*Physics > Big idea PSL: Sound, light and waves > Topic PSL6: Wave model of light*

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| **Key concept (age 14-16)** |
| **PSL6.1: Explaining refraction and dispersion** |

**What’s the big idea?**

A big idea in physics is waves because it is the key to explaining how energy can be transferred from one object to another object by radiation, even when the objects are not touching. Waves carry information that can be detected by humans or manufactured detectors. Understanding waves helps us to communicate, explore the universe, and transfer energy to where we want it.

**How does this key concept develop understanding of the big idea?**

This key concept helps to develop the big idea by building on a description of refraction and an understanding of waves, in order to develop understanding of how the wave properties of light explain how it can be refracted at a boundary between transparent media.

****The first conceptual progression starts by checking recall of some general rules for how light rays refract at a boundary between two transparent media. It then supports the development of an understanding of how wavefront diagrams can be used to explain the refraction of water waves, in order to enable understanding of how light refracts at a boundary between transparent media, because it too has wave properties. The second conceptual progression provides opportunity to apply understanding of refraction in order to explain the dispersion of white light and the formation of a visible spectrum of light.

**Using the progression toolkit to support student learning**

Use diagnostic questions to identify quickly where your students are in their conceptual progression. Then decide how to best focus and sequence your teaching. Use further diagnostic questions and response activities to move student understanding forwards.

**Progression toolkit: Explaining refraction**

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| **Learning focus** | Light has wave properties, which allows it to be refracted at a boundary between one transparent medium  and another in which it travels at a different speed. | | | | |
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| **As students’ conceptual understanding progresses they can:** | **C o n c e p t u a l p r o g r e s s I o n** | | | | |
| Use ray diagrams to show how light refracts at a boundary between transparent media.  **P** | Describe rules for the refraction of light at a boundary between transparent media. | Use wavefront diagrams to show how water waves refract. | Use a wave model to explain how light refracts. | Compare the refraction of light at the boundary of different pairs of transparent media.  **B** |
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| **Diagnostic questions** | Refracting rays | Bending bananas | Refracting water waves | Representing light | Liquid refraction |
| Refracting light |
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| **Response**  **activities** | Measuring refraction | | Modelling refraction | | Turning expectations |
|  | Explaining refraction |

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| Key: | | | |
| **P** | Prior understanding from earlier stages of learning | **B** | Bridge to later stages of learning |

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| **Refracting rays** | **Bending bananas** | **Refracting water waves** | **Representing light** | **Refracting light** |
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| Simple multiple choice | Explanation story | Simple multiple choice | Simple multiple choice | Confidence grid |
| **Liquid refraction** | **Measuring refraction** | **Modelling refraction** | **Explaining refraction** | **Turning expectations** |
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| Two-tier multiple choice | Application and practice - practical | Critiquing a representation | Explanation story | Predict, explain; observe, explain (PEOE) |

**Progression toolkit: Explaining dispersion**

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| **Learning focus** | The frequency of a light wave determines the colour of the light. When light refracts at a boundary, the size of the angle by which each different colour changes direction is different. | | | | |
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| **As students’ conceptual understanding progresses they can:** | **C o n c e p t u a l p r o g r e s s I o n** | | | | |
| Use ray diagrams to show how red light refracts as it passes through a prism with three 60o angles.  **P** | Explain why red light refracts in the way it does through a prism with three 60o angles. | Explain why blue light refracts more at a boundary than red light. | Predict how blue light refracts as it passes through a prism with three 60o angles. | Compare different colours of pure light.  **B** |
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| **Diagnostic questions** | Refracting red | Prism rules | Refraction blues | Double refraction | The colour violet |
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| **Response**  **activities** |  | Prism blues | | | Light comparison |
|  | Rainbow light | |
| Making rainbows | |

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| Key: | | | |
| **P** | Prior understanding from earlier stages of learning | **B** | Bridge to later stages of learning |

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| **Refracting red** | **Prism rules** | **Refraction blues** | **Double refraction** | **The colour violet** |
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| Simple multiple choice | Linking ideas | Confidence grid | Two-tier multiple choice | Confidence grid |
| **Prism blues** | **Rainbow light** | **Making rainbows** | **Light comparison** |  |
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| Application and practice | Explanation story | Explanation story | Application and practice |  |

**What’s the science story?**

Light behaves in ways that are similar to mechanical waves (such as water waves, or waves on a spring): it is reflected by surfaces, refracted at boundaries between media, and diffracted at edges. In contrast to mechanical waves and sound, light can travel through a vacuum.

Light can refract (change direction) as it enters or leaves a transparent material if it travels at a different velocity than in the air.

The frequency of a light wave determines the colour of the light. When light refracts at a boundary, the size of the angle by which each different colour changes direction is different.

**Earlier development of understanding (BEST 11-14)**

When applying their understanding to novel situations, students of all ages often revert to earlier misunderstandings. Before moving forward, it is worthwhile using diagnostic questions from earlier topics to check that students do not have any persistent misunderstandings that can form barriers to learning. Time spent consolidating the scientific understanding of earlier key concepts before moving forward can accelerate progression later.

