*Physics > Big idea PFM: Forces and motion > Topic PFM4: Measuring and calculating motion*

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| **Key concept (age 14-16)** |
| **PFM4.1: Velocity** |

**What’s the big idea?**

A big idea in physics is force, because it is the key to explaining changes in the motion or the shape of an object. The motion of an object can be explained or predicted if you know the sizes and directions of all the forces that act on it. Understanding forces helps us to predict and control the physical world around us.

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

This key concept helps to develop the big idea by developing an understanding of vector quantities, in particular displacement and velocity. It builds on existing understanding of speed and distance, whilst identifying the differences, in order to develop clear and accurate descriptions of motion needed to understand acceleration, velocity-time graphs, and dynamics.

****The conceptual progression starts by using an understanding of speed to calculate the magnitude of velocity. It then develops an understanding of the vector nature of displacement and velocity, and of the differences between average speed and average velocity. Ideas about average and instantaneous velocity are explored, and the notion of a change in velocity, paying due attention to its vector nature, is introduced as preparation for an understanding of acceleration.

**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: Velocity**

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| **Learning focus** | Velocity and displacement are vector quantities. Velocity measures by how much displacement changes in a given time interval. | | | | |
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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** | | | | |
| Explain the difference between distance and displacement, and between speed and velocity.  **P** | Calculate displacement and velocity for one-dimensional motion. | Calculate average velocity and instantaneous velocity for one-dimensional motion. | Identify the difference between speed, instantaneous velocity and average velocity for two-dimensional motion. | Calculate differences in velocity for 1-dimensional and 2-dimensional motion.  **B** |
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| **Diagnostic questions** | Going in the right direction | Displacement and velocity | Average velocity and instantaneous velocity | Spaghetti junction | The difference matters |
| Setting it out | There and back again | Who’s going fastest? | Round the bend | Changing velocity |
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| **Response**  **activities** | How fast are they going? | Calculating average speed and average velocity |  | Velocity and speed in two dimensions | Bumps and orbits |

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

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| **Going in the right direction?** | **Setting it out** | **Displacement and velocity** | **There and back again** | **Average velocity and instantaneous velocity** |
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| Focused CLOZE | Two tier multiple choice | Confidence grid | Simple multiple choice | Simple multiple choice |
| **Who’s going fastest?** | **Spaghetti junction** | **Round the bend** | **The difference matters** | **Changing velocity** |
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| Simple multiple choice | Confidence grid | Confidence grid and simple multiple choice | Simple multiple choice | Simple multiple choice |

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| **How fast are they going?** | **Calculating av. speed & av. velocity** | **Velocity and speed in 2-D** | **Bumps and orbits** |
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| Response, talking heads | Application and practice - calculations | Application and practice - calculations | Application and practice |

**What’s the science story?**

Displacement and velocity are vector quantities and give a direction to the motion of an object. Displacement-time and velocity-time graphs describe the motion of an object moving in one-dimension over time.

A vector has both a magnitude and a direction. Distance and speed are scalar quantities because they have a magnitude, but no direction.

Displacement tells us both how far an object has moved from its starting point, and in what direction. As an object moves, the change in the displacement is the arrow that joins the starting point of the motion to the end point. The displacement arrow has a magnitude and a direction, and its magnitude is most often different to the distance travelled.

Velocity is measured indirectly and calculated:

* Velocity = change of displacement/change of time

Velocity, like speed, is measured in metres per second (m/s), but average velocity is rarely equal to average speed because displacement usually has a different magnitude to the distance travelled.

Instantaneous velocity, the velocity at an instant of time, is the same as the instantaneous speed and its direction is the same as the object at that instant.

The change of velocity of an object is the difference between the instantaneous velocity of the object at two different times. Change of velocity is a vector.

**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 PFM 2.1 Describing speed**  **Learning focus:** Speed is a measure of how fast an object travels: how far it goes in a given time.  This key concept:   * builds on an existing understanding of what speed is; * develops clear and accurate descriptions of motion that are needed to understand motion graphs and dynamic systems; * develops the use of the speed equation to enable a comparison of different speeds and a qualitative understanding of acceleration. |

**What does the research say?**

**Students may conflate words that have related meanings, such as distance and displacement, or speed and velocity , and use a theory-like understanding based on everyday experiences that does not accord with the physicist’s view.**

Students have developed their understanding of motion, both kinematics and dynamics, through a lifetime of experience, and have built up an understanding that has been termed ‘gut dynamics’, or ‘lay dynamics’ (Driver *et al.*, 1994). These ideas are persistent and resistant to change, are systematic, and may be ‘theory-like’; they have been found among different groups of students and at different academic levels (Saltiel and Malgrange, 1980; Lemmer, 2013).

Students have a somewhat undifferentiated understanding of the kinematical terms speed, velocity and acceleration, merging them together into a general idea of ‘motion’, and conflate words that have related meanings, such as distance and displacement, or speed and velocity, not always realising the important differences between them (de Winter and Hardman, 2021). Although these terms are connected, the differences matter, and teachers should use terms carefully, taking care to be precise in their use of language.

**Students may not differentiate clearly between the scalar quantity, speed, and the vector quantity, velocity.** **It is important to establish a good understanding of displacement and velocity as vectors before studying acceleration.**

Students need to be clear about the vector nature of quantities such as displacement, velocity and acceleration; despite being taught about vectors at school, very many students on undergraduate introductory physics courses in the USA have no *useful* knowledge of vectors (Aguirre, 1988; Knight, 1995). Understanding two dimensional motion, such as the orbits of planets and circular motion, requires an understanding of vectors, both mathematically and intuitively, and has been a subject of research for school students (Mihas and Gemousakakis, 2007; Tairab *et al.*, 2020), and at university level, where both undergraduates and expert physicists struggled with some aspects of the vector nature of acceleration when asked to reason qualitatively (Reif and Allen, 1992).

