AC 2009-759: WHAT LIES BENEATH THE MATERIALS SCIENCE AND ENGINEERING MISCONCEPTIONS OF UNDERGRADUATE STUDENTS?

Senay Purzer, Purdue University

Senay Purzer is an assistant professor in the School of Engineering Education at Purdue University. She received a Ph.D. and a M.A in Science Education, Department of Curriculum and Instruction from Arizona State University. She has a B.S. degree in Physics Education and a B.S.E. degree in engineering. Her creative research focuses on collaborative team learning and the role of engineering self-efficacy on student achievement.

Stephen Krause, Arizona State University

Stephen J. Krause is Professor in the School of Materials in the Fulton School of Engineering at Arizona State University. He teaches in the areas of bridging engineering and education, design and selection of materials, general materials engineering, polymer science, and characterization of materials. His research interests are in innovative education in engineering and K-12 engineering outreach. He has been working on Project Pathways, an NSF supported Math Science Partnership, in developing modules for Physics and Chemistry and also a course on Engineering Capstone Design. He has also co-developed a Materials Concept Inventory for assessing fundamental knowledge of students in introductory materials engineering classes.

Jacquelyn Kelly, Arizona State University

What Lies Beneath the Materials Science and Engineering Misconceptions of Undergraduate Engineering Students?

Abstract

Students from various engineering disciplines who enroll in an Introductory Materials Science and Engineering (MSE) class often harbor a variety of robust misconceptions. The goal of this study is to investigate the origins of these misconceptions and identify barriers to student learning of introductory MSE concepts. To categorize the sources of student misconceptions, Taber's typology of learning impediments was used. A synthesis of research literature concerning K-12 and undergraduate physical science and chemistry misconceptions was also conducted to reveal origins of MSE related misconceptions. Misconceptions that are present in undergraduate introductory MSE students were revealed using the Materials Concept Inventory (MCI). The misconceptions were linked to four distinct categories of K-12 misconceptions in physical science and chemistry: 1) the nature of crystalline structure and unit cells, 2) the relationship between material characteristics and bonding, 3) material processing, and 4) saturation and super-saturation. These misconceptions were caused by deficiency, fragmentation, ontological, and pedagogical learning impediments. From the comparison and categorization of these misconceptions' origins, we have made suggestions for developing effective misconception interventions and teaching approaches for introductory MSE classes.

Introduction

Introductory Materials Science and Engineering (MSE) is a required course for engineering students from fields which include materials, mechanical engineering, electrical engineering, aerospace engineering, and chemical engineering. For students to be successful in the course and as engineers, they must develop an understanding of the basis for a material's macroscale properties. This requires an intuitive awareness of a material's structural, nanoscale, and microscale features and their influence on macroscopic properties. However, achieving this goal is a significant conceptual challenge that confronts all levels of learners in developing useful *mental models*[1] that link the concrete "macroworld" of everyday objects and phenomena to the abstract "nano and microworlds" of atoms, molecules, and microstructure. Many students enrolling in introductory MSE classes enter with physical science and chemistry misconceptions, causing a predisposition to MSE learning barriers. Therefore, there is a need to understand *what* knowledge and experiences students bring to introductory materials science and engineering courses, *why* this knowledge poses challenges for learning MSE concepts, and *how* effective strategies can be implemented in introductory MSE courses to enhance student understanding.

Theoretical Framework

From a constructivist perspective, learning involves transfer of information from prior knowledge and previous experiences[2]. According to conceptual change theories, a major source of students' learning challenges are due to students failing to achieve such a transfer or failing to make linkages between old and new information that are non-normative or scientifically inaccurate[2-4].

