# Measuring and fostering biological thinking beyond short-answer questions

*Christian Moore-Anderson*

**Abstract** Short-answer questions are commonly used for assessment in secondary biology education, but their scope limits what can be observed. If a curriculum intends to encourage students to think deeply about how biological systems function, or to integrate physiology, development, evolution and ecology, then longer-answer assessments are required. This article presents two simple frameworks that can be used for assessing biological thinking beyond short-answer questions over educational stages and different contexts, to complement standardised testing. Additionally, by sharing the frameworks with students, it is postulated that they will understand better how to learn in biology.

A curriculum must endeavour to provide students with a learning experience that will allow them to form an interconnected view of a subject domain. The role of assessment, in addition to recognising the learning of students, is to enable a feedback loop between curriculum design and pedagogy that can ensure that pedagogy is adjusted to meet the goals of the curriculum.

In their book, *Leading Modern Learning*, McTighe and Curtis (2019) argue for new methods of assessment and student-performance reporting in education. Using their backward design model, curricular design begins with the desired learning outcomes (which may go beyond success in standardised testing, such as GCSEs) and moves on to the evidence that could be collected to measure them. They summarise this as the I-O-I model: Impact (student outcomes), Outputs (evidence of these outcomes), and Inputs (pedagogy), in that ('backward') order of design. When content, or standards, come first in planning, they argue, an overcrowded curriculum and pedagogy of content coverage often emerge.

Current biology courses, such as GCSEs in England (ages 14–16), generally stipulate content to be learnt, which is then assessed with short-answer questions. Isolating content in short-answer questions can promote a fragmented view of the curriculum, which may lead to beginning curriculum design with the content that must be learnt, rather than the overall desired learning outcomes. Hence, planning for how we want students to think, or see the biological world, may be low in priority. Internal assessment and reporting of students are often skewed towards forming a prediction of the potential GCSE grade students may achieve, or a relative cohort position (student ranking) after sitting an exam. While such systems may report how students are achieving relative to their peers, do they measure everything a biologist would value?

In two of my publications (Moore-Anderson, 2021a; 2021b), I argue for learning outcomes that typically go beyond what is tested in GCSE exams. The first (2021a) provides a framework for teachers for planning and assessing for a student's understanding of biological systems (systems thinking). The second publication (2021b) provides a framework for biology curricular design to integrate the (often dominant) learning of physiological systems with their ecological and evolutionary facets. This framework for integration was intended to foster a student's capability to develop an enquiring mind about the nature they observe around them by focusing thinking on the whole organism through the lenses of evolution, ecology, physiology, and development. I concluded that '*with the use of the framework and the constant practice given to students …* [they] *may come to acquire this line of seeing as a disposition, a biologist's gaze that can facilitate them in reading nature*' (Moore-Anderson, 2021b: 13). Unfortunately, typical biology assessments seen in schools that utilise short-answer questions do not provide the opportunity for students to demonstrate this broader understanding of biological systems, or their capability to integrate biological knowledge.

Crucially, McTighe and Curtis (2019: 81) stress that '*we measure what we value*', and '*what gets measured is what gets done*'. Without inclusion of assessment tools that measure understanding beyond short-answer questions, there will be little incentive to shape pedagogy (for the teacher) and learning (for the student) to foster what Darwin famously referred to as longer trains of thought (Gruber, 1981).

The purpose of this article, hence, is to present adapted versions of my two frameworks (Moore-Anderson, 2021a; 2021b) that can be used for assessment, performance reporting, and helping students understand how to learn within biology. Rubrics have long been a classroom tool that share success criteria with students, yet they are often complex and context specific. The frameworks presented here are simple enough for both ease of comprehension and generalisability across biological contexts and educational stages. They are not intended to replace other assessment methods but to complement them. I shall explain them in turn and if readers are interested, they are encouraged to read the original articles where they can find the full depth of rationale behind their creation.

