Using Evolution as a Narrative Framework for Teaching Introductory Biology

J. Christopher Gaiser* and Michael F. Roberts

Department of Biology
Linfield University
McMinnville, Oregon, USA 97128

*Corresponding Author:
J. Christopher Gaiser, Biology Department
Linfield University A468 , 900 SE Baker Street
McMinnville, OR, USA 97128
email: cgaiser@linfield.edu

Abstract: We describe a novel, university-level, introductory biology course that uses evolution as a narrative framework. Our course conveys the content in an introductory biology course by telling the story of the evolution of life on Earth. We begin with early Earth environments in which biological molecules and processes evolved and led to the first RNA-based living entities, then to DNA-based cells, and then to all of the life around us. We use this framework to describe the evolution of the physiological processes important for beginning biology students. This structure contrasts with the widespread "levels of organization" approach in which the order of topics treats the molecular level first, then cells and organisms, and finally evolutionary and ecological processes. This traditional approach is limited in at least two ways: 1) The material taught at each level is not explicitly connected to that at other levels, making the concepts more difficult to assimilate and retain; 2) Evolution is taught as a discrete section of the course, rather than as the integrating principle of life itself. We find that our narrative evolutionary approach enables students to more effectively assimilate, retain, and connect the vast amount of information presented in an introductory biology course.

Keywords: Evolution, pedagogy, introductory biology, narrative, vision and change

Introduction

> "This class was my favorite course of my freshman year . . . I am confident in explaining the material that I have learned to others, and I use this material daily when it comes to applying it to daily decisions."—Linfield Introductory Biology student

Teaching a complex and inherently historical topic like introductory biology requires a thoughtful approach. Narrative is an emerging technique in science education because it uses history to help students understand the complexity of the subject matter. Avraamidou and Osborne's (2009) review of narrative as a teaching technique reveals advantages over the traditional approach to science education. First, there is higher student interest when content is presented as a narrative as compared to a standard biology text (Prins et. al., 2017). Second, a course whose content is organized as an evolutionary narrative provides students with a framework that both structures the content and provides a scaffold upon which to hang each new concept as the course progresses. Third, comprehension is improved for many students, as a narrative structure is much more effective at conveying scientific content than presenting it simply as a set of facts. In addition, there is a significant increase in mid- to long-term retention. The students who read a narrative text do significantly better on a post-test questionnaire given two weeks after the lesson than those students who use a standard text (Prins et. al., 2017).

In seeking to design a better introductory biology course, we were intrigued by these findings. Most of the students in our introductory biology course are not biology majors but are majors in related scientific fields who enroll in our course to fulfill prerequisites for various careers in the allied health sciences. It can be a challenge to sustain these students' attention throughout a year-long biology course that must also serve the more directed needs of Biology majors. In addition, these students often have taken fewer science courses in high school than their biology (or biochemistry) major peers. Therefore, the reported benefits of a narrative approach seemed particularly important for the students we routinely teach in our course.

Evolution as an Organizing Narrative

At the same time, we knew from our own experience that teaching evolutionary principles is often challenging in introductory biology courses. Even those students with an advanced secondary school biology experience have a poor understanding of evolution and natural selection and unless the courses integrate biology as a whole with evolution, students frequently leave these courses with misconceptions: "evolution is goal-oriented," "evolution cannot craft complex structures," and "evolution led inexorably to humans" are examples (Wescott and Cunningham 2005; Gregory 2009). Recent reports have pointed at this inadequate state of evolutionary knowledge and have called for evolution to become a core competency in undergraduate education. The National Academy of Sciences (1998) published a booklet on the teaching of evolution and the Vision and Change Initiative, put forward by the American Association for the Advancement of Science (Brewer and Smith, 2011), provides a widely accepted framework for content in an undergraduate biology curriculum. It emphasizes that students need to understand five core competencies: evolution, energy transformations, information flow, structure and function, and systems. Likewise, a report from the Association of American Medical Colleges and the Howard Hughes Medical Institute (2009) lists eight core competencies required of students entering medical school, one of which is evolutionary biology. Indeed, a 2010 study by Nesse et al. (2010) underscores the importance of evolutionary thinking in medicine and points out that "most introductory biology courses are insufficient to establish competency in evolutionary biology." Most relevant to the course we describe here, this report emphasizes that "evolutionary biology is not just another topic vying for inclusion in the curriculum; it is an essential foundation."

