FEATURE ARTICLE

How Do Species Change Over Time? Designing a Hybrid Teaching Unit on Five Factors of Evolution

BERRIT K. CZINCZEL, DANIELA FIEDLER, UTE HARMS

Abstract

Evolution is the central concept of biology and key to a comprehensive understanding of any complex biological interaction. It has proven to be a particularly difficult subject for both teachers and students. Hybrid teaching environments have the potential to support students in learning about complex topics and simultaneously enable researchers to collect data on students' learning, giving them the opportunity to diagnose concrete obstacles for learning. Thus, we developed a teaching unit on five factors of evolution that utilizes digital tools in a traditional biology classroom for a hybrid teaching environment. The teaching unit is theoretically founded on biology education research (e.g., about students' misconceptions) and utilizes validated teaching materials. Using various kinds of data from the unit, we expect to be able to gain a deeper understanding of students' learning by analyzing students' individual learning trajectories. This will lay the foundation for enhanced individualized feedback in the future.

Key Words: *evolution education; digital teaching and learning; secondary school; factors of evolution; genetics.*

> *Using methods of learning analytics, we aim to trace students' individual trajectories taking into consideration various data generated through the hybrid teaching unit with a particular focus on concept mapping tasks.*

○ Introduction

Evolution as the overarching explanatory principle of biology provides the conceptual foundation for all biological processes (Dobzhansky, 1973). These processes are crucial for biology education as they are at the core of prevalent challenges threatening humanity's survival, such as multi-resistant pathogens or biodiversity loss. This makes evolution not only the central topic of biology education but the connective thread that should run through the entire biology curriculum to link the various subdisciplines (Brewer & Smith, 2011; German National Academy of Sciences Leopoldina, 2017).

In order to understand evolutionary change, students must understand the processes that cause it. Processes that can change the frequency of alleles in a gene pool over time are known as *factors of evolution*. They encompass mutation, selection (both natural and sexual), genetic drift, and gene flow (Sadava et al., 2019). Mutations in the germ lines, for instance, cause intraspecific variation, which lays the foundation for selection processes. Selection processes cause directed change in populations that can lead to greater fitness in specific habitats or enhance traits desired in mating partners (Storch et al., 2013). Genetic drift triggered by randomly occurring natural events can also cause changes in allele frequencies independent of individuals' fitness. This process is often offset to an extent by the genetic exchange caused by migration of individuals between populations (Storch et al., 2013).

Despite the importance of the topic, evolution has proven to be difficult for students to learn and educators to teach (Nehm, 2019). A full understanding of evolution necessitates the understanding of several key and threshold concepts, which are in themselves challenging (Tibell & Harms, 2017). Students may also hold a variety of misconceptions about evolution and biological phenomena that can hinder learning (Coley & Tanner, 2012). Moreover, they often struggle with the timeframe in which evolution happens as well as the idea that there is no underlying design (see Ayala, 2013). Additionally, the interactions between processes on the cellular, individual, and population levels can complicate matters for students (Nehm, 2019), as does transferring concepts between different biological kingdoms, especially to the plant kingdom (Nehm, 2018). All of these difficulties have to be carefully considered by researchers and educators aiming to successfully develop teaching materials covering evolution.

There are several established theoretical learning progressions on the topic of evolution that were taken into consideration for the

The American Biology Teacher, Vol. 87, No. 2, pp. 78–83, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2025.87.2.78.

development of the unit. For instance, Furtak (2012) developed a learning progression on natural selection, while Zabel and Gropengießer (2011) described different conceptions students might hold while striving toward a scientifically correct one. Moreover, Catley and colleagues (2005) traced evolution learning over the entire K–12 range while Wyner and Doherty (2017) focused on macroevolution. Students' individual paths along these theoretical learning progressions are called learning trajectories. They describe the order in which concepts within a topic are ideally learned. Using methods of learning analytics, we aim to trace students' individual trajectories (see Kubsch et al., 2022) taking into consideration various data generated through the hybrid teaching unit with a particular focus on concept mapping tasks.

