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ПЕРЕДМОВА

У сучасному світі знання іноземної мови є не лише необхідністю для загального розвитку, а й важливим елементом професійної компетентності майбутніх фахівців технічних спеціальностей. Володіння професійною іноземною мовою відкриває нові можливості для розвитку кар'єри, співпраці з міжнародними партнерами, а також для використання передових технологій і наукових досягнень.

Методичний посібник «Іноземна мова професійного спрямування» для студентів технічних спеціальностей» розроблений з урахуванням потреб майбутніх фахівців у сфері техніки та технологій. Мета цього видання — допомогти студентам оволодіти базовими мовними знаннями та навичками, необхідними для професійної діяльності, а також розвинути вміння ефективно використовувати іноземну мову в різних ситуаціях професійного спілкування.

Посібник складається із двох частин. Перша частина містить сучасні професійно-орієнтовані тексти та комплекс вправ, спрямованих на засвоєння нових лексичних одиниць-термінів, що ними оперують фахівці-інженери у своїй професійній діяльності. Кожен юніт першої частини має вправи та ситуативні задачі для формування та розвитку навичок монологічного та діалогічного мовлення. Друга частина складається із автентичних текстів професійного спрямування для позааудиторного читання та збагачення словникового запасу студента. Посібник можна використовувати як на практичних заняттях англійської мови, так і для самостійної роботи студентів.

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UNIT 1
Engineering

Engineering is the application of science to make the most of the resources of nature for the benefit of humankind. The Engineers Council for Professional Development in the US says that engineering is all about using scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works that use them in some way. It also includes building or operating these things with a good understanding of how they work and what they're designed to do, as well as predicting how they'll behave in certain situations. The term engineering is sometimes used more loosely, especially in Great Britain, to mean the manufacture or assembly of engines, machine tools and machine parts.

The words 'engine' and 'ingenious' come from the same Latin root, 'ingenerare', which means 'to create'. The word 'engine' in English originally meant 'to contrive'. So, the engines of war were things like catapults, floating bridges and assault towers. The person who designed them was the military engineer, or 'engineer'. The civil engineer is basically the military engineer's counterpart. They use the same knowledge and skills to design buildings, streets, water supplies, sewage systems, and other projects.

Engineering is a field with a lot of specialized knowledge, and professionals have to undergo extensive training to learn how to apply that knowledge in practice. Professional societies, usually set up at a national or regional level, work to maintain standards of engineering practice. All members have a responsibility to the public, above and beyond their responsibilities to their employers or to other members of their society.

The scientist's job is to know, while the engineer's job is to do. Scientists add to our understanding of the physical world, while engineers use this knowledge to solve practical problems. Engineering is mostly about physics, chemistry and maths, and how they can be used in materials science, solid and fluid mechanics, thermodynamics, transfer and rate processes, and systems analysis.

Engineers aren't free to choose the problems they work on, unlike scientists. They have to solve problems as they come up, and their solutions have to meet conflicting requirements. As a rule of thumb, efficiency costs money, safety adds to the complexity, and improved performance increases weight. The engineering solution is the best one, taking many factors into account and aiming for the end result that is most desirable. It might be the most reliable one within a given weight limit, the simplest that will satisfy certain safety requirements, or the most efficient one for a given cost. A lot of engineering problems have a big social and environmental impact.

Engineers use two types of natural resources: materials and energy. Materials are useful because of what they can do: they can be strong, easy to make, light, or long-lasting; they can insulate or conduct; they can be chemical, electrical, or acoustic. Important sources of energy include fossil fuels (coal, petroleum, natural gas), wind, sunlight, falling water, and nuclear fission. Since most resources are limited, engineers must think about how to develop new resources as well as how to use existing ones in a more efficient way.

Exercise 1. Choose the correct answer:

1. What is the primary goal of engineering?
   ○ a) To study nature
   ○ b) To apply science for human benefit
   ○ c) To observe natural phenomena
   ○ d) To control the environment
2. What does the term "engineering" refer to in Great Britain?
   ○ a) Designing buildings
   ○ b) The manufacture of engines and machines
   ○ c) Developing scientific theories
   ○ d) Operating vehicles
3. Which of the following is NOT considered a natural resource used by engineers?
   ○ a) Wind
   ○ b) Sunlight
   ○ c) Nuclear fission
   ○ d) Plastic
4. The Latin root 'ingenerare' means:
   ○ a) To build
   ○ b) To create
   ○ c) To destroy
   ○ d) To experiment
5. What are the main sciences involved in engineering?
   ○ a) Biology, physics, and chemistry
   ○ b) Physics, chemistry, and mathematics
   ○ c) Physics, literature, and history
   ○ d) Chemistry, sociology, and mathematics
6. What is the role of a civil engineer according to the text?
   ○ a) To design engines for war

- b) To solve practical problems for society
- c) To maintain machines
- d) To manage manufacturing processes

7. Engineers must consider conflicting requirements like:
- a) Weight, complexity, and cost
- b) Time, safety, and color
- c) Performance, aesthetics, and fashion
- d) Profit, materials, and location

8. What type of energy is not renewable?
- a) Solar
- b) Wind
- c) Fossil fuels
- d) Hydroelectric

9. What responsibility do engineers have beyond their employers?
- a) To make profits
- b) To serve the public
- c) To create new machines
- d) To improve performance

10. What are "transfer and rate processes" an example of in engineering?
- a) Social sciences
- b) Engineering disciplines
- c) Mathematics applications
- d) Chemistry concepts

Exercise 2. True or False:

1. Engineers are free to choose the problems they work on. (True/False)
2. Efficiency always reduces costs in engineering. (True/False)
3. Scientists add to our knowledge, while engineers apply that knowledge to solve problems. (True/False)
4. The word 'engineer' comes from the Latin word for 'to destroy'. (True/False)
5. Civil engineers originally used military engineering knowledge to build civilian structures. (True/False)
6. Materials science is irrelevant to most engineering fields. (True/False)
7. Renewable energy sources include wind and sunlight. (True/False)
8. Engineers must balance performance with safety and cost. (True/False)
9. The only responsibility engineers have is to their employers. (True/False)

10. Engineering problems often have a social and environmental impact. (True/False)

Exercise 3. Fill in the Blanks

1. Engineering is the application of ___________ to solve practical problems.
2. Engineers use ___________ and ___________ resources.
3. The term 'engineering' is sometimes used to refer to the manufacture of ___________ and machine parts.
4. Civil engineers work on projects like streets, water supplies, and ___________ systems.
5. Engineers must take into account conflicting requirements such as efficiency, safety, and ___________.
6. Engineers must think about developing new ___________ and using existing ones efficiently.
7. Fossil fuels, wind, and nuclear fission are sources of ___________.
8. ___________ adds to the complexity of engineering solutions.
9. Engineering relies heavily on physics, chemistry, and ___________.
10. Professional societies ensure that engineers maintain high standards of ___________.

Exercise 4. Match the terms on the left with their correct definitions on the right:

Term	**Definition**
1. Civil engineer	a) Applies scientific knowledge to solve problems
2. Energy	b) Designing structures like streets and buildings
3. Materials	c) Includes fossil fuels, wind, and sunlight
4. Engineering	d) Substance used in engineering for their properties
5. Safety	e) Ensuring a design does not pose risk

6. Scientist	f) Someone who adds to our understanding of the world
7. Transfer	g) The movement of energy or matter
8. Efficiency	h) Achieving more output with less input
9. Cost	i) An expense related to creating or maintaining work
10. Complexity	j) The degree to which a system has intricate parts

Exercise 5. Give short answers to the questions

1. What is the main difference between scientists and engineers according to the text?
2. What are the two types of resources engineers use?
3. What types of projects do civil engineers typically work on?
4. How does efficiency affect cost and complexity in engineering?
5. What are some of the main sciences that engineering relies on?
6. Why do engineers have to consider conflicting requirements in their solutions?
7. What is the role of professional engineering societies?
8. How do renewable and non-renewable energy sources differ?
9. What impact do engineering solutions have on society and the environment?
10. Why is safety important in engineering?

Exercise 6. Complete the sentences

1. Engineers apply ___________ principles to solve practical problems.
2. Civil engineers use similar knowledge to ___________ engineers.
3. Scientists work to ___________ knowledge, while engineers ___________ that knowledge.
4. Efficiency often ___________ the cost of an engineering solution.
5. Engineering relies on natural resources like ___________ and ___________.
6. Materials used in engineering can have properties such as strength, conductivity, or ___________.

7. The word 'engineer' is derived from the Latin root meaning __________.

8. Engineering often involves __________ trade-offs between cost, safety, and performance.

9. Engineers have a responsibility to the __________, in addition to their employers.

10. Fossil fuels are a limited resource, so engineers need to think about using them __________.

Exercise 7. Discuss the following questions

1. How do engineers balance conflicting requirements like cost, safety, and performance in their work?
2. What is the significance of renewable energy sources in modern engineering?
3. In what ways do engineering solutions impact society and the environment?
4. How does the role of a civil engineer differ from that of a military engineer?
5. Why is the responsibility to the public so important for engineers?
6. How does engineering contribute to the development of new resources?
7. What role does efficiency play in the design of machines and structures?
8. What are some challenges engineers face when using limited natural resources?
9. How do engineers predict how their designs will behave in specific situations?
10. How do engineering and science complement each other in solving global problems?

Exercise 8. Answer the following questions in short paragraphs:

1. Why must engineers take into account the limited availability of natural resources when designing solutions?
2. How do conflicting requirements like weight and safety challenge engineers when creating new designs?
3. Discuss how renewable energy resources might change the future of engineering.
4. How do engineers contribute to the well-being of society, beyond creating machines or buildings?

5. How can improving efficiency in engineering benefit both the economy and the environment?

Exercise 9. Problem-Solving Scenarios

1. You are an engineer tasked with designing a bridge. You have limited materials and a strict budget. How will you prioritize safety, efficiency, and cost?
2. Your project involves creating a device that needs to be lightweight but also durable. What materials would you consider and why?
3. You are developing a machine that uses renewable energy. What energy sources will you choose, and how will you ensure the machine operates efficiently?
4. A new city project requires the design of a water supply system. As a civil engineer, what factors must you consider to ensure sustainability and efficiency?
5. Your engineering team needs to reduce the weight of a car without sacrificing safety. What trade-offs will you make?

Exercise 10. Use the following vocabulary from the text in your own sentences:

1. Engineering
2. Efficiency
3. Renewable
4. Materials
5. Civil engineer
6. Energy
7. Safety
8. Professional society
9. Conflicting requirements
10. Thermodynamics

Exercise 11. Discuss the following questions in pairs or groups:

1. How do engineers manage conflicting requirements such as efficiency, safety, and cost in their designs?
2. What role do renewable energy sources play in the future of engineering?
3. How do you think the balance between science and engineering is important for solving global challenges?
4. What are some of the biggest social and environmental impacts of engineering solutions?

5. Why is the responsibility to the public a crucial aspect of being a professional engineer?

Exercise 12. Role-play the following scenario with a partner:

One of you is an engineer working on a new sustainable energy project, and the other is a member of the public concerned about environmental impact. Discuss the benefits and challenges of using renewable resources versus traditional energy sources like fossil fuels.

Exercise 13. Explain the Concept

1. The difference between civil and military engineering.
2. The meaning of efficiency in engineering and its impact on cost and complexity.
3. How engineers use scientific principles to solve practical problems.
4. The importance of balancing safety, cost, and performance in engineering projects.
5. The role of professional societies in maintaining engineering standards.

Exercise 14. Debate the following topic in two teams:

"Engineering solutions should prioritize environmental sustainability over cost and efficiency."

Exercise 15. Prepare a short presentation on one of the following topics:

1. How engineers use natural resources like materials and energy to solve practical problems.
2. The evolution of civil engineering and its impact on modern infrastructure.
3. The future of engineering in a world focused on renewable energy and sustainability.
4. How the responsibilities of engineers extend beyond their employers to society as a whole.
5. The differences between scientific research and engineering problem-solving, and why both are necessary.

UNIT 2
Engineering functions

Problem solving is common to all engineering work. The problem may involve quantitative or qualitative factors; it may be physical or economic; it may require abstract mathematics or common sense. Of great importance is the process of creative synthesis or design, bringing together ideas to create a new and optimal solution.

Although engineering problems vary in size and complexity, the general approach is the same. It starts with an analysis of the situation and a preliminary decision on a plan of attack. Following this plan, the problem is reduced to a more categorical question that can be clearly stated. The stated question is then answered by deductive reasoning from known principles or by creative synthesis, as in a new design. The answer or design is always checked for accuracy and appropriateness. Finally, the results for the simplified problem are interpreted in terms of the original problem and reported in an appropriate form.

In order of decreasing importance, the main functions of all branches of engineering are as follows

Research. Using mathematical and scientific concepts, experimental techniques and inductive reasoning, the research engineer seeks new principles and processes.

Development. Development engineers apply the results of research to useful purposes. The creative application of new knowledge may result in a working model of a new electrical circuit, chemical process or industrial machine.

Design. In designing a structure or product, the engineer selects methods, specifies materials and determines forms to meet technical requirements and performance specifications.

Construction. The construction engineer is responsible for preparing the site, determining procedures that will achieve the desired quality economically and safely, directing the placement of materials, and organising personnel and equipment.

Production. Plant layout and equipment selection are the responsibility of the production engineer, who selects processes and tooling, integrates the flow of materials and components, and provides for testing and inspection.

Operations. The operations engineer controls machinery, plant and organisations that provide power, transport and communications, establishes procedures and supervises personnel to achieve reliable and economical operation of complex equipment.

Management and other functions. In some countries and industries, engineers analyse customer needs, recommend equipment to meet those needs economically, and solve related problems.

Exercise 1. Choose the correct answer:

1. What is a common factor in all engineering work?
   ○ a) Problem-solving
   ○ b) Creativity
   ○ c) Management
   ○ d) Construction
2. What does creative synthesis in engineering involve?
   ○ a) Abstract mathematics
   ○ b) Testing and inspection
   ○ c) Bringing ideas together to create a new solution
   ○ d) Plant layout
3. Which of the following is **not** mentioned as part of the engineering process?
   ○ a) Design
   ○ b) Analysis
   ○ c) Manufacturing
   ○ d) Reporting
4. The first step in solving an engineering problem is:
   ○ a) Deductive reasoning
   ○ b) Creative synthesis
   ○ c) Analyzing the situation
   ○ d) Reporting the results
5. In the order of importance, which is considered the most important engineering function?
   ○ a) Construction
   ○ b) Research
   ○ c) Operations
   ○ d) Production
6. What is the primary role of a research engineer?
   ○ a) To control machinery
   ○ b) To find new principles and processes
   ○ c) To supervise personnel
   ○ d) To design products
7. What does a design engineer focus on?
   ○ a) Plant layout
   ○ b) Site preparation
   ○ c) Choosing methods, materials, and forms

- ○ d) Selecting processes and tooling

8. Which engineer is responsible for preparing construction sites and organizing personnel?
   - ○ a) Research engineer
   - ○ b) Construction engineer
   - ○ c) Production engineer
   - ○ d) Operations engineer
9. What is the role of an operations engineer?
   - ○ a) To design new machines
   - ○ b) To control equipment and manage operations
   - ○ c) To develop new electrical circuits
   - ○ d) To analyze customer needs
10. In some countries, engineers are involved in:
    - ○ a) Recommending equipment to meet customer needs
    - ○ b) Working only in laboratories
    - ○ c) Providing military support
    - ○ d) Working only in design roles

Exercise 2: Decide if the statement is true or false

1. Problem-solving is unique only to the field of engineering. (True/False)
2. Engineering problems can be either physical or economic in nature. (True/False)
3. The research engineer's main task is to manage personnel. (True/False)
4. The development engineer applies research results to practical use. (True/False)
5. A construction engineer is responsible for site preparation and organization. (True/False)
6. Deductive reasoning is never used in engineering problem-solving. (True/False)
7. A design engineer selects methods and materials to meet performance specifications. (True/False)
8. The final step in solving an engineering problem is often reporting the results. (True/False)
9. Operations engineers work mostly with machinery and equipment. (True/False)
10. Engineers in some countries analyze customer needs as part of their job. (True/False)

Exercise 3: Fill in the Blanks

1. Engineering involves solving both __________ and __________ problems.
2. Creative __________ is essential for designing new solutions.
3. The first step in engineering problem-solving is __________ the situation.
4. Research engineers focus on discovering new __________ and processes.
5. Development engineers apply research results to create working __________.
6. In design, engineers specify materials and determine __________.
7. Construction engineers are responsible for organizing __________ and preparing the __________.
8. Production engineers manage plant layout and equipment __________.
9. Operations engineers control machinery and manage __________.
10. Engineers may also analyze __________ needs in some industries.

Exercise 4. Match the engineering functions with their definitions:

Function	Definition
1. Research	a) Control and management of machinery and personnel
2. Development	b) Application of research results to practical uses
3. Design	c) Finding new principles and processes
4. Construction	d) Preparing sites and organizing materials and personnel
5. Production	e) Choosing plant layout and equipment, integrating materials
6. Operations	f) Creating new products or structures

Exercise 5. Give short answers to the questions:

1. What is the general approach to solving engineering problems?
2. How does creative synthesis contribute to engineering design?
3. What is the role of deductive reasoning in solving engineering problems?
4. What does a research engineer typically focus on?

5. How does a development engineer differ from a design engineer?
6. What responsibilities does a construction engineer have?
7. What is the role of a production engineer in a manufacturing setting?
8. How do operations engineers ensure reliable and economical operations?
9. Why is reporting an important part of the engineering process?
10. How do engineers use both quantitative and qualitative factors in problem-solving?

Exercise 6. Complete the sentences:

1. Problem-solving is common to all ___________ work.
2. Engineers use creative ___________ to bring ideas together.
3. The process of engineering starts with an analysis of the ___________.
4. Research engineers use ___________ and scientific principles to find new processes.
5. Development engineers apply new knowledge to create working ___________.
6. Design engineers choose methods and materials to meet ___________ specifications.
7. The construction engineer is responsible for preparing the ___________ and organizing personnel.
8. The production engineer integrates the flow of ___________ and components.
9. Operations engineers control ___________ and plant operations.
10. In some countries, engineers also ___________ customer needs.

Exercise 7. Discuss:

1. What skills and qualities do engineers need to solve complex problems effectively?
2. How does creative synthesis differ from deductive reasoning in the engineering process?
3. Why is research an essential part of engineering, especially in developing new technologies?
4. What is the importance of design in the overall engineering process?
5. How do engineers ensure the safety and efficiency of construction projects?
6. How do production engineers balance the need for efficiency and quality in manufacturing?

7. What role do operations engineers play in the success of industrial plants?
8. How does the engineering process help solve both physical and economic problems?
9. What challenges do engineers face when managing large-scale projects?
10. How do engineers ensure their solutions are both cost-effective and innovative?

Exercise 8. Answer the following in short paragraphs:

1. Why is creative synthesis important in engineering, and how does it contribute to innovation?
2. What are the challenges engineers face when working with complex, multi-disciplinary problems?
3. How does the role of a design engineer differ from that of a construction engineer in real-world projects?
4. Discuss the importance of accurate reporting in the engineering process.
5. What are the potential consequences if an operations engineer fails to manage complex machinery effectively?

Exercise 9. Problem-Solving Scenarios

1. You are an engineer designing a new machine. How will you balance safety, cost, and efficiency?
2. You’ve been asked to develop a new chemical process. What steps would you take to ensure it is both safe and innovative?
3. As a construction engineer, you encounter a problem with the placement of materials. How will you solve it while staying within budget?
4. You are tasked with optimizing a manufacturing plant’s layout. What factors would you consider to improve efficiency?
5. A client requests an energy-efficient building. As a design engineer, how will you approach the project to meet their needs?

Exercise 10. Use the following vocabulary from the text in your own sentences:

1. Synthesis
2. Deductive reasoning
3. Research
4. Development
5. Construction

6. Production
7. Operations
8. Materials
9. Machinery
10. Problem-solving

Exercise 11. Role-play the following scenario with a partner:

One of you is an operations engineer explaining to a manager why a machine is malfunctioning. The other plays the manager, who is concerned about how to fix it and maintain productivity.

Exercise 12. Debate the following topic:

- **Topic:** "Which engineering function is the most important for society: Research, Development, or Operations?"
-

Exercise 13. Explain the Concept

1. The difference between a design engineer and a construction engineer.
2. How deductive reasoning is used in solving engineering problems.
3. The role of research in developing new engineering technologies.
4. The responsibilities of a production engineer in a manufacturing setting.
5. How operations engineers ensure the reliable operation of complex systems.

Exercise 14. Prepare a 2-3 minute presentation on one of the following topics:

1. The role of creative synthesis in engineering design.
2. The challenges of managing large construction projects.
3. How research engineers contribute to technological innovation.
4. The importance of accurate reporting in engineering projects.
5. The role of engineering in solving economic and physical problems.

Exercise 15. Discuss in a group:

How can engineers balance environmental concerns with economic efficiency in large-scale projects? Share ideas from the text and your own experiences.

UNIT 3

Importance Of Computers In Engineering

Every technical graduate knows about the importance of computers in engineering there use to be three main branches in traditional engineering

Traditional engineering that worked well in the past two centuries are

Civil engineering

Electrical engineering

Mechanical engineering

The late 1900 year went into rapid progress after the invention of transistors in Bell Laboratory which replaced the huge vacuum tubes.

Due to the use of vacuum tubes the size of traditional computers used to occupy large storied buildings.

This issue was resolved by the heavy use of transistors and integrated circuits in 1, 2 and 3rd generations of computers past 2000 years which gave rise to microcomputers or more commonly known as personal computers.

Later in the 21st century, the advent of laptops and tablets changed the whole way of computing in the 4th generation of computers,

The use of smartphones, Laptops, and the Internet in combination with various Personal digital assistance is significant in our daily routine activities.

All new engineering branches such as

Information technology,

Computer science engineering

Electronics and communication

These all-new branches of engineering brought about new inventions of today such as Big data, Artificial Intelligence, Predictive Analytics, the Internet Of Things, machine learning, and Cloud computing

Computer engineering deals with information processing with programming and instructing the hardware to perform a particular task, Now we have Big data analysis which works in synchronization with various inputs from diverse platforms.

Use of Computers in Civil engineering

There is a lot of use of computer processing in the blueprint designing of infrastructure commercial civil engineering buildings through the use of CAD with the use of computers in engineering design.

Uses of Computers in Mechanical engineering

Computers are used in designing graphics, and automated control of manufacturing. In mechanical engineering, JCB cranes are integrated with high-end computers to perform tasks. There are a lot of uses for computers in engineering and manufacturing.

Uses of Computers in Electrical engineering

In electrical engineering, the power distribution is controlled and monitored through the use of smart computers which divert a load of heavy-use electricity consumption to overcome blackouts in the electricity grid. Computers play a vital role in the operation and proper functioning of various electrical appliances.

Uses of Computers in Information Technology engineering

In newer versions of engineering top-rated smart computers play a vital role in information technology. Cyberspace is the best example of this.

Uses of Computers in Electronics and communication engineering

In the electronics and communication base receiver station is integrated with high computing power to maintain flawless virtual communications. A smartphone is the best example of the use of computers in embedded engineering now we have android phones multitasking on various mobile apps.

Uses of Computers in computer science engineering

The advent of Big Data, Predictive Analytics in eCommerce, the Internet of things, machine learning, and artificial intelligence are the best examples of it.

