From Backwater to Center Stage: Using Electronegativity as a Central Concept for Understanding Chemical Principles in Biology Classes

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Abstract

Understanding basic chemical concepts, including bonding, polar and nonpolar molecules, and hydrogen bonds is difficult for many biology students, who often have minimal chemistry backgrounds. The concept of electronegativity is introduced at the beginning of the chemical foundations part of a biology course as a central integrative concept. By using the electronegativity concept and an associated line graph, students gain an understanding of why ionic and covalent bonds form and which atoms form them, why atoms form polar and nonpolar covalent bonds, and what chemical groups can form hydrogen bonds. Positive student reviews indicate that this is an effective method for introducing chemical principles.

Key Words: *Electronegativity; chemical bonding; polar and hydrophobic; hydrogen bonding; introductory biology courses.*

One of the most challenging parts of introductory high school or college biology courses is helping students understand basic chemical concepts, such as hydrogen bonds, polar and hydrophobic molecules, and chemical bonding. Most secondary school biology courses are taken prior to chemistry courses; at the college level, introductory chemistry is generally either a corequisite or is not required at all for introductory biology. Therefore, students' background in chemistry is frequently weak or even absent. These chemical concepts, however, are critical in understanding the properties of biological macromolecules and cellular function. Students often fail to grasp the chemical foundation or view it as a series of disconnected facts. What is needed is a simple, integrative conceptual framework that helps students understand these chemical principles.

> *Electronegativity can be used effectively as an integrative core concept to assist student understanding of chemical principles.*

Electronegativity can be used effectively as an integrative core concept to assist student understanding of chemical principles. Introduced at the very beginning of the chemical-foundations part of a biology course, the concept of electronegativity can help students understand chemical bonding, polarity, and hydrogen bonding. A simple explanation of the concept along with a simple line graph is strongly emphasized as an integrative framework that "ties it all together."

Electronegativity is often given little coverage and emphasis in introductory biology texts. A survey of several major current and older college introductory-biology texts (Raven & Johnson, 1996; Campbell & Reece, 2005; Brooker et al., 2008; Campbell et al., 2009; Krogh, 2009; Mader, 2009; Starr et al., 2009; Audesirk et al., 2010; Freeman, 2010) shows that electronegativity generally is not strongly emphasized and only gets explained in a few paragraphs. However, introduced as a central concept early in the course, electronegativity can be used to explain vital chemical concepts such as ionic and covalent bonding, polarity, and hydrogen bonding.

○ Introducing Electronegativity & the Line Graph

In order to understand the nature and properties of biological molecules such as proteins and nucleic acids, I review basic chemical concepts that are necessary in understanding fundamental biochemistry at the beginning of the course. Because many students have weak or even no chemistry background, basic concepts of atomic structure, chemical bonding, and chemical reactions are introduced and emphasized to assist student understanding of properties and roles of biological molecules. The introduction of chemical principles provides only the concepts essential for understanding biochemistry and also serves as a review for students with stronger chemical backgrounds.

Students are first introduced to the concept of electron shells, emphasizing that each shell can only hold a specific number of electrons, two for the first, eight each for the second and third. Discussions about electron orbitals are avoided because many students have not yet had college chemistry and the concept of orbitals is unnecessary for the discussion of chemical foundations at the level of an introductory biology course. The importance of the outermost (valence) electron shell is strongly emphasized. I emphasize that ***chemical reactions and chemical bonding involve interactions of the outer or valence electrons.*** Using these fundamental

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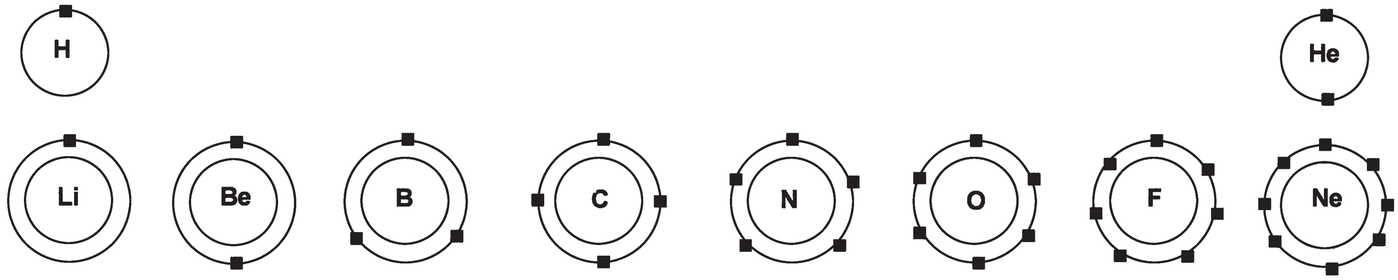

Figure 1. Partial periodic table used in student instruction. Circles represent electron shells, and squares within the outer circle represent the valence electrons.

concepts, a partial periodic table is built. The periodic table is introduced, starting with hydrogen, by emphasizing the number of electrons. Electron shells are shown as circles around the chemical symbol for the element, with dots in the circle representing the valence electrons and circles representing the inner electron shells. Figure 1 shows a representative example of this notation. The elements with filled valence shells are also emphasized and their lack of chemical reactivity is pointed out. The periodic-table diagram is completed to chlorine, and then only a few atoms of strong biological importance such as calcium, sulfur, and phosphorus are shown.