Concept mapping is a method that can be used to assess students learning about a topic and reflect conceptual change if recursively applied over time (Kern & Crippen, 2008). Over the course of the unit, we incorporated recursive concept mapping tasks preceded by a method training into the unit to (1) support students' conceptual learning about evolution and (2) trace their individual learning trajectories throughout the unit and analyze them using learning progression analytics (LPA; Kubsch et al., 2022) approaches.

In this article, we describe a hybrid teaching unit for upper-secondary level that aims at supporting students in learning about the factors of evolution as well as collecting data on students' learning in order to provide better formative feedback in the future. The teaching unit is implemented in the digital learning platform Moodle, which is used in a traditional classroom setting. The digital teaching unit (1) contains digital learning tools that help support students in their learning, (2) allows teachers to see students' answers in real time on their own screen, and (3) collects data that can be analyzed by researchers to improve knowledge about students' learning. The data will be analyzed as a part of an interdisciplinary project called ALICE (Analyzing Learning for Individualized Competence development in mathematics and science Education) that aims at examining students' learning trajectories for one central topic in each of the natural sciences and mathematics.

○ The Teaching Unit

Learning Objectives

After completing the unit, the students will be able to explain the processes causing intraspecific variation. They can name intraspecific variation as a prerequisite for evolutionary change and explain differential reproductive success as a cause for species' adaptation to their respective environment. They can also explain adaptations that seem maladapted to the environment as a result of assortative mating. Students will be able to explain genetic drift as a random process that causes undirected evolutionary change and gene flow as the process that can counteract genetic drift. Moreover, they can critically evaluate the consequences of human actions on evolutionary processes.

Conceptual Prerequisites

In order to successfully engage with the teaching unit, students need to be familiar with the following concepts from their lower secondary biology classes: (1) the central dogma of molecular biology, (2) sexual reproduction and inheritance, (3) meiosis, and (4) Darwin's theory of evolution. They may also already have a basic understanding of the following processes: (1) mutation and (2) natural selection.

Digital Learning Environment

In this hybrid teaching unit, students work in a traditional classroom setting while using the digital learning platform Moodle as an online workbook. The unit combines published materials for teaching evolution with digital media (i.e., videos, images, and digital worksheets) and digital tools (i.e., concept mapping tool or a collaborative whiteboard tool; see following chapters).

For the teachers, the digital workbook provides a better overview of students' progress and enables them to catch misconceptions or a lack of understanding early, especially in students who might otherwise not volunteer in group discussions. It also simplifies assessments, as multiple-choice and short-answer quizzes can be evaluated quickly.

Alignment with NGSS

Within the unit, instruction is structured into lesson sets that follow cycles of activities that emulate the process of knowledge generation in science (Figure 1). These inquiry cycles (Kubsch et al., 2022) consist of the activities (1) asking questions, (2) planning and conducting investigations, (3) analyzing and interpreting data, (4) developing and using models, and (5) developing and arguing about explanations. The activities are adapted from the NGSS Science and Engineering Practices (Next Generation Science Standards; NGSS Lead States, 2013) for the use in the digital learning environment and our teaching unit (Kubsch et al., 2022).

Each inquiry cycle is structured around a driving question in a project-based learning approach (Krajcik & Shin, 2014; Kubsch et al., 2022). Project-based learning is designed to help students construct integrated knowledge and develop a deeper understanding of scientific concepts (Krajcik & Shin, 2014), making it a promising method for teaching evolution. In the unit, students work on predefined driving questions while engaging with real-life examples and problems such as habitat fragmentation in forest trees and the emergence of antibiotic-resistant bacteria strains (Krajcik & Shin, 2014). They work collaboratively on the tasks, supported by digital learning technologies embedded in the Moodle platform (Krajcik & Shin, 2014).

Figure 1. Inquiry cycle (Kubsch et al., 2022).

Outline of the Unit

The unit is structured into four lesson sets consisting of nine 90-minute periods in total (Figure 2) and preceded by a 90-minute concept mapping crash course (see next section for more details). The unit includes a variety of tasks designed for individual, partner, and group work using different kinds of materials, all of which are described in detail in the Supplemental Material provided with the online version of this article.