The first framework (adapted from Moore-Anderson, 2021a) focuses on biological systems understanding and the importance of students developing a connected understanding of the underlying causes of phenomena in systems. The wording has been highly modified to provide a framework that is easily accessible for both students and teachers, and to be generalisable across educational contexts. My second framework (adapted and modified from Moore-Anderson, 2021b) focuses on integrating what can be seen as separate facets of biology: physiology and development, with ecology and evolution. An explanation of the framework and an example are provided for both.

## Framework 1: Assessing and fostering students' biological systems understanding

The first framework (Figure 1) helps students distinguish between two important aspects of their learning:

- The connectedness, which can be considered the difference between rote learning (isolated memorisation) and meaningful learning (connected knowledge).
- The quality of knowledge, which refers to how useful the knowledge is to the student for explaining phenomena. In this framework, it is the difference between knowing an overview of a system's entities and their functions, and knowing the underlying causal processes that explain observations of a system.

While the framework is organised into quadrants, the two axes are continuous.

When understanding is centred around description of what there is and their functions, it is useful, but limited. Knowledge of the underlying causal mechanism is more useful as it allows thinking about how the system works. Nevertheless, it is the conjunction of both mechanistic and connected (not rote) knowledge that empowers students with flexible understanding. By understanding the underlying causal processes, students can rationalise how changes to the system affect its outputs.

Below I explore this idea with a concrete example for ages 14-plus, and what I would expect students to talk about for each quadrant.

### *Example question*

*Tell me about the heart and what would happen if there were a hole in the septum between the ventricles.*

#### Novice knowledge

Novice students might recall the names and position of some components of the heart, especially the most salient, such as the atria and ventricles. They may mention