Source: https://www.jbitdoon.com/blog/importance-of-computers-in-engineering/

Exercise 1. Choose the correct answer:

1. What replaced vacuum tubes in computers?
   - a) Diodes
   - b) Transistors
   - c) Capacitors
   - d) Microprocessors
2. Which century saw the invention of laptops and tablets?
   - a) 19th century
   - b) 20th century
   - c) 21st century
   - d) 18th century
3. What is CAD primarily used for in civil engineering?
   - a) Controlling electrical grids
   - b) Designing blueprints of infrastructure
   - c) Predictive analysis
   - d) Managing Big Data

4. How do computers assist in mechanical engineering?
   - a) Powering smart appliances
   - b) Controlling power distribution
   - c) Designing graphics and automated control of manufacturing
   - d) Collecting data from the Internet of Things
5. What is the key role of computers in electrical engineering?
   - a) Creating architectural designs
   - b) Monitoring power distribution and preventing blackouts
   - c) Designing software applications
   - d) Developing smartphones
6. What is a major example of the use of computers in Information Technology?
   - a) CAD software
   - b) Cyberspace
   - c) Civil engineering structures
   - d) Manufacturing processes
7. Which engineering branch deals with multitasking in smartphones?
   - a) Civil engineering
   - b) Computer science engineering
   - c) Electronics and communication engineering
   - d) Electrical engineering
8. What gave rise to personal computers?
   - a) Invention of smartphones
   - b) Development of artificial intelligence
   - c) Use of transistors and integrated circuits
   - d) Creation of CAD software
9. Big Data and machine learning are examples of advancements in which field?
   - a) Civil engineering
   - b) Electronics and communication engineering
   - c) Information Technology
   - d) Computer science engineering
10. What is a common use of computers in mechanical engineering?
   - a) Monitoring power grids
   - b) Predictive analysis in eCommerce
   - c) Automated control of manufacturing
   - d) Controlling base receiver stations

Exercise 2. Decide if the statement is true or false

Vacuum tubes were replaced by transistors in Bell Laboratory. (True/False)

1. Civil engineers use CAD software for blueprint designs. (True/False)
2. Computers in mechanical engineering are mainly used for electrical circuit design. (True/False)
3. Smartphones are an example of the use of computers in embedded systems engineering. (True/False)
4. Big Data is mostly used in civil engineering. (True/False)
5. Laptops and tablets became common during the 19th century. (True/False)
6. Computers in electrical engineering help prevent blackouts by managing electricity grids. (True/False)
7. Cyberspace is an important element of Information Technology engineering. (True/False)
8. Personal computers were introduced before the invention of transistors. (True/False)
9. Machine learning is an example of an advancement in electronics and communication engineering. (True/False)

Exercise 3: Fill in the Blanks

1. The invention of ___________ replaced vacuum tubes in computers.
2. ___________ are used in civil engineering for designing blueprints of buildings.
3. ___________ is an example of the use of computers in mechanical engineering.
4. Computers help in electrical engineering by monitoring and controlling ___________.
5. The use of ___________ revolutionized computing in the 21st century.
6. Smartphones are an example of the use of computers in ___________ engineering.
7. Information Technology relies heavily on ___________, such as cyberspace.
8. Transistors and integrated circuits gave rise to ___________ computers.
9. Big Data analysis works with inputs from diverse ___________.
10. The field of ___________ deals with programming and information processing.

Exercise 4. Match the engineering branch with its computer application:

Engineering Branch	Computer Application
1. Civil engineering	a) Monitoring electricity grids
2. Mechanical engineering	b) Designing blueprints using CAD
3. Electrical engineering	c) Automated control of manufacturing
4. Electronics and communication	d) Multitasking smartphones on mobile apps
5. Information Technology engineering	e) Managing cyberspace

Exercise 5. Give short answers to the questions

1. How did the invention of transistors impact traditional computers?
2. What role do computers play in civil engineering?
3. How are computers integrated into mechanical engineering tasks?
4. Describe the use of computers in electrical engineering.
5. How has the advent of smartphones changed communication engineering?
6. What are some key inventions brought about by computer science engineering?
7. How do computers contribute to the prevention of electrical blackouts?
8. What is the role of CAD software in modern engineering?
9. Explain the significance of Big Data in today's technological world.
10. How have laptops and tablets changed the way computing is performed?

Exercise 6. Complete the sentences

1. Computers in civil engineering are used for __________.
2. In mechanical engineering, computers help with __________ and manufacturing automation.
3. The introduction of transistors in computers replaced __________.
4. Electrical engineers use computers to __________ electricity grids and manage power distribution.
5. The field of electronics and communication engineering uses high computing power to __________.
6. Laptops and smartphones revolutionized computing in the __________ century.
7. Big Data and Artificial Intelligence are significant advancements in __________ engineering.

8. Civil engineers rely on __________ to create detailed infrastructure designs.
9. Mechanical engineers use computers to control __________ like JCB cranes.
10. Cyberspace is a key example of the use of computers in __________.

Exercise 7. Discuss:

1. How has the role of computers in engineering evolved over the past century?
2. Why are transistors and integrated circuits considered pivotal in the history of computing?
3. What are the benefits of using CAD software in civil engineering?
4. How do computers enhance the efficiency of manufacturing in mechanical engineering?
5. Discuss the importance of smart computers in controlling power distribution in electrical engineering.
6. How have smartphones transformed the field of electronics and communication?
7. Why is Big Data analysis critical in modern computing?
8. What challenges do engineers face when integrating computers into traditional fields like civil engineering?
9. In what ways can the use of computers in engineering improve energy efficiency?
10. How does predictive analytics work in synchrony with diverse inputs from various platforms?

Exercise 8. Answer the following in a paragraph:

1. How did the transition from vacuum tubes to transistors influence the size and performance of computers?
2. What are the potential risks of over-reliance on computers in engineering fields?
3. Explain how smartphones have changed the nature of engineering in electronics and communication.
4. Discuss the ethical considerations involved in using predictive analytics in modern computing.
5. How do computers improve both accuracy and creativity in civil engineering design?

Exercise 9. Problem-Solving

1. Imagine you're a civil engineer designing a new building. How would you use CAD software to make the process more efficient?
2. You are an electrical engineer dealing with power fluctuations in the grid. How can smart computers help you prevent blackouts?
3. As a mechanical engineer, you are tasked with improving an assembly line's efficiency. What computer-based systems would you implement?
4. If you are working in electronics and communication engineering, how would you integrate computing power to maintain virtual communications?
5. You are tasked with implementing Big Data analytics in your engineering firm. How would you ensure the data is accurately synchronized across different platforms?

Exercise 10. Use the following words in your own sentences:

1. Transistor
2. CAD
3. Microcomputers
4. Power distribution
5. Manufacturing automation
6. Big Data
7. Predictive analytics
8. Smart computers
9. Integrated circuits
10. Information technology

Exercise 11. Role Play

One person plays a mechanical engineer explaining how computers help in automated control of machinery on the assembly line. The other plays a manager who wants to know about the advantages of using this technology.

Exercise 12. Debate

"Are computers indispensable in modern engineering, or can some engineering fields function without them?"

Exercise 13. Prepare a 2-minute presentation on one of the following topics:

1. The role of computers in civil engineering.
2. How computers assist in preventing electrical grid failures.

3. The impact of smartphones on electronics and communication engineering.
4. The rise of Big Data in modern computing and its applications.
5. How transistors and integrated circuits revolutionized personal computing.

Exercise 14. Explain the Concept

Explains the role of computers in mechanical engineering, and then explain their role in electrical engineering.

Exercise 15. Group Discussion

"How do you think the continued advancement of computers and AI will affect traditional engineering fields like civil or mechanical engineering over the next 20 years?"

UNIT 4
Types of materials

Everything we make is made up of one or more materials. Different materials have different **properties**. Because of these different properties, they can be used to make many kinds of objects. Materials can be soft or hard. They can be flexible or stiff. They can be delicate or very strong. Let's take a look at some examples of different materials.

Wood

Wood can be classified as either **hardwood** or **softwood**.

Hardwood comes from **deciduous trees**. These are trees that lose their leaves in the fall. Hardwood is usually used to make furniture and in construction projects that need to last for a long time. Examples of hardwoods are oak, maple, and walnut.

Softwood comes from **coniferous** trees. Coniferous, or evergreen trees, keep their needles all year round. Most **timber**, or wood that is prepared for construction, is made from softwood trees. Softwood is usually used in parts of buildings, like windows and doors. It is also used in some kinds of furniture. Examples of softwoods are pine, fir, and spruce.

Misconception Alert

The terms "hardwood" and "softwood" do not refer to how hard the wood in a tree is. These terms refer to how the tree reproduces. Coniferous (softwood) trees reproduce through seeds in cones. Deciduous (hardwood) trees reproduce through seeds that come from a fruit or flower.

Different types of trees produce wood with different properties. But all types of wood have some physical characteristics in common. First, wood is strong. Its strength depends on its **grain**. Grainis the natural direction of growth of the fibres in the wood. Wood is very resistant to **compression** when force is applied in the direction of the grain. But it can break easily if force is applied against the grain.
Wood also has an interesting relationship with water. It is a very **buoyant** material. This means it can float. This is why wood is often used to make ships and boats. But wood is also **hygroscopic**. This means that it can absorb water. Some types of wood can absorb and hold a lot of water. It is important to consider this characteristic when choosing wood for a project. If a wood contains too much water it may eventually **rot**. When wood rots, it breaks down.

Did you know?

Balsa wood is one of the lightest and least dense woods, but it's technically considered a hardwood because the trees that produce it create seeds!

Exercise 1. Multiple Choice

1. What type of tree produces hardwood?
   - a) Coniferous
   - b) Deciduous
   - c) Evergreen
2. Which of the following is an example of a hardwood?
   - a) Pine
   - b) Maple
   - c) Fir
3. What is a common use for softwood?
   - a) Furniture
   - b) Boat construction
   - c) Windows and doors
4. What does "hygroscopic" mean in relation to wood?
   - a) Wood that can float
   - b) Wood that repels water
   - c) Wood that absorbs water
5. How does wood typically react to force applied against the grain?
   - a) It is very strong
   - b) It breaks easily
   - c) It resists compression
6. What type of tree reproduces through seeds in cones?
   - a) Hardwood
   - b) Softwood
   - c) Deciduous
7. What type of wood is Balsa classified as?
   - a) Softwood
   - b) Hardwood
   - c) Coniferous
8. Which property of wood makes it a good material for boats?
   - a) Its density
   - b) Its strength against compression
   - c) Its buoyancy

9. What does “grain” refer to in wood?
   - a) The color of the wood
   - b) The direction of the fibers
   - c) The type of tree it comes from
10. Why is it important to consider the water content in wood for a project?
   - a) It affects the wood's buoyancy
   - b) It determines the color of the wood
   - c) Too much water can cause the wood to rot

Exercise 2. True or False

1. Hardwood trees keep their needles all year round.
2. Softwood is usually used in construction projects that need to last a long time.
3. The terms “hardwood” and “softwood” refer to the hardness of the wood.
4. Wood is resistant to compression when force is applied along the grain.
5. Balsa wood is considered a softwood.
6. Wood’s buoyancy is one of its characteristics.
7. Deciduous trees reproduce through seeds in cones.
8. Wood can break easily if force is applied in the direction of the grain.
9. Balsa wood is both light and dense.
10. Wood absorbs water because it is hygroscopic.

Exercise 3. Fill in the Blanks

1. Hardwood comes from _______ trees that lose their leaves in the fall.
2. Examples of hardwoods include _______ and _______.
3. Softwood comes from _______ trees that keep their needles all year round.
4. Wood is _______ to compression when force is applied in the direction of the grain.
5. Wood is _______ and can float, which is why it is used to make boats.
6. The term “hygroscopic” means that wood can _______ water.
7. The grain of wood refers to the _______ direction of the fibers in the wood.
8. Balsa wood is classified as a _______ because it comes from trees that produce seeds.
9. Wood that contains too much water may eventually _______.

10. The difference between hardwood and softwood is based on how the trees _______.

Exercise 4. Short Answer

1. What are the main uses of hardwood?
2. How does wood's buoyancy affect its use in construction?
3. Describe the difference between hardwood and softwood in terms of their reproductive processes.
4. What property of wood affects how it reacts to force applied against the grain?
5. Why is it important for wood used in construction projects to have a low water content?

Exercise 5. Match each type of wood with its characteristic or use:

1. Hardwood
2. Softwood
3. Hygroscopic
4. Buoyant
5. Balsa Wood

a) Used for furniture and long-lasting construction
b) Absorbs water
c) Can float on water
d) Comes from coniferous trees
e) One of the lightest woods but classified as a hardwood

Exercise 6. Discussion

In pairs or small groups, discuss the differences between hardwood and softwood. Include aspects such as their sources, uses, and properties. Share examples of each type of wood and their applications.

Exercise 7. Wood Properties and Uses

Choose a type of wood (e.g., oak, pine, or balsa). Explain its properties, how it reacts to force, and its common uses. Discuss how these properties make the wood suitable for specific applications.

Exercise 8. Discussion

Imagine you are selecting wood for a new project, such as building a wooden boat or designing furniture. Discuss with a partner what type of wood you would choose and why, considering factors like durability, buoyancy, and water absorption.

Metals

Metals are some of the most important materials used in manufacturing and building. Some examples of metals are iron, aluminum, copper, zinc, tin, and lead. Many metals we use today are **alloys**. Alloys are made by combining two or more metals. They can also combine a metal with a nonmetal material. Alloys are made to give the metal new characteristics. Things like increased hardness or strength. For example, **steel** is an alloy of iron that contains a small amount of carbon.

All metals share three main characteristics:

- **Lustre**: they are shiny when cut or scratched
- **Malleability**: although they are strong, they can be bent or shaped with the right amount of heat and force
- **Conductivity**: they conduct heat and electricity

But individual metals have different properties. Metals and metal alloys are usually chosen for objects based on their properties. Many types of metals are used in household objects, from copper to steel, even gold!

Many metals are likely to corrode. **Corrosion** is a chemical reaction where metal reacts with oxygen. Sometimes this is good because it strengthens the metal. But when iron or steel react with oxygen, **rust** is created. Corrosion can eventually make metal break down entirely into rust.

Exercise 1. Multiple Choice

1. What is an alloy?
   - a) A pure metal
   - b) A combination of two or more metals
   - c) A metal combined with a non-metal material
2. Which of the following is NOT a characteristic of metals?
   - a) Lustre
   - b) Malleability
   - c) Insulation
3. What does malleability allow metals to do?
   - a) Conduct electricity

○ b) Be bent or shaped
○ c) Resist corrosion

4. What is steel an alloy of?
   ○ a) Zinc and copper
   ○ b) Iron and carbon
   ○ c) Aluminum and tin
5. Which metal is known to rust when it corrodes?
   ○ a) Copper
   ○ b) Gold
   ○ c) Iron
6. What property allows metals to conduct heat and electricity?
   ○ a) Lustre
   ○ b) Malleability
   ○ c) Conductivity
7. Why are alloys made?
   ○ a) To make the metal shiny
   ○ b) To give the metal new characteristics
   ○ c) To reduce the metal's strength
8. What happens to metal when it corrodes?
   ○ a) It becomes shiny
   ○ b) It reacts with oxygen
   ○ c) It becomes less malleable
9. Which metal is commonly used in household objects and is known for its high conductivity?
   ○ a) Lead
   ○ b) Aluminum
   ○ c) Tin
10. What is one positive effect of corrosion?
   ○ a) It makes the metal break down entirely
   ○ b) It strengthens the metal
   ○ c) It makes the metal less shiny

Exercise 2. True or False

1. All metals are shiny when cut or scratched.
2. Malleability means metals cannot be bent or shaped.
3. Alloys can combine a metal with a non-metal material.
4. Rust is created when iron or steel corrodes.

5. Metals are chosen for objects based on their properties.
6. Corrosion is always beneficial to metals.
7. Conductivity refers to a metal’s ability to conduct heat and electricity.
8. Gold is a common metal used in household objects.
9. Steel is an example of a metal alloy.
10. Corrosion can eventually cause metal to break down into rust.

Exercise 3. Fill in the Blanks

1. Metals are combined in alloys to give them new ________.
2. Alloys can be made by combining metals with ________ materials.
3. ________ is a chemical reaction where metal reacts with oxygen.
4. Metals are chosen for their specific ________.
5. An example of an alloy is steel, which is made from iron and ________.
6. Metals have the property of ________, meaning they are shiny when cut or scratched.
7. ________ refers to a metal’s ability to conduct heat and electricity.
8. When metals corrode, they can eventually break down into ________.
9. ________ is a property of metals that allows them to be bent or shaped with heat and force.
10. Many metals, including iron, copper, and aluminum, are used in ________ objects.

Exercise 4. Short Answer

1. What are the three main characteristics of metals?
2. Why is steel considered an alloy?
3. How does corrosion affect metals?
4. What property of metals allows them to conduct heat and electricity?
5. Give two examples of metals that are commonly used in household objects.

Exercise 5. Match each property of metals with its definition:

1. Lustre
2. Malleability
3. Conductivity
4. Corrosion
5. Alloy

a) A mixture of two or more metals or a metal with a non-metal material
b) The ability to be bent or shaped with heat and force
c) A chemical reaction with oxygen that can cause metals to break down
d) The ability to conduct heat and electricity
e) The shiny appearance of metals when cut or scratched

Exercise 6. Discussion

In pairs, discuss the properties of metals listed in the text. Explain how these properties (lustre, malleability, conductivity) impact the use of metals in various applications. Provide examples of metals used for different purposes and why their properties are important.

Exercise 7. Alloy Analysis

Choose an alloy (e.g., steel, bronze, brass) and explain to a partner how it is made, its components, and the benefits it provides compared to its constituent metals. Discuss how the properties of the alloy make it suitable for specific applications.

Exercise 8. Corrosion Case Study

Imagine you are a materials engineer. Discuss with a partner how you would address the issue of corrosion in a metal used for outdoor construction. Talk about preventive measures, materials choices, and maintenance strategies to minimize corrosion and extend the lifespan of the metal.

Ceramics

Ceramics are often defined by what they're not. They are **nonmetallic** and **inorganic** solids. This means they aren't made of metal, wood, plastics, or rubber. They are made by baking clay, sand, and other natural materials at very high temperatures.

A few examples of ceramics are bricks, tiles, and concrete. Ceramic materials are used to make everything from the homes we live in to the pots we cook food in to dental implants for our teeth. It is even used to make the insulating tiles on space shuttles! Glass (see below) is also a ceramic. So, you are surrounded by ceramics and you may not know it!

The main properties of ceramics are:

- They are usually hard
- Heat resistant: they have a high melting point

- Resistant to chemical corrosion
- They do not conduct heat or electricity: this means they make good **insulators**

Some types of ceramics, like glass and porcelain, can also be **brittle** (they can be broken easily). Nonetheless they can last a very long time.

Exercise 1. Multiple Choice

1. What materials are ceramics made from?
   - a) Metal and rubber
   - b) Clay, sand, and natural materials
   - c) Wood and plastics
2. Which of the following is NOT an example of a ceramic?
   - a) Bricks
   - b) Concrete
   - c) Leather
3. What is one property of ceramics?
   - a) They are usually soft
   - b) They are heat resistant
   - c) They conduct electricity well
4. What common household item is made from ceramics?
   - a) A wooden chair
   - b) A plastic cup
   - c) A ceramic tile
5. Why are ceramics good insulators?
   - a) They are very dense
   - b) They do not conduct heat or electricity
   - c) They are very soft
6. What happens to some ceramics, like glass and porcelain, when they are dropped?
   - a) They become more flexible
   - b) They can break easily
   - c) They change color
7. What is the melting point of ceramics compared to other materials?
   - a) Low
   - b) High
   - c) Average
8. Which of the following is NOT a use of ceramics?

○ a) Space shuttle tiles
○ b) Dental implants
○ c) Wooden furniture
9. How are ceramics typically created?
○ a) By melting metals
○ b) By baking at high temperatures
○ c) By molding plastics
10. What is one characteristic that ceramics share with glass?
○ a) They are both made from clay
○ b) They are both brittle
○ c) They both conduct electricity well

Exercise 2. True or False

1. Ceramics are made from metal and rubber.
2. Ceramics are heat resistant and have a high melting point.
3. Ceramics are good conductors of electricity.
4. Glass is considered a type of ceramic.
5. Ceramics can be used in dental implants.
6. Some ceramics are very brittle and can break easily.
7. Ceramics are used to make insulating tiles for space shuttles.
8. Ceramics do not last a long time.
9. Clay is a common material used in ceramics.
10. Ceramics are often used in making plastic items.

Exercise 3. Fill in the Blanks

1. Ceramics are defined as nonmetallic and _________ solids.
2. They are made by baking clay, sand, and other natural _________.
3. Examples of ceramics include bricks, tiles, and _________.
4. Ceramics are _________ resistant and have a high melting point.
5. They do not conduct heat or _________.
6. Glass is a type of _________.
7. Some ceramics, like glass and porcelain, can be _________.
8. Ceramics can be used in space shuttles for _________ tiles.
9. Ceramics are made by heating materials at _________ temperatures.
10. Ceramic materials can last a very _________ time.

Exercise 4. Short Answer

1. What are the main properties of ceramics?
2. How are ceramics made?
3. Give three examples of items made from ceramics.
4. Why do ceramics make good insulators?
5. What is one reason ceramics can be brittle?

Exercise 5. Match the ceramic property with its description:

1. Hard
2. Heat resistant
3. Resistant to chemical corrosion
4. Does not conduct heat or electricity
5. Brittle

a) Can be broken easily
b) Can withstand high temperatures
c) Can last a very long time
d) Does not allow heat or electricity to pass through
e) Strong and not easily deformed

Exercise 6. Ceramic Uses

In pairs, discuss the different uses of ceramics in everyday life. Each person should provide at least two examples and explain why ceramics are suitable for those uses. Share your findings with the group.

Exercise 7. Properties Discussion

Describe the main properties of ceramics to a partner. Discuss how these properties affect their usage in different applications, such as construction, household items, and space technology.

Exercise 8.Ceramic Comparisons

Compare ceramics with another material (e.g., metals or plastics) in terms of their properties and uses. Discuss with a partner the advantages and disadvantages of ceramics compared to the other material.

Glass

Glass is one of the most versatile materials created by humans. Glass is made mostly of sand, which is made up of **silicon dioxide**. When sand is heated to a very high temperature (about 1700°C) it becomes a liquid. When it cools again, it undergoes a complete transformation and becomes a clear solid.

The glass we are most familiar with today is called **soda-lime-silica-glass**. It is made mostly of sand, but some other ingredients as well. Soda ash, which is made up of sodium carbonate, reduces the sand's melting point. This means it doesn't have to be heated to as high a temperature before it turns into a liquid. But soda ash also makes the glass **water-soluble**. This means it can dissolve in water! Limestone, or calcium carbonate, is added to stop this from happening.

When the liquid glass mixture is cooled a bit, it can be used in many different ways. It can be poured into a mould to create things like bottles or lightbulbs. It can also be "floated" to create perfectly flat sheets that will become windows or mirrors. The mixture is then allowed to cool and become solid.

The main properties of glass are:

- **transparency:** you can see through it
- **heat resistance:** it doesn't melt easily
- **hardness:** inability to break

You may not think glass is particularly strong. But the objects you're familiar with, like lightbulbs and water glasses, are made of very thin pieces of glass. If you had a very thick piece of glass (think of a brick made of glass) it would be very strong!

