Introduction to Materials Science and Technology

What is Materials Science?

Materials make modern life possible—from the polymers in the chair you're sitting on, the metal ball-point pen you're using, and the concrete that made the building you live or work in to the materials that make up streets and highways and the car you drive. All these items are products of materials science and technology (MST). Briefly defined, materials science is the study of "stuff." Materials science is the study of solid matter, inorganic and organic. Figures 1.1, 1.2, 1.3, and 1.4 depict how these materials are classified.

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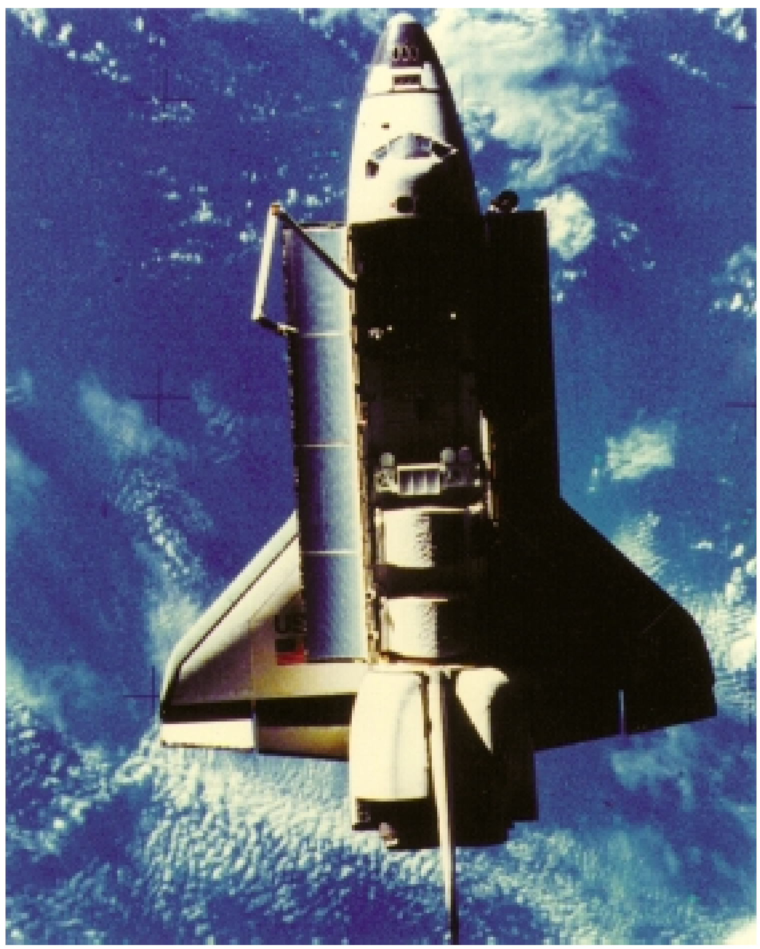