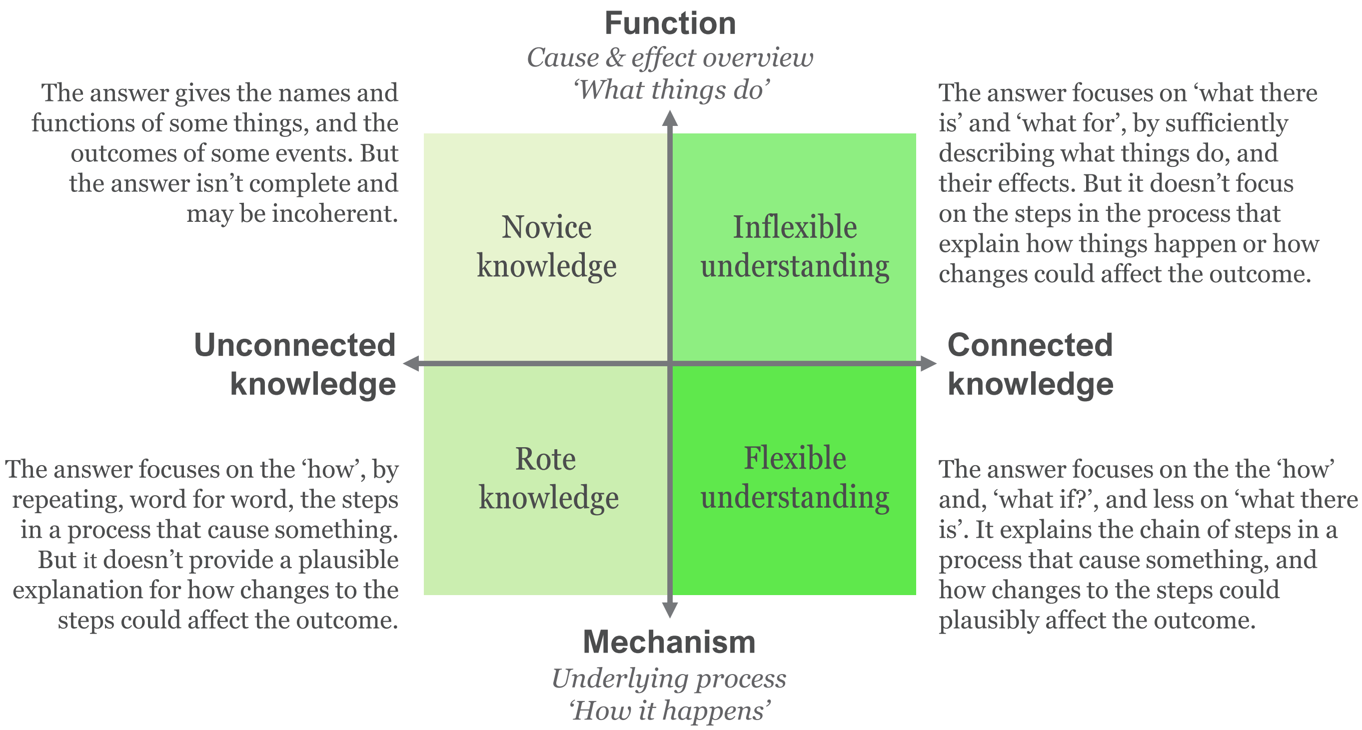


**Figure 1** The assessment framework for biological systems understanding with an explanation of the meaning of the quadrants, adapted from Moore-Anderson (2021a)

some functions, such as '*the ventricles pump blood out of the heart*', but these may not be related to the working of associated structures, or their role in the whole organism. This may give an incomplete feeling to the answer. As these knowledge structures are not very meaningful for the student, typically memorised verbatim, the answer may state names and functions incorrectly interchanged.

### Inflexible understanding

This student's answer is similar to the above (novice knowledge) in that it focuses more on the names and functions of the heart's components. The answer may give the notion of a list, even if it is in the correct order of the cardiac cycle, as it generally lacks reference to the underlying step-by-step causality of a mechanism that links the components. For example, a concise student answer may read: '*The atria pump blood into the ventricles. The ventricles pump blood out of the heart, and the valves prevent backflow. The arteries take blood away from the heart*.' The lack of explicit mechanistic reasoning and the lack of a coherent answer to the 'what if?' question is what differentiates this answer from flexible understanding.

However, the answer does give an overview of the heart and its general function, which gives the student an understanding of its role in the larger organism system. This point is important, as it distinguishes it from novice knowledge. The student connects the heart to the organism and the organismal systems in a coherent manner. I would expect the student to situate the components of the heart correctly, but also mention their role in the organism.

### Rote knowledge

Students who focus on rote knowledge in their answers differ from both novice knowledge, and inflexible understanding in that they are usually coherent, following the cardiac cycle in order and denoting the mechanism by which the heart functions. Mechanistic reasoning includes considering the spatial relationships between components, and how one step in a process causally leads to another (Russ *et al.*, 2008). For example, rather than simply stating that a chamber pumps blood, the answer could refer to how the contraction of muscle leads to an increase in blood pressure that causes blood to flow. Likewise, rather than simply stating that valves prevent backflow, a mechanistic response may refer to how valves are closed by the pressure of the blood, so preventing passage of the blood.

Nevertheless, because such students have memorised most of their answers verbatim, they lack meaning to the student. This is observed in answers that incorrectly interchange components and functions, or steps in the process, and those that don't mention how the process relates to the whole organism. A highly coherent rote knowledge answer can be differentiated from flexible understanding by its lack of explanation of what would happen if there were a hole in the septum, or, if this were attempted, the explanation would be incoherent.

### Flexible understanding

We are able to observe performance of flexible understanding by including a 'what if?' clause in the question. The answer is similar to rote knowledge in that it focuses on mechanism. It is similar to inflexible understanding in that it holds meaning to the student, which is shown in the answer through how the student connects their knowledge. Yet, the answer differs from all other quadrants because it coherently answers the 'what if?' question, showing flexibility in thinking.

In this section of the answer, I would expect students to refer to blood pressure and its causes. They would distinguish between the ability of the left and right ventricles' muscle mass, the blood pressure they cause, and thus the consequential flow of blood from the left ventricle to the right ventricle. I would expect the student to attempt, but not necessarily perfectly deduce, an explanation of the consequences of this on the heart, blood flow through it, and the flow of oxygenated blood in the circulatory system. Of course, these expectations will depend on the educational stage of the students.

