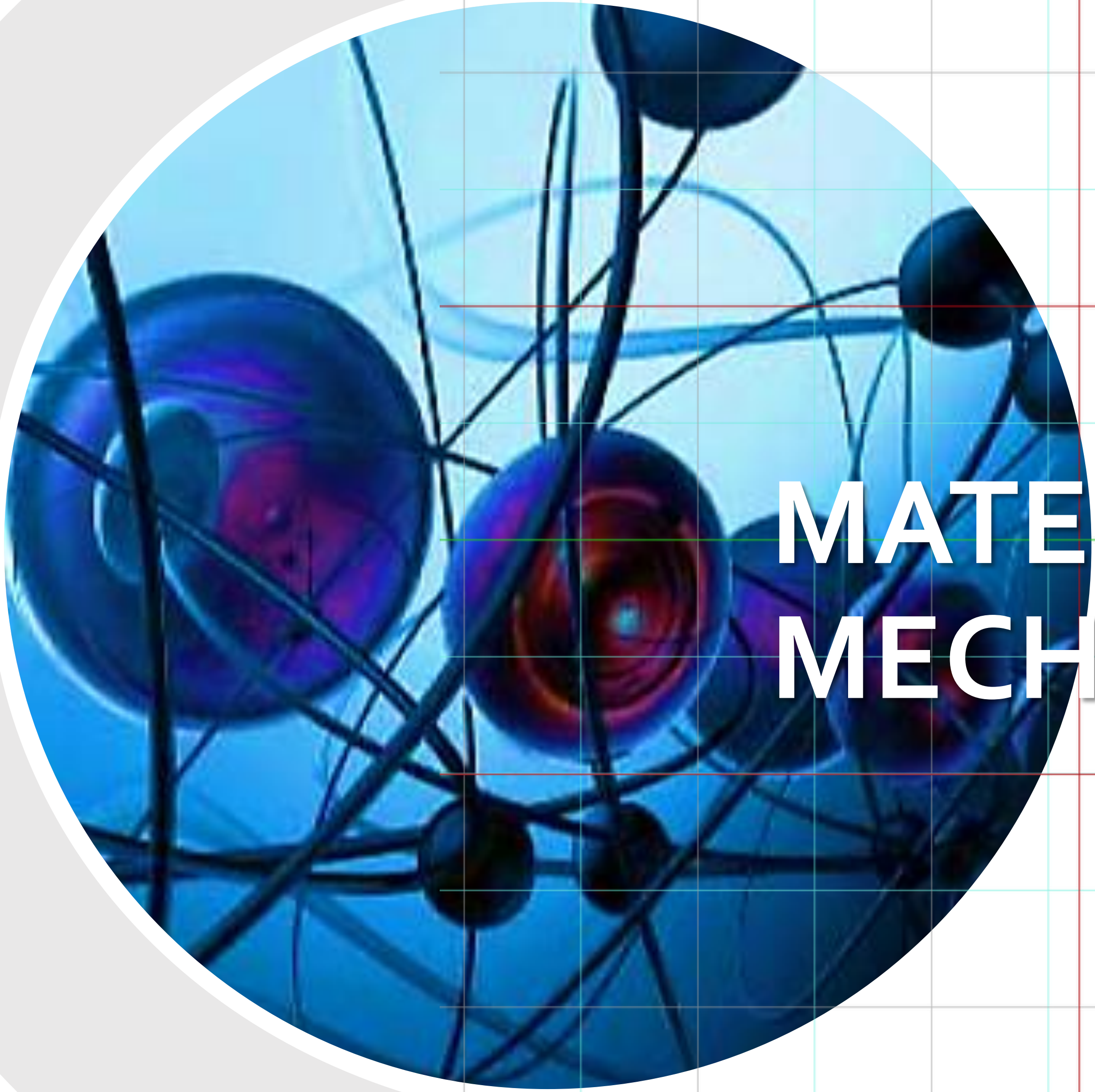
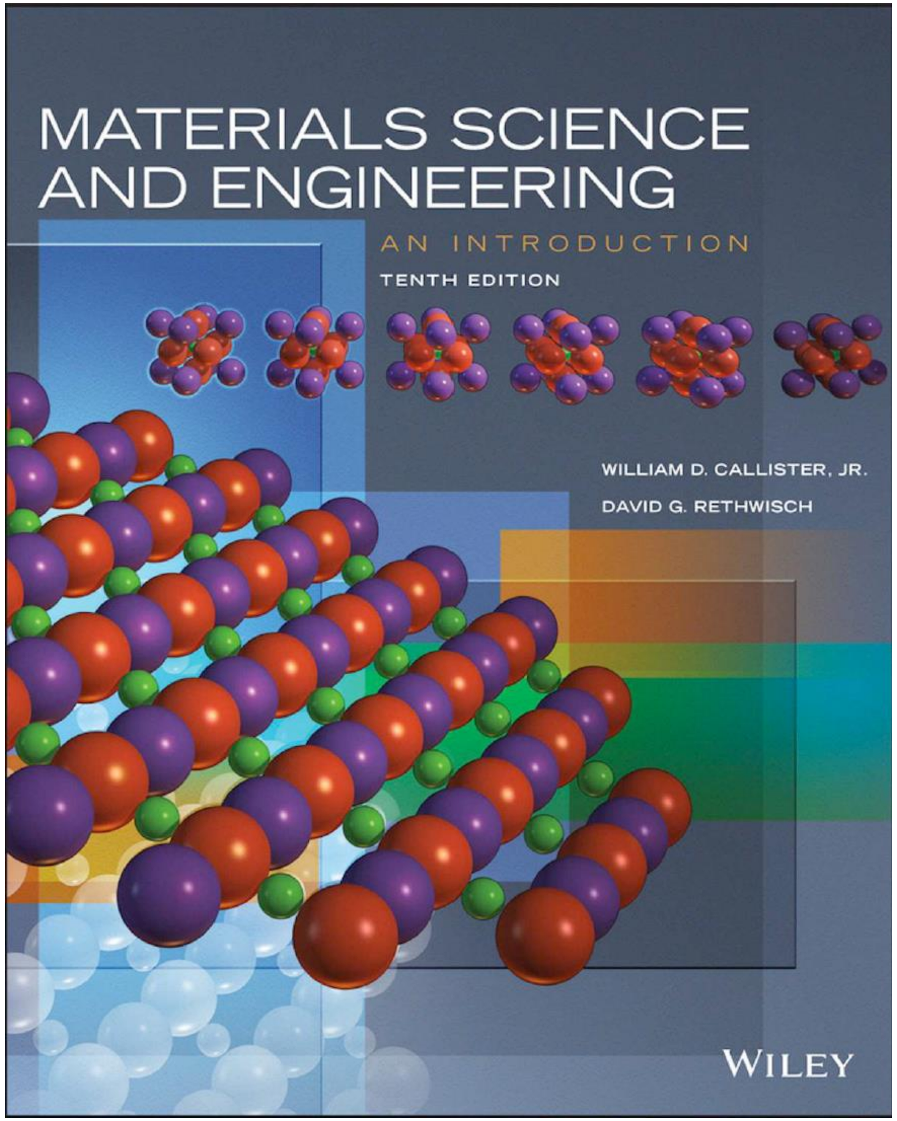
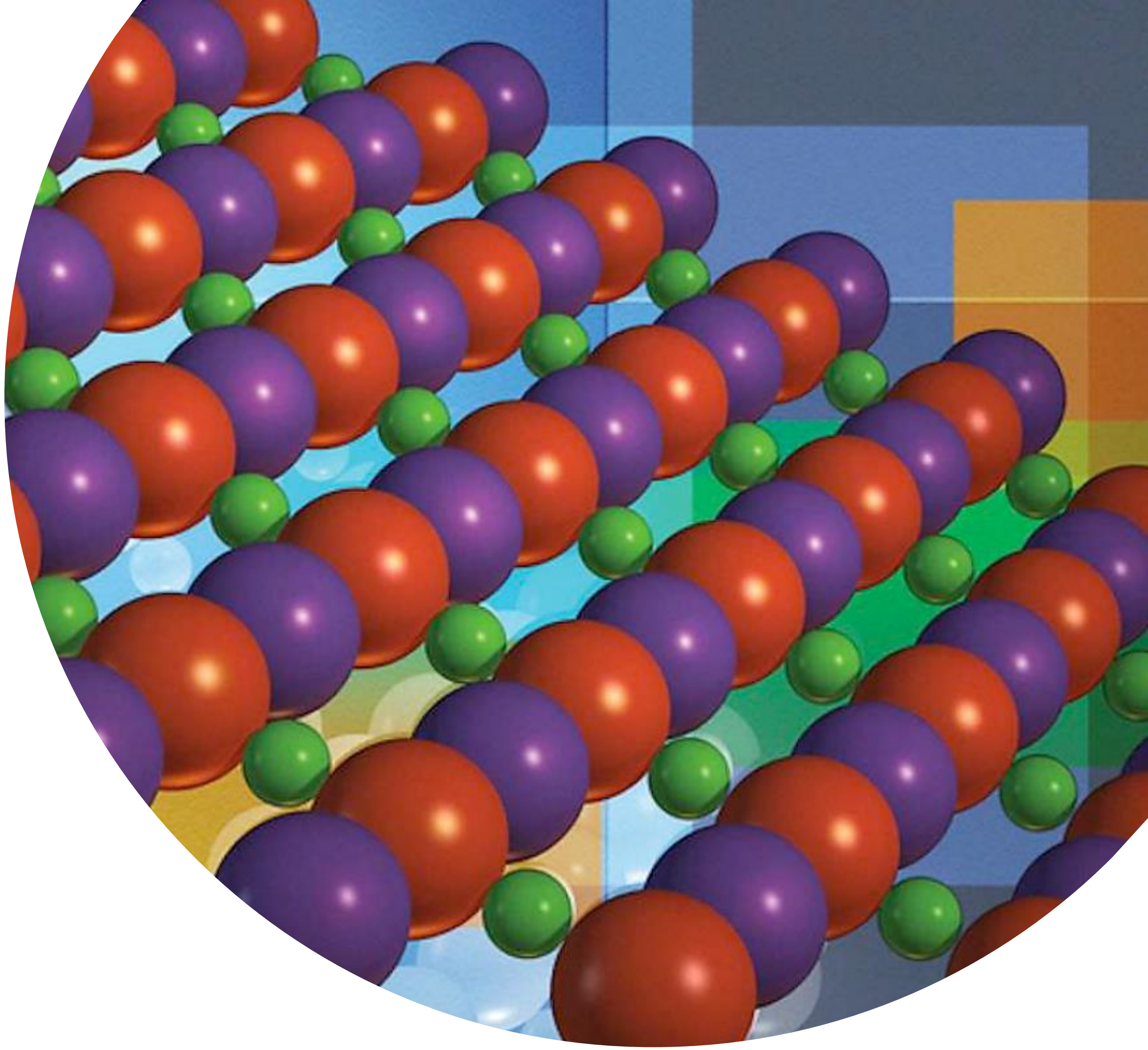


