*Biology > Big idea BCL: The cellular basis of life > Topic BCL3: Biochemistry*

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| **Key concept (age 11-14)** |
| **BCL3.2: Cellular respiration** |

**What’s the big idea?**

A big idea in biology is that organisms are made of one or more cells, which need a supply of energy and molecules to carry out life processes.

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

This key concept helps to develop the big idea by exploring the basics of the process of cellular respiration, which all living cells use to make energy available for other life processes.

The conceptual progression starts by checking understanding of respiration as a characteristic process of all living organisms, and how it differs from breathing. It then considers the role of mitochondria and a simple model summarising what aerobic cellular respiration requires and what it synthesises, and develops understanding of the relationship between photosynthesis and cellular respiration and their role in food chains.

**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: Cellular respiration**

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| **Learning focus** | Energy for life processes is provided by a chemical process called cellular respiration inside all living cells, which uses glucose (from food) as fuel. | | | | | | | | | |
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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 all living organisms need energy for life processes, which is provided by cellular respiration.  **P** | Distinguish between cellular respiration and breathing, including the nature of the processes and where they take place. | | Link living animals’ and plants’ need for oxygen and the presence of mitochondria in their cells to aerobic respiration. | | Describe aerobic cellular respiration using a simple model of the process, including what it uses as fuel (glucose plus oxygen) and what it makes as waste products (carbon dioxide and water). | | Apply understanding of photosynthesis and cellular respiration to explain when and why they take place in plants. | | Recognise that biomass is transferred through food chains, and energy for life processes is made available when some of this biomass is used as fuel for cellular respiration. |
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| **Diagnostic questions** | Animal life  and plant life | Respiration | | Busy brain cell | | A simple model of aerobic cellular respiration | | Making gas, Part 2 | | Along the food chain |
| Energy for life | Respiration  and breathing | | How many mitochondria? | | Making gas (Part 1) | | Plant parts | |
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| **Response**  **activities** | Ball of energy | Deep breath | | | | Flames | |  | |  |
|  | | What do cells need? | | Respiration indications | | | |  |

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

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| **Animal life**  **and plant life** | **Energy for life** | **Respiration** | **Respiration**  **and breathing** | **Busy brain cell** |
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| Confidence grid | Simple multiple choice | Confidence grid | Focused cloze | Linking ideas;  two-tier multiple choice |
| **How many mitochondria?** | **A simple model of aerobic cellular respiration** | **Making gas (Part 1)** | **Making gas, Part 2** | **Plant parts** |
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| Two-tier multiple choice | Modelling, linking ideas | Two-tier multiple choice | Two-tier multiple choice | Two-tier multiple choice; linking ideas |
| **Along the food chain** | **Ball of energy** | **Deep breath** | **What do cells need?** | **Flames** |
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| Simple multiple choice;  linking ideas | Challenge to thinking | Concept map, discussion | Discussion, card-sort | Practical PEOE (predict-explain-observe-explain) |
| **Respiration indications** |  |  |  |  |
|  |  |  |  |  |
| Practical PEOE (predict-explain-observe-explain) |  |  |  |  |

**What’s the science story?**

All living organisms require energy for life processes. The energy is provided by a chemical process called cellular respiration that takes place in cells. One type of cellular respiration is aerobic – it uses oxygen and glucose from carbohydrate food as fuel. This process breaks down the glucose, and makes carbon dioxide and water as waste products. It takes place in the cytoplasm and mitochondria inside plant and animal cells. Cellular respiration can be modelled very simply using a summary of the inputs and outputs of the process.

**What does the research say?**

Researchers have suggested that understanding cellular respiration is central to understanding a number of organising concepts in biology; these include explaining why organisms need food and oxygen (as fuel for aerobic respiration to provide energy for life), explaining some of the adaptations of multicellular organisms (e.g. digestion, ventilation, circulation and excretion, which support cellular respiration, by delivering fuel and removing the waste products), and explaining carbon cycling and energy flow through ecosystems. However, many researchers have reported that the topic of cellular respiration is abstract and challenging for students of all ages (e.g. Haslam and Treagust, 1987; Songer and Mintzes, 1994; Driver et al., 1994; Brown and Schwartz, 2009; Ummels et al., 2015; Bergan-Roller et al., 2020).