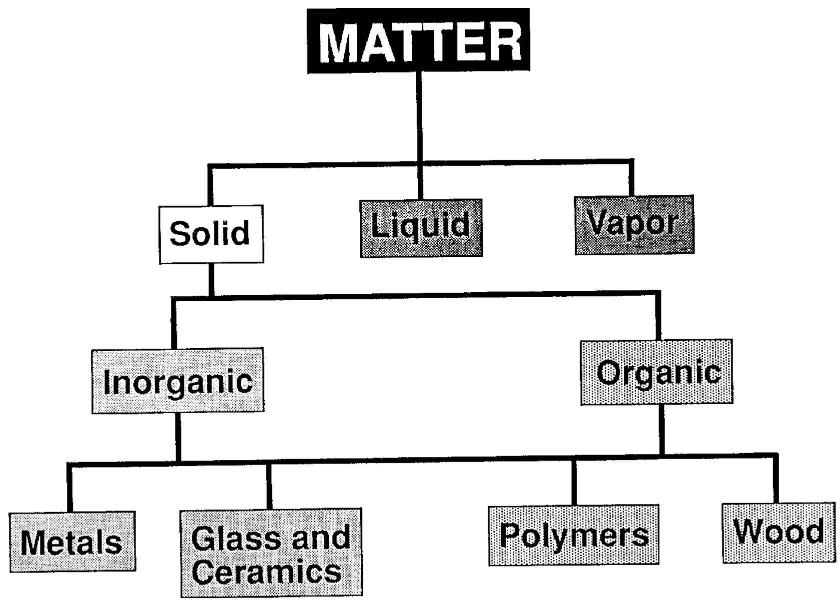


Figure 1.1. Physical Classification of Materials by State

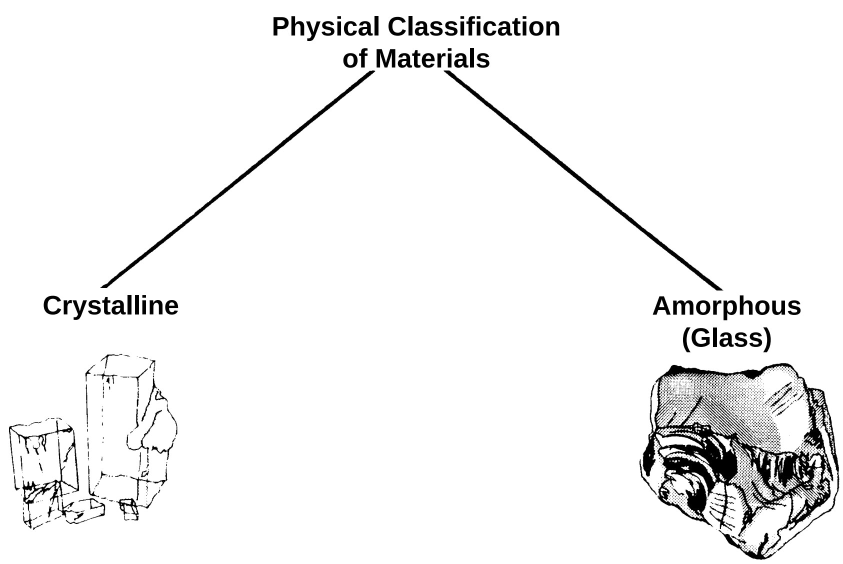


Figure 1.2. Physical Classification of Materials by Morphological Structure

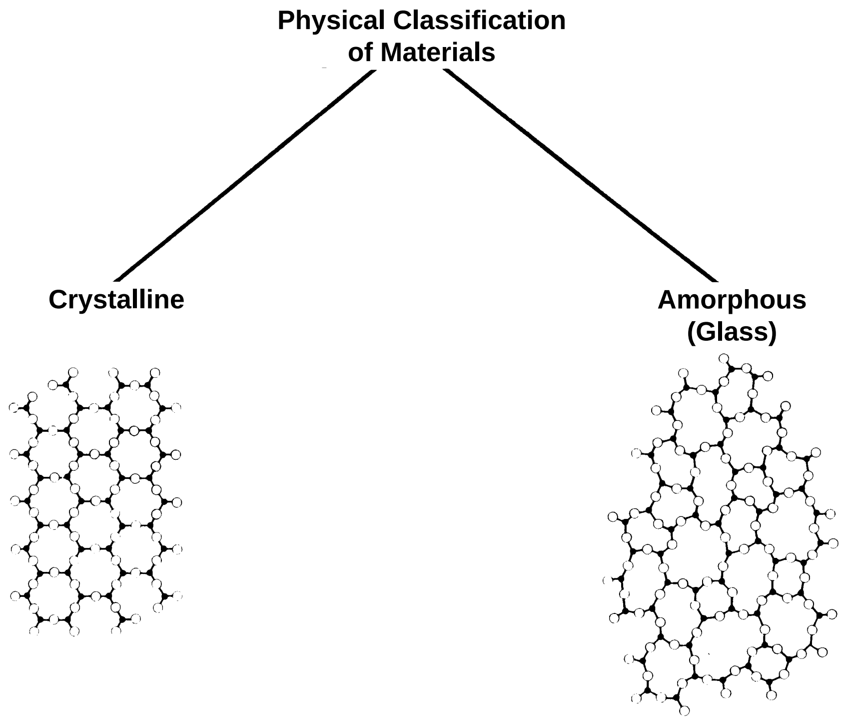


Figure 1.3. Physical Classification of Materials by Atomic Structure

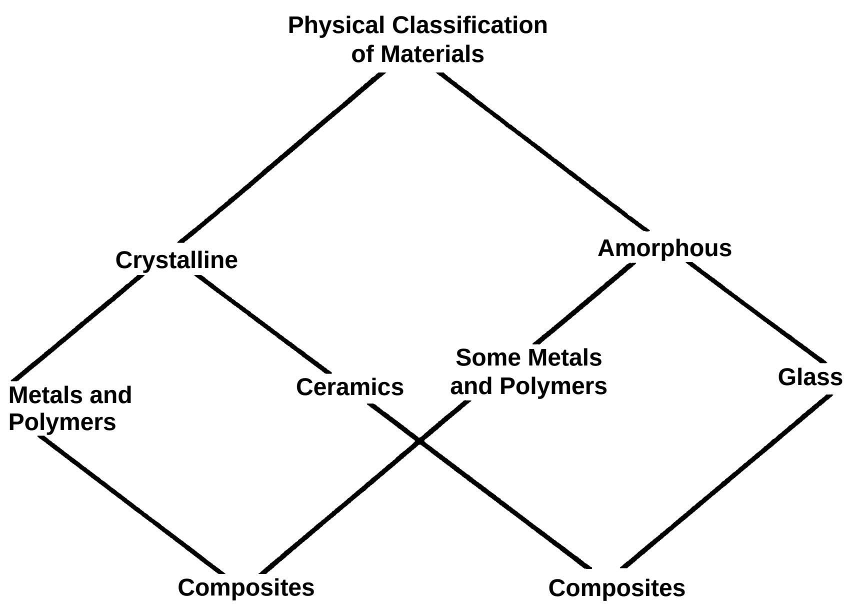


Figure 1.4. Interrelationships Between Classes of Materials

"Technology draws on science and contributes to it."

—AAAS Project 2061
Science for All Americans

Materials science and technology is a multidisciplinary approach to science that involves designing, choosing, and using three major classes of materials—metals, ceramics, and polymers (plastics). Wood also could be used. Another class of materials used in MST is composites, which are made of a combination of materials (such as in particle board or fiberglass).

Materials science combines many areas of science. Figure 1.5 illustrates how materials science draws from chemistry, physics, and engineering to make better, more useful, and more economical and efficient "stuff."