MATERIAL SCIENCE FOR MECHANICAL ENGINEERS

SPRING 2022-2023


MATERIALS SCIENCE AND ENGINEERING
AN INTRODUCTION
TENTH EDITION
WILLIAM D. CALLISTER, JR.
DAVID G. RETHWISCH
WILEY



TODAY'S LECTURE OUTLINE

GENERAL COURSE INSTRUCTIONS

COURSE POLICIES

EXPECTATIONS (OUTCOMES)

COURSE SYLLABUS

GENERAL INTRODUCTION

Introduction

Learning Objectives

1. List six different property classifications of materials that determine their applicability. **2.** Cite the four components that are involved in the design, production, and utilization of materials, and briefly describe the interrelationships between these components. **3.** Cite three criteria that are important in the materials selection process.	**4. (a)** List the three primary classifications of solid materials, and then cite the distinctive chemical feature of each. **(b)** Note the four types of advanced materials and, for each, its distinctive feature(s). **5. (a)** Briefly define *smart material/system*. **(b)** Briefly explain the concept of *nanotechnology* as it applies to materials.

Introduction

- Virtually every segment of our everyday lives is influenced to one degree or another by materials.

- Materials utilization was totally a selection process that involved deciding from a given, rather limited set of materials, the one best suited for an application by virtue of its characteristics.

- Scientists came to understand the relationships between the structural elements of materials and their properties. This knowledge, acquired over approximately the past 100 years, has empowered them to fashion, to a large degree, the characteristics of materials.

- Tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society, including metals, plastics, glasses, and fibres.

MATERIALS SCIENCE AND ENGINEERING

- Materials science involves investigating the relationships that exist between the **structures** and **properties** of materials (i.e., why materials have their properties).

- Materials engineering involves, on the basis of these structure–property correlations, designing or engineering the structure of a material to produce a predetermined set of properties.

- The role of a materials scientist is to develop or synthesize new materials.

- A materials engineer is called upon to create new products or systems using existing materials and/or to develop techniques for processing materials.

- Tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society, including metals, plastics, glasses, and fibres.

MATERIALS SCIENCE AND ENGINEERING

The **structure** of a material usually relates to the arrangement of its internal components.

Structural elements may be classified on the basis of size and in this regard there are several levels:

- Subatomic structure—involves electrons within the individual atoms, their energies and interactions with the nuclei.

- Atomic structure—relates to the organization of atoms to yield molecules or crystals.

- Nanostructure—deals with aggregates of atoms that form particles (nanoparticles) that have nanoscale dimensions (less that about 100 nm).

- Microstructure—those structural elements that are subject to direct observation using some type of microscope (structural features having dimensions between 100 nm and several millimetres).

MATERIALS SCIENCE AND ENGINEERING

- Macrostructure—structural elements that may be viewed with the naked eye (with scale range between several millimetres and on the order of a meter).

A **property** is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus. Generally, definitions of properties are made independent of material shape and size.

Properties of solid materials may be grouped into six different categories: mechanical, electrical, thermal, magnetic, optical, and deteriorative.

- Mechanical properties—relate deformation to an applied load or force; examples include elastic modulus (stiffness), strength, and resistance to fracture.

- Electrical properties—the stimulus is an applied electric field; typical properties include electrical conductivity and dielectric constant.

- Thermal properties—are related to changes in temperature or temperature gradients across a material; examples of thermal behaviour include thermal expansion and heat capacity.

MATERIALS SCIENCE AND ENGINEERING

- Magnetic properties—the responses of a material to the application of a magnetic field; common magnetic properties include magnetic susceptibility and magnetization

- Optical properties—the stimulus is electromagnetic or light radiation; index of refraction and reflectivity are representative optical properties.

- Deteriorative characteristics—relate to the chemical reactivity of materials; for example, corrosion resistance of metals.

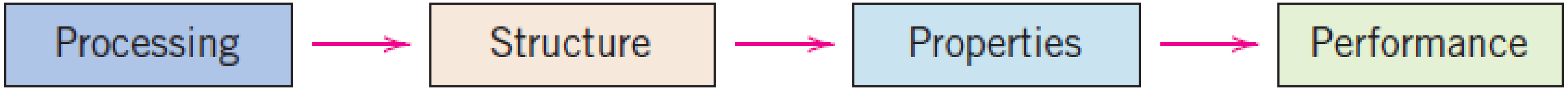
Three thin disk specimens of aluminium oxide

"Differences in optical properties are a consequence of differences in structure of these materials, which have resulted from the way the materials were processed."

MATERIALS SCIENCE AND ENGINEERING

In addition to **structure** and **properties**, two other important components are involved in the science and engineering of materials—namely, **processing** and **performance**.

The *materials paradigm* describes the protocol for selecting and designing materials for specific and well defined applications, and has had a profound influence on the field of materials.



"The *central paradigm of materials science and engineering* or the *materials paradigm*"

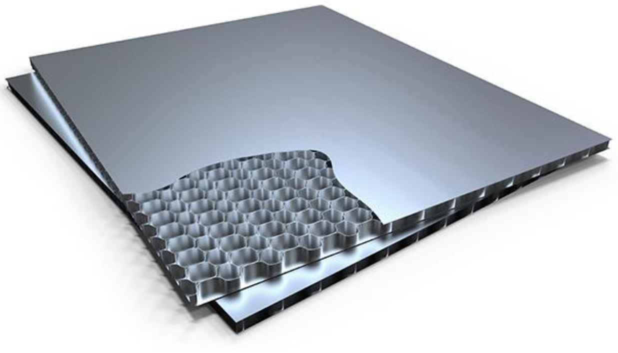
". . . whenever a material is being created, developed, or produced, the properties or phenomena the material exhibits are of central concern. Experience shows that the properties and phenomena associated with a material are intimately related to its composition and structure at all levels, including which atoms are present and how the atoms are arranged in the material, and that this structure is the result of synthesis and processing."

WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

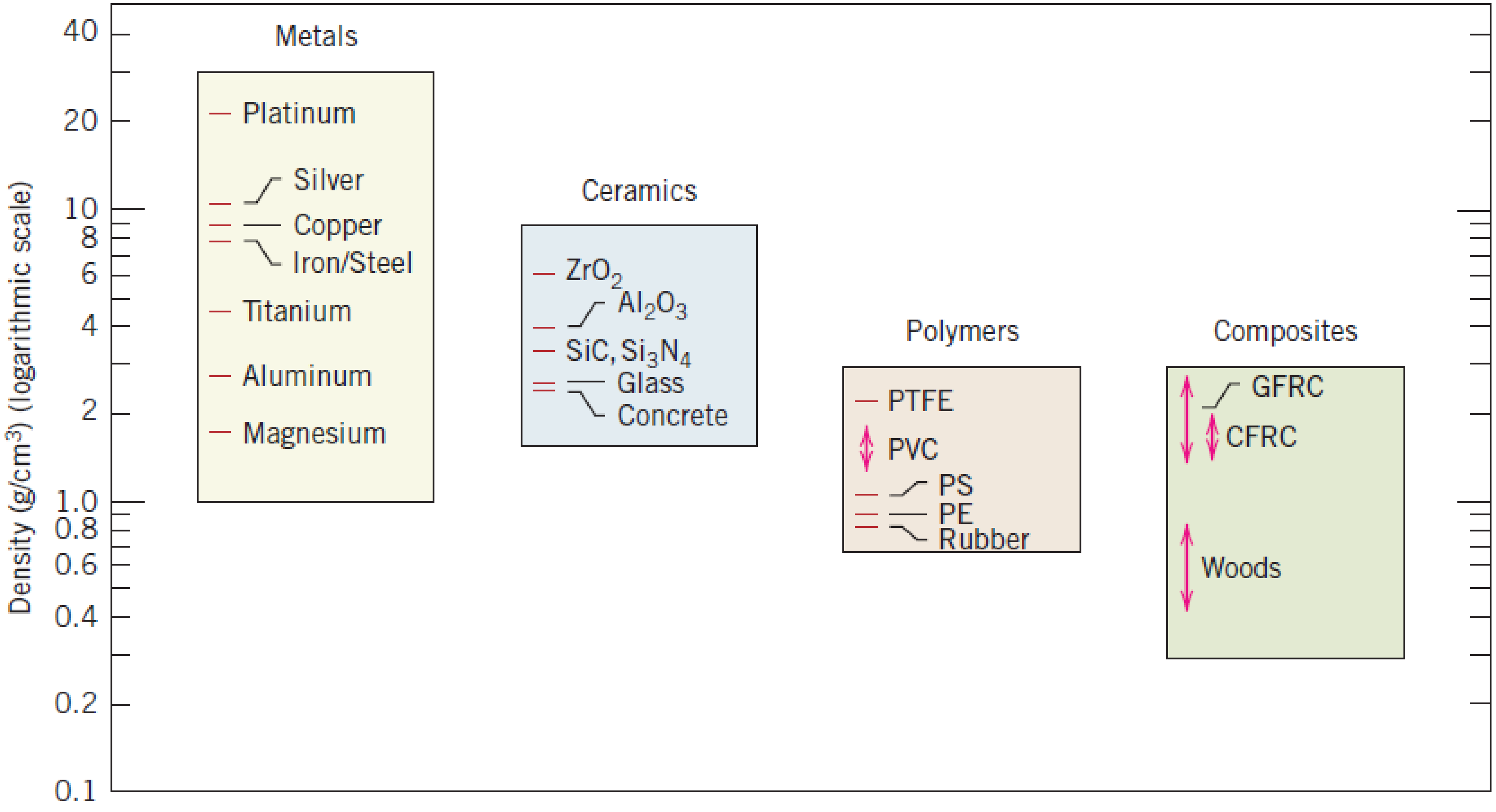
Why do engineers and scientists study materials? Simply, because things engineers design are made of materials.