There are several conceptual change theories that are commonly used by science and engineering education researchers[5]. Posner, Strike, and Gertzong's[6] theory of conceptual change requires four conditions necessary for conceptual change to occur: 1) there must be dissatisfaction with the students' existing conception, 2) the new conception must be intelligible, 3) the new conception must be plausible, and 4) the new conception should be fruitful. The use of discrepant events had been used in the light of this theory. A common example involves demonstration of the buoyancy of a large and a heavy object such as wood in water forcing students to reconsider the possible misconception that heavy objects always sink. More recently, new theories have emerged that focus more on understanding why some science concepts are so difficult for students to learn. For example, Vosniadou and Ioannides's[7] "theory-theory" states that students form their own theories of science concepts which are sometimes in contrast with scientific theories. An example of such a misconception is the impetus theory that all moving objects have to have a force that acts in the direction the object is moving. diSessa[3], on the other hand, argues that students have partial and fragmented understanding of concepts that he calls "knowledge in pieces." According to this conceptual change theory, a child can have a normative understanding of a concept such as thermal equilibrium in room temperature in one context (e.g., for wood) but not in another context (e.g., for metals). Chi's[4] "ontological theory of conceptual change" is yet another theory that sheds light on the causes of robust misconceptions. According to Chi, concepts such as electric current and heat are difficult for students because they miscategorize these concepts as "things" rather than "processes." In addition to these theories that aim to describe the nature and causes of student misconceptions, there are also theories that inform teaching. A challenge for engineering and science educators is to decide which framework to use to study conceptual change.

We believe that students' challenges in learning MSE concepts are caused by diverse factors. Therefore, for this research study, we selected a framework that is built on a combination of conceptual change and learning theories. We used Taber's topology of learning impediments as our framework. This model also serves as a heuristic tool that not only informs teaching but also provides recommendations for future research[8]. Taber[9] provides a framework that serves as a simple analytical tool educators can use to determine why students have challenges and what type of transformation can help bring change (See Table 1).

According to Taber[9], learning can be impeded by the lack of background knowledge, interpretation of personal experience, previous non-normative learning, or inappropriate application of prior knowledge to new subject material. Consequently, he proposes two general types of impediments, each with two specific subtypes (See Table 1). Null impediment refers to missing information (necessary for learning new material) due to students: 1) not having prior knowledge (null *deficiency* impediment) or; 2) not recognizing the links between new material and their existing prior knowledge on the topic (null *fragmentation* impediment). Substantive impediment refers to faulty concept models students hold from: 1) personal experience or observations (substantive *ontological* impediment); and 2) prior courses and teaching (substantive *pedagogic* impediment). Taber proposes that identification of the origins of misconceptions will aid in the ability to develop successful interventions and resolutions.

Table Typology of Learning Impediments by Taber[9]

Category	Sub-Category	Description
Null	Deficiency Impediment	Learner knows no relevant material in existing cognitive structure
	Fragmentation Impediment	Learner does not see the relationship or relevance of material held in cognitive structure to the new material presented
Substantive	Ontological Impediment	New material is inconsistent with the intuitive ideas and everyday experiences of the learner
	Pedagogic Impediment	New material is inconsistent with the concepts previously learned

Synthesis of K-16 Literature

Because our goal was to investigate the origins and causes of student misconceptions, we started our investigation with a comprehensive review of literature, ranging from kindergarten to undergraduate, on students' understanding of physical science and chemistry concepts. There are few studies that explore engineering students' misconceptions and even fewer on engineering students' conceptual understanding of chemistry and materials science concepts[5, 10]. However, there are a large number of studies exploring primary, secondary, and college students' understanding of chemistry concepts (See Table 2).

Table 2. Summary of K-16 Literature on Chemistry Misconceptions

Category	Elementary School	Middle School	High School	Undergraduate
1. Matter: Mixtures & Diffusion	Liu 2005* Paik 2004*	Chin 2002 Liu 2005* Paik 2004* Snir 2003*	Liu 2005* Nieswandth 2001 Noh 1997 Snir 2003* Odom 2001 Panizzon 2003*	Panizzon 2003*
2. Matter: Liquids, Air, Gasses	Benson 1993*	Benson 1993*	Benson 1993*	Benson 1993* Naughton 2008
3. Heat & Temperature	Jones 2000 Paik 2007*	Paik 2007*	Harrison1999 Kaper 2002 Paik 2007*	Thomas 1998
4. Atoms & Molecules			Griffiths 1992 Taber 2005 Wu 2001	
5. Bonding			Boo 1998 Nahum 2007	Nicoll 2001 Teichert 2002
6. Bonding			Coll 2003*	Coll 2003*

Category	Elementary School	Middle School	High School	Undergraduate
(Ionic & Covalent)				Taber 2003
7. Bonding (Metallic)			Acar 2008 De Posada 1999	

*cross age study (note: only first authors are listed in the table)