Because of the interdisciplinary nature of materials science, it can be used both as an introductory course to interest students in science and engineering and also as an additional course to expand the horizons of students already taking science and mathematics courses.

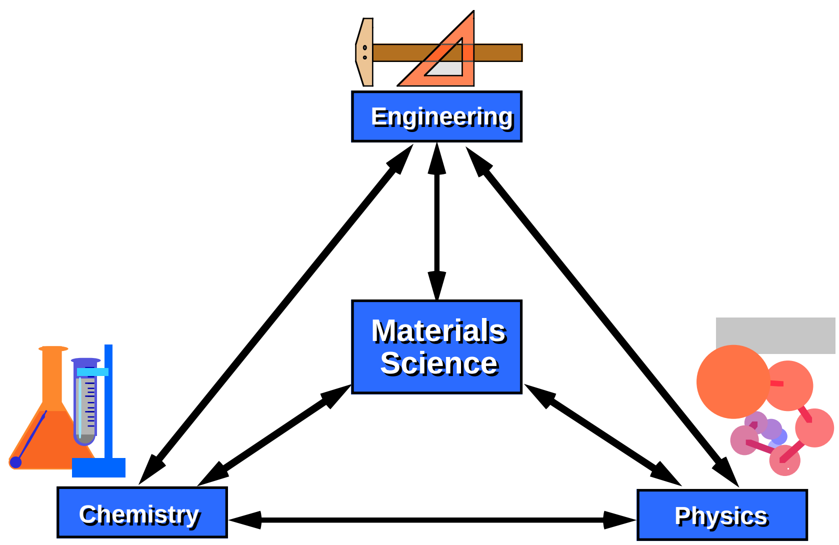


Figure 1.5. Materials Science and Technology—A Multidisciplinary Approach

The Relationship of Science and Technology

In the MST classroom, the boundaries are blurred between science and technology. It is not easy to know where one ends and the other begins. In this way, the learning environment of MST reflects the scientific and technical enterprise where scientists, engineers, and technologists work together to uncover knowledge and solve problems. In the school environment, these overlapping and complementary roles of science and technology are found most often in courses called "technology education."