The first lesson set covers recombination and crossing-over contextualized through intraspecific variation in doves (*Columba livia*). Students are confronted with the phenomenon by watching a video of doves in a courtyard and prompted to form hypotheses on the origin of their varying colors and patterns. This is followed by a modeling activity in which students recreate recombination and crossing-over using paper templates (Homburger et al., 2019). At the end of the lesson set, students are prompted to explain the origin of intraspecific variation using the concepts recombination and crossing-over. This lesson is designed to activate prior knowledge on genetics and challenge the misconceptions that traits do not change when they are inherited (Gregory, 2009).

In the second lesson set, students start with the first three factors of evolution: mutation, natural selection, and sexual selection. Students formulate questions about the origin of intraspecific variation in guppies (*Poecilia reticulata*). To answer their questions, they work in groups on the topics of gene, chromosome, and genome mutations (Markl, 2010) and collect results on an interactive whiteboard (Menzel et al., 2022). Afterward, students recreate a simplified version of John Endler's guppy experiment in different environmental settings and interpret the outcome (Staatsinstitut für Schulqualität und Bildungsforschung München, 2016). After this, the initial questions are revisited and students formulate their answers using the concepts of mutation and selection. This lesson set challenges the misconceptions that mutation and selection are not necessarily directional processes and that selection processes lead to the prevalence of just one type of individual (Gregory, 2009). The use of an example in which natural and sexual selection favor different traits supports students in focusing on differential reproductive success rather than just survival (Spier & Dauer, 2023). In addition, this lesson set also emphasizes the random character of evolutionary processes such as mutations (see Tibell & Harms, 2017).

The third lesson set covers the remaining two factors of evolution, genetic drift and gene flow as a counteracting factor. Students work on the topic of habitat fragmentation in forest trees, its origins, and its consequences (Hansen, 2001). Through a simulation with a population of colored sticky notes, students encounter three processes that cause genetic drift (i.e., the founder effect, random deaths, and the bottleneck effect; Lee et al., 2017), and explore the underlying issues and consequences of habitat fragmentation by referring to these processes. In addition, they encounter gene flow as a process counteracting genetic drift by posing the question why genetic drift is not causing an infinite number of individual tree species. Improving on the simplified island model of gene flow, they are led through the process of model improvement toward the stepping stone model of gene flow (Seitz, 1998). This lesson set tackles the preconceived notion that evolutionary change is directional and progressive (Gregory, 2009) and introduces another instance of randomness in evolution (i.e., genetic drift; Tibell & Harms, 2017).

The fourth and last lesson set recontextualizes the factor's mutation and selection in the socioscientific issue which is the emergence of antibiotic-resistant bacteria strains. Students explain mutation and selection as the underlying factors leading to the development of antibiotic-resistant bacteria strains and explore the consequences of human influence on evolutionary processes. They prepare a classroom discussion in a talk show format, highlighting the societal implications from the viewpoint of three groups (i.e., pharmacists, medical experts, and farmers) that are affected by this issue (Sagmeister et al., 2021). This lesson set aims to help students to realize the relevance of evolutionary processes for their

		Lesson set 1 (2 periods)		Lesson set 2 (3 periods)		Lesson set 3 (2 periods)		Lesson set 4 (2 periods)	
Concepts	*Concept Map 1 (unguided)*	Variation Recombination Crossing-over	*Concept Map 2 (guided)*	Variation Mutation Natural Selection Sexual Selection	*Concept Map 3 (guided, reworked from CM 2)*	Genetic drift Gene flow Gene pool Population	*Concept Map 4 (guided, reworked from CM 3)*	Variation Mutation Selection	*Concept Map 5 (guided, reworked from CM 4)*
Example organism *(kingdom)*		*Columba livia* (animal)		*Poecilia reticulata* (animal)		Forest trees (plant)		Bacteria (bacteria)	
Epistemic activities		(1) Asking Questions (2) Developing and using models (3) Developing and arguing about explanations		(1) Asking Questions (2) Planning and conducting investigations (3) Analyzing and interpreting data (4) Developing and arguing about explanations		(1) Asking Questions (2) Developing and using models (3) Planning and conducting investigations (4) Analyzing and interpreting data (5) Developing and arguing about explanations		(1) Developing and arguing about explanations	

Figure 2. Overview of the lesson sets containing relevant concepts, example organisms used, and included activities.

