P1. Chemistry in the Natural Sciences

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Abstract

This paper describes the role that chemistry plays in the two-term integrated science course “Science of Everyday Life” that is being taught at the University of Pittsburgh. The principal goals of this course are to engage students in thinking about the natural world that surrounds them, and to encourage them to develop an understanding of the fundamental scientific principles that govern its behavior, as well as to appreciate the “beauty of all things”. The principal topics discussed in the first term include the laws of motion, work, and energy; the molecular world, including the kinetic theory of gases and degrees of freedom; sources of energy, renewable and non-renewable, and energy transfer; electricity and magnetism; atomic theory, the chemical bond; intermolecular forces; materials (including an introduction to organic chemistry); radioactivity; and the sub-atomic world. The course continues in the second term with discussions of astronomy, geology and planetary science, energy and the environment, and biology. All topics are taught from a conceptual point of view, though quantitative ideas (orders of magnitude, statistics, etc.) are introduced when necessary. Knowledge of the simple physical and chemical ideas discussed early in the course gives the students a basis for understanding the more complex topics discussed later in the course. Most instructors in the course attend all lectures, making it possible to reinforce connections between “old” topics and “new” ones as they are introduced.

Introduction

Although still incomplete, the knowledge about and the understanding of the natural world that surrounds us are an impressive human achievement. And in today's world every person must deal with issues and often make personal choices that require some basic understanding of the natural sciences. Thus, the principal goals of this two-semester course are to make students more aware of the natural world that surrounds them, challenge them to ask questions and think about the answers, develop in them an understanding the fundamental scientific principles that govern its behavior, enjoy and appreciate the new developments in science that occur every day, and enable them to deal with challenges involving scientific and technological issues they will face in the future. The course employs a minimum of scientific jargon and mathematics.

Connections are also made to historical developments and to scientific and technological issues that impact individuals and society.

As the "central science", chemistry plays a key role in this course, providing many of the laws and principles by which our physical world is governed, and many of the connections between the sciences that are needed to understand the technological challenges that we are faced with everyday, and will continue to develop in the years ahead. Thus, while focusing on the key ideas in each of the separate disciplines, we also work hard to integrate them.

These attempts at integration are guided by several course aids and activities. First is the text, "The Sciences. An Integrated Approach", by James Trefil and Robert M. Hazen, published by Wiley and now in its Fifth Edition. This book is designed for nonscience majors in US colleges and universities, and thereby avoids the specialization and jargon that are characteristic of most introductory courses in science. It also works hard to synthesize the sciences by taking advantage of the fact that virtually everything in science is based on a few overarching principles. Other course aids reinforce these ideas, including a three-lecture-a-week format that features demonstrations, interactions among the students and the different course instructors, all of whom attend each class, peer instruction ("clickers"), weekly recitations led by "natural science" TA's, a resource center, field trips to local museums, institutions, and laboratories, and term papers in which the students are challenged to write a 2000-word description of a topic of their own choosing in which science plays a role.

Summarized in what follows is a brief discussion of the topics in chemistry that are covered in the first term of this course. A follow-up paper will offer a similar summary of the second term. Persons interested in more information about any aspect of the course are encouraged to contact one of the authors.

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A main focus of the first term of this course is energy; where it comes from, how we use it, and where it goes. We begin our discussion of this topic with a description of the scientific method, and illustrate its function by describing the development of our current understanding of our solar system, pointing out the key role played by scientific measurements, hypothesis, and prediction in the process, and the discovery of the first fundamental force of nature, gravity. This leads naturally to a discussion of kinematics, Newton's laws of motion, work and energy, the transformation of energy between different forms, kinetic and potential, and the law of conservation of energy.

Next on the agenda is the first "chemical topic"; **atoms, molecules, and kinetic theory of gases**. Atoms and molecules are identified as the principal species present in all materials, whether solids, liquids, or gases, and the "carriers" of energy in all things. We demonstrate that these species move in the gas phase, and that collisions with the walls lead to a pressure, from which we "derive" the ideal gas law and introduce Avogadro's number and the concept of a mole. We learn that "temperature reflects molecular motion" from these basic ideas, and introduce the temperature scales now in use around the world. We then go on to show that the atoms and molecules in liquids and solids are also in motion, and have energy, stored in vibrational and rotational **degrees of freedom**, as well as translational ones. The earlier discussion of springs, the pendulum, and rotating bodies helps us understand these things. We introduce the equipartition theorem of Boltzmann, and use it to describe the molecular origins of heat capacity, heat transfer, and the three laws of thermodynamics. In closing this section, we attempt to establish a causal relation between naturally occurring events and changes in energy, a key learning objective in the course. Nothing happens "without cause".