CLASSIFICATION OF MATERIALS

- Solid materials have been conveniently grouped into three basic categories: metals, ceramics, and polymers, a scheme based primarily on chemical makeup and atomic structure.
- Most materials fall into one distinct grouping or another. In addition, there are the composites that are engineered combinations of two or more different materials.
- Another category is advanced materials—those used in high-technology applications, such as semiconductors, biomaterials, smart materials, and nanoengineered materials.

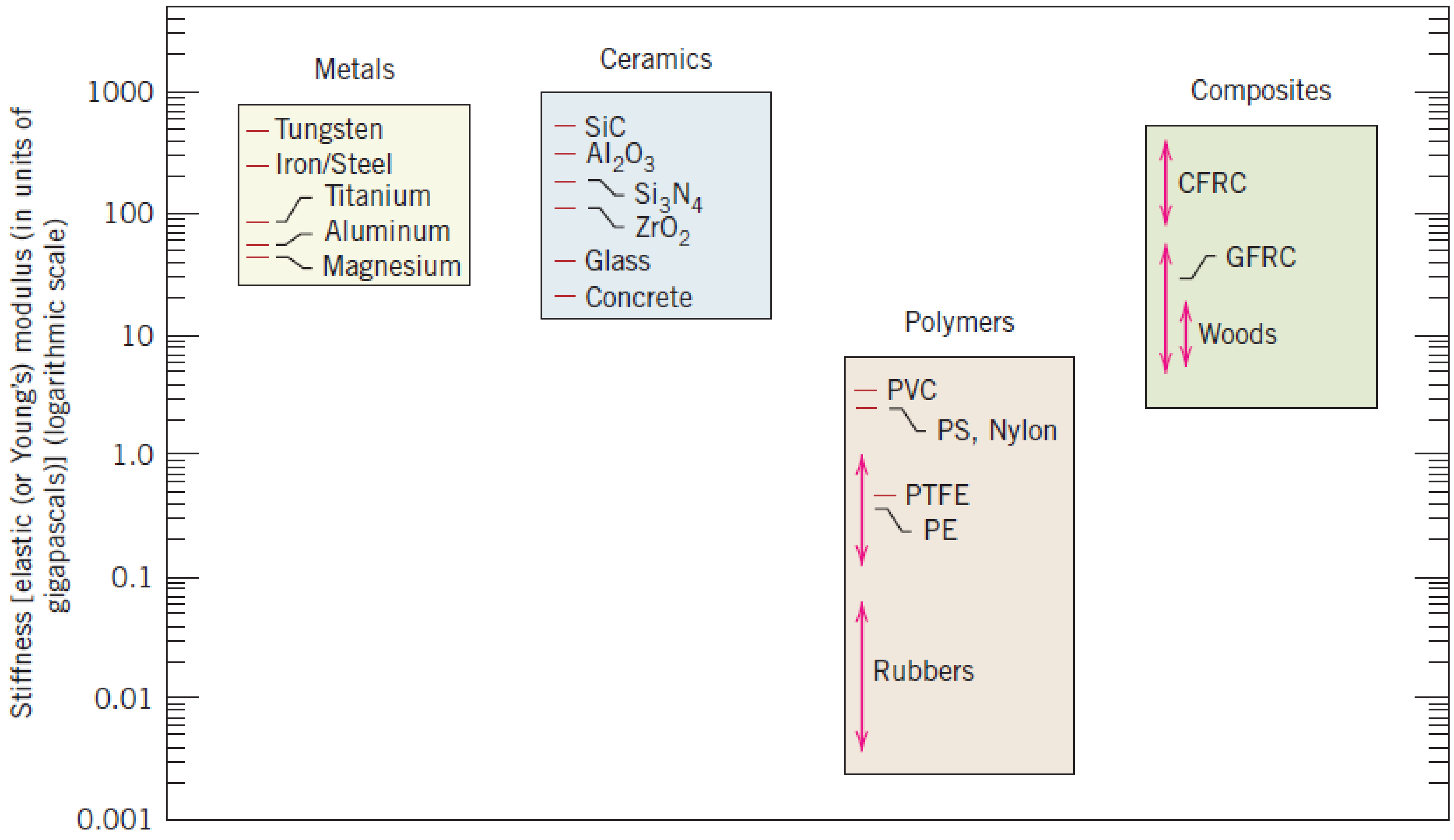


CLASSIFICATION OF MATERIALS



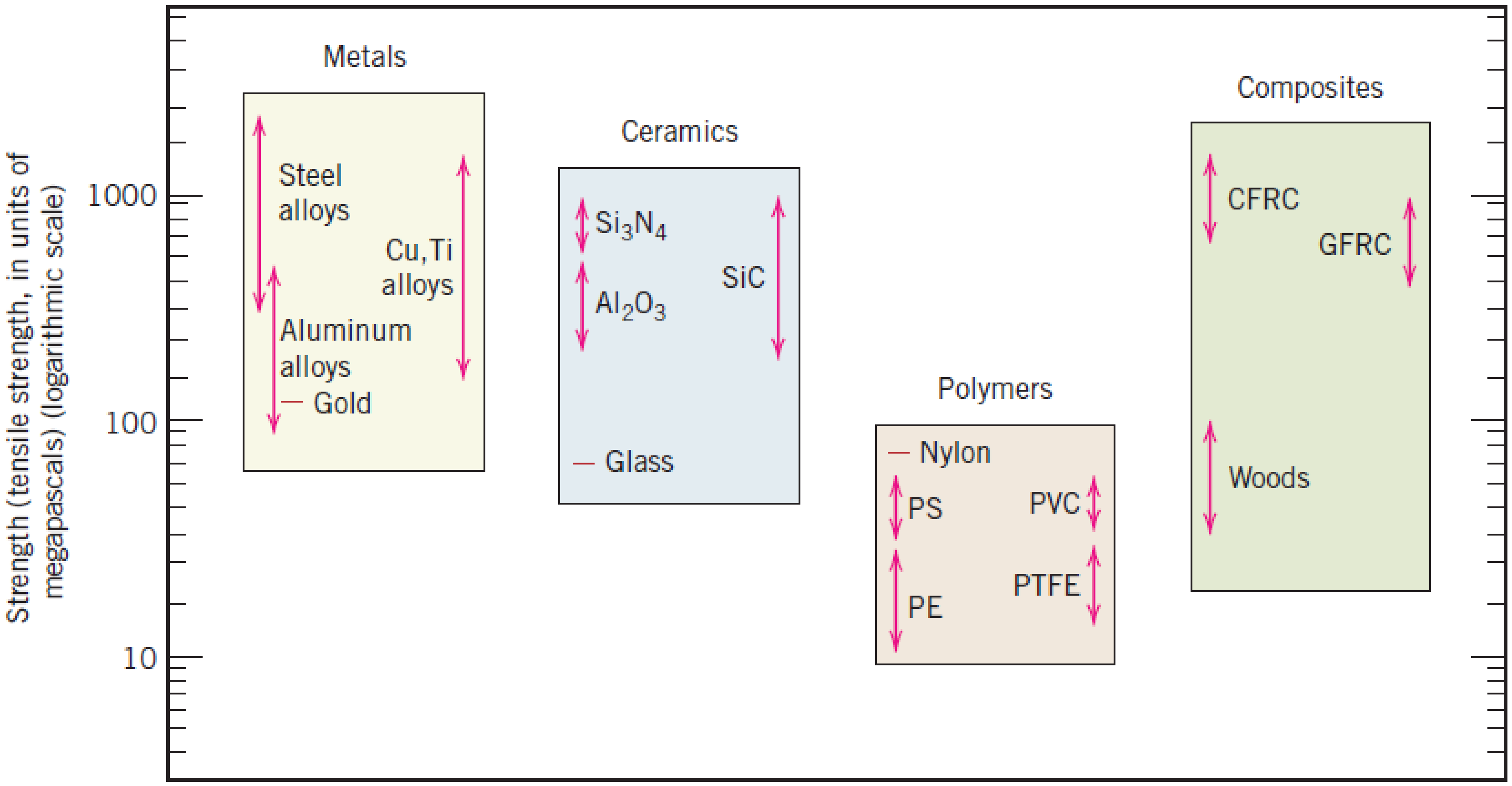
Bar chart of room-temperature density values for various metals, ceramics, polymers, and composite materials.

