The Great Ideas of Chemistry[1]

Ronald J. Gillespie
Department of Chemistry, McMaster University, Hamilton, ON, L8S 4M1, Canada

To answer the question "What must be in general chemistry?" we need to ask what fundamental ideas of chemistry are essential to understand and appreciate modern chemistry. We must remember that the general chemistry course is not (or should not be) designed as the first step in the training of future professional chemists. Biologists, physicists, geologists, engineers, medical practitioners, environmentalists, and indeed every educated citizen need to understand chemistry. The course should be oriented toward the needs of these science, engineering, and medical students, so that they know how chemists think about the material world, what chemists are doing today, and what questions chemistry can answer. We need to show them the importance of chemistry in their chosen field as well as in everyday life.

I call these fundamental ideas the "great ideas of chemistry". Here is my list of the six concepts that form the basis of modern chemistry. I believe every high school and college introductory chemistry course should include these ideas—indeed, the course should be built around them. In what depth each is treated depends on the level and aims of the course. I will illustrate what I think is the minimum depth to which these ideas should be treated in the college general chemistry course. Part of the problem with the present overloaded freshman course is that these concepts are often presented in greater detail than necessary for good understanding at the level appropriate for the students' needs.

Atoms, Molecules, and Ions

Modern chemistry starts with Dalton and the concepts of atoms and molecules. Elements are a kind of matter that consists of atoms of only one kind. Compounds consist of two or more kinds of atoms held together in definite ratios. To understand how atoms are held together to form molecules, we move on to Rutherford and the concept that an atom consists of a central nucleus surrounded by electrons. The arrangement of these electrons in energy levels or shells can be readily deduced from data provided by ionization energies and photoelectron spectra, leading to the concept of a positively charged core surrounded by a valence shell.

The Chemical Bond: What Holds Atoms Together in Molecules and Crystals

All chemical bonds are formed by electrostatic attractions between positively charged cores and negatively charged valence electrons. *Electrostatic forces are the only important force in chemistry*. Bonds are not formed by the overlap of orbitals, as we read not infrequently; this is just a model—admittedly a very useful one and essential for the chemistry major, but I don't think it is essential for students at the introductory level. We can obtain a very good understanding of chemistry without it; indeed, many chemists make little use of it. It distracts attention from the real reason for bond formation: the electrostatic attraction between electrons and nuclei. There are more important and more relevant topics to treat at the introductory level. Moreover, the orbital model gives students the incorrect impression that chemistry is a difficult, abstract, mathematical subject based on a mysterious concept that is not and cannot be satisfactorily explained at the introductory level. We can simply describe ionic bonds as resulting from the electrostatic attraction between ions, and covalent bonds as resulting from a shared pair of electrons' attraction for the two atomic cores. The corresponding Lewis structures tell us how many bonds an atom will form. In my opinion, these concepts are all we need to discuss chemical bonding at the introductory level.

Molecular Shape and Geometry: Three-Dimensional Chemistry

The concept of molecular shape and geometry has been important in chemistry since the days of le Bel and van't Hoff. It has gained increased importance since the advent of X-ray crystallography. Understanding shape is vital to understanding a wide range of topics in modern chemistry: for example, biomolecules and their functions, industrial catalysts such as zeolites and solid surfaces, and synthetic polymers. Our understanding of shape and ability to control it are now such that we can synthesize almost any shape needed for a specific purpose: cages that trap ions of a particular size; molecules that have the shape necessary to bind to only one specific type of molecule (molecules that "recognize" each other); long-chain molecules that conduct an electric current and thus behave as molecular wires; and so on. The variety and complexity of molecules that chemists can now create is amazing and illustrates a very important aspect of chemistry, namely, that it is a creative science in the material sense. Chemists make new structures (molecules) that never existed before. This aspect of chemistry receives too little emphasis in the introductory course, although it is one that can stimulate and excite students by showing that chemistry is practical, useful, and challenging, not dull, theoretical, mathematical, and abstract.

We have a very simple model, the VSEPR model, that provides a basis for discussing the shapes of simple molecules and most features of even very large molecules. We need go no further at the introductory level. Hybrid orbitals, often discussed in this part of the course, are just another aspect of the orbital model. Moreover, they do not explain molecular geometry but merely describe it in terms of the orbital model. Understanding the concept of hybrid orbitals is essential for chemistry majors but not for general chemistry students. Molecular modeling programs now make it even easier for students to understand and become familiar with the shapes of molecules.

Kinetic Theory

By kinetic theory I do not mean the derivation of $pV = 1/3\ nmc^2 = nRT$, which is not an essential topic in the course, but rather the concept that above absolute zero atoms and molecules are in constant random motion: the higher the temperature the faster the molecules are moving. Combining this concept with that of intermolecular forces—electrostatic forces between nuclei and electrons—provides an understanding of the gas, solid, and liquid states. The constant motion of atoms means not only that molecules are moving in space but that they are not static objects—they are rotating, librating, and vibrating. We can use this concept to introduce infrared spectra and their use, for example, in the identification of organic molecules.

The Chemical Reaction

This brings us to the concept of the chemical reaction. Reactions occur because molecules are moving and when they bump into each other sufficiently violently bonds break and atoms are exchanged to give new molecules. Or a molecule that is vibrating sufficiently violently may break up into smaller molecules. These statements constitute a simple but fundamental explanation of a chemical reaction. To go further we can introduce the concept of activation energy so that we can explain why some reactions are very fast and others are immeasurably slow at ordinary temperatures. This is the minimum that students need to understand about how chemical reactions take place. All the details commonly presented—the plots needed to establish reaction rate and reaction order, the integrated rate laws, and so on, are secondary to these fundamental ideas. These details are essential for the chemistry major but I doubt that they are necessary for students in the introductory course.