Parenthetically, we point out that since no one has ever "seen" an atom or molecule, they remain postulated objects in the course at this time. Later, we will visit a surface science laboratory at Pitt where the students will get their first glimpse of such objects using a scanning tunneling microscope (STM), verifying that Dalton's hypothesis concerning atoms is correct.

The course next turns to the sources of energy on our planet, from the sun and from the decay of radioactive nuclei. We discuss this topic quantitatively…for example, we ask the students to calculate how much energy the earth receives from the sun, and the fraction of this energy we actually use. We track this energy through the food chain, and work to determine the efficiency of the process. We talk about the sources of energy we use in daily life, the rates at which the supplies of energy are being used, the possible environmental impacts of such usages, and possible strategies that are being suggested to counter these trends. The "wedge concept" (Scientific American, September 2006) is a particular focus of recitations this week; an objective for us is to get the students to understand things like the "Greenhouse Effect" from a molecular (i.e., chemical) point of view. We return to a more extensive discussion of this topic and "alternative" energies in the second term of the course.

Recalling that some collections of molecules interact very strongly with each other, forming solids and liquids, whereas others do not, we then introduce the electric force and Coulomb's Law. We discuss static electricity and electrical charge, the electric field, the oil-drop experiment, electric current, and magnetism. We establish that electricity and magnetism are intimately related, and demonstrate the links between them with several demonstrations of loudspeakers, microphones, motors, and generators. Ohm's law is introduced, and the differences between DC and AC current are described. This leads naturally to a discussion of waves and wave phenomena, the electromagnetic spectrum, Maxwell's equations, reflection, absorption, and transmission, and interference phenomena. Here, we work hard to "bridge the gap" between the macroscopic properties of materials and the underlying microscopic explanations of their behavior.

Next, we introduce the "quantum revolution", first discussing the important experiments in Twentieth Century physics that forced us to relinquish the deterministic view of Newtonian mechanics when describing the "world of the small", and then providing some intuitive descriptions of matter at small length scales. Observing the emission spectrum of the hydrogen atom with its discrete lines at selected frequencies and contrasting this behavior with the standing waves on a string leads naturally to an understanding of wave-particle duality and the Bohr model of the hydrogen atom. Calculations leading to predicted values for the energies of an electron "in orbit" about the nucleus make possible direct comparisons of the predicted wavelengths with observed ones, thereby confirming Bohr's "postulates" (and, consequently, providing a "real-time", "in-your-face" demonstration of the scientific method). Lasers are introduced, as an example of "quantum mechanics in action." Then, with the aid of Schrödinger and Heisenberg, we refine our view and introduce the concept of an **atomic orbital**, the heart of chemistry.

What follows is chemistry. We first establish the relationship between the electronic configurations of the atoms and the structure of the **periodic table**. The periodic table of elements provides a powerful conceptual framework for understanding the structure of atoms, and the ways in which one element is different from another. (Passing around actual samples of different elements makes this point clear.) But some elements are "similar", thus establishing the periodicity of their properties and its relation to the number of valence electrons. We make a connection between the chemical properties of the elements; whether metal, nonmetal, or semimetal; and the number of its valence electrons. We show that different orbitals have different energies (using Coulomb's Law), and develop the concept of an electron shell, noting that the movement of an electron from one shell to another would result in a change in energy, and that full "octets" are especially stable.

A description of the different types of **chemical reactions** follows, with ample demonstrations to illustrate redox reactions ($Na + Cl_2$ to give ordinary table salt always amazes!), solution and precipitation reactions ("cold" packs and "hot" packs are a favorite of ours!), acid-base reactions, and polymerization reactions. Here, we focus on two objectives; to demonstrate that while the atoms themselves are not transformed by such reactions, their properties are, and therefore chemistry is all about the transfer or sharing of electrons; and to make connections to the everyday world. To witness a fuel cell at work or the synthesis of Nylon clearly demonstrates the essential idea of chemistry; that the properties of compounds are different from the properties of the elements from which they are constructed. And, again, we emphasize that most chemistry (but not all) is “downhill”; most chemical reactions liberate energy in the form of heat.

