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

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| **Key concept (age 14-16)** |
| **PFM4.2: Acceleration** |

**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 acceleration as a vector quantity. It builds on existing understanding of acceleration as a change in speed, and of displacement and velocity as vector quantities, in order to develop clear and accurate descriptions of motion needed to understand velocity-time graphs, and dynamics.

****The conceptual progression starts by exploring prior understanding of acceleration as a change in speed to establish that acceleration can mean slowing down or changing direction as well as speeding up. It then develops an understanding of the vector nature of acceleration in one dimension, and of how to use acceleration in calculations, including considering changes in direction.

**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: Acceleration**

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| **Learning focus** | Acceleration, like displacement and velocity, is a vector quantity. Acceleration measures by how much velocity 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** | | | | |
| Recall that acceleration in one dimension describes the motion of an object that is speeding up or slowing down.  **P** | Describe acceleration and differentiate between displacement, velocity and acceleration. | Calculate and describe acceleration in one dimension from the equation | Recognise that in one dimension, velocity and acceleration may be in different directions. | Rearrange the equation a=(v-u)/Δt to calculate a velocity or a time. |
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| **Diagnostic questions** | Going faster | Accelerating tortoise | Thinking about acceleration | Down, up, down | New arrangements |
| Accelerating cars | Going in the right direction |
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| **Response**  **activities** | Faster, slower | To the top of the hill and down again | Calculating acceleration | Which way now? | Calculating with steady acceleration |

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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 faster** | **Accelerating tortoise** | **Accelerating cars** | **Thinking about acceleration** | **Down, up, down** |
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| Confidence grid | Simple multiple choice | Confidence grid | Simple multiple choice | Confidence grid |
| **Going in the right direction** | **New arrangements** | **Faster, slower** | **To the top of the hill and down again** | **Calculating acceleration** |
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| Simple multiple choice | Simple multiple choice | Talking heads | Focused CLOZE | Application and practice - calculations |

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| **Which way now?** | **Calculating with steady acceleration** |  |  |  |
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| Application and practice | Application and practice - calculations |  |  |  |
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**What’s the science story?**

If we want to explain why objects move as they do, we first need to be able to describe motion clearly and accurately.

Objects move in a particular direction. We therefore need to work with quantities that have both a magnitude and a direction. These quantities are called vectors. Examples include displacement and velocity. Quantities that have a magnitude only, like distance and speed, are called scalar quantities.

In everyday language, acceleration often means speeding up. Scientists define acceleration as the rate of change of velocity:

Velocity is a vector, and therefore so is acceleration, as it is a vector divided by a scalar. Because velocity is a vector, it can change in magnitude or direction, or both. Therefore, an object accelerates when it speeds up, when it slows down, or when it changes direction. This is a much more general definition than the everyday definition of acceleration. An object may have an acceleration even when the speed remains constant because the direction of the velocity changes.

The equation relating acceleration and the rate of change of velocity is a relationship between vectors, and both the numerical values and the directions must be the same on both sides of the equation. The direction of the acceleration must be the same as the direction of the change in velocity. However, this does not have to be the same as the direction of the velocity itself.

Units in the equation must match, too, and because acceleration tells us by how much the velocity changes in each unit of time, the units of acceleration are those of velocity divided by the unit of time, i.e. (metres/second)/second. This is written as metres/second2 (m/s2).

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

Acceleration is a particularly difficult concept to understand as it is a rate of change of a rate of change. Students may use a position criterion to compare the accelerations of different objects, or may equate acceleration with ‘catching up’ or ‘going faster’ because they think wrongly that if speed increases, acceleration must also be increasing (Trowbridge and McDermott, 1981; Jones, 1983). In a similar way, they may think that if the acceleration of an object is constant, the distance it travels is proportional to the time taken (Ebersbach, Van Dooren and Verschaffel, 2011).

In everyday language, ‘acceleration’ may be taken to mean ‘speeding up’, rather than describing the rate of change of velocity. (An object moving in a circle at a constant speed is accelerating.) This means that misinterpretations about acceleration, due to students' pre-existing knowledge, are very common (Reif and Allen, 1992). The use of correct language (referring to change in *velocity*, not change in *speed*) can help students to understand that to a physicist, acceleration can refer to speeding up, slowing down, or changing direction.

**It is important to establish a good understanding of velocity, change in velocity and acceleration as vectors before studying forces and dynamics.**

Students do not always differentiate between velocity and change in velocity when thinking about acceleration. They may compare the accelerations of objects on the basis of final velocities, and may fail to take into account initial velocities. When they do consider changes in velocity, they may not take into account the time interval over which the change in velocity occurs, or the distance over which the change in velocity occurs (Trowbridge and McDermott, 1981).

Students need to be clear about the vector nature of quantities such as displacement, velocity, change in 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 velocity, change in velocity and acceleration as vectors before studying forces and dynamics.

Acceleration is a vector quantity, defined as the rate of change of velocity:

Often this equation is written with time instead of time taken, but this can lead to confusion. For example, when students study graphs of motion it is common for them to calculate the gradient at a point using the absolute value of time at that point, rather than an interval of time stretching to either side

(McDermott, Rosenquist and van Zee, 1987).

When thinking about the directions of velocity and acceleration, students tend to think that these must be in the same direction as each other, and that if velocity is zero, even if only instantaneously, then so must be acceleration. When given information about acceleration of an object, students find it challenging to reason correctly about its velocity. However, when they are given information about velocity of an object they are better at reasoning about its acceleration. There is an asymmetry in their thinking about the relationship between these quantities (Rosenblatt and Heckler, 2011).

Students may think differently about horizontal and vertical components of accelerated motion because they are used to thinking about a world with gravity (Hast and Howe, 2013). Where acceleration leads to non-linear motion (e.g. motion under gravity), students may think that different components of velocity act one after another, rather than simultaneously (Aguirre, 1988). When thinking about motion where the direction of the velocity changes, but the magnitude remains the same (e.g. circular motion at a constant speed), students may think that the acceleration is zero.

**There is a gap between students’ use of algebraic equations and their understanding of scientific concepts. Students should be able to interpret calculations in terms of physical quantities and physical meaning.**

Students sometimes do not understand the scientists use of the word ‘over’ to mean ‘divided by’, and interpret it as meaning ‘during’. This can lead to their failing to take time into account correctly in calculations (using a moment in time rather than a time interval in the denominator), or when comparing accelerations (Trowbridge and McDermott, 1981). They may use average velocities in calculating accelerations, rather than instantaneous velocities (Marshall and Carrejo, 2008). Correct and careful use of language and symbols can help students to avoid misunderstandings.

Rearranging formulae is something that students can often find challenging (Boohan, 2016). The difficulty in students being able to use mathematics 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). The units of acceleration may be particularly problematic as acceleration is a rate of change of a rate of change, and is measured in metres/second2, a unit that is unfamiliar to students.

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**

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, require them to understand that motion at constant speed in a circle implies acceleration towards the centre of the circle, and so requires 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. Even in one dimension, a change in direction of the velocity requires an understanding of the vector nature of velocity and acceleration in order to reason correctly about physical quantities, and to calculate acceleration correctly.

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