezing it against the wood of the neck of the guitar.

28.15 Tumour detection through Ultrasound

Advanced

This simulation was produced to illustrate how micro-bubbles can be used to enhance the contrast of ultrasound images.



Ultrasound images are routinely used in hospitals in order to image soft tissues inside the body. The most dramatic application is that of imaging unborn babies, however it can also be used to image internal organs, searching for any anomalies. One difficulty however, is that the images often lack in contrast, so some subtle features cannot be seen clearly.

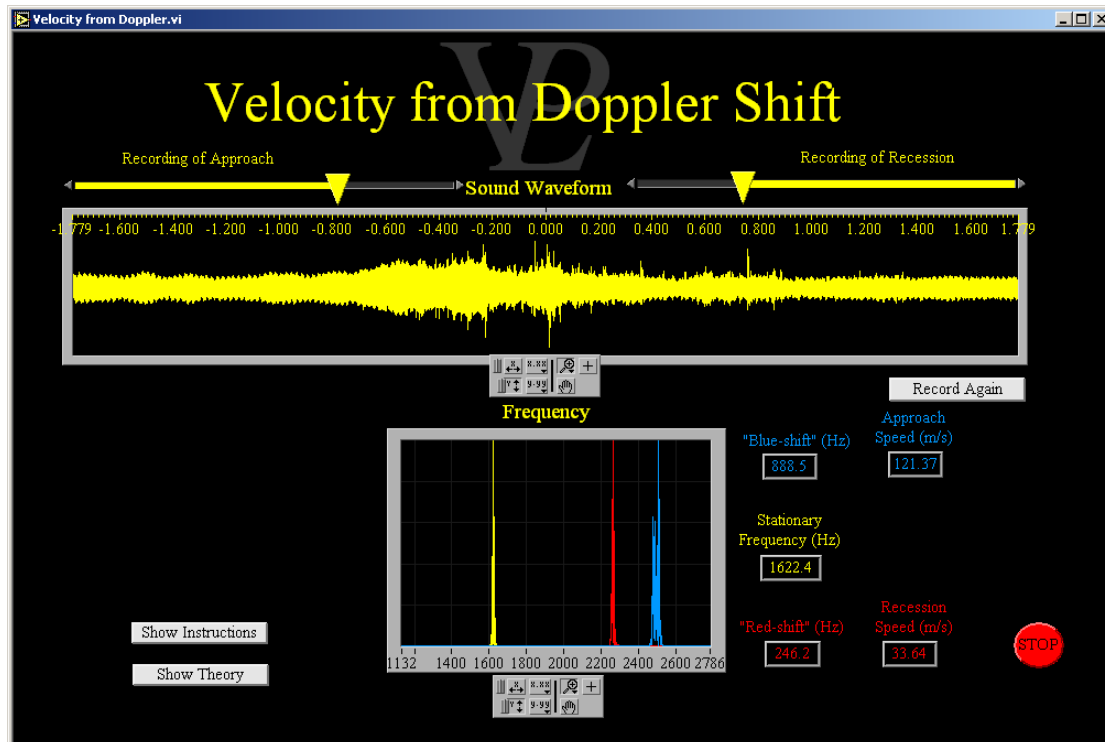
Microscopic bubbles can be injected safely into the blood stream, and as these travel round the body they can attach themselves to tumours or other organ walls, and when an ultrasonic wave passes through the body it causes it to scatter and reflect more than it would otherwise do. The overall effect is that it enhances the contrast, making it more easy to detect features that might otherwise have been overlooked.

In time, the lipid coating of the microbubble dissolves and the very small amount of gas air inside it will diffuse safely through the bloodstream without causing any ill effects whatsoever.

28.16 Velocity from Doppler

Advanced

To run this experiment you need a microphone and a moving source of sound that emits a constant note



The Doppler Effect is the name given to the change of frequency in the sound heard when the source or the listener are moving relative to each-other.

If F_s is the frequency of the source and F_r is the frequency detected by the receiver, the full relationship between F_r and F_s is as follows: $F_r = [(C+V_r)/(C-V_s)] F_s$

Where C is the speed of sound in the medium

V_r is the velocity of the receiver through the medium
(+ve if moving towards the source)

V_s is the velocity of the source through the medium
(+ve if moving towards the source)

In our case, the microphone is stationary and the air is stationary too; this makes matters much simpler!

$V_r = 0$ and we can therefore remove it from the equation..

$F_{\text{approach}} = [C/(C-V_s)] F_s$, $F_{\text{recession}} = [C/(C+V_s)] F_s$

$\Delta F = F_{\text{approach}} - F_{\text{recession}}$

$\Delta F = C F_s / [(C-V_s)-(C+V_s)] = 2 C V_s / (C - V_s)$

If $C \gg V_s$, $C - V_s \sim C$ so $\Delta F \sim 2 V_s / C$, rearranging we find $V_s \sim C \Delta F / 2$

This result assumes $V_s \ll C$, which I assume will be the case for any practical experiment in a laboratory!

CHAPTER 29

TEMPERATURE

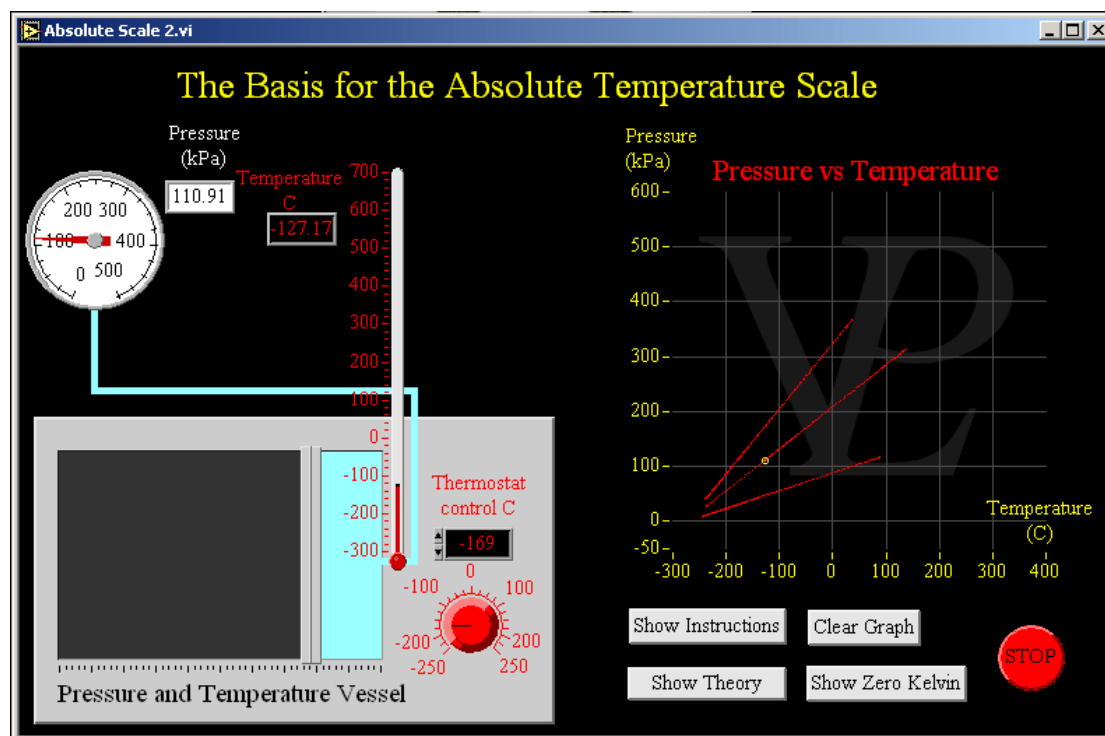


This is how I know how hot or cold it is.
What other ways can we measure temperature?

29.1 Absolute Scale

Advanced

Cool a gas down until the pressure drops to exactly zero. You will notice that the pressure reaches zero at the same temperature regardless of the initial volume or quantity of gas used!



Zero pressure occurs when the molecules are completely at rest. For this reason the temperature at which the pressure drops to exactly zero is called the absolute zero. Many applications including this one cannot reach absolute zero, but at least they can point towards it.

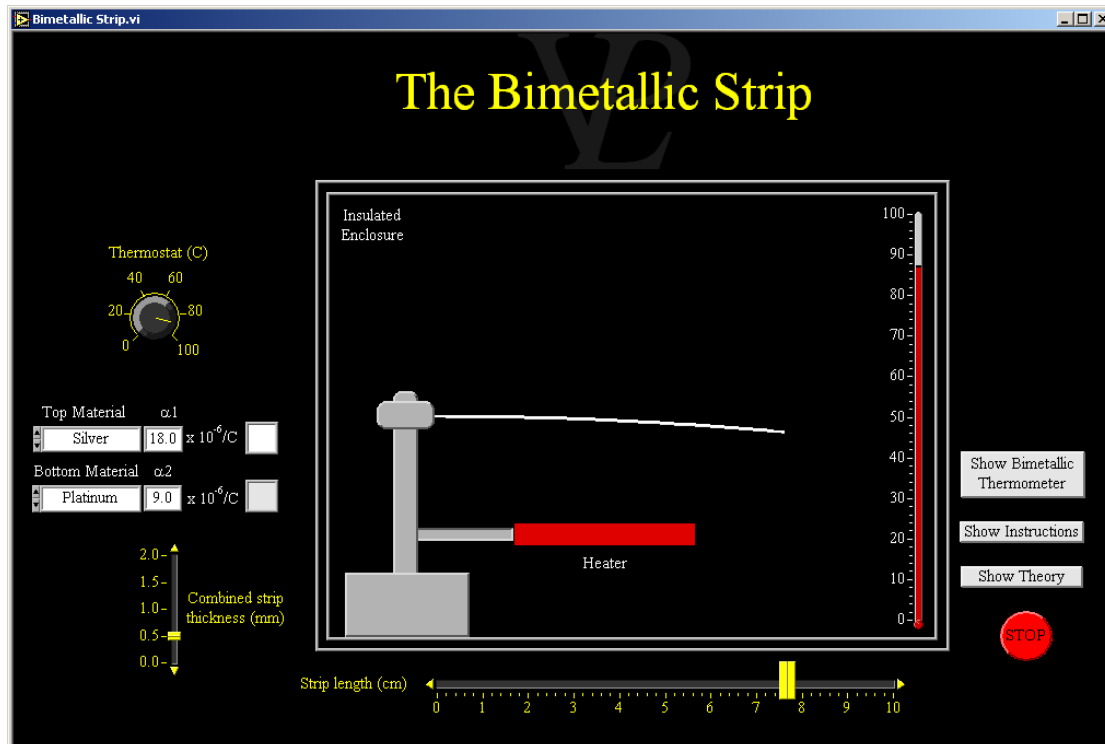
If we use degrees of the same size as those on the Celsius scale, we predict that absolute zero (0 Kelvin) should happen at -273.16°C .

The absolute zero is independent of the initial volume of the gas, or even the type of gas used.

29.2 Bimetallic Strip

Advanced

This simulation shows what happens when materials of dis-similar expansion coefficients are bonded together.



The rate at which materials expand is governed by their linear expansion coefficient (often denoted by the Greek letter alpha). When heated, materials with a larger alpha expand more than materials with a smaller alpha. Typical alpha values for metals range between 0.000025 to 0.000008 /°C. This means that the expansion is quite small.

The extension of a rod is proportional to its length as well as its thermal expansion coefficient. The expression for the extension is as follows:

Extension = Length \times alpha \times Temperature change

The total length $L(T)$ at temperature T is given by

$$L(T) = L(20) \times (1 + \alpha \times (T - 20))$$

Where $L(20)$ is the length at 20°C and T is the temperature in °C.

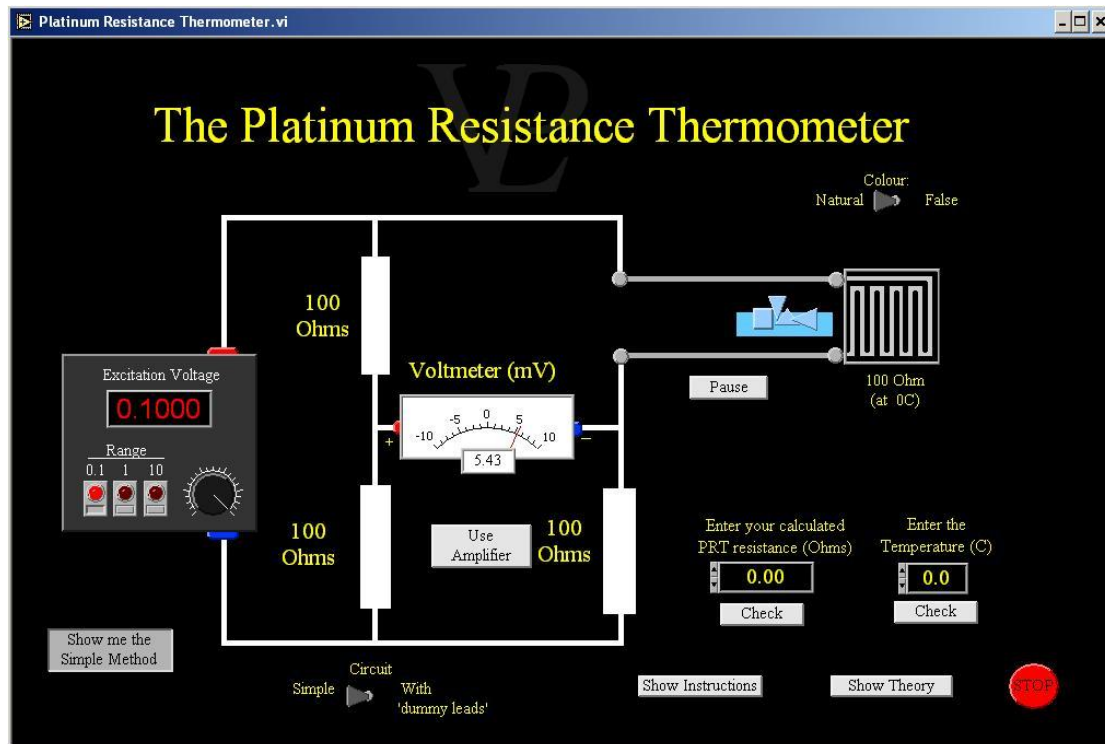
When two materials with different thermal expansion coefficients are bonded together along their length and then heated (or cooled), the differential expansion will cause the strip to arc one way or the other. This can be a nuisance in some instances. Machines made up of different materials will be put in to strain when the machine heats up.

The "Bimetallic Strip" is a way of using this effect for a good purpose. The bending strip can be made to operate a switch which controls a heater. The strip can also be used as a "thermal cut-out" in an electric circuit: when the current flowing through it is too high the bimetallic strip can heat up sufficiently to cause it to bend and open the circuit so that no more current flows. Bimetallic spirals can also be used as simple (and cheap) thermometers!

29.3 Platinum Resistance Thermometer

Advanced

This simulation shows how the resistance of platinum can be used to measure temperature. An unbalanced Wheatstone Bridge is frequently used.



The Platinum Resistance Thermometer (PRT) is a useful device to measure temperature because it can be made very small so that it can respond to rapid temperature differences. PRTs also have a large measurement range (-200 to + 850C). The resistance of platinum changes with temperature. Since the change is fairly small ($\sim 0.385\%$ Ohm/C), a Wheatstone Bridge (WB) is frequently used.

The easiest way to use the PRT thermometer over the range 0 to 100C is to calibrate the Voltage output of the WB directly against the fixed points of water (freezing and boiling) and then divide the Voltage interval into 100 equal parts. However, the Voltage to Temperature relationship will not be linear even if the change in resistance with temperature is fairly close to linear.

The Resistance of PRTs over the range 0 to 100 C varies according to

$$R(T) = R_0 (1 + aT)$$

where $a = (R_{100} - R_0) / 100 R_0$. For platinum $a = 0.00385$ Ohms/C.

So calculating R_{prt} from first principles makes it possible to measure the Temperature accurately.

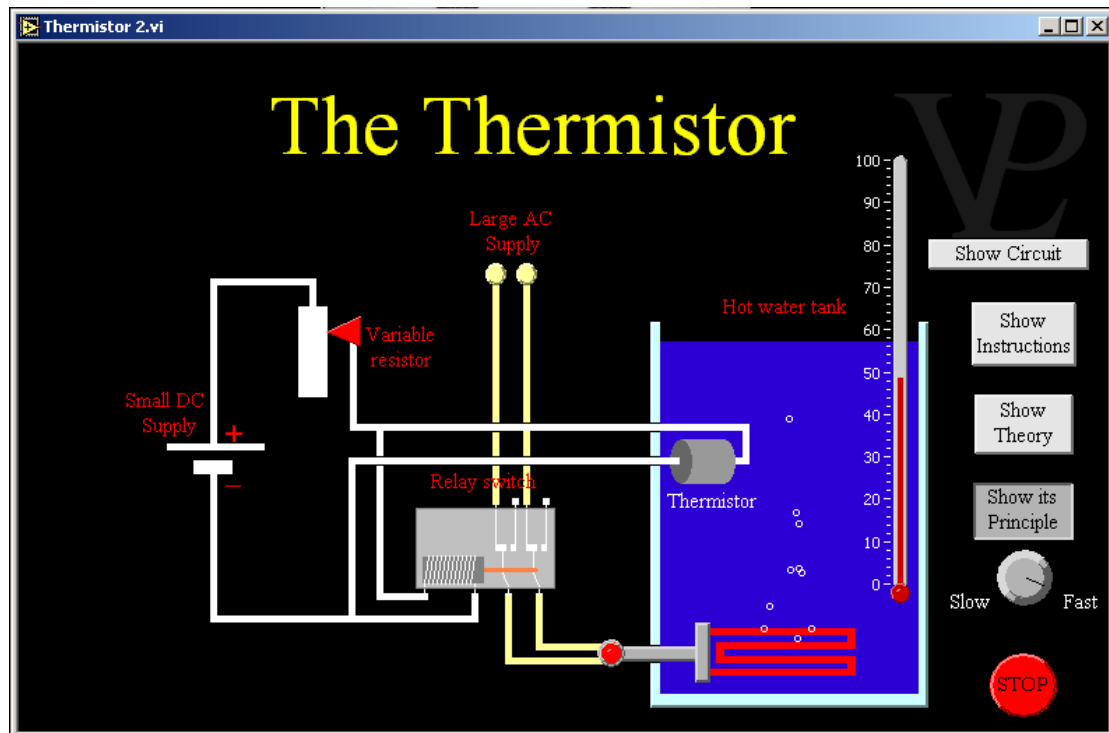
For more accurate measurements "dummy leads" are used in order to compensate for the resistance of the leads going from the WB to the PRT. PRTs are normally made with a resistance of 100 Ohms at 0C, so a convenient WB would also be fitted with matching 100 Ohm resistors.

It is important to keep the excitation Voltage as low as possible in order to prevent self heating. For this reason, small excitation currents are preferred, even if a Voltage amplifier is then needed to measure the small Voltage difference!

29.4 Thermistor

Basic/Advanced

This simulation shows the principle of a thermistor, and also shows how a thermistor may be used in a practical circuit to control the temperature of water.



The thermistor is a component which is made of semi-conducting material. Its ability to conduct electricity increases when it is heated.

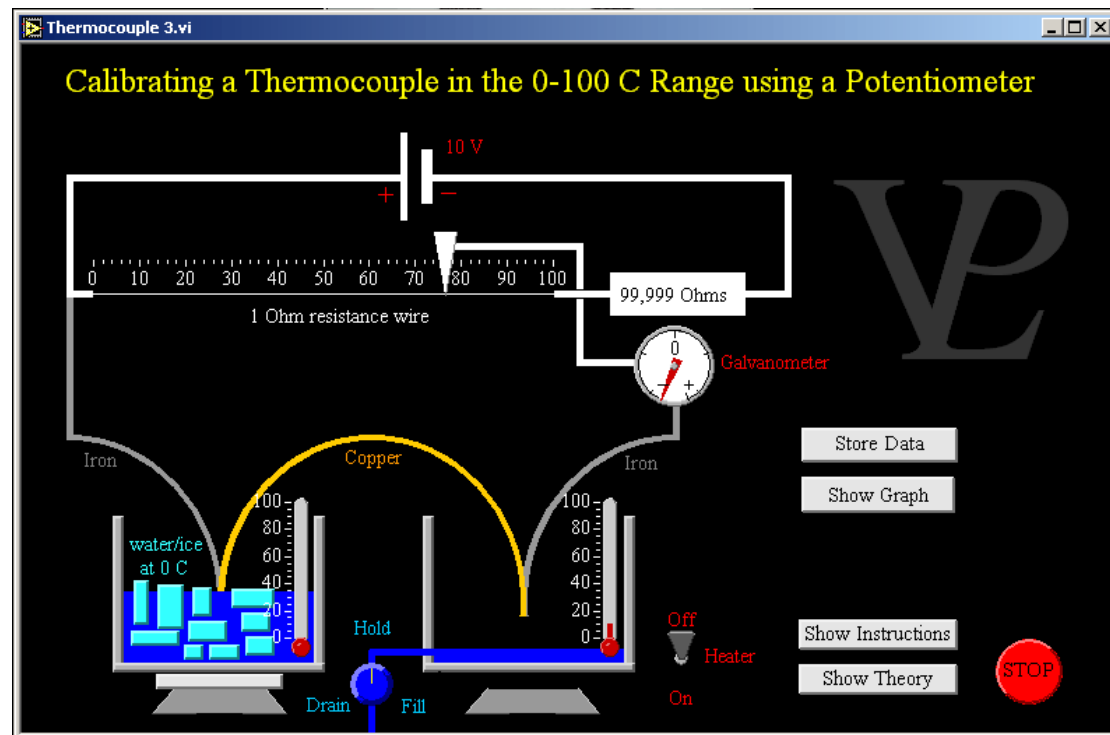
This happens because a semiconductor does not have many free electrons to carry the charge across. When the thermistor is heated, the thermal energy given to the atoms causes some of the bound electrons manage to break loose and so start to move and carry charge through the circuit.

