TEACHING ABOUT SCIENCE

A THEORETICAL MODELS: ELECTROMAGNETISM

This is a lesson aimed at helping students to develop their understanding of the role of theories in science, using James Clerk Maxwell's model of magnetic vortices as an example.

Resources for students and teachers

downloaded from www.nuffieldfoundation.org/aboutscience

OHT A0.1 Aims of the lesson
OHT A1.1 Observable phenomena <—> Abstract ideas
Student sheet A1.2 Catapult effect
Teacher resource sheets A2.1A, A2.1B Background information (2 sheets)
OHT A2.2 Maxwell says … , A2.3 Maxwell's model
Teachers' sheet A2.4 Maxwell's model, with key
Student sheet A2.5 The story of Faraday, Maxwell, and field theory (2 sheets)
Student sheet A3.1 A kinetic model of gases and temperature

Teachers' notes (separate download)

download from www.nuffieldfoundation.org/aboutscience

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A THEORETICAL MODELS: ELECTROMAGNETISM

You will develop your understanding in the following areas.

IN THE FIRST ACTIVITY

• The distinction between observable phenomena / objects and abstract ideas in science.

• How abstract ideas form a key part of many theoretical models in science.

IN THE SECOND ACTIVITY

• That not all analogies in science are equally useful.

• How, by using an analogy to link a poorly understood area of science with a well understood area of science, scientists can draw upon old resources to solve new problems.

• How *useful* analogies can link areas of science previously considered as separate (e.g. electromagnetism and light).

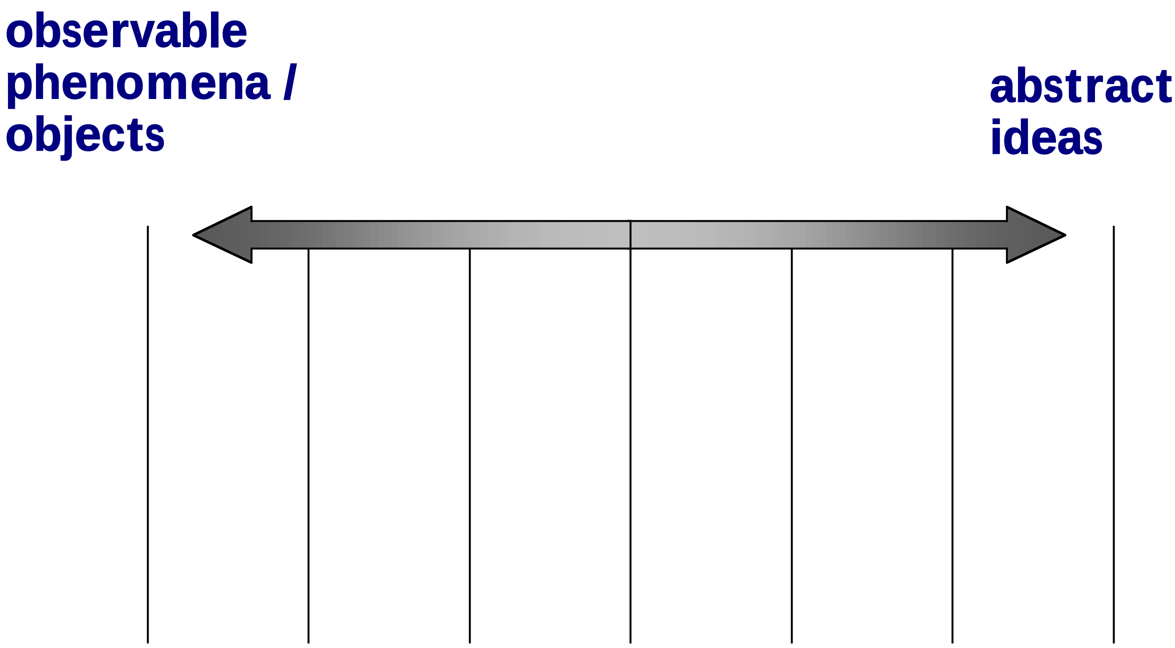
IN THE FINAL ACTIVITY

• How *useful* analogies can be judged by their ability to generate testable predictions.

A THEORETICAL MODELS: ELECTROMAGNETISM

When an inflated balloon is **cooled down,** the **volume of the balloon decreases**.