When people make glass objects, they can add different ingredients to give the glass new properties. For example, oven-proof glass like Pyrex contains boron oxide. Glass used to make decorative crystal objects, like vases and figurines, contains lead oxide. This allows it to be cut more easily. Stained or coloured glass has different colours because metals are added when it's in its liquid form!

Exercise 1: Multiple Choice

1. What is the main ingredient in glass?
   - ○ a) Sodium carbonate
   - ○ b) Silicon dioxide
   - ○ c) Calcium carbonate
2. At what temperature does sand become a liquid to make glass?
   - ○ a) 1000°C
   - ○ b) 1500°C
   - ○ c) 1700°C
3. What ingredient is added to reduce the melting point of sand in glass production?
   - ○ a) Soda ash

- b) Limestone
- c) Boron oxide

4. Which ingredient is added to prevent glass from dissolving in water?
   - a) Soda ash
   - b) Limestone
   - c) Lead oxide
5. How can glass be formed into flat sheets?
   - a) By cooling it quickly
   - b) By floating it on a molten metal
   - c) By pouring it into molds
6. What is one of the main properties of glass?
   - a) Flexibility
   - b) Transparency
   - c) Porosity
7. What property of glass makes it suitable for windows and mirrors?
   - a) Heat resistance
   - b) Hardness
   - c) Transparency
8. What does the addition of boron oxide to glass do?
   - a) Makes it easier to cut
   - b) Increases transparency
   - c) Makes it oven-proof
9. Why might a thick piece of glass be considered very strong?
   - a) It is more flexible
   - b) It has a higher melting point
   - c) It is less likely to break
10. What is added to stained glass to create different colors?
    - a) Sodium carbonate
    - b) Lead oxide
    - c) Metal ions

Exercise 2. True or False

1. Glass is made primarily from sand.
2. Soda ash makes glass more resistant to water dissolution.
3. The addition of limestone lowers the melting point of sand.
4. Glass can be used to make flat sheets for windows by floating it.
5. Pyrex glass contains lead oxide to increase its heat resistance.

6. The main property of glass is its flexibility.
7. Stained glass gets its color from metal ions added during production.
8. A thin piece of glass is stronger than a thick piece of glass.
9. Soda ash makes the glass easier to cut.
10. The process of making glass involves cooling it quickly to solidify.

Exercise 3. Fill in the Blanks

1. Glass is made mostly of sand, which is composed of ________ dioxide.
2. When sand is heated to about ________°C, it becomes a liquid.
3. Soda ash reduces the sand's melting point but also makes the glass ________-soluble.
4. Limestone is added to prevent the glass from ________ in water.
5. The liquid glass mixture can be poured into a ________ to create bottles or lightbulbs.
6. Glass used for windows and mirrors is made by ________ it to create flat sheets.
7. One of the main properties of glass is its ________, which allows us to see through it.
8. Oven-proof glass contains ________ oxide.
9. Decorative glass contains ________ oxide for easier cutting.
10. Colored glass has different colors because ________ are added when the glass is in its liquid form.

Exercise 4. Short Answer

1. What are the main ingredients used to make soda-lime-silica-glass?
2. How does the addition of soda ash affect the properties of glass?
3. Describe the process of making flat sheets of glass.
4. Why is thick glass considered strong compared to thin glass?
5. What are some examples of special types of glass and their additional ingredients?

Exercise 5. Match the type of glass or its property with its description:

1. Soda-lime-silica-glass
2. Pyrex glass
3. Decorative crystal glass
4. Stained glass
5. Transparency

a) Contains lead oxide for easier cutting
b) Made from sand, soda ash, and limestone
c) Contains boron oxide to make it oven-proof
d) Allows you to see through it
e) Colored by adding metal ions during production

Exercise 6. Properties Discussion

Discuss the properties of glass mentioned in the text. Explain how these properties make glass suitable for different applications like windows, mirrors, and cookware. Share your discussion with the class.

Exercise 7. Glass Types and Uses

Describe different types of glass and their specific uses. Talk about why certain ingredients are added to glass to change its properties. For example, explain why Pyrex glass is used for baking and why stained glass is used for decoration.

Exercise 8. The Glass-Making Process

Explain the process of making glass from sand to finished products. Include details about how the glass is heated, molded, and cooled. Discuss how different ingredients are used to create various types of glass and their final properties.

Plastics

Plastics come in many different forms. They are used to make a wide variety of products. Plastic molecules are made up of long chains. These molecules are called **polymers**.

Did you know?

The word "plastic" comes from the Greek "plastikos" which means "able to be shaped".

Most plastics are either thermoplastics or thermoset plastics. **Thermoplastics** are heated and then moulded into shape. They can be reheated later and reshaped. Most plastic bottles are thermoplastic. **Thermoset plastics** can only be heated and shaped once. Thermoset plastics are used to make things like electrical insulation, dinner plates and automobile parts.

Plastics have many useful properties. They are:

- Usually easy and low-cost to manufacture
- Strong and durable

- Resistant to electricity and water
- Resistant to many types of chemical corrosion

But this durability and resistance to damage can be a problem as well. Plastics can take a very long time to break down. Plastic bottles take about 450 years to break down. Plastic shopping bags can take as long as 10,000 years! This is why it is important to **recycle** plastics. Thermoplastics are recyclable, but thermoset plastics are not. When possible, it's better to choose thermoplastics over thermoset plastics so the plastic can be given a new life after use.

Exercise 1. Multiple Choice

1. What are the long chains in plastic molecules called?
   - a) Polymers
   - b) Monomers
   - c) Fibers
2. What does the word "plastic" mean in Greek?
   - a) Flexible
   - b) Able to be shaped
   - c) Lightweight
3. What type of plastic can be reheated and reshaped?
   - a) Thermoset plastics
   - b) Thermoplastics
   - c) Bioplastics
4. Which of the following is an example of a thermoset plastic?
   - a) Plastic bottles
   - b) Electrical insulation
   - c) Plastic bags
5. Why can plastic be problematic for the environment?
   - a) It is biodegradable
   - b) It takes a very long time to break down
   - c) It can easily be recycled
6. How long does it take for plastic bottles to break down?
   - a) 100 years
   - b) 450 years
   - c) 1000 years
7. Why is recycling important for plastics?
   - a) To increase their durability
   - b) To reduce their weight

○ c) To give them a new life after use

8. What is one property of plastics mentioned in the text?
   - a) They are expensive to manufacture
   - b) They are resistant to water
   - c) They are easily degradable
9. Which type of plastic is not recyclable?
   - a) Thermoplastics
   - b) Thermoset plastics
   - c) Bioplastics
10. What can thermoplastics be used to make?
   - a) Dinner plates
   - b) Automobile parts
   - c) Plastic bottles

Exercise 2. True or False

1. Plastics are made up of short chains of molecules.
2. Thermoplastics can only be shaped once.
3. Thermoset plastics are used for electrical insulation.
4. Plastic shopping bags take about 450 years to break down.
5. Thermoplastics are not recyclable.
6. Plastics are resistant to many types of chemical corrosion.
7. The Greek word “plastikos” means “easily broken”.
8. Thermoset plastics are usually used for products like dinner plates.
9. Plastics are difficult and costly to manufacture.
10. Recycling helps to give plastic a new life after use.

Exercise 3. Fill in the Blanks

1. The word “plastic” comes from the Greek word ________ which means “able to be shaped”.
2. Plastic molecules are long chains called ________.
3. Thermoplastics can be ________ and reshaped multiple times.
4. Thermoset plastics can only be shaped ________.
5. Plastic bottles take about ________ years to break down.
6. Thermoplastics are ________ but thermoset plastics are not.
7. Plastics are resistant to electricity and ________.
8. It is important to ________ plastics to reduce environmental impact.
9. The moplastics are used for making ________ bottles.

10. Plastic shopping bags can take as long as ________ years to break down.

Exercise 4. Short Answer

1. What is the primary difference between thermoplastics and thermoset plastics?
2. Why is plastic recycling important for the environment?
3. Name two products that are made from thermoset plastics.
4. What are some properties of plastics that make them useful?
5. How does the breakdown time of plastic bags compare to that of plastic bottles?

Exercise 5. Match the type of plastic with its property or example:

1. Thermoplastics
2. Thermoset plastics
3. Plastic bottles
4. Plastic bags
5. Recycling

a) Can be reshaped multiple times
b) Takes about 10,000 years to break down
c) Example of a thermoplastics product
d) Cannot be recycled
e) Helps to reduce environmental impact

Exercise 6. Discussing Plastic Properties

In pairs or small groups, discuss the properties of plastics mentioned in the text. Explain how these properties make plastics suitable for different applications, such as bottles, bags, and insulation. Share your discussion with the class.

Exercise 7. Comparing Plastics

Compare and contrast thermoplastics and thermoset plastics. Discuss their uses, properties, and recyclability. Explain why one might be chosen over the other for specific products.

Exercise 8. Environmental Impact

Talk about the environmental impact of plastics based on the text. Discuss the challenges associated with plastic waste and the importance of recycling. Suggest ways individuals and communities can help reduce plastic waste.

Textiles

The word textiles originally referred to woven fabrics. Now it usually refers to all fibres, yarns, and fabrics. **Textiles** can be made from natural materials like wool and cotton, or from synthetic materials like polyester. Textiles are used to make clothing, carpet, and many other products.

Did you know?

The earliest-produced textiles have been traced back to about 5000 BCE. Some of the oldest forms of textile production include net-making and basket-weaving.

Textiles are made up of many tiny parts called **fibres**. Textile fibres must have specific properties in order to be spun into yarn or made directly into fabrics. They must be strong, flexible, elastic, and durable. Fibres with these properties can be made into yarns and fabrics with similar properties.

But not all fibres have the same properties. Some are warmer, some are more durable, some are softer or more comfortable. Sometimes it takes a mix of fibres to achieve the desired properties of a finished textile product!

Exercise 1. Multiple Choice

1. What does the term "textiles" refer to today?
    - a) Only woven fabrics
    - b) All fibres, yarns, and fabrics
    - c) Only synthetic materials
2. Which of the following is a natural textile material?
    - a) Polyester
    - b) Wool
    - c) Nylon
3. When were some of the earliest textiles produced?
    - a) 1000 BCE
    - b) 3000 BCE
    - c) 5000 BCE
4. What are the key properties textile fibres must have to be spun into yarn or made into fabrics?
    - a) Weak, rigid, and brittle
    - b) Strong, flexible, elastic, and durable

○ c) Soft, rough, and inflexible
5. What is one of the oldest forms of textile production?
○ a) Knitting
○ b) Basket-weaving
○ c) Sewing
6. Which of these is an example of a synthetic textile material?
○ a) Cotton
○ b) Wool
○ c) Polyester
7. What is a characteristic of fibres used in textiles?
○ a) They must be weak and rigid
○ b) They must be strong, flexible, and durable
○ c) They must be brittle and inflexible
8. Why might different fibres be mixed in textile production?
○ a) To achieve a mix of desired properties
○ b) To make the textile less durable
○ c) To reduce production time
9. What kind of products are textiles used to make?
○ a) Only clothing
○ b) Only carpets
○ c) Clothing, carpets, and many other products
10. How have textiles evolved since the earliest productions?
○ a) They are now only made from natural materials
○ b) They include both natural and synthetic materials
○ c) They are no longer used for practical purposes

Exercise 2. True or False

1. The term "textiles" originally referred to all types of fabrics.
2. The earliest textiles have been traced back to around 5000 BCE.
3. Synthetic textiles cannot be made from polyester.
4. Textile fibres need to be strong, flexible, and durable.
5. Only natural fibres can be spun into yarn.
6. Some textiles are made from a mix of different fibres to achieve desired properties.
7. The text mentions that textiles have been used for making carpets and clothing.
8. Basket-weaving is one of the oldest forms of textile production.

9. Synthetic materials like polyester were used in the earliest textiles.
10. Textiles today only include woven fabrics.

Exercise 3. Fill in the Blanks

1. The word "textiles" now refers to all fibres, ________, and fabrics.
2. Some of the earliest textiles were made around ________ BCE.
3. Textile fibres must be strong, flexible, elastic, and ________.
4. Natural materials like ________ and synthetic materials like polyester can be used to make textiles.
5. The oldest forms of textile production include net-making and ________-weaving.
6. Fibres with specific properties can be spun into ____ or made into fabrics.
7. Textiles are used to make products like ________ and carpets.
8. Not all fibres have the same ________.
9. Mixing fibres can help achieve the desired properties of a finished ________ product.
10. The text mentions that textiles are used in ________ many products.

Exercise 4. Short Answer

1. What materials can textiles be made from?
2. What were some of the oldest forms of textile production?
3. List three key properties that textile fibres must have.
4. Why might fibres with different properties be combined in textile production?
5. How has the definition of textiles changed over time?

Exercise 5. Matching

Match the following terms with their descriptions:

1. Natural Materials
2. Synthetic Materials
3. Textile Fibres
4. Early Textile Production
5. Properties of Fibres

a) Polyester and nylon
b) Wool and cotton
c) Strong, flexible, elastic, and durable

d) Net-making and basket-weaving

e) Tiny parts that are spun into yarn or made into fabrics

Exercise 6. Discussing Textile Materials

In pairs or small groups, discuss the differences between natural and synthetic textile materials. Talk about their uses, benefits, and any drawbacks. Share your findings with the class.

Exercise 7. History of Textiles

Describe the evolution of textiles from their earliest forms to modern-day products. Discuss how textile production has changed over time and the impact of these changes on daily life.

Exercise 8. Properties and Applications

Discuss the importance of different properties of textile fibres (such as strength, flexibility, and durability) in their applications. Provide examples of products and explain why specific properties are important for those products.

Leather

Traditional leather is made from animal skins. **Synthetic**, or faux leather is manufactured. Leather is used to make everything from car seats to furniture to footballs to handbags. It is durable and has a natural finish. These properties are difficult to recreate with synthetic materials.

Did you know?

About 65% of leather comes from cows. The other 35% comes mostly from sheep, pigs, and goats.

Cowhide is often used to make traditional leather. It is thick and durable, and is often used to make jackets, coats, and furniture. Sheepskin is usually **tanned** with its soft fleece still attached to the skin. It is used to make jackets, rugs, and slippers. Pigskin makes a comfortable and water-resistant leather. It is used to make shoes, gloves, and some sports equipment. Goat skin is very soft and **malleable**. It is often used to make bags, gloves, and rugs. Skins from other animals, like snakes, alligators, crocodiles, ostriches, and even fish can be used to make leather too.

Faux leather is usually made of a mix of natural and synthetic fibres that are coated with a plastic polymer. This material mimics the properties of genuine leather. Like genuine leather, faux leather is soft to the touch and water-resistant. Although it is not as durable as traditional leather, faux leather is difficult to cut or tear. As a result, it’s often used to make furniture.

There are ethical concerns about traditional leather because it is an animal product. But because traditional leathers are made of a natural material, they can **biodegrade,** or break down naturally. Faux leather behaves more like plastic and takes a very long time to break down.

Exercise 1. Multiple Choice

1. What is the primary source of traditional leather?
○ a) Synthetic materials
○ b) Animal skins
○ c) Plant fibers

2. What percentage of leather comes from cows?
○ a) 50%
○ b) 65%
○ c) 75%

3. What is one characteristic that traditional leather has that is difficult to recreate with synthetic materials?
○ a) Color variety
○ b) Durability and natural finish
○ c) Low cost

4. What type of leather is often used to make jackets, coats, and furniture?
○ a) Sheepskin
○ b) Pigskin
○ c) Cowhide

5. Faux leather is typically made from a mix of:
○ a) Natural and synthetic fibers coated with plastic polymer
○ b) 100% synthetic fibers
○ c) 100% natural fibers

6. What is a common use for pigskin leather?
○ a) Handbags
○ b) Shoes and gloves
○ c) Rugs

7. Which type of leather is known for being soft and malleable, often used for bags and gloves?
○ a) Cowhide
○ b) Sheepskin

- c) Goat skin

8. What is a major ethical concern associated with traditional leather?
   - a) Its production process
   - b) Its origin from animal products
   - c) Its price
9. How does faux leather compare to traditional leather in terms of durability?
   - a) It is more durable
   - b) It is less durable
   - c) It has the same durability
10. Which material is more likely to break down naturally?
    - a) Faux leather
    - b) Traditional leather
    - c) Both materials break down at the same rate

Exercise 2. True or False

1. Faux leather is usually more durable than traditional leather.
2. Cowhide is often used to make jackets and furniture.
3. Sheepskin is commonly used for making shoes and gloves.
4. Traditional leather is considered an ethical concern because it is made from animal skins.
5. Faux leather is made from a combination of natural fibers and plastic polymers.
6. Leather from goats is known for being stiff and not very flexible.
7. Traditional leather can biodegrade, unlike faux leather.
8. About 35% of leather comes from cows.
9. Pigskin is used for making some sports equipment due to its water-resistant properties.
10. Faux leather is easy to tear but difficult to cut.

Exercise 3. Fill in the Blanks

1. Traditional leather is made from ____________ skins.
2. About ____________% of leather comes from cows.
3. Faux leather is coated with a ____________ polymer.
4. ________ is used to make jackets, rugs, and slippers due to its soft fleece.
5. Goat skin is often used to make ____________ and gloves.
6. The ethical concern about traditional leather is that it is an _____ product.

7. Faux leather behaves more like ___________ and takes a long time to break down.
8. Pigskin leather is known for being ___________ and water-resistant.
9. Leather from _____ is often used in luxury items like handbags and shoes.
10. Sheepskin is usually tanned with its _________ still attached to the skin.

Exercise 4. Short Answer

1. What are some common uses for cowhide leather?
2. What is one advantage of faux leather over traditional leather?
3. Name two types of animals, other than cows, whose skins are used to make leather.
4. Why is faux leather often used to make furniture?
5. What happens to traditional leather when it biodegrades?

Exercise 5. Match the type of leather with its common use:

1. Cowhide
2. Sheepskin
3. Pigskin
4. Goat skin
5. Faux leather

a) Furniture
b) Jackets, coats, and furniture
c) Shoes and gloves
d) Rugs and slippers
e) Bags and gloves

Exercise 6. Discussing Leather Types

In pairs or small groups, discuss the different types of leather and their common uses. Compare the properties of traditional and faux leather and decide which one would be more suitable for various products. Share your conclusions with the class.

Exercise 7. Ethical Considerations

Debate the ethical concerns associated with traditional leather versus faux leather. Discuss the environmental impacts and biodegradability of each type. Share your opinions and suggest possible solutions or alternatives.

Exercise 8. Practical Applications

Present a short talk on the best type of leather to use for a specific product (e.g., car seats, handbags, sports equipment). Explain your choice based on the properties of the leather and its suitability for the product's intended use.

Paper and Boxboard

Paper is an important material that many people use every day. From reading newspapers to drawing pictures to wrapping presents, you probably don't realize how often you use paper. Paper can also be used to make other materials, like **cardboard**.

Paper is made from a material called **pulp**. Pulp is made from wood fibres mixed with water. These fibres usually come from softwood trees like spruce and pine. To make paper, trees are cut up and the bark is removed. Then the wood is ground into tiny pieces and mixed with water to create pulp. The pulp is chemically treated then pressed flat and dried.

Cardboard is made up of several layers of paper combined. **Corrugated** cardboard is made up of two sheets of flat paper that have a third sheet of paper corrugated or bent to form a wave shape between them. The final product is stiff, strong, and very lightweight. This cardboard can be folded up and glued to create boxes or other packing materials.

Rubber

There are two main types of rubber: natural rubber and synthetic rubber. Natural rubber is made from **latex**, which is produced by plants. Synthetic rubber is made using a mix of chemicals. Synthetic rubber has many of the same characteristics as natural rubber. It can be used in tires, hoses, belts, flooring and more.

Did you know?

If you've ever picked a dandelion, you may have seen the milky white fluid on the inside of the stem. This is latex!

Almost 99% of the world's natural rubber is made from the latex of a plant called *Hevea brasiliensis*. This plant is commonly known as the rubber tree. Latex undergoes a number of different processes to be made into the versatile, springy material we think of as "rubber". First, it is "chewed up", then chemicals are added to it. Next, it is squeezed and stretched, and then cooked at about 140°C so that it holds its shape. The final product is strong, stretchy, elastic, durable, and waterproof. It can be used to make products ranging from pencil erasers to running shoes to wetsuits!

https://letstalkscience.ca/educational-resources/backgrounders/types-materials

Exercise 1. Multiple Choice

1. What is paper primarily made from?
   ○ a) Cotton
   ○ b) Wood fibers
   ○ c) Plastic
2. What is the primary source of fibers used to make paper?
   ○ a) Hardwood trees
   ○ b) Softwood trees
   ○ c) Fruit trees
3. What does corrugated cardboard include that makes it strong and lightweight?
   ○ a) A single sheet of paper
   ○ b) Two sheets of flat paper with a third wave-shaped sheet between them
   ○ c) Multiple layers of plastic
4. What is natural rubber made from?
   ○ a) Chemicals
   ○ b) Latex from plants
   ○ c) Synthetic materials
5. What is the common plant source for natural rubber?
   ○ a) Dandelion
   ○ b) Hevea brasiliensis
   ○ c) Oak tree
6. What process is used to make latex into rubber?
   ○ a) It is blended with water and dried.
   ○ b) It is chewed up, treated with chemicals, squeezed, and cooked.
   ○ c) It is mixed with other fibers and pressed flat.
7. What is one property of synthetic rubber mentioned in the text?
   ○ a) It is always more elastic than natural rubber.
   ○ b) It is used in similar applications as natural rubber.
   ○ c) It is not waterproof.
8. What does corrugated cardboard typically get used for?
   ○ a) Newspaper
   ○ b) Drawings
   ○ c) Boxes and packing materials
9. What happens to the wood in the paper-making process after it is ground into pieces?
   ○ a) It is heated directly.

- b) It is mixed with water to create pulp.
- c) It is immediately dried.

10. How is latex treated to become rubber?
    - a) It is mixed with plastic and shaped.
    - b) It is chewed, treated with chemicals, and then cooked.
    - c) It is ground into powder and pressed.

Exercise 2. True or False

1. Paper is made from a mixture of wood fibers and chemicals.
2. Cardboard is created by combining several layers of paper.
3. Synthetic rubber cannot be used in tires.
4. The latex used for making natural rubber is obtained from the Hevea brasiliensis plant.
5. Corrugated cardboard is known for being heavy and brittle.
6. Natural rubber is not as stretchy as synthetic rubber.
7. To make paper, the wood is ground into tiny pieces and mixed with water.
8. The milky white fluid inside a dandelion stem is latex.
9. Synthetic rubber is produced from plant latex.
10. Cardboard can be folded and glued to make packing materials.

Exercise 3. Fill in the Blanks

1. Paper is made from a material called ___________.
2. The fibers used to make paper usually come from ___________ trees.
3. To make cardboard, layers of paper are combined, and corrugated cardboard has a wave-shaped ___________ between two flat sheets.
4. Natural rubber is made from ___________, which is produced by plants.
5. Synthetic rubber is created using a mix of ___________.
6. The process of making rubber includes chewing, adding chemicals, squeezing, and cooking at about ___________°C.
7. Corrugated cardboard is ___________, strong, and lightweight.
8. Almost 99% of natural rubber comes from the latex of the _________ tree.
9. Rubber can be used to make products like _________ shoes and wetsuits.
10. Paper is made by mixing wood fibers with ___________, then pressing and drying the mixture.