Three categories of physical science and chemistry misconceptions have become apparent from elementary to undergraduate: 1) mixtures and diffusion, 2) structure of matter, and 3) heat and temperature. Our literature review confirms that these misconceptions are often carried with students from elementary school to college. Such robust science misconceptions are not uncommon. For example, the video, *A Private Universe*[16], reveals the misconceptions that Harvard and MIT graduates hold about photosynthesis are similar to that of middle school students'. Like this example, fundamental misconceptions, such as macroscopic properties of materials, are often developed at elementary levels. More abstract misconceptions such as characteristics of atoms, molecules, and bonding, are often developed at high school and college levels. Therefore, misconceptions regarding the macroscopic behavior and properties of materials are most likely to originate at elementary levels where bonding-related misconceptions and misconceptions pertaining to the nano and micro scale views of matter are most likely to be acquired in high school. Regardless of time of their origination, these misconceptions are brought with students to the undergraduate introductory MSE classroom.

To aid in identifying possible areas for misconceptions in physical science and chemistry, we examined the content students learn as they progress though their K-12 education. This was determined by analyzing the National Science Education K-12 content Standards (National Research Council, 1996). Specific learning objectives for K-4, 6-8, and 9-12 grade levels in physical science are presented in the appendix.

Research Question

What factors support or impede student learning of introductory MSE concepts? To answer this question, this research will identify robust misconceptions in materials science and engineering, determine the origins of these misconceptions, and make recommendations to help scaffold student learning to repair these misconceptions.

Research Methods

In this paper, we employ Taber's model of learning impediments[9] to determine what lies beneath the misconceptions of undergraduate students in MSE classes. To achieve this goal, qualitative and quantitative data were collected and analyzed from several sections of an introductory course in materials science and engineering (MSE). Qualitative data was obtained through focus groups and individual interviews of students enrolled in an introductory MSE course. Students were prompted with questions from the MCI after course instruction and asked to choose the most appropriate answer and explain their reasoning. Quantitative data on materials-related misconceptions were collected through the MCI[10]. The MCI was given prior to instruction and at the conclusion of instruction in an introductory MSE course in Fall 2002, Spring 2003, and Spring 2007. The courses were comprised of mostly sophomores and juniors from the disciplines of mechanical engineering, materials, aerospace engineering, chemical engineering, bioengineering and industrial engineering. We determined a concept to be challenging when the class gains between pre-test and post-test MCI scores were less than 10%. Next, we examined the K-12 curriculum, namely the National Science Education Standards[11] and literature on K-16 chemistry misconceptions (See Table 2) to determine the causes of student challenges and whether they emerge from concepts learned at school or from intuitive beliefs. These misconceptions were examined in detail using Taber's typology of learning impediments and will be discussed in the following section.

Results & Discussion

The results from the MCI revealed four categories of robust student misconceptions and learning challenges in materials science and engineering: 1) unit cells and crystalline structure, 2) effect of microstructure on macroscopic material characteristics, 3) material processing, and 4) solubility, saturation, and phase diagrams and their relevance in solid state diffusion. In the following sections we present the origin of these misconceptions.

Null Deficiency Impediments

We determined that the misconceptions related to the nature of crystalline structure and unit cells were caused by null deficiency impediments. Though students may have experience with macroscopic crystals, the internal structure is not addressed in the K-12 curriculum. Therefore, the atomic structure that is responsible for these macroscopic observations is first introduced in the college classrooms to students with no prerequisite knowledge of the content. Pretest MCI data revealed that 74% of students answered questions correctly on this topic. New concepts are often introduced in correlation with new terms and vocabulary. Sometimes these terms are not discussed explicitly or at a level students can relate to. Other times, these new scientific terms are misinterpreted when their meaning in a scientific context differs from the words' meaning in everyday discourse. For example, the term, defect, is an example that would be challenging for students. This may inhibit students from learning, thus adding to their collection of null deficiency impediments.