Scientists explain this phenomenon by using the kinetic theory of gases. This theoretical model relates the temperature and volume of the gas to the behaviour of '**billiard ball-like' particles** of gas.



A THEORETICAL MODELS: ELECTROMAGNETISM

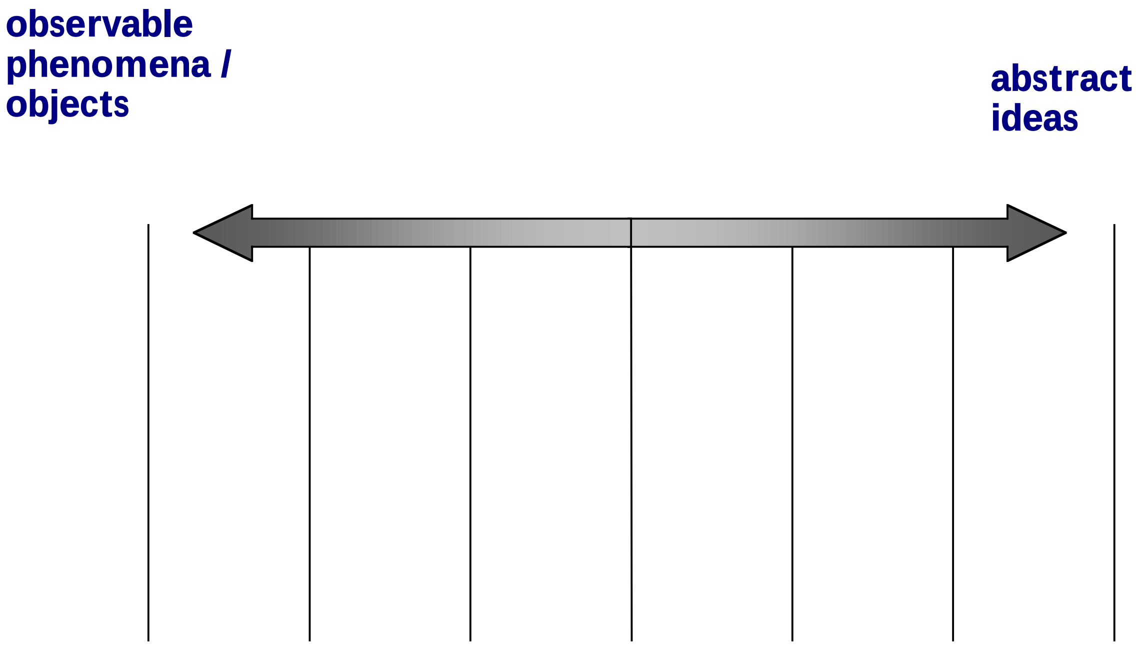
THE CATAPULT EFFECT

You will have observed in your physics lessons how electricity and magnetism can interact. If an electric current is passed though a **wire** placed between two **magnets** the wire will **move to one side**. This is due to an interaction between the electric current and **magnetic field lines** around the wire.

In your group decide whether you think the features highlighted in bold text are:

- observable phenomena / objects;
- abstract ideas.

You can record your ideas on the grid below.



A THEORETICAL MODELS: ELECTROMAGNETISM

Activity A2: Background information for teachers: Outline of the story of James Clerk Maxwell's field theory

(See sheet A2.1B for further detail.)

Faraday develops a concept of lines of force to explain the action of a magnetic field

Faraday looked at electromagnetic phenomena in a new way which suggested that electromagnetism is propagated through space rather than acting instantaneously at a distance.

Faraday was unable to develop an analogy that could provide any testable new understanding of magnetic force, but did provide a new way of thinking about magnetism that differed from the Newtonian concept of action at a distance.

Maxwell picks up on Faraday's ideas and develops an analogy between magnetic field and spinning vortices (OHT A2.2, Quote 1)

Faraday's work stimulated Maxwell to develop an analogy that gave a possible mechanism to explain how magnetic forces could interact with electricity.

Maxwell predicts from his analogy that electromagnetism would be propagated through the ether at a finite rate. (OHT A2.3 'Maxwell's model')

Maxwell's analogy with fluid vortices enabled him to 'borrow' mathematical equations from fluid hydrodynamics to generate a mathematical model of magnetic field.