This increase in the number of charge carries drastically reduces the resistance of the thermistor.

29.5 Thermocouple

Advanced

This program shows the calibration procedure for a thermocouple for the range between 0 and 100°C. The non-linearities are apparent, and serve to illustrate the limitations on accuracy.



The thermoelectric effect is the name given to a phenomenon where a tiny current flows when a junction between two different metals is heated up.

The thermocouple is a device that makes use of this effect to measure temperature. If one junction is kept at 0°C and the other is heated up, the small voltage produced can be used as a measure of the temperature difference.

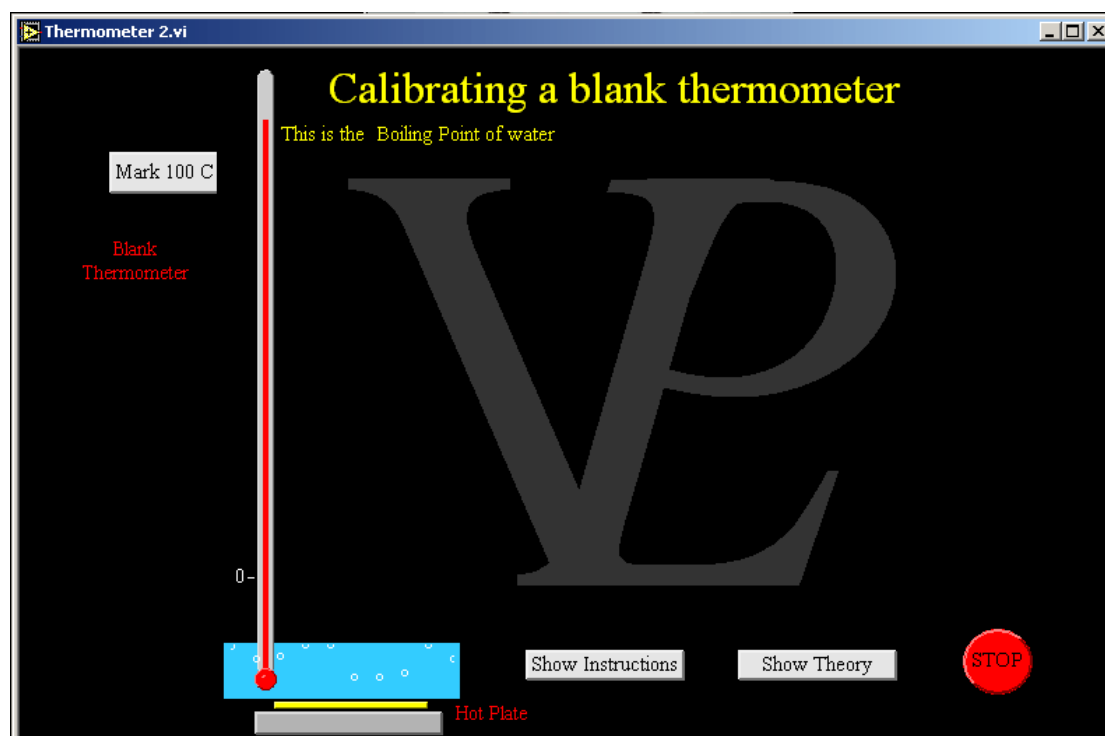
Note: the potentiometer wire which has a resistance of just 1 Ohm, shares the 10 Volts with a 99,999 Ohm resistor. In this way the potential difference across its entire length is only $10/100,000$ ($= 100 \mu\text{V}$). Each cm represents $1 \mu\text{V}$

Thermocouples are cheap and are normally connected to electronic circuits which display the temperature directly. Thermocouples can be used at temperatures as high as 1200°C inside ovens and industrial furnaces whereas here it is only used up to 100°C

29.6 Thermometer

Basic/Advanced

This program shows the calibration procedure for a mercury in glass thermometer, using the ice point and the steam point, and interpolating the range in between.



A thermometer of this type works on the principle that the liquid inside the bulb, usually mercury or alcohol with a dye, expands when it is heated.

As it expands it has nowhere else to go than up the thin pipe going up the body of the thermometer. If the tube is made of uniform bore, the level the liquid reaches will be proportional to the temperature.

The equation relating the temperature to the length is:

$$\text{Temp} = 100 \times (L_{\text{temp}} - L_0) / (L_{100} - L_0)$$

Where:

- L_{temp} is the length at the temperature
- L_{100} is the length reached at boiling point
- L_0 is the length reached at freezing point.

CHAPTER 30

WAVES

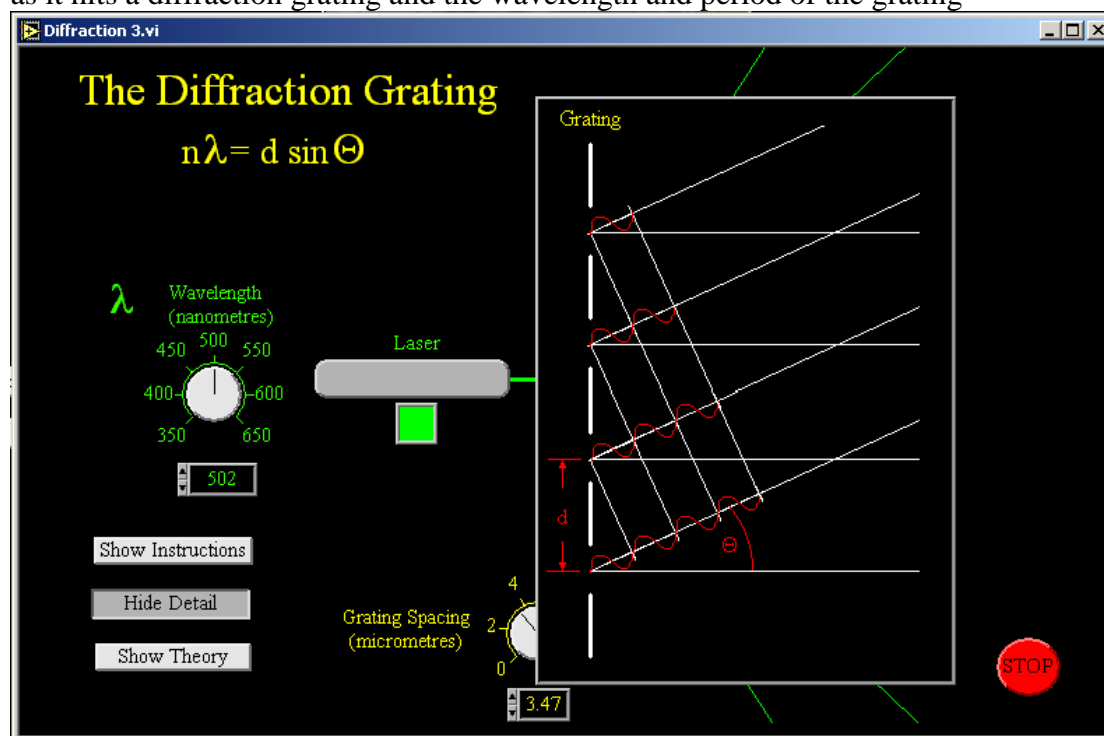


Microwaves can be used to cook food.
What other waves do you use around the house?

30.1 Diffraction

Advanced

This simulation shows the relationship between the angular diffraction of a laser beam as it hits a diffraction grating and the wavelength and period of the grating



The theory of the Diffraction Grating builds on the theory of Young's Slits. Light travelling through any one slit interferes with light travelling through all the other slits. To understand the explanation, press the 'show geometry' button. Light is diffracted by each slit and travels out in all directions like water ripples. Using the Huygens principle, consider the points in the centre of each slit as source of secondary waves.

In the special deviation angle shown in the diagram the light from the centre of the first slit is exactly in phase with that of the all the other slits. In this way all the waves interfere constructively giving rise to a very bright fringe of light. At other angles where the path difference between the light from consecutive slits differs by even a small amount, there will be a slit which is say 100 slits away whose light is in exact anti-phase, and this will destructively interfere with the first slit, so a dark fringe will appear.

Notice that there is a large dark gap between the bright diffracted orders. The edges of the bright spots are sharp because the use of hundreds of slits dictates that the angle needs to be nearly exactly right for constructive interference to take place.

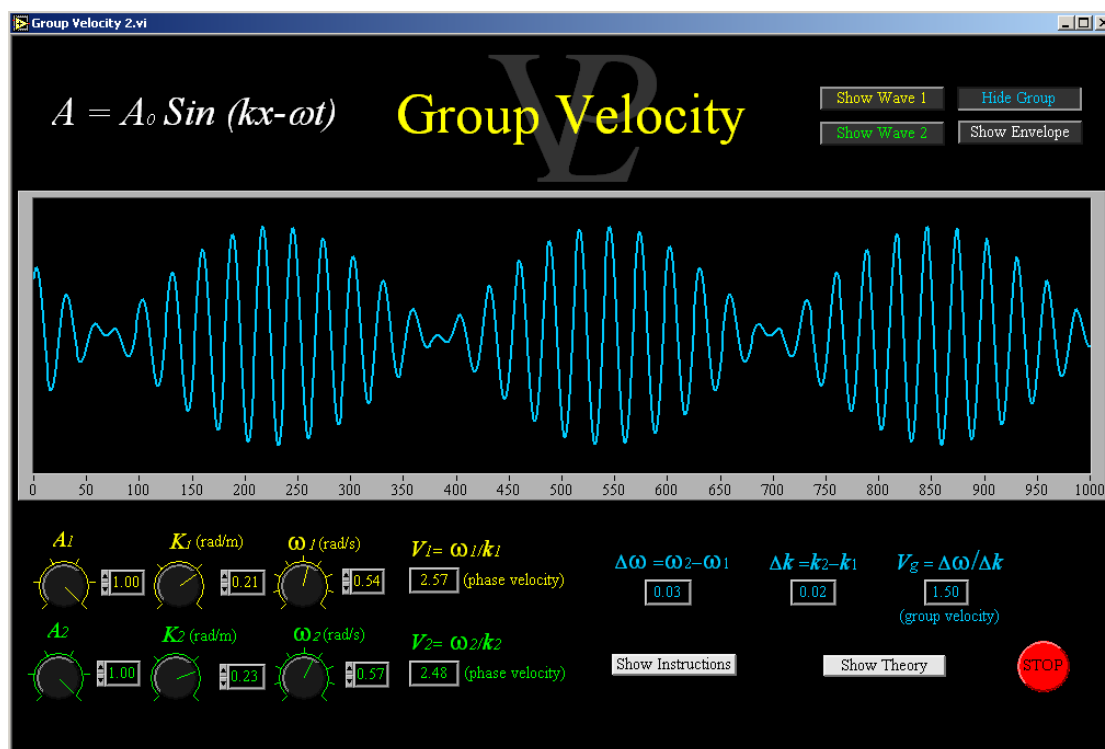
Gratings are very useful for separating different colours. For that reason they are used in spectrometers; each colour will make a separate diffracted order. The atomic lattice of crystals makes a good grating for X rays.

The line spacing in gratings needs to be of the order of the wavelength that is going to be diffracted. If several diffracted orders are needed, the line spacing needs to be made bigger.

30.2 Group Velocity

Advanced

This simulation shows what happens to waves of different frequencies travelling in a dispersive medium. The user can change the frequencies as well as the dispersion of the medium.



In a non-dispersive medium waves of all frequencies travel at the same speed. This is true for light in a vacuum. However in real media (air, water, glass) different frequencies travel at different speeds. This phenomenon is called dispersion. The most visual demonstration of this is the dispersion of white light through a prism. However, at optical frequencies it is not possible to notice the different speeds!

Water ripples of different frequencies also travel at different speeds to each other. Tsunami waves (very low frequency) can travel at hundreds of km/h (in deep water), whilst normal waves travel at around 50 km/h. In shallow water the speeds of waves are also reduced.

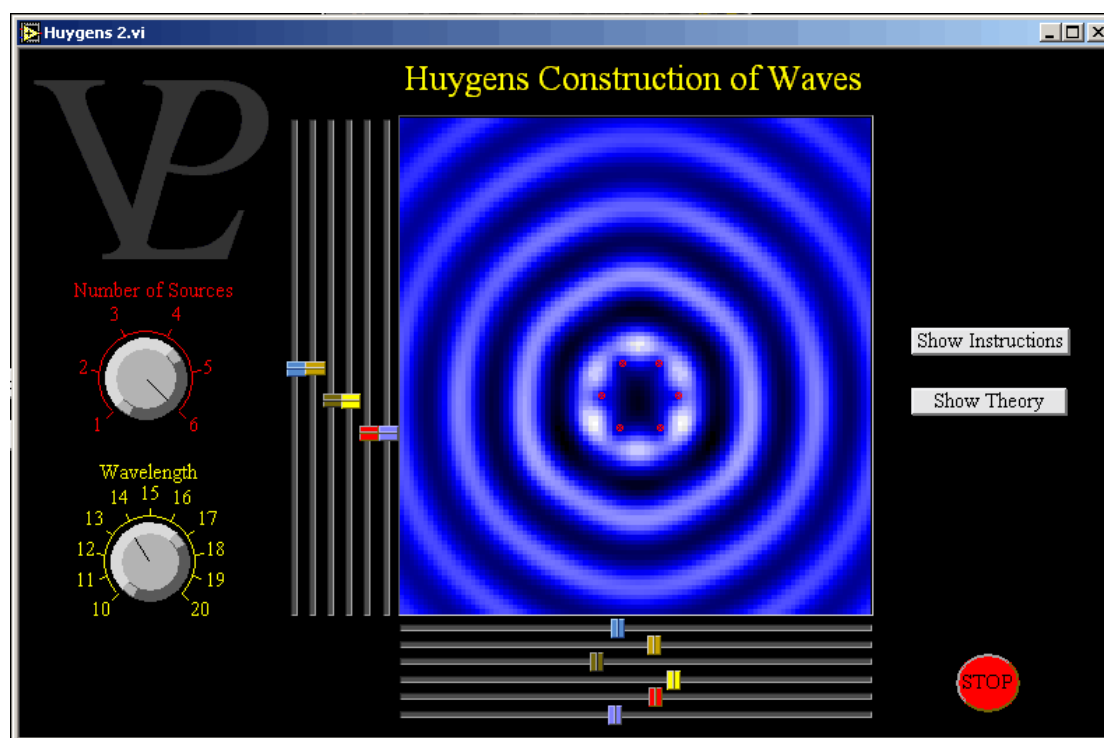
In optical fibres pulses of light containing more than a single frequency gradually get spread out because of dispersion. The 'envelope' of light normally travels a little slower than the phases of the single frequency wave. This poses a limitation on how far a pulse can travel before it 'smudges out'.

The group velocity (the speed at which useful information can travel) is defined as $d\omega/dk$. In some instances this can be significantly slower than the speed of light. In rare non-linear media it is possible to get a negative group velocity - or even a group velocity that is faster than the speed of light! This however is an anomaly, it is not possible to transmit information at speeds greater than that of light.

30.3 Huygens Wavelets

Advanced

This simulation shows how sources that are significantly closer together than the wavelength begin to look like a single source. The position of 6 spatially separate but coherent sources can be changed to see how it affects the overall interference pattern.



Have you ever wondered why the ripples produced when a stone is thrown into the water are always circular, regardless of the shape of the stone?

In 1680, The Dutch scientist Huygens, who was a contemporary of Isaac Newton, proposed the wave theory of light.

This theory proposes that each part of a wave should become a source of secondary wavelets. The next wave is the sum of all the little 'wavelets' from all these secondary sources. As a consequence of this, light should bend a little round corners and spread out after going through narrow gaps, a process called diffraction.

About 120 years later Thomas Young of the famous for Young's Slits experiment, demonstrated that light did indeed behave like waves.

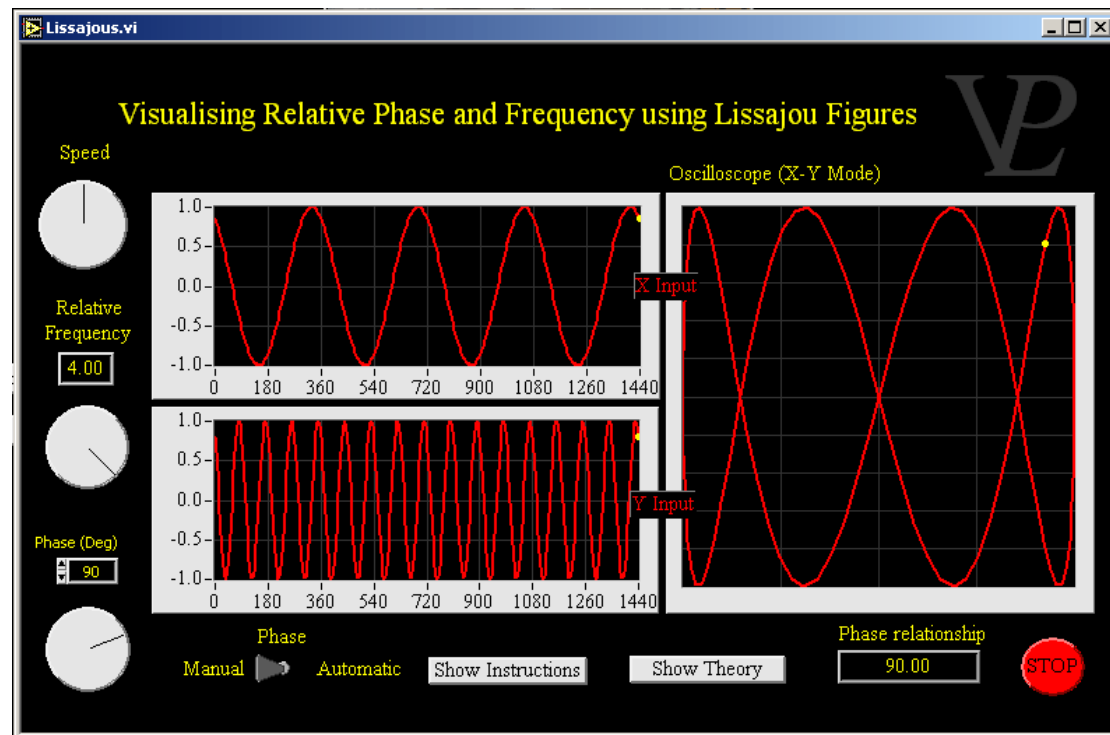
When the separation between the sources is small compared to the wavelength or when the waves have travelled a long distance from the sources, the waves appear to come from a single source.

This explains why a stone thrown into still water produces circular rings regardless of the original shape of the stone.

30.4 Lissajou

Advanced

This simulation shows Lissajou figures which are commonly used in visualising two sinusoidal signals with a phase difference between them. They can also be used to visualise the relationship between a signal and one of its harmonics.



The phase relationship between two signals at the same frequency can be visualised on a cathode ray oscilloscope using the X-Y setting.

When the signals are exactly in phase, a line at 45 degrees is displayed on the screen.

When they are exactly in anti-phase, a line at -45 (or 135) degrees is displayed.

