Learning by Listing
Synthesizing Biological Concepts Using Groups of Four
By Nora Demers

Undergraduate STEM students may be overwhelmed by the complex information they are exposed to during their education. Even so, there are a handful of fundamental and powerful concepts that could be identified for each discipline. General education courses introduce students to the material and provide them with the habits of mind that will help them excel. Equally important is to not overwhelm students with details without a mechanism to learn the concepts, retain them, and use them in future classes. Students benefit when instructors chunk the information of those concepts and provide helpful strategies to recall them. Mnemonics are a proven device to accomplish that purpose. This article offers concepts that can be chunked together in biology to support student understanding. Every scientific discipline is built on a collection of basic concepts that are the fundamental facts regarding our world and how it functions (Nosich, 2005). However, students may find the vocabulary describing these concepts unfamiliar and hard to recall. Teaching students how to learn has become an important feature of higher education, with many resources available for faculty, including the book Teach Students How to Learn (McGuire & McGuire, 2015).

“Chunking information” (Simon, 1974) is an especially valuable tool that can help students recall the extensive amount of information that we require in many general science survey courses. Therefore, categorizing the many concepts in introductory courses by group capitalizes on the brain’s capacity to make connections while guarding against cognitive overload. Using these key ideas to scaffold learning for novice college science students should help them excel (van de Pol et al., 2010). I have created a list of concepts with four key terms that expand on and align those concepts with the Vision and Change in Undergraduate Biology Education framework’s (Brownell et al., 2014) five core concepts: evolution; structure and function; information flow, exchange, and storage; pathways and transformation of energy; and systems. I present the list in Table 1 in the order in which the concepts are often encountered in an introductory biology textbook.

I find using the four “E”s as fundamental concepts is a good way to start my introductory biology class. The following four principles are the reason that living organisms exist on Earth:
1. Evolution
2. Electronegativity
3. Emergent properties
4. Enzymes

These four concepts became the foundation on which I built my introductory course. The first fundamental concept is evolution. As Dobzhansky (1973) titled an article, “Nothing in biology makes sense except in the light of evolution.” This concept unites all the biological sciences and has four interacting forces itself:
1. Mutation
2. Natural selection
3. Genetic drift
4. Gene flow

Looking at the role that evolution plays for populations and how mutations of DNA sequences affect natural selection so that the “fittest survive” is a topic with which most students are familiar. Genetic drift, in which offspring in a generation are a random sample of the population reproducing, builds on evolution and helps students focus on the evolution of smaller populations. Another key factor in evolution is gene flow, the migration of genes into or out of a population, resulting in a change in genetic frequency.

The second fundamental concept is electronegativity—that is, the fact that electrons are more attracted to some elements than to others. This
singular concept explains everything about how living organisms evolved. Electronegativity also explains the polarity of water (see the discussion of water’s emergent properties later in this article). The hydrogen bonding that maintains the secondary structures of proteins occurs because of electronegativity that, in turn, allows self-assembly. The fundamental concepts of hydrophobic and hydrophilic interactions derived from electronegativity provide the mechanism for the self-assembly of phospholipid bilayers and viruses and the bonding of elements to form compounds and macromolecules. A complicated but fundamental concept becomes “doable” when you connect it to something as ubiquitous as water.

Emergent properties are the third “E.” As the common saying goes, “The whole is greater than the sum of its parts.” Here, again, is a bundle of four emerging properties of water that can serve as an example:

1. Cohesion and adhesion
2. Floatation of ice
3. Universal solvency
4. High specific heat capacity

The concept of cohesion and adhesion explains how water travels up a plant, and the floating property of ice supports the existence of life on Earth. Electronegativity is the driving force of these properties, resulting in the polarity of water, which also explains water’s role as a universal solvent. Finally, the high specific heat of water and its role in temperature modulation plays a fundamental role in the evolution of living organisms. Once again, students are taken from fundamental to higher levels of thinking by focusing on four properties.