Researchers have suggested that the high challenge of topics such as cellular respiration and photosynthesis arises, at least in part, because learners must develop understanding of different conceptual aspects of the topic at different levels of abstraction. In the teacher notes for key concept BCL3.1 *Plant nutrition and photosynthesis* it is noted that for photosynthesis these different aspects have been characterised as behavioural, energetic, biochemical, physiological an ecological (Waheed and Lucas, 1992; Marmaroti and Galanopoulou, 2006). We might apply a similar framework to cellular respiration:

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| **Aspect** | **Key ideas** |
| **Behavioural** | respiration as one of the characteristic processes of life, by which all living organisms get energy from food |
| **Energetic** | the transfer of energy between chemical stores as a result of cellular respiration |
| **Biochemical** | the inputs, outputs and chemical reactions of aerobic and anaerobic cellular respiration |
| **Physiological** | cellular respiration takes place inside cells in the cytoplasm and mitochondria (in the case of aerobic respiration in eukaryotes) |
| **Ecological** | biomass is transferred through food chains, and energy is made available for life processes when part of this biomass is respired |

Common misunderstandings have been reported across these aspects for cellular respiration; many are described over the following pages. Marmaroti and Galanopoulou (2006) add a sixth major category of misunderstanding: namely, of the relationship between cellular respiration and photosynthesis.

**Note:** In the learning progression presented on page 2 of this document, the first column relates to the behavioural aspect, the second column relates to the physiological aspect; the third column to the biochemical aspect, the fourth column probes confusion between cellular respiration and photosynthesis in plant cells, and the fifth column relates to the ecological aspect.

In a review of research, Songer and Mintzes (1994) noted that students commonly have fragmented knowledge of cellular respiration, which can result from rote learning, and that many misunderstandings of cellular respiration persist up to undergraduate/college age. A narrow focus on one or two of the five aspects described above may encourage rote learning. A more balanced approach to teaching ideas about cellular respiration across the different aspects and levels of abstraction will challenge students, but may help to encourage understanding.

*Cellular respiration as a characteristic process of life*

Students are likely to have learnt at primary school level that respiration is a characteristic process of living organisms, often as one of a list of processes introduced using the mnemonic MRS (C) GREN (movement, respiration, sensitivity, (control), growth, reproduction, excretion, nutrition). It has been suggested that this can lead to superficial rote learning (Brumby, 1982); for example, recalling that one of the Rs stands for the word “respiration” is unhelpful for conceptual development without the understanding that this refers to the process by which living organisms use food as fuel to provide energy for other life processes.

A study of children aged 10-15 found that the characteristics most commonly used to justify the identification of things as being alive were nutrition, movement, breathing (but not “respiration”), and growth; only 36% of children aged 14-15 used cellular respiration as a criterion for life (Arnold and Simpson, 1979), despite the fact that cellular respiration must take place in all living cells to provide energy for life processes.

It can be difficult to convince children that even familiar living organisms, particularly plants, demonstrate all of these characteristics. There is some evidence that while most children regard animals as alive, only 30% of children aged 6, and 70-80% of children aged 12-15, regarded plants as alive (Stavy and Wax, 1989).

*Confusion between cellular respiration and breathing*

Wierdsma et al. (2016) note that some concepts – such as respiration – have different meanings in different contexts, and that in science lessons students have to learn to recontextualise them. In everyday life, the word ‘respiration’ is often used to refer to breathing; in biology, ‘respiration’ refers to the chemical process that takes place in cells, while ‘breathing’ (or strictly, ventilation) refers to the movement of air into and out of the lungs. Yet another term – ‘gas exchange’ or ‘gaseous exchange’ – refers to the diffusion of molecules of gasses across an exchange surface, such as the lining of the alveoli between the blood and the air in the lungs. Many studies have noted that secondary school students incorrectly think breathing and (cellular) respiration are the same thing (e.g. Haslam and Treagust, 1987; Seymour and Longden, 1991; Songer and Mintzes, 1994; Wierdsma et al., 2016).

An in-depth analysis was conducted by Seymour and Longden (1991) with 13-16 year-olds. 32% of the students incorrectly thought that respiration and breathing are the same thing; and 57% thought that respiration took place (only) in the lungs. Some of the students defined respiration in terms of breathing (e.g. “it’s when we inhale and exhale”), and some thought that some animals, particularly invertebrates such as worms, do not respire because there are no visible breathing movements. When asked how they thought you could tell if an organism was respiring, a typical response was that you would be able to see breathing movements. Many of the students believed that plants do not respire, which may be associated with the perception that they do not visibly breathe in the same way as humans and other animals, but was also linked to the misunderstanding that it’s because they photosynthesise instead – see further discussion of this latter misunderstanding below.