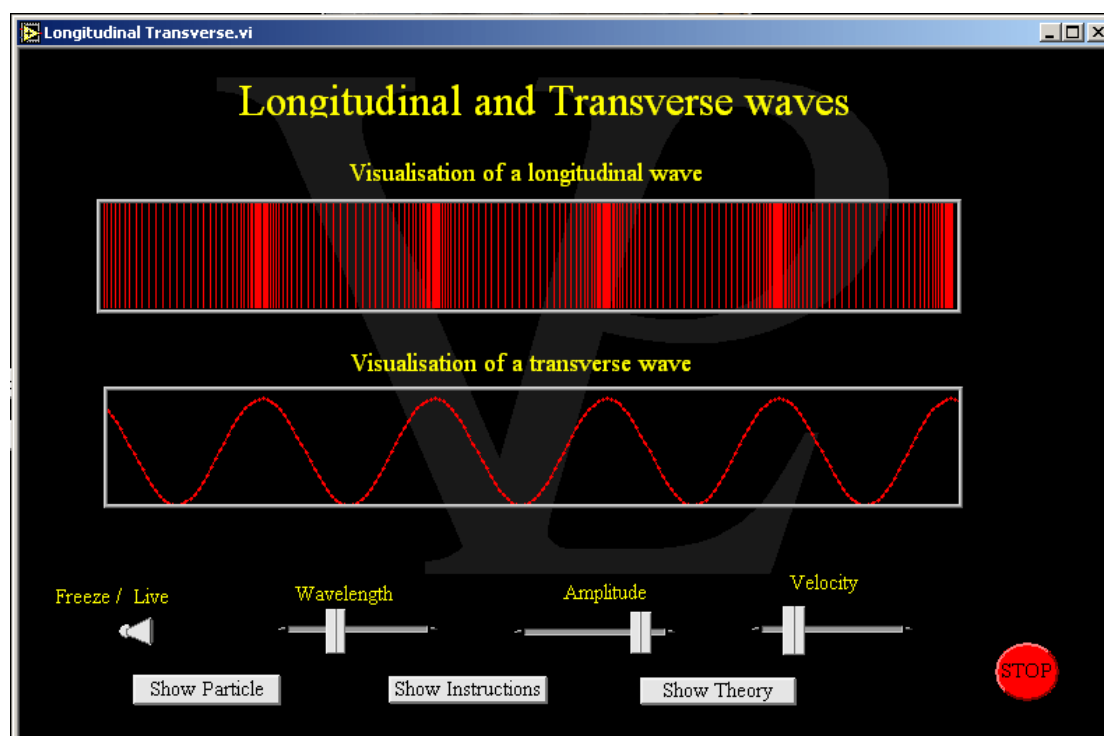
When they are exactly 90 degrees out of phase they are said to be in 'phase quadrature', and a circle is displayed. Which way the rotating point rotates depends on which of the two signals is leading the other. This is the basis of many commercial up-down counters.

If the phase of one signal is an exact multiple or sub-multiple of the other, an interesting figure is displayed which is difficult to describe in words. If studied carefully, it is possible to deduce the ratio of the two frequencies.

30.5 Longitudinal Transverse

Basic/Advanced

This simulation helps to visualise Longitudinal and Transverse waves, and makes clear that it is the disturbance that propagates, and not the actual particles, which execute simple harmonic motion about a fixed locus.



A longitudinal wave is given that name because the movement of the disturbance is along the line that the wave is travelling. We say the disturbance is parallel to the line of propagation of the wave. A typical example of a longitudinal wave is a sound wave.

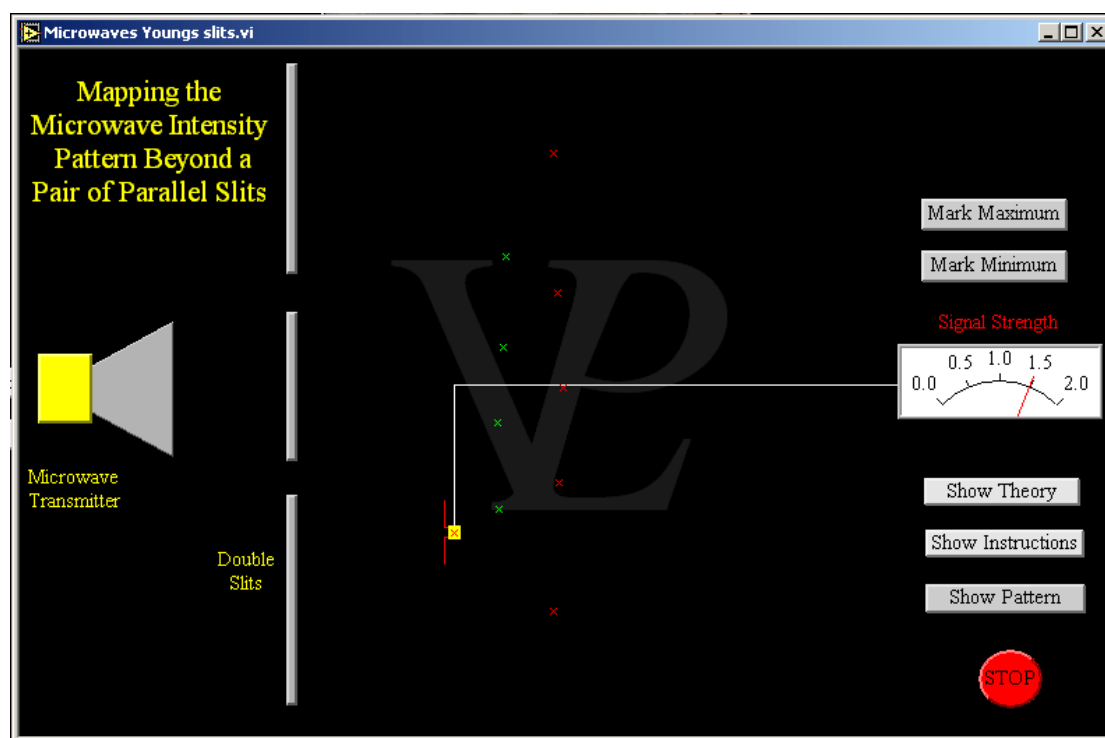
A transverse wave is given that name because the movement of the disturbance is perpendicular to the line along which the wave is travelling. A typical example of a transverse wave is water ripples on the surface of still water.

When you look at the motion of an individual particle in the wave, you will notice that in a longitudinal wave it oscillates back and forth in what is called 'simple harmonic motion' along the line of propagation. But in a transverse wave you will see the particle oscillating up and down in a direction perpendicular to the direction of propagation of the wave this is also the case in simple harmonic motion.

30.6 Microwaves Young's Slits

Advanced

This simulation allows the user to map out the pattern of microwaves after they have diffracted and interfered in a Young's Slits arrangement. After locating and marking the positions of nodes and antinodes, the pattern should gradually emerge.



Microwaves are electromagnetic waves with a wavelength around 2.5 cm. They are blocked by a metal sheet.

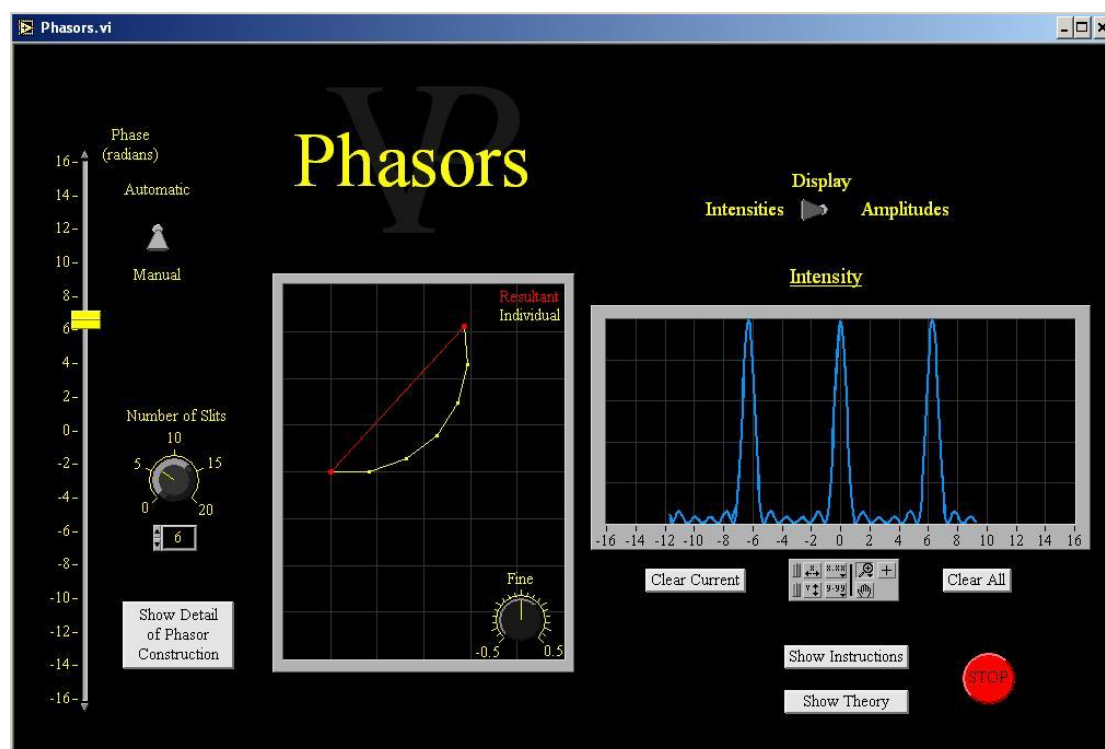
When microwaves are passed through a pair of slits whose size is comparable to their wavelength then they diffract and interfere with each other. This produces what is known as an interference pattern.

Since microwaves are invisible the pattern cannot be seen. However, with the aid of a detector it is possible to map out the positions of the maxima and minima.

30.7 Phasors

Advanced

A very useful way of understanding diffraction gratings. I wish I had learned this way first!



"PHASORS" are a useful concept in mathematics and physics. They are something like a combination of PHASES and vectORS. They are often used in AC circuits to understand the Voltages and currents when there are phase differences between them. In the context of Young's Slits and Diffraction gratings they can be used as an alternative way of understanding and visualising Huygens wavelets.

In this example all the phasors have the same amplitude (same length in the construction) but each has a different phase from its neighbouring phasor. As with the addition of vectors, phasors are all placed nose to tail, and the resultant is the arrow going from the tail of the first one to the nose of the last one. Notice that periodically the resultant will be zero (the phasors all add up such that their contribution is total destructive interference). At other phases the resultant will be non zero. The phase difference between consecutive slits is numerically equal to $d \sin \theta / \lambda$ (see the simulation on the diffraction grating).

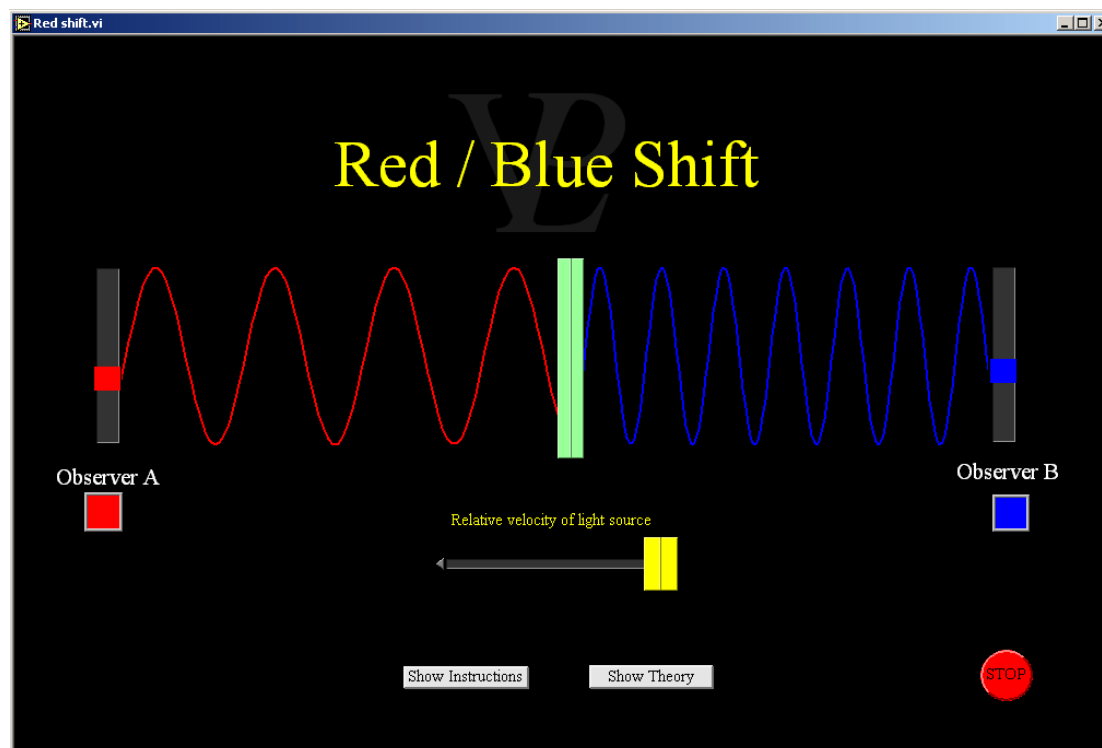
With a greater number of phasors (more slits), the resultant intensity becomes much more sensitive to small phase changes. This is why the diffraction pattern becomes sharper. When there are many phasors, the phase between them needs to be nearly exactly 0 or 2π or 4π , otherwise they quickly curve round and reduce the amplitude of the resultant to nearly nothing.

Notice that the number of small peaks between the tall peaks is an indicator of how many phasors (or slits) are actively contributing to the interference pattern. With a diffraction grating, even a narrow laser beam can easily be hitting more than 100 slits. This makes the smaller peaks imperceptibly small (that explains why we don't see them!).

30.8 Red Shift

Advanced

See how the light from a moving source becomes red or blue shifted depending on whether the source is moving toward or away from the observer.



When a source of light moves towards or away from an observer, it affects the wavelength of the light that the observer sees.

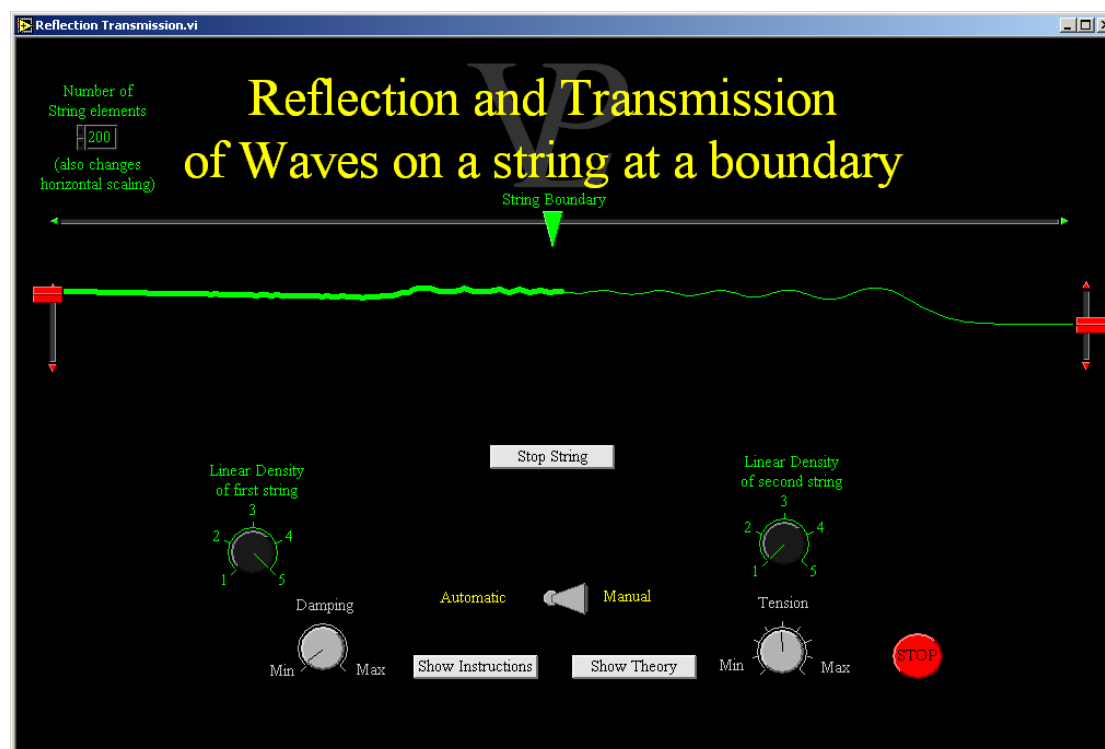
It is this 'bunching up' of the waves in front of the moving source, or 'spreading out' of the waves behind the moving source, that causes a change in wavelength, and hence frequency and colour.

What starts out as a typical green wavelength in the visible spectrum gets shifted towards the red when the source is moving away from the observer (or shifted towards the blue when it is moving towards the observer). For this to be noticeable, the sources of light need to be moving at speeds that are a significant fraction of the speed of light (i.e. very fast!)

30.9 Reflection Transmission

Advanced

This simulation permits the user to send a wave through to an impedance boundary and see the effect it has on the transmission of the wave as well as the phase change and amplitude of reflection experienced at the boundary.



When transverse waves travelling down an elastic string encounter a different string, the disturbance will be partly reflected back on to the original string and partly transmitted to the other string. The phase and amplitude of the reflection and transmission depend on the "impedance" of the strings. In general, the speed of the waveform will also be different in both strings.

The speed of the waves is given by $V = (T / \rho)^{1/2}$ where T is the tension (equal in both strings) and ρ is the "linear density" (mass per unit length of the strings).

The "Impedance" Z of each string is defined by $Z = (T \rho)^{1/2}$ (the symbols have the same meaning as above)

If the wave is travelling from string 1 to string 2 The amplitude of the reflection R is given by $R = (Z_1 - Z_2) / (Z_1 + Z_2)$ and the amplitude of transmission T is given by $T = 2Z_1 / (Z_1 + Z_2)$

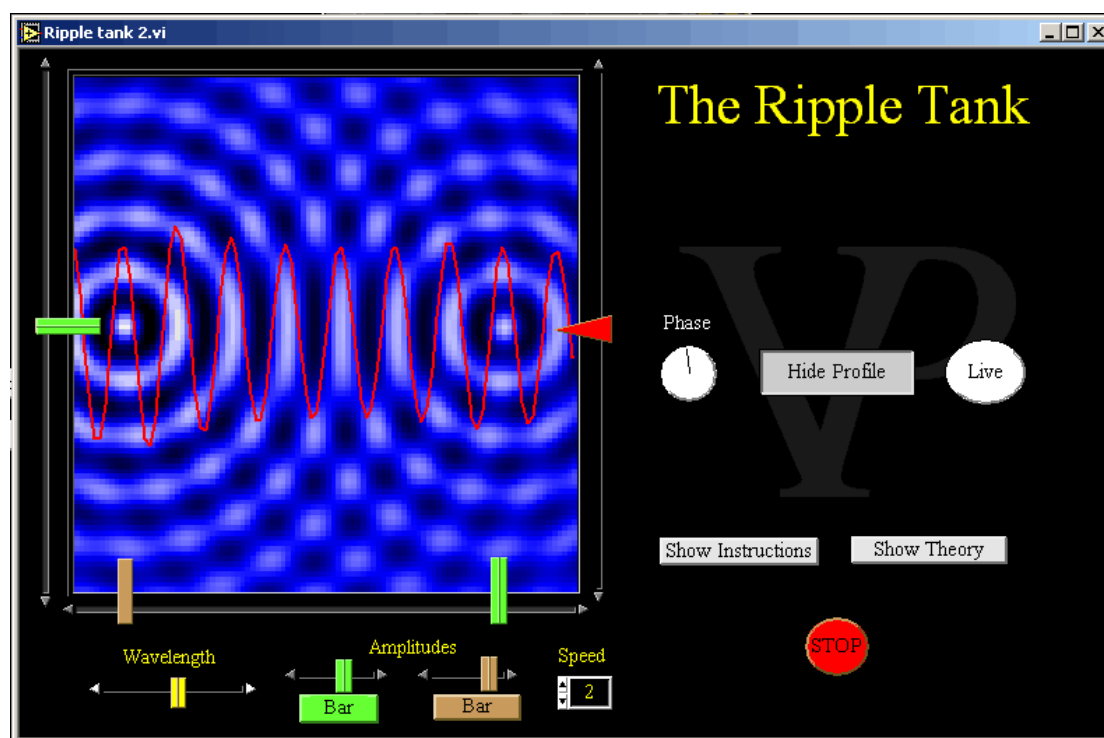
Notice that:

- If $Z_1 > Z_2$ then $R > 0$ so there will be no phase change on reflection; a peak will reflect a peak.
- If $Z_1 < Z_2$ then $R < 0$ so there will be a 180 degree phase change on reflection; a peak will reflect a trough.
- If $Z_1 = Z_2$ then $T = 1$ and $R = 0$ so there will be no reflection and the wave travels through perfectly. This is called "impedance matching", a useful concept in electronics and communications.

30.10 Ripple Tank

Basic/Advanced

Two point or bar sources oscillating in phase can be moved about the surface of a tank. The pattern of nodes and antinodes is clearly visible. A vertical profile across the tank can be selected and displayed.



A ripple tank is a fairly inexpensive way of visualising two dimensional interference effects.