Maxwell uses his analogy and some 'borrowed' mathematics to develop a series of equations that enable him to predict the speed of this propagation. (OHT A2.2, Quote 2)

From the mathematical model (Maxwell's field equations) he was able to predict that electricity/magnetism would be propagated through space at a measurable speed. (A testable prediction).

Maxwell is struck by the similarity between the predicted speed of his electromagnetism and the speed of light. (OHT A2.2, Quote 3)

The speed of propagation of electromagnetism predicted by Maxwell's field theory was strikingly similar to the speed of light which had recently been measured. This caused Maxwell to speculate on a link between electromagnetism and light.

Maxwell's theory is supported by experimental evidence from other scientists.

Other groups of scientists carried out experiments to test Maxwell's new theory. The results they obtained supported Maxwell's theory.

A THEORETICAL MODELS: ELECTROMAGNETISM

THE STORY OF FARADAY, MAXWELL AND FIELD THEORY

Faraday develops a concept of lines of force to explain the action of a magnetic field.

It was the scientist Michael Faraday who first studied in detail the phenomena involving the interaction between electricity and magnetism. At the time of Faraday's experiments, the popular view of physicists was that forces such as gravity and magnetism act instantly between objects, even though some distance separates them. They also thought that this happened through an undetectable 'ether'. This ether was thought to be a substance that existed in the spaces between particles of matter.

Faraday was uncomfortable with this idea of the forces acting instantly at a distance. He was also uneasy with mathematical models that have no visual expression. His intuition was that the magnetic force was transmitted through the ether in some way – that the effect wasn't instant.

The inspiration for Faraday's theory came from observations of the way iron filings arrange around a magnet. They appear to follow lines of magnetism leading out from one magnetic pole and back to the other pole. He suggested that the effect of a magnet on a wire carrying a current is the result of 'lines of force'. These lines of force transmit the magnetic field through the ether. Faraday worked throughout the rest of his life to devise an experiment to confirm his theory of electromagnetic fields but without success.

Maxwell picks up on Faraday's ideas and develops an analogy between magnetic field and spinning vortices.

James Clerk Maxwell was successful in developing a theory of electromagnetism which enabled testable predictions to be made. Inspired by Faraday's lines of force, he developed a model that unified magnetic and electrical forces.

Maxwell's idea was to draw on an analogy between the ether and a moving fluid. He described the ether as having a series of molecular vortices. These rotate around the axis of the magnetic lines of force. Since they would all have to spin in the same direction in a uniform magnetic field, Maxwell imagined that there were tiny idle wheels spinning in the opposite direction between the vortices. He described these idle wheels as particles of electricity and imagined them as free to move between the vortices. (See OHT A2.3 and teachers' sheet A2.4.)

Continued

Maxwell predicts from his analogy that electromagnetism would be propagated through the ether at a finite rate.

Now Maxwell could think about how the magnetic 'vortices' and the electrical 'particles' could interact. By considering the interaction between the vortices and the electrical particles, he was able to show how a magnetic field might induce a current.

It was never Maxwell's intention to suggest that the ether was physically composed of an array of whirling vortices and particles. His intention was to create an analogy to help him develop his understanding of electricity and magnetism.

Maxwell uses his analogy and some 'borrowed' mathematics to develop a series of equations that enable him to predict the speed of this propagation.

By borrowing maths from the field of hydrodynamics, Maxwell was able to develop a series of equations based on a mathematical model. This enabled him to make a link between electricity and magnetism, this time without referring to his model of the ether. Like Faraday he predicted that electromagnetism would be propagated at a finite speed, but he could also predict the speed of this transmission from his mathematical model. His mathematical model also showed that the electromagnetic vibrations would be in the form of a transverse wave.

Maxwell is struck by the similarity between the predicted speed of his electromagnetism and the speed of light.

The speed of electromagnetic radiation predicted by his model was remarkably similar to the speed of light that had recently been measured. Maxwell suggested that light was in fact an electromagnetic wave. This was a remarkable suggestion to make based on an analogy, but it was a very persuasive idea.

By now Maxwell had left behind his original analogy. In his later work he referred only briefly to his model of vortices.

Maxwell's theory is supported by experimental evidence from other scientists.

Other groups of scientists designed and carried out experiments to test Maxwell's new theory. The results they obtained supported the values predicted by Maxwell's theory.