Seymour and Longden (1991) note that in order to fully understand the difference between breathing and respiration, students must accept that respiration is a biochemical process that takes place inside cells. Consistency in referring to ‘cellular respiration’ (rather than just ‘respiration’) while teaching may help to establish a distinction between the processes of cellular respiration and breathing. However, they point out that students who have heard the term ‘respiration’ (e.g. as a characteristic process of living organisms) without further explanation will have formed their own conceptions of what it is; simply telling students that respiration is a chemical cellular process may not change their existing conceptions unless it helps to build connections between what they already know. For example, linking the roles of breathing and the gas exchange system, and of eating and the digestive system, in humans to the provision of substances that are transported by the circulatory system to cells, where they are used for cellular respiration to provide energy for other life processes.

However, linking concepts in this way may be challenging for students, as they often lack experience in establishing meaningful connections between concepts – particularly at different levels of biological organisation, such as cellular explanations for phenomena observed at the organism level (Songer and Mintzes, 1994; Ummels et al., 2015). A study by Anderson and Sheldon (1990) found that even university students in the US did not connect food, oxygen, carbon dioxide and energy in a coherent conception of cellular respiration.

*Confusion between cellular respiration and photosynthesis*

Many researchers have found evidence that school-age students have misunderstandings about the relationship between cellular respiration and photosynthesis (e.g. Haslam and Treagust, 1987; Cañal, 1999; Marmaroti and Galanopoulou, 2006; Özay and Öztas, 2003; Svandova, 2014). It was noted by Songer and Mintzes (1994) that failure to understand the differences and relationship between the two processes is amongst the most common difficulties reported in the research into students’ understanding in this area.

In a review of numerous research studies published over 20 years, Cañal noted the “frequency and extraordinary persistence” of the misunderstanding that photosynthesis is simply ‘inverse respiration’ in students of all ages from primary school to university level, in countries such as Australia, France, Israel, New Zealand, Spain, the UK and the USA (Cañal, 1999). This misunderstanding can lead to incorrect beliefs such as that cellular respiration does not take place at all in plants because they photosynthesise instead (“plants do photosynthesis, animals do respiration”), or that cellular respiration only happens in plants when there is no light for photosynthesis (e.g. during the night) (Haslam and Treagust, 1987; Maeng and Gonczi, 2019).

In a study with 13-year-old students by Marmaroti and Galanopoulou (2006), 20% of the students thought cellular respiration only occurs in plants when photosynthesis is not taking place, and a further 20% thought photosynthesis is one of the ways in which plants respire. In a study with 11-16 year-olds by Svandova (2014), one of the most frequent student misunderstandings was that cellular respiration and photosynthesis are the same process in plants, differing only in name and in which part of the day they take place (photosynthesis during daylight and cellular respiration during the night); 77% of the oldest students held this misunderstanding. Svandova also found that, when questioned, most students would select the answer stating that respiration takes place in all living cells (perhaps learned by rote), but would contradict this in a subsequent question by selecting an answer stating that in plants, cellular respiration only takes place in cells in the leaves – a misunderstanding also observed by Haslam and Treagust (1987).

Cañal’s review of research noted various studies in which it was suggested that the information given by teachers and textbooks “may be one of the most important factors in the formation of” the misunderstanding that photosynthesis is ‘inverse respiration’ (Cañal, 1999). Maeng and Gonczi (2019) asked high school students who believed that plants only do photosynthesis (and do not do cellular respiration) where they got that idea. Most of the students suggested that they had heard it in a previous science lesson; while it seems unlikely that they will have been taught this, their perception of what they had been taught was typified by the quote “when talking about plants we talk about photosynthesis, and when talking about animals we talk about cellular respiration”. This suggests that care needs to be taken when teaching about cellular respiration so that it is not perceived as only taking place in animals, by exploring the idea that it has to take place continually in plant cells as well as in animal cells (as the process that provides energy for life processes).

Although it is true that the chemical inputs and outputs of photosynthesis and cellular respiration are inverses of one another, it may be best to avoid describing the two processes as “opposites” – a description which could reinforce incorrect binary perceptions of the two processes as “light-only” and “dark-only”, or “plant-only” and “animal-only”.

