Materials Selection and Design

Introduction

Design is a common word with elaborate meanings close to fashion, aesthetics, culture, so on

Fashion design, hair design, interior design, city planning, industrial design, etc.

Basically it is the process of translating an idea into a product or system

Mechanical design is referred to as the design explained in the context of this course

e.g. Mechanical components carry loads, conduct heat and electricity, they are exposed to wear and corrosion, made of one or more materials, have shape and must be manufactured

The role of materials in mechanical design will be elaborated in the following courses

A methodology for materials selection and process selection will be given

The selection of materials is as important in mechanical design as selection of function, shape and process