Exercise 4. Short Answer

1. What are the main steps involved in making paper from wood?

2. Describe the structure of corrugated cardboard.
3. How does synthetic rubber compare to natural rubber in terms of properties?
4. What are some common uses for natural rubber?
5. Explain the process of turning latex into rubber.

Exercise 5. Match the material to its description or use:

1. Paper
2. Cardboard
3. Natural Rubber
4. Synthetic Rubber
5. Latex

a) Made from wood fibers and used for newspapers, drawing, and wrapping presents.

b) Used in tires, hoses, and belts, made from a mix of chemicals.

c) Created by combining layers of paper with a wave-shaped sheet between them.

d) Obtained from the Hevea brasiliensis plant and used in products like running shoes and wetsuits.

e) A milky white fluid inside dandelion stems that is processed to make rubber.

Exercise 6. Material Comparison

In pairs or small groups, compare and contrast the properties and uses of paper and cardboard. Discuss how each material is made and its different applications.

Exercise 7. Rubber Applications

Present a brief talk on the various applications of natural and synthetic rubber. Explain how the properties of each type of rubber make them suitable for different uses. Discuss the benefits and limitations of each type.

Exercise 8. The Process of Making Rubber

Describe the process of making rubber from latex in a short presentation. Include details about the steps involved and the transformation from latex to rubber. Highlight any interesting facts about the rubber-making process.

UNIT 5
Principles of physical science

Principles of physical science, the procedures and concepts employed by those who study the inorganic world.

Physical science, like all the natural sciences, is concerned with describing and relating to one another those experiences of the surrounding world that are shared by different observers and whose description can be agreed upon. One of its principal fields, physics, deals with the most general properties of matter, such as the behaviour of bodies under the influence of forces, and with the origins of those forces. In the discussion of this question, the mass and shape of a body are the only properties that play a significant role, its composition often being irrelevant. Physics, however, does not focus solely on the gross mechanical behaviour of bodies but shares with chemistry the goal of understanding how the arrangement of individual atoms into molecules and larger assemblies confers particular properties. Moreover, the atom itself may be analyzed into its more basic constituents and their interactions.

The present opinion, rather generally held by physicists, is that these fundamental particles and forces, treated quantitatively by the methods of quantum mechanics, can reveal in detail the behaviour of all material objects. This is not to say that everything can be deduced mathematically from a small number of fundamental principles, since the complexity of real things defeats the power of mathematics or of the largest computers. Nevertheless, whenever it has been found possible to calculate the relationship between an observed property of a body and its deeper structure, no evidence has ever emerged to suggest that the more complex objects, even living organisms, require that special new principles be invoked, at least so long as only matter, and not mind, is in question. The physical scientist thus has two very different roles to play: on the one hand, he has to reveal the most basic constituents and the laws that govern them; and, on the other, he must discover techniques for elucidating the peculiar features that arise from complexity of structure without having recourse each time to the fundamentals.

This modern view of a unified science, embracing fundamental particles, everyday phenomena, and the vastness of the Cosmos, is a synthesis of originally independent disciplines, many of which grew out of useful arts. The extraction and refining of metals, the occult manipulations of alchemists, and the astrological interests of priests and politicians all played a part in initiating systematic studies that expanded in scope until their mutual relationships became clear, giving rise to what is customarily recognized as modern physical science.

Exercise 1. Choose the correct answer

1. Physical science is primarily concerned with:

a) The study of organic life
b) Describing the inorganic world
c) Examining human behavior
d) Exploring abstract concepts

2. What field of science deals with the general properties of matter?

a) Chemistry
b) Biology
c) Physics
d) Geology

3. Which property of a body is often irrelevant in physics?

a) Mass
b) Shape
c) Composition
d) Behavior

4. Quantum mechanics is used to:

a) Understand only large-scale phenomena
b) Calculate behavior of fundamental particles
c) Solve problems without mathematics
d) Disprove physical principles

5. Which discipline shares its goals with physics in understanding molecular structures?

a) Biology
b) Mathematics
c) Chemistry
d) Philosophy

6. What is the relationship between observed properties of a body and its deeper structure?

a) They are unrelated
b) They can often be calculated
c) They depend on unique principles
d) They require new laws

7. What does the term “unified science” refer to?

a) Separate scientific disciplines with no connection
b) The combination of different fields like physics and chemistry

c) Only the study of fundamental particles
d) A specific branch of alchemy

8. The term "gross mechanical behavior" refers to:

a) Fundamental particles’ actions
b) The overall movement and forces on bodies
c) Human thought processes
d) The shape of an object

9. What ancient practice contributed to the development of modern physical science?

a) Alchemy
b) Poetry
c) Literature
d) Medicine

10. The modern understanding of physical science includes:

a) Only material objects
b) A broad spectrum of phenomena, from atoms to the cosmos
c) Philosophical questions
d) Mathematics alone

Exercise 2. True or False

1. Physical science focuses solely on the gross mechanical behavior of bodies. (True/False)
2. Physics studies the general properties of matter and the forces affecting it. (True/False)
3. The composition of a body is crucial in determining its mechanical behavior in physics. (True/False)
4. Quantum mechanics is used to analyze fundamental particles. (True/False)
5. All material objects can be described mathematically without exception. (True/False)
6. Living organisms require special new principles to be explained by physical science. (True/False)
7. Physical scientists focus solely on the fundamental principles of matter. (True/False)
8. The understanding of modern physical science has grown from independent disciplines. (True/False)

9. The astrological interests of ancient priests contributed to the rise of physical science. (True/False)

10. Modern physical science does not include the study of cosmic phenomena. (True/False)

Exercise 3. Fill in the Blanks

1. Physical science focuses on the study of the __________ world.
2. Physics deals with the general __________ of matter.
3. In discussing the behavior of bodies, the __________ and shape are most significant.
4. The arrangement of __________ into molecules gives materials their particular properties.
5. __________ mechanics helps describe the behavior of fundamental particles.
6. The complexity of real things can defeat the power of __________.
7. The modern view of science involves a __________ of originally independent disciplines.
8. Alchemists and ancient __________ contributed to the early development of physical science.
9. Chemistry shares its goals with physics in understanding __________ structures.
10. Physical science explains material objects, not the __________.

Exercise 4. Match the following terms with their definitions:

Term	**Definition**
1. Quantum mechanics	a) The general properties of matter under forces
2. Physics	b) Involves calculating the behavior of fundamental particles

3. Complexity c) Often irrelevant in determining the behavior of a body

4. Composition d) A branch of science dealing with the inorganic world

5. Alchemy e) Old practice influencing modern chemistry and physical science

6. Chemistry f) Studies molecular arrangement and interaction

7. Unified science g) A combination of multiple fields to form modern physical science

8. Gross mechanical behavior h) Deals with forces and the movement of large bodies

9. Cosmos i) The study of the universe as part of physical science

10. Deduction j) Logical reasoning from known principles

Exercise 5. Give short answers to the questions:

1. What are the two main roles of physical scientists?
2. How do chemistry and physics overlap in their goals?
3. What is quantum mechanics used for in physical science?
4. Why is it difficult to describe the behavior of complex objects mathematically?
5. What is meant by the term "unified science"?
6. How did ancient practices contribute to modern physical science?
7. What are the key properties of a body that are important in physics?
8. Why are fundamental particles so important in physical science?
9. How does physics study the forces acting on matter?
10. What distinguishes physical science from other natural sciences?

Exercise 6. Sentence Completion

1. Physics studies the ___________ properties of matter.
2. The behavior of complex objects cannot always be _____ mathematically.
3. Chemistry aims to understand how atoms form ___________.
4. Physical science is concerned with ___________ of the surrounding world.
5. Quantum mechanics deals with ___________ particles.
6. The idea of a unified science comes from a ___________ of disciplines.
7. The laws of physics govern the behavior of ___________ and forces.
8. The mass and ___________ of a body are key to understanding its behavior in physics.
9. Physical scientists study both simple and ___________ structures.
10. The early interest in astrology helped ___________ the development of modern science.

Exercise 7. Discuss:

1. How does quantum mechanics help explain the behavior of fundamental particles?
2. What challenges do scientists face when trying to apply mathematics to complex objects?
3. How do physics and chemistry work together to explain material properties?
4. Why is a unified science important for understanding the physical world?
5. How did ancient practices like alchemy and astrology evolve into modern physical science?
6. How does modern physical science connect small particles to cosmic phenomena?
7. Why is composition often irrelevant in determining the mechanical behavior of a body?
8. What is the significance of complexity in the study of physical science?
9. How do scientists reveal the basic laws that govern fundamental particles?
10. In what ways can physical science be applied to everyday phenomena?

Exercise 8. Critical Thinking

1. How do the laws of quantum mechanics differ from classical mechanics?
2. Why might it be difficult to apply mathematical principles to living organisms?

3. Discuss how the ancient practice of alchemy contributed to the modern understanding of chemistry.
4. How do physical scientists balance studying fundamental particles with complex structures?
5. What does the term “gross mechanical behavior” imply about the study of physics?

Exercise 9. Problem-Solving Scenarios

1. Imagine you are a physicist tasked with explaining the behavior of a falling object. What properties would you focus on?
2. You are a chemist studying molecular structures. How might physics help you understand how molecules form?
3. As a physical scientist, how would you use quantum mechanics to describe the behavior of fundamental particles?
4. How would you apply the principles of physical science to explain why some materials conduct electricity?
5. If you were studying the universe, how might the idea of a unified science help you connect small-scale and large-scale phenomena?

Exercise 10. Use the following words in your own sentences:

1. Quantum mechanics
2. Gross mechanical behavior
3. Fundamental particles
4. Composition
5. Unified science
6. Alchemy
7. Molecular structure
8. Physics
9. Complexity
10. Deductive reasoning

Exercise 11. Role Play

One student plays a physicist explaining the role of quantum mechanics in studying fundamental particles. The other plays a student learning about the topic for the first time.

Exercise 12. Debate

"Can all physical phenomena be explained mathematically, or are there limits to what mathematics can describe in physical science?"

Exercise 13. Prepare a 2-3 minute presentation on one of the following topics:

1. The role of quantum mechanics in physical science
2. The historical development of physical science from alchemy to modern physics
3. How physical science helps us understand the cosmos

Exercise 14. Group Discussion

Discuss how different scientific disciplines like physics, chemistry, and astronomy come together in the study of physical science. How does a unified science approach benefit scientific discovery?

Exercise 15. Question and Answer

One student asks questions about the role of chemistry in physical science, while the other student answers, explaining how chemistry relates to physics and other disciplines.

UNIT 6

The development of quantitative science

Modern physical science is characteristically concerned with numbers—the measurement of quantities and the discovery of the exact relationship between different measurements. Yet this activity would be no more than the compiling of a catalog of facts unless an underlying recognition of uniformities and correlations enabled the investigator to choose what to measure out of an infinite range of choices available. Proverbs purporting to predict weatherare relics of science prehistory and constitute evidence of a general belief that the weather is, to a certain degree, subject to rules of behaviour. Modern scientific weather forecastingattempts to refine these rules and relate them to more fundamental physical laws so that measurements of temperature, pressure, and wind velocity at a large number of stations can be assembled into a detailed model of the atmosphere whose subsequent evolution can be predicted—not by any means perfectly but almost always more reliably than was previously possible.

Between proverbial weather lore and scientific meteorology lies a wealth of observations that have been classified and roughly systematized into the natural history of the subject—for example, prevailing winds at certain seasons, more or less predictable warm spells such as Indian summer, and correlation between Himalayan snowfall and intensity of monsoon. In every branch of science this preliminary search for regularities is an almost essential background to serious quantitative work, and in what follows it will be taken for granted as having been carried out.

Compared with the caprices of weather, the movements of the stars and planets exhibit almost perfect regularity, and so the study of the heavens became quantitative at a very early date, as evidenced by the oldest records from China and Babylon. Objective recording and analysis of these motions, when stripped of the astrological interpretations that may have motivated them, represent the beginning of scientific astronomy. The heliocentric planetary model (*c.* 1510) of the Polish astronomer Nicolaus Copernicus, which replaced the Ptolemaic geocentric model, and the precise description of the elliptical orbits of the planets (1609) by the German astronomer Johannes Kepler, based on the inspired interpretation of centuries of patient observation that had culminated in the work of Tycho Brahe of Denmark, may be regarded fairly as the first great achievements of modern quantitative science.

A distinction may be drawn between an observational science like astronomy, where the phenomena studied lie entirely outside the control of the observer, and an experimentalscience such as mechanics or optics, where the investigator sets up the arrangement to his own taste. In the hands of Isaac Newton not only was the study of colours put on a rigorousbasis but a firm link also was forged between the experimental science of mechanics and observational astronomy by virtue of his law of universal gravitation and his explanation of Kepler's laws of planetary motion. Before proceeding as far as this, however, attention must be paid to the mechanical studies of Galileo Galilei, the most important of the founding fathers of modern physics, insofar as the central procedure of his work involved the application of mathematical deduction to the results of measurement.

Exercise 1. Choose the correct answer:

1. What is a central concern of modern physical science?

a) Colors and sounds
b) Measurement of quantities
c) Human behavior
d) Philosophy

2. What would science be without recognizing uniformities and correlations?

a) A catalog of facts
b) A creative process
c) An artistic endeavor
d) An exact science

3. What ancient practice is mentioned as a prehistory of weather science?

a) Meteorology
b) Astronomy
c) Proverbs predicting weather
d) Astrology

4. What is the goal of modern scientific weather forecasting?

a) To create proverbs
b) To refine weather rules
c) To predict earthquakes
d) To observe celestial bodies

5. Who proposed the heliocentric planetary model?

a) Johannes Kepler
b) Nicolaus Copernicus
c) Isaac Newton
d) Galileo Galilei

6. What is the main difference between observational and experimental science?

a) Observational science is concerned with human subjects
b) Experimental science deals only with colors
c) Observational science cannot control phenomena
d) Experimental science requires only observation

7. Isaac Newton's law of universal gravitation linked which two fields?

a) Chemistry and biology
b) Meteorology and physics
c) Mechanics and observational astronomy
d) Astrology and physics

8. What was Johannes Kepler's contribution to astronomy?

a) Discovery of gravity
b) Description of elliptical planetary orbits
c) Invention of the telescope
d) Geocentric model of the solar system

9. Whose observations culminated in Kepler’s laws of planetary motion?

a) Isaac Newton
b) Tycho Brahe
c) Galileo Galilei
d) Nicolaus Copernicus

10. What central procedure did Galileo Galilei apply in his mechanical studies?

a) Experimentation without measurement
b) Mathematical deduction from measurement results
c) Astrological interpretations
d) Random observations

Exercise 2. True or False

1. Modern physical science primarily focuses on qualitative observations.
2. Proverbs predicting the weather are considered a form of ancient meteorology.
3. Weather forecasting today is less reliable than in ancient times.
4. The heliocentric model was developed by Johannes Kepler.
5. Tycho Brahe's observations were crucial for the development of Kepler’s laws.
6. Isaac Newton linked astronomy with mechanics through his law of universal gravitation.
7. Galileo Galilei focused on observational science only.

8. Copernicus' geocentric model is the modern accepted model.
9. Observational science gives scientists full control over the studied phenomena.
10. The study of colors was made more rigorous by Galileo.

Exercise 3. Fill in the Blanks

1. Modern physical science is concerned with the __________ of quantities.
2. Weather forecasting attempts to refine the rules of weather and relate them to __________ laws.
3. The __________ planetary model was proposed by Nicolaus Copernicus.
4. Johannes Kepler described the __________ orbits of the planets.
5. Isaac Newton’s law of universal __________ linked mechanics and astronomy.
6. __________ developed the geocentric model that was replaced by Copernicus’ heliocentric model.
7. __________ carried out the mechanical studies that laid the foundation of modern physics.
8. In observational science, phenomena are ____ the control of the observer.
9. __________ is an example of experimental science.
10. Tycho Brahe’s work helped ______ develop his laws of planetary motion.

Exercise 4. Match the terms on the left with the appropriate description on the right:

Term	**Description**
1. Copernicus	a) Described elliptical orbits of planets
2. Kepler	b) Proposed the heliocentric planetary model
3. Tycho Brahe	c) Conducted extensive observations of planetary movements

4. Isaac Newton	d) Linked mechanics with astronomy through universal gravitation
5. Galileo Galilei	e) Applied mathematical deduction to measurement results
6. Quantitative science	f) Focused on the measurement and exact relationships between quantities
7. Meteorology	g) The scientific study of weather patterns and forecasting
8. Experimental science	h) Involves setting up experiments under controlled conditions
9. Observational science	i) Science where the studied phenomena are beyond the control of the observer
10. Astrological interpretations	j) Beliefs motivating early studies of celestial bodies

Exercise 5. Give short answers:

1. What is the role of uniformities and correlations in modern physical science?
2. How did ancient weather proverbs influence modern meteorology?
3. What is the main distinction between observational and experimental science?
4. What did Isaac Newton's law of universal gravitation explain?
5. How did Tycho Brahe contribute to the work of Johannes Kepler?
6. What is the significance of the heliocentric planetary model?
7. How did Galileo's approach to physics differ from earlier scientists?
8. What do we mean by quantitative science?
9. Why is weather forecasting more reliable today than in ancient times?
10. How does modern astronomy differ from its early astrological roots?

Exercise 6. Complete the sentences:

1. The measurement of __________ is central to modern physical science.
2. Tycho Brahe's observations led to the discovery of ____ planetary orbits.
3. In experimental science, the investigator has control over __________.
4. Isaac Newton's law linked mechanics and __________.
5. The __________ model of the solar system places the sun at the center.
6. Johannes Kepler's laws describe the __________ of planetary motion.
7. Modern weather forecasting relies on measurements of temperature, pressure, and ______.
8. Ancient weather predictions were based on __________ rather than scientific measurements.
9. __________ was one of the founding fathers of modern physics.
10. Quantitative science focuses on the _ relationship between measurements.

Exercise 7. Critical Thinking

1. How has the transition from astrological interpretations to scientific observations shaped modern astronomy?
2. Discuss the significance of quantitative measurement in predicting natural phenomena like the weather.
3. Why was the heliocentric model a breakthrough in scientific thought?
4. How did Isaac Newton's work unify different branches of science?
5. In what ways did Galileo's use of mathematical deduction advance modern physics?

Exercise 8. Problem Solving

1. Imagine you are tasked with creating a weather model based on temperature and wind data. What measurements would be critical?
2. If you were observing planetary movement, how would you use Kepler's laws to predict their orbits?
3. How could you apply Newton's law of universal gravitation to explain the motion of a satellite around Earth?
4. In an experiment to test the behavior of light, what variables might you control, and what measurements would be necessary?
5. If you were analyzing Galileo's work, how would you apply his methods of mathematical deduction to modern physics experiments?

Exercise 9. Put the following events in the correct order:

1. Johannes Kepler describes the elliptical orbits of planets.
2. Isaac Newton develops the law of universal gravitation.
3. Nicolaus Copernicus proposes the heliocentric planetary model.
4. Tycho Brahe makes extensive observations of planetary motion.
5. Galileo Galilei applies mathematical deduction to physics.

Exercise 10: Use the following words in sentences:

1. Quantitative science
2. Heliocentric model
3. Elliptical orbits
4. Universal gravitation
5. Mathematical deduction
6. Experimental science
7. Observational astronomy
8. Kepler's laws
9. Tycho Brahe
10. Meteorology

Exercise 11. Role Play

One student plays Isaac Newton explaining his law of universal gravitation, and the other plays a modern scientist discussing its application in today's space exploration.

Exercise 12.

"Which is more important for modern science: experimental science or observational science?"

Exercise 13. Prepare a 2-3 minute presentation on one of the following topics:

1. The heliocentric model and its significance in the history of science
2. The role of mathematics in modern physics
3. How weather forecasting has evolved over time

Exercise 14. Group Discussion

How has the shift from qualitative to quantitative methods influenced scientific discovery? Discuss in small groups.

UNIT 7
Aerodynamics

Aerodynamics, branch of physics that deals with the motion of air and other gaseous fluids and with the forces acting on bodies passing through such a fluid. Aerodynamics seeks, in particular, to explain the principles governing the flight of aircraft, rockets, and missiles. It is also concerned with the design of automobiles, high-speed trains, and ships, as well as with the construction of such structures as bridges and tall buildings to determine their resistance to high winds.

Observations of the flight of birds and projectiles stirred speculation among the ancients as to the forces involved and the manner of their interaction. They, however, had no real knowledge of the physical properties of air, nor did they attempt a systematic study of those properties. Most of their ideas reflected a belief that the air provided a sustaining or impelling force. These notions were based to a large degree on the principles of hydrostatics (the study of the pressures of liquids) as they were then understood. Thus, in early times, it was thought that the impelling force of a projectile was associated with forces exerted on the base by the closure of the flow of air around the body. This conception of air as an assisting medium rather than a resisting force persisted for centuries, even though in the 16th century it was recognized that the energy of motion of a projectile was imparted to it by the catapulting device.

Near the end of the 15th century, Leonardo da Vinci observed that air offered resistance to the movement of a solid object and attributed this resistance to compressibility effects. Galileo later established the fact of air resistance experimentally and arrived at the conclusion that the resistance was proportional to the velocity of the object passing through it. In the late 17th century, Christiaan Huygens and Sir Isaac Newton determined that air resistance to the motion of a body was proportional to the square of the velocity.

Newton's work in setting forth the laws of mechanics marked the beginning of the classical theories of aerodynamics. He considered the pressure acting on an inclined plate as arising from the impingement of particles on the side of the plate that faces the airstream. His formulation yielded the result that the pressure acting on the plate was proportional to the product of the density of the air, the area of the plate, the square of the velocity, and the square of the sine of the angle of inclination. This failed to account for the effects of the flow on the upper surface of the plate where low pressures exist and from which a major portion of the lift of a wing is produced. The idea of air as a continuum with a pressure field extending over great distances from the plate was to come much later.

Various discoveries were made during the 18th and 19th centuries that contributed to a better understanding of the factors influencing the movement of solid bodies through air. The relationship of resistance to the viscous properties of a fluid, for example, was perceived in part by the early 1800s, and the experiments of the British physicist Osborne Reynolds in the 1880s brought into clearer view the significance of viscous effects.

Modern aerodynamics emerged about the time that the Wright brothers made their first powered flight (1903). Several years after their historic effort, Frederick W. Lanchester, a British engineer, proposed a circulation theory of lift of an airfoil of infinite span and a vortex theory of the lift of a wing of finite span. The German physicist Ludwig Prandtl, commonly regarded as the father of modern aerodynamics, arrived independently at the same hypotheses as Lanchester and developed the mathematical treatment. Prandtl's work, refined and expanded by subsequent investigators, formed the theoretical foundation of the field. Among others who played a prominent role in the development of modern aerodynamics was the Hungarian-born engineer Theodore von Kármán, whose contributions led to major advances in such areas as turbulence theory and supersonic flight.

Exercise 1. Vocabulary and Definition Matching

1. Match the term "aerodynamics" with its definition.
2. Define "forces" in the context of aerodynamics.
3. What are "gaseous fluids"?
4. Match "compressibility effects" with its role in aerodynamics.
5. Define "velocity" as it applies to a body passing through a fluid.
6. Match "lift" with its meaning in aerodynamics.
7. Define "air resistance" based on the text.
8. What is "viscous properties"?
9. Match "Newton's laws of mechanics" with their contribution to aerodynamics.
10. Define "supersonic flight."