CLASSIFICATION OF MATERIALS



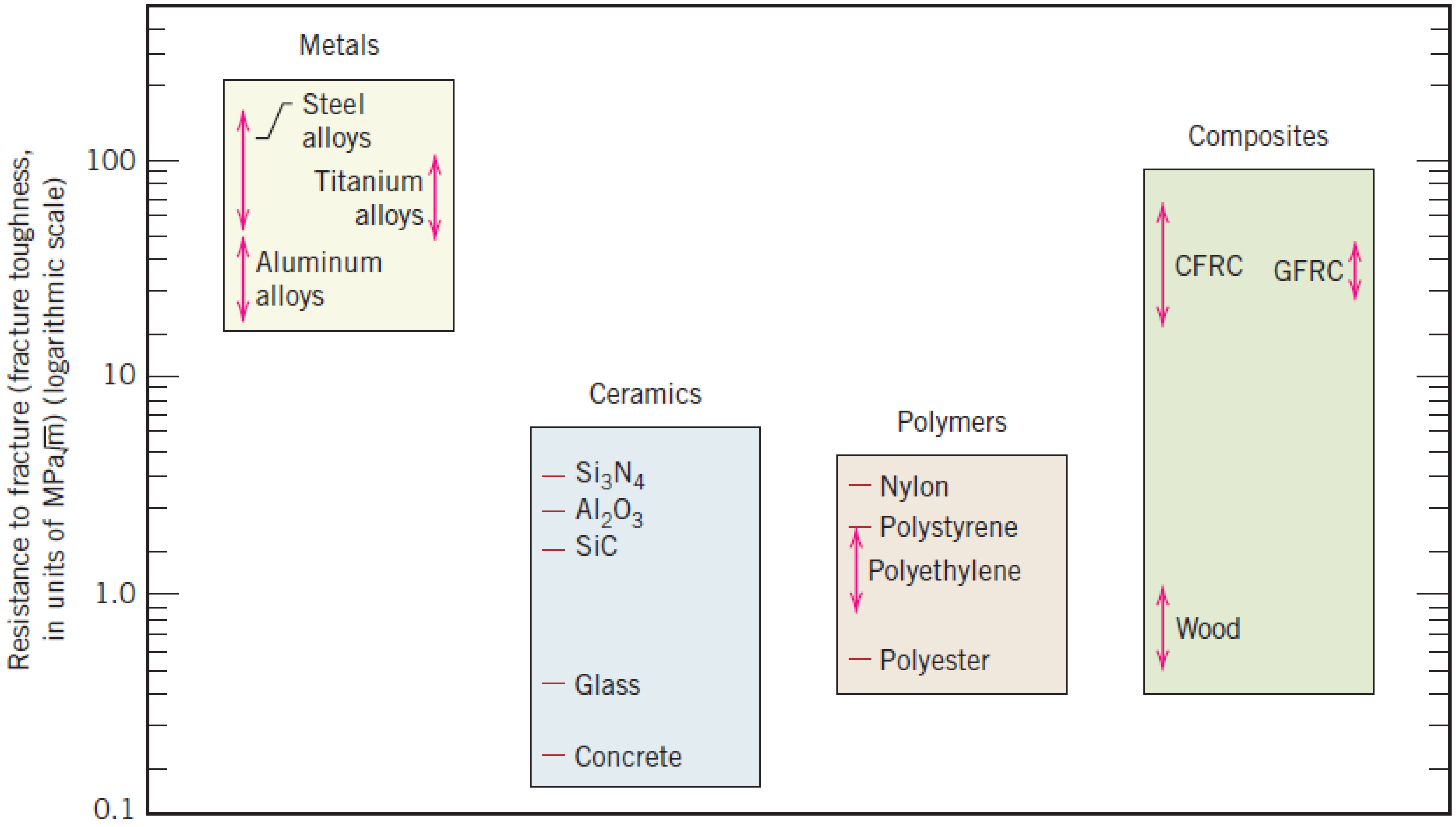
Bar chart of room-temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.

CLASSIFICATION OF MATERIALS



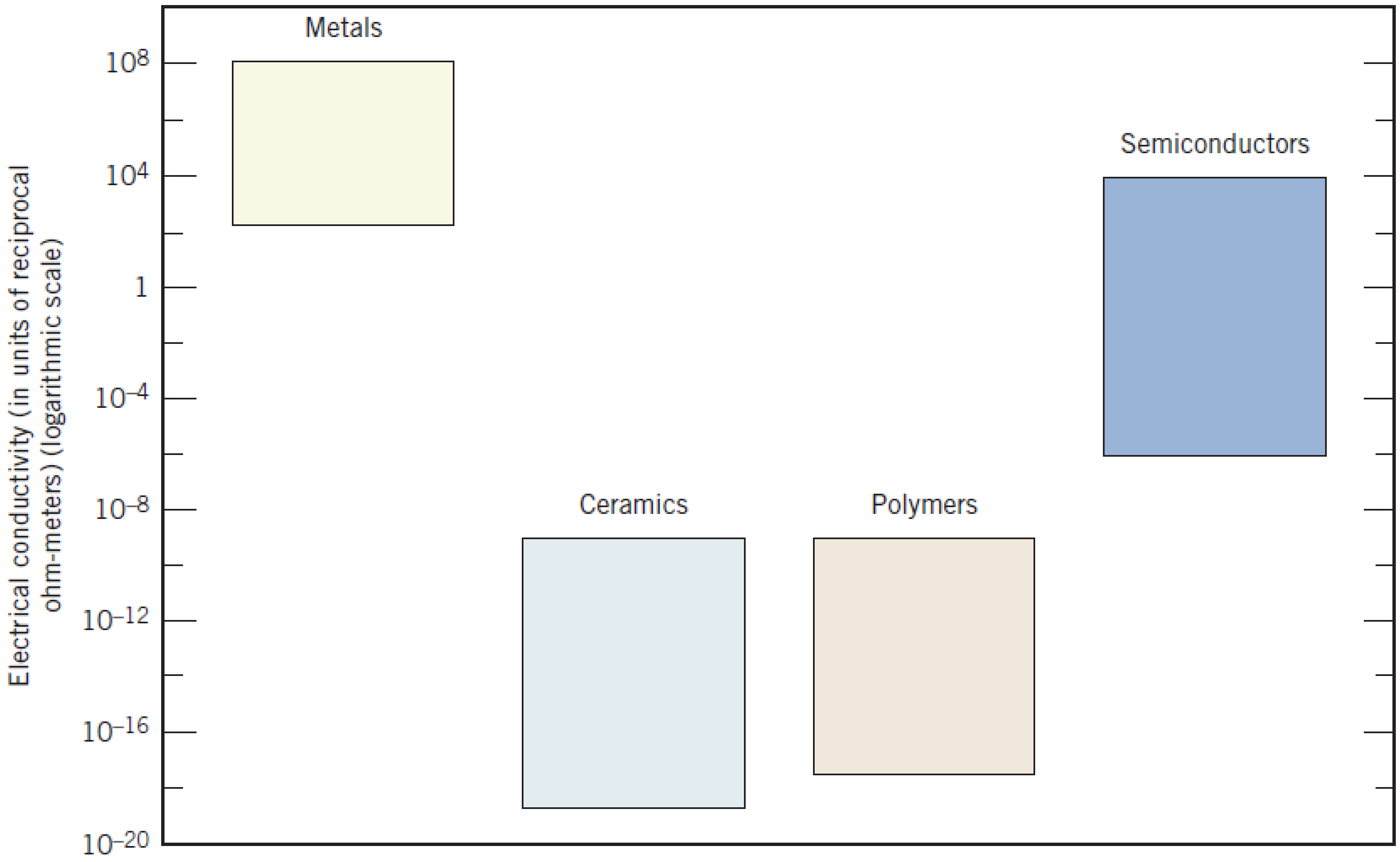
Bar chart of room-temperature strength (i.e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

CLASSIFICATION OF MATERIALS



Bar chart of room-temperature resistance to fracture (i.e., fracture toughness) for various metals, ceramics, polymers, and composite materials.

CLASSIFICATION OF MATERIALS



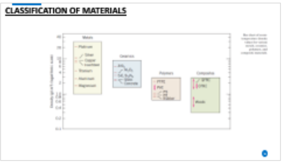
Bar chart of room-temperature electrical conductivity ranges for metals, ceramics, polymers, and semiconducting materials.

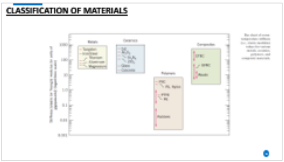
CLASSIFICATION OF MATERIALS

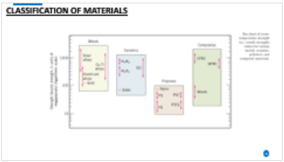
Metals

Metals are composed of one or more metallic elements (e.g., iron, aluminium, copper, titanium, gold, nickel), and often also non-metallic elements (e.g., carbon, nitrogen, oxygen) in relatively small amounts.

Atoms in metals and their alloys are arranged in a *very orderly manner* and are *relatively dense* in comparison to the ceramics and polymers.





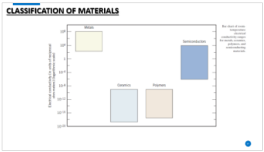


With regard to mechanical characteristics, these materials are *relatively stiff and strong yet are ductile* (i.e., capable of large amounts of deformation without fracture), and are *resistant to fracture*, which accounts for their widespread use in structural applications.

Metallic materials have large numbers of nonlocalized electrons—that is, these electrons are not bound to particular atoms.

CLASSIFICATION OF MATERIALS

Many properties of metals are directly attributable to these electrons. For example, metals are extremely good conductors of electricity and heat, and are not transparent to visible light; a polished metal surface has a lustrous appearance.



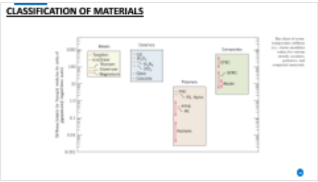
In addition, some of the metals (i.e., Fe, Co, and Ni) have desirable magnetic properties.

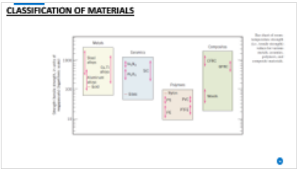
Ceramics

Ceramics are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, common ceramic materials include aluminium oxide (or alumina, Al_2O_3), silicon dioxide (or silica, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and, in addition, what some refer to as the traditional ceramics—those composed of clay minerals (e.g., porcelain), as well as cement and glass.