An additional feature of answers showing flexible understanding is the focus on what is happening, rather than what there is. Hence, an answer from a student with highly meaningful mechanistic knowledge may also be more abstract, referring more to system processes than component parts. For example, a student may refer to the mammalian heart '*as a pump with four chambers, two of which function to pump blood under high pressure around the body (called the ventricles), and two of which function to receive and fill the ventricles with blood*.'

This flexible understanding is also known as systems thinking, which the US National Research Council (2010: 63) defines as: '*the ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a 'big picture' perspective on work*'. This is important in developing biological thinking as it helps students to draw together what happens across levels of organisation from cell through organ and organism, as well as through lenses of ecological and evolutionary success. The current literature on systems thinking in biology shows that students generally struggle to trace matter across levels of organisation in physiological and ecological systems (Moore-Anderson, 2021a), which suggests that students need explicit guidance, and practice in connecting the phenomena they learn in biology courses.

In my first article (Moore-Anderson, 2021a), I summarise the literature on systems thinking in biology education, which indicates how students without guidance incline towards the learning of entities and their functions, and how they need explicit guidance in focusing on the causal mechanisms of systems. Equally, experts are much more likely to include mechanisms in their explanations compared with novices who focus more on functions. In my personal experience, this function–mechanism distinction, when shared explicitly with students, helps empower them to understand what good learning in biology looks like.

Assessments that focus on short-answer questions are more likely to measure either rote knowledge or inflexible understanding. A major cause of this is probably the limited scope of the question for the elaboration required to exhibit flexible understanding. While short-answer forms of assessments provide ease of standardisation, I recommend including some assessment with biology students that requires extended and open writing, using this framework. A question is required that allows for answers that can be assigned to any of the four quadrants in the framework (novice knowledge, rote knowledge, inflexible understanding and flexible understanding).

A model that has worked in my classroom is to ask the question in this format: '*Tell me about X, and what would happen if Y*'. Initially, students may try to answer this as two separate questions, attempting to write everything they know for the first section. However, with guidance, examples and time or space restrictions, their focus should improve on choosing what they consider to be the most important information to discuss. Other examples that might work are:

- *Tell me about the human digestive system, and what would happen if the stomach had to be removed and the oesophagus was joined to the intestine.*
- *Tell me about population dynamics in this marine food chain, and what may happen if fishing of X was banned.*

### Curricular use of the framework

Following McTighe and Curtis's I-O-I model (2019), it is important that evidence of student performance is recorded for three reasons. Firstly, the qualitative nature of the frameworks allows assessment to focus on the quality of learning rather than numerical grades. Secondly, it informs on the success of the correspondence between the chosen pedagogy and the desired impact on the students. Thirdly, by recording this evidence and using it in the reporting of student progress, it gives it equal status to the other types of data that are obtained (e.g. quizzes, end-of-term exams). This then provides the incentive to shape the curriculum and classroom pedagogy around these goals. Of course, before being able to perform at the level of flexible understanding, students will require practice. Following the backward design stipulated by McTighe and Curtis (2019), it would be beneficial to plan the 'what if?' questions that should be reserved for assessing answers more formally using this framework, and then for those to be used during teaching. Teachers may choose to use the framework for assessment once per term, once per topic or more frequently, depending on the course, the range of student capabilities and time constraints. I also believe it would be beneficial to share the framework as much as possible with students to promote their own metacognition and help develop self-regulated learners.

## Framework 2: Assessing and fostering students' capability for integrated thinking

The second framework (Figure 2) is a modified version of my framework for curricular design (Moore-Anderson, 2021b), the purpose of which was for biology curricular design to integrate more explicitly and frequently the different facets of biology: physiology and development with ecology and evolution. For example, when students study the human heart and the circulatory system in isolation, it can seem like a course on how your body works. By integrating physiology and development with ecology and evolution, students will form a better understanding of patterns in nature. By integrating the encompassing concepts of evolution and the organism in its environment, students are provided with frameworks for finding meaning in the new content they learn. Ultimately, however, a principal goal of the use of the framework is to foster the disposition of seeing like a biologist: '*Indeed, when students leave the classroom, whether in an urban or rural environment, they generally see whole organisms* [such as plants, birds, and insects], *and the questions they pose should pertain to the lives of the organism, how it lives, how it is able to survive, how it reproduces, and why it is the way it is*' (Moore-Anderson, 2021b: 3).