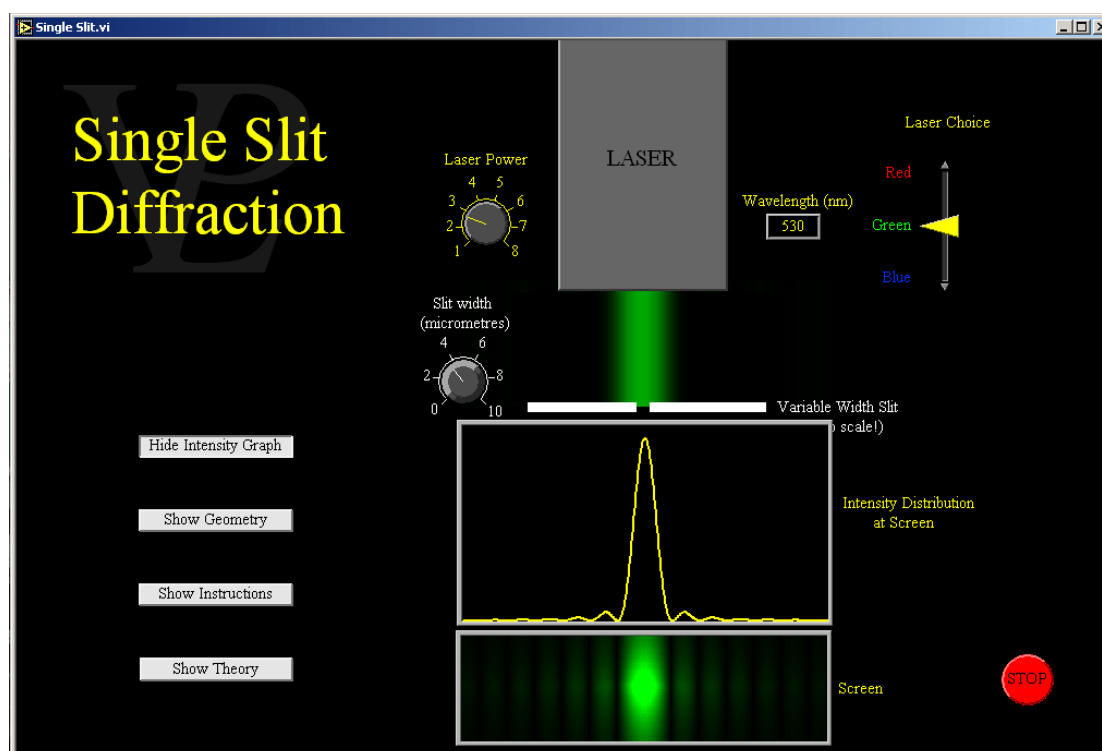
The water waves (ripples) made by one dipper interfere with those made by the other dipper. The resultant water surface is an addition of the displacements caused by the two dippers.

Interesting patterns can be made with this simulation, especially since it does not suffer from reflections from the edges of the tank!

30.11 Single Slit Diffraction

Advanced

See the diffraction patterns obtained from a single slit (Fraunhofer diffraction). Vary the slit width and use three different colour wavelengths. Study the conditions for intensity minima.



Single slit diffraction is also known as Fraunhofer diffraction. Light travelling through one part of the slit interferes with light travelling through another part of the same slit. The theory is somewhat complicated, but is still based on the principles of constructive and destructive interference.

To understand the explanation, press the 'show geometry' button. Light is diffracted by the slit and travels out in all directions like water ripples. Using the Huygens principle, consider all the points in the aperture of the slit as sources of secondary waves. In the forward direction (undeviated) all these secondary wavelets will add up in constructive interference and a bright central fringe will be seen.

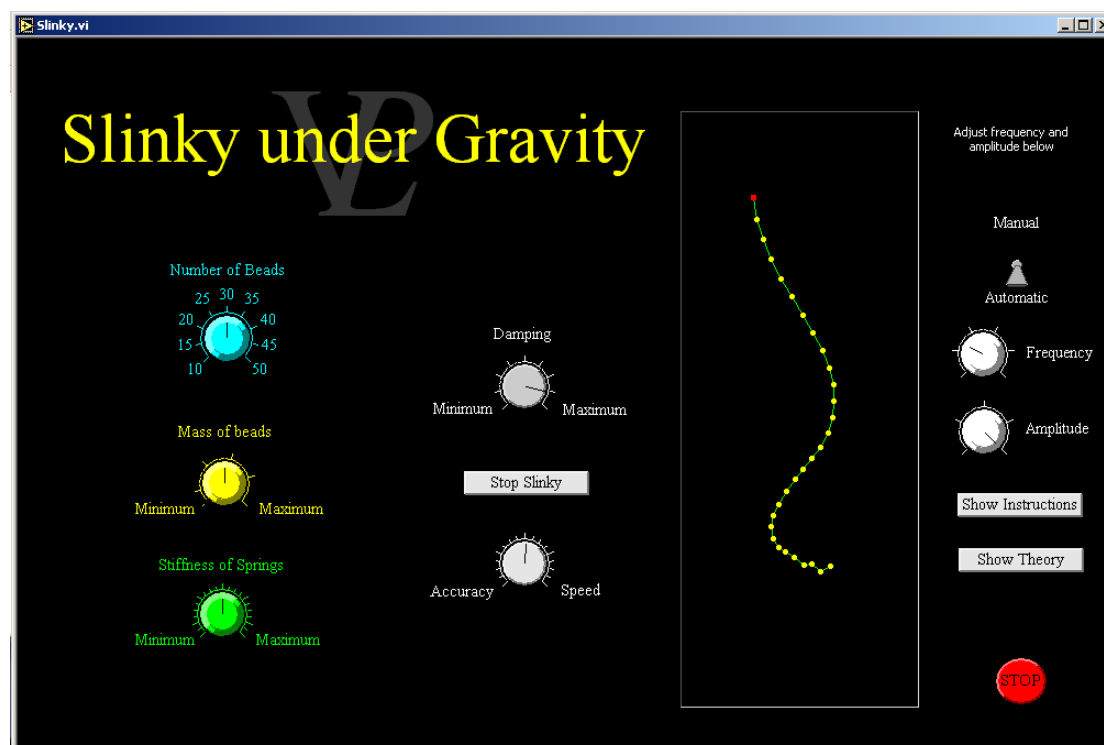
In the special deviation angle shown in the diagram where the light from the centre of the slit (C) is exactly in anti-phase with light from the edge (O), these two contributions will cancel out. Furthermore, the contributions from (1) and (C+1) will also cancel out, and so forth for all the point sources in the aperture of the slit. This will give rise to a total destructive interference (a dark fringe).

The equation shown in the geometry window shows the condition which is obeyed at each dark fringe (n is any integer). In other directions the constructive interference will not be as complete as in the forward direction, so bright fringes will appear less intense than the central one.

30.12 Slinky

Advanced

This simulation of a slinky shows how a wave can reflect back from the loose end of an elastic string. The elasticity and mass of the slinky can be varied.



A typical slinky is a very long spring with a fairly low stiffness. It is normally used as a toy, but it can be used to learn about the propagation of waves and other disturbances along springs, strings and other elastic media.

In this simulation the slinky has been modelled as a series of beads joined together with springs. The stiffness as well as the mass of the coils making up the slinky have an effect on the speed with which the disturbances will travel along it. Generally the greater the stiffness to mass ratio, the faster the disturbance will propagate.

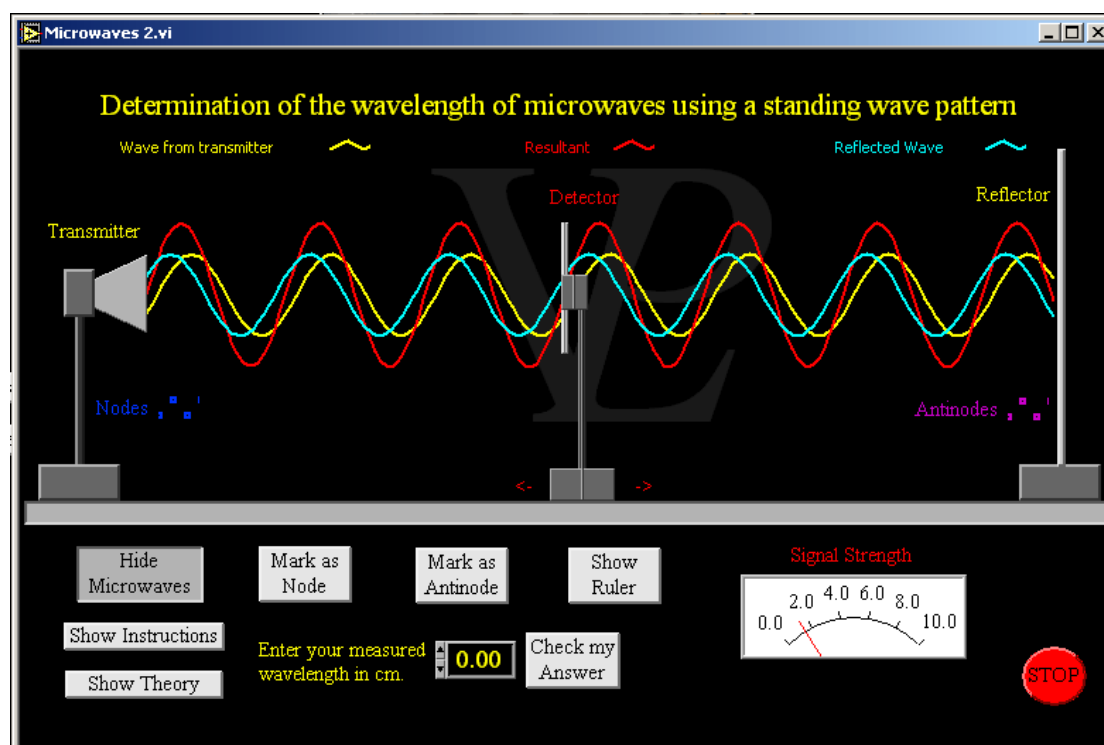
When disturbances reach the end of a slinky (whether a loose end or an attached end) there will be some kind of reflection of the disturbance. The difference between the two types of termination affects the phase of the reflected wave. A free end will always be an antinode but an attached end will always be a node. The overall effect is that at a loose end a crest will reflect a crest, whereas at an attached end a crest will reflect a trough!

In most cases waves will experience some form of damping which will gradually dissipate the energy in the wave. The energy loss normally becomes heat (of the elastic medium as well as of the air around it)

30.13 Standing Microwaves

Advanced

This simulation allows the user to locate nodes and antinodes in a standing wave pattern of invisible microwaves by moving the dipole antenna back and forth. The wavelength of the microwaves may then be calculated and checked against the computer.



The easiest way to find the wavelength of a microwave source is to reflect the microwaves back towards the transmitter using a plane sheet of conducting material. This sets up a standing wave pattern. Read more information on this in the stationary waves simulation.

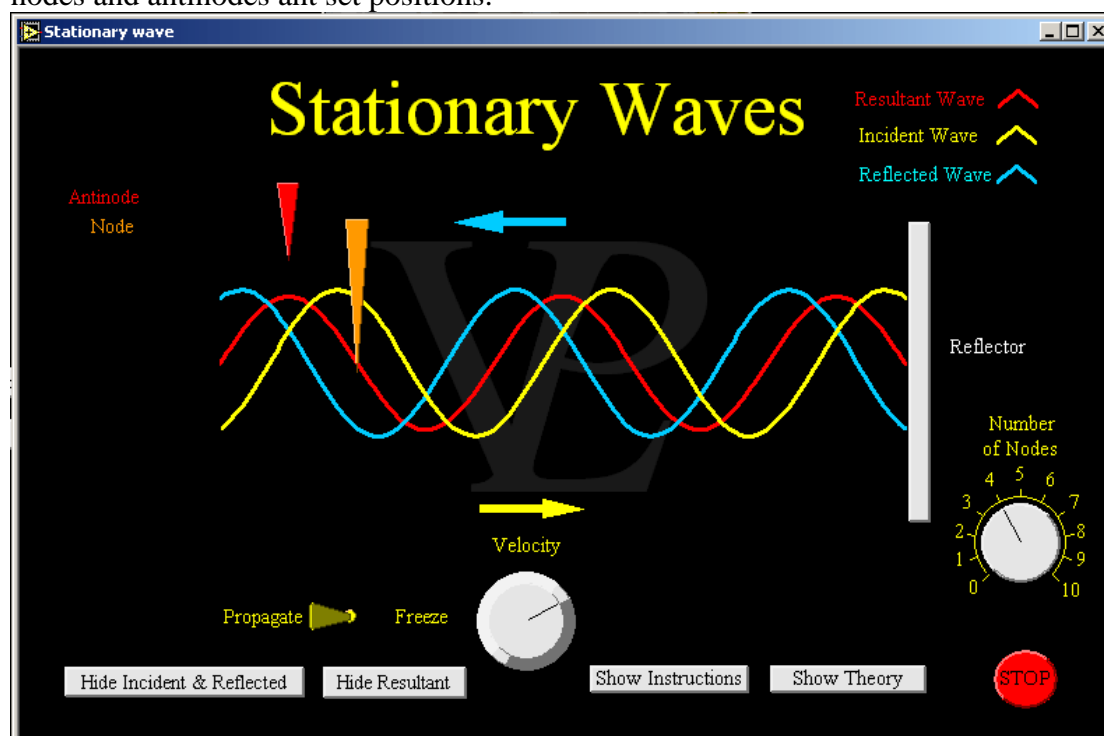
A detector is then moved along the line between the transmitter and the reflector, marking off nodes and antinodes. The separation between consecutive nodes or antinodes is always half the wavelength.

Locating as many nodes or antinodes as possible reduces the measurement uncertainty.

30.14 Stationary Waves

Advanced

This simulation shows clearly how two coherent waves travelling in opposite directions interfere with each other and produce a 'standing' or stationary wave with nodes and antinodes at set positions.



Whenever a wave encounters another wave, they interfere with each-other. In the particular case where a wave encounters another with the same frequency, but travelling in the opposite direction, a 'stationary wave' is produced.

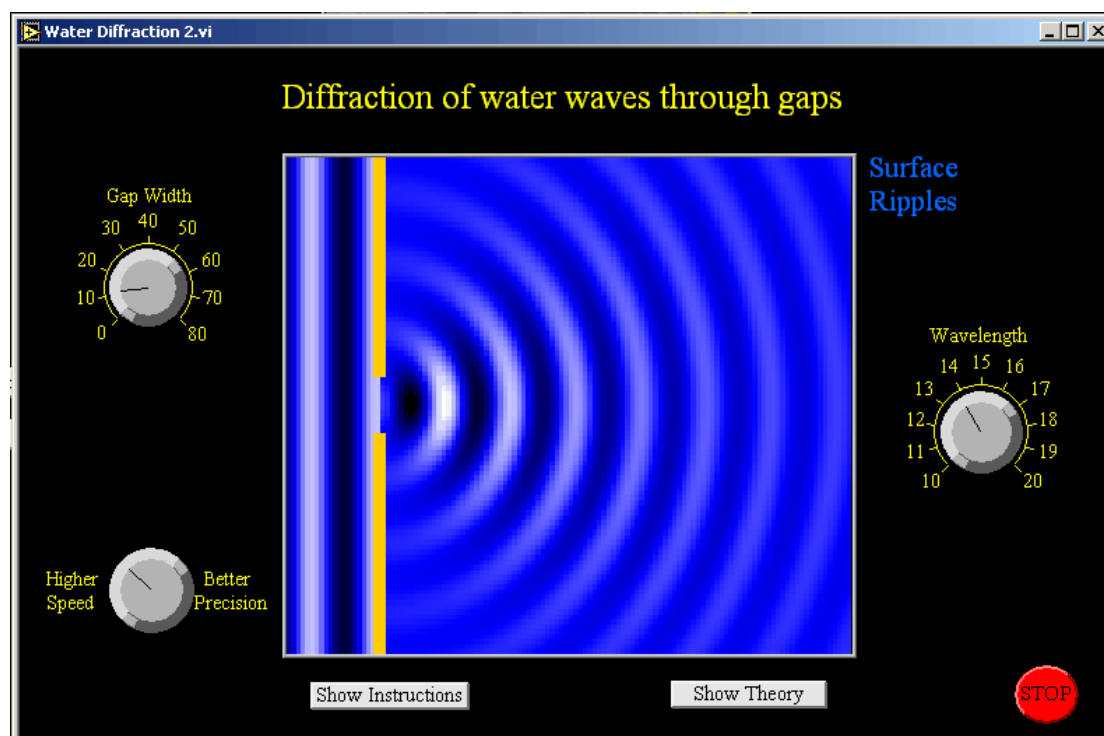
The characteristic of a stationary wave is that it has nodes where there is minimum resultant displacement and anti-nodes where the resultant displacement is maximum. The wave appears to be going nowhere.

This behaviour can be seen clearly in plucked strings, and also in a ripple tank.

30.15 Water Diffraction

Advanced

This simulation shows how water ripples diffract when they go through a gap. Both the wavelength and the gap can be varied.



Warning: This simulation is very computer processor intensive. Don't be surprised if it runs painfully slow on your machine even if it is relatively new.

Diffraction is the name given to the phenomenon whereby waves spread out into places where you would not expect them to be after they have gone past a gap or a sharp edge.

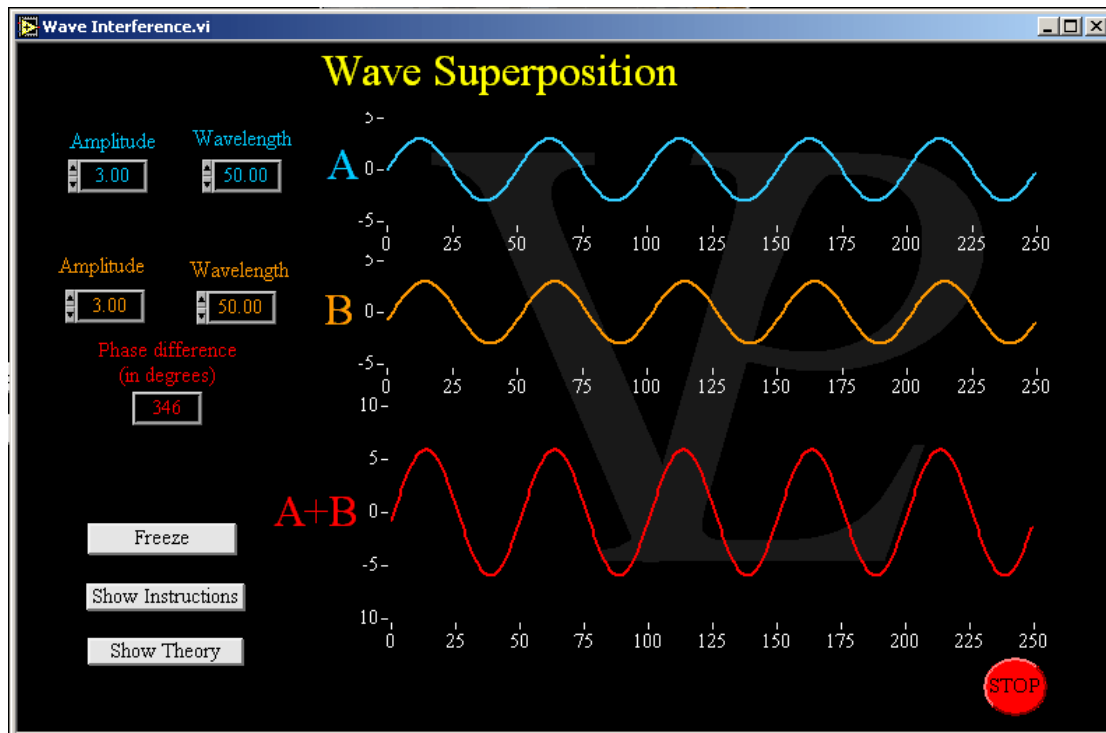
Diffraction is increased or reduced depending on the relative sizes of the gap and the wavelength. Investigate for yourself when the diffraction is at its greatest.

This simulation uses Huygens wavelets where every point in the gap which receives the incident wave becomes a source, and the resultant wave pattern to the right of the gap is the sum or resultant of the all the circular waves produced by these point sources. The number of calculations this creates is what take such a long time for the computer to calculate.

30.16 Wave Interference

Advanced

This simulation shows the principle of superposition of waves clearly. Constructive and destructive interference can be seen clearly.



Interference is a very interesting effect that happens to all types of wave such as water ripples, sound, light and radio waves.

When two waves propagate over the same space, they interfere with each-other in such a way that the overall effect is the instantaneous sum of the two. We call the sum the resultant wave.