Students then learn that the periodic table originally grouped elements in columns on the basis of chemical properties, not number of valence electrons. At this point, the concept of electronegativity is introduced. Electronegativity is explained as *how **tightly an atom holds on to its valence electrons.*** Additionally, highly electronegative atoms such as oxygen and fluorine ***tend to remove electrons from other atoms.*** The line graph in Figure 2 is introduced, containing the major atoms that are important in biochemistry and a few others to illustrate the underlying principles of chemical bonding.

The importance of the electronegativity concept and the graph are strongly emphasized as vital for understanding chemical bonding and the other principles that are described later, and is referred to again repeatedly as each chemical concept is explained. In class, I repeatedly emphasize "Understand this chart and you will understand the rest of the concepts that follow!"

Several general points about electronegativity are emphasized:

- Atoms with one or two valence electrons, such as sodium and potassium, have low electronegativity and lose their valence electrons easily, whereas atoms with five to seven valence electrons, such as nitrogen, oxygen, and fluorine, are highly electronegative and, additionally, tend to remove electrons from less electronegative atoms.
- Heavier (higher atomic weight) elements with the same number of valence electrons are less electronegative than their lighter counterparts. For instance, phosphorus is much less electronegative than nitrogen, and sulfur is much less electronegative than oxygen.
- Oxygen is extremely electronegative, second only to fluorine, giving it a strong tendency to remove electrons from other molecules. Removal of electrons from other atoms is the process of oxidation, and oxidation reactions of various types are the major energetic reactions in energy-producing metabolic processes.

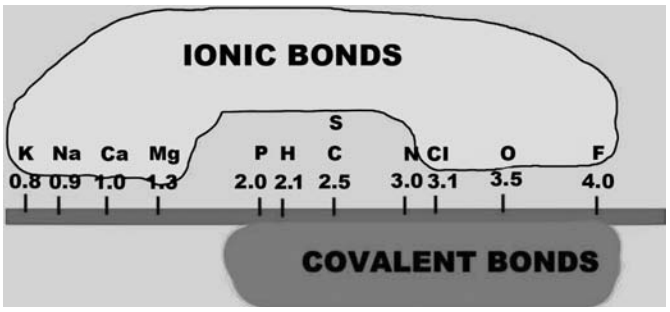

Figure 2. Electronegativity line graph. The scale represents numerical electronegativity values. Regions where ionic and covalent bonds are formed are approximate. Numerical electronegativity values can be omitted depending on classroom needs.

Students are evaluated on these concepts by test or quiz questions. For example:

- Arrange the following atoms from the least to most electronegative: O, Na, Ca, C, N. (Answer: Na [one valence electron], Ca [two valence electrons], C [four valence electrons], N [five valence electrons], O [six valence electrons].)
- Which atom is more electronegative, O or S? (Answer: O, because it has a lower atomic weight than S, even though both have six valence electrons.)

○ Electronegativity, Ionic & Covalent Bonds, Polarity, & Hydrogen Bonds

Ionic bonds are explained as occurring between atoms of *opposite electronegativity* (differences of 2 or more on the numerical electronegativity scale). To emphasize this concept, I point out the location of these atoms on the linear electronegativity scale, especially the vast electronegativity differences between atoms with one or two valence electrons and atoms with seven valence electrons. In these examples, the ***electronegativity difference is so great that the more electronegative atom actually removes valence electrons from its partner(s)***, forming the ionic bond. Covalent bonds are described as occurring between atoms with less pronounced differences in electronegativity, so that ***none of the atoms involved can remove electrons from the other and they have to share pairs of valence electrons.*** Atoms of very similar electronegativity (less than ~0.5) share electron pairs evenly and form ***nonpolar covalent bonds***, such as carbon and hydrogen, whereas atoms with greater (0.5–2) electronegativity differences form ***polar covalent bonds***, with the bonds being more polar the greater the electronegativity differences. Effective illustrative examples include nitrogen and hydrogen combining to form moderately polar ammonia, whereas oxygen and hydrogen, having much greater electronegativity differences, form highly polar water. It should be emphasized that the ***difference in electronegativities***, not the absolute electronegativity values, determines whether a covalent bond is polar or nonpolar. A good example of this point is that O_2, despite the high electronegativity of oxygen atoms, forms nonpolar covalent bonds and is therefore sparingly soluble in water because the two atoms are equal in electronegativity, whereas HCl, formed between highly electronegative Cl and much less electronegative H, forms polar covalent bonds and is highly water-soluble. The ***difference*** in electronegativity is the critical issue in determining whether a molecule is polar or not.