Null Fragmentation Impediments

The misconceptions related to the relationship between material properties and bonding are categorized under null fragmentation impediments. Neither bonding nor the properties of materials are new concepts to college students. However, what is new for the students is the linkage between these two concepts. Pretest MCI data showed that only 49% of students answered questions correctly that were related to this topic. Chemistry and physical science train students to consider the atomic level interactions as indicators of macroscopic properties. However, students are not often taught to link the two through a material's microstructure (the larger scale organization of atoms). Therefore, when students are asked to make the link between material properties and the material's microstructures, they have difficulty seeing the relationship. Visualization tools and explicit linkages between these two concepts can help scaffold students learning of these concepts. To resolve null fragmentation impediments, content should be introduced in diverse contexts. By allowing students to discuss the concepts in teams and in a variety of contexts, students showed 15% gain at the end of the semester. A variety of perspectives and applications give students additional opportunities to develop connections between new information and their current mental models. Additionally, students can be given the opportunity to discuss differences with peers in order to negotiate the most appropriate operational model.

Substantive Ontological Impediments

Student misconceptions related to material processing were attributed to substantive ontological impediments. Material behavior is often counterintuitive to observations from everyday experience. When a task involves describing macro level behavior using micro level processes, novice problem solvers most often offer macro level descriptions representing tangible and observable entities[12]. Due to this reason, the understanding of the particulate nature of matter is quite challenging for students.

A typical example of a faulty *mental model* that results in a misconception is "the malleable copper atom"[13] which is due to attribution of macroscale properties to an atomic level entity. Similarly, in the context of materials science, when students are asked to explain why a cold-worked metal softens when annealed; students select choices, which incorrectly reflect changes in the strength of bonds as the reason. The scientific explanation, however, is that the density of defects, technically known as *dislocations* are reduced during annealing. This is because a cold worked metal will recrystallize during annealing which sweeps out dislocations when newly formed crystals are grown. Preliminary MCI data revealed that only 2% of students answered correctly on questions in reference to this material. Team-based concept sketching activities are effective in helping students learn these types of concepts[13]. Students showed only 11% gain with lecture only, 56% gain in score to these questions teamwork discussions, and 73% after engaging in teamwork discussions and concept sketching. In these activities, students are asked to defend their understanding by creating a visual sketch of their mental model. By verbalizing content and defending and critiquing peer's ideas, students will be able to identify strengths and weaknesses in their conceptual understanding, allowing them revise thinking to maximize conceptual gain.

Substantive Pedagogical Impediments

Students' challenges in understanding of chemistry concepts and processes such as solubility are often non-normative (i.e., scientifically inaccurate) and exist at all levels of formal education. For example, students incorrectly perceive that when salt is added to a saturated salt solution the concentration of salt in the solution will increase. These concepts are not new to the students and are taught within the National Science Education Standards[11] as early as elementary school. However, it is clear from the literature on student misconceptions that previous instruction has not been successful.

Understanding of solubility and saturation are important for students to understand phase diagrams[14]. Phase diagrams are key tools used to describe solid state strengthening processes. Without a working understanding of the microscopic interactions that occur in solubility and saturation, as taught in physical science and chemistry, students will be restricted in their understanding of strengthening mechanisms which will later keep them from being able to connect processing methods with material behavior. Initial MCI data showed that 43% of students answered correctly on questions related to solubility and saturation, with only 10% gain at the end of the semester. These data suggest that this type of impediment is most robust. We suggest that the materials science lessons related to solution and saturation concepts for alloys should include explicit instruction on student misconceptions and provide students with discrepant events and first-hand experiences that can help challenge their beliefs, allowing for resolution of substantive pedagogical impediments. In order to best repair substantive pedagogical impediments, student mental models must be exposed. Misconceptions and prior content knowledge must be known. Once prior knowledge is revealed, inconstancies or inaccurate information can be addressed.

Summary & Recommendations

As revealed by the MCI, misconceptions exist, and are often not resolved in introductory MSE courses. Some materials science and engineering concepts are difficult for undergraduate students merely because students are being introduced to these concepts for the first time in their educational experience. These concepts include new terms, vocabulary, and processes. Other topics are difficult because instruction has not been successful in helping them make the link between existing mental frameworks and prior experiences. Materials science and engineering courses cover a wide range of concepts and there is a need to identify and build upon a conceptual framework that will enable connections between diverse concepts.

The literature on student misconceptions in chemistry shows that concepts such as solubility and structure of matter have been challenging for students not only during undergraduate courses but also at K-12 levels education. K-12 science content standards cover macro level properties at the primary level while micro level characteristics (i.e., atomic structure and bonding) at the secondary level. However, science content standards include no specific links between macro level properties and micro level structure, which is the foundation to understanding MSE concepts.