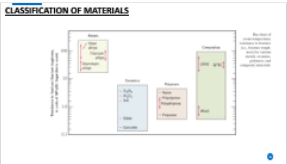
CLASSIFICATION OF MATERIALS

With regard to mechanical behaviour, ceramic materials are relatively stiff and strong—stiffnesses and strengths are comparable to those of the metals.



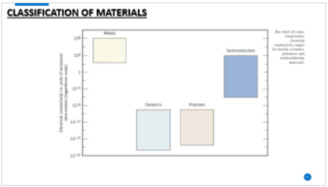


In addition, they are typically very hard. Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are highly susceptible to fracture.



However, newer ceramics are being engineered to have improved resistance to fracture; these materials are used for cookware, cutlery, and even automobile engine parts.

Furthermore, ceramic materials are typically insulative to the passage of heat and electricity (i.e., have low electrical conductivities) and are more resistant to high temperatures and harsh environments than are metals and polymers.



With regard to optical characteristics, ceramics may be transparent, translucent, or opaque, and some of the oxide ceramics (e.g., Fe_3O_4) exhibit magnetic behaviour.

CLASSIFICATION OF MATERIALS

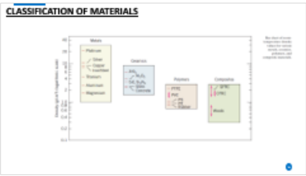
Polymers

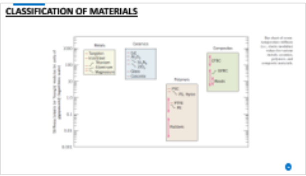
Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other non-metallic elements (i.e., O, N, and Si).

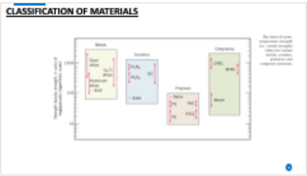
Furthermore, they have very large molecular structures, often chainlike in nature, that often have a backbone of carbon atoms.

Some common and familiar polymers are polyethylene (PE), nylon, poly(vinyl chloride) (PVC), polycarbonate (PC), polystyrene (PS), and silicone rubber.

These materials typically have low densities, whereas their mechanical characteristics are generally dissimilar to those of the metallic and ceramic materials—they are not as stiff or strong as these other material types .







CLASSIFICATION OF MATERIALS

However, on the basis of their low densities, many times their stiffnesses and strengths on a per-mass basis are comparable to those of the metals and ceramics.

In addition, many of the polymers are extremely ductile and pliable (i.e., plastic), which means they are easily formed into complex shapes.

In general, they are relatively inert chemically and unreactive in a large number of environments.

Furthermore, they have low electrical conductivities and are nonmagnetic.

One major drawback to the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use.

CLASSIFICATION OF MATERIALS

Carbonated Beverage Containers

One common item that presents some interesting material property requirements is the container for carbonated beverages. The material used for this application must satisfy the following constraints: (1) provide a barrier to the passage of carbon dioxide, which is under pressure in the container; (2) be nontoxic, unreactive with the beverage, and, preferably, recyclable; (3) be relatively strong and capable of surviving a drop from a height of several feet when containing the beverage; (4) be inexpensive, including the cost to fabricate the final shape; (5) if optically transparent, retain its optical clarity; and (6) be capable of being produced in different colors and/or adorned with decorative labels.

All three of the basic material types—metal (aluminum), ceramic (glass), and polymer (polyester plastic)—are used for carbonated beverage containers (per the chapter-opening photographs). All of these materials are nontoxic and unreactive with beverages. In addition, each material has its pros and cons. For example, the aluminum alloy is relatively strong (but easily dented), is a very good barrier to the diffusion of carbon dioxide, is easily recycled, cools beverages rapidly, and allows labels to be painted onto its surface. However, the cans are optically opaque and relatively expensive to produce. Glass is impervious to the passage of carbon dioxide, is a relatively inexpensive material, and may be recycled, but it cracks and fractures easily, and glass bottles are relatively heavy. Whereas plastic is relatively strong, may be made optically transparent, is inexpensive and lightweight, and is recyclable, it is not as impervious to the passage of carbon dioxide as aluminum and glass. For example, you may have noticed that beverages in aluminum and glass containers retain their carbonization (i.e., "fizz") for several years, whereas those in two-liter plastic bottles "go flat" within a few months.

CLASSIFICATION OF MATERIALS

Composites

A composite is composed of two (or more) individual materials that come from the categories previously discussed—metals, ceramics, and polymers.

The design goal of a composite is to achieve a combination of properties that is not displayed by any single material and also to incorporate the best characteristics of each of the component materials.

A large number of composite types are represented by different combinations of metals, ceramics, and polymers.

Furthermore, some naturally occurring materials are composites—for example, wood and bone.

However, most of those we consider in our discussions are synthetic (or human-made) composites.

CLASSIFICATION OF MATERIALS

One of the most common and familiar composites is fiberglass, in which small glass fibres are embedded within a polymeric material (normally an epoxy or polyester).

The glass fibres are relatively strong and stiff (but also brittle), whereas the polymer is more flexible. Thus, fiberglass is relatively stiff, strong, and flexible. In addition, it has a low density.

Another technologically important material is the carbon fibre–reinforced polymer (CFRP) composite—carbon fibres that are embedded within a polymer. These materials are stiffer and stronger than glass fibre–reinforced materials but more expensive.

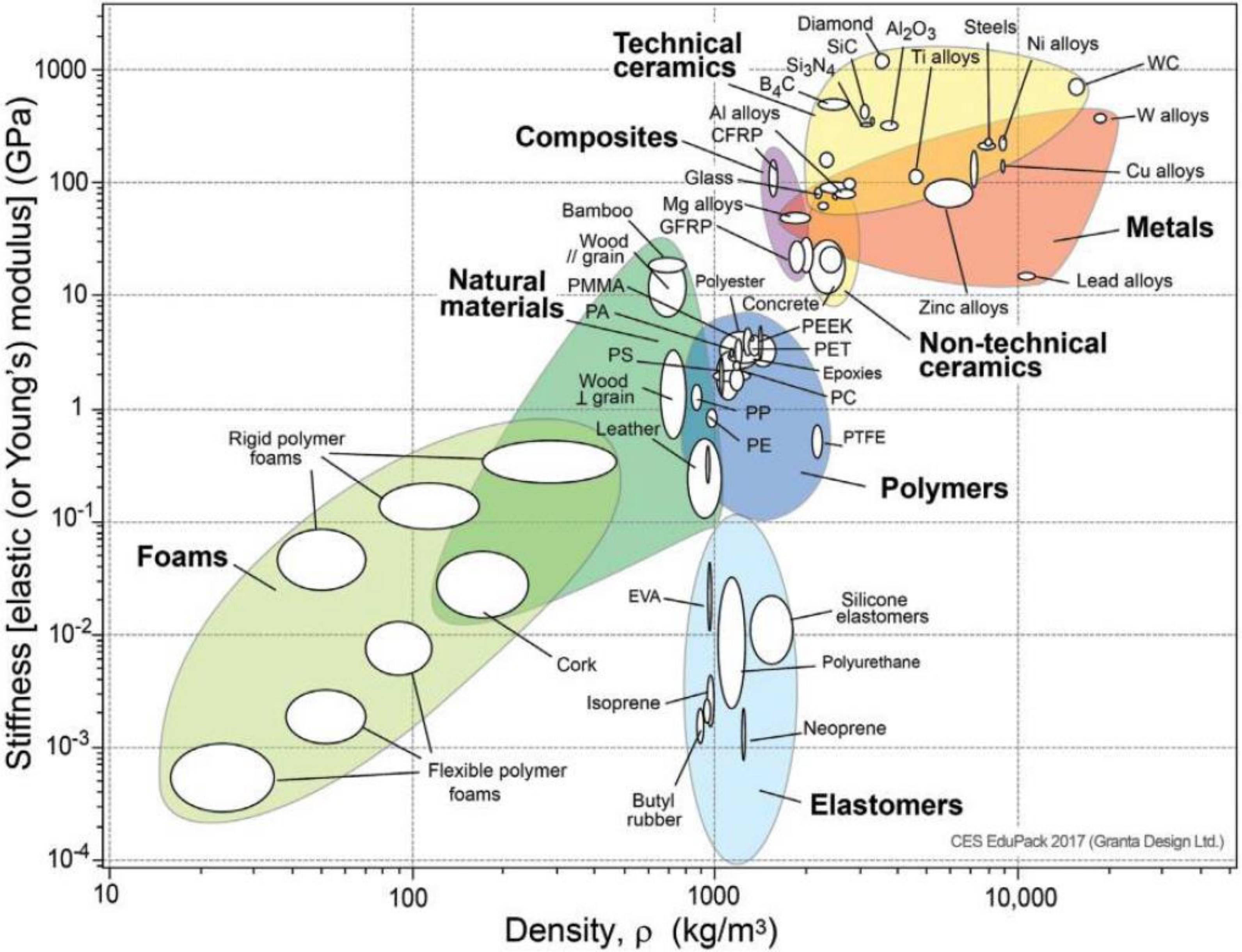
CFRP composites are used in some aircraft and aerospace applications, as well as in high-tech sporting equipment (e.g., bicycles, golf clubs, tennis rackets, skis/ snowboards) and recently in automobile bumpers.

The new Boeing 787 fuselage is primarily made from such CFRP composites.