The curriculum should encourage students to look around them, observe nature and reflect upon it. Are students able to actively transfer their knowledge to these observations, such as pondering how physiological systems affect the organism's autecology, or indeed why it evolved? This capability for integrated biology thinking and inquiring is important, but it is not readily observable in the short-answer questions. Thus, as with the previous framework, space must be made for extended student cogitation and writing.

Following the I-O-I model of McTighe and Curtis (2019), the desired impact of the course, in this case, is the capability to think in an integrated manner. The

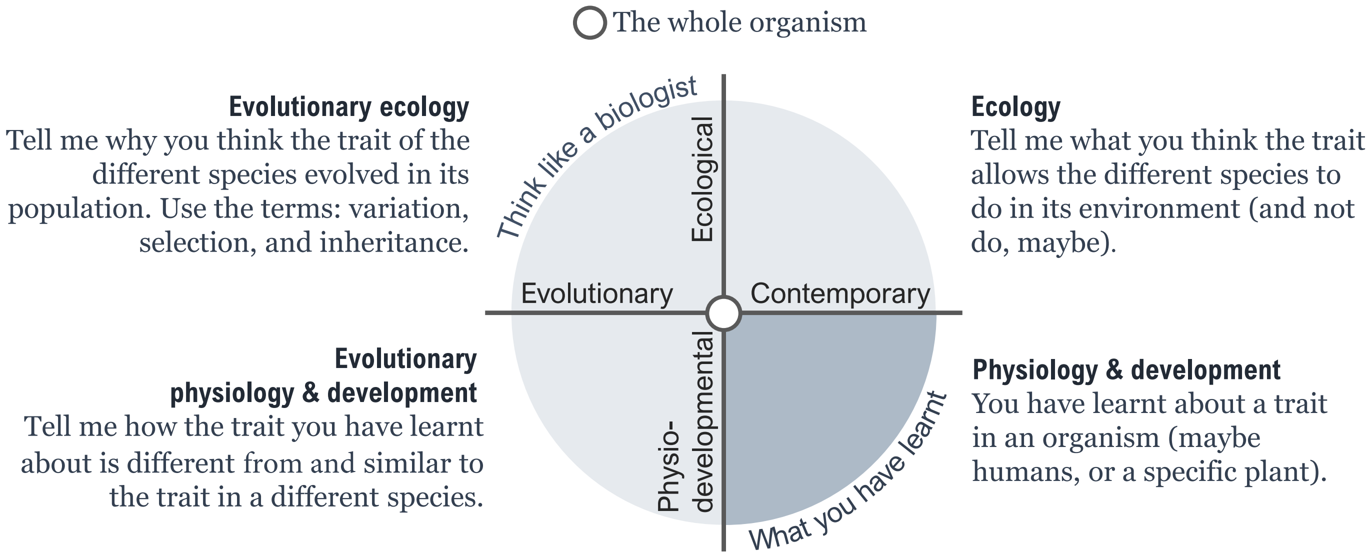


**Figure 2** The assessment framework for integrated understanding with an explanation of the meaning of the quadrants, adapted from Moore-Anderson (2021b)

following step is to consider what evidence of student performance could be obtained to ascertain the effectiveness of the pedagogy for the defined goal. The framework for integration (Moore-Anderson, 2021b) has been modified (Figure 2) to one that can be used by the teacher for assessment and shared with students to foster their understanding of learning in biology.