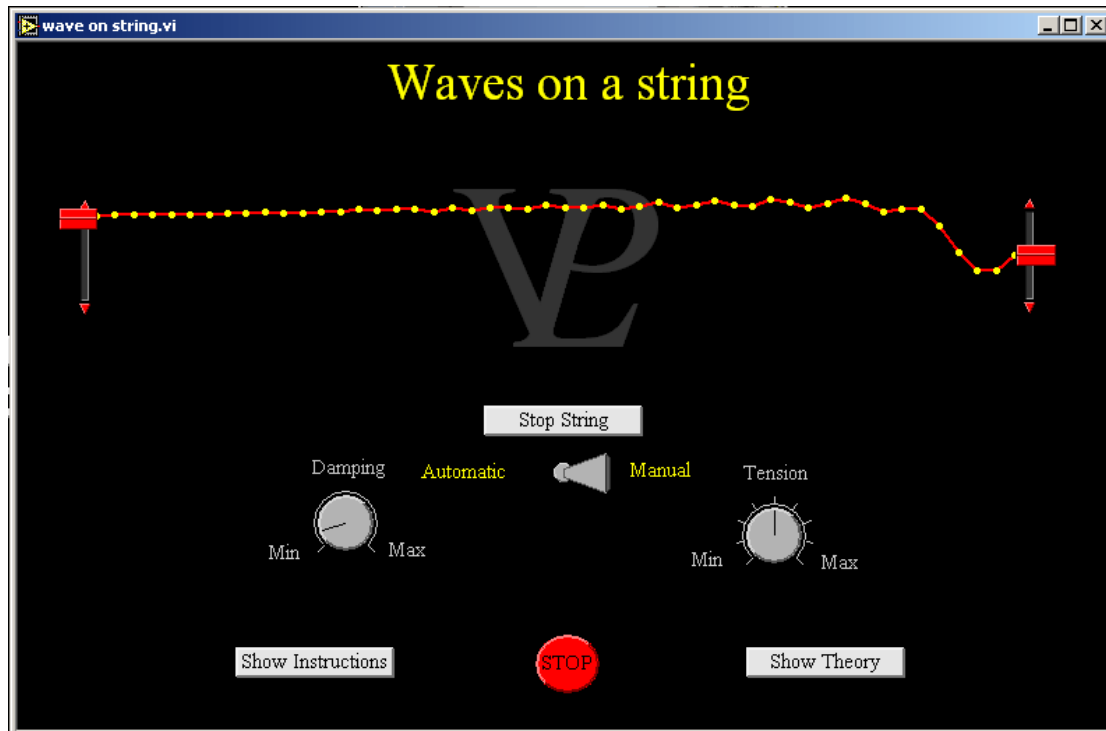
Where a peak meets with another peak, the result is called constructive interference. Where a peak meets with a trough, the result is called destructive interference.

In the special case where the amplitude and the wavelength are exactly the same we get the best contrast, going from double the amplitude to complete cancellation.

30.17 Wave on a string

Advanced

This simulation illustrates how a wave motion travels down a taught string. It reveals the phase change on reflection, and also how standing wave patterns can be set up with nodes and antinodes at different places depending on the frequency.



A tight string supported at two fixed points serves as a good tool to learn a fair amount about waves.

In this simulation you can see clearly that it is the disturbance that travels down the string, and not the particles themselves. You will also notice that the string cannot propagate a step change in its position; it tends to attenuate the signal as it propagates, especially if the damping is significant.

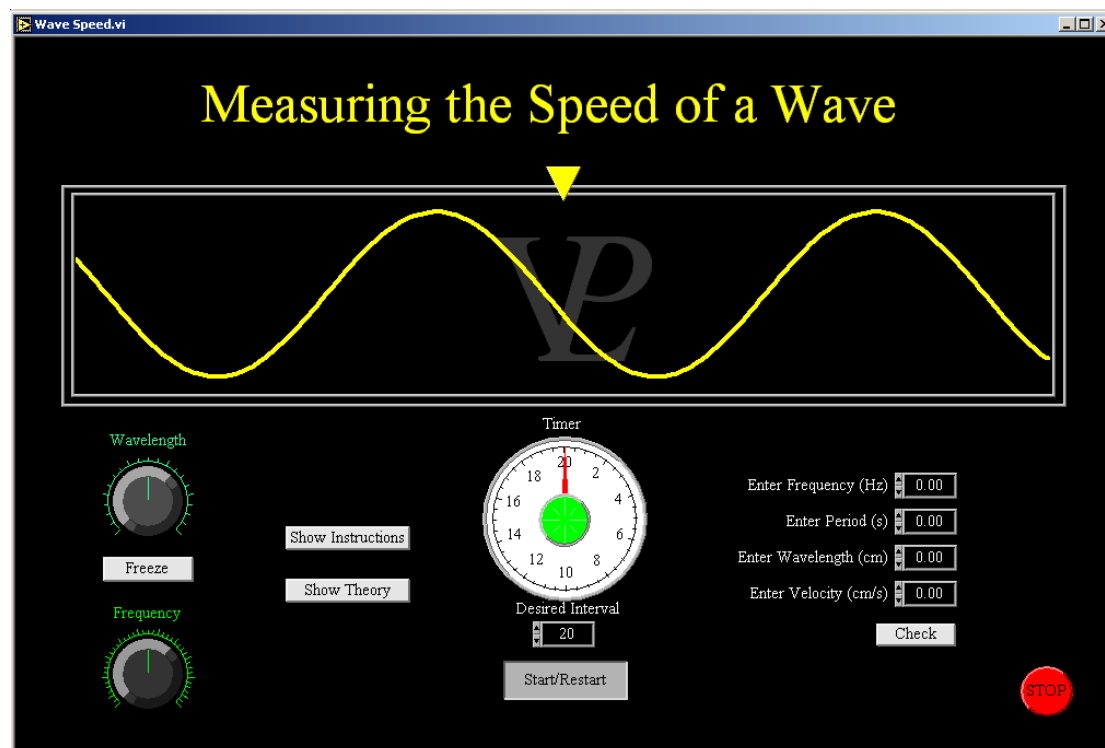
The tension of the string affects the speed with which the wave will travel down it. (The speed actually increases with the square root of the tension!) With a constant frequency disturbance you will notice how the wavelength increases with tension.

When a wave propagating towards the right encounters one which is propagating towards the left they will interfere with each other. In the special case where the length of the string is a multiple of half the wavelength it will produce a 'standing wave' pattern. The positions which hardly move are called 'nodes' and those where the motion is maximum are called 'anti-nodes'

30.18 Wave Velocity

Basic/Advanced

This simulation is a simple illustration of how the velocity of a wave can be calculated from the frequency and the wavelength.



The wavelength of a wave is defined as the shortest distance along a wave train between two points oscillating in phase. This could be measured from peak to peak, or trough to trough, or positive going edge to the next positive going edge (or between negative going edges). The wavelength is normally given the symbol ' λ '.

The frequency is the number of waves going past any given point in one second. One wave per second is one Hertz (or Hz), five and a half would be 5.5 Hz. (it does not have to be a round number). The frequency is normally given the symbol ' f '.

The time period is the time taken for a complete wave to travel past any given point. It is the same as $1/f$. (number of seconds per wave). The period is normally given the symbol ' T '

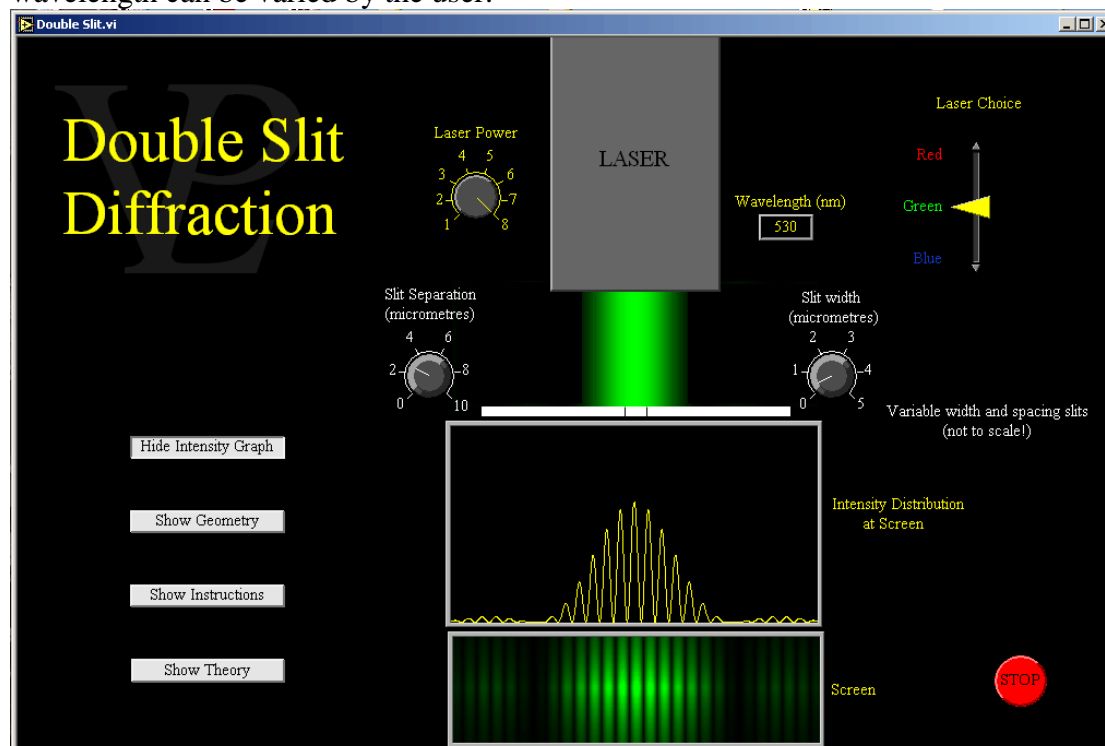
The wave will travel a distance of one wavelength every period. So the velocity of the wave is given by the equations $v = \lambda/T$ or $v = f \lambda$.

These equations apply to all types of waves, sound, light, water, strings, etc.

30.19 Young's Slits

Advanced

This simulation shows clearly how slit separation and wavelength combine to determine the angle of the diffracted orders. Both the slit separation and the wavelength can be varied by the user.



Whenever coherent light is split up and then allowed to recombine interesting things happen. Coherent light is light of a single colour that is coming from the same source.

If the two light beams re-combine 'in phase' (that is, 'in step' with each other), the light becomes a bright beam. We call that constructive interference.

If the beams re-combine in anti-phase (that is completely 'out of step' with each other), the light beams cancel each other out. We call that destructive interference.

Notice that the waves may be 'out' by exactly one wavelength, two wavelengths, three wavelengths or more. We call these the different orders of interference.

See if you can work out what effect the wavelength and the slit separation each have on the angles by which light is diffracted.

From the geometric diagram in the simulation you will see that the path difference is given by $d \sin \theta$. Whenever this is equal to a multiple of the wavelength (λ) there will be constructive interference. That is where the equation $n\lambda = d \sin \theta$ comes from.

CHAPTER 31

X-RAYS

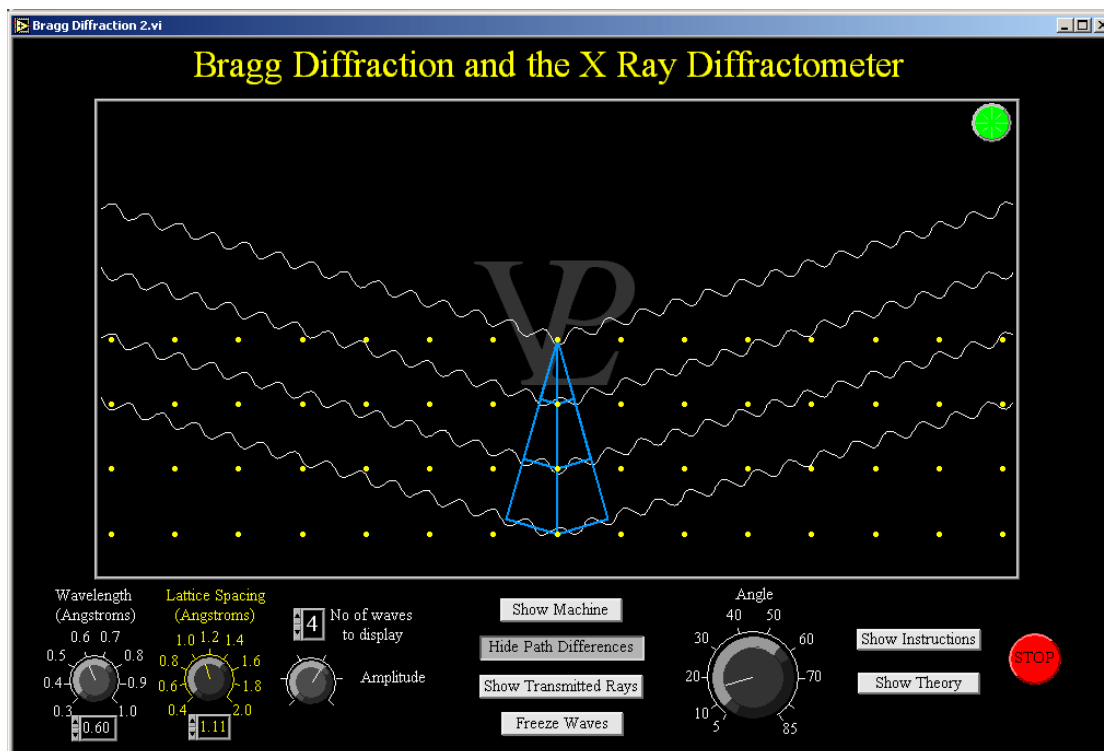


Pictures taken with X-Rays can 'see right through' my body.
How are X-Rays made?

31.1 Bragg Diffraction

Advanced

This simulation shows how X rays are diffracted by crystal lattices, and how an X Ray Diffractometer can be used to measure inter atomic lattice spacing.



X Rays diffract when they encounter periodic structures which are similar in size to the wavelength of the X Rays. Typical lattice spacings are measured in Angstroms ($=0.1 \text{ nm}$), and X Ray wavelengths are also in the Angstrom region.

When the X rays encounter a plane of atoms, most of the X Rays pass straight through. However some of the X Rays scatter in different directions. When the X Rays scattered from one plane are exactly in phase with those scattered from the next plane, constructive interference occurs and the X Ray intensity in that direction increases rapidly. This happens when the path difference between the rays is a multiple of the X Ray wavelength. This is called Bragg Diffraction. In Equation form we write this as: $n \lambda = 2 d \sin \theta$ where n is an integer, λ is the wavelength, d is the lattice spacing and θ is the angle (incident = diffracted)

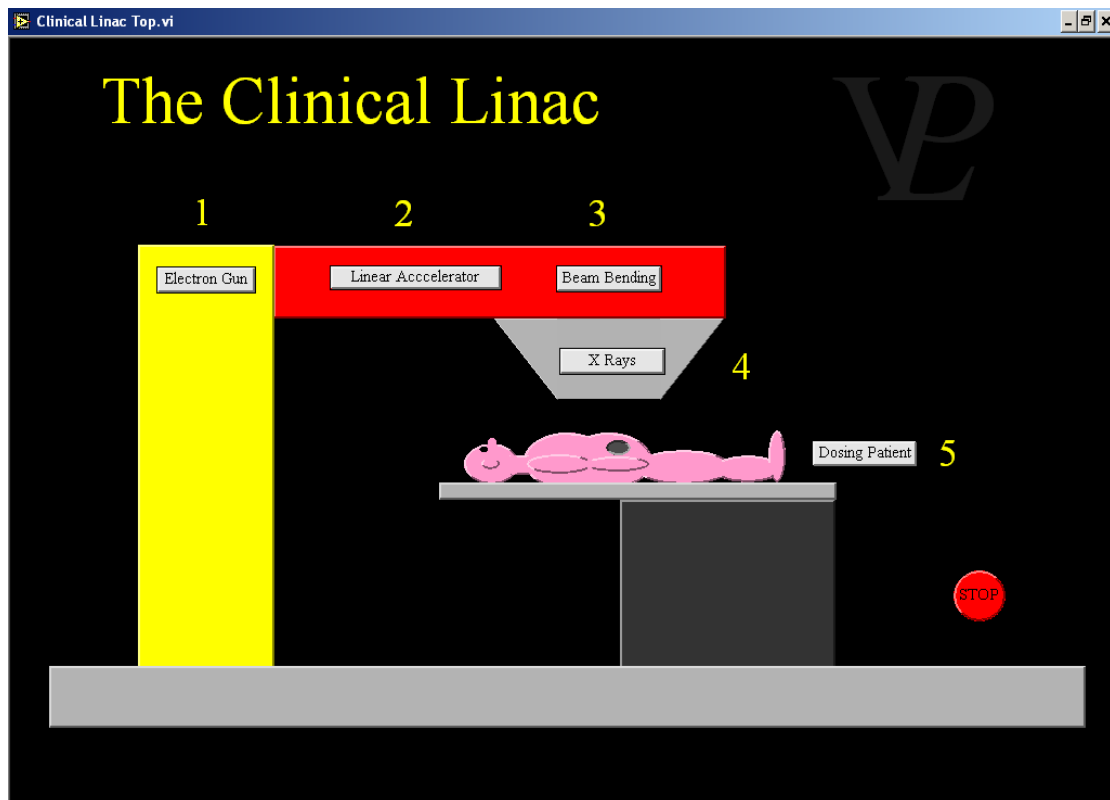
When the path differences are not an exact multiple of the wavelength, destructive interference takes place, and the intensity of the diffracted X Rays is greatly reduced.

An X Ray diffractometer has a special arrangement that moves the detector at twice the angle of the table so that the incident angle is always the same as the diffracted angle. The angular separation of the peaks is a measure of the lattice spacing of the material being analysed.

31.2 Clinical Linac

Advanced

This simulation shows how a medical “LinAc” (Linear Accelerator) works, starting from the electron gun through the accelerator, the steering of the electron beam and then the production of X rays and how these are targeted on to the patient to achieve the optimum dose whilst at the same time as minimising the unnecessary damage to surrounding tissue.



Radiotherapy is used in cases where the tumour or malignant growth is inoperable (where the additional risk of operating is likely to kill, or severely disable the patient). The method consists in killing the tumour through radiation, but doing it in such a way that the rest of the body is affected as little as possible.

Radiation doses are measured in Grays (Gy). A lethal dose for a tumour is typically 50 Gy. A maximum daily dose given to a patient is typically 2 Gy.

If a tumour can be radiated from every possible direction, the 'collateral damage' can be kept to a minimum, while the dose received by the tumour is large enough to kill it.

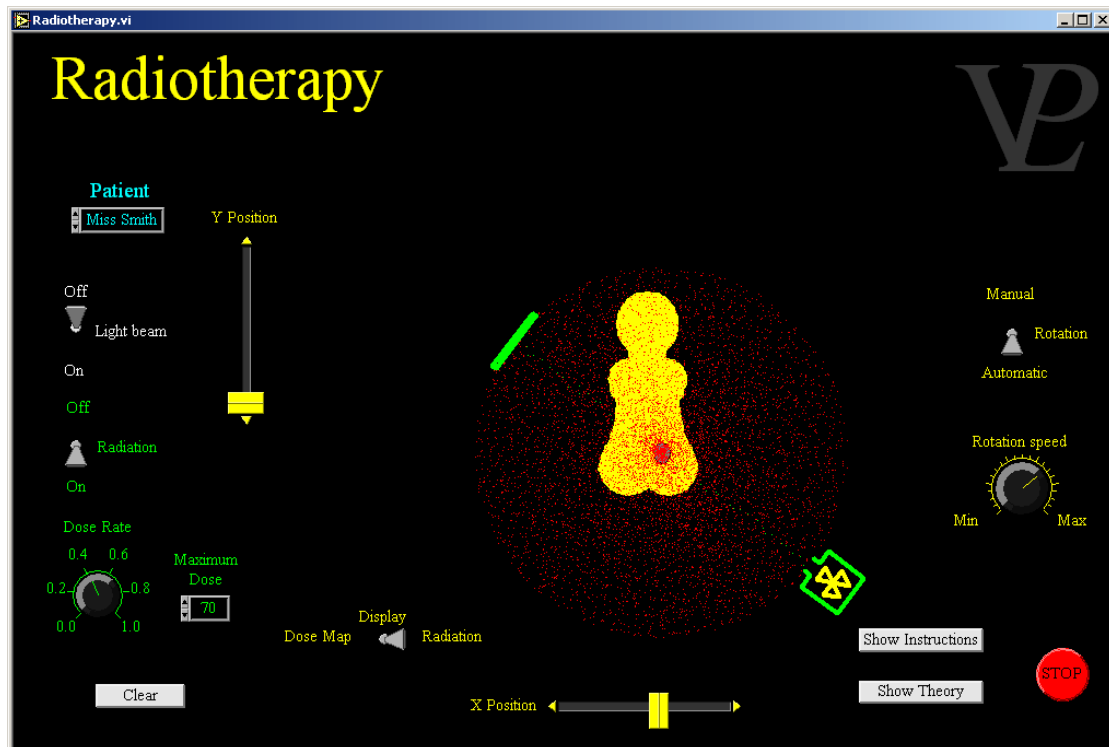
In a real radiotherapy clinic they avoid radiating the brain and the reproductive organs wherever possible, but they are able to radiate the body over an entire sphere (not just over a circle as simulated here).