(The first confirmation of the success of Maxwell's equations came from observations by Herman Helmholtz and Ludwig Boltzmann. This confirmed experimentally the prediction, made by Maxwell from his equations, that the dielectric constant of a material is proportional to the square of its refractive index. Since this is too complex to communicate to students in the context of this activity, the role of testable hypotheses in evaluating analogies is dealt with more thoroughly in activity A3.)

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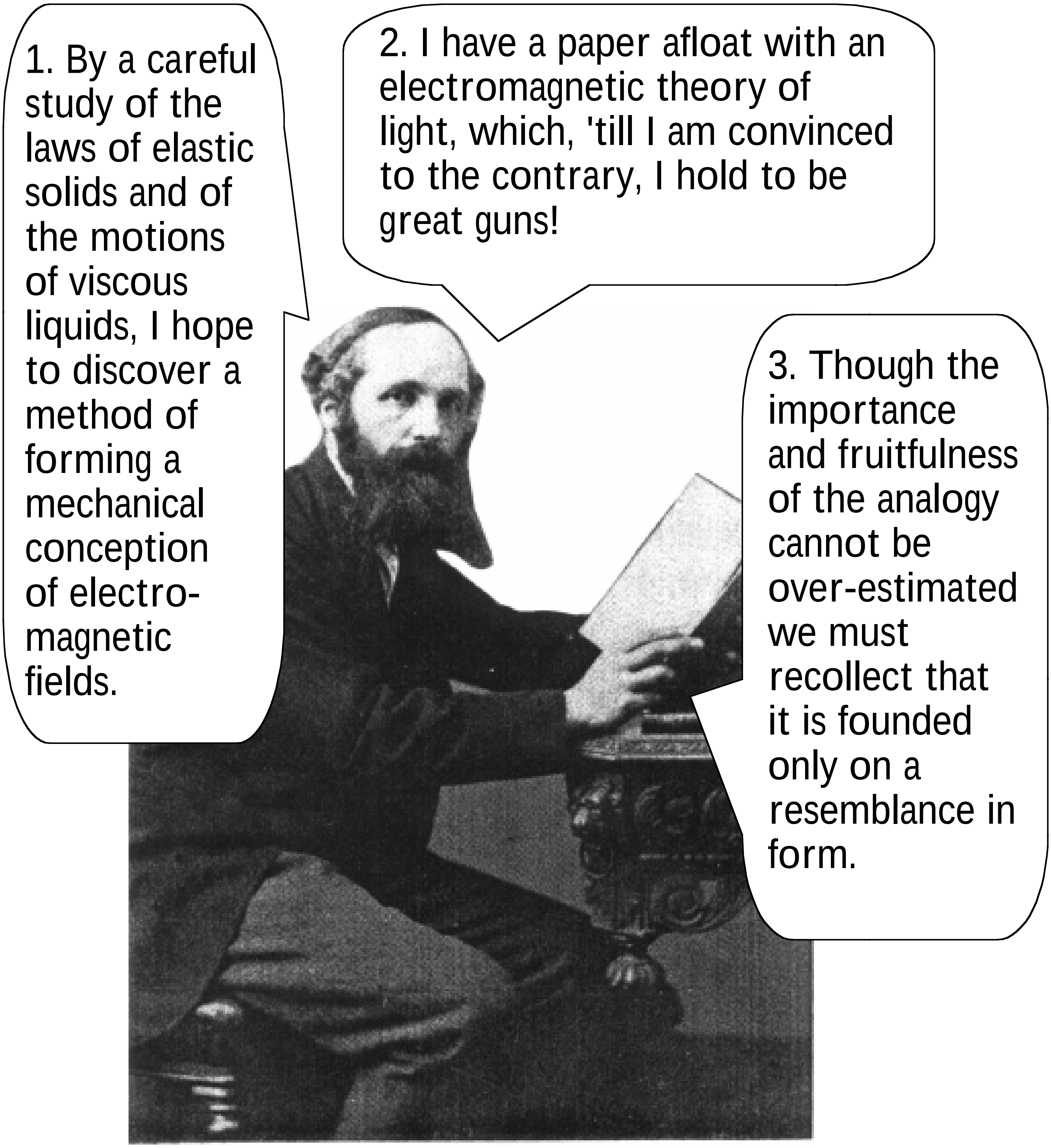