Unlike the first framework (for biological understanding), which categorises answers into one of the four quadrants, this framework is designed to represent, in simple terms, the capability to integrate the different facets (and thus quadrants) of the whole organism. For assessment, a question is required that provides enough scope for students to show their thinking in each quadrant. I recommend this format:

*You have learnt about X (a trait) in species 1. Using this knowledge:*

- *Compare X (a trait) in species 1 with Y in species 2.*
- *Tell me what you think Y allows species 2 to do in its environment.*
- *Tell me why you think Y may have evolved in species 2's population, using the terms 'variation', 'selection' and 'inheritance'.*

The addition of comparative biology allows us to observe pattern recognition in students across different contexts, and the comparison point should help students to answer the questions about ecology and evolution. It would be necessary for either, or both, an annotated graphic and a short text with a description of the trait in species 2 to be shared with the students.

Below I give a concrete example of a text, a question and the possible answers that would indicate thinking in each quadrant.

## Example text

Bats are small mammals that can fly using wings that are formed from living skin spread between elongated fingers and the body. Bats are generally of two groups: those that are larger and eat fruits, and those that are smaller and hunt flying insects or fly to locate flower nectar. Most bats are very proficient fliers and more agile than most birds but flying is costly in terms of energy. Like all mammals, bats have lungs for gas exchange. However, they can also carry out around 10% of their gas exchange through their wings. While these wings are made of skin, it is different from their other body skin. Their body skin is thicker (around 60 µm), with hair, sweat glands and a fat layer. The wing skin is thin (around 10 µm), has lots of blood vessels, and no hair follicles or fat layer. (Makanya and Mortola, 2007)

## Example question

*You have learnt about gas exchange in human lungs. Using this knowledge:*

- *Compare gas exchange in bat wings with gas exchange in human lungs.*
- *Tell me about what you think gas exchange in wings allows bats to do in their environment.*
- *Tell me why you think gas exchange in wings has evolved in the bat population, using the terms 'variation', 'selection' and 'inheritance'.*

## Expected answers

### Evolutionary physiology

*Tell me how the trait you have learnt about is different from and similar to the trait in a different organism.*

Depending on the educational stage, I would expect students to observe the general similarities found in exchange surfaces: short diffusion distance, highly vascular, and large surface area. For the differences, students could refer to the external and exposed nature of wings compared with lungs and the difference in the method of maintaining a concentration gradient: breathing compared with movement of wings through air.

### Ecology

*Tell me what you think the trait allows the different organism to do in its environment (and not do, maybe)?*

Students could refer to the high energy cost of flying and the need for a rapid supply of oxygen to the bat's muscles, or the necessity for excretion of large quantities of carbon dioxide. The extra oxygen supply could be especially useful in bats that hunt insects, which require fast, agile flying. Students could also explore a trade-off, such as the idea that the highly vascular wings could make temperature homeostasis more difficult if it is cold.

### Evolutionary ecology

*Tell me why you think the trait of the different organism evolved in its population. Use the terms: variation, selection and inheritance.*

An important problem for the students is to identify the appropriate trait to discuss. I would expect students to identify the wings as gas-exchange surfaces, but they could discuss more deeply that there are several components to this, such as vascularity, and the development of a thin wing. I would want students to then express that there would be variation of this trait in the population. Then, I would want students to identify the selection pressure that has acted on this trait for it to be in its current form. In this case I would expect students to refer to flying ability, which directly affects hunting ability, or food location ability, and thus the energy intake of the bats. Finally, I would expect students to discuss how individuals with the selective advantage are more likely to survive, reproduce and transmit their genetic material.

### *Ideas for more questions*

- Comparing the mammalian four-chambered heart with the two-chambered heart of fish.
- Comparing the digestive tracts of mammals with that of a hydra.
- Comparing the gas-exchange systems of mammals and birds.
- Comparing C4 plants with CAM plants
- Comparing a temperate plant's stomatal anatomy with a xerophyte such as *Nerium oleander*, which has stomata in pits with trichomes.

### *Curricular use of the framework*

Like the first framework (for biological systems for understanding), assessment should only come after classroom practice and I recommend planning into the curriculum the examples that can be used in teaching, and those that are appropriate for assessing.

Unlike the first framework, the second one is likely to be used for assessment less frequently as it requires extensive reflection on several different facets of biology and the creation of a good example for comparison. I would recommend its use at least termly, although teachers may find it useful at the end of any physiology or development topic, depending on their goals.