Because these twin issues—the challenges associated with teaching a large, diverse class of students with widely varying preparation, and the specific issues with evolution education—we designed a course that uses the evolution of life on earth as a narrative framework. At least one other author came to the same conclusion. Alles (2001) designed a biology course that uses evolution as a framework, though unlike the course described here, that course was designed for non-science majors and only a portion of it used evolution as an organizing principle. Nevertheless, Alles' course has been successful, even for students challenged by the very idea of evolution, and demonstrates that the evolutionary model can be effective for teaching a diverse class of students. However, the most important way our course differs from other courses is the use of narrative.

Evolution possesses all of the components of a narrative framework. Avraamidou and Osborne (2009) reviewed the use of narrative as a teaching technique and summarized its essential elements as a history with: 1) a specific purpose, 2) a defined chain or sequence of events, 3) a beginning, middle and end, 4) the passage of time, 5) an agent or entity that causes the events, 6) a narrator and 7) a reader. The evolution of life on Earth is the story of a sequence of events that starts with the first cells and continues until today. It is a story that unfolds over time and has a clear agent of change and causality: natural selection. Instructors serve as the narrators of this story for their students (the readers).

> "I took an AP Biology class, and we went in order of the book, rather than when it actually occurred, and Linfield's method helped me understand it so much more." -Linfield Introductory Biology Student

Existing Textbooks and Introductory Biology Courses

Our experience and our many conversations with other biology faculty members over many years of teaching indicate that most faculty use their textbook as the guiding structure for their course. It is therefore worth analyzing the structure of textbooks to obtain an understanding of how faculty, in general terms, organize their courses.

Other educators have already published thoughtful critiques of introductory text structure: Hellman (1965) described texts written between the 1880s and 1930s, illustrating the gradual incorporation of evolutionary thought into these books. Hellman's examples indicate that vitalist processes dominated texts from the 19th century and that both evolution and natural selection were controversial until the 1920s. In all these texts, evolutionary processes are not included in chapters that were not themselves "about" evolution.

Considering now the 21st century, both Hillis (2007) and Nehm et al. (2009) described the content of modern biology texts. Hillis analyzed texts used in the high school system in Texas in 2006. The books covered evolution with factual accuracy but generally ignored natural selection; they were "stuck in the 19th century" (meaning their treatment of evolution did not consider either 20th or 21st century thought); they rarely integrated evolution into the cellular or organismal parts of the texts.

Nehm et al. (2009) state that many introductory biology courses do not use evolution as the "cognitive framework" for organization. They evaluated three texts from 2003 and 2004 and showed that evolutionary terms were used rarely outside the chapters dealing specifically with evolution and diversity. They concluded that this textbook format encourages a lack of integration such that students retain a diverse array of isolated biological facts without grasping that natural selection and evolution are the unifying concepts for these facts. The authors proposed a "desegregation" of evolutionary ideas, suggesting that such ideas be integrated into the entire topical structure of textbooks.

We believe that this integration has not yet occurred on a large scale and is particularly lacking in the available textbooks. These books (and, one presumes, their corresponding course syllabi) are written and organized, with minor variations, in essentially the same way: as a collection of facts loosely held together by "levels of organization." They cover the following topics in this order: atoms, molecules, cells, organisms, populations, communities, etc. This is logical in the sense that these levels progress from simple (most reductive) to complex (most universal and inclusive) in an attempt to show that the foundations of biology rest upon chemistry.

While this is certainly a correct and useful concept, this structure actively masks evolutionary relationships because it does not emphasize the connections between and among organisms, nor does it account for the important elements of time and natural selection. Our most important concern as biologists is that the "levels of organization" approach is a non-evolutionary way to structure content. Our concern as science instructors is that the levels of organization approach suffers because it is a static collection of facts with no unifying theme. There is no concept of time, no sequence of events (although there are plenty of events), and the causal agent (evolution) is relegated to just another chapter, often at the end of the course. For these reasons, a levels-of-organization approach to teaching introductory biology does not promote a deep understanding of evolution specifically nor does it facilitate student learning of introductory biology in general.

In this paper we describe a course that combines these two ideas: 1) a narrative framework and 2) explicit treatment of evolution as a unifying principle. The introductory biology course we describe here discusses the evolution of the first biotic molecules and replicative nucleic acids, then outlines the origin of protocells that used RNA as both a genetic and catalytic molecule. Natural selection then led to the first DNA-based cells (prokaryotes), then Eukaryotes, then multicellular organisms. Within the multicellular Eukaryotes, we describe the physiological, developmental, and ecological principles that illustrate how natural selection has resulted in the organisms we see today. Thus, the narrative of evolution serves both as the framework by which course content is organized and as the context within which introductory biology "makes sense" (Dobzhansky, 1964).