Exercise 2. True or False

1. Aerodynamics deals exclusively with the motion of air and does not concern other gases.
2. The text mentions that aerodynamics only applies to the design of aircraft and rockets.

3. Galileo experimentally proved that air offers resistance to objects moving through it.

4. Christiaan Huygens and Sir Isaac Newton determined that air resistance is proportional to the velocity of the object.

5. Newton's early theory of pressure on an inclined plate was entirely accurate for describing lift.

6. Leonardo da Vinci believed air resistance was due to compressibility.

7. Osborne Reynolds' experiments in the 1880s clarified the importance of viscous effects in fluid motion.

8. Theodore von Kármán contributed significantly to the theory of subsonic flight.

9. Modern aerodynamics emerged after the first powered flight by the Wright brothers.

10. The idea of air as a continuum was known before the 19th century.

Exercise 3. Multiple Choice

1. What field of physics deals with the forces acting on bodies moving through gaseous fluids?
a) Mechanics
b) Chemistry
c) Aerodynamics
d) Thermodynamics

2. Which scientist observed that air offered resistance due to compressibility effects?
a) Isaac Newton
b) Leonardo da Vinci
c) Galileo
d) Christiaan Huygens

3. Air resistance to motion was determined to be proportional to what?
a) Mass of the object
b) Square of the velocity
c) Density of air
d) Shape of the object

4. What factor did Newton fail to account for in his early aerodynamic theories?
a) Density of air
b) Pressure field on the upper surface

c) Impingement of air particles
d) Viscous effects

5. Who is considered the father of modern aerodynamics?

a) Frederick W. Lanchester
b) Ludwig Prandtl
c) Theodore von Kármán
d) Isaac Newton

6. The Wright brothers made their first powered flight in which year?

a) 1903
b) 1880
c) 1920
d) 1905

7. What does "lift" primarily depend on according to modern aerodynamics?

a) Air resistance
b) Low pressures on the upper surface
c) Compressibility of air
d) Viscous drag

8. Which of the following scientists helped establish turbulence theory?

a) Theodore von Kármán
b) Galileo
c) Isaac Newton
d) Frederick W. Lanchester

9. In early times, what was air incorrectly believed to provide to a moving object?

a) Resistance force
b) Impelling force
c) Lift force
d) Drag force

10. Who proposed a circulation theory of lift?

a) Ludwig Prandtl
b) Galileo
c) Frederick W. Lanchester
d) Christiaan Huygens

Exercise 4 Fill in the Blank

1. Aerodynamics is a branch of ________ that deals with the motion of air and other gaseous fluids.

2. The forces acting on bodies passing through gaseous fluids include _______ and _______.
3. Early scientists thought that air provided a _______ force rather than a _______ force.
4. _______ experimentally proved that air resistance exists and is proportional to velocity.
5. Christiaan Huygens and Isaac Newton showed that air resistance is proportional to the _______ of velocity.
6. Newton’s theories of mechanics laid the foundation for _______ theories of aerodynamics.
7. Modern aerodynamics began to emerge after the _______ flight by the Wright brothers.
8. Ludwig Prandtl is known for his _______ theory of aerodynamics.
9. The experiments of _______ in the 1880s highlighted the significance of viscous effects in fluid dynamics.
10. Aerodynamics is essential for designing _______ and high-speed trains.

Exercise 5. Give short answers to the questions:

1. What does aerodynamics aim to explain?
2. Why were early ideas about air's role in motion incorrect?
3. How did Galileo contribute to aerodynamics?
4. Explain Newton’s initial understanding of pressure on a plate in an airstream.
5. What role did Prandtl play in modern aerodynamics?
6. Why was the work of Theodore von Kármán significant for supersonic flight?
7. What is the relationship between velocity and air resistance according to Newton?
8. How did Lanchester’s circulation theory contribute to understanding lift?
9. In what way did Reynolds’ experiments advance the study of fluid dynamics?
10. How is aerodynamics applied outside of aviation?

Exercise 6. Put the events in chronological order:

○ Galileo’s experiments with air resistance.
○ Newton’s development of mechanics.
○ The Wright brothers' first powered flight.
○ Leonardo da Vinci's observation of air resistance.
○ Prandtl’s mathematical treatment of aerodynamic principles.

Exercise 7. Think and answer:

1. What was the effect of Leonardo da Vinci’s observation on the development of aerodynamic theory?
2. How did Galileo’s experiments influence later studies of air resistance?
3. What was the result of Newton’s laws of mechanics on the understanding of aerodynamic forces?
4. Explain the impact of Osborne Reynolds' work on viscous properties in fluid motion.
5. How did the Wright brothers' flight contribute to the field of modern aerodynamics?

Exercise 8. Diagram Labeling

1. Label a diagram of an aircraft wing, indicating areas of high and low pressure.
2. On a chart, show the relationship between velocity and air resistance.
3. Label key figures in the development of aerodynamics on a timeline.
4. Diagram the forces acting on a projectile passing through air.
5. Indicate where viscous effects and compressibility come into play in fluid motion.

Exercise 9. Critical Thinking

1. Why was air incorrectly believed to provide an impelling force in early times?
2. How would aerodynamic principles differ if air were incompressible?
3. What challenges did Newton’s early theories of air pressure face?
4. Why is viscosity important in aerodynamics?
5. How has modern technology like supersonic jets advanced due to developments in aerodynamics?

Exercise 10. Answer the questions:

1. How do Newton’s laws apply to modern aerodynamic design?
2. What connection can be drawn between Galileo’s findings and modern aircraft?
3. How do Prandtl’s contributions still influence modern aviation?
4. Why is air resistance a crucial consideration for high-speed trains?
5. How do supersonic jets use principles from early aerodynamic discoveries?

Exercise 11.

Debate whether Newton or Prandtl contributed more to modern aerodynamics.

Exercise 12.
Explain how air resistance affects the flight of an aircraft.

Exercise 13.
Discuss how aerodynamic principles apply to the design of modern vehicles.

Exercise 14.
Compare early ideas of air as an impelling force to modern understandings of air resistance.

Exercise 15.
Discuss the importance of aerodynamic principles in modern engineering (aviation, trains, and skyscrapers).

UNIT 8

An internal combustion engine

An **internal combustion engine** (ICE or IC engine) is a heat engine where fuel and an oxidiser (usually air) are combined in a combustion chamber that's part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is usually applied to pistons (in a piston engine), turbine blades (in a gas turbine), a rotor (in a Wankel engine), or a nozzle (in a jet engine). This force moves the component over a distance. This process turns chemical energy into kinetic energy, which is used to move or power whatever the engine is attached to.

The first commercially successful internal combustion engine was created by Étienne Lenoir around 1860, and the first modern internal combustion engine, known as the Otto engine, was created in 1876 by Nicolaus Otto. The term 'internal combustion engine' usually refers to an engine where combustion happens in bursts, like the more familiar two-stroke and four-stroke piston engines, as well as variants like the six-stroke piston engine and the Wankel rotary engine. There's another type of internal combustion engine that uses continuous combustion. These include gas turbines, jet engines and most rocket engines. They work on the same principle as the engines we've already talked about. Firearms are also a form of internal combustion engine, but they're so specialised that they're often treated as a separate category, along with weaponry like mortars and anti-aircraft cannons. On the other hand, external combustion engines, like steam or Stirling engines, use a working fluid that isn't contaminated by combustion products. These working fluids can be air, hot water, pressurised water, or even boiler-heated liquid sodium.

While there are lots of stationary applications, most ICEs are used in mobile applications and are the main source of power for vehicles like cars, aircraft and boats. ICEs are usually powered by hydrocarbon-based fuels like natural gas, gasoline, diesel fuel, or ethanol. There are also renewable fuels like biodiesel used in compression ignition (CI) engines and bioethanol or ETBE (ethyl tert-butyl ether) produced from bioethanol in spark ignition (SI) engines. Rudolf Diesel, the inventor of the diesel engine, was using peanut oil to run his engines as early as 1900. Renewable fuels are commonly blended with fossil fuels. Hydrogen, which is rarely used, can be obtained from either fossil fuels or renewable energy.

Exercise 1. Choose the correct answer.

1. What does an internal combustion engine primarily do?
○ a) It cools down the fuel.
○ b) It converts chemical energy into kinetic energy.
○ c) It stores electrical energy.
○ d) It separates oxygen from air.

2. Who created the first modern internal combustion engine?
○ a) Étienne Lenoir
○ b) Rudolf Diesel
○ c) Nicolaus Otto
○ d) Isaac Newton

3. What type of fuels are commonly used in internal combustion engines?
○ a) Hydrocarbon-based fuels
○ b) Nuclear fuels
○ c) Compressed air
○ d) Liquid nitrogen

4. What are some examples of continuous combustion internal combustion engines?
○ a) Piston engines
○ b) Gas turbines and jet engines
○ c) External combustion engines
○ d) Steam engines

5. Which renewable fuel was used by Rudolf Diesel for his engines?
○ a) Ethanol
○ b) Peanut oil
○ c) Biodiesel
○ d) Hydrogen

6. In what year was the first commercially successful internal combustion engine created?
○ a) 1900
○ b) 1800
○ c) 1860
○ d) 1876

7. What component of an internal combustion engine usually moves due to the expansion of gases?
○ a) Cylinder
○ b) Rotor

- c) Crankshaft
- d) Piston

8. Which of the following is not typically powered by an internal combustion engine?
   - a) Cars
   - b) Airplanes
   - c) Solar panels
   - d) Boats
9. What is a significant advantage of using renewable fuels in internal combustion engines?
   - a) Lower fuel costs
   - b) Reduced environmental impact
   - c) Increased engine power
   - d) Easier maintenance
10. What is the primary function of a combustion chamber in an internal combustion engine?
    - a) To cool down the engine
    - b) To mix fuel and air
    - c) To ignite the fuel-air mixture
    - d) To store energy

Exercise 2. True or False

1. The first commercially successful internal combustion engine was created in the 20th century. (True/False)
2. External combustion engines use a working fluid that is contaminated by combustion products. (True/False)
3. Firearms are considered a form of internal combustion engine. (True/False)
4. ICEs are rarely used in mobile applications. (True/False)
5. Hydrogen is a common fuel used in internal combustion engines. (True/False)
6. Gasoline is an example of a hydrocarbon-based fuel. (True/False)
7. Jet engines are a type of external combustion engine. (True/False)
8. Internal combustion engines convert thermal energy into electrical energy. (True/False)
9. The Otto engine was invented before the Lenoir engine. (True/False)
10. Biodiesel is derived from renewable sources. (True/False)

Exercise 3. Fill in the Blanks

1. The internal combustion engine converts ____ energy into kinetic energy.
2. The first modern internal combustion engine, known as the _______ engine, was created by Nicolaus Otto.
3. _______ fuels like biodiesel and bioethanol are used in internal combustion engines.
4. Continuous combustion engines include _______ and jet engines.
5. Rudolf Diesel used _______ oil to run his engines.
6. An internal combustion engine's combustion chamber is part of the working fluid flow _______.
7. _______ is an example of a renewable fuel used in spark ignition engines.
8. _______ was the creator of the first commercially successful internal combustion engine.
9. High-temperature and high-pressure gases in an internal combustion engine apply force to the _______.
10. Firearms, although specialised, are considered a form of _______ combustion engine.

Exercise 4. Match the terms on the left with their corresponding descriptions on the right.

Term	**Description**
1. Étienne Lenoir	a) Inventor of the diesel engine
2. Otto engine	b) A type of engine where combustion happens in bursts
3. Rudolf Diesel	c) Created the first commercially successful internal combustion engine
4. Hydrocarbon-based fuels	d) Invented the first modern internal combustion engine
5. External combustion engine	e) Uses a working fluid that isn't contaminated by combustion products
6. Continuous combustion	f) A process in certain engines like gas turbines and jet engines
7. Biodiesel	g) A renewable fuel commonly

used in diesel engines

8. Piston engine — h) An engine type where force is applied directly to pistons

9. Combustion chamber — i) The part of an engine where fuel and air mix and ignite

10. Hydrogen — j) A fuel that can be produced from fossil fuels or renewable energy sources

Exercise 5. Answer the questions:

1. Explain the primary function of an internal combustion engine.
2. What is the difference between internal and external combustion engines?
3. Why are renewable fuels blended with fossil fuels in internal combustion engines?
4. Describe the role of pistons in a piston engine.
5. What is unique about the fuel Rudolf Diesel used for his engines?
6. What are the advantages of using continuous combustion in certain types of internal combustion engines?
7. How does a Wankel engine differ from a traditional piston engine?
8. What factors led to the commercial success of the first internal combustion engines?
9. Discuss the environmental impact of hydrocarbon-based fuels used in ICEs.
10. How does the design of the combustion chamber affect the efficiency of an internal combustion engine?

Exercise 6: Put the events in chronological order: The first modern internal combustion engine, known as the Otto engine, was created.

1. **Event:** Rudolf Diesel used peanut oil to run his engines.
2. **Event:** Firearms are recognised as a specialised form of internal combustion engine.
3. **Event:** The first commercially successful internal combustion engine was created by Étienne Lenoir.
4. **Event:** Renewable fuels like biodiesel and bioethanol start being used in internal combustion engines.
5. **Event:** The concept of continuous combustion in internal combustion engines is introduced.

6. **Event:** Hydrocarbon-based fuels become the primary energy source for internal combustion engines.
7. **Event:** The development of gas turbines and jet engines.
8. **Event:** External combustion engines like steam engines are developed.
9. **Event:** Internal combustion engines become the main source of power for vehicles.

Exercise 7. Complete the Sentences

1. The first commercially successful internal combustion engine was created by ____________ around 1860.
2. Nicolaus Otto is credited with creating the first modern internal combustion engine, known as the ____________.
3. In a gas turbine, the force generated by combustion is usually applied to _____.
4. Hydrocarbon-based fuels, such as ____________ and ____________, are commonly used in ICEs.
5. Continuous combustion engines, like gas turbines, differ from piston engines because ____________.
6. Rudolf Diesel's early engines ran on ____________ oil, showing the potential for ____________ fuels.
7. External combustion engines are distinct because their working fluid is ____________ by combustion products.
8. Jet engines are a type of internal combustion engine that uses ____________ combustion.
9. The primary advantage of renewable fuels in ICEs is ____________.
10. An internal combustion engine converts ______ energy into kinetic energy.

Exercise 8. Provide definitions for the following terms:

1. Internal Combustion Engine (ICE)
2. Piston Engine
3. Wankel Engine
4. Combustion Chamber
5. Hydrocarbon-based Fuels
6. Renewable Fuels
7. Continuous Combustion
8. External Combustion Engine
9. Kinetic Energy

10. Bioethanol

Exercise 9. Identify the Components

1. The component that moves due to the expansion of gases in a piston engine: ___________.
2. The type of fuel that can be derived from both fossil fuels and renewable energy: ___________.
3. A process where combustion occurs continuously rather than in bursts: ___________.
4. A specialised internal combustion engine used in weaponry: __________.
5. The working fluid in an external combustion engine that is not contaminated by combustion products: ___________.
6. An example of a hydrocarbon-based fuel: ___________.
7. The first successful internal combustion engine was created by: _______.
8. The engine named after its inventor, Nicolaus Otto: ___________.
9. A type of engine that uses turbine blades to generate power: _______.
10. A renewable fuel derived from vegetable oils or animal fats: __________.

Exercise 10. Write an essay on one of the following topics (100-150 words):

1. **The Evolution of Internal Combustion Engines:** Discuss the development of internal combustion engines from the first successful model to modern applications.
2. **The Impact of Renewable Fuels on the Environment:** Explore how the use of renewable fuels in internal combustion engines can affect the environment.
3. **The Role of Internal Combustion Engines in Modern Transportation:** Explain why ICEs are the primary source of power for most vehicles today.
4. **Comparing Internal and External Combustion Engines:** Analyze the key differences between internal and external combustion engines and their respective applications.
5. **The Future of Internal Combustion Engines:** Discuss potential advancements and the future of ICE technology in the context of environmental sustainability.

Exercise 11. Discuss the following questions in pairs or groups:

1. Why do you think internal combustion engines have become the primary source of power for transportation? What are their advantages and disadvantages?
2. How do you see the future of internal combustion engines in the context of environmental concerns and renewable energy sources?

3. Compare and contrast internal combustion engines with external combustion engines. Which do you think is more efficient and why?

4. What are the implications of using renewable fuels like biodiesel and bioethanol in internal combustion engines?

5. Discuss the impact of Étienne Lenoir's and Nicolaus Otto's inventions on modern technology and society.

Exercise 12. Role-play the following scenario with a partner.

One of you is a car manufacturer trying to convince a potential customer to buy a new car powered by an internal combustion engine. The other person is the customer who is concerned about environmental issues and is considering an electric vehicle instead. Discuss the benefits and drawbacks of each type of engine.

Exercise 13. Explain the Concept

1. The process by which an internal combustion engine converts chemical energy into kinetic energy.
2. The difference between two-stroke and four-stroke piston engines.
3. The significance of continuous combustion engines, such as jet engines and gas turbines.
4. The role of renewable fuels in internal combustion engines.
5. The historical development of the internal combustion engine, focusing on key figures like Étienne Lenoir and Nicolaus Otto.

Exercise 14. Hold a debate on the following topic:

"Internal combustion engines are obsolete and should be replaced entirely by electric engines in the next decade."

Exercise 15. Prepare a short presentation on one of the following topics:

1. The history and development of internal combustion engines.
2. The environmental impact of hydrocarbon-based fuels versus renewable fuels in internal combustion engines.
3. How different types of internal combustion engines (e.g., piston, Wankel, turbine) work and where they are used.
4. The advantages and challenges of using hydrogen as a fuel for internal combustion engines.
5. The future of internal combustion engines in a world transitioning to renewable energy sources.

TEXTS FOR ADDITIONAL READING

Materials science

(Written by John D. Venables, Louis A. Girifalco)

Materials science, the study of the properties of solid materials and how those properties are determined by a material's composition and structure. It grew out of an amalgam of solid-state physics, metallurgy, and chemistry, since the rich variety of materials properties cannot be understood within the context of any single classical discipline. With a basic understanding of the origins of properties, materials can be selected or designed for an enormous variety of applications, ranging from structural steels to computer microchips. Materials science is therefore important to engineering activities such as electronics, aerospace, telecommunications, information processing, nuclear power, and energy conversion.

This article approaches the subject of materials science through five major fields of application: energy, ground transportation, aerospace, computers and communications, and medicine. The discussions focus on the fundamental requirements of each field of application and on the abilities of various materials to meet those requirements.

The many materials studied and applied in materials science are usually divided into four categories: metals, polymers, semiconductors, and ceramics. The sources, processing, and fabrication of these materials are explained at length in several articles: metallurgy; elastomer (natural and synthetic rubber); plastic; man-made fibre; and industrial glass and ceramics. Atomic and molecular structures are discussed in chemical elements and matter. The applications covered in this article are given broad coverage in energy conversion, transportation, electronics, and medicine.

Materials for energy

An industrially advanced society uses energy and materials in large amounts. Transportation, heating and cooling, industrial processes, communications—in fact, all the physical characteristics of modern life-depend on the flow and transformation of energy and materials through the techno-economic system. These two flows are inseparably intertwined and form the lifeblood of industrial society. The relationship of materials science to energy usage is pervasive and complex. At every stage of energy production, distribution, conversion, and utilization, materials play an essential role, and often special materials properties are needed. Remarkable growth in the understanding of the properties and structures of materials enables new materials, as well as improvements of old ones, to be developed on a scientific basis, thereby contributing to greater efficiency and lower costs.

Classification of energy-related materials

Energy materials can be classified in a variety of ways. For example, they can be divided into materials that are passive or active. Those in the passive group do not take part in the actual energy-conversion process but act as containers, tools, or structures such as reactor vessels, pipelines, turbine blades, or oil drills. Active materials are those that take part directly in energy conversion—such as solar cells, batteries, catalysts, and superconducting magnets.

Another way of classifying energy materials is by their use in conventional, advanced, and possible future energy systems. In conventional energy systems such as fossil fuels, hydroelectric generation, and nuclear reactors, the materials problems are well understood and are usually associated with structural mechanical properties or long-standing chemical effects such as corrosion. Advanced energy systems are in the development stage and are in actual use in limited markets. These include oil from shale and tar sands, coal gasification and liquefaction, photovoltaics, geothermal energy, and wind power. Possible future energy systems are not yet commercially deployed to any significant extent and require much more research before they can be used. These include hydrogen fuel and fast-breeder reactors, biomass conversion, and superconducting magnets for storing electricity.

Classifying energy materials as passive or active or in relation to conventional, advanced, or future energy systems is useful because it provides a picture of the nature and degree of urgency of the associated materials requirements. But the most illuminating framework for understanding the relation of energy to materials is in the materials properties that are essential for various energy applications. Because of its breadth and variety, such a framework is best shown by examples. In oil refining, for example, reaction vessels must have certain mechanical and thermal properties, but catalysis is the critical process.

Applications of energy-related materials

High-temperature materials

In order to extract useful work from a fuel, it must first be burned so as to bring some fluid (usually steam) to high temperatures. Thermodynamics indicates that the higher the temperature, the greater the efficiency of the conversion of heat to work;

therefore, the development of materials for combustion chambers, pistons, valves, rotors, and turbine blades that can function at ever-higher temperatures is of critical importance. The first steam engines had an efficiency of less than 1 percent, while modern steam turbines achieve efficiencies of 35 percent or more. Part of this improvement has come from improved design and metalworking accuracy, but a large portion is the result of using improved high-temperature materials. The early engines were made of cast iron and then ordinary steels. Later, high-temperature alloys containing nickel, molybdenum, chromium, and silicon were developed that did not melt or fail at temperatures above 540° C (1,000° F). But modern combustion processes are nearing the useful temperature limits that can be achieved with metals, and so new materials that can function at higher temperatures—particularly intermetallic compounds and ceramics—are being developed.

The structural features that limit the use of metals at high temperatures are both atomic and electronic. All materials contain dislocations. The simplest of these are the result of planes of atoms that do not extend all through the crystal, so that there is a line where the plane ends that has fewer atoms than normal. In metals, the outer electrons are free to move. This gives a delocalized cohesion so that, when a stress is applied, dislocations can move to relieve the stress. The result is that metals are ductile: not only can they be easily worked into desired shapes, but when stressed they will gradually yield plastically rather than breaking immediately. This is a desirable feature, but the higher the temperature, the greater the plastic flow under stress—and, if the temperature is too high, the material will become useless. In order to get around this, materials are being studied in which the motion of dislocations is inhibited. Ceramics such as silicon nitride or silicon carbide and intermetallics such as nickel aluminide hold promise because the electrons that hold them together are highly localized in the form of valence or ionic bonds. It is as if metals were held together by a slippery glue while in nonmetals the atoms were connected by rigid rods. Dislocations thus find it much harder to move in nonmetals; raising the temperature does not increase dislocation motion, and the stress needed to make them yield is much higher. Furthermore, their melting points are significantly higher than those of metals, and they are much more resistant to chemical attack. But these desirable features come at a price. The very structure that makes them attractive also makes them brittle; that is, they do not flow when subject to a high stress and are prone to failure by cracking. Modern research is aimed at overcoming this lack of ductility by modification of the material and how it is made. Hot pressing of ceramic powders, for example, minimizes the number of defects at which cracks can start, and the addition of small amounts of certain metals to intermetallics strengthens the cohesion among crystal grains at which fractures normally develop. Such advances, along with intelligent design, hold the promise of being able to build heat engines of much higher efficiency than those now available.