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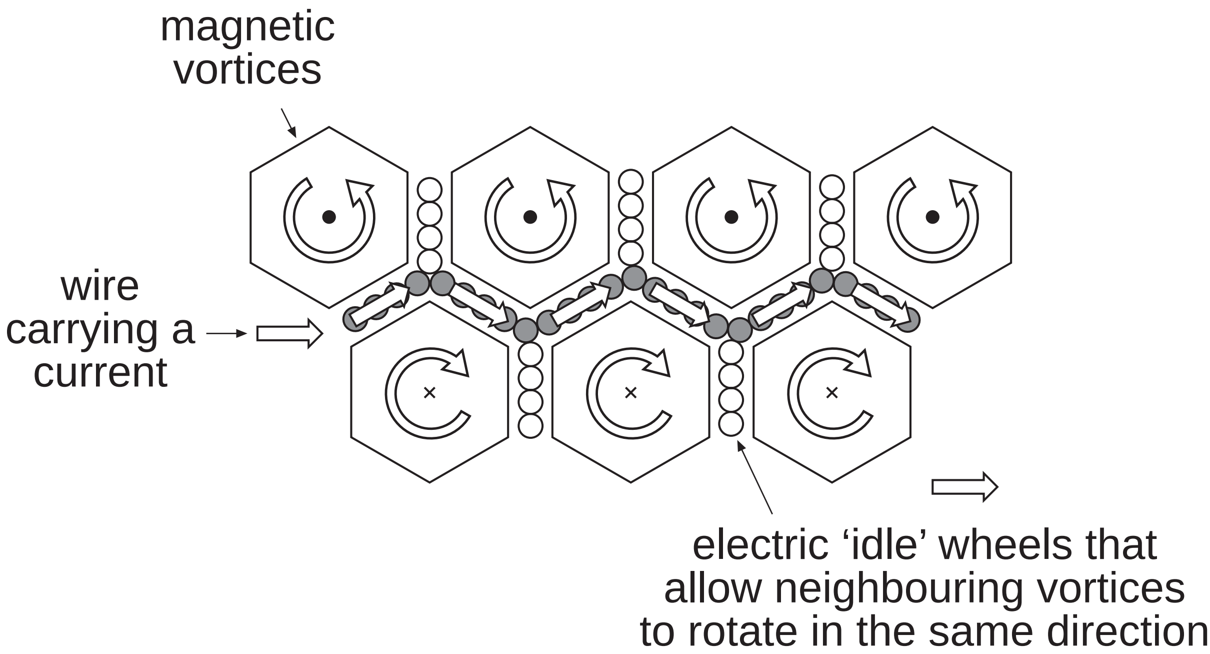
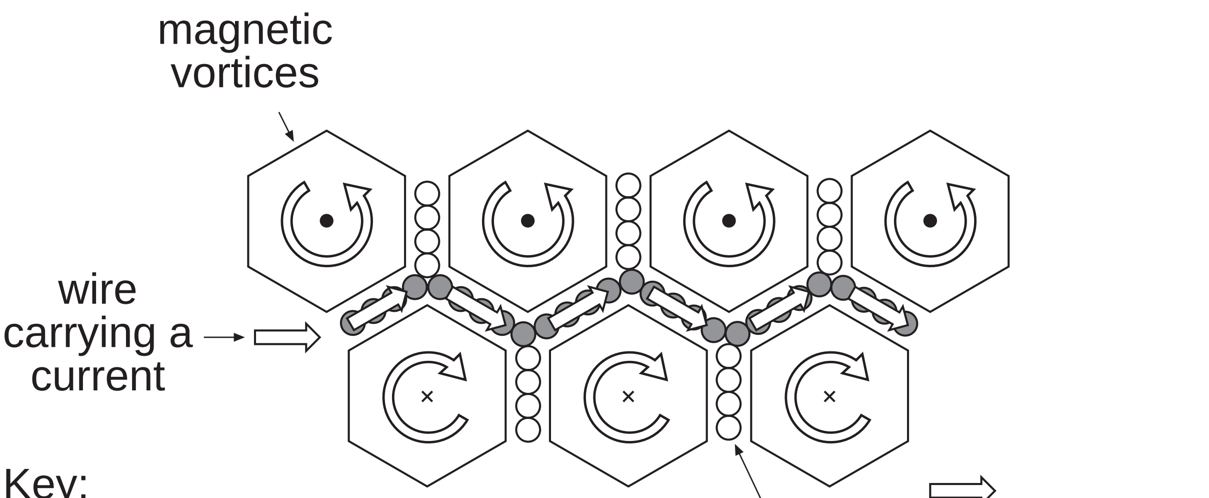
A THEORETICAL MODELS: ELECTROMAGNETISM

Maxwell's model

The magnetic field around a current carrying wire.