Some confusion exists between the labels "technology education" and "educational or informational technology." Educational technology refers to delivery systems for teaching and tools for instruction such as computers, satellite television, laser discs, and even chalk. It refers to laboratory equipment such as microscopes, telescopes, and calculators. These tools can access and process information and perform numerical calculations that describe physical phenomena—but they are not technology education in the sense we describe.

In a technology education course, technology is treated as a substantive content area, a subject with a competence or performance-based curriculum involving learned intellectual and physical processes and skills. As such, technology is viewed as a part of the essential curriculum content in mathematics and science, and understanding of the principles and practices of mathematics and science is viewed as essential to effective technology curricula. Science and technology as it is practiced in the real-world supports this relationship.

Even though the activities in an MST classroom may not call out the difference between science and technology, it is important to know that they are fundamentally different from each other (see Figure 1.6). Knowing the difference can assist you in designing and delivering the curriculum and in assessing and reporting learning attained by students. The National Center for Improving Science Education makes the following distinction:

> Science proposes explanations for observations about the natural world.
>
> Technology proposes solutions for problems of human adaptation to the environment.

In science, we seek the "truth" about, for example, the basic constituents of matter or the reason why the sky is blue. Inherent in the pursuit is the sense that scientific explanations are tentative; as new knowledge is uncovered, the explanations evolve. But the desired goal of this pursuit is an answer that explains the scientific principle (the physics and chemistry, for example), behind the phenomenon.

In technology, no one best answer may exist for a given problem. Humans need protection and food, for example. Or they want to move objects from one place to another, or create objects of beauty to be shared and displayed. Numerous tools, strategies, techniques, and processes can be developed to solve these problems. Trade-offs among constraints and variables lead to one or more solutions. We may develop better ways to solve a problem over time, but we don't expect any given solution to be the one answer in the face of all variables and constraints.

Hand in hand, science and technology help us know enough about our world to make intelligent decisions that impact the quality of our lives and help us solve problems that ultimately impact that quality. Technologists develop tools that help us make new observations that advance science. Science reveals new knowledge that extends our ability to adapt to our environment. Taken together, science and technology in the MST classroom are combined to prepare students who not only create, design, and build, but understand the nature and behavior of the materials used in the building. They have the "know-why (science)" and the "know-how (technology)" that lead to creativity, ingenuity, and innovation.

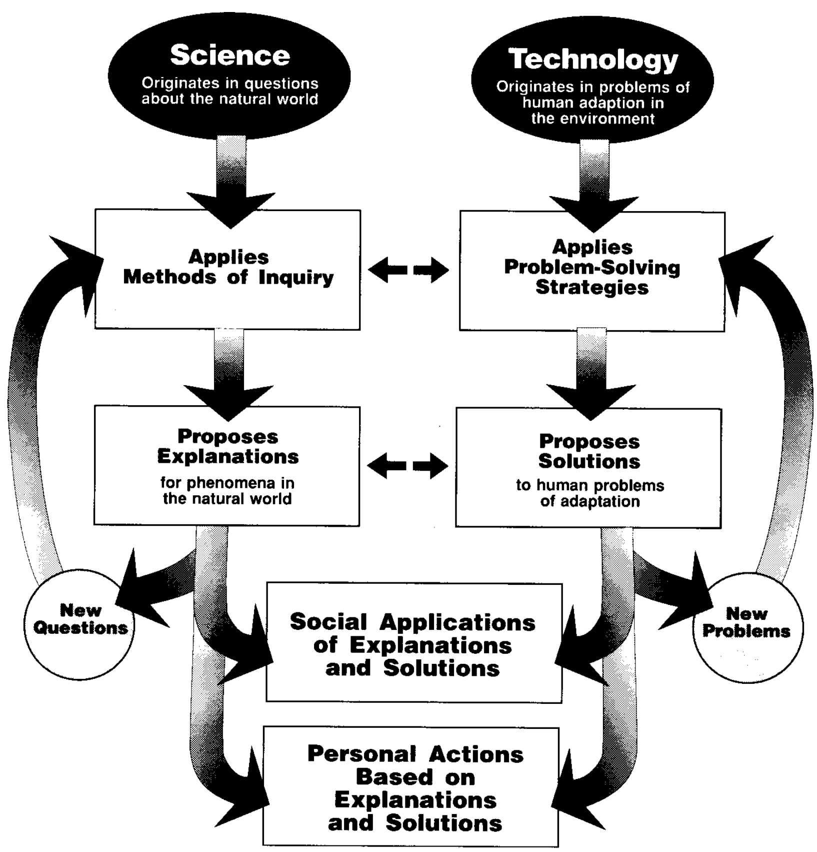


Figure 1.6. The Relationships between Science and Technology, (National Center for Improving Science Education)

How is Basic Science Linked to Everyday Materials?