Diamond drills

Diamond drill bits are an excellent example of how an old material can be improved. Diamond is the hardest known substance and would make an excellent drill bit except that it is expensive and has weak planes in its crystal structure. Because natural diamonds are single crystals, the planes extend throughout the material, and they cleave easily. Such cleavage planes allow a diamond cutter to produce beautiful gems, but they are a disaster for drilling through rock. This limitation was overcome by Stratapax, a sintered diamond material developed by the General Electric Company of the United States. This consists of synthetic diamond powder that is formed into a thin plate and bonded to tungsten-carbide studs by sintering (fusing by heating the material below the melting point). Because the diamond plate is polycrystalline, cleavage cannot propagate through the material. The result is a very hard bit that does not fail by cleavage when it is used to drill through rock to get at oil and natural gas.

Oil platforms

An important example of dealing with old problems by modern methods is provided by the prevention of crack growth in offshore oil-drilling platforms. The primary structure consists of welded steel tubing that is subject to continually varying stress from ocean waves. Since the cost of building and deploying a platform can amount to several billion dollars, it is imperative that the platform have a long life and not be lost because of premature metal failure.

In the North Sea, 75 percent of the waves are higher than two metres (six feet) and exert considerable stresses on the platform. Cyclic loading of a metal ultimately results in fatigue failure in which surface cracks form, grow over time, and eventually cause the metal to break. Welds are the weak spots for such a process because weld metal has mechanical properties that are inferior to steel, and these are made even worse by internal stresses and defects (such as tiny voids and oxide particles) that are introduced in the welding process. Furthermore, the tube geometry at the weld consists of T- and K-shaped joints, which are natural stress concentrators. Fatigue failure in oil platforms therefore takes place at welds.

Fatigue occurs because cyclic stress causes dislocations to form and to move back and forth in the metal. Dislocation motion can be impeded by the presence of barriers such as small voids, grain boundaries, other dislocations, impurities, or even the surface itself. When dislocations are thereby pinned down, they stop the motion of other dislocations created by the stress, and a tangled dislocation network forms that results in a hard spot in the weld. The stress is then not easily relieved, and types of dislocation motion that are characteristic of the fatigue process initiate a crack at the weld surface. This phenomenon is a direct result of the microstructure of the weld and could be minimized by making the weld very uniform, preferably of the same material as the tubing, and having a very gently curved geometry at the joint. But, in spite of the sophistication of modern welding techniques, this is not yet feasible. An alternate strategy is therefore used in which the progress of the weld crack is monitored so that repairs can be made in time to avoid catastrophic failure. This can be done because, given the geometry of the joint, the depth of the crack is proportional to time until the crack is quite large. By contrast, in laboratory tests in which simple strips of metal are subject to cyclic stress, the growth rate increases as the crack becomes larger. In the T or K configuration in oil platforms, stress is much more evenly distributed, and the crack does not grow at an increasing speed until it is close to being fatal.

A technique for measuring the crack depth is based on the skin effect, the phenomenon in which a high-frequency alternating current is confined to the surface of a conductor. This makes it possible to measure the surface area of a small region with a simple meter, since an increase in crack depth means an increase in current path, and this in turn causes an increase in voltage drop. Measurement over time then allows the time to failure to be estimated; repairs can be effected before failure occurs. In this case, a knowledge of microstructure, the materials science of fatigue, and the study of crack formation have led to a simple testing technique of great economic importance.

Mathematical modeling of mass motion and heat transfer (including convection), along with studies of solidification, gas dissolution, and the effects of fluxes, are providing a much more detailed understanding of the factors controlling weld structure. With this knowledge, it should be possible to make welds with far fewer defects.

Radioactive waste

A different example is provided by the disposal of radioactive waste. Here the issue is primarily safety and the perception of safety rather than economics. Waste disposal will continue to be one of the factors that inhibit the exploitation of nuclear power until the public perceives it as posing no danger. The current plan is to interpose three barriers between the waste and human beings by first encapsulating it in a solid material, putting that in a metal container, and finally burying that container in geologically stable formations. The first step requires an inert, stable material that will hold the radioactive atoms trapped for a very long time, while the second step requires a material that is highly resistant to corrosion and degradation.

There are two good candidates for encapsulation. The first is borosilicate glass; this can be melted with the radioactive material, which then becomes a part of the glass structure. Glass has a very low solubility, and atoms in it have a very low rate of migration, so that it provides an excellent barrier to the escape of radioactivity. However, glass devitrifies at the high temperatures resulting from the heat of radioactive decay; that is to say, the amorphous glassy state becomes crystalline, and, during this process, many cracks form in the material so that it no longer provides a good barrier against the escape of radioactive atoms. (This problem is more severe in rock than in salt formations, because salt has higher thermal conductivity than rock and dissipates the heat more easily.) The problem can be eased by storing the waste above ground for a decade or so. This would allow the initially high rate of decay to decrease, thereby lowering the temperature that would be reached after encapsulation. Handled in this way, borosilicate glass would be an excellent encapsulation material for reactor waste that had been aged for a decade or so.

The other candidate is a synthetic rock made of mineral mixtures such as zirconolite and perovskite. These are very insoluble and, in their natural state, are known to have sequestered radioactive elements for hundreds of millions of years. They are crystalline, ceramic materials whose crystal structures allow radioactive atoms to be immobilized within them. They are not subject to devitrification, since they are already crystalline.

Once encapsulated, radioactive waste must be put into canisters that are corrosion-resistant. These can be made of nickel-steel alloys, but the best candidate so far is a titanium material containing small amounts of nickel and molybdenum and traces of carbon and iron. Even though they are meant to be buried in as dry an environment as possible, these metals are tested by immersing them in brine. Tests show that seawater at 250° C (480° F) would corrode away less than one micrometre (one-thousandth of a millimetre, or four ten-thousandths of an inch) of the surface of the titanium material (known as Ti code 12) per year. This remarkable performance is primarily the result of a tough, highly resistant oxide skin that forms on titanium when exposed to oxygen. It would take thousands of years for the canisters to be penetrated by corrosion.

In order to estimate the effectiveness of such waste disposal, it must be noted that the waste is highly radioactive and dangerous initially but that the danger decreases with time. Radioactivity decays to such levels that the danger is much less after a few hundred years, extremely low after 500 years, and negligible after 1,000 years. In order to breach the triple-barrier system, groundwater must migrate to the canister, eat it away, and then leach out the radioactive atoms from the encapsulating glass or ceramic. This is a process that most probably would take far longer than a single millennium. A careful application of materials science can make radioactive waste disposal safer than current disposal methods for other toxic wastes.

Photovoltaics

Photovoltaic systems are an attractive alternative to fossil or nuclear fuels for the generation of electricity. Sunlight is free, it does not use up an irreplaceable resource, and its conversion to electricity is nonpolluting. In fact, photovoltaics are now in use where power lines from utility grids are either not possible or do not exist, as in outer space or remote, nonurban locations.

The barrier to widespread use of sunlight to generate electricity is the cost of photovoltaic systems. The application of materials science is essential in efforts to lower the cost to levels that can compete with those for fossil or nuclear fuels.

The conversion of light to electricity depends on the electronic structure of solar cells with two or more layers of semiconductor material that can absorb photons, the primary energy packets of light. The photons raise the energy level of the electrons in the semiconductor, exciting some to jump from the lower-energy valence band to the higher-energy conduction band. The electrons in the conduction band and the holes they have left behind in the valence band are both mobile and can be induced to move by a voltage. The electron motion, and the movement of holes in the opposite direction, constitute an electric current. The force that drives electrons and holes through a circuit is created by the junction of two dissimilar semiconducting materials, one of which has a tendency to give up electrons and acquire holes (thereby becoming the positive, or *p*-type, charge carrier) while the other accepts electrons (becoming the negative, or *n*-type, carrier). The electronic structure that permits this is the band gap; it is equivalent to the energy required to move an electron from the lower band to the higher. The magnitude of this gap is important. Only photons with energy greater than that of the band gap can excite electrons from the valence band to the conduction band; therefore, the smaller the gap, the more efficiently light will be converted to electricity—since there is a greater range of light frequencies with sufficiently high energies. On the other hand, the gap cannot be too small, because the electrons and holes then find it easy to recombine, and a sizable current cannot be maintained.

The band gap defines the theoretical maximum efficiency of a solar cell, but this cannot be attained because of other materials factors. For each material there is an intrinsic rate of recombination of electrons and holes that removes their contribution to electric current. This recombination is enhanced by surfaces, interfaces, and crystal defects such as grain boundaries, dislocations, and impurities. Also, a fraction of the light is reflected by the cell's surface rather than being absorbed, and some can pass through the cell without exciting electrons to the conduction band.

Improvements in the trade-off between cell efficiency and cost are well illustrated by the preparation of silicon that is the basic material of current solar cells. Initially, high-purity silicon was grown from a silicon melt by slowly pulling out a seed crystal that grew by the accretion and slow solidification of the molten material. Known as the Czochralski process, this resulted in a high-purity, single-crystal ingot that was then sliced into wafers about 1 millimetre (0.04 inch) thick. Each wafer's surface was then "doped" with impurities to create *p*-type and *n*-type materials with a junction between them. Metal was then deposited to provide electrical leads, and the wafer was encapsulated to yield a cell about 100 millimetres in diameter. This was an expensive and time-consuming process; it has been much improved in a variety of ways. For example, high-purity silicon can be made at drastically reduced cost by chemically converting ordinary silicon to silane or trichlorosilane and then reducing it back to silicon. This silane process is capable of continuous operation at a high production rate and with low energy input. In order to avoid the cost and waste associated with sawing silicon into wafers, methods of directly drawing molten silicon into thin sheets or ribbons have been developed; these can produce crystalline, polycrystalline, or amorphous material. Another alternative is the manufacture of thin films on ceramic substrates—a process that uses much less silicon than other methods. Single-crystal silicon has a higher efficiency than other forms, but it is also much more expensive. The materials challenge is to find a combination of cost and efficiency that makes photovoltaic electricity economically possible.

Surface treatments that increase efficiency include deposition of antireflecting coatings, such as silicon nitride, on the front of the cell and highly reflective coatings on the rear. Thus, more of the light that strikes a cell actually enters it, and light that escapes out the back is reflected back into the cell. An ingenious surface treatment is part of the point contact method, in which the surface of the cell is not planar but microgrooved so that light is randomly reflected as it strikes the cell. This increases the amount of light that can be captured by the cell.

Louis A. Girifalco

Materials for ground transportation

The global effort to improve the efficiency of ground transportation vehicles, such as automobiles, buses, trucks, and trains, and thereby reduce the massive amounts of pollutants they emit, provides an excellent context within which to illustrate how materials science functions to develop new or better materials in response to critical human needs. For the automobile industry in particular, the story is a fascinating one in which the desire for lower vehicle weight, reduced emissions, and improved fuel economy has led to intense competition among aluminum, plastics, and steel companies for shares in the enormous markets involved (40 million to 50 million cars and trucks per year worldwide). In this battle, materials scientists have a key role to play because the success of their efforts to develop improved materials will determine the shape and viability of future automobiles.

Just how seriously suppliers to the industry view the need either to protect or to increase their share of these enormous markets is demonstrated by their establishing of special programs, consortia, or centres that are specifically designed to develop better alloys, plastics, or ceramics for automotive applications. For example, in the United States a program at the Aluminum Company of America (Alcoa) called the aluminum intensive vehicle (AIV), and a similar one at Reynolds Metals, were established to develop materials and processes for making automobile "space frames" consisting of aluminum-alloy rods and die-cast connectors joined by welding and adhesive bonding. Not to be outdone, another aluminum company, Alcan Aluminium Limited of Canada, in a program entitled aluminum structured vehicle technology (ASVT), began to investigate the construction of automobile unibodies from adhesively bonded aluminum sheet. The plastics industry, of course, has a powerful interest in replacing as many metal automobile components as possible, and in order to help bring this about a centre called D&S Plastics International was formed in the Detroit, Mich., area of the United States by three corporations. The specific aim of this centre was to develop materials and a process suitable for forming several connected panels or components (*e.g.*, body panels and bumper fascias) simultaneously out of different types of plastics. The centrepiece of the operation was a 4,000-ton co-injection press that could lead to cost reductions as great as 50 percent and thereby make the use of plastics for automotive applications more attractive.

In programs such as these, and in many more carried out by vendors and within the automobile companies themselves, materials scientists with specialized training in advanced metals, plastics, and ceramics have been leading a revolution in the automotive industry. The following sections describe specific needs that have been identified for improving the performance of automobiles and other ground-transportation vehicles, as well as approaches that materials scientists have taken in response to those needs.

Metals

Aluminum

Since aluminum has about one-third the density of steel, its substitution for steel in automobiles would seem to be a sensible approach to reducing weight and thereby increasing fuel economy and reducing harmful emissions. Such substitutions cannot be made, however, without due consideration of significant differences in other properties of the two materials. This is one important facet of the materials scientist’s job—to help evaluate the suitability of a material for a given application based on how its properties balance against load and performance requirements specified by the design engineer. In this case (aluminum versus steel), it is instructive to consider the materials scientist’s approach to evaluating the use of aluminum in automotive panels—such components as doors, hoods, trunk decks, and roofs that can make up more than 60 percent of a vehicle’s weight.

Two primary properties of any metal are (1) its yield strength, defined as its ability to resist permanent deformation (such as a fender dent), and (2) its elastic modulus, defined as its ability to resist elastic or springy deflection like a drum head. By alloying, aluminum can be made to have a yield strength equal to a moderately strong steel and therefore to exhibit similar resistance to denting in an automobile panel. On the other hand, alloying does not normally affect the elastic modulus of metals significantly, so that automotive door panels or hoods made from aluminum alloys, all of which have approximately one-third the modulus of steel, would be floppy and suffer large deflections when buffeted by the wind, for example. From this point of view, aluminum would appear to be a marginal choice for body panels.

One might attempt to overcome this deficiency by increasing the thickness of the aluminum sheet stock to three times the thickness of the steel it is intended to replace. This, however, would simply increase the weight to roughly that of an equivalent steel structure and thus defeat the purpose of the exercise. Fortunately, as was elegantly demonstrated in 1980 by two British materials scientists, Michael Ashby and David Jones, when proper account is taken of the way an actual door panel deflects, constrained as it is by the door edges, it is possible to use aluminum sheet only slightly thicker than the steel it would replace and still achieve equivalent performance. The net result would be a weight savings of almost two-thirds by the substitution of aluminum for steel on such body components. This suggests that understanding the interrelationship between materials properties and structural design is an important factor in the successful application of materials science.

Another important activity of the materials scientist is that of alloy development, which in some cases involves designing alloys for very specific applications. For example, in Alcoa’s AIV effort, materials scientists and engineers developed a special casting alloy for use as cast aluminum nodes (connecters) in their space frame design. Ordinarily, metal castings exhibit very little toughness, or ductility, and they are therefore prone to brittle fracture followed by catastrophic failure. Since the integrity of an automobile would be limited by having relatively brittle body components, a proprietary casting alloy and processing procedure were developed that provide a material of much greater ductility than is normally available in a casting alloy.

Many other advances in aluminum technology, brought about by materials scientists and design engineers, have led to a greater acceptance of aluminum in automobiles, trucks, buses, and even light rail vehicles. Among these are alloys for air-conditioner components that are designed to be chemically compatible with environmentally safer refrigerants and to withstand the higher pressures required by them. Also, alloys have been developed that combine good formability and corrosion resistance with the ability to achieve maximum strength without heat treating; these alloys develop their strength during the forming operation. As a consequence, the list of vehicles that contain significant quantities of aluminum substituted for steel has steadily grown. A milestone was reached in 1992 with a limited-edition Jaguar sports car that was virtually all aluminum, including the engine, adhesively bonded chassis, and skin. Somewhat less expensive and in full production were Honda’s Acura NSX, containing more than 400 kilograms (900 pounds) of aluminum compared with about 70 kilograms for the average automobile, and General Motors’ Saturn, with an aluminum engine block and cylinder heads. These vehicles and others took their place alongside the British Land Rover, which was built with all-aluminum body panels beginning in 1948—a choice dictated by a shortage of steel during World War II and continued by the manufacturer ever since.

Steel

While the goal of the aluminum and plastics industries is to achieve vehicle weight reductions by substituting their products for steel components, the goal of the steel industry is to counter such inroads with such innovative developments as high-strength, but inexpensive, “microalloyed” steels that achieve weight savings by thickness reductions. In addition, alloys have been developed that can be tempered (strengthened) in paint-baking ovens rather than in separate and expensive heat-treatment furnaces normally required for conventional steels.

The microalloyed steels, also known as high-strength low-alloy (HSLA) steels, are intermediate in composition between carbon steels, whose properties are controlled mainly by the amount of carbon they contain (usually less than 1 percent), and alloy steels, which derive their strength, toughness, and corrosion resistance primarily from other elements, including silicon, nickel, and manganese, added in somewhat larger amounts. Developed in the l960s and resurrected in the late 1970s to satisfy the need for weight savings through greater strength, the HSLA steels tend to be low in carbon with minute additions of titanium or vanadium, for example. Offering tensile strengths that can be triple the value of the carbon steels they are designed to replace (*e.g.*, 700 megapascals versus 200 megapascals), they have led to significant weight savings through thickness reductions—albeit at a slight loss of structural stiffness, because their elastic moduli are the same as other steels. They are considered to be quite competitive with aluminum substitutes for two reasons: they are relatively inexpensive (steel sells for one-half the price of aluminum on a per-unit-weight basis); and very little change in fabrication and processing procedures is needed in switching from carbon steel to HSLA steel, whereas major changes are usually required in switching to aluminum.

Bake-hardenable steels were developed specifically for the purpose of eliminating an expensive fabrication step—*i.e.*, the heat-treating furnace, where steels are imparted with their final strength. To do this, materials scientists have designed steels that can be strengthened in the same ovens used to bake body paint onto the part. These furnaces must operate at relatively low temperatures (170° C, or 340° F), so that special steels had to be developed that would achieve suitable strengths at heat-treatment temperatures very much below those normally employed (up to 600° C, or 1,100° F). Knowing that high-alloy steels would never be hardenable at such low temperatures, materials scientists focused their attention on carbon steels, but even here adequate strengths could not be obtained initially. Then in the 1980s scientists at the Japanese Sumitomo Metal Industries developed a steel containing nitrogen (a gas that constitutes three-quarters of the Earth's atmosphere) in addition to carbon and several other additives. Very high strengths (over 900 megapascals) and excellent toughness can be achieved on formed parts with this inexpensive addition after baking for 20 minutes at temperatures typical for a paint-baking operation.

Plastics and composites

The motive for replacing the metal components of cars, trucks, and trains with plastics is the expectation of large weight savings due to the large differences in density involved: plastics are one-sixth the weight of steel and one-half that of aluminum per unit volume. However, as in evaluating the suitability of replacing steel with aluminum, the materials scientist must compare other properties of the materials in order to determine whether the tradeoffs are reasonable. For two reasons, the likely conclusion would be that plastics simply are not suitable for this type of application: the strength of most plastics, such as epoxies and polyesters, is roughly one-fifth that of steel or aluminum; and their elastic modulus is one-sixtieth that of steel and one-twentieth that of aluminum. On this basis, plastics do not appear to be suitable for structural components. What, then, accounts for the successful use that has been made of them? The answer lies in efforts made over the years by materials scientists, polymer chemists, mechanical engineers, and production managers to combine relatively weak and low-stiffness resins with high-strength, high-modulus reinforcements, thereby making new materials called composites with much more suitable properties than plastics alone.

The reinforcements used in composites are generally chosen for their high strength and modulus, as might be expected, but economic considerations often force compromises. For example, carbon fibres have extremely high modulus values (up to five times that of steel) and therefore make excellent reinforcements. However, their cost precludes their extensive use in automobiles, trucks, and trains, although they are used regularly in the aerospace industry. More suitable for non-aerospace applications are glass fibres (whose modulus can approach 1.5 times that of aluminum) or, in somewhat special cases, a mixture of glass and carbon fibres.

The physical form and shape of the reinforcements vary greatly, depending on many factors. The most effective reinforcements are long fibres, which are employed either in the form of a woven cloth or as separate layers of unidirectional fibres stacked upon one another until the proper laminate thickness is achieved. The resin may be applied to the fibres or cloth before laying up, thus forming what are termed prepregs, or it may be added later by "wetting out" the fibres. In either case, the assembly is then cured, usually under pressure, to form the composite. This type of composite takes full advantage of the properties of the fibres and is therefore capable of yielding strong, stiff panels. Unfortunately, the labour involved in the lay-up operations and other factors make it very expensive, so that long-fibre reinforcement is used only sparingly in the automobile industry.

One attempt to avoid expensive hand lay-up operations involves chopped fibres that are employed in mat form, somewhat like felt, or as loose fibres that may be either blown into a mold or injected into a mold along with the resin. Another method does not use fibres at all; instead the reinforcement is in the form of small, high-modulus particles. These are the least expensive of all to process, since the particles are simply mixed into the resin, and the mixture is used in various types of molds. On the other hand, particles are the least efficient reinforcement material; as a consequence, property improvements are not outstanding.

In choosing the other major constituent in composites, the polymer matrix, one faces a somewhat daunting variety, including epoxies, polyimides, polyurethanes, and polyesters. Each has its advantages and disadvantages that must be evaluated in order to determine suitability for a particular application. Among the factors to be considered are cost, processing temperature (curing temperature if using a thermoset polymer and melting temperature if using a thermoplastic), flow properties in the molding operation, sag resistance during paint bake out, moisture resistance, and shelf life. The number of combinations of resins, reinforcements, production methods, and fibre-to-resin ratios is so challenging that materials scientists must join forces with polymer chemists and engineers from the design, production, and quality-control departments of the company in order to choose the right combination for the application.

Judging by the inroads that have been made in replacing metals with composites, it appears that technologists have been making the right choices. The introduction of fibreglass-reinforced plastic skins on General Motors' l953 Corvette sports car marked the first appearance of composites in a production model, and composites have continued to appear in automotive components ever since. In 1984, General Motors' Fiero was placed on the market with the entire body made from composites, and the Camaro/Firebird models followed with doors, roof panels, fenders, and other parts made of composites. Composites were also chosen for exterior panels in the Saturn, which appeared in 1990. In addition, they have had less visible applications—for example, the glass-reinforced nylon air-intake manifold on some BMW models.

Ceramics

Ceramics play an important role in engine efficiency and pollution abatement in automobiles and trucks. For example, one type of ceramic, cordierite (a magnesium aluminosilicate), is used as a substrate and support for catalysts in catalytic converters. It was chosen for this purpose because, along with many ceramics, it is lightweight, can operate at very high temperatures without melting, and conducts heat poorly (helping to retain exhaust heat for improved catalytic efficiency). In a novel application of ceramics, a cylinder wall was made of transparent sapphire (aluminum oxide) by General Motors' researchers in order to examine visually the internal workings of a gasoline engine combustion chamber. The intention was to arrive at improved understanding of combustion control, leading to greater efficiency of internal-combustion engines.

Another application of ceramics to automotive needs is a ceramic sensor that is used to measure the oxygen content of exhaust gases. The ceramic, usually zirconium oxide to which a small amount of yttrium has been added, has the property of producing a voltage whose magnitude depends on the partial pressure of oxygen surrounding the material. The electrical signal obtained from such a sensor is then used to control the fuel-to-air ratio in the engine in order to obtain the most efficient operation.