*The ecological aspect*

As noted above, students lack experience in establishing meaningful connections between concepts, particularly across different levels of biological organisation from the sub-cellular to a whole ecosystem (Songer and Mintzes, 1994; Ummels et al., 2015). However, by the end of their secondary school science education they should appreciate the essential roles played by photosynthesis and cellular respiration in the cycling of substances and energy through ecosystems. However, research suggests that by the end of secondary school, most students are not able to describe and explain how carbon and energy move through the different components of ecosystems (Mohan, Chen and Anderson, 2009).

A focus only on the biochemistry of cellular respiration and the role of mitochondria could lead to compartmentalised learning, in which students miss the significance of cellular respiration in the wider ecosystem beyond an individual and its cells (Brown and Schwartz, 2009). It will provide a useful foundation for progression if by age 14 students have developed the understanding that photosynthesis makes food, which is turned into *biomass* that is passed along food chains and used by both producers and consumers as a fuel for cellular respiration to provide energy for life processes; this is consistent with the reality that *matter* (not energy) is what is transferred to an organism when it eats another (Ross, 2013; Needham, 2014).

**Guidance notes**

*Connecting prior understanding*

Learning about cellular respiration will be most effective if it helps students make connections between concepts with which they are already familiar (Seymour and Longden, 1991), for example:

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| **Key concepts with which students should already be familiar:** | **Conceptual development when learning about cellular respiration:** |
| Respiration and nutrition are characteristic processes of all living organisms (*BCL1.1 Living, dead and never been alive*) | Oxygen and glucose (from food) are used for aerobic cellular respiration, which provides energy for other life processes. |
| Animals and plants need a supply of oxygen and food to stay alive (*BCL1.1 Living, dead and never been alive*) |
| Chemical reactants are transformed into products, which are new substances, during chemical reactions (*CCR1.1 Formation of new substance*) | Cellular respiration is a process of chemical change that takes place inside cells. Mitochondria enable a cell to carry out aerobic cellular respiration. |
| All organisms are made up of cells; animal and plant cells contains organelles called mitochondria (*BCL1.2 Cells and cell structures*) |
| The cells that make up animals and plants need to be supplied with oxygen and glucose (from food) to stay live (*BCL2.1: Working together – cells, tissues and organ systems*) | The human gas exchange and digestive systems absorb oxygen and glucose that are then transported by the circulatory system to cells, where they are used to fuel cellular respiration to provide energy for other life processes. |
| The tissues and organs of the human digestive, gas exchange and circulatory systems work together to support the life processes of the cells that make up our bodies (*BCL2.2: Supplying cells – the human circulatory, digestive and gas exchange systems*) |
| Plants and other producers make their own food, in the form of glucose and other carbohydrates (*BCL3.1: Plant nutrition and photosynthesis*) | Biomass (not energy) is transferred through food chains, and energy for life processes is made available when some of this biomass is digested and used as fuel for cellular respiration. |
| The arrows in a food chain diagram represent transfers of biomass from producer to consumer, or from prey to predator (*BOE1.1: Food chains and food webs*) |
| Humans and other consumers cannot make their own food but obtain it by eating plants and other producers, so are dependent upon them (*BOE1.2 Interdependence within ecosystems*) |

*Teaching the biochemistry of cellular respiration: facilitating learning progression with increasingly detailed models*

In many curricula, students are required to learn about respiration at multiple points. Students could get the impression that what they were told “last time” was wrong. To avoid this, it may be helpful to be explicit about the fact that we use *models* of respiration to explain it, and that models containing different amounts of detail – but all describing the same process – are useful at different stages of learning about it. The EEF *Improving Secondary Science* guidance report advocates explicitly teaching pupils about models to help them develop a deeper understanding of scientific concepts (Holman and Yeomans, 2018).

Any model, including a scientific model:

* may be a physical model, or may be made from words, pictures or numbers;
* represents something in the real world but is a simplification – it includes some, but not all, of the features of the thing it represents;
* can show how these features are connected and interact;
* can be used to explain things, answer questions and make predictions.