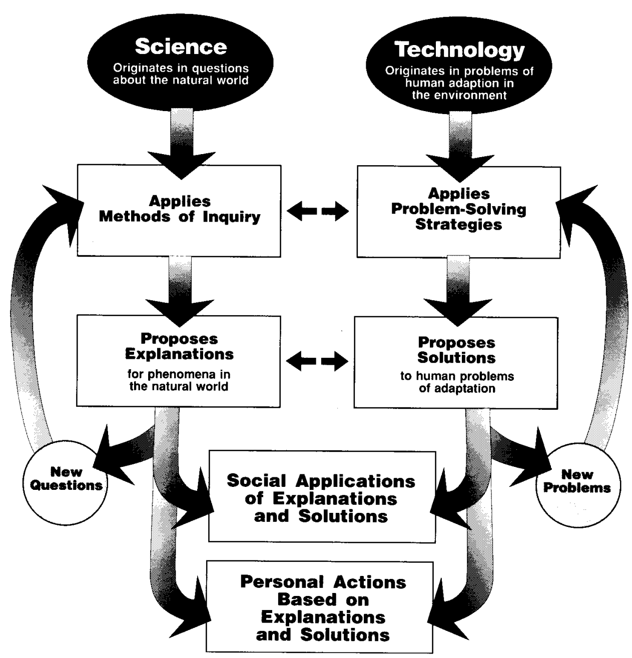
A primary application of materials science is matching the right material or combination of materials to the intended purpose and use of a specific product, such as a car. To do this, materials scientists must consider such things as the weight and strength of a certain material as well as its ability to conduct electricity or insulate the product from heat. They must also consider the material's chemical stability, corrosion resistance, and economy. This is the basic science part.

Table 1.1 shows some of the properties the major classes of materials exhibit. We use observable properties of materials to show the consequences of atomic- and molecular-level events. How atoms in different materials are bonded makes a profound difference in the properties they exhibit.

As students experiment with the different classes of materials, they will discover what terms like ductility mean and what makes these properties important in designing and producing stuff. Take the properties of metal, for example. The shared outer electrons of metal are wholly or partially responsible for high electrical conductivity, high thermal conductivity, and ductility. Ceramics exhibit the opposite properties as their localized, mostly ionic, bonding produces low electrical and low thermal conductivity and contributes to the extreme brittleness of ceramics. Students will also see as they experiment why one class of material is preferred over another for certain products and how they can change or "improve" certain materials.

"The metals, plastics, and glasses every human being uses must be the seed bed from which the periodic table and thermodynamics sprout."

—Rustum Roy, The Pennsylvania State University



A Short History of Materials Science

Humans have been using materials for at least 10,000 years of recorded history, but the real beginning of materials' use was long before recorded history. The first materials scientists may well have been Grog or Grogette (a fictional character of caveman origin) as Table 1.2 shows. In an initial, or "first," materials science era, men and women used materials just as they found them, with little or no modification. Even in these early times, though, they had reasons for choosing wood or stone objects for certain purposes.

In more recent times, during what is called the second era of materials history, humans learned enough chemistry and physics to use heat and chemicals to process natural materials to obtain what they needed. For example, researchers learned how to separate metals from ore by heat and reduction. These processes made available whole new classes of materials, most of them metals. Table 1.3 shows a longer listing of materials discovery through history (compiled by the *EPRI Journal*, December 1987).