This study illustrates that there are many reasons why materials science and engineering concepts are challenging for undergraduate students. To achieve effective conceptual learning of new material, misconceptions must be identified, defined, categorized, and repaired. It has become apparent that students need instructional tools and methods that are sensitive to their prior knowledge and experiences. Student prior knowledge must be revealed through reliable instruments such as the MCI. This gives insight as to what specific misconceptions students hold. After these misconceptions are identified, their origins must be investigated. Do students think of these things as a result of a lack of familiarity with content? Or has there been misinterpretation or miscommunication? Once origins are examined, misconceptions can be classified as either *null deficiency, null fragmentation, substantive ontological,* or *substantive pedagogical*. This classification allows for understanding what type of intervention may be most appropriate for confrontation and repair of a misconception. We suggest that it would be useful to develop a materials science and engineering framework that would extend from K-12 through to undergraduate materials courses taking into account the necessities listed above. Using such a framework would make possible instruction that could activate and engage students' previously held mental models while introducing diverse introductory MSE concepts. In doing so, such a proposed framework would guide future research on student learning by developing student knowledge and skills necessary to elicit, confront, and repair misconceptions in not only introductory materials science and engineering but also .

References

1. Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models in science education, in Gilbert, J. K., & Boulter, C. J. (Eds.), *Developing models in science education*. Dordrecht, Netherlands, Kluwer Academic Publishers.

2. Driver, R. & Bell, B. (1986). Students' thinking and the learning of science; A constructivist view. *School Science Review, 67*, 443-356.

3. diSessa, A. (1988) "Knowledge in Pieces", in Constructivism in the Computer Age G. Forman and P. Pufall, Ed.

4. Chi, M.T.H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), Cognitive models of science (pp.129–186). Minneapolis, MN: Minnesota Press.

5. Streveler, R.A., Litzinger, T.A., Miller, R.L., and Steif, P.S. (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. *Journal of Engineering Education, 97*(3), 279-294.

6. Posner, G.J., Strike, K.A., Hewson, P.W., & Gertzog, W.A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211–227.

7. Vosniadou, S. & Ioannides, C. (1998). From conceptual development to science education: A psychological point of view. International Journal of Science Education, 20, 1213–1230.

8. Taber, K.S. (2004). Learning quanta; Barriers to simulating transitions in student understanding of orbital ideas. *Science Education, 89*, 94-116.

9. Taber, K.S. (2001). The mismatch between assumed prior knowledge and the learner's conceptions: A typology of learning impediments. *Educational Studies, 27*(2), 159-171.

10. Krause, S., Decker, J. C., & Griffin, R. (2003). Using a Materials Concept Inventory to assess conceptual gain in introductory materials engineering courses. *2003 Frontiers in Education Conference Proceeding,* Savannah, GA.

11. National Research Council (1996). *National Science Education Standards.* Washington, D.C: National Academy Press.

12. Larkin, J.H. (1983). The role of problem representation in physics. In D. Gentner & A.L. Stevens (Eds.), Mental models (pp. 75–98). Hillsdale, NJ: Lawrence Erlbaum.

13. Ben-Zvi, R., Eylon, B., & Silverstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education*, *63*, 64–66.

14. Krause, S. Tasooji, (2008) A., An intervention using concept sketching for addressing dislocation-related misconceptions in introductory materials science and engineering classes, accepted for publication, *ASEE Annual Conference Proceedings.*

15. Krause, S. Tasooji, A., (2007) Diagnosing students' misconceptions on solubility and saturation for understanding of phase diagrams, *ASEE Annual Conference Proceedings, on CD.*

16. Schneps, M. Sadler, P. (2003) A Private Universe: Minds of Our Own. *Harvard-Smithsonian. Center for Astrophysics.*

Appendix

*K-12 Physical Science Content Standards Related to Materials Science and Engineering Concepts (*National Research Council, 1996*)*