Because of their brittleness, ceramics have not been used as load-bearing components in ground-transportation vehicles to any great extent. The problem remains a challenge to be solved by materials scientists of the future.

Materials for aerospace

(John D. Venables)

The primary goal in the selection of materials for aerospace structures is the enhancement of fuel efficiency to increase the distance traveled and the payload delivered. This goal can be attained by developments on two fronts: increased engine efficiency through higher operating temperatures and reduced structural weight. In order to meet these needs, materials scientists look to materials in two broad areas—metal alloys and advanced composite materials. A key factor contributing to the advancement of these new materials is the growing ability to tailor materials to achieve specific properties.

Metals

Many of the advanced metals currently in use in aircraft were designed specifically for applications in gas-turbine engines, the components of which are exposed to high temperatures, corrosive gases, vibration, and high mechanical loads. During the period of early jet engines (from about 1940 to 1970), design requirements were met by the development of new alloys alone. But the more severe requirements of advanced propulsion systems have driven the development of novel alloys that can withstand temperatures greater than 1,000° C (1,800° F), and the structural performance of such alloys has been improved by developments in the processes of melting and solidification.

Melting and solidifying

Alloys are substances composed of two or more metals or of a metal and a nonmetal that are intimately united, usually by dissolving in each other when they are melted. The principal objectives of melting are to remove impurities and to mix the alloying ingredients homogeneously in the base metal. Major advances have been made with the development of new processes based on melting under vacuum (hot isostatic pressing), rapid solidification, and directional solidification.

In hot isostatic pressing, prealloyed powders are packed into a thin-walled, collapsible container, which is placed in a high-temperature vacuum to remove adsorbed gas molecules. It is then sealed and put in a press, where it is exposed to very high temperatures and pressures. The mold collapses and welds the powder together in the desired shape.

Molten metals cooled at rates as high as a million degrees per second tend to solidify into a relatively homogeneous microstructure, since there is insufficient time for crystalline grains to nucleate and grow. Such homogeneous materials tend to be stronger than the typical "grainy" metals. Rapid cooling rates can be achieved by "splat" cooling, in which molten droplets are projected onto a cold surface. Rapid heating and solidification can also be achieved by passing high-power laser beams over the material's surface.

Unlike composite materials (see below Composites), grainy metals exhibit properties that are essentially the same in all directions, so they cannot be tailored to match anticipated load paths (*i.e.*, stresses applied in specific directions). However, a technique called directional solidification provides a certain degree of tailorability. In this process the temperature of the mold is precisely controlled to promote the formation of aligned stiff crystals as the molten metal cools. These serve to reinforce the component in the direction of alignment in the same fashion as fibres reinforce composite materials.

Alloying

These advances in processing have been accompanied by the development of new “superalloys.” Superalloys are high-strength, often complex alloys that are resistant to high temperatures and severe mechanical stress and that exhibit high surface stability. They are commonly classified into three major categories: nickel-based, cobalt-based, and iron-based. Nickel-based superalloys predominate in the turbine section of jet engines. Although they have little inherent resistance to oxidation at high temperatures, they gain desirable properties through the addition of cobalt, chromium, tungsten, molybdenum, titanium, aluminum, and niobium.

Aluminum-lithium alloys are stiffer and less dense than conventional aluminum alloys. They are also “superplastic,” owing to the fine grain size that can now be achieved in processing. Alloys in this group are appropriate for use in engine components exposed to intermediate to high temperatures; they can also be used in wing and body skins.

Titanium alloys, as modified to withstand high temperatures, are seeing increased use in turbine engines. They are also employed in airframes, primarily for military aircraft but to some extent for commercial planes as well.

Composites

While developments in metals have had an impact on engine design, there is a growing trend toward the application of composite materials to aerospace structures. One of the reasons for this is that alloys do not offer substantial weight savings, which is a primary advantage of composites. Indeed, advanced composites have been used most widely where saving mass results in either significantly improved performance or significantly lower life-cycle costs. The most extensive application, therefore, has been in satellite systems, military aircraft, radomes, helicopters, commercial transport aircraft, and general aviation.

Broadly defined, composites are materials with two or more distinct components that combine to yield characteristics superior to those of the individual constituents. Although this definition can apply to such ordinary building materials as plywood, concrete, and bricks, within the aerospace industry the term composite generally refers to the fibre-reinforced metal, polymer, and ceramic products that have come into use since World War II. These materials consist of fibres (such as glass, graphite, silicon carbide, or aramid) that are embedded in a matrix of, for example, aluminum, epoxy, or silicon nitride.

In the late 1950s a revolution in materials development occurred in response to the space program's need for lightweight, thermally stable materials. Boron-tungsten filaments, carbon-graphite fibres, and organic aramid fibres proved to be strong, stiff, and light, but one problem with using them as fibres was that they were of limited value in any construction other than rope, which can bear loads in only one direction. Materials scientists needed to develop a way to make them useful under all loading conditions, and this led to the development of composites. While the structural value of a bundle of fibres is low, the strength of individual fibres can be harnessed if they are embedded in a matrix that acts as an adhesive, binding the fibres and lending solidity to the material. The matrix also protects the fibres from environmental stress and physical damage, which can initiate cracks. In addition, while the strength and stiffness of the composite remain largely a function of the reinforcing material—that is, the fibres—the matrix can contribute other properties, such as thermal and electrical conductivity and, most important, thermal stability. Finally, fibre-matrix combination reduces the potential for complete fracture. In a monolithic (or single) material, a crack, once started, generally continues to propagate until the material fails; in a composite, if one fibre in an assemblage fails, the crack may not extend to the other fibres, so the damage is limited.

To some extent, the composite-materials engineer is trying to mimic structures made spontaneously by plants and animals. A tree, for example, is made of a fibre-reinforced material whose strength is derived from cellulose fibres that grow in directions that match the weight of the branches. Similarly, many organisms naturally fabricate "bioceramics," such as those found in shells, teeth, and bones. While the designers of composites for the aerospace industry would like to copy some of the features of bioceramics production—room-temperature processing and net-shape products, for example—they do not want to be constrained by slow processing methods and limited fibre and matrix material choices. In addition, unlike a mollusk, which has to produce only one shell, the composites manufacturer has to use rapid, repeatable processing methods that can fabricate hundreds or even thousands of parts.

Modern composites are generally classified into three categories according to the matrix material: polymer, metal, or ceramic. Since polymeric materials tend to degrade at elevated temperatures, polymer-matrix composites (PMCs) are restricted to secondary structures in which operating temperatures are lower than 300° C (570° F). For higher temperatures, metal-matrix and ceramic-matrix composites are required.

Polymer-matrix composites

PMCs are of two broad types, thermosets and thermoplastics. Thermosets are solidified by irreversible chemical reactions, in which the molecules in the polymer "cross-link," or form connected chains. The most common thermosetting matrix materials for high-performance composites used in the aerospace industry are the epoxies. Thermoplastics, on the other hand, are melted and then solidified, a process that can be repeated numerous times for reprocessing. Although the manufacturing technologies for thermoplastics are generally not as well developed as those for thermosets, thermoplastics offer several advantages. First, they do not have the shelf-life problem associated with thermosets, which require freezer storage to halt the irreversible curing process that begins at room temperature. Second, they are more desirable from an environmental point of view, as they can be recycled. They also exhibit higher fracture toughness and better resistance to solvent attack. Unfortunately, thermoplastics are more expensive, and they generally do not resist heat as well as thermosets; however, strides are being made in developing thermoplastics with higher melting temperatures. Overall, thermoplastics offer a greater choice of processing approaches, so that the process can be determined by the scale and rate of production required and by the size of the component.

A variety of reinforcements can be used with both thermoset and thermoplastic PMCs, including particles, whiskers (very fine single crystals), discontinuous (short) fibres, continuous fibres, and textile preforms (made by braiding, weaving, or knitting fibres together in specified designs). Continuous fibres are more efficient at resisting loads than are short ones, but it is more difficult to fabricate complex shapes from materials containing continuous fibres than from short-fibre or particle-reinforced materials. To aid in processing, most high-performance composites are strengthened with filaments that are bundled into yarns. Each yarn, or tow, contains thousands of filaments, each of which has a diameter of approximately 10 micrometres (0.01 millimetre, or 0.0004 inch).

Depending on the application and on the type of load to be applied to the composite part, the reinforcement can be random, unidirectional (aligned in a single direction), or multidirectional (oriented in two or three dimensions). If the load is uniaxial, the fibres are all aligned in the load direction to gain maximum benefit of their stiffness and strength. However, for multidirectional loading (for example, in aircraft skins), the fibres must be oriented in a variety of directions. This is often accomplished by stacking layers (or lamina) of continuous-fibre systems.

The most common form of material used for the fabrication of composite structures is the preimpregnated tape, or "prepreg." There are two categories of prepreg: tapes, generally 75 millimetres (3 inches) or less in width, intended for fabrication in automated, computer-controlled tape-laying machines; and "broad goods," usually several metres in dimension, intended for hand lay-up and large sheet applications. To make prepregs, fibres are subjected to a surface treatment so that the resin will adhere to them. They are then placed in a resin bath and rolled into tapes or sheets.

To fabricate the composite, the manufacturer "lays up" the prepreg according to the reinforcement needs of the application. This has traditionally been done by hand, with successive layers of a broad-goods laminate stacked over a tool in the shape of the desired part in such a way as to accommodate the anticipated loads. However, efforts are now being directed toward automated fibre-placement methods in order to reduce costs and ensure quality and repeatability. Automated fibre-placement processes fall into two categories, tape laying and filament winding. The tape-laying process involves the use of devices that control the placement of narrow prepreg tapes over tooling with the contours of the desired part and along paths prescribed by the design requirements of the structure. The width of the tape determines the "sharpness" of the turns required to place the fibres in the prescribed direction—*i.e.,* wide tapes are used for gradual turns, while narrow tapes are required for the sharp turns associated with more complex shapes.

Filament winding uses the narrowest prepreg unit available—the yarn, or tow, of impregnated filaments. In this process, the tows are wound in prescribed directions over a rotating mandrel in the shape of the part. Successive layers are added until the required thickness is reached. Although filament winding was initially limited to geodesic paths (*i.e.,* winding the fibres along the most direct route between two points), the process is now capable of fabricating complex shapes through the use of robots.

For thermosetting polymers, the structure generated by either tape laying or filament winding must undergo a second manipulation in order to solidify the polymer through a curing reaction. This is usually accomplished by heating the completed structure in an autoclave, or oven. Thermoplastic systems offer the advantage of on-line consolidation, so that the high energy and capital costs associated with the curing step can be eliminated. For these systems, prepreg can be locally melted, consolidated, and cooled at the point of contact so that a finished structure is produced. A variety of energy sources are used to concentrate heat at the point of contact, including hot-gas torches, infrared light, and laser beams.

Pultrusion, the only truly continuous process for manufacturing parts from PMCs, is economical but limited to the production of beamlike shapes. On a pultrusion line, fibres and the resin are pushed through a heated die, or shaping tool, at one end, then cooled and pulled out at the other end. This process can be applied to both thermoplastic and thermoset polymers.

Resin transfer molding, or RTM, is a composites processing method that offers a high potential for tailorability but is currently limited to low-viscosity (easily flowing) thermosetting polymers. In RTM, a textile preform—made by braiding, weaving, or knitting fibres together in a specified design—is placed into a mold, which is then closed and injected with a resin. After consolidation, the mold is opened and the part removed. Preforms can be made in a wide variety of architectures, and several can be joined together during the RTM process to form a multi-element preform offering reinforcement in specific areas and load directions.

The similarity of meltable thermoplastic polymers to metals has prompted the extension of techniques used in metalworking. Sheet forming, used since the 19th century by metallurgists, is now applied to the processing of thermoplastic composites. In a typical thermoforming process, the sheet stock, or preform, is heated in an oven. At the forming temperature, the sheet is transferred into a forming system, where it is forced to conform to a tool, with a shape that matches the finished part. After forming, the sheet is cooled under pressure and then removed. Stretch forming, a variation on thermoplastic sheet forming, is specifically designed to take advantage of the extensibility, or ability to be stretched, of thermoplastics reinforced with long, discontinuous fibres. In this process, a straight preconsolidated beam is heated and then stretched over a shaped tool to introduce curvature. The specific advantage of stretch forming is that it provides an automated way to achieve a very high degree of fibre-orientation control in a wide range of part sizes.

Metal-matrix and ceramic-matrix composites

The requirement that finished parts be able to operate at temperatures high enough to melt or degrade a polymer matrix creates the need for other types of matrix materials, often metals. Metal matrices offer not only high-temperature resistance but also strength and ductility, or "bendability," which increases toughness. The main problems with metal-matrix composites (MMCs) are that even the lightest metals are heavier than polymers, and they are very complex to process. MMCs can be used in such areas as the skin of a hypersonic aircraft, but on wing edges and in engines temperatures often exceed the melting point of metals. For the latter applications, ceramic-matrix composites (CMCs) are seeing increasing use, although the technology for CMCs is less mature than that for PMCs. Ceramics consist of alumina, silica, zirconia, and other elements refined from fine earth and sand or of synthetic materials, such as silicon nitride or silicon carbide. The desirable properties of ceramics include superior heat resistance and low abrasive and corrosive properties. Their primary drawback is brittleness, which can be reduced by reinforcing with fibres or whiskers. The reinforcement material can be a metal or another ceramic.

Unlike polymers and metals, which can be processed by techniques that involve melting (or softening) followed by solidification, high-temperature ceramics cannot be melted. They are generally produced by some variation of sintering, a technique that renders a combination of materials into a coherent mass by heating to high temperatures without complete melting. If continuous fibres or textile weaves (as opposed to short fibres or whiskers) are involved, sintering is preceded by impregnating the assembly of fibres with a slurry of ceramic particles dispersed in a liquid. A major benefit of using CMCs in aircraft engines is that they allow higher operating temperatures and thus greater combustion efficiency, leading to reduced fuel consumption. An additional benefit is derived from the low density of CMCs, which translates into substantial weight savings.

Other advanced composites

Carbon-carbon composites are closely related to CMCs but differ in the methods by which they are produced. Carbon-carbon composites consist of semicrystalline carbon fibres embedded in a matrix of amorphous carbon. The composite begins as a PMC, with semicrystalline carbon fibres impregnated with a polymeric phenolic resin. The resin-soaked system is heated in an inert atmosphere to pyrolyze, or char, the polymer to a carbon residue. The composite is re-impregnated with polymer, and the pyrolysis is repeated. Continued repetition of this impregnation/pyrolysis process yields a structure with minimal voids. Carbon-carbon composites retain their strength at 2,500° C (4,500° F) and are used in the nose cones of reentry vehicles. However, because they are vulnerable to oxidation at such high temperatures, they must be protected by a thin layer of ceramic.

While materials research for aerospace applications has focused largely on mechanical properties such as stiffness and strength, other attributes are important for use in space. Materials are needed with a near-zero coefficient of thermal expansion; in other words, they have to be thermally stable and should not expand and contract when exposed to extreme changes in temperature. A great deal of research is focused on developing such materials for high-speed civilian aircraft, where thermal cycling is a major issue. High-toughness materials and nonflammable resin composite systems are also under investigation to improve the safety of aircraft interiors.

Efforts are also being directed toward the development of “smart,” or responsive, materials. Representing another attempt to mimic certain characteristics of living organisms, smart materials, with their built-in sensors and actuators, would react to their external environment by bringing on a desired response. This would be done by linking the mechanical, electrical, and magnetic properties of these materials. For example, piezoelectric materials generate an electrical current when they are bent; conversely, when an electrical current is passed through these materials, they stiffen. This property can be used to suppress vibration: the electrical current generated during vibration could be detected, amplified, and sent back, causing the material to stiffen and stop vibrating.

Materials for computers and communications

(R.L. McCullough, Diane S. Kukich)

The basic function of computers and communications systems is to process and transmit information in the form of signals representing data, speech, sound, documents, and visual images. These signals are created, transmitted, and processed as moving electrons or photons, and so the basic materials groups involved are classified as electronic and photonic. In some cases, materials known as optoelectronic bridge these two classes, combining abilities to interact usefully with both electrons and photons.

Among the electronic materials are various crystalline semiconductors; metalized film conductors; dielectric films; solders; ceramics and polymers formed into substrates on which circuits are assembled or printed; and gold or copper wiring and cabling.

Photonic materials include a number of compound semiconductors designed for light emission or detection; elemental dopants that serve as photonic performance-control agents; metal- or diamond-film heat sinks; metalized films for contacts, physical barriers, and bonding; and silica glass, ceramics, and rare earths for optical fibres.

Electronic materials

Between 1955 and 1990, improvements and innovations in semiconductor technology increased the performance and decreased the cost of electronic materials and devices by a factor of one million—an achievement unparalleled in the history of any technology. Along with this extraordinary explosion of technology has come an exponentially upward spiral of the capital investment necessary for manufacturing operations. In order to maintain cost-effectiveness and flexibility, radical changes in materials and manufacturing operations will be necessary.

Semiconductor crystals

Silicon

Bulk semiconductor silicon for the manufacture of integrated circuits (sometimes referred to as electronic-grade silicon) is the purest material ever made commercially in large quantities. One of the most important factors in preparing this material is control of such impurities as boron, phosphorus, and carbon (not to be confused with the dopants added later during circuit production). For the ultimate levels of integrated-circuit design, stray contaminant atoms must constitute less than 0.1 part per trillion of the material.

For fabrication into integrated circuits, bulk semiconductor silicon must be in the form of a single-crystal material with high crystalline perfection and the desired charge-carrier concentration. The size of the silicon ingot, or boule, has been scaled up in recent years, in order to provide wafers of increasing diameter that are demanded by the economics of integrated-circuit manufacturing. Most commonly, a 60-kilogram (130-pound) charge is grown to an ingot with a diameter of 200 millimetres (8 inches), but the semiconductor industry will soon require ingots as large as 300 millimetres. The ingots are then converted into wafers by machining and chemical processes.

III–V compounds

Although silicon is by far the most commonly used crystal material for integrated circuits, a significant volume of semiconductor devices and circuits employs III–V technology, so named because it is based on crystalline compounds formed by combining metallic elements from column III and nonmetallic elements from column V of the periodic table of chemical elements. When the elements are gallium and arsenic, the semiconductor is called gallium arsenide, or GaAs. However, other elements such as indium, phosphorus, and aluminum are often used in the compound to achieve specific performance characteristics.

For electronic applications, the III–V semiconductors offer the basic advantage of higher electron mobility, which translates into higher operating speeds. In addition, devices made with III–V compounds provide lower voltage operation for specific functions, radiation hardness (especially important for satellites and space vehicles), and semi-insulating substrates (avoiding the presence of parasitic capacitance in switching devices).

III–V materials are more difficult to handle than silicon, and a III–V wafer or substrate usually is less than half the size of a silicon wafer. In addition, a gallium arsenide wafer entering the processing facility can be expected to cost 10 to 20 times as much as a silicon wafer, although that cost difference narrows somewhat after fabrication, packaging, and testing. Nevertheless, there is one major characteristic of III–V materials with which silicon cannot compete: a III–V compound can be tailored to generate or detect photons of a specific wavelength. For example, an indium gallium arsenide phosphide (InGaAsP) laser can generate radiation at 1.55 micrometres to carry digitally coded information streams. (See below Photonic materials.) This means that a III–V component can fill both electronic and photonic functions in the same integrated circuit.

Photoresist films

Patterning polished wafers with an integrated circuit requires the use of photoresist materials that form thin coatings on the wafer before each step of the photolithographic process. Modern photoresists are polymeric materials that are modified when exposed to radiation (either in the form of visible, ultraviolet, or X-ray photons or in the form of energetic electron beams). A photoresist typically contains a photoactive compound (PAC) and an alkaline-soluble resin. The PAC, mixed into the resin, renders it insoluble. This mixture is coated onto the semiconductor wafer and is then exposed to radiation through a “mask” that carries the desired pattern. Exposed PAC is converted into an acid that renders the resin soluble, so that the resist can be dissolved and the exposed substrate beneath it chemically etched or metallically coated to match the circuit design.

Besides practical properties such as shelf life, cost, and availability, the key properties of a photoresist include purity, etching resistance, resolution, contrast, and sensitivity. As the feature sizes of integrated circuits shrink in each successive generation of microchips, photoresist materials are challenged to handle shorter wavelengths of light. For example, the photolithography of current designs (with features that have shrunk to less than one micrometre) is based on ultraviolet radiation in the wavelength range of 365 to 436 nanometres, but, in order to define accurately the smaller features of future microchips (less than 0.25 micrometre), shorter wavelengths will be necessary. The problem here is that electromagnetic radiation in such frequency regions is weaker. One solution is to use the chemically amplified photoresist, or CAMP. The sensitivity of a photoresist is measured by its quantum efficiency, or the number of chemical events that occur when a photon is absorbed by the material. In CAMP material, the number of events is dramatically increased by subsequent chemical reactions (hence the amplification), which means that less light is needed to complete the process.

Electric connections

The performance of today's electronic systems (and photonic systems as well) is limited significantly by interconnection technology, in which components and subsystems are linked by conductors and connectors. Currently, very fine gold or copper wiring, as thin as 30 micrometres, is used to carry electric current to and from the many pads along the sides or ends of a microchip to other components on a circuit board. The capacitance involved in such circuitry slows down the flow of electrons and, hence, of information. However, by integrating several chips into a single multichip module, in which the chips are connected on a shared substrate by various conducting materials (such as metalized film), the speed of information flow can be increased, thus improving the assembly's performance. Ideally, all the chips in a single module would be fabricated simultaneously on the same wafer, but in practice this is not feasible: Silicon crystal manufacture is still subject to an average of one flaw per wafer, meaning that at least one of the many chips cut from each wafer is scrapped. If the whole wafer area were dedicated to a single multifunction assembly, that one flaw would scrap the entire module. Multichip modules are therefore made up of as many as five microchips bonded to a silicon or ceramic substrate on which resistors and capacitors have been constructed with thin films. Typical materials used in a multichip module include the substrate; gold paste conductors applied in an additive process resembling silk screen printing; vitreous glazes to insulate the gold paste conductors from subsequent film layers; a series of thin films made with tantalum nitride, titanium, palladium, and plated gold; and a final package of silicone rubber.

Packaging materials

Several major types of packaging material are used by the electronics industry, including ceramic, refractory glass, premolded plastic, and postmolded plastic. Ceramic and glass packages cost more than plastic packages, so they make up less than 10 percent of the worldwide total. However, they provide the best protection for complex chips. Premolded plastic packages account for only a small but important fraction of the market, since they are required for packaging devices with many leads. Most plastic packages are postmolded, meaning that the package body is molded over the assembly after the microchip has been attached to the fan-out pattern.

Precursors

The starting materials for most semiconductor devices are volatile and ultrapure gaseous derivatives of various organic and inorganic precursors. Many of them are toxic, and many will ignite spontaneously in the atmosphere. These gases are transported in high-pressure cylinders from the plant where they were made to the site where they will be used. One possible method of replacing these precursors with materials that are environmentally safe is known as in situ synthesis. In this method, dangerous reagents would be generated on demand in only the desired quantities, instead of being shipped cross-country and stored until needed at the semiconductor processing plant.