Hydrogen bonding is of critical importance in biochemistry, ensuring accuracy of DNA replication and transcription of RNA by hydrogen bonding between opposite or complementary bases, as well as forming and stabilizing protein secondary structure (alpha helices and beta sheets) and contributing to protein tertiary and quaternary structure. Once again, electronegativity can be used as a central concept to describe hydrogen bonds. First, using water and ammonia as examples, hydrogen bonding is explained as requiring three factors:

1. A hydrogen with a partial positive charge due to it being covalently bonded to *a* ***much more electronegative atom***, such as O or N.
2. A highly electronegative terminal atom with a partial negative charge due to it being ***covalently bonded to a much less electronegative atom***, using C=O and H–F as examples.
3. Both hydrogen-bonding functional groups must be within approximately an atomic diameter for the hydrogen bond to form.

Several examples of closely spaced functional groups are shown and the students, using these three factors, are asked to determine whether hydrogen bonds do or do not form between these groups; then the instructor describes why hydrogen bonds do or do not form. Examples include the following: **=N–H** and **O=C=**, which forms hydrogen bonds because all three criteria are satisfied, whereas **=C=O** and **H–C=C=** or **=C=O** and **O=C=** do not satisfy the above criteria and therefore do not form hydrogen bonds. In the case of **=C=O** and **H–C=C=,** the oxygen bonded to the carbon has a partial negative charge, but the hydrogen has no charge because it is bonded to carbon, which has similar electronegativity to carbon. In the case of **=C=O** and **O=C=**, both the oxygens have partial negative charges because they are much more electronegative than the carbon atoms they are bonded to, so the two functional groups repel each other. Additionally, neither of these functional groups has a hydrogen atom.

○ Electronegativity & Redox Reactions

Oxidation and reduction reactions are critical for many biochemical processes. Nearly all energy-producing metabolic processes involve oxidation of either organic or inorganic molecules to provide energy that is used to generate ATP. Oxidation can be described as transfer of electrons from a less to a more electronegative atom, resulting in a release of energy. For example, many anaerobic bacteria and archeans utilize oxidation of hydrogen sulfide or metal ions as an energy source. Oxygen, being highly electronegative, therefore is a powerful oxidizing agent and can be used as an electron acceptor in many reactions. By using highly electronegative oxygen as a terminal electron acceptor in the process of oxidative phosphorylation (oxidative metabolism), far more energy is released that can be used for ATP production than is obtained from metabolic processes that use other electron acceptors, such as occurs in fermentation reactions.

○ Assessment & Student Response

In an attempt to quantitatively assess the effectiveness of an early and strong emphasis on electronegativity as a central integrative concept, first exam scores, which require knowledge of chemical bonding and chemical principles, were analyzed for the two classes in which I utilize this technique. BY 101, our introductory concepts-of-biology course, is a dual major–nonmajor course that fulfills the general science requirement required by the university. Approximately 90–95% of the students are non–science majors or are undecided. One of our core biology courses, BY 373, cell biology, is required by all biology majors and minors and the course is almost exclusively populated by biology majors and minors. First exam scores for the period 2000–2004, prior to emphasizing electronegativity, and 2006–2010, after emphasizing electronegativity, were pooled and compared.

For BY 101, there was no significant differences in exam 1 scores between the two periods analyzed (2000–2004 mean = 52.88, standard deviation = 16.85, n = 389; 2006–2010 mean = 53.19, standard deviation = 18.58, n = 376). The two means were not significantly different by t-test (P = 0.41)).

For BY 373, however, there was a significant improvement in exam 1 scores after the electronegativity emphasis was introduced (2000–2004 mean = 66.85, standard deviation = 21.70, n = 274; 2006–2010 mean = 70.58, standard deviation = 20.31, n = 280). The means were different by t-test (P = 0.018).

It is likely that the lack of differences in exam scores for BY 101 is due to the fact that the vast majority of the students are nonmajors simply fulfilling their science distribution requirement and are often poorly motivated. Class attendances at any given point typically range from 50% to 65%. BY 373 has more motivated students and a far higher attendance, typically in the range of 80%.

Caution must be exercised in interpreting these results, however, because of many other factors that could affect the exam scores. These include that each exam for each class differs to some extent depending on scheduling and class needs, with between 20% and 40% of the questions directly asking about chemical principles. Additionally, changes in high school education standards such as the No Child Left Behind act, and changes in student demographics (higher percentages of female students) over the time frames examined, could affect exam scores as well.

In informal conversational questioning of students, the majority, especially those who had weak chemistry backgrounds, felt that emphasizing electronegativity as a central concept explained chemical bonding, polarity, and hydrogen bonding and helped them to understand and integrate these concepts into a coherent framework. Students who had college chemistry backgrounds, depending on their chemistry instructors, sometimes thought that this was a review of what they had already learned, but in other cases, the emphasis on electronegativity helped them in both the biology and their chemistry courses. A few of the more positive comments:

- "I'm learning more about chemistry in this course than in my chemistry course" (as told to his chemistry student tutor)
- "I'm a chemistry major, and this really helped me to understand *why* different chemical bonds form"

Overall, an early and strong emphasis on electronegativity is an effective teaching strategy in the chemical and biochemical foundations part of secondary school and introductory college courses.

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