Next, we establish that the amount of energy required for (or released in) chemical reactions reflects the relative strengths of the **chemical bonds** that need to be broken (or are formed). It takes energy to break bonds; energy is released when bonds are formed. That there is competition between two or more effects is essential to chemical behavior. We then discuss the forces that are responsible for the two main types of chemical bonds, **ionic** and **covalent**. That ions exist is shown by the observation that aqueous solutions of NaCl conduct; that ions of opposite charge attract is, of course, the subject of Coulomb’s Law. Potential energy curves are described, leading to the conclusions that the force underlying the formation of covalent bonds must have something to do with the constructive interference of waves, and that some bonds are stronger than others. We demonstrate this by showing what happens when hydrogen and oxygen combine to form two molecules of water. And we also discuss at some length why water is a “polar” molecule, and for the first time introduce the notion of a **molecular shape**, or geometry.

We then discuss the forces that are responsible for the formation of liquids and solids from isolated molecules in the gas phase. We call these forces **intermolecular forces**, because they occur between molecules, and we include three types; metallic, dipolar, and van der Waals forces. While we are careful to delineate these, we also note that all such forces have their origins in Coulomb’s Law. We also note, once again, that whether a substance is a gas, a liquid, or a solid depends on a competition between the strength of these forces and the natural, thermal energy of the sample (recall Boltzmann’s Equipartition Theorem).

Having thus established the basic principles, we go on to discuss three main topics of chemistry in significant detail; **water and solutions, organic chemistry, and the properties of materials.** An entire lecture is devoted to each topic. When discussing water, we talk about phase changes, and what is going on at the molecular level. This allows us to understand why different substances have different physical properties, again emphasizing the importance of molecular shape, and the water dipole (a linear water molecule wouldn’t have one!). We discuss what happens when things dissolve. We talk about solution concentrations, how one can measure them, and when one can’t. We define pH, and talk about its use. We demonstrate an electrochemical cell and talk about it’s use. Also we explain what is meant by **chemical equilibrium**.

In organic chemistry, we introduce the element, talk about its allotropes (including the fantastic story of C60, which allows us to talk about serendipity in scientific research), hydrocarbons (and hybridization), hydrocarbon derivatives, functional groups and their role in synthesis ("shape counts"), and polymers. Time permitting, we talk a bit about biochemistry, setting the stage for lipids, carbohydrates, proteins, and the nucleic acid bases and their important role in biology, discussed next term. And in materials science, we focus on the strengths of materials, conductors and insulators, cells and batteries, magnetic materials, and the fascinating new world of nanoscience. A second field trip takes us to a chemistry lab, "science in action", often involving synthesis, lasers, and/or NMR.

SEL 1 closes with discussions of applications of materials science in computer technology, nuclear physics and nuclear reactions (the strong force), radioactivity (the weak force), isotopes and half lives, fission and fusion, "peaceful" uses of nuclear processes in chemistry, biology, and medicine, Einstein's theory of relativity, and particle physics.

Closing remarks

Developing these courses at the University of Pittsburgh has been a wonderful experience. We have learned that it is possible to "reduce" science to a few essentials, and to provide access to these essentials to college students majoring in the humanities and social sciences through lectures and other course activities that focus on the role of science in everyday life. Most students are, in fact, curious about the world around them. The computer, TV, and the popular press have all played a major role in raising this consciousness. Our courses "tap into" this curiosity by being responsive to it, and encouraging it, and thereby help to provide the graduating seniors at Pitt with the knowledge and confidence they will need to address the many technological issues that will challenge them in the future.

SEL 1 and 2 are currently being offered to approximately 100 students per year in the Schools of Arts and Sciences and Health and Rehabilitation Sciences at the University of Pittsburgh. Additionally, we anticipate participation by students in the Schools of Business and Education in the near future. The development of analogous courses for science majors is under discussion.

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