Normally a radiotherapy treatment will involve having a few minutes of radiation a day for several weeks. After that the treatment is stopped and the patient is given a few weeks to recover before further test are carried out to see if the tumour has reduced in size or disappeared completely.

31.3 Radiotherapy

Advanced

This simulation shows how it is possible to concentrate the radiation dose on a tumour at a particular position inside the body. The centre of rotation of the radiation source can be adjusted so that it radiated the tumour from all possible angles.



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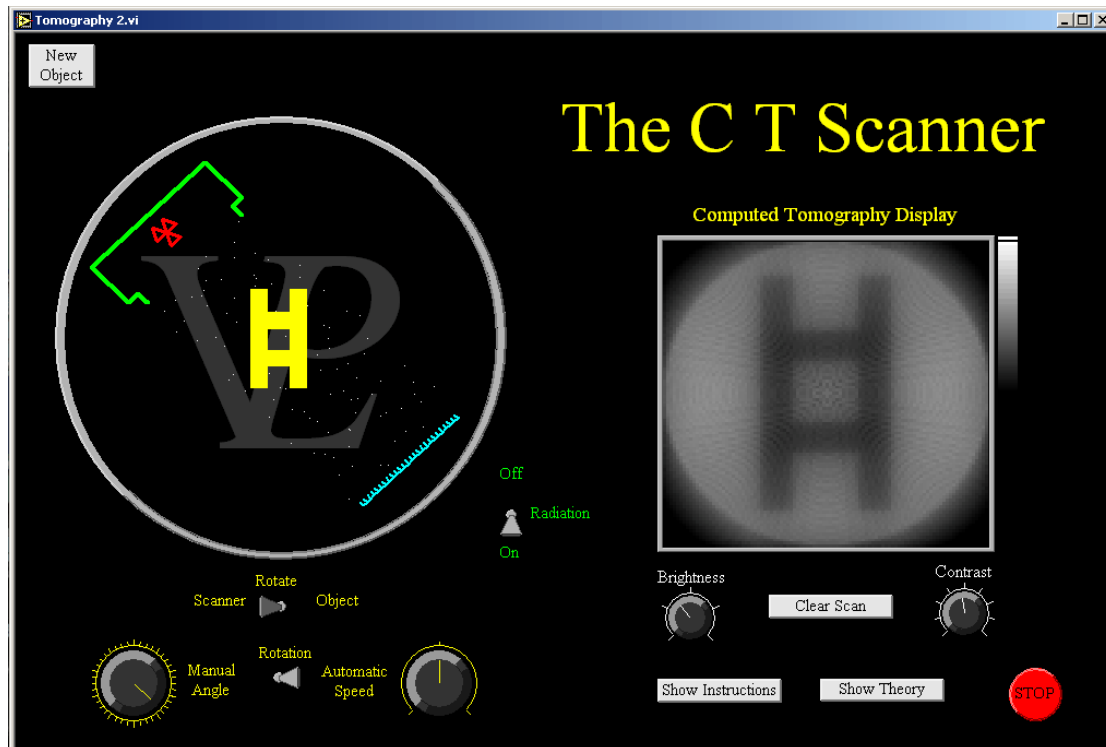
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Normally a radiotherapy treatment will involve having a few minutes of radiation a day for several weeks. After that the treatment is stopped and the patient is given a few weeks to recover before further test are carried out to see if the tumour has reduced in size or disappeared completely.

31.4 Tomography

Advanced

This simulation shows how a composite X Ray picture can be built up to reveal internal structures (not just simple 'shadow-graphs') when the object (or the source and detector) are continuously rotated during exposure.



X Ray Tomography is also known as Computed Tomography (C T Scan or CAT Scan). Its principle is that same as that of conventional X rays except that many different images are taken from many different angles and the final image is made up of a sum of all the images.

The detector is a CCD array instead of simple photographic plate. This makes it possible to adjust the contrast and brightness of the final image electronically.

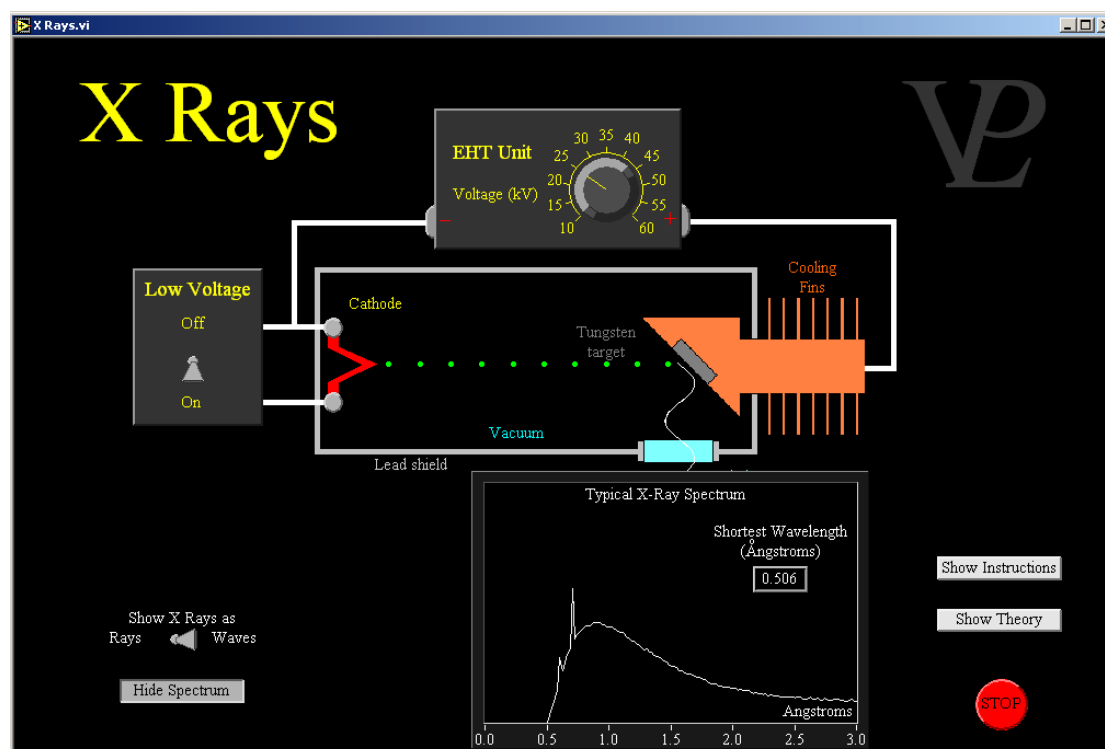
Rotating the scanner makes the principle easier to understand, but rotating the object instead is an equivalent process. Medical CT Scanners tend to keep the patient stationary and they rotate around them. Instruments designed to scan objects instead, are often made with a fixed source and detector, and the object rotates on a turn-table.

This simulation builds up a 2 D Object from a simple linear 1 D array detector, however real CT Scanners build up a 3 D image from a 2D Array detector. The image can then be manipulated and rotated at will.

31.5 X Rays

Advanced

This simulation shows how a typical X Ray tube produces X Rays. The relationship between the electron acceleration voltage and the minimum wavelength is shown, and also on the typical “Bremstrahlung” radiation plus target line spectrum.



X Rays are very penetrating electromagnetic waves. Their wavelength is much shorter than ultra-violet, and is of the order of 0.1 nm. Because this unit is quite useful it has been given a name of its own: 1 Angstrom = 1×10^{-10} m. Its symbol is \AA

X Rays are produced when very energetic electrons lose their kinetic energy in collisions with heavy atoms. Tungsten is frequently used as a target because of its high melting temperature.

The kinetic energy of the electron is equal to the charge e multiplied by the accelerating voltage V . If the electron loses all its energy in a single collision it will produce the most energetic X Ray photon (highest frequency and shortest wavelength). So the shortest possible X Ray wavelength spectrum from an X Ray tube can be calculated from the accelerating voltage.

$$e V = \frac{1}{2} m v^2 = h f = h c / \lambda$$

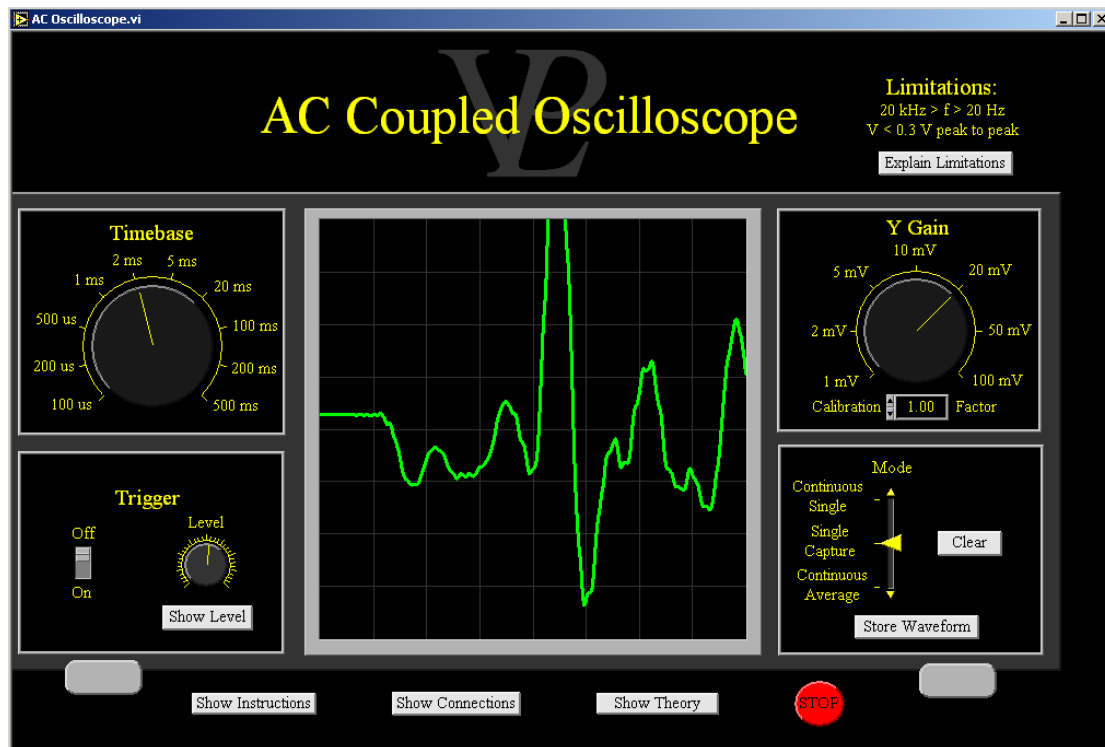
If the accelerating voltage is higher, the minimum X ray wavelength will be shorter. Most of the fast electrons will lose their energy over several collisions, and this gives rise to a continuum spectrum called Bremsstrahlung. If the electrons are energetic enough to match the energy gap of the K shell of electrons of the target, the spectrum will also have spikes corresponding to these energy transitions.

CHAPTER 32 EXTRAS

32.1 AC Oscilloscope

Advanced

This program converts the microphone input of your computer into an AC coupled oscilloscope which samples at 44100 Hz and can measure Voltages with a maximum amplitude of around 0.3V.



WARNING: Be careful with this AC Coupled Transient Recorder. Careless use may damage the audio input of your computer! Nevertheless, if you are monitoring Voltages that are less than 0.3V peak to peak, there should be no problem.

The audio input of a typical computer sound card is AC coupled. It has a capacitor in series with the input. DC signals cannot be measured because DC electricity does not flow through a capacitor. AC signals on the other hand do flow through a capacitor, and so the signals can be recorded and measured. However, the trace shown by this AC coupled oscilloscope most closely resembles the first time derivative of the signal that a normal oscilloscope would display! When looking at sine waves this is not a great limitation as the derivative of a sine is a cosine, and they both look very similar! However, if the traces you are capturing seem strange, bear this fact in mind!

This simulation was tested on a Dell Inspiron 2200 laptop, and it was compared against an oscilloscope. The Timebase was found to be accurate to better than 1%, and the Gain was within around 5%.

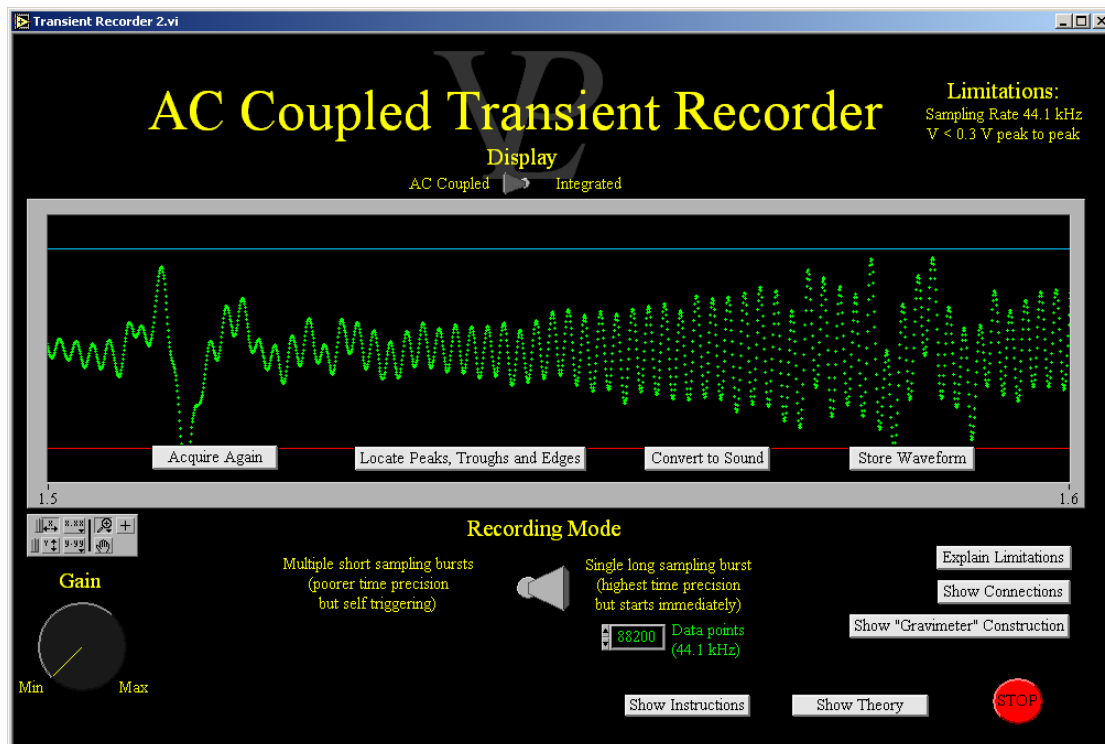
The default Calibration is set at 1.00. If you have access to a calibrated oscillator, you can change this number to obtain a more precise Amplitude measurement.

For further understanding on the oscilloscope, please run the Oscilloscope simulation in the Charged Particles chapter of the Virtual Physical Laboratory.

32.2 AC Coupled Transient Recorder

Advanced

This Transient Recorder is ideal for capturing short electrical signals that do not repeat periodically. e.g. the pulse generated in a small coil when a magnet drops through it. For periodically repeating signals use the "AC Oscilloscope" program instead.



WARNING: Be careful with this AC Coupled Transient Recorder. Careless use may damage the audio input of your computer! Nevertheless, if you are monitoring Voltages that are less than 0.3V peak to peak, there should be no problem.

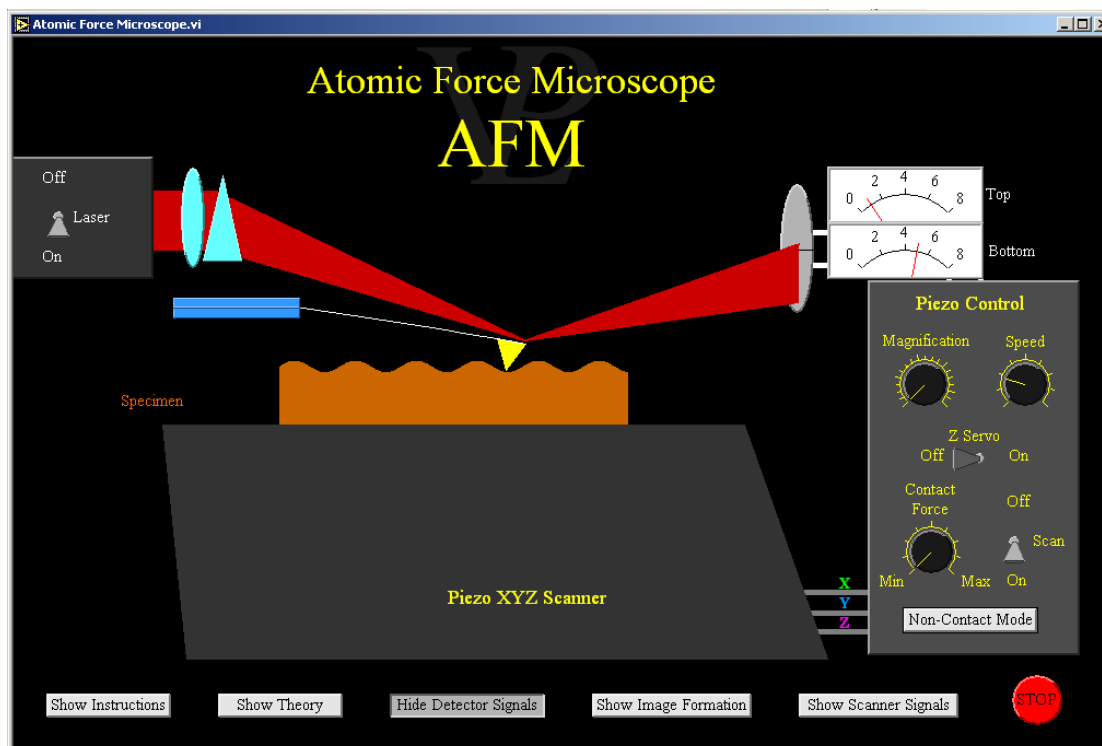
The audio input of a typical computer sound card is AC coupled. It has a capacitor in series with the input. DC signals cannot be measured because DC electricity does not flow through a capacitor. AC signals on the other hand do flow through a capacitor, and so the signals can be recorded and measured. The consequence of this is that the default AC Coupled trace that is displayed on the screen is something approximating to the first time derivative of the signal. Integrating this trace with respect to time produces something that approximates what a real oscilloscope or transient recorder would display.

This program includes instructions on how to make a gravimeter using nothing more than a plastic pipe and a few metres of copper wire.

32.3 Atomic Force Microscope

Advanced

This simulation shows the basic operation of an AFM operating either in contact or non contact mode.



The Atomic Force Microscope (AFM) is one of a family of "Scanning Probe Microscopes". It creates an image by continually sampling the surface height and displaying the height array as a colour ramp or mesh plot.

The specimen is brought in to contact with a very small and sharp stylus at the end of a thin cantilever by raising the "piezoelectric scanner tube". Once in contact the scanner is then made to raster back and forth, the vertical position of the stylus changes, causing a laser beam that reflects off the back of the stylus to move up and down over a split detector. If the signals from the upper and lower half are amplified and processed, they can be used to control the Z position of the scanner to bring the laser reflection back to the central "null position".

The voltage to the Z part of the scanner is inverted and scaled to represent the surface height. The surface height is stored in a two dimensional array and plotted either as a surface mesh or a colour intensity map. The magnification is controlled by changing how far the piezoelectric scanner moves in both X and Y. The smaller the travel, the larger the magnification of the image produced.