(everyday) lives and enable them to discuss currently relevant issues by introducing the processes that lead to antibiotic resistance (Williams et al., 2018).

Concept Mapping in the Unit

The teaching unit is preceded by a 90-minute concept mapping crash course to prepare the students for the recursive concept mapping tasks in the unit. Concept mapping has been shown to have positive effects on students' conceptual learning in biology (Schmid & Telaro, 1990) and support knowledge integration processes (Schwendimann, 2011). Digital concept mapping is particularly useful as it makes it easier for students to move concepts and connections or erase them and create new ones (Brandstädter et al., 2012).

The concept mapping crash course starts with a theoretical introduction, which aims at explaining the application and benefits of the method (Lenski & Großschedl, 2021). This is followed by an explanatory video in which students learn to use the digital concept mapping tool imbedded in the learning platform (Chiu, 2004). After this, students engage in a first concept mapping task in which they collaboratively create a concept map on a well-known topic (i.e., the school system; Chiu, 2004; Lenski & Großschedl, 2021; Schwendimann & Linn, 2016). This is followed by a consolidation phase, in which students find the mistakes in a faulty concept map and are given the opportunity to ask questions (Lenski & Großschedl, 2021; Schwendimann & Linn, 2016). In the final task, students create their first concept map on evolution based on their prior knowledge (Lenski & Großschedl, 2021).

Throughout the unit, four concept mapping tasks are implemented after each of the lesson sets, meaning students will create five concept maps in total (Figure 2). The first concept mapping task does not provide students with concepts or a detailed task in order to assess students' prior knowledge without interference (see above). The consecutive four tasks follow the same basic structure: They provide (1) a task sheet containing the guiding questions of the respective learning set and metacognitive prompts (Cañas & Novak, 2006; Großschedl & Harms, 2013), (2) a concept mapping cheat sheet recounting the process of creating a concept map (Lenski & Großschedl, 2021), and (3) a list of fourteen central concepts available to the students for use in their maps (Ruiz-Primo & Shavelson, 1996). From the third concept map onward, students are redirected to their previous concept map and instructed to rework it to include newly acquired knowledge and change their maps where necessary (see Kern & Crippen, 2008). This provides them with an opportunity to reflect on their knowledge structure and integrate newly learned concepts (Linn, 2006).

Adaptations

The unit is structured into four lesson sets and the concept mapping crash course with limited interdependence between the parts. The concept mapping crash course and the tasks could be omitted entirely, as could the first lesson set if the students are well acquainted with recombination and crossing-over. The second and third lesson set form the core of the unit and could be taught independently of the rest as a short unit on factors of evolution. The fourth lesson set could be added to any unit on factors of evolution as transfer and consolidation. Alternatively, parts of the lessons that are meant as individual or partner work could be worked out with the entire student group and students could be provided with questions, hypotheses, or partial explanations from the script by the teacher. There are many possibilities to adapt the unit to learners' preexisting knowledge, time constraints, or curricular demands.

○ Enactment

A small pilot study was conducted with upper-secondary-level biology courses (*N* = 76) in the school year 2021/22 in Schleswig-Holstein, Germany. Two of the courses completed either the fourth lesson set or the concept mapping training and one course completed both. The lessons were taught by the first author while the respective biology teachers were present. Afterward, the students were asked to fill out a short questionnaire covering students' perception of the tasks, materials, and lesson structure. The teachers were also asked to provide feedback. The answers were analyzed and used to improve the respective lesson sets.