As mentioned above, I recommend recording evidence of our students' capability to integrate their learning after using this framework for assessment. The data should be recorded separately for each student so that teachers can assess the effectiveness of their pedagogy in developing the different capabilities. For example, students may prove to be well versed in looking for patterns in different species, but may not yet be thinking, as a habit, about why such systems have evolved.

## Feedback

There has been increased attention on the value and effectiveness of marking and feedback in recent years (e.g. Education Endowment Foundation, 2021). One issue with book marking is that book work is often used as a sketch pad for external thought processes, or simply to record and correct answers to questions. The generalised use of the frameworks presented in this article allows the teacher to observe, communicate and record something more meaningful. To avoid increasing already-heavy workloads, feedback does not have to be the annotation of the work by the teacher; recording of the data can be done through a quick read, expert judgement, and a best-fit strategy. Equally, feedback to students can be through self-assessment, and whole-class feedback with teacher-selected examples. The latter could be particularly fruitful if students are accustomed to the frameworks and the teacher asks students to compare examples before explaining why they represent the specific quadrants of the frameworks (Siegler, 1995; 2002). It is the communication and discussion that will support students in acquiring a broader and more connected approach to biological thinking.

## Conclusion

With consistent use of the frameworks, not just in assessment but as part of everyday learning, it is more likely that students will develop a better understanding of learning itself. While standardised testing has its place in biology education, this currently favours short-answer questions as evidence of biological knowledge and understanding. Providing feedback on these answers can be difficult, as in many contexts it is restricted to telling the student what they need to learn or relearn. The frameworks presented in this article offer the opportunity for students and teachers to participate in more fruitful conversations about a student's improvement in biological thinking. Ultimately, students may themselves be empowered to generate their own learning and biological understanding, towards goals that exist beyond the answering of short-answer exam questions.

### References


Education Endowment Foundation (2021) *Teacher Feedback to Improve Pupil Learning: Guidance Report*. https://d2tic4wvo1iusb.cloudfront.net/eef-guidance-reports/feedback/Teacher_Feedback_to_Improve_Pupil_Learning.pdf?v=1635355218.

Gruber, H. (1981) *Darwin on Man: A Psychological Study of Scientific Creativity*. 2nd edn. Chicago, IL: University of Chicago Press.

Makanya, A. and Mortola, J. (2007) The structural design of the bat wing web and its possible role in gas exchange. *Journal of Anatomy*, **211**(6), 687–697.

McTighe, J. and Curtis, G. (2019) *Leading Modern Learning: A Blueprint for Vision-Driven Schools.* 2nd edn. Bloomington, IN: Solution Tree Press.

Moore-Anderson, C. (2021a) Designing a curriculum for the networked knowledge facet of systems thinking in secondary biology courses: a pragmatic framework. *Journal of Biological Education*, DOI: 10.1080/00219266.2021.1909641.

Moore-Anderson, C. (2021b) Putting nature back into secondary biology education: a framework for integration. , DOI: 10.1080/00219266.2021.1979628.

National Research Council (2010) *Standards for K–12 Engineering Education?* Washington, DC: National Academies Press.

Russ, R., Scherr, R., Hammer, D. and Mikeska, J. (2008) Recognizing mechanistic reasoning in student scientific inquiry: a framework for discourse analysis developed from philosophy of science. *Science Education*, **92**(3), 499–525.

Siegler, R. (1995) How does change occur: a microgenetic study of number conservation. *Cognitive Psychology*, **28**(3), 225–273.

Siegler, R. (2002) Microgenetic studies of self-explanation. In *Microdevelopment: A Process-Oriented Perspective for Studying Development and Learning*, ed. Granott, N. and Parziale, J. pp. 31–58. Cambridge: Cambridge University Press.


**Christian Moore-Anderson** is a biology teacher at Oak House School, Barcelona, Spain.
Email: cdmoore28@gmail.com Twitter: @CMooreAnderson