Students’ misunderstandings of vector ideas may be compounded by the different approaches taken in school mathematics and physics teaching: although students may be able to add and subtract column vectors in mathematics, graphical addition and subtraction of vectors of the sort more likely to be encountered in physics proved more problematic (Tairab *et al.*, 2020). It is important, therefore, to establish a good understanding of displacement and velocity as vectors before studying accelerations and forces.

Speed is a scalar quantity and is often defined as:

This can lead to misunderstandings when students are not clear that the time referred to is the *time interval* during which the distance is travelled. This can lead to confusion when students study graphs of motion, and do not differentiate between the slope of a graph, and the division of coordinates at a point (McDermott, Rosenquist and van Zee, 1987), especially as students do not always take time into their thinking about motion appropriately (Trowbridge and McDermott, 1980; Driver *et al.*, 1994). It is better, therefore, to define speed as:

‘’ (the Greek letter delta) is the symbol used by physicists to denote a change in a quantity.

Velocity is a vector quantity, and is sometimes defined as “speed in a given direction”. This is not a good definition. It is true that the magnitude of the instantaneous velocity is equal to the instantaneous speed, but the magnitude of the average velocity is not, in general, equal to the average speed. Velocity is not simply speed with a direction tacked on, and a better (and correct) definition is that velocity is the rate of change of displacement, so that the average velocity is the change in the (vector) displacement divided by the time interval over which the change occurs:

The bold typeface for **s** and **v** is used to show that they are vector quantities.

The idea of an instantaneous velocity should be carefully developed and made clear that it is different to instantaneous speed.

Everyday experience is of moving at speeds or velocities for finite periods of time. Instantaneous speed or instantaneous velocity is the speed or velocity at one moment of time, when the time interval is unimaginably small. For this reason, it is better to use ‘change in time’ in the definitions of these quantities and in calculations, not just ‘time’.

**Students may conflate speed with velocity if definitions are not clear, and if calculations are not carried out carefully. Students should be able to interpret calculations in terms of physical quantities and physical meaning.**

Another obvious source of confusion here is in the symbols that physicists conventionally use for these quantities (de Winter and Hardman, 2021). The same letter is used for distance and displacement, and for speed and velocity, despite one being a scalar and the other a vector, nor even necessarily numerically equal. Here is a case where the use of language matters: if teachers speak of velocity, and calculate a scalar speed by dividing distance by time, making no reference to displacement or to direction, the equivalence of speed and velocity in students’ minds will be reinforced. If new concepts – such as velocity – are introduced by appeal to familiar concepts – such as speed – without being clearly and explicitly defined and differentiated, students are left with the confusing task of discriminating between them and their everyday ideas (Reif and Allen, 1992).

As motion is often studied in one dimension with students aged 14-16, the direction of velocity is sometimes indicated with a + or – sign, but this on its own is not enough unless the direction with respect to which the sign is defined is given. Experts will assume an implicit definition of the direction, but novices may not.

Rearranging formulae is something that students can often find challenging (Boohan, 2016). The difficulty in students being able to use maths in physics may be that they can’t do the maths, but it could also be to do with students struggling with the way symbols in equations are used to make meaning differently in maths and physics (Redish and Kuo, 2015).

Boohan (2016) describes four steps to rearranging formulae involving multiplication and division. First, swap sides if necessary, so the variable to be made the subject of the formula is on the left; multiply or divide both sides by the same variable(s) to leave the subject of the equation on its own; cancel out these variables on the left-hand side. Finally, students should always check that the meaning of the new equation makes sense. Through this process, confident students might take shortcuts, but Boohan recommends that teaching always emphasises an understanding of the principles by carrying out all the steps.

Units in equations should be treated explicitly and with care. It is good practice always to include units in calculations, not least because this may help students to appreciate that symbols refer to physical quantities. Keeping track of units can also help in checking that calculations make sense physically, and prepares the way for dimensional analysis post-16 (Boohan, 2016).

Whilst carrying out calculations is an important part of students’ learning, success in using equations is not the same thing as developing conceptual understanding in mechanics (Kim and Pak, 2002), and misconceptions may remain. To expert physicists, symbols stand for physical quantities, and the results of the mathematical manipulations must be interpreted in terms of their meaning for a given physical system. Experts draw on their experience and (often tacit) knowledge of physical systems in order to make meaning from the mathematics (Carson, 1999; Redish and Kuo, 2015). To novices, the manipulation of the symbols, and the substitution of numbers into formulae may be ends in themselves, devoid of physical meaning. Even after having been taught mechanics, students may lack the ability to reason about the vectors that represent kinematical quantities and forces (Flores, Kanim and Kautz, 2004). This is why asking students to think qualitatively as well as quantitatively, about kinematical quantities is important.

**Guidance notes**

Students need to have a good understanding of speed in order to understand velocity and the differences between speed and velocity.

Understanding the vector nature of velocity is important if students are to understand acceleration and Newton’s laws properly, and it may be worth exploring their understanding of vectors from their work in mathematics. Examination specifications in physics for students aged 14-16, for example, often require them to understand that motion at constant speed in a circle implies acceleration towards the centre of the circle, caused by a centripetal force, as the direction of the velocity is changing. Therefore, they need to understand, at least qualitatively, the direction of the change in velocity in this case, which requires a knowledge of how to subtract vectors.

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