Table 1.2. A Short History of Materials Science

Initial or First Era		
Grog/Grogette— The First Materials Scientist		Using things as found or with slight adaptation
8000 BC	Hammered copper	
6000 BC	Silk production	
Second Era		
5000 BC	Glass making	Changing things with heat or chemicals to improve properties
3500 BC	Bronze Age	
1000 BC	Iron Age	
(Hiatus, as scientific background develops)		
Third or Final Era		
1729 AD	Electrical conductivity of metals	Understanding, making new materials
1866	Microstructure of steel	
1866	Discovery of polymers	
1871	Periodic table	
1959	Integrated circuit	
1960	Artificial diamond	
1986	High-temperature superconductors	

Table 1.3. Materials Footnotes Through History

8000	Hammered copper
7000	Clay pottery
6000	Silk production
5000	Glass making
4000	Smelted copper
4000-3000	Bronze Age
3200	Linen cloth
2500	Wall plaster
2500	Papyrus
1000	Iron Age
300	Glass blowing
20	Brass alloy
105	Paper
600-900	Porcelain
1540	Foundry operation
late-1500s	Magnetization of iron demonstrated
1729	Electrical conductivity of metals demonstrated
1774	Crude steel
1789	Discovery of titanium
1789	Identification of uranium
1800	Volta's electric pile (battery)
1824	Portland cement
1839	Vulcanization of rubber
1850	Porcelain insulators
1850s	Reinforced concrete
1856	Bessemer steelmaking
1866	Microstructure of steel discovered
1866	Discovery of polymeric compounds
1868	Commercial steel alloy
1870	Celluloid
1871	Periodic table of the elements
1875	Open-hearth steelmaking
1880	Selenium photovoltaic cells
1884	Nitrocellulose (first man-made fiber)
1886	Electrolytic process for aluminum
1889	Nickel-steel alloy
1891	Silicon carbide (first artificial abrasive)
1896	Discovery of radioactivity
1906	Triode vacuum tube
1910	Electric furnace steelmaking
1913	Hydrogenation to liquefy coal
1914	X-ray diffraction introduced
1914	Chromium stainless steels
1923	Tungsten carbide cutting materials
1930	Beginnings of semiconductor theory
1930	Fiberglass
1934	Discovery of amorphous metallic alloys
1937	Nylon
1940s	Synthetic polymers

Table 1.3. (contd.)

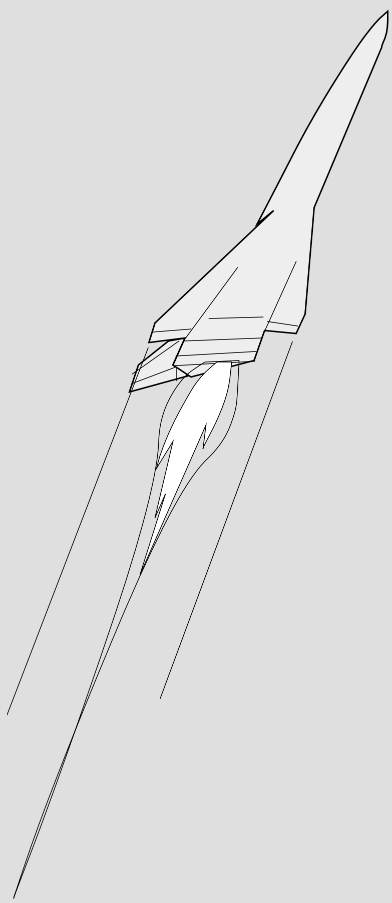
1947	Germanium transistor
1950	Commercial production of titanium
1952	Oxygen furnace for steelmaking
1950s	Silicon photovoltaic cells
1950s	Transmission electron microscope
mid-1950s	Silicon transistor
1957	First supercritical U.S. coal plant
1958	Ruby-crystal laser
1959	Integrated circuit
1960	Production of amorphous metal alloy
1960	Artificial diamond production
1960s	Microalloyed steels
1960s	Scanning electron microscope
1966	Fiber optics
late-1970s	Discovery of amorphous silicon
1984	Discovery of quasi-periodic crystals
1986	Discovery of high-temperature superconductors
1989	Buckyballs (Buckminsterfullerene)

About the time early polymers were introduced in the late 19th century, we had learned enough about organic chemistry to manipulate materials at the molecular level. At this point, it became possible to design specific materials to fit specific needs.

Designed materials constituted much of the accelerating pace of materials science. This has launched us into the third and final era of materials history, which began its accelerated pace in the 1950s. Today, we hear about newly designed materials daily as the demand for new and better materials gives rise to these new products.

Designed materials are probably best illustrated by composites, which allow us to reinforce materials at the right places and in the right amounts to minimize weight and produce the desired mechanical properties. The graphite tennis racquet, golf club shaft, and fishing rod are all products of this designed materials revolution, as are the wings of new high-performance aircraft such as the Harrier.