But there is much more to the chemical reaction—perhaps the most important of the six great ideas—because reactions are the heart of chemistry. Understanding reactions has been a primary aim of chemists from the days of the alchemists. We now recognize many different types of reactions, but two in particular, acid–base and redox, are of fundamental importance throughout inorganic, organic, and biochemistry, and I believe they must be dealt with in the introductory course. But they cannot be fully understood simply in terms of their definitions as proton transfer and electron transfer. They should be introduced and discussed in terms of observations on real reactions carried out by the student in the laboratory or, as a second best, as lecture demonstrations live or on video. These two reaction types along with a few others such as precipitation reactions, and in organic chemistry addition and substitution reactions, enable us to make sense of the many thousands of reactions that we use and study in chemistry. The study of reactions has been neglected in the introductory course partly because it has come to be known as descriptive chemistry and therefore to be regarded as dull. Of course mere description is dull. But chemistry has advanced far beyond the stage of mere description: understanding reactions and using them for specific purposes is what chemists are trying to do. Much of both industrial and academic chemistry is concerned with the synthesis of new substances—materials, plastics, drugs—and the preparation of known substances by better methods—cheaper, more environmentally friendly methods, and so on. What causes the most excitement in the chemical world? The preparation of new molecules such those of the noble gases and buckminsterfullerne. We need to place more emphasis on the fantastic things that imaginative chemists have done and will continue to do in making new molecules, to show students that chemistry offers endless opportunities for creative and imaginative minds.

The periodic table is of great assistance in classifying and understand reactions. It has been of such importance in the development of chemistry that I might well have included it as one of the great ideas. It is important to emphasize that it was invented by Mendeleef long before anything was known about the detailed structure of the atom, as a means for classifying and better understanding the properties of the elements and their compounds. It remains one of the chemist's most useful tools for this purpose. In understanding reactions we also make extensive use of concepts such as electronegativity, atomic size, and core charge or effective nuclear charge, which can be developed directly from the simple model of atomic structure described earlier.

Energy and Entropy

Finally we need to know why some reactions occur and others do not, or more exactly, why some reactions reach equilibrium when very little product has been formed while others go essentially to completion. We understand this in terms of thermodynamics—more particularly in terms of the concepts of energy and entropy, the 1st and 2nd laws of thermodynamics. Thermodynamics is a forbidding term for students and the equations on which formal thermodynamics is based are even more forbidding. If it is taught in a formal way it can be dull and difficult. Even entropy can be a frightening word that can be made to seem abstract and difficult. But it need not be. Everyone can understand the concept of disorder and that is really all there is to entropy. The students will have already met the concept of random chaotic motion in the discussion of kinetic theory. Reactions occur when the disorder of the universe (or more simply the reacting system and its surroundings) is increased. This is the case for exothermic reactions: heat transferred to the surroundings increases its entropy or disorder. The majority of reactions that occur under ordinary conditions are exothermic because the heat released to the surroundings causes a large increase in the disorder or entropy of the surroundings; this is usually larger than any entropy decrease that might be occurring in the system. But we can have endothermic reactions if the increase in disorder in the system is greater than the decrease in the disorder of the surroundings owing to heat transferred from the surroundings to the system. This is basically all there is to understanding the role of thermodynamics in reaction chemistry: a reaction will go if the total entropy of the system and its surroundings increases. These are the important ideas that must be understood before it is worthwhile to go on any further to the concept of free energy and equations such as $\Delta G = \Delta H - T\Delta S$. In my view we do not need to go this far in the introductory course. Plugging numbers into equations will not appreciably enhance a student's understanding of basic concepts, and solving numerical problem will be a dull, uninteresting, and irrelevant exercise if students have not understood the basic concepts.

Basing the Freshman Course on the Great Ideas

These great ideas are the concepts I think must be in the freshman chemistry course to give a basic understanding of chemistry. For chemistry majors they will be expanded and applied throughout all courses. Students in other science, engineering, and medicine courses will also meet them again. I have indicated the minimum treatment needed to understand these concepts at the freshman level. I do not think they need to be taken further, although some instructors will wish to do so. In any case a substantial amount of time needs to be spent in making sure that the great ideas are truly understood. We need to use a large number and variety of qualitative questions to really test students' understanding of basic concepts. Quantitative problems that can so often be answered byplugging numbers into memorized formulas generally do little to test students' understanding. Treating these concepts at the level indicated would give students the needed understanding but would not take up all available time. Such a treatment would go a long way toward solving the major problems of present courses: too much material; too much emphasis on abstract theory and not enough on reaction chemistry; no time for updating the course with new, more relevant material such as environmental chemistry, materials science, macromolecules and polymers, and biochemistry—some of which also must be in general chemistry if we are to present a true introduction to modern chemistry.

How should we present the basic ideas? It would not be satisfactory to treat each one completely and in sequence because most of them are needed from early on. Rather we should *introduce* the ideas early but not develop them fully, and then show how they are used to understand the properties of substances and their reactions, developing them further as needed. In other words we would use them to rationalize a limited number of properties and reactions of inorganic and organic substances—choosing as far as possible simple, relatively well-known or common substances and those of some relevance in every-day life. Then we can show that they also provide a basis for understanding areas where much of the current progress in chemistry is occurring, such as environmental chemistry, materials science, and biochemistry. Only in the context of applications such as these can students fully appreciate the importance and usefulness of the great ideas of chemistry.

Note

1. Presented at the 210th American Chemical Society Meeting, Chicago, August 1995 in the Symposium "What Must Be in General Chemistry".