Grade Level	Concepts	Objectives	Summary
K-4	Properties of Objects and Materials	☐ Objects have many observable properties, including size, weight, shape, color, temperature, and the ability to react with other substances. Those properties can be measured using tools, such as rulers, balances, and thermometers. ☐ Objects are made of one or more materials, such as paper, wood, and metal. Objects can be described by properties of the materials from which they are made, and those properties can be used to separate or sort a group of objects or materials. ☐ Materials can exist in different states—solid, liquid, and gas. Some common materials, such as water, can be changed from one state to another by heating or cooling.	Macro-level properties of materials Extrinsic properties of matter Classification of materials States of matter (solid, liquid, gas) Changes in states of matter
5-8	Properties and Changes of Properties in Matter	☐ A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample. A mixture of substances often can be separated into the original substances using one or more of the characteristic properties. ☐ Substances react chemically in characteristic ways with other substances to form new substances (compounds) with different characteristic properties. In chemical reactions, the total mass is conserved. Substances often are placed in categories or groups if they react in similar ways; metals is an example of such a group. ☐ Chemical elements do not break down during normal laboratory reactions involving such treatments as heating, exposure to electric current, or reaction with acids. There are more than 100 known elements that combine in a multitude of ways to produce compounds, which account for the living and nonliving substances that we encounter.	Intrinsic properties of matter Mixtures & solutions Elements (periodic table) Compounds Chemical reactions Classification of materials (metals)
9-12	Structure of Atoms	☐ Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between nucleus and electrons holds the atom together. ☐ The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element. ☐ The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces. Fusion is the joining of two nuclei at extremely high temperature and pressure, and is the process responsible for the energy of the sun and other stars. ☐ Radioactive isotopes are unstable and undergo spontaneous nuclear reactions, emitting particles and/or wavelike radiation. The decay of any one nucleus cannot be predicted, but a large group of identical nuclei decay at a predictable rate. This predictability can be used to estimate the age of	Structure of atoms Fission & fusion Radioactive decay

		materials that contain radioactive isotopes.	
9-12	Structure and Properties of Matter	☐ Atoms interact with one another by transferring or sharing electrons that are furthest from the nucleus. These outer electrons govern the chemical properties of the element. ☐ An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This "Periodic Table" is a consequence of the repeating pattern of outermost electrons and their permitted energies. ☐ Bonds between atoms are created when electrons are paired up by being transferred or shared. A substance composed of a single kind of atom is called an element. The atoms may be bonded together into molecules or crystalline solids. A compound is formed when two or more kinds of atoms bind together chemically. ☐ The physical properties of compounds reflect the nature of the interactions among its molecules. These interactions are determined by the structure of the molecule, including the constituent atoms and the distances and angles between them. ☐ Solids, liquids, and gases differ in the distances and angles between molecules or atoms and therefore the energy that binds them together. In solids the structure is nearly rigid; in liquids molecules or atoms move around each other but do not move apart; and in gases molecules or atoms move almost independently of each other and are mostly far apart. ☐ Carbon atoms can bond to one another in chains, rings, and branching networks to form a variety of structures, including synthetic polymers, oils, and the large molecules essential to life.	Bonding (electron sharing & transfer) Elements Periodic table Macro & micro connection!! Carbon atoms & polymers!!
9-12	Chemical Reactions	☐ Chemical reactions occur all around us, for example in health care, cooking, cosmetics, and automobiles. Complex chemical reactions involving carbon-based molecules take place constantly in every cell in our bodies. ☐ Chemical reactions may release or consume energy. Some reactions such as the burning of fossil fuels release large amounts of energy by losing heat and by emitting light. Light can initiate many chemical reactions such as photosynthesis and the evolution of urban smog. ☐ A large number of important reactions involve the transfer of either electrons (oxidation/reduction reactions) or hydrogen ions (acid/base reactions) between reacting ions, molecules, or atoms. In other reactions, chemical bonds are broken by heat or light to form very reactive radicals with electrons ready to form new bonds. Radical reactions control many processes such as the presence of ozone and greenhouse gases in the atmosphere, burning and processing of fossil fuels, the formation of polymers, and explosions. ☐ Chemical reactions can take place in time periods ranging from the few fem to seconds (10^{-15} seconds) required for an atom to move a fraction of a chemical bond distance to geologic time scales of billions of years. Reaction rates depend on how often the reacting atoms and molecules encounter one another, on the temperature, and on the properties—including shape—of the reacting species. ☐ Catalysts, such as metal surfaces, accelerate chemical reactions. Chemical reactions in living systems are catalyzed by protein molecules called enzymes.	Chemical reactions Chemical bonds Radial reactions