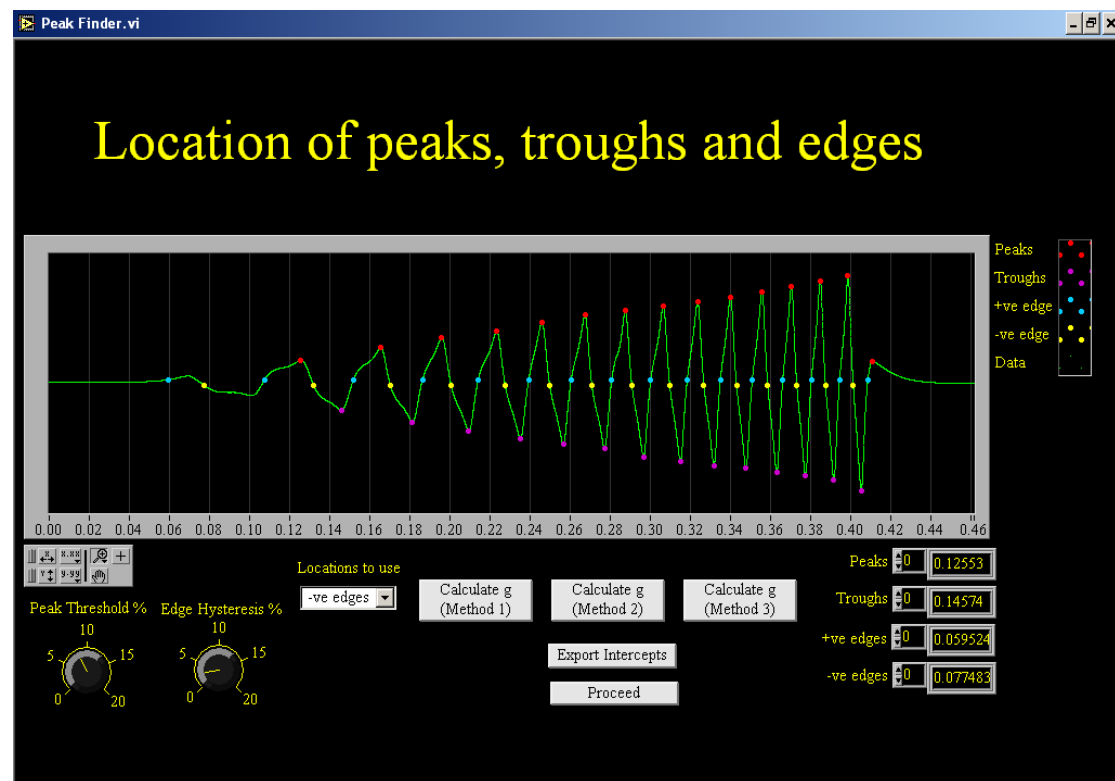
The amount of bend in the cantilever determines the contact force. Too much force, and the stylus will wear out (or damage fragile specimens). Too little force, and the stylus will lose contact with the surface when scanning over topographic features.

There are a number of modes in which an AFM can operate. One of them is non-contact! A stiffer cantilever is first made to resonate at its natural frequency (in air). When it is then brought into close proximity to the surface of the specimen its resonating frequency (or amplitude) will change, giving the instrument feedback that the surface is only a few nanometres below!

32.4 Gravimeter

Advanced

This is NOT a simulation! It is a real program that you can use in order to measure the acceleration due to gravity. With suitable care you should be able to obtain a value which is within about 1%. Full instructions are given. Some students of mine built one within 90 minutes and were obtaining real data.



When a magnet falls (without tumbling) through the gravimeter, it induces an EMF through each of the coils. As the magnet accelerates under gravity, the magnitude of the EMF increases, and the time interval between successive pulses also decreases.

From the time between pulses it is possible to calculate the mean velocity at the point mid way between successive coils.

Using some of the equations of motion and plotting successive values of v or v^2 on the Y axis at 5 cm (coil separation) intervals on the X axis we obtain a graphs from which gravity can be derived.

It may be necessary to trim off some of the first data points (because the signal was too small) and also some of the last data points (because they may be affected by magnet rebound at the bottom).

Generally a value somewhat smaller than 9.81 m/s^2 is obtained because of air resistance and friction, but improvements can be made to this experiment to improve its accuracy.

32.5 Morse Code Receiver

Basic/ Advanced

This program receives Morse code peeps and converts them into text. Use it in conjunction with the Morse code transmitter to send messages from one computer to another. Investigate the effect of bandwidth as well as that of noise in the background.



Morse Code was invented before conventional Radio Transmission was invented. Characters had to be converted into 'dots' and 'dashes' ('dit' and 'dah') and then transmitted either on a radio carrier frequency (or light pulses - if within sight).

The code follows these 4 rules:

- 1 - Each dah is three times longer than a dit
 - 2 - The space between parts of the same letter are separated by a space equal in length to a dit.
 - 3 - The space between separate letters are separated by a space equal in length to two dits.
 - 4 - The space between two words is separated by a space equal in length to seven dits.
- Historically there were at least 3 different codes. The one used in this simulation is the International Morse Code.

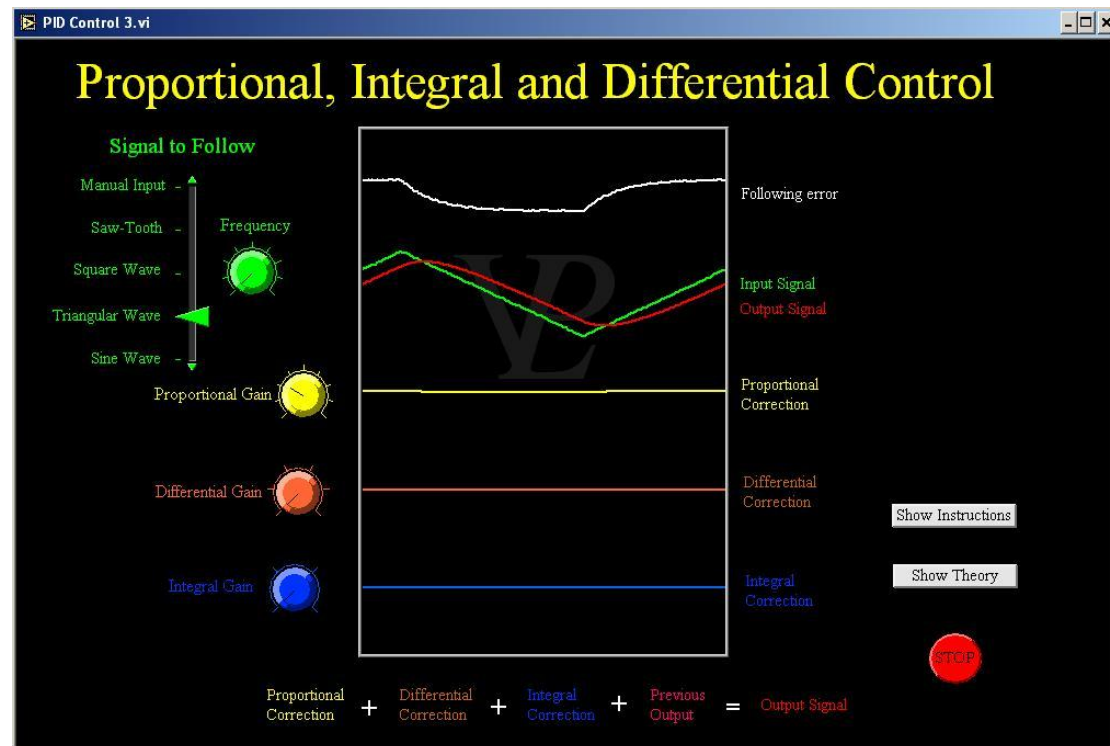
Skilled Morse code operators could transmit (or decode) up to 40 words per minute!).

The Morse Code Transmitter and Morse Code Receiver simulations are included in the Virtual Physical Laboratory as curiosities (or toys!) through which it is possible to learn a little of the principles of broadcasting speed (band-width) and the influence of noise (signal to noise ratio).

32.6 PID Control

Advanced

This simulation helps to understand a little of what goes on inside controllers and servo systems.



It is often necessary to control instruments and machines based on a sensor. A simple example could be controlling the position of a machine based on the position of a target.

Proportional control is the simplest: The correction to the current position is proportional to the current error.

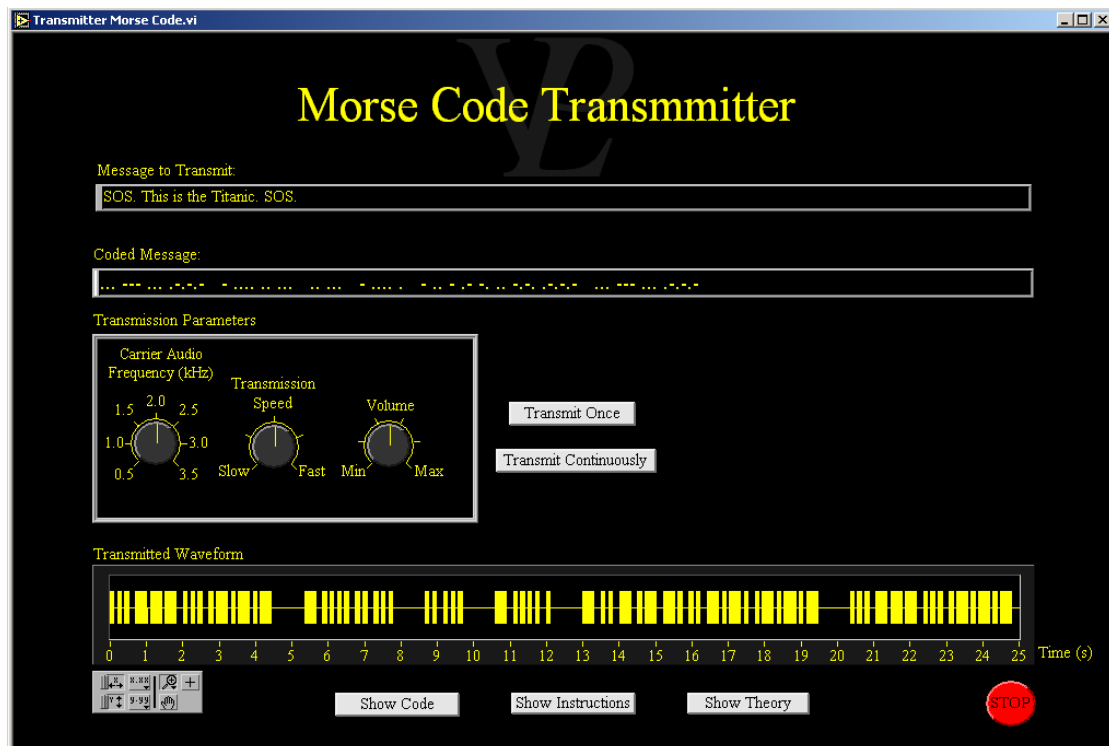
Differential control is a little more complex: calculate how much the target has moved since last time and multiply this difference by a constant. Differential control is very useful when the target position changes rapidly.

Integral control is perhaps the most difficult to achieve in practice: It consists of keeping a cumulative addition of the error history and multiplying this sum by a scaling factor. This control is very useful when the output starts to lag consistently behind the target. This can happen, for example, when a mechanical system is loaded more heavily.

In practice the gains of the Proportional, Differential and Integral (G_p , G_d and G_i) need to be 'tuned' to the application until an acceptable level of delay or overshoot is achieved. Increasing the gains too high can lead to system instabilities and uncontrolled oscillations may ensue.

Basic/Advanced

The Morse Code Transmitter and Morse code Receiver simulations can be used in conjunction on two different computers (within hearing distance of each-other) in order to transmit messages.



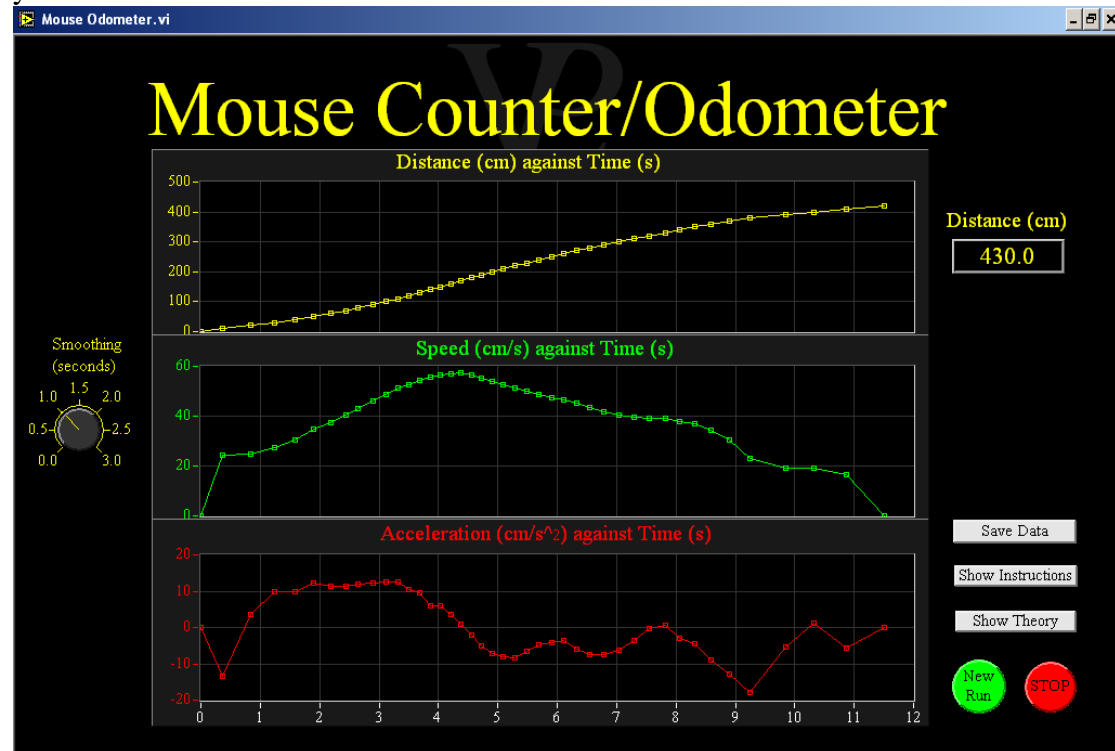
If you want to hear the Morse Code conversion, ensure your computer speakers are switched ON.

- 1 - Type the message you want to broadcast and press the "Convert to Code" button.
- 2 - See how the characters in the message get converted into . and - ("dit" and "dah")
- 3 - Adjust the Carrier Frequency, Transmission Speed and Volume and then Press the "Create Waveform" button to prepare a waveform to be sent to the speakers.
- 4 - Press the "Transmit" button to send the waveform to the speakers.
- 5 - Press the "New Message" button to transmit a new message.
- 6 - Press the "Show Code" button to see the 'key' to the code.

32.8 Odometer Mouse

Advanced

This program allows you to convert a cordless mouse into a revolution counter for the wheel of a laboratory trolley. It needs a reed switch and a magnet, and the rest is up to you!



This program was written to be used with a 'modified mouse' where the switch of the left buttons is replaced with a reed switch. In this way the mouse can be used something like a bicycle odometer for a lab trolley.

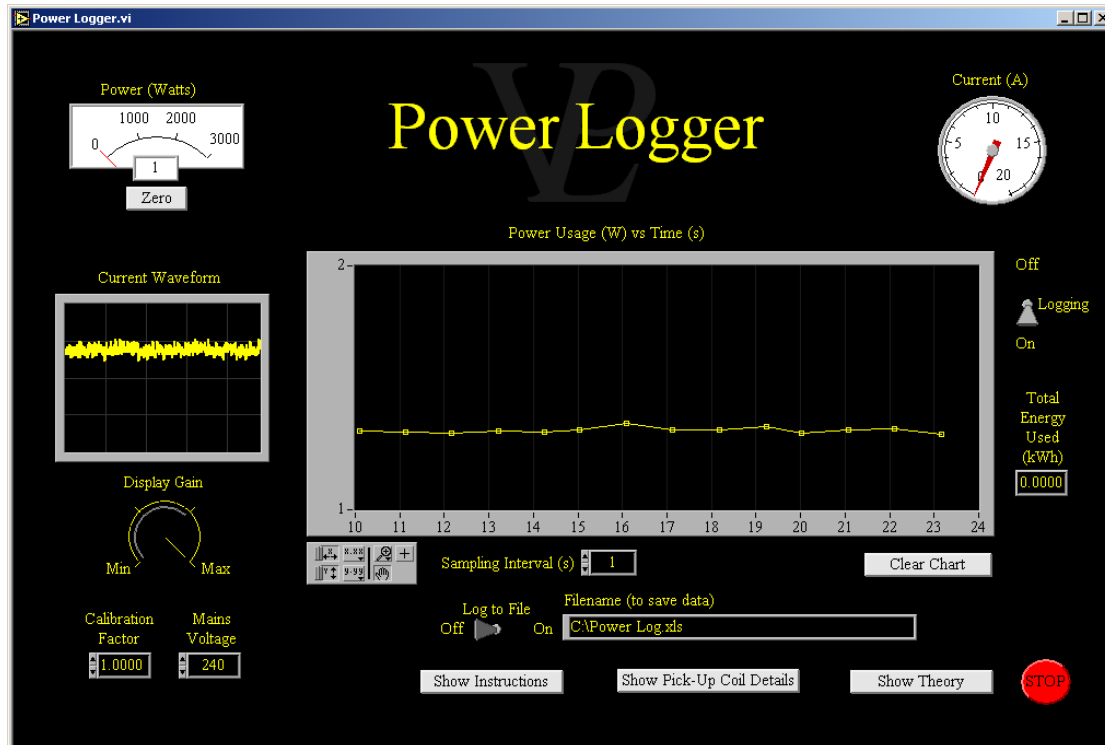
- 1 - fix a magnet to the wheel you are wanting to monitor.
- 2 - Place the reed-switch in such a position that the passing magnet will cause it to close momentarily.
- 3 - Enter the perimeter of the wheel you are monitoring
- 4 - Bring the normal mouse into the white square area.
- 5 - The timing (and recording) will start immediately the first click is recorded.
- 6 - Subsequent clicks will increment the position by one perimeter amount, and the velocity will also be calculated and displayed. You can set some smoothing on the velocity calculation.
- 7 - As soon as a right click is pressed, or the mouse is moved out of the white box, the program will terminate the acquisition and display displacement, speed and acceleration graphs. Again some smoothing can be applied to these graphs.
- 8 - You can then select to save the data, to run again, or to quit.

The timing of a modified mouse will not be perfect as it is complicated by delays in the computer reading the mouse, and on the exact timing of the loop in this computer program. Nevertheless, it should be possible to obtain timing results with timing errors which are in the region of 10 ms or less. Happy experimenting!

32.9 Power Logger

Advanced

This program has instructions on how to make a system that can log the power consumed by any household electrical appliance. It can record the power used over any period of time, and can export the data for subsequent analysis.



When a conductor carries a current through it, a circular magnetic field is formed around it in a plane perpendicular to the direction in which the current is flowing. The direction of the magnetic field follows the "cork-screw" rule.

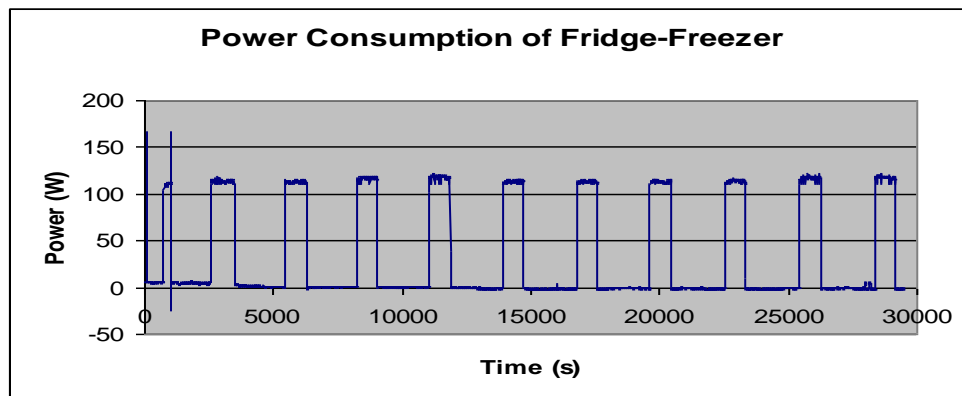
If a closed hoop of ferromagnetic material is made to surround the conductor, the field is strengthened further. If the current through the conductor is alternating, then the magnetic flux through the ferromagnetic hoop will also change direction continually.

If a coil is wrapped around the ferromagnetic hoop, the change in flux induces a small Voltage. If the number of turns around the ferromagnetic hoop is sufficiently large, this Voltage is large enough to be detected and used.

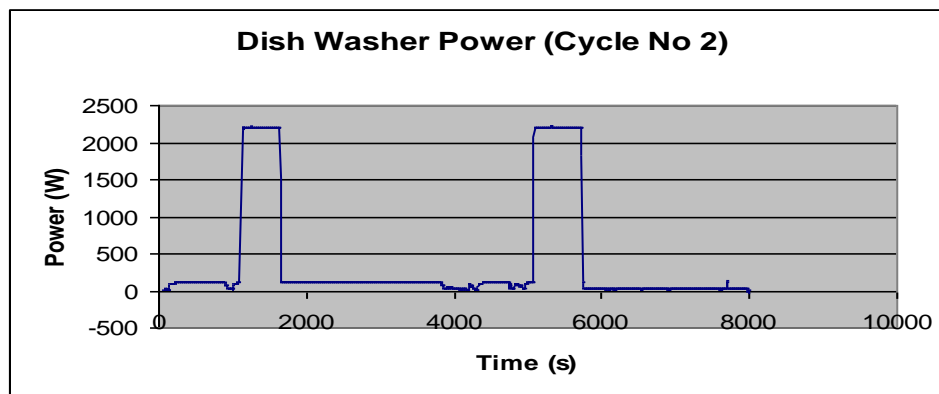
This principle is the basis of 'clamp meters', as well as domestic power consumption monitors.

In this program, the Voltage from the coil around the ferromagnetic hoop is recorded using the audio input of the computer. After suitable calibration it is possible to use this signal a scaled measure of the current flowing through the conductor. If the AC Voltage is known, the power can also be calculated. If the time is also recorded it is possible to integrate the power to obtain a measure of the energy used by the appliance drawing the current.