Photonic materials

Computers and communications systems have been dominated by electronic technology since their beginnings, but photonic technology is making serious inroads throughout the information movement and management systems with such devices as lasers, light-emitting diodes, photodetecting diodes, optical switches, optical amplifiers, optical modulators, and optical fibres. Indeed, for long-distance terrestrial and transoceanic transmission of information, photonics has almost completely displaced electronics.

Crystalline materials

The light detectors and generators listed above are actually optoelectronic, because they link photonic and electronic systems. They employ the III–V compound semiconductors described above, many of them characterized by their band gaps—*i.e.*, the energy minimum of the electron conduction band and the energy maximum of hole valence bands occur at the same location in the momentum space, allowing electrons and holes to recombine and radiate photons efficiently. (By contrast, the conduction band minimum and the valence band maximum in silicon have dissimilar momenta, and therefore the electrons and holes cannot recombine efficiently.) Among the important compounds are gallium arsenide, aluminum gallium arsenide, indium gallium arsenide phosphide, indium phosphide, and aluminum indium arsenide.

Fabricating a single crystal from these combinations of elements is far more difficult than creating a single crystal of electronic-grade silicon. Special furnaces are required, and the process can take several days. Notwithstanding the precision involved, the sausage-shaped boule is less than half the diameter of a silicon ingot and is subject to a much higher rate of defects. Researchers are continuously seeking ways to reduce the thermal stresses that are primarily responsible for dislocations in the III–V crystal lattice that cause these defects. The purity and structural perfection of the final single-crystal substrates affect the qualities of the crystalline layers that are grown on them and the regions that are diffused or implanted in them during the manufacture of photonic devices.

Epitaxial layers

For the efficient emission or detection of photons, it is often necessary to constrain these processes to very thin semiconductor layers. These thin layers, grown atop bulk semiconductor wafers, are called epitaxial layers because their crystallinity matches that of the substrate even though the composition of the materials may differ—*e.g.*, gallium aluminum arsenide (GaAlAs) grown atop a gallium arsenide substrate. The resulting layers form what is called a heterostructure. Most continuously operating semiconductor lasers consist of heterostructures, a simple example consisting of 1000-angstrom thick gallium arsenide layers sandwiched between somewhat thicker (about 10000 angstroms) layers of gallium aluminum arsenide—all grown epitaxially on a gallium arsenide substrate. The sandwiching and repeating of very thin layers of a semiconductor between layers of a different composition allow one to modify the band gap of the sandwiched layer. This technique, called band-gap engineering, permits the creation of semiconductor materials with properties that cannot be found in nature. Band-gap engineering, used extensively with III–V compound semiconductors, can also be applied to elemental semiconductors such as silicon and germanium.

The most precise method of growing epitaxial layers on a semiconducting substrate is molecular-beam epitaxy (MBE). In this technique, a stream or beam of atoms or molecules is effused from a common source and travels across a vacuum to strike a heated crystal surface, forming a layer that has the same crystal structure as the substrate. Variations of MBE include elemental-source MBE, hydride-source MBE, gas-source MBE, and metal-organic MBE. Other approaches to epitaxial growth are liquid-phase epitaxy (LPE) or chemical vapour deposition (CVD). The latter method includes hydride CVD, trichloride CVD, and metal-organic CVD.

Normally, epitaxial layers are grown on flat surfaces, but scientists are searching for an economical and reliable method of growing epitaxial material on nonplanar structures—for example, around the “mesas” or “ridges” or in the “tubs” or “channels” that are etched into the surface of semiconducting devices. Nonplanar epitaxy is considered necessary for producing monolithic integrated optical devices or all-photonic switches and logic elements, but mastery of this method requires better understanding of the surface chemistry and surface dynamics of epitaxial growth.

Optical switching

Research in this area is driven by the need to switch data streams of higher and higher speed efficiently as customers for computer and communications services demand transmission and switching rates far higher than can be provided by a purely electronic system. Thanks to developments in semiconductor lasers and detectors (described above Epitaxial layers) and in optical fibres (described below Optical transmission), transmission at the desired high speeds has become possible. However, the switching of optical data streams still requires converting the data from the optical to the electronic domain, subjecting them to electronic switching and to manipulation inside the switching apparatus, and then reconverting the switched and reconfigured data into the optical domain for transmission over optical fibres. Electronic switching therefore is seen as the principal barrier to achieving higher switching speeds. One approach to solving this problem would be to introduce optics inside digital switching machines. Known as free-space photonics, this approach would involve such devices as semiconductor lasers or light-emitting diodes (LEDs), optical modulators, and photodetectors—all of which would be integrated into systems combined with electronic components.

One commercially available device for photonic switching is the quantum-well self-electro-optic-effect device, or SEED. The key concept for this device is the use of quantum wells. These structures consist of many thin layers of two different semiconductor materials. Individual layers are typically 10 nanometres (about 40 atoms) thick, and 100 layers are used in a device about 1 micrometre thick. When a voltage is applied across the layers, the transmission of photons through the quantum wells changes significantly, in effect creating an optical modulator—an essential component of any photonic circuit. Variations on the SEED concept are the symmetric SEED (S-SEED) and the field-effect transistor SEED. Neighbouring S-SEEDs could be connected by pairs of back-to-back quantum-well photodiodes, and commercially sized interconnection networks could be built by using free-space photonic interconnections between two-dimensional arrays of switching nodes. However, even this type of free-space optical interconnection technology would only enhance and extend electronic technology, not replace it.

The move of optoelectronic and photonic integrated circuits out of the research laboratory and into the marketplace has been made possible by the availability of high-quality epitaxial growth techniques for building up lattice-matched crystalline layers of indium gallium arsenide phosphide and indium phosphide (InGaAsP/InP). This III–V compound system is central to the light emitters and detectors used in the 1.3-micrometre and 1.5-micrometre wavelength ranges at which optical fibre has very low transmission loss.

Optical transmission

As the rates of transmission are increased from millions of bits (megabits) per second to billions of bits (gigabits) per second, commercially available lasers encounter a physical limitation called "chirping," in which the optical frequency of the laser begins to waver during a pulse. Future systems, which may require from 2.4 to 30 gigabits per second, are probably going to be based on the use of a continuously operating distributed-feedback laser, whose output will be modulated in intensity by passing it through a modulator. This device consists of a crystal substrate of lithium niobate onto which a titanium channel is diffused to function as a light guide. The signal is encoded onto the light beam via a microwave radio-frequency feed through neighbouring channels in the coupler. Such a device is used only at the transmitter end of the optical path.

Both communications and computer systems rely on silica glass fibres to transmit light signals from lasers and LEDs. For long-distance transmission, optical-fibre cables are usually equipped with electro-optical repeater assemblies approximately every 100 kilometres. A new approach, called optical amplifiers, has been developed for deployment in transoceanic fibre-optic cables. Unlike traditional repeaters, optical amplifiers work by adding photons to a light signal without changing it to an electrical signal and without changing its bit-rate. Since they can be used at any desired transmission bit-rate, a transoceanic cable equipped with these devices can be upgraded to higher bit-rates simply by changing the lasers and photodiodes at each end. No retrofitting of higher bit-rate amplifiers is necessary.

The optical amplifier is a module containing a semiconductor pump laser and a short length of optical fibre whose core has been doped with less than 0.1 percent erbium, an optically active rare-earth element. The pump laser is powered by an electrical conductor that runs the length of the cable. The amplifier functions by converting the optical energy generated by the pump source into signal photon energy. When a signal-carrying stream of laser pulses passes through the optical amplifier, it is combined with the pump light through a wavelength division multiplexer located in the module. The combined signal is fed through the erbium-doped fibre length, where the excited erbium ions contribute photons coherently to the signal. The amplified signal is then fed to the next section of cable for transmission to the next optical amplifier, perhaps 200 to 300 kilometres away.

Materials for medicine

(*C. Kumar N. Patel)*

The treatment of many human disease conditions requires surgical intervention in order to assist, augment, sustain, or replace a diseased organ, and such procedures involve the use of materials foreign to the body. These materials, known as biomaterials, include synthetic polymers and, to a lesser extent, biological polymers, metals, and ceramics. Specific applications of biomaterials range from high-volume products such as blood bags, syringes, and needles to more challenging implantable devices designed to augment or replace a diseased human organ. The latter devices are used in cardiovascular, orthopedic, and dental applications as well as in a wide range of invasive treatment and diagnostic systems. Many of these devices have made possible notable clinical successes. For example, in cardiovascular applications, thousands of lives have been saved by heart valves, heart pacemakers, and large-diameter vascular grafts, and orthopedic hip-joint replacements have shown great long-term success in the treatment of patients suffering from debilitating joint diseases. With such a tremendous increase in medical applications, demand for a wide range of biomaterials grows by 5 to 15 percent each year. In the United States the annual market for surgical implants exceeds $10 billion, approximately 10 percent of world demand.

Nevertheless, applications of biomaterials are limited by biocompatibility, the problem of adverse interactions arising at the junction between the biomaterial and the host tissue. Optimizing the interactions that occur at the surface of implanted biomaterials represents the most significant key to further advances, and an excellent basis for these advances can be found in the growing understanding of complex biological materials and in the development of novel biomaterials custom-designed at the molecular level for specific medical applications.

This section describes biomaterials that are used in medicine, with emphasis on polymer materials and on the challenges associated with implantable devices used in the cardiovascular and orthopedic areas.

General requirements of biomaterials

Research on developing new biomaterials is an interdisciplinary effort, often involving collaboration among materials scientists and engineers, biomedical engineers, pathologists, and clinicians to solve clinical problems. The design or selection of a specific biomaterial depends on the relative importance of the various properties that are required for the intended medical application. Physical properties that are generally considered include hardness, tensile strength, modulus, and elongation; fatigue strength, which is determined by a material's response to cyclic loads or strains; impact properties; resistance to abrasion and wear; long-term dimensional stability, which is described by a material's viscoelastic properties; swelling in aqueous media; and permeability to gases, water, and small biomolecules. In addition, biomaterials are exposed to human tissues and fluids, so that predicting the results of possible interactions between host and material is an important and unique consideration in using synthetic materials in medicine. Two particularly important issues in biocompatibility are thrombosis, which involves blood coagulation and the adhesion of blood platelets to biomaterial surfaces, and the fibrous-tissue encapsulation of biomaterials that are implanted in soft tissues.

Poor selection of materials can lead to clinical problems. One example of this situation was the choice of silicone rubber as a poppet in an early heart valve design. The silicone absorbed lipid from plasma and swelled sufficiently to become trapped between the metal struts of the valve. Another unfortunate choice as a biomaterial was Teflon (trademark), which is noted for its low coefficient of friction and its chemical inertness but which has relatively poor abrasion resistance. Thus, as an occluder in a heart valve or as an acetabular cup in a hip-joint prosthesis, Teflon may eventually wear to such an extent that the device would fail. In addition, degradable polyesterurethane foam was abandoned as a fixation patch for breast prostheses, because it offered a distinct possibility for the release of carcinogenic by-products as it degraded.

Besides their constituent polymer molecules, synthetic biomaterials may contain several additives, such as unreacted monomers and catalysts, inorganic fillers or organic plasticizers, antioxidants and stabilizers, and processing lubricants or mold-release agents on the material's surface. In addition, several degradation products may result from the processing, sterilization, storage, and ultimately implantation of a device. Many additives are beneficial—for example, the silica filler that is indispensable in silicone rubber for good mechanical performance or the antioxidants and stabilizers that prevent premature oxidative degradation of polyetherurethanes. Other additives, such as pigments, can be eliminated from biomedical products. Indeed, a “medical-grade” biomaterial is one that has had nonessential additives and potential contaminants excluded or eliminated from the polymer. In order to achieve this grade, the polymer may need to be solvent-extracted before use, thereby eliminating low-molecular-weight materials. Generally, additives in polymers are regarded with extreme suspicion, because it is often the additives rather than the constituent polymer molecules that are the source of adverse biocompatibility.

Polymer biomaterials

The majority of biomaterials used in humans are synthetic polymers such as the polyurethanes or Dacron (trademark; chemical name polyethylene terephthalate), rather than polymers of biological origin such as proteins or polysaccharides. The properties of common synthetic biomaterials vary widely, from the soft and delicate water-absorbing hydrogels made into contact lenses to the resilient elastomers found in short- and long-term cardiovascular devices or the high-strength acrylics used in orthopedics and dentistry. The properties of any material are governed by its chemical composition and by the intra- and intermolecular forces that dictate its molecular organization. Macromolecular structure in turn affects macroscopic properties and, ultimately, the interfacial behaviour of the material in contact with blood or host tissues.

Since the properties of each material are dependent on the chemical structure and macromolecular organization of its polymer chains, an understanding of some common structural features of various polymers provides considerable insight into their properties. Compared with complex biological molecules, synthetic polymers are relatively simple; often they comprise only one type of repeating subunit, analogous to a polypeptide consisting of just one repeating amino acid. On the basis of common structures and properties, synthetic polymers are classified into one of three categories: elastomers, which include natural and synthetic rubbers; thermoplastics; and thermosets. The properties that provide the basis for this classification include molecular weight, cross-link density, percent crystallinity, thermal transition temperature, and bulk mechanical properties.

Elastomers

Elastomers, which include rubber materials, have found wide use as biomaterials in cardiovascular and soft-tissue applications owing to their high elasticity, impact resistance, and gas permeability. Applications of elastomers include flexible tubing for pacemaker leads, vascular grafts, and catheters; biocompatible coatings and pumping diaphragms for artificial hearts and left-ventricular assist devices; grafts for reconstructive surgery and maxillofacial operations; wound dressings; breast prostheses; and membranes for implantable biosensors.

Elastomers are typically amorphous with low cross-link density (although linear polyurethane block copolymers are an important exception). This gives them low to moderate modulus and tensile properties as well as high elasticity. For example, elastomeric devices can be extended by 100 to 1,000 percent of their initial dimensions without causing any permanent deformation to the material. Silicone rubbers such as Silastic (trademark), produced by the American manufacturer Dow Corning, Inc., are cross-linked, so that they cannot be melted or dissolved—although swelling may occur in the presence of a good solvent. Such properties contrast with those of the linear polyurethane elastomers, which consist of soft polyether amorphous segments and hard urethane-containing glassy or crystalline segments. The two segments are incompatible at room temperature and undergo microphase separation, forming hard domains dispersed in an amorphous matrix. A key feature of this macromolecular organization is that the hard domains serve as physical cross-links and reinforcing filler. This results in elastomeric materials that possess relatively high modulus and extraordinary long-term stability under sustained cyclic loading. In addition, they can be processed by methods common to thermoplastics.

Thermoplastics

Many common thermoplastics, such as polyethylene and polyester, are used as biomaterials. Thermoplastics usually exhibit moderate to high tensile strength (5 to 1,000 megapascals) with moderate elongation (2 to 100 percent), and they undergo plastic deformation at high strains. Thermoplastics consist of linear or branched polymer chains; consequently, most can undergo reversible melt-solid transformation on heating, which allows for relatively easy processing or reprocessing. Depending on the structure and molecular organization of the polymer chains, thermoplastics may be amorphous (*e.g.*, polystyrene), semicrystalline (*e.g.*, low-density polyethylene), or highly crystalline (*e.g.*, high-density polyethylene), or they may be processed into highly crystalline textile fibres (*e.g.*, polyester Dacron).

Some thermoplastic biomaterials, such as polylactic acid and polyglycolic acid, are polymers based on a repeating amino acid subunit. These polypeptides are biodegradable, and, along with biodegradable polyesters and polyorthoesters, they have applications in absorbable sutures and drug-release systems. The rate of biodegradation in the body can be adjusted by using copolymers. These are polymers that link two different monomer subunits into a single polymer chain. The resultant biomaterial exhibits properties, including biodegradation, that are intermediate between the two homopolymers.

Thermosets

Thermosetting polymers find only limited application in medicine, but their characteristic properties, which combine high strength and chemical resistance, are useful for some orthopedic and dental devices. Thermosetting polymers such as epoxies and acrylics are chemically inert, and they also have high modulus and tensile properties with negligible elongation (1 to 2 percent). The polymer chains in these materials are highly cross-linked and therefore have severely restricted macromolecular mobility; this limits extension of the polymer chains under an applied load. As a result, thermosets are strong but brittle materials.

Cross-linking inhibits close packing of polymer chains, preventing formation of crystalline regions. Another consequence of extensive cross-linking is that thermosets do not undergo solid-melt transformation on heating, so that they cannot be melted or reprocessed.

Applications of biomaterials

Cardiovascular devices

Biomaterials are used in many blood-contacting devices. These include artificial heart valves, synthetic vascular grafts, ventricular assist devices, drug-release systems, extracorporeal systems, and a wide range of invasive treatment and diagnostic systems. An important issue in the design and selection of materials is the hemodynamic conditions in the vicinity of the device. For example, mechanical heart valve implants are intended for long-term use. Consequently, the hinge points of each valve leaflet and the materials must have excellent wear and fatigue resistance in order to open and close 80 times per minute for many years after implantation. In addition, the open valve must minimize disturbances to blood flow as blood passes from the left ventricle of the heart, through the heart valve, and into the ascending aorta of the arterial vascular system. To this end, the bileaflet valve disks of one type of implant are coated with pyrolytic carbon, which provides a relatively smooth, chemically inert surface. This is an important property, because surface roughness will cause turbulence in the blood flow, which in turn may lead to hemolysis of red cells, provide sites for adventitious bacterial adhesion and subsequent colonization, and, in areas of blood stasis, promote thrombosis and blood coagulation. The carbon-coated holding ring of this implant is covered with Dacron mesh fabric so that the surgeon can sew and fix the device to adjacent cardiac tissues. Furthermore, the porous structure of the Dacron mesh promotes tissue integration, which occurs over a period of weeks after implantation.

While the possibility of thrombosis can be minimized in blood-contacting biomaterials, it cannot be eliminated entirely. For this reason, patients who receive artificial heart valves or other blood-contacting devices also receive anticoagulation therapy. This is needed because all foreign surfaces initiate blood coagulation and platelet adhesion to some extent. Platelets are circulating cellular components of blood, two to four micrometres in size, that attach to foreign surfaces and actively participate in blood coagulation and thrombus formation. Research on new biomaterials for cardiovascular applications is largely devoted to understanding thrombus formation and to developing novel surfaces for biomaterials that will provide improved blood compatibility.

Synthetic vascular graft materials are used to patch injured or diseased areas of arteries, for replacement of whole segments of larger arteries such as the aorta, and for use as sewing cuffs (as with the heart valve mentioned above). Such materials need to be flexible to allow for the difficulties of implantation and to avoid irritating adjacent tissues; also, the internal diameter of the graft should remain constant under a wide range of flexing and bending conditions, and the modulus or compliance of the vessel should be similar to that of the natural vessel. These aims are largely achieved by crimped woven Dacron and expanded polytetrafluoroethylene (ePTFE). Crimping of Dacron in processing results in a porous vascular graft that may be bent 180° or twisted without collapsing the internal diameter.

A biomaterial used for blood vessel replacement will be in contact not only with blood but also with adjacent soft tissues. Experience with different materials has shown that tissue growth into the interstices of the biomaterials aids healing and integration of the material with host tissue after implantation. In order for the tissue, which consists mostly of collagen, to grow in the graft, the vascular graft must have an open structure with pores at least 10 micrometres in diameter. These pores allow new blood capillaries that develop during healing to grow into the graft, and the blood then provides oxygen and other nutrients for fibroblasts and other cells to survive in the biomaterial matrix. Fibroblasts synthesize the structural protein tropocollagen, which is needed in the development of new fibrous tissue as part of the healing response to a surgical wound.

Occasionally, excessive tissue growth may be observed at the anastomosis, which is where the graft is sewn to the native artery. This is referred to as internal hyperplasia and is thought to result from differences in compliance between the graft and the host vessels. In addition, in order to optimize compatibility of the biomaterial with the blood, the synthetic graft eventually should be coated with a confluent layer of host endothelial cells, but this does not occur with current materials. Therefore, most proposed modifications to existing graft materials involve potential improvements in blood compatibility.

Artificial heart valves and vascular grafts, while not ideal, have been used successfully and have saved many thousands of lives. However, the risk of thrombosis has limited the success of existing cardiovascular devices and has restricted potential application of the biomaterials to other devices. For example, there is an urgent clinical need for blood-compatible, synthetic vascular grafts of small diameter in peripheral vascular surgery—*e.g.*, in the legs—but this is currently impracticable with existing biomaterials because of the high risk of thrombotic occlusion. Similarly, progress with implantable miniature sensors, designed to measure a wide range of blood conditions continuously, has been impeded because of problems directly attributable to the failure of existing biomaterials. With such biocompatibility problems resolved, biomedical sensors would provide a very important contribution to medical diagnosis and monitoring. Considerable advances have been made in the ability to manipulate molecular architecture at the surfaces of materials by using chemisorbed or physisorbed monolayer films. Such progress in surface modification, combined with the development of nanoscale probes that permit examination at the molecular and submolecular level, provide a strong basis for optimism in the development of specialty biomaterials with improved blood compatibility.

Orthopedic devices

Joint replacements, particularly at the hip, and bone fixation devices have become very successful applications of materials in medicine. The use of pins, plates, and screws for bone fixation to aid recovery of bone fractures has become routine, with the number of annual procedures approaching five million in the United States alone. In joint replacement, typical patients are age 55 or older and suffer from debilitating rheumatoid arthritis, osteoarthritis, or osteoporosis. Orthopedic surgeries for artificial joints exceed 1.5 million each year, with actual joint replacement accounting for about half of the procedures. A major focus of research is the development of new biomaterials for artificial joints intended for younger, more active patients.

Hip-joint replacements are principally used for structural support. Consequently, they are dominated by materials that possess high strength, such as metals, tough plastics, and reinforced polymer-matrix composites. In addition, biomaterials used for orthopedic applications must have high modulus, long-term dimensional stability, high fatigue resistance, long-term biostability, excellent abrasion resistance, and biocompatibility (*i.e.,* there should be no adverse tissue response to the implanted device). Early developments in this field used readily available materials such as stainless steels, but evidence of corrosion after implantation led to their replacement by more stable materials, particularly titanium alloys, cobalt-chromium-molybdenum alloys, and carbon fibre-reinforced polymer composites. A typical modern artificial hip consists of a nitrided and highly polished cobalt-chromium ball connected to a titanium alloy stem that is inserted into the femur and cemented into place by in situ polymerization of polymethylmethacrylate. The articulating component of the joint consists of an acetabular cup made of tough, creep-resistant, ultrahigh-molecular-weight polyethylene. Abrasion at the ball-and-cup interface can lead to the production of wear particles, which in turn can lead to significant inflammatory reaction by the host. Consequently, much research on the development of hip-joint materials has been devoted to optimizing the properties of the articulating components in order to eliminate surface wear. Other modifications include porous coatings made by sintering the metal surface or coatings of wire mesh or hydroxyapatite; these promote bone growth and integration between the implant and the host, eliminating the need for an acrylic bone cement.

While the strength of the biomaterials is important, another goal is to match the mechanical properties of the implant materials with those of the bone in order to provide a uniform distribution of stresses (load sharing). If a bone is loaded insufficiently, the stress distribution will be made asymmetric, and this will lead to adaptive remodeling with cortical thinning and increased porosity of the bone. Such lessons in structure hierarchy and in the structure-property relationships of materials have been obtained from studies on biologic composite materials, and they are being translated into new classes of synthetic biomaterials. One development is carbon fibre-reinforced polymer-matrix composites. Typical matrix polymers include polysulfone and polyetheretherketones. The strength of these composites is lower than that of metals, but it more closely approximates that of bone.