Table 1. Comparison of traditional approach to introductory biology with our approach.

Traditional Approach	Our Course
<u>Semester 1</u>	<u>Semester 1</u>
Chemistry	Environment of the early Earth
Macromolecules of life	Chemistry and energy transformation
Cell Structure	Abiotic synthesis of macromolecules including early RNA
Metabolism	RNA World: Ribozymes and replication
Genetics	Natural selection and origin of cells
DNA➔RNA➔Protein	RNA➔Protein
Evolution	The origin of DNA from RNA
Phylogeny	Origin of cells and metabolic pathways
Bacteria	Structure, diversity, genetics of Bacteria and Archaea
Origin of eukaryotic cells	Origin of eukaryotic cells: Endosymbiosis
	Eukaryotic genetics: meiosis
<u>Semester 2</u>	<u>Semester 2</u>
Plant Biology	Phylogenetics: Definition of eukaryotic clades
Fungal Biology	Origin of multicellularity
Animal biology	Biology and diversity of plants
Ecology	Biology and diversity of unicellular clades
	Biology and diversity of fungi and animals

> "The course progression…was much easier to follow. It's pretty odd for me to not have a complaint or an issue with any aspect of a class, but every morning I found myself excited to get up and go to class to learn about bacteria, cell functions, cell processes, evolution and genetics. I honestly loved this class and how it was taught."—Linfield Introductory Biology student

Our Introductory Biology Course

When we began work on our restructured course, our goal was not to radically change the content of introductory biology courses, but rather to arrange existing content in a way that would allow students to better understand and retain it. The laboratories for this course have not been completely revised, for example. Some laboratories have been reframed with an overt evolutionary context, and we arrange the laboratories to follow the sequence of topics shown in Table 1. This table shows a side-by-side comparison of the order of topics that we previously used in our course, which closely followed our old textbook, Campbell Biology (Urry et. al., 2016) with largely the same course content re-structured around an evolutionary framework.

Comparison of the two approaches illustrates that all of the concepts and topics we covered in our previous ("Traditional") approach are present in our current approach. However, telling the story of life on Earth, the story of how each new group of organisms arose through natural selection from previous groups, requires a substantial rearrangement of that content. This new arrangement means that we currently present several topics and concepts in a more evolutionary reasonable order, and that some previously understated content acquires a more prominent role. Below are a few examples:

- Taking into account the recommendations of recent researchers (Hillis 2007, Nehm and Reilly 2007, Nehm et al. 2009) we introduce concepts such as thermodynamics, ecology and natural selection at the very beginning of the course. This provides the content students need for an in-depth understanding of the origin and evolution of the first cells.
- Our evolutionary framework focuses student attention on how early Earth abiotic conditions, which were very different from today's conditions, enabled the evolution of the first organic molecules and the first catalytic replicator: RNA. This emphasis on how RNA evolved helps our students better understand that the early Earth environment was not a hindrance to life, as students often initially think, but was in fact a prerequisite.
- RNA-templated protein synthesis, or "translation" as it is usually called, almost certainly predated DNA and DNA-templated RNA synthesis (transcription). Because we cover these topics in the order in which they arose—RNA catalysis, RNA-directed catalysis of proteins, DNA, then transcription—students better understand the ability of RNA to act as an enzyme and that DNA is derived from RNA, not the other way around as the traditional method of teaching these topics—DNA, RNA, proteins—would lead anyone to believe.
- The first cells (similar to today's Bacteria) appeared somewhat before 3.5 billion years ago and existed for over one billion years in a unicellular and largely asexual state. It was in these cells that basic metabolic processes arose; thus, we cover metabolic processes and pathways in the context of Bacterial biology.
- We do not present evolution and ecology as discrete chapters, but rather as needed for student understanding. For example, natural selection is discussed in the context of self-replicating molecules, the first cells, and the eventual explosion of prokaryotic life forms, whereas other concepts such as genetic drift and migration are presented within the context of Eukaryotic organismal biology. Certain ecological concepts such as abiotic factors, organism-environment interactions, and competition for resources, are discussed in the context of early Earth environments and the origin of RNA. For example, the nitrogen cycle

is discussed as part of the biology of the prokaryotes—rather than as a cycle that is merely in service to plants and animals as it usually is presented to students. In contrast, biome-level ecological concepts such as biogeography are discussed in the context of Eukaryotic organismal biology.