Maxwell's model
The magnetic field around a current carrying wire.
Version with Key for teachers' information



Key:

- Vortex
- Direction of vortex
- × Magnetic field out of OHT
- • Magnetic field into OHT
- ○ Electric 'idle' wheels – not changing position
- ● Electric 'idle' wheels –changing position
- ⇨ Direction of movement of electric 'idle' wheels

A THEORETICAL MODELS: ELECTROMAGNETISM

THE STORY OF FARADAY, MAXWELL AND FIELD THEORY

In your pairs discuss the questions below. These relate to the story presented by your teacher. To help you some of the key points of the story are included below.

1 Faraday made an analogy between magnetism and lines of force that transmitted vibrations. In what way was this useful?

2 Maxwell used an analogy between magnetism and spinning vortices in a liquid. In what way was this useful?

3 How were scientists persuaded that Maxwell's analogy was useful?

SUMMARY OF THE MAIN POINTS OF THE STORY

Faraday develops a concept of lines of force to explain the action of a magnetic field

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Faraday was unable to develop an analogy that could provide any testable new understanding of magnetic force. However he did provide a new way of thinking about magnetism that differed from the Newtonian concept of action at a distance.

Maxwell picks up on Faraday's ideas and develops an analogy between magnetic field and spinning vortices

Faraday's work stimulated Maxwell to develop an analogy that gave a possible mechanism to explain how magnetic forces could interact with electricity.

Continued

Maxwell predicts from his analogy that electromagnetism would be propagated through the ether at a finite rate

Maxwell's analogy with fluid vortices enabled him to 'borrow' mathematical equations from fluid hydrodynamics to generate a mathematical model of magnetic field.

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From the mathematical model (Maxwell's field equations) he was able to predict that electricity/magnetism would be propagated through space at a measurable speed (a testable prediction).

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The speed of propagation of electromagnetism predicted by Maxwell's field theory was strikingly similar to the speed of light which had recently been measured. This caused Maxwell to speculate on a link between electromagnetism and light.

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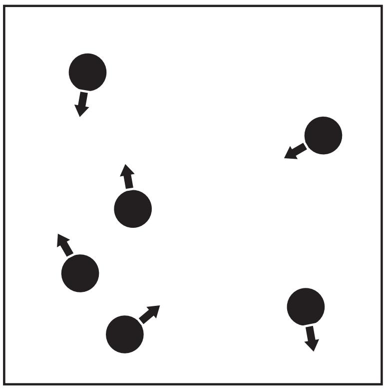
A KINETIC MODEL OF GASES AND TEMPERATURE

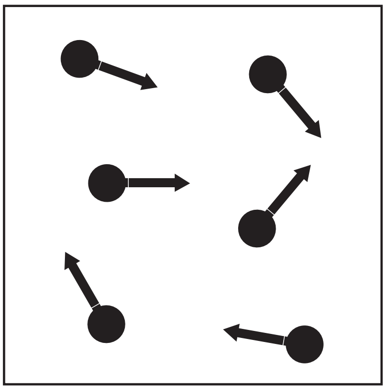
What is temperature? What makes something hot or cold?

The early view of temperature was of something that was simply present and measurable in the world. Temperature had no limits. In principle there was no minimum temperature.

A more recent understanding of temperature involves a theoretical model of matter. The kinetic model of gases describes a gas as consisting of tiny moving particles. The higher the average kinetic energy of the particles the higher the temperature of the gas. Temperature is a measurement of the kinetic energy of the particles. These particles are considered to be like tiny 'billiard balls'.



Low average kinetic energy = low temperature



High average kinetic energy = high temperature

If the kinetic energy of a gas falls the particles must be moving less so the temperature will be lower. At very low temperatures the particles in a gas must be moving very little.

Use this model to answer the questions below.

1 How does the kinetic model of a gas predict that there is a minimum temperature?

2 Are there any other predictions that you could make about the behaviour of gases using this model? How could your predictions be tested?