Advanced materials developed by Battelle and researchers at Pacific Northwest National Laboratory are described in the Resource Appendix.



A New Scientific Frontier

Atomic structure and chemical composition were once major focuses of materials science research. However, over the last few decades, this focus has changed dramatically as analytical chemistry, the electron microscope, X-ray diffraction, and a host of spectrometers have been developed that can analyze materials with accuracy.

Because scientists can now understand what materials are made of (chemical composition) and how they work (physical properties), the major focus of materials science has shifted to understanding how materials can be improved and what new materials can be developed to meet society's needs. These scientific advances caused a revolution in knowledge in materials. What was known about materials only 50 years ago could be printed in several volumes of books; today's advances fill shelves of books.

Examples of new materials abound and are reported regularly in newspapers and magazines. The space shuttle tile, which is used as a heat shield to protect the aluminum shell on the shuttle, is one example of this development of new and improved materials. When NASA (the National Aeronautics and Space Administration) decided to build a space shuttle that would rocket into orbit and eventually plunge through the atmosphere and land on the ground like an airplane, no known insulating material existed that would protect the flight crew from the fierce re-entry heat, be light enough to coat the entire craft, and be reused a number of times.

So, ceramists (materials scientists who work with ceramics) designed special tiles made from high-temperature glass fibers and sintered them to form a rigid, but almost unbelievably light structure. These tiles are glued to the shuttle with silicone rubber and now do an admirable job of keeping heat away from the crew. The ceramists designed the tiles from "scratch" by adapting their knowledge of glass properties to meet the needs of the space shuttle. (See the Appendix to find out how you can order a space shuttle tile from NASA for your classroom experiments.) Further development continues as less bulky and more reliable materials are being developed to shield the Orient Express, a supersonic transport being developed for near-space travel over long distances around the Earth.

Materials Science in Our Everyday Lives

Another example of the development of new materials is in biomedicine. The recent controversy over silicone breast implants shows how much care must be taken in choosing, testing, and using materials that are used inside human bodies. More successful examples of materials developed for human bodies are such things as hip, knee, and finger joint replacements made from composite materials.

"Technology provides the eyes and ears of science—and some of the muscle, too."

—AAAS Project 2061 Science for All Americans

A modern automobile is a good example of how materials have changed to keep pace with industry and culture. The American car of the 1950s was a durable machine and pretty well suited to its environment. Gas was cheap, metal was thick and lavishly used. The resulting car was heavy, but Americans demanded high performance for use on newly built freeways designed for speeds of at least 75 miles per hour. Engines were correspondingly large, with displacements approaching 500 cubic inches (that's about 8 liters!). Americans tended to abuse these cars, and they were built to take abuse.

No one ever claimed these cars were fuel efficient. Then came the oil shock of 1973, and cars had to change radically, and have kept changing to meet the demand for more fuel-efficient transportation. In the quest for efficiency, car weight was reduced, and some changes were made in streamlining. Sheet metal used to build car bodies became much thinner and had to be much stronger. Unit body construction provided a way to produce stiffness without all the weight of a separate frame. Plastics and aluminum were used extensively in many parts of the car, and aluminum use increased dramatically.

The electronics revolution has provided onboard computers to manage the fuel and ignition systems of the engine, which now operate much closer to optimum parameters because of the need for both fuel efficiency and reduced emissions. Removing lead from gasoline stimulated use of better alloys for valves and valve seats. Spark plugs no longer exposed to lead deposits last 30,000 miles. Many other changes have occurred to the automobile, and you and your students doubtless know a few more.

However you look at it, materials have become a scientific frontier that continues to develop new and improved ways for people to live and travel now and in the future.

Looking at MST as a Career— "The Field of Dreams"

Materials engineers and scientists will be required in ever-greater numbers as designs for everything from tennis racquets to space shuttles are driven harder by requirements for ever-higher efficiency in manufacturing and by use and re-use of materials. And, increasingly, the disposal of used materials will require attention with emphasis on recycling these materials. "Environmentally friendly" materials that can be produced, used, and disposed of without harmful effects to the biosphere is a field of study just beginning to emerge. This will require much research in our future. But, whether the need in 2010 is for 1000 materials scientists or 100,000, matters little. The greater need is for technologically literate citizens.