Strengths of the Approach

In our course student learning is improved in many ways. Below, three such strengths are described.

Evolution of the Central Dogma

It is vital to begin an introductory course with the concepts of early-Earth environments, natural selection, and thermodynamics. The evolutionary framework we use links the evolutionary history of organisms to the ecology and environment at that particular moment in Earth's history and describes processes and organisms in the order in which they likely evolved.

Introductory biology texts report the Miller-Urey experiments (Miller, 1953) demonstrating that abiotic mechanisms could have generated a variety of organic molecules on the early Earth. However, the descriptions of these syntheses do not cover two topics: how these simple organic molecules were involved in the processes that ultimately generated life, and what scientists have learned since Miller-Urey regarding abiotic synthesis of complex organic molecules.

Both of these topics can be explained by reference to experimental studies (Keller et al. 2014) showing how the principles of thermodynamics and mechanisms of inorganic catalysis guided biochemical reactions on early Earth even before cells evolved and produced the molecules that later cells appropriated for their own synthetic pathways. This pre-biotic complexity led to biotic complexity in the form of self-replicating and catalytic RNA, thus providing the basis for both early heredity and protein synthesis.

Our framework also provides a basis for the evolution of the Central Dogma. This concept is usually introduced to students in the form shown in the left-hand column of Table 1. Though this scheme is the basis for protein synthesis in extant organisms, the idea behind it was developed at a time (ca. 1958) before RNA was recognized as the actual catalyst for protein synthesis. Our course takes advantage of the wealth of recent research that shows that RNA likely preceded DNA as the genetic material and that RNA is itself a catalytic molecule. Thus, RNA was the first genetic material and the first enzymatic catalyst (Table 1, "RNA World"). Later, proteins replaced RNA as enzymatic catalysts and DNA replaced RNA as the genetic material in cellular organisms. Students presented with an RNA-first model therefore are not confused as to why cells use RNA for translation, as the catalytic role of RNA has already been established. Though the importance of the early RNA World has been understood by researchers for three decades, it has yet to become a central concept in beginning biology courses; our treatment of RNA replication and catalysis introduces students to these important ideas

Evolution of Metabolic Processes

In our course, metabolism is also taught quite differently from the way this topic is presented in textbooks. Standard depictions of metabolic pathways describe metabolism as if aerobic heterotrophic organisms preceded autotrophic organisms; descriptions thus usually begin with oxidative pathways such as glycolysis, and then move to the tricarboxylic acid cycle and the electron transport system. These processes are usually described as if 1) aerobic mechanisms had always been the basis for metabolism and 2) the pathways evolved for the purpose of glucose oxidation for production of ATP. In addition, textbooks often describe photosynthesis, which uses solar energy to generate complex organic molecules, as if it evolved after the respiratory processes that then break down those same molecules for energy; this is likely a reversal of the actual evolutionary order in which these fundamental metabolic processes evolved.

Synthetic pathways, such as photosynthesis, therefore preceded heterotrophic organisms' oxidative pathways for ATP synthesis (Smith and Morowitz, 2004). Indeed, the pathways generally taught as oxidative, energy-producing reactions may have evolved as reductive pathways in anaerobic Bacteria for the purpose of synthesis of large organic molecules. Only later were these pathways run "backwards" for oxidative purposes (Hügler et al., 2003) in non-photosynthetic organisms – or in photosynthesizers when sunlight was not available. Heterotrophs, whose metabolism is based on oxidative processes, evolved from photosynthetic Bacteria, and allow us to understand the later origin of cellular oxidative electron transport processes (Castresana et al. 1994).

The emphasis of most textbooks on the canonical glycolysis > tricarboxylic acid cycle > electron transport chain appears to result from this order being the metabolic system used by multicellular eukaryotes. Because these aerobic processes generate more ATP than do anaerobic pathways, it is difficult for students to understand why cells would use anything else. Our approach solves this dilemma.

Evolution and Diversity of Eukaryotes

Once we have established the basic biology of eukaryotic cells, we naturally move on to discuss how these cells diversified through time. Most textbooks and courses present this material using the levels of organization approach from little (unicellular) to big (multicellular). Some textbooks even place the unicellular ancestors of the plants and animals in a chapter (often still under the phylogenetically outmoded title "Protists") separate from their multicellular descendants. Thus, not only do most textbooks group all of the "small things" together into one phylogenetically questionable chapter, but this chapter comes before large sections of text on plants and animals. This arrangement prevents students from understanding the evolutionary relationships within the larger plant and animal groups by implying that unicellular eukaryotes are more related to each other than they are to the multicellular species within their own phylogenetic lineages.