CLASSIFICATION OF MATERIALS

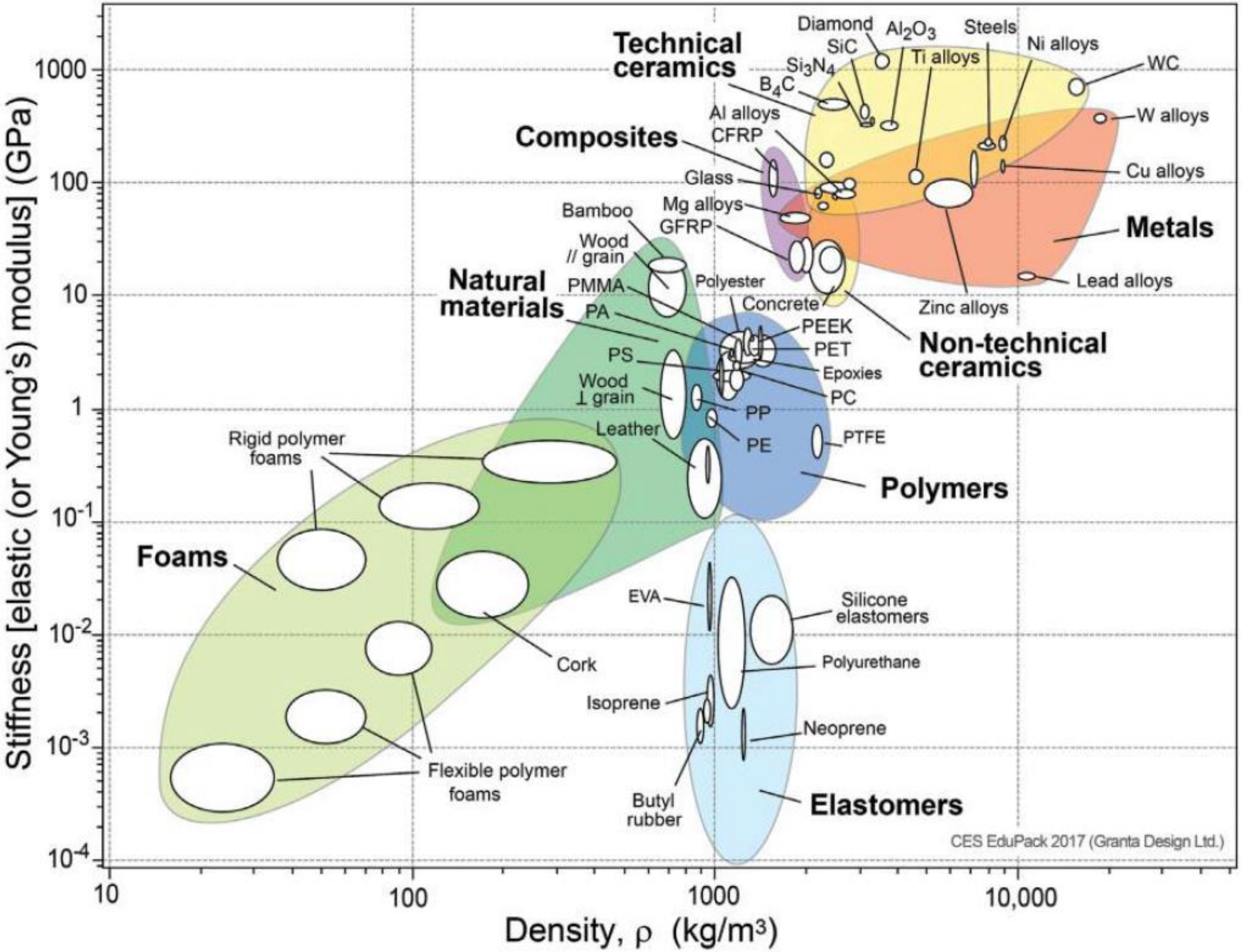
The figure shown is a plot of the values of one property versus those of another property for a large number of different types of materials.

Both axes are scaled logarithmically and usually span several (at least three) orders of magnitude, so as to include the properties of virtually all materials.



CLASSIFICATION OF MATERIALS

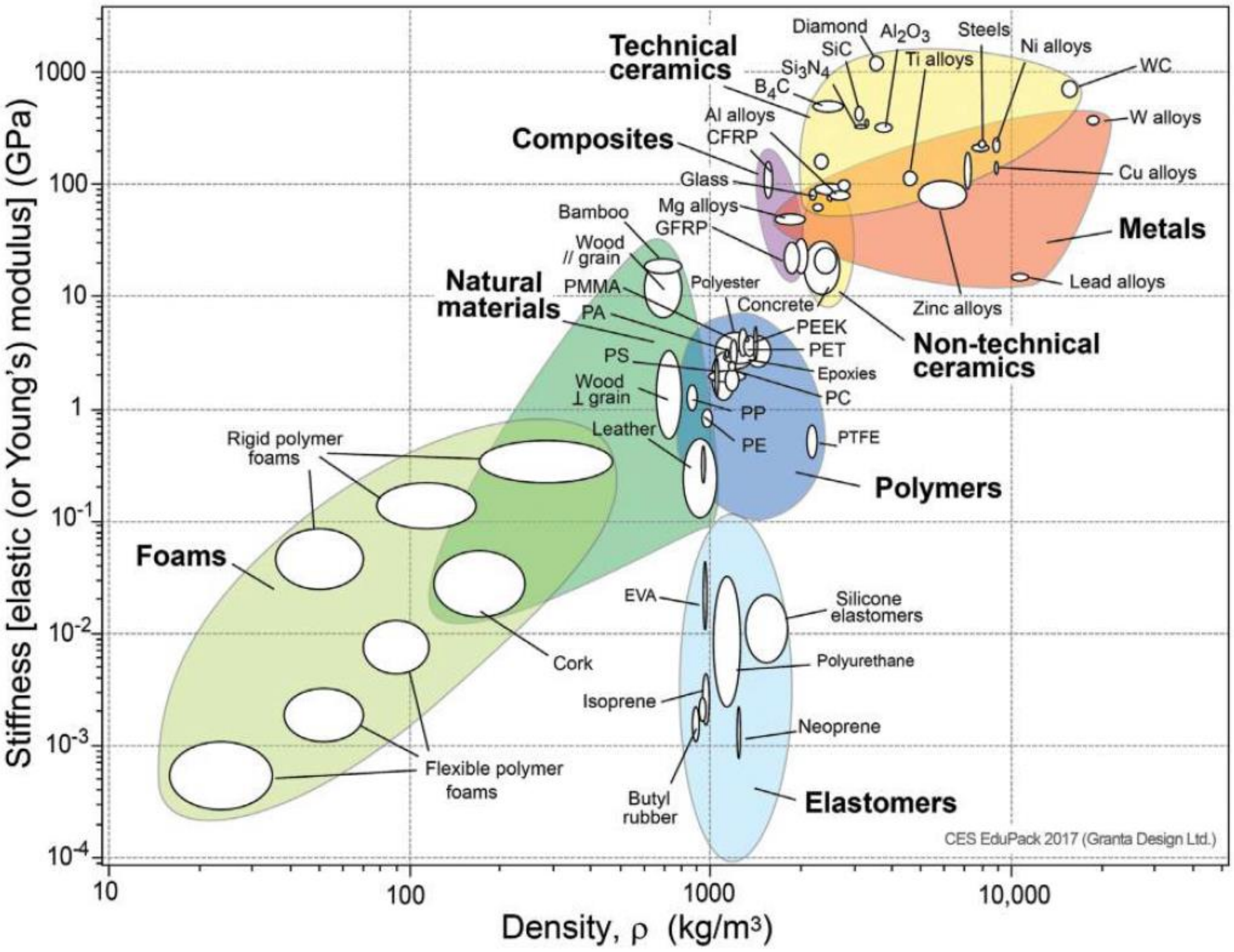
It may be noted that data values for a specific type (or "family") of materials (e.g., metals, ceramics, polymers) cluster together and are enclosed within an envelope (or "bubble") delineated with a bold line; hence, each of these envelopes defines the property range for its material family.



CLASSIFICATION OF MATERIALS

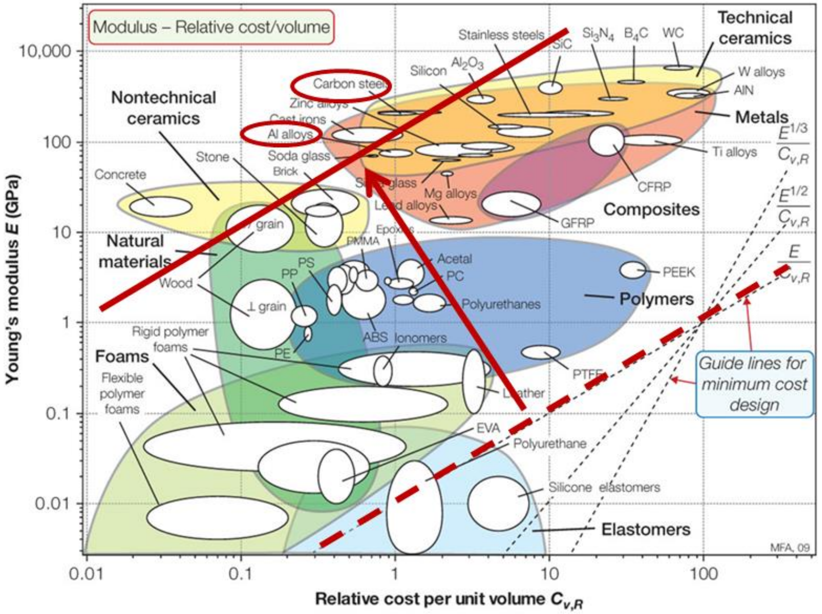
This is a simple, comprehensive, and concise display of the kind of information that shows how density and stiffness correlate with one another among the various kinds of materials.