The main data collection was conducted in the school year 2022/23 with upper-secondary biology courses (*N* = 382) in Schleswig-Holstein, Germany. Interested biology teachers received a one-day professional development workshop from the developers of the unit. In the following weeks, these teachers taught the unit to their upper-secondary-level courses. Each teacher was supported by the developers through visits for pre- and post-test, an online seminar after completing half of the unit, and ongoing support as needed. The teachers also received extensive materials on the unit including lesson plans, sample solutions, and additional information and tips for each lesson phase incorporated into the Moodle platform (see Supplemental Material provided with the online version of this article).

Data collection included data from (1) pre- and post-tests, (2) tasks within the unit, and (3) students' interaction with the unit (process data). In order to assess students' prior knowledge on the topic as well as additional variables such as reading competency or motivation, a pre-test was conducted before the first lesson. Students' knowledge before and after the unit was assessed using the CANS (Conceptual Assessment of Natural Selection; Kalinowski et al., 2016) and two ACORNS items (Assessing Contextual Reasoning about Natural Selection; Nehm et al., 2012). In addition, two ACORNS items were given after each lesson set.

○ Conclusion and Outlook

At present, the teaching unit has received mostly enthusiastic feedback from teachers. Preliminary analysis of pre- and post-test results of the first groups hints at an increase in conceptual knowledge about evolution. The ensuing analysis of the learning trajectories will be based on learning progression analytics approaches (Kubsch et al., 2022). We will analyze students' tests, artifacts from tasks, and, most importantly, their concept maps. Through the use of machine learning methods, we plan to integrate as much of the various data generated within the unit as possible into the analyses.

Upon completion of the enactment, the unit will be revised utilizing feedback received from the participating teachers and students as well as the developers' own experiences during data collection. Depending on the data, focal points for revision may be the structure of the tasks (e.g., some small tasks could be combined for better usability), a wider variety of example species used in the lesson sets, and the overall usability of the unit on the learning platform. By developing this unit and analyzing the generated data using machine learning methods, we will gain deeper insights into students' learning about evolution, which in the future will support students and teachers more individually.

○ Acknowledgments

Our special thanks go to the teachers who enacted our unit with their courses, especially those who granted us the chance to test parts of the units with their course during the piloting phase. We are ever so grateful for your time, effort, and invaluable feedback.

References

Ayala, F. J. (2013). *Die großen Fragen: Evolution*. Springer-Verlag. https://doi.org/10.1007/978-3-642-33006-3

Brandstädter, K., Harms, U., & Großschedl, J. (2012). Assessing system thinking through different concept-mapping practices. *International Journal of Science Education*, *34*(14), 2147–2170. https://doi.org/10.1080/09500693.2012.716549

Brewer, C. A., & Smith, D. (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action*. American Association for Advancement of Science.

Cañas, A. J., & Novak, J. D. (2006). Re-Examining the foundations for effective use of concept maps. *Concept Maps: Theory, Methodology, Technology*. Second International Conference on Concept Mapping, San José, Costa Rica.

Catley, K., Lehrer, R., & Reiser, B. (2005). *Tracing a Prospective Learning Progression for Developing Understanding of Evolution*. National Academy of Sciences.

Chiu, C.-H. (2004). Evaluating system-based strategies for managing conflict in collaborative concept mapping. *Journal of Computer Assisted Learning*, *20*, 124–132. https://doi.org/10.1111/j.1365-2729.2004.00072.x

Coley, J. D., & Tanner, K. D. (2012). Common origins of diverse misconceptions: Cognitive principles and the development of biology thinking. *CBE—Life Sciences Education*, *11*(3), 209–215. https://doi.org/10.1187/cbe.12-06-0074

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *The American Biology Teacher*, *35*(3), 125–129. https://doi.org/10.2307/4444260

Furtak, E. M. (2012). Linking a learning progression for natural selection to teachers' enactment of formative assessment. *Journal of Research in Science Teaching*, *49*(9), 1181–1210. https://doi.org/10.1002/tea.21054

German National Academy of Sciences Leopoldina (Ed.). (2017). *Teaching evolutionary biology at schools and universities*. Deutsche Akademie der Naturforscher Leopoldina e.V. Nationale Akademie der Wissenschaften.

Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach*, *2*, 156–175. https://doi.org/10.1007/s12052-009-0128-1

Großschedl, J., & Harms, U. (2013). Effekte metakognitiver prompts auf den Wissenserwerb beim concept mapping und Notizen Erstellen [Effects of metacognitive prompts on knowledge gain during concept mapping and note taking]. *Zeitschrift Für Didaktik Der Naturwissenschaften*, *19*, 375–395.

Hansen, J.-P. H. (2001). Habitat fragmentation: A threat to arctic biodiverstiy and wilderness. In P. Kankaanpää & H. P. Huntington (Eds.), *Arctic flora and fauna: Status and conservation*. Edita.

Homburger, S. A., Drits-Esser, D., Malone, M., Pompei, K., Breitenbach, K., Perkins, R. D., Anderson, P. C., Barber, N. C., Hawkins, A. J., Katz, S., Kelly, M., Starr, H., Bass, K. M., Roseman, J. E., Hardcastle, J., DeBoer, G., & Stark, L. A. (2019). Development and pilot testing of a three-dimensional, phenomenon-based unit that integrates evolution and heredity. *Evolution: Education and Outreach*, *12*(13), 17. https://doi.org/10.1186/s12052-019-0106-1

Kalinowski, S. T., Leonard, M. J., & Taper, M. L. (2016). Development and validation of the Conceptual Assessment of Natural Selection (CANS). *CBE—Life Sciences Education*, *15*, 1–11. https://doi.org/10.1187/cbe.15-06-0134

Kern, C. L., & Crippen, K. (2008). Mapping for conceptual change. *Science Teacher*, *75*(6), 32–38.

Krajcik, J. S., & Shin, N. (2014). Project-Based learning. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (2nd ed., pp. 275–297). Cambridge University Press.

Kubsch, M., Czinczel, B., Lossjew, J., Wyrwich, T., Bednorz, D., Bernholt, S., Fiedler, D., Strauß, S., Cress, U., Drachsler, H., Neumann, K., & Rummel, N. (2022). Toward learning progression analytics—Developing learning environments for the automated analysis of learning using evidence centered design. *Frontiers in Education*, 7(981910), 1–15. https://doi.org/10.3389/feduc.2022.981910

Lee, T. W., Grogan, K. E., & Liepkalns, J. S. (2017). Making evolution stick: Using sticky notes to teach the mechanisms of evolutionary change. *Evolution: Education and Outreach*, *10*(11), 13. https://doi.org/10.1186/s12052-017-0074-2

Lenski, S., & Großschedl, J. (2021). *Kurze Trainingseinheit zur Einführung von Concept Maps im Unterricht [Short Training Course for Introducing Concept Maps in School]*. https://osf.io/t4q2u/

Linn, M. C. (2006). The knowledge integration perspective on learning and instruction. In *The Cambridge handbook of: The learning sciences*. Cambridge University Press.

Markl, J. (Ed.). (2010). *Markl Biologie Oberstufe [Markl Biology for Upper Secondary Level]*. Klett.

Menzel, L., Gombert, S., Di Mitri, D., & Drachsler, H. (2022). Superpowers in the classroom: Hyperchalk is an online whiteboard for learning analytics data collection. In I. Hilliger, P. J. Muñoz-Merino, T. De Laet, A. Ortega-Arranz, & T. Farrell (Eds.), *Educating for a New Future: Making Sense of Technology-Enhanced Learning Adoption* (Vol. 13450, pp. 463–469). Springer International Publishing. https://doi.org/10.1007/978-3-031-16290-9_37

Nehm, R. H. (2018). Evolution. In K. Kampourakis & M. J. Reiss (Eds.), *Teaching biology in schools: Global issues and trends*. Taylor and Francis: Routledge.