Our approach also promotes better student understanding of the evolutionary relationships between Eukaryotic clades. We emphasize that several groups of unicellular Eukaryotes arose after the lineage that would become plants through secondary endosymbiosis. For example, a red algal cell (an early member of the plant lineage) was engulfed by another (presumably heterotrophic) eukaryotic cell (in a manner analogous to the earlier acquisition of mitochondria and chloroplasts). This new organism, a eukaryotic cell harboring another eukaryotic cell, subsequently evolved and eventually diverged into two groups known today as the Stramenopiles and the Alveolates (Medlin et al, 1997).

The evolutionary arc of our course structure makes this entire topic much easier for students to understand. By presenting these groups in the actual evolutionary order in which they arose, rather than as "little things evolved before big things," it is much easier for our students to understand the interesting evolutionary relationships within and between Eukaryotic groups.

> "Humans spend more time focusing on themselves and how things affect them than on all the other critical aspects of life around them." –Linfield Introductory Biology Student

Discussion

We present here a theoretical paper that describes a novel framework and arrangement of the course content in an introductory biology course. We have designed this course based on two ideas: that students are not learning evolutionary theory (well) and that a narrative approach to organizing course content is superior to the much more common "levels of organization" approach. For our course, the evolution of life on Earth serves as the narrative framework that allows us to effectively teach introductory biology.

In fact, the resulting course described here covers much of the same material as traditional courses. We discuss fundamental biological principles and processes (e.g., genetics, metabolism, cell biology, physiology, ecology, etc.) and their contribution to the diversity of organisms on Earth (Table 1). Our course organizes this content quite differently, however, and our experience has been that the way the content in a course is conceptualized and presented has a direct impact on student learning (Paolini, 2015). That is, the organization of the course content by itself can improve student learning.

We have done no formal assessment of our approach, that is, we have not quantitatively compared the learning of students in our course with students enrolled in a different, "traditional," introductory biology course. We do, however, have ample anecdotal evidence that students prefer the narrative framework described here, and that their comprehension and retention of biological content is increased as compared to our previous "levels of organization" approach. These assertions are based on anonymous student essays written in response to a general prompt we have long used in our student evaluation of course instruction:

> Discuss one thing you liked, <u>and</u> one thing you didn't like, about your year in introductory biology. Please let us know why you thought specific things worked, or didn't work, and why you liked, or didn't like, something.

Before we switched to the narrative framework described here, students most commonly focused their responses to this prompt on the usual suspects: the laboratories that we use, examination instruments, instructor-student interactions or the inhumanity of 8:00 AM classes; we never received comments on course organization. In contrast, after instituting our current evolutionary narrative framework, the majority of the feedback (55%) of these essays specifically focused on course organization, and all of these comments (100%) were favorable. We did not ask students to comment on course organization, yet most of them did.

These comments provide an illuminating window into how students view this approach to teaching introductory biology:

> "I enjoyed that the focus was on how these processes … had evolved from simpler processes. For me, the order in which the course was taught worked better than any other course I've taken. It made sense to start from the beginning and follow the train of life as best we know it."

But the comments we have received go beyond merely course organization, and we have placed student comments as illustrative epigraphs at appropriate places in this paper. For example, the second epigraph appears immediately before our review of existing textbooks, because this student pointed out (unprompted by us) how much better they understood the material when it was presented in an evolutionary sequence, rather than in the levels of organization sequence of the textbook that was used in their previously taken Advanced Placement (AP) course.

Another common theme was a self-reported improvement in critical thinking skills and evolutionary understanding, exemplified by comments such as

> "… [the course] let me think more critically about how the things in semester one connect to things in semester two, which is what I like about science, how it all ends up connecting together."

and from another student

> "… we were able to create a hypothesis on how cells evolved from what they were billions of years ago to the cells found on Earth today. Being able to create these kinds of connections encouraged the class to create other connections and think about more than just what our textbook taught us. I feel that this is a useful skill and is something that every college student should be able to do."

In conclusion, our biology faculty have embraced the narrative approach described here and will not return to the more traditional approach. To support faculty at other institutions who may wish to adopt this course organization, the authors of this paper are well underway on a textbook that supports the narrative framework. Most importantly, we have seen greater student engagement, comprehension, and retention. Our students enjoy this course, and that alone promotes their learning.

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