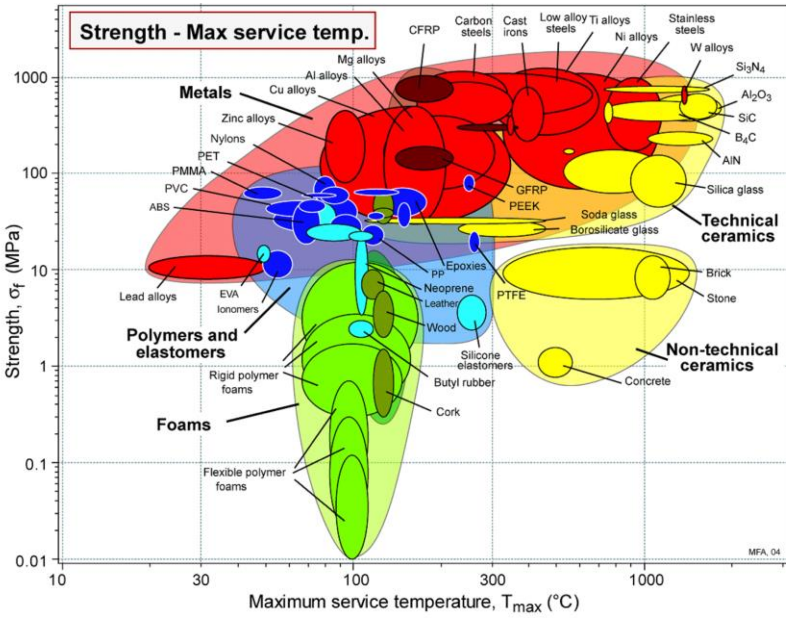
Charts such as this one may be constructed for any two material properties—for example, thermal conductivity versus electrical conductivity.

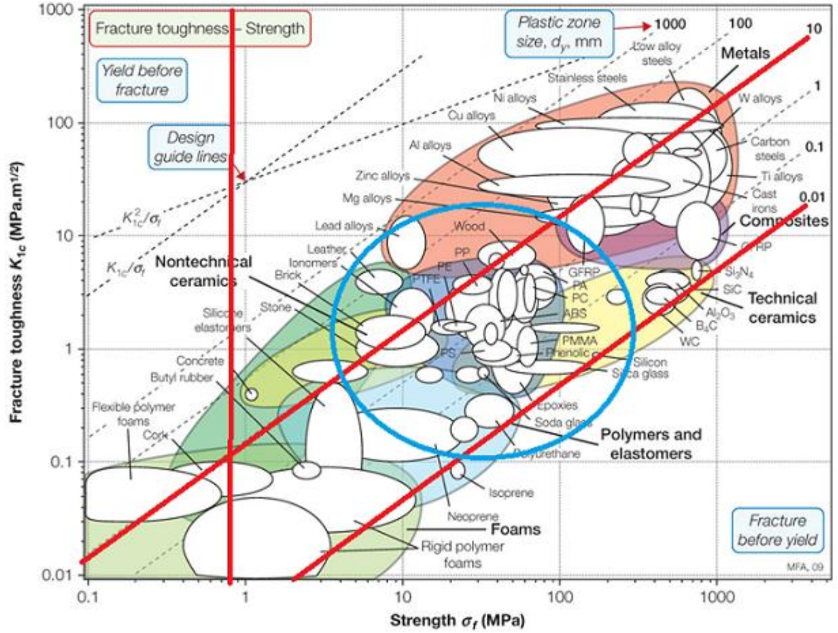


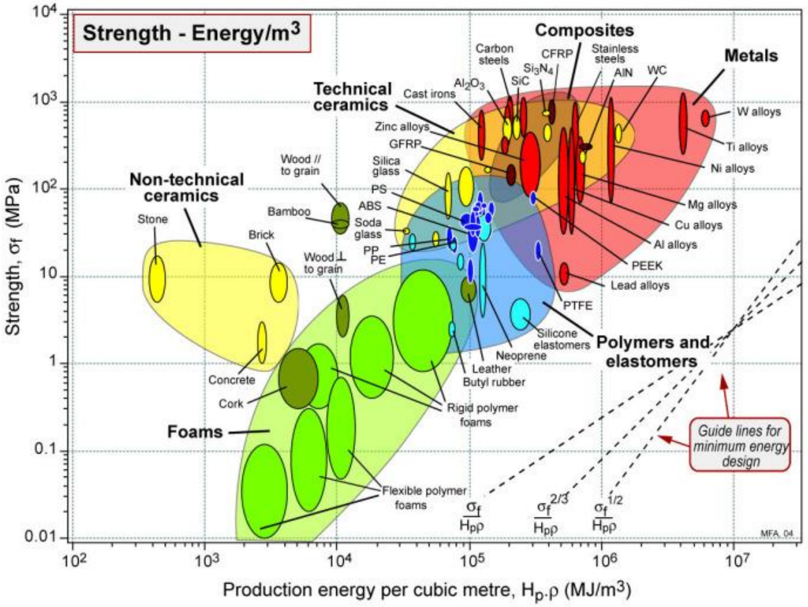
CLASSIFICATION OF MATERIALS

This type of charts is often referred to as "materials property charts," "materials selection charts," "bubble charts," or "Ashby charts" (after Michael F. Ashby, who developed them).









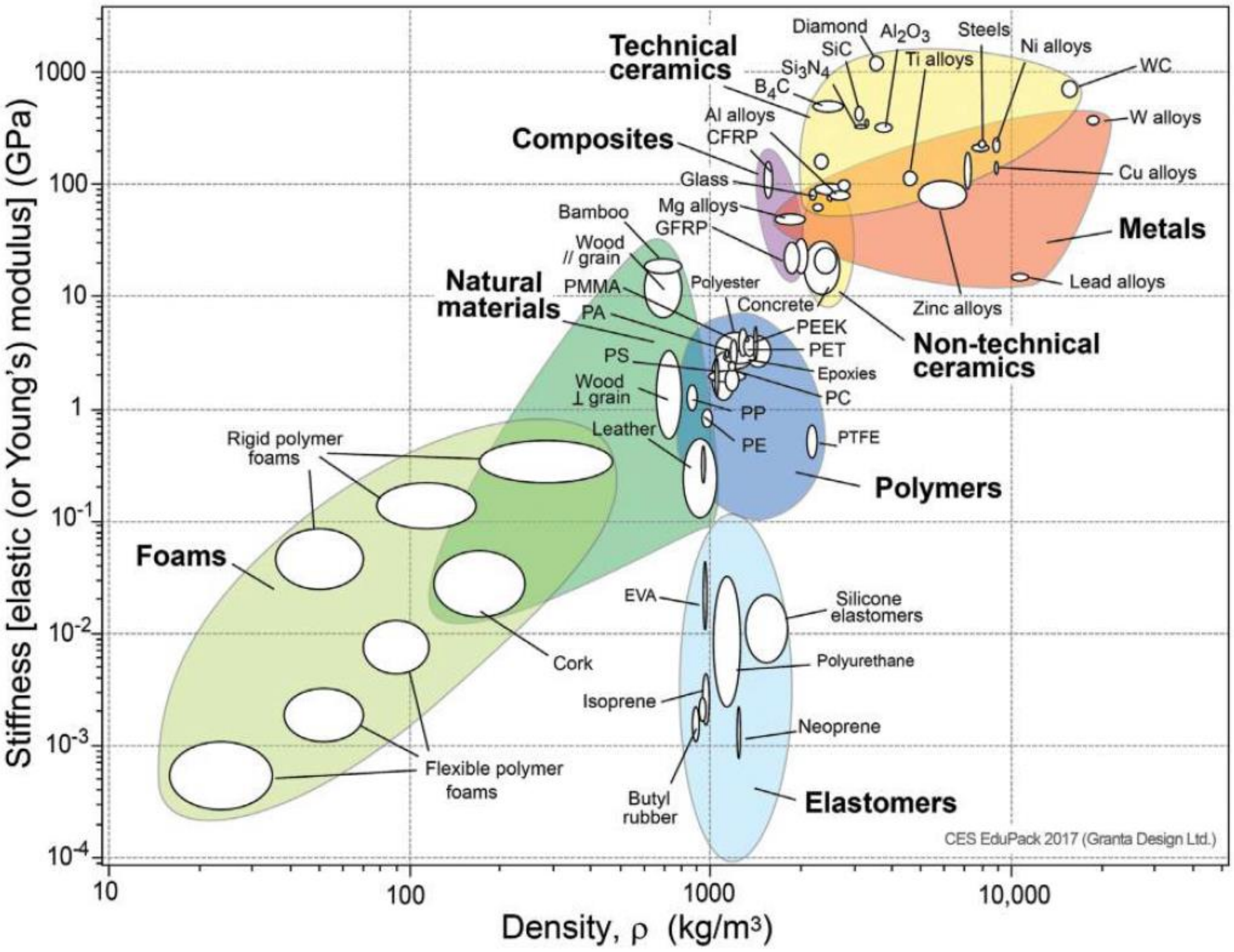
CLASSIFICATION OF MATERIALS

This figure envelopes for three important engineering material families are included.

These are as follows:

• Elastomers—polymeric materials that display rubbery-like behaviour (high degrees of elastic deformation).