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| **Key concept PSL2.1: The ‘passive eye’ model of vision**  **Learning focus:** Objects are seen when light reflects off them into our eyes.  This key concept:   * Consolidates the understanding that light can enter an eye through a hole that is its pupil. * Develops the understanding that luminous objects are seen because light from them enters the eye. * Develops this understanding further to understand that non-luminous objects are seen by the light that they scatter. |

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| **Key concept PSL3.1.1: Explaining images made by a pinhole**  **Learning focus:** Only some light rays from each point of an illuminated object can pass through a pinhole, hitting a screen at distinct points to make an inverted image.  This key concept:   * Consolidates the understanding of what a light ray is. * Develops the understanding that a light source emits light rays in multiple directions. * Extends this understanding to explain how an image is formed by a pinhole camera. |

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| **Key concept PSL3.2: Refraction and lenses**  **Learning focus:** All light from each point of an object that passes through a converging lens is bent (refracted) to a corresponding point in a sharp image.  This key concept:   * Consolidates understanding that light can change direction (refract) when it passes across a boundary between transparent media. * Develops this understanding to explain why water can appear shallower than it really is. * Extends this understanding to explain how the shape of a lens enables it to focus light to form a sharp image. |

**What does the research say?**

**Light rays**

When students learn about light, rays are typically used to describe refraction and reflection, but to explain these requires using wave theory (Fyttas, Komis and Ravanis, 2013). This is why students have difficulty using ray diagrams to make predictions or to explain observed phenomena (Galili, Bendall and Goldberg, 1993).

Galili and Hazan (2000) found over half of 14- to 16-year-olds (n=166) consider rays to be actual physical things that are the constituents of light, perhaps because it is rarely made explicit in teaching that rays are imaginary lines that show the direction in which light is travelling (Andreou and Raftopoulos, 2011).

**Refraction of light**

A common strategy for teaching students about refraction is to demonstrate examples of refraction phenomena and to explain the observations using ray diagrams that show how light is bent by glass blocks. In this approach students may use a ray box to explore how light travels through a parallel sided glass block to understand the nature of refraction. They change the angles of incidence to establish: a change of direction only occurs at an interface; light travelling perpendicular to the interface is not refracted; and light bends towards the ‘normal’ when entering an optically more dense medium and vice versa (Davenport, 2021).

Measuring angles of incidence and refraction and constructing accurate, labelled ray diagrams is normally carried out at this stage of learning (Department for Education, 2014) and is useful for comparing the refraction of light at the boundary between different pairs of media.

**Explaining refraction**

In a study of (n=213) students age 14-15, who had previously studied refraction, Fyttas et al. (2013) found that most struggled to explain refraction clearly. They found that whilst the students realised the direction of light could change as it moved from one transparent medium into another, they usually did not have a clear understanding of cause and effect. When answering questions about refraction most did not consider a general rule for refraction.

Explanations of refraction should include rays, but also include wavefronts and ideas about changing speed and therefore changing wavelength (Sengoren, 2010).

Fredlund, Airey and Linder (2012) found that even experienced undergraduate students tend to attempt to explain refraction using ray diagrams first, and wave theory only when this approach fails. They postulate that this is because ray diagrams are used more often and students are most familiar with them. This is perhaps similar to the way, described by Bing and Redish (2012), that students often approach calculations – by quoting a remembered equation and (sometimes blindly) trying to fit in the given quantities, rather than by examining the situation to see what approach is most appropriate.

This suggests that it could be helpful to scaffold answering questions about refraction using general rules based on wave theory and the speed of light in different media.

**Wavefront diagrams**

Wavefront diagrams can be used to explain how light is refracted, but students struggle to interpret these. They find it hard to visualise how the wave pattern moves out from the source, or to relate it to a photograph [or to a real wave] (Knight, 2004).

Wosilait et al. (1999) suggest that the process of developing a wave model of light should begin by using the context of water waves. This gives students the opportunity to develop and consolidate their understanding of wavefront diagrams by articulating what happens at different points in space as a wave moves forwards (Knight, 2004). This understanding could then be extended to explain refraction.

**Electromagnetic waves**

This key concept does not explore the understanding that light is an electromagnetic wave, because students’ understanding of electromagnetic waves is dependent on an understanding of the relationship between electric and magnetic forces (AAAS Project 2061, 2001; AAAS Project 2061, 2007). These ideas are addressed in a subsequent BEST topic: *PEM7 Electromagnetism* that precedes the BEST topic: *PSL7 Electromagnetic waves*.

**Guidance notes**

In a vacuum the speed of light (and of all electromagnetic waves) is 3.00 x 108 m/s and does not vary. The speed of light through air is slightly slower than in a vacuum, but also rounds up to 3.00 x 108 m/s. In glass the speed of light is reduced by about a third, to about 2 x 108 m/s.

For light waves, the higher the optical density of a transparent medium, the slower the speed of light through it. However, *the speed of light through a transparent medium is also affected by its frequency*.

All colours of light travel at the same speed in a vacuum, but the frequency of each colour determines how quickly it moves through other transparent media. This is because the way that light photons interact with particles in a medium is dependent on their frequency. This fact, that the speed of light in a transparent medium depends both on the medium *and* on the frequency of the light, distinguishes light waves from mechanical waves and is rarely brought to the notice of students. This lack of awareness can lead to confusion.

The phrase ‘a more dense medium’, in the context of refraction, refers to optical properties of a material: light travels more slowly in a material that is optically more dense.

A *refraction cup* is a useful piece of apparatus for comparing refraction at the boundary between air and different transparent liquids. A *refraction cup* is a protractor shaped container with sides, which can hold a liquid. It can be used to compare liquids that have different refractive indexes and which refract the same incident ray by measurably different angles. A similar experiment does not work using solid blocks made of materials such as glass and acrylic (Perspex), because these materials have refractive indexes that are too similar.

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