Examples of ways materials science has become a career for a number of people are highlighted in the this section.

"In the years ahead, materials science will truly be the field of dreams. The special knowledge and skills of materials scientists will be needed to develop and produce materials that make other things possible....materials that enable us to fulfill our dreams of traveling and working in space, cleaning up the environment, improving the quality of life, revitalizing our industrial complex, restoring our economic competitiveness, and conserving and making better use of our resources."

—Adrian Roberts, Brookhaven, National Laboratory Associate Director for Applied Science and Technology

Materials Scientists at Work

Mary Bliss

Astronomy was my first love. I joined an amateur astronomy club when I was 13 or 14. What I really liked about it was light and telescopes. At my high school, if you were good in science, that meant biology and you wanted to be a doctor or nurse. Chemistry was taught like history. The labs were set up to reproduce some result, and everything seemed to be known. So, instead of doing a regular senior year of high school, I enrolled in an advanced studies program for high school students at Pace University. I took chemistry and liked it this time. By the time I finished high school, I had 29 college credits.

"One January session I also signed up for a class called Gemstones: Myth and Mystery with a professor in the College of Ceramics. I had a blast! I got to run the transmission electron microscope myself."

—Mary Bliss

I was in my sophomore-level classes when I arrived at Alfred University with my 29 credits. I wanted to take physics because I was still interested in astronomy. I also took organic chemistry because I figured if I didn't like physics, maybe I would major in chemistry. I never worked so hard in my life. I didn't have the faintest ideas of what was going on in physics. Having a study partner was the only way I could handle those classes. One January session I also signed up for a class called Gemstones: Myth and Mystery with a professor in the College of Ceramics. I had a blast! I got to run the transmission electron microscope myself. We found an error in the literature, and I ended up presenting the paper at a regional society meeting and won an award for the best undergraduate research project at Alfred. So, professors in the Ceramics Department encouraged me to change my major. Besides, in exchange for changing my major, one ceramics professor was going to give me a matched pair of Herkimer diamonds.

I worked the summers of my junior and senior years at Corning Glass Works in Corning, New York. I learned what engineers do all day there. I also met some really good engineers. I liked Corning, but I knew I wouldn't be happy as a production engineer forever. So, I got a master's degree in ceramic science at Penn State University (working on piezoelectric materials). I wasn't very happy with this work so I did my doctorate in the Solid State Science Department doing spectroscopy on silicate minerals. What strikes me most is that I liked spectroscopy even when I was in high school.

Mike Schweiger

As I was growing up, I had an innate curiosity about bugs, animals, trees, plants, and most anything in nature. I loved incubating eggs and raising chicks. My heart was always broken the day the chicks were taken away to a farm because they had grown too big for the house we had in Idaho Falls. I raised other animals more acceptable to a city environment when I had time, such as ants, frogs, bunnies, snails, caterpillars, and water striders.

As a vivid memory of these years, I retain a large scar on my arm from when I excitedly raced down the hall of our home with a 3-pound glass peanut butter jar full of the latest collection of ants for my ant farm. I tripped on some toys and fell on the shattered jar, severely cutting my left arm. This incident had no effect on my love of living things.

I liked biology and chemistry throughout school. I graduated from college as a teacher with a major in natural sciences. As I taught grade school, students enjoyed learning science, and it was one of my favorite subjects to teach. I found out I wasn't teacher material, and after 5 years in the education field, I joined the Materials Science Department at Battelle as a technician.

I was assigned to the glass development laboratory in the basement of Battelle's Physical Sciences Building. I was determined to take this position so I would have an easier time transferring to the Biology Department. The in-depth study of glass intrigued me, however, and I turned some of my love of nature into studying inorganic materials. There is something intriguing about making glass out of common, dull elements of the earth and having it melt and then cool into a material that can be clear and smooth. This same material can also be heat treated and crystallized, and these crystals are a unique world of their own and a part of nature not readily seen or understood.

My 14 years at Battelle have been involved with this small area of materials study. The field is so vast I know I could spend the rest of my life studying glass and still only have understood some of the science of this material. I look forward to the interesting career ahead of me.

"There is something intriguing about making glass out of common, dull elements of the earth and having it melt and then cool into a material that can be clear and smooth."

—Mike Schweiger