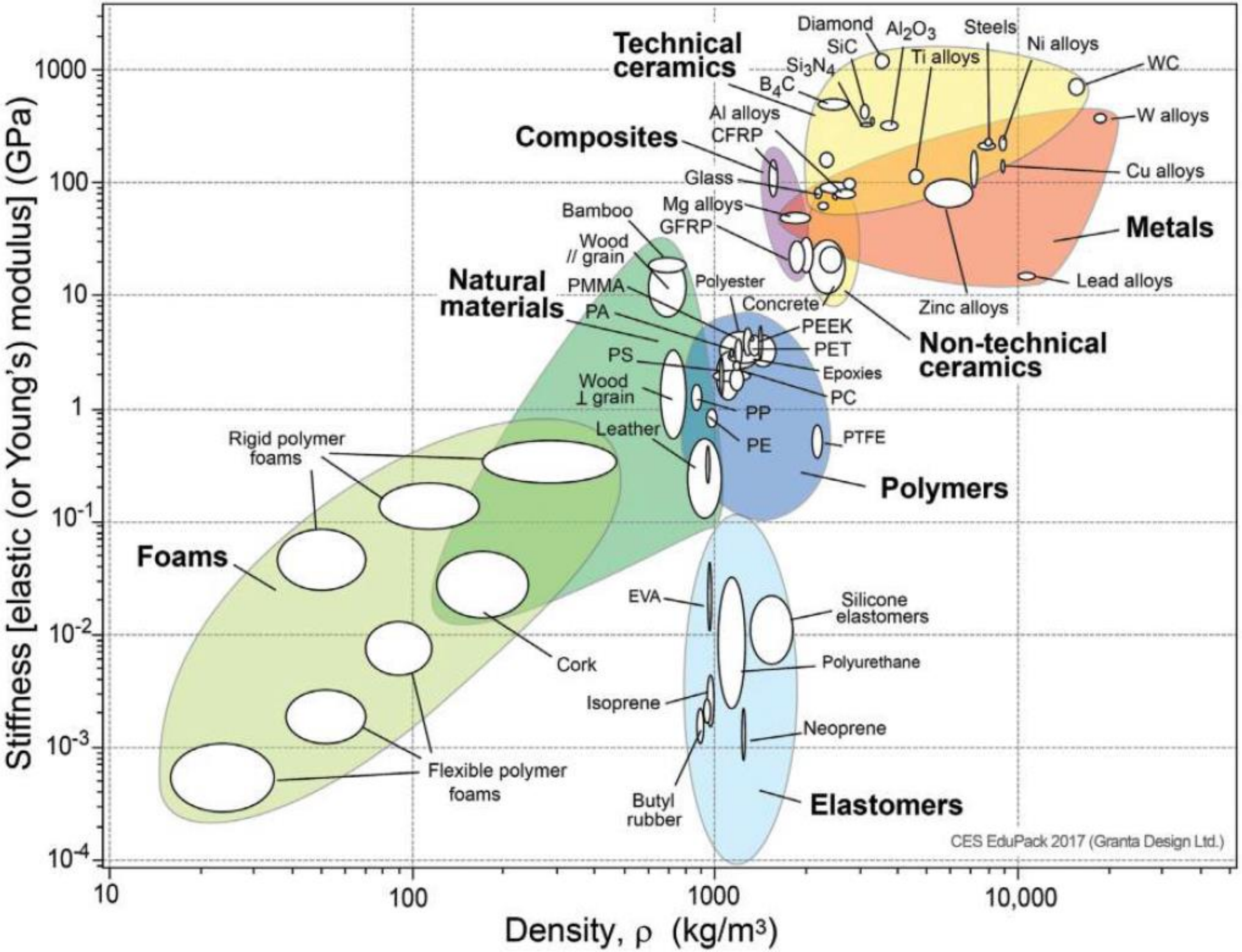
• Natural materials—those that occur in nature; for example, wood, leather, and cork.



CLASSIFICATION OF MATERIALS

• Foams—typically polymeric materials that have high porosities (contain a large volume fraction of small pores), which are often used for cushions and packaging.

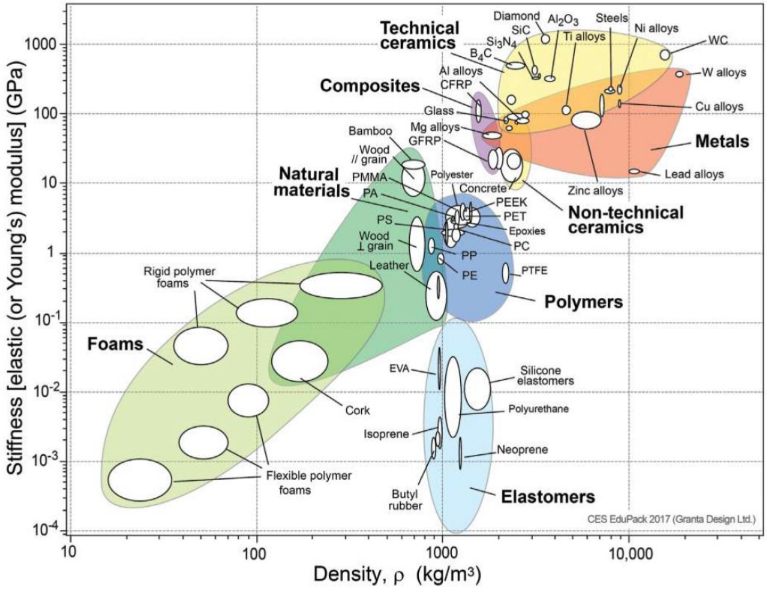
These bubble charts are extremely useful tools in engineering design and are used extensively in the materials selection process in both academia and industry.



CLASSIFICATION OF MATERIALS

When considering materials for products, an engineer is often confronted with competing objectives (e.g., light weight and stiffness) and must be in a position to assess possible trade-offs among any competing requirements.

Insights into the consequences of trade-off choices may be gleaned by using appropriate bubble charts.



ADVANCED MATERIALS

Materials utilized in high-technology (or high-tech) applications are sometimes termed advanced materials.

By high technology, we mean a device or product that operates or functions using relatively complicated and sophisticated principles, including electronic equipment (cell phones, DVD players, etc.), computers, fiber-optic systems, high-energy density batteries, energy-conversion systems, and aircraft.

These advanced materials are typically traditional materials whose properties have been **enhanced** and also newly developed, high-performance materials.

Furthermore, they may be of all material types (e.g., metals, ceramics, polymers) and are normally expensive.

Advanced materials include semiconductors, biomaterials, and what we may term materials of the future (i.e., smart materials and nanoengineered materials).

Semiconductors

Semiconductors have electrical properties that are intermediate between those of electrical conductors (i.e., metals and metal alloys) and insulators (i.e., ceramics and polymers).

The electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms, for which the concentrations may be controlled over very small spatial regions.

Semiconductors have made possible the introduction of integrated circuitry that has totally revolutionized the electronics and computer industries (not to mention our lives) over the past few decades.

ADVANCED MATERIALS

Biomaterials

The length and the quality of our lives are being extended and improved, in part, due to advancements in the ability to replace diseased and injured body parts.

Replacement implants are constructed of biomaterials—nonviable (i.e., non-living) materials that are implanted into the body, so that they function in a reliable, safe, and physiologically satisfactory manner, while interacting with living tissue.

That is, biomaterials must be biocompatible—compatible with body tissues and fluids with which they are in contact over acceptable time periods.

Biocompatible materials must neither elicit rejection or physiologically unacceptable responses nor release toxic substances.

Consequently, some rather stringent (strict) constraints are imposed on materials in order for them to be biocompatible.

ADVANCED MATERIALS

Over the past several years the development of new and better biomaterials has accelerated rapidly; today, this is one of the “hot” materials areas, with an abundance of new, exciting, and high-salary job opportunities.

Example biomaterial applications include joint (e.g., hip, knee) and heart valve replacements, vascular (blood vessel) grafts, fracture-fixation devices, dental restorations, and generation of new organ tissues.

ADVANCED MATERIALS

Smart Materials

The length and the quality of our lives are being extended and improved, in part, due to advancements in the ability to replace diseased and injured body parts.

Smart (or intelligent) materials are a group of new and state-of-the-art materials now being developed that will have a significant influence on many of our technologies.

The adjective smart implies that these materials are able to sense changes in their environment and then respond to these changes in predetermined manners—characteristics that are also found in living organisms. In addition, this smart concept is being extended to rather sophisticated systems that consist of both smart and traditional materials.

Components of a smart material (or system) include some type of sensor (which detects an input signal) and an actuator (which performs a responsive and adaptive function).

ADVANCED MATERIALS

Actuators may be called upon to change shape, position, natural frequency, or mechanical characteristics in response to changes in temperature, electric fields, and/or magnetic fields.

Four types of materials are commonly used for actuators: shape-memory alloys, piezoelectric ceramics, magneto-strictive materials, and electrorheological/magnetorheological fluids.

Shape-memory alloys are metals that, after having been deformed, revert to their original shape when temperature is changed.

Piezoelectric ceramics expand and contract in response to an applied electric field (or voltage); conversely, they also generate an electric field when their dimensions are altered.

ADVANCED MATERIALS

The behaviour of magneto-strictive materials is analogous to that of the piezoelectrics, except that they are responsive to magnetic fields.

Also, electrorheological and magnetorheological fluids are liquids that experience dramatic changes in viscosity upon the application of electric and magnetic fields, respectively.

Materials/devices employed as sensors include optical fibers, piezoelectric materials (including some polymers), and microelectromechanical systems (MEMS).

For example, one type of smart system is used in helicopters to reduce aerodynamic cockpit noise created by the rotating rotor blades. Piezoelectric sensors inserted into the blades monitor blade stresses and deformations; feedback signals from these sensors are fed into a computer-controlled adaptive device that generates noise-cancelling anti-noise.

ADVANCED MATERIALS

Nanomaterials

One new material class that has fascinating properties and tremendous technological promise is the nanomaterials, which may be any one of the four basic types—metals, ceramics, polymers, or composites.

Unlike these other materials, they are not distinguished on the basis of their chemistry but rather their size; the nano prefix denotes that the dimensions of these structural entities are on the order of a nanometre (10^{-9} m)—as a rule, less than 100 nanometres (nm; equivalent to the diameter of approximately 500 atoms).

Because of these unique and unusual properties, nanomaterials are finding roles in electronic, biomedical, sporting, energy production, and other industrial applications.

WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

Homework01

Research /search and present a case study that illustrates the role that materials scientists and engineers are called upon to assume in the area of materials performance: analyse mechanical failures, determine their causes, and then propose appropriate measures to guard against future incidents.

Examples can be such as the Challenger shuttle failure, The liberty ship failure, the infamous liberty bell, etc.

INDIVIDUAL WORK

No more than 10 pages. Should be neat, font size 12, type: Arial

File name: IDNumber_HW0X.pdf

Use the assigned Cover page

Q&A

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