Nehm, R. H. (2019). Biology education research: Building integrative frameworks for teaching and learning about living systems. *Disciplinary and Interdisciplinary Science Education Research*, *1*(15), 1–18. https://doi.org/10.1186/s43031-019-0017-6

Nehm, R. H., Beggrow, E. P., Opfer, J. E., & Ha, M. (2012). Reasoning about natural selection: Diagnosing contextual competency using the ACORNS instrument. *The American Biology Teacher*, *74*(2), 92–98. https://doi.org/10.1525/abt.2012.74.2.6

NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States*. The National Academies Press.

Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. *Journal of Research in Science Teaching*, *33*(6), 569–600. https://doi.org/10.1002/(SICI)1098-2736(199608)33:6<569::AID-TEA1>3.0.CO;2-M

Sadava, D., Hillis, D. M., Heller, H. C., & Hacker, S. D. (2019). *Purves Biologie [Purves' Biology]* (J. Markl, Ed.). Springer-Verlag. https://doi.org/10.1007/978-3-662-58172-8

Sagmeister, K. J., Schinagl, C. W., Kapelari, S., & Vrabl, P. (2021). Students' experiences of working with a Socio-Scientific Issues-Based curriculum unit using Role-Playing to negotiate antibiotic resistance. *Frontiers in Microbiology*, *11*, 14. https://doi.org/10.3389/fmicb.2020.577501

Schmid, R. F., & Telaro, G. (1990). Concept Mapping as an Instructional Strategy for High School Biology. *The Journal of Educational Research*, *84*(2), 78–85. https://doi.org/10.1080/00220671.1990.10885996

Schwendimann, B. A. (2011). *Mapping biological ideas: Concept maps as knowledge integration tools for evolution education*. University of California.

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. *Journal of Research in Science Teaching*, *53*(1), 70–94. https://doi.org/10.1002/tea.21244

Seitz, A. (1998). Genfluß und die genetische Struktur von Populationen [Gene Flow and the Genetic Structure of Populations]. *Laufener Seminarbeiträge*, *98*(2).

Spier, S. K., & Dauer, J. T. (2023). Sexual selection as a tool to improve student reasoning of evolution. *The American Biology Teacher*, *85*(2), 91–96. https://doi.org/10.1525/abt.2023.85.2.91

Staatsinstitut für Schulqualität und Bildungsforschung München (Ed.). (2016, December 8). *Aufgabe: Guppys sind unterschiedlich. [Task: Guppies are Different.]*. https://www.lehrplanplus.bayern.de/sixcms/media.php/72/B8_LB_5_Evolution_Guppy.pdf

Storch, V., Welsch, U., & Wink, M. (2013). *Evolutionsbiologie*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-32836-7

Tibell, L. A. E., & Harms, U. (2017). Biological principles and threshold concepts for understanding natural selection: Implications for developing visualizations as a pedagogic tool. *Science & Education*, *26*(7), 953–973. https://doi.org/10.1007/s11191-017-9935-x

Williams, M. A., Friedrichsen, P. J., Sadler, T. D., & Brown, P. J. B. (2018). Modeling the emergence of antibiotic resistance in bacterial populations. *The American Biology Teacher*, *80*(3), 210–216. https://doi.org/10.1525/abt.2018.80.3.214

Wyner, Y., & Doherty, J. H. (2017). Developing a learning progression for three dimensional learning of the patterns of evolution. *Science Education*, *101*, 787–817. https://doi.org/10.1002/sce.21289

Zabel, J., & Gropengießer, H. (2011). Learning progress in evolution theory: Climbing a ladder or roaming a landscape? *Journal of Biological Education*, *45*(3), 143–149. https://doi.org/10.1080/00219266.2011.586714

BERRIT K. CZINCZEL (czinczel@leibniz-ipn.de) is a Ph.D. student in Biology Education at the Leibniz Institute for Science and Mathematics Education. DANIELA FIEDLER (dfiedler@ind.ku.dk) is a tenure-track assistant professor in the Science Education department at the University of Copenhagen. UTE HARMS (harms@leibniz-ipn.de) is a professor in the Biology Education department at the Leibniz Institute for Science and Mathematics Education.