The fourth fundamental concept is enzymes. Enzymes unite all of biology, and their importance and function are emphasized in introductory biology courses. Introductory courses typically focus on the two metabolic pathways of cellular respiration and photosynthesis, each of which is dependent on a series of enzymatic pathways. As the class curriculum moves forward, students’ exploration of the central dogma of gene expression and gene regulation provides an essential opportunity to revisit and refocus on enzymes and their role in molecular and cellular biology. Repeated practice builds a web of connections and scaffolds students in their synthesis of these concepts.

I begin with the four most abundant chemical elements in all living organisms (carbon, hydrogen, nitrogen, and oxygen), but by expanding the list from four to six (with the addition of phosphorus and sulfur), we (and our students) can distinguish nucleic acids (phosphorus) from proteins (sulfur).

The class moves forward with a focus on four ions: sodium-potassium, calcium, iron, and

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**TABLE 1**

A listing of fundamental concepts in the biological sciences, presented in groups of four.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Four topics to cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 <em>E</em>s</td>
<td>electronegativity, emergent properties, enzymes, evolution</td>
</tr>
<tr>
<td>Evolution processes</td>
<td>mutation, natural selection, genetic drift, gene flow</td>
</tr>
<tr>
<td>Emergent properties of water</td>
<td>cohesion and adhesion, floatation of ice, universal solvency, high specific heat capacity</td>
</tr>
<tr>
<td>Most abundant elements</td>
<td>carbon, hydrogen, nitrogen, oxygen (can be expanded to six to include phosphorus and sulfur to aid in distinguishing proteins from nucleic acids)</td>
</tr>
<tr>
<td>Important ions</td>
<td>sodium-potassium, calcium, iron</td>
</tr>
<tr>
<td>Types of bonds</td>
<td>ionic, covalent, hydrogen, van der Waals</td>
</tr>
<tr>
<td>Macromolecule types</td>
<td>nucleic acids, protein, carbohydrates, lipids</td>
</tr>
<tr>
<td>Nucleotides</td>
<td>adenine-thymine (or uracil in RNA), guanine-cytosine</td>
</tr>
<tr>
<td>Nucleic acids</td>
<td>DNA, mRNA, tRNA, rRNA</td>
</tr>
<tr>
<td>Types of amino acids</td>
<td>polar, nonpolar, negatively charged, positively charged</td>
</tr>
<tr>
<td>Levels of protein structure</td>
<td>primary, secondary, tertiary, quaternary</td>
</tr>
</tbody>
</table>

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the body. Students are then ready to recognize that all elements are joined into compounds or larger macromolecules using one of these four bonding types (ionic, covalent, hydrogen, and van der Waals). This recognition supports students’ discovery that all living organisms possess four types of macromolecules.

Building on the “power of four,” course content continues to get more complex without seeming that way to students. The connections to the unseen processes in living organisms may not seem so daunting because a firm foundation has been created by the intentional focus on essential properties and actions. Students view complicated content as “doable” and see the connections in a clearer and more concise way. As they persist with more complicated relationships like those between nucleotides and nucleic acids, the focus remains on of lists of four. Four is a number that students recognize as doable, so they are more persistent in their learning, and their success on assessments supports their continued awareness of their critical mass of biology content.

Listing and interweaving concepts is one of many ways I have found to help students learn biology. The importance of scaffolding is integral to synthesizing knowledge (Hammond & Gibbons, 2005), and the “power of four” supports consistent scaffolding and review of connections. I encourage each of us to consider fundamental concepts for our classes. I encourage each of us to consider fundamental concepts for our classes and to continue the conversations and teaching discoveries we can share with one another.

References
Hammond, J., & Gibbons, P. (2005). What is scaffolding? In A. Burns & H. de Silva Joyce (Eds.), Teacher’s voices 8: Explicitly supporting reading and writing in the classroom (pp. 8–16). National Center for English Language Teaching and Research.

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