Different models of the same thing, comprising different amounts of detail, are appropriate – ‘good enough’ – at different stages of learning. For example:

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| To demonstrate (or predict) that a car will roll on its wheels from the top of a slope to the bottom, a simple wooden model of a car is good enough. | To demonstrate that we can change a car’s direction of travel, we need a more detailed model that includes a steering mechanism. | To demonstrate that a car can be driven from the bottom of a slope to the top, we need an even more detailed model that includes a motor. |

Analogously, when using models to explain aerobic cellular respiration:

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| Aerobic  cellular  respiration  energy  water  glucose from carbohydrate food  oxygen  carbon dioxide | water (H2O)  glucose  (C6H12O6)  First stage of aerobic cellular  respiration  carbon  dioxide (CO2)  Remaining stages of aerobic cellular respiration  oxygen (O2)  2 x  three-carbon molecules  (C3H3O3)  36 x ATP  2 x ATP  Cytoplasm  Mitochondria | Oxidative phosphorylation  water (H2O)  glucose  (C6H12O6)  Glycolysis  carbon  dioxide (CO2)  oxygen (O2)  2 x  pyruvate  (C3H3O3)  34 x ATP  2 x ATP  Cytoplasm  Mitochondria  2 x ATP  NADH  +  FADH2  Link reaction  and  Krebs cycle |
| At ages 11-14, a simple model of the inputs and outputs of the process may be good enough to explain what aerobic respiration requires, what the outputs of the process are, and to make predictions about the effects of decreasing or increasing an input.  (Use of a word or symbol equation may reinforce the misunderstanding that aerobic respiration is a single reaction, so has been avoided.) | By age 16, ideas about ATP and a more detailed, two-part model could be introduced. This model would help develop understanding that the initial breakdown of glucose takes place in the cytoplasm, does not require oxygen and generates some ATP, but the remaining stages of aerobic respiration are completed in the mitochondria and require oxygen – generating many more molecules of ATP. | By age 18, an even more detailed model could include more of the biochemistry of the process, including ideas about the Krebs cycle and oxidative phosphorylation, and the roles of intermediates such as pyruvate, NAD and FAD. |

*(Car analogy adapted from Moore, 2016)*

*Cellular respiration and energy*

Teaching about cellular respiration has the potential to create or reinforce misunderstandings about energy. Children at age 11 have many incorrect preconceptions about energy, including that it is a substance (e.g. an ingredient in energy drinks) and that it is used up (rather than conserved) when work is done (e.g. when a person says they have “run out of energy”). In the UK, subject organisations such as the Institute of Physics and others have argued against the use of the ‘nine types’ model of energy, for example through references to energy being converted to and from different types such as “chemical energy” and “light energy”, and argued in favour of a ‘stores and transfers’ model. Articles by Tracy and others in the September 2014 issue of *School Science Review* and the freely downloadable BEST article ‘Teaching Energy’ (Fairhurst, 2018) present a fuller discussion of the issues.

Energy is an important idea when teaching and learning about cellular respiration. The idea that cellular respiration is what makes energy available for other life processes explains why it does – and must – occur continuously in living cells, why animals and plants need food and oxygen to stay alive, and why humans and other animals breathe. We must strive to talk about energy in the context of cellular respiration in such a way as to avoid creating or reinforcing misunderstandings that will be difficult to overcome later.

It has been suggested that teaching should avoid perpetuating the misunderstanding that food *contains* energy which can be ‘released’ by respiration or combustion (Ross, 2013). In the parlance of the stores and transfers model, there is a chemical store of energy associated with the *glucose-oxygen system* created by photosynthesis. Energy from the nuclear store associated with the Sun was transferred into this chemical store when oxygen was pulled away from oxides (water and carbon dioxide) during photosynthesis. During aerobic respiration, glucose and oxygen are combined and the oxides (water and carbon dioxide) are reformed; during th is process energy is transferred to a chemical store associated with ATP. While it may be appropriate to develop this level of understanding, including ideas about energy stores and ATP, at age 14-16, it is perhaps too abstract and challenging for 11-14.

At 11-14, it may be helpful to develop the idea that the glucose in the carbohydrate food made by photosynthesis is a *fuel*. This builds on students’ everyday familiarity with fuels as an energy source, and because a fuel is used up it fits with students’ intuitive assumption that something is used up when work is done (Ross, 2013; Millar, 2014; Needham, 2014; Airey and Lupton, 2020). In the BEST 11-14 resources we have chosen to develop the ideas that aerobic cellular respiration uses glucose from carbohydrate food as fuel, and that breaking down this fuel and combining it with oxygen “provides energy for life processes”. The alternative phrase “makes energy available for life processes” was considered but not adopted because it contains the word “makes” - it is important to avoid the misunderstanding that cellular respiration *makes* or *creates* energy, which would violate the law of conservation of energy (Maeng and Gonczi, 2019). The notions of using fuel and “providing energy for life processes” are used as conceptual placeholders; ideas about energy stores, energy transfers and ATP will be introduced in the BEST 14-16 resources for cellular respiration.

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