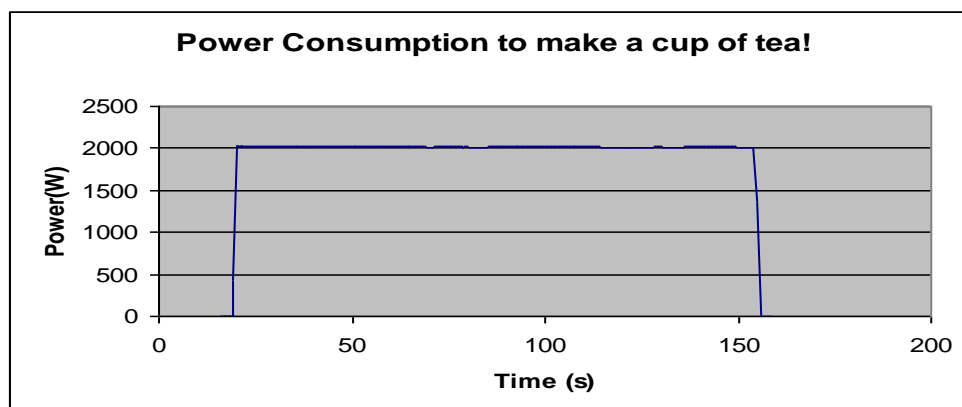
Some examples of power consumption of household appliances are shown below.



The figure above shows the power consumption of a fridge-freezer. The period when the compressor switches on can be clearly seen. Average power per period = 32.5W. Energy per Day = 0.778 kWh.



The figure above shows the power consumption of a Dish Washer on cycle No 2. The two main peaks are due to the water heater. The predominantly flat areas are due to the spraying pump, and the smaller dips are due to the draining pump. Total energy consumption = 0.883 kWh.

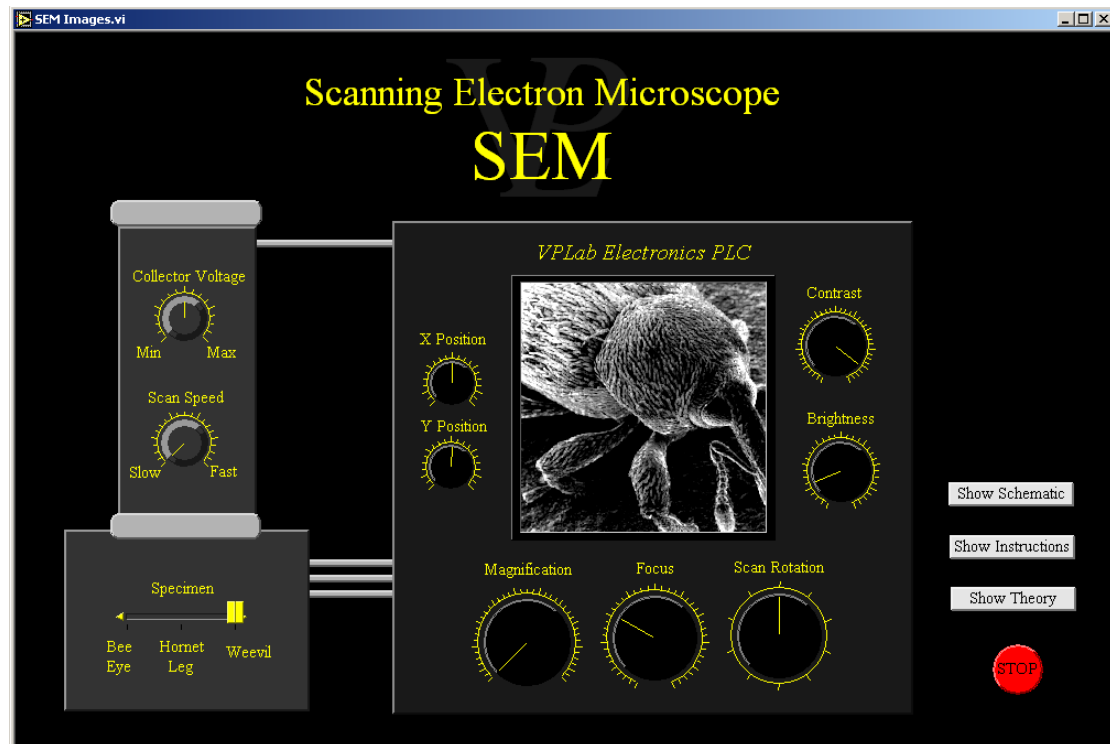


The figure above shows the power consumption of a kettle boiling just enough water to make a cup of tea. 0.078kWh in total.

32.10 Scanning Electron Microscope

Advanced

This program explains the basic image formation process of a scanning electron microscope. Three different images are stored and the effect of scan speed, collector voltage scan rotation etc can be explored.



The Scanning Electron Microscope (SEM) is one of a family of "Scanning Probe Microscopes". In this case the probe is an electron beam which is continually sampling the surface. In order to work, the SEM needs to be evacuated inside down to very low pressures.

In order to produce a finely focused beam of electrons, a typical SEM accelerates electrons which leave an electron gun attracted by a large positive voltage. Typical operating energies are around 20 keV. The image of the electron source (sharp tip) is then progressively de-magnified by means of three electron lenses until it is around 5 nm in diameter or smaller. Electron lenses are electromagnets with a hollow core; their focal length can be adjusted by varying the current through the coil. The beam is then rastered in a zig-zag fashion with the aid of some additional scanning coils.

When the high energy electron beam strikes the specimen it liberates a large number of 'secondary electrons'. These slow secondary electrons can be attracted towards a collector by applying a positive voltage to a grid in front of the detector. 'Backscattered electrons' are higher energy electrons which were originally in the beam but have encountered a largely elastic collision and bounced back out of the specimen. The detectors for these are located immediately below the final lens.

The choice of signal detected is then amplified and used to modulate the intensity of the beam that is rastering on the screen of the SEM; this generates the picture. The

magnification is the ratio of the side of the screen to the side of the rastered pattern on the specimen. State of the art SEMs can readily reach magnifications of $\times 100,000$. It should be noted however that depending on the specimen, sometimes greater magnification does not produce better resolution. The limitation arises from factors such as finite beam diameter, beam penetration and signal noise.

Many SEMs are fitted with X ray detectors so that the instrument can detect different elements present in the specimen by analysing their X Ray spectra.

The quality of the images obtained from an SEM is affected by a number of parameters: Signal choice, Accelerating voltage, Beam Current, Focus, Scan speed, Collector voltage, Contrast and Brightness - to list but a few... Getting good SEM images is a combination of good science and art!

The focus affects the diameter of the beam spot as it rasters over the specimen. The smaller the beam diameter, the better the image resolution will be.

The Collector voltage is only relevant when imaging using secondary electrons. A high collector voltage enables the microscope to image the 'dark side' of specimens as well. Turning the collector voltage down yields an image where only parts of the specimen inclined towards the collector appear bright, all the others appear dark.

The Accelerating voltage affects both the beam current as well as the penetration of the beam into the specimen! The best acceleration voltage is a compromise: Higher accelerating voltages improve the beam current (less noise in the picture) but penetrate the specimen, increasing the volume of interaction and so deteriorating the resolution.

The choice of raster speed is also a compromise; too fast and the image will be dominated by 'snow' (white noise), too slow and the image will take a long time to form! In practice microscopists normally focus the image and adjust the intensity levels at a fairly fast raster, and then take a final good quality picture at slow raster rates.

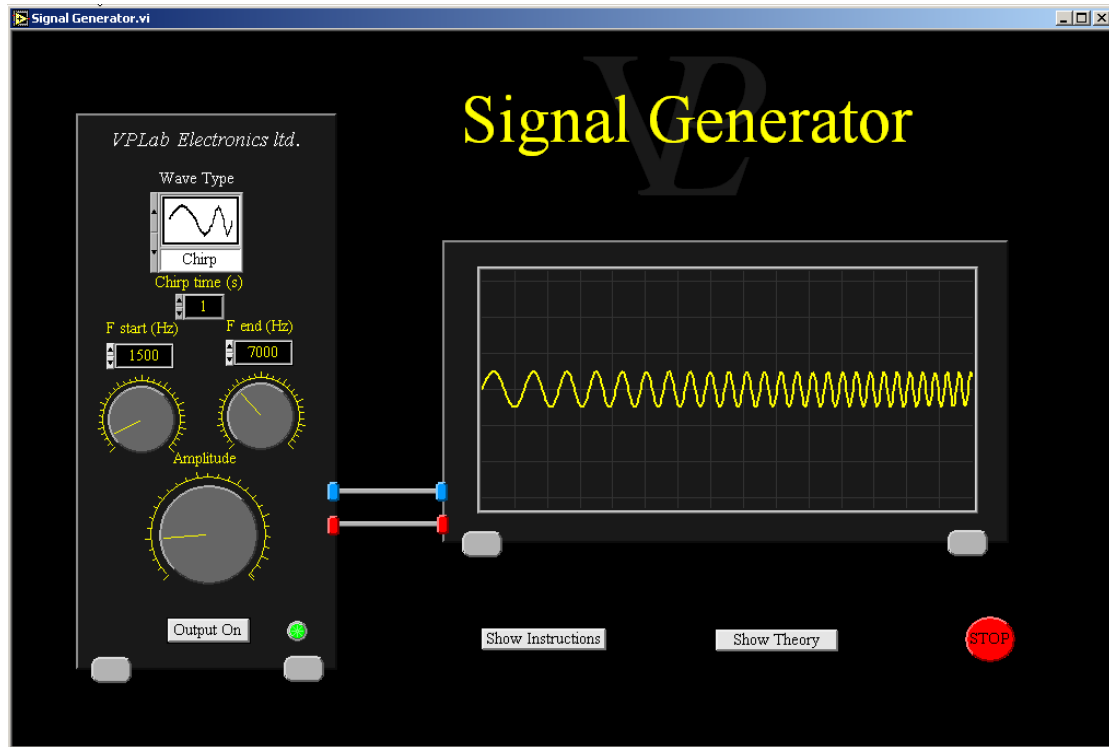
The Brightness and Contrast settings are common to many other imaging instruments. These need to be adjusted so that the image uses the full range between black and white without getting saturated at either end.

Electron lenses tend to rotate the orientation of a raster pattern! - As the focus is changed, the orientation also changes. Scan rotation enables the microscopist to orient the picture in such a way that others will be able to interpret his images with ease.

32.11 Signal Generator

Advanced

This program makes it possible to use the computer as a signal generator. Depending on the application intended, the audio output of the computer can be passed through an amplifier in order to give it more power.



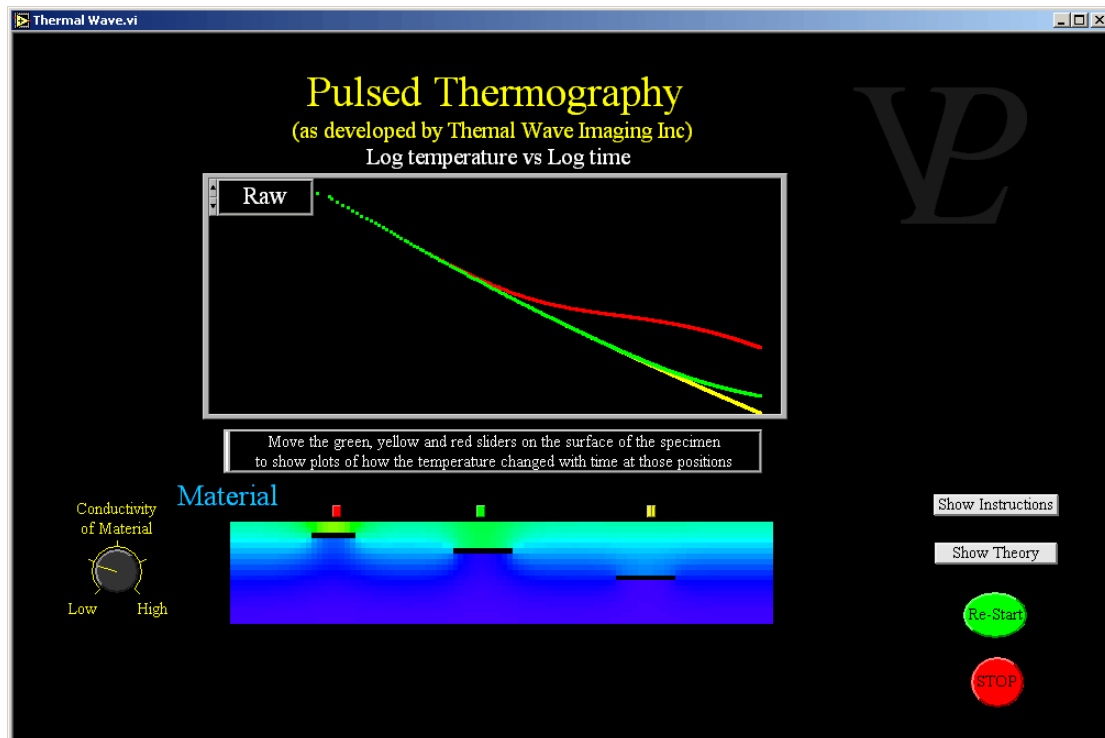
The output of this signal generator is updated at 44100 Hz. The maximum frequency that it can generate (Nyquist limit) is 22050 Hz, but in practice it is probably a little lower.

Warning: Computer sound cards seem to be designed to operate with loads of around 20-30 Ω . If you want to draw greater powers, or drive lower impedances please drive them through a signal amplifier to minimise any risk of damaging the sound card of your computer.

32.12 Thermal Wave Imaging

Advanced

This simulation shows the operating principle of a non-destructive testing method based on heat propagation. The technique is used to detect the presence of sub-surface defects by looking purely at the heat distribution on the surface following a powerful flash of light.



Pulsed thermography is a non-destructive technique to detect sub-surface defects in materials. It uses a powerful flash and an infra-red camera. When a pulse of heat is radiated on to the surface, some of it will be reflected away instantaneously, but some of it will be absorbed by the material and will get conducted down into the material.

As the heat is conducted into the material, the surface that is seen by the thermal camera will cool down. If there are no defects inside the material, the surface will cool down uniformly, but if there is a defect that impedes the conduction of heat downwards, the surface above it will cool down a little more slowly than other parts.

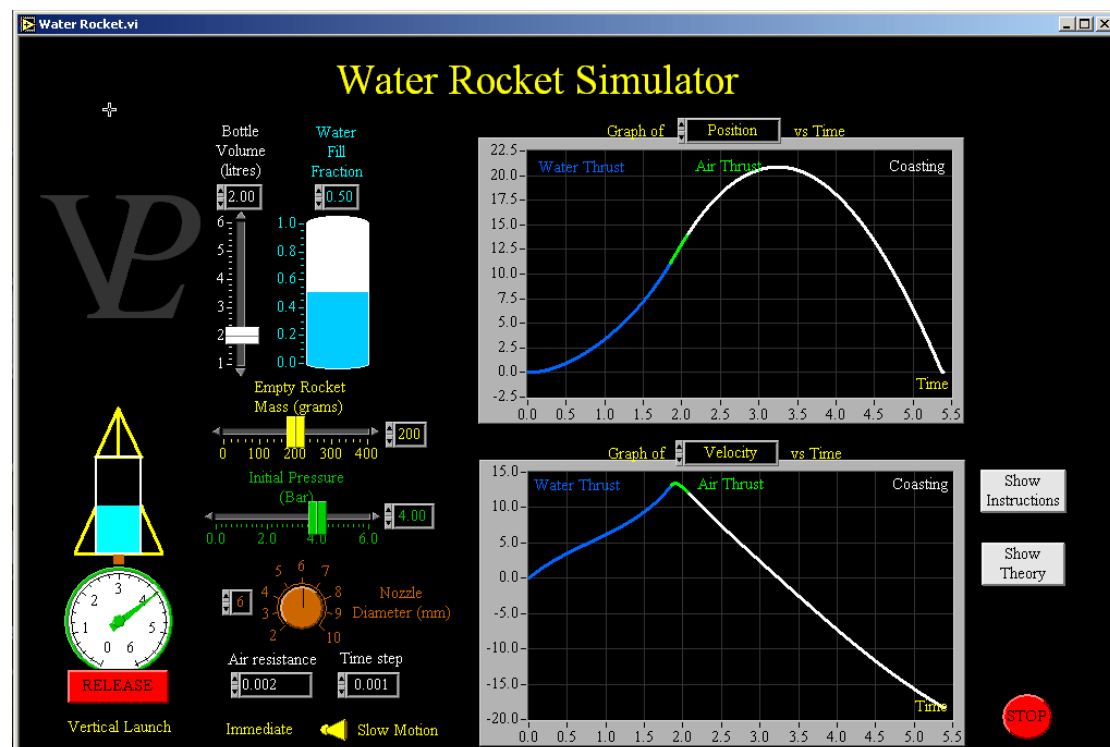
This slight change of cooling rate can be used to diagnose the defect. If the defect is close to the surface, it will be detected very early; if it is deeper it may take several seconds before it shows any effect. Plotting the logarithm of the temperature vs the logarithm of the time is a particularly suitable graph to study the effects as it expands short time scales and compresses longer times.

If the defect is isolated (surrounded by good material), the heat will eventually get conducted around it, and the cooling at the surface will resume. If the cooling does not resume, either the defect is very large, or the heat has reached the other side of a thin specimen. Read more about it at www.thermalwave.com

32.13 Water Rocket

Advanced

This simulation allows the user to vary the water level, pressure and nozzle diameter of a water rocket and see what effect it has on the overall height achieved. The plot separates the portions of the trajectories during water acceleration, air acceleration and coasting. Useful for anyone wishing to compete in a water rocket challenge!



A reasonably detailed explanation of the water rocket is surprisingly long! Even the explanation that follows is a bit of a simplification.

As the water is expelled from the rocket, the air inside the rocket expands. When the air inside the water rocket expands, it does work which can be equated to the kinetic energy of the slug of water leaving the rocket. Action and reaction, being equal, cause the rocket body to recoil from the exhaust. The volume of air increases rapidly causing the pressure inside to decrease adiabatically. The mass of the rocket decreases as it loses water. The velocity is changed by the reaction to the thrust and by gravity.

As you can see this is not a simple problem. Thankfully we have computers and we can make them work very hard, solving the problem numerically. The equations we need are as follows:

$$\text{Work done during expansion } Work = PdV_o = \frac{1}{2} dm v_e^2 \dots\dots\dots(1)$$

$$\text{The mass of the slug of water } dm \text{ is } dm = \pi r^2 l \rho \dots\dots\dots(2)$$

$$\text{The slug length is related to the exhaust velocity by } \frac{dl}{dt} = v_e \dots\dots\dots(3)$$

$$\text{The slug mass is related to the volume expansion by } dV_o = \frac{dm}{\rho} \dots\dots\dots(4)$$

Substituting 2, 3 and 4 into 1 we obtain $v_e = \sqrt{\frac{2P}{\rho}}$ (5)

The change of momentum of the rocket is also modified by gravity and also by air resistance $MdV_e = v_e dm - Mgdt - A_r V_e^2 dt$ (6)

At the end of the step:

the mass of the rocket is given by $M_2 = M_1 - dm$ (7)

the air volume is given by $V_{o2} = V_{o1} + dV_o$ (8)

the velocity is given by $V_{e2} = V_{e1} + dV_e$ (9)

the pressure is given by $P_2 = P_1 \left(\frac{V_{o1}}{V_{o2}} \right)^{1.4}$ (10)

the average velocity is $\bar{V}_e = \frac{(V_{e1} + V_{e2})}{2}$ (11)

the change in height is $H_2 = H_1 + (V_{e1} + V_{e2})dt$ (12)

To make matters more interesting, it is necessary to keep track of when the water runs out! From that point onwards, the density of the exhaust changes to that of air, which is expelled much faster, but delivers very little thrust.

The symbols in the equation have the following meanings:

l = length of water slug

r = radius of nozzle

v_e = exhaust velocity

g = gravity

dt = time element

A_r = Air resistance coefficient (assumed proportional to velocity squared)

P, P_1 & P_2 = Pressure, and initial and final pressures,

dV_o, V_{o1}, V_{o2} = Volume increment, initial and final volume,

$dV_e, V_{e1}, V_{e2}, \bar{V}_e$ = Velocity increment, initial, final and average velocity

dm, M_1, M_2 = Mass decrement, initial and final mass.

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First of all I would like to thank God for making such a fantastic universe; vast and intricate, and for giving us senses that can experience so much of it and minds that can (at least start to) make sense of how it might all work!

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I am grateful and humbled to have been able to make a positive difference to the way physics is taught and learned by so many around the world, especially those who have little or no access to equipment (students in developing countries, remote locations, hospitals, prisons). I hope you enjoy using the simulations (and learn some physics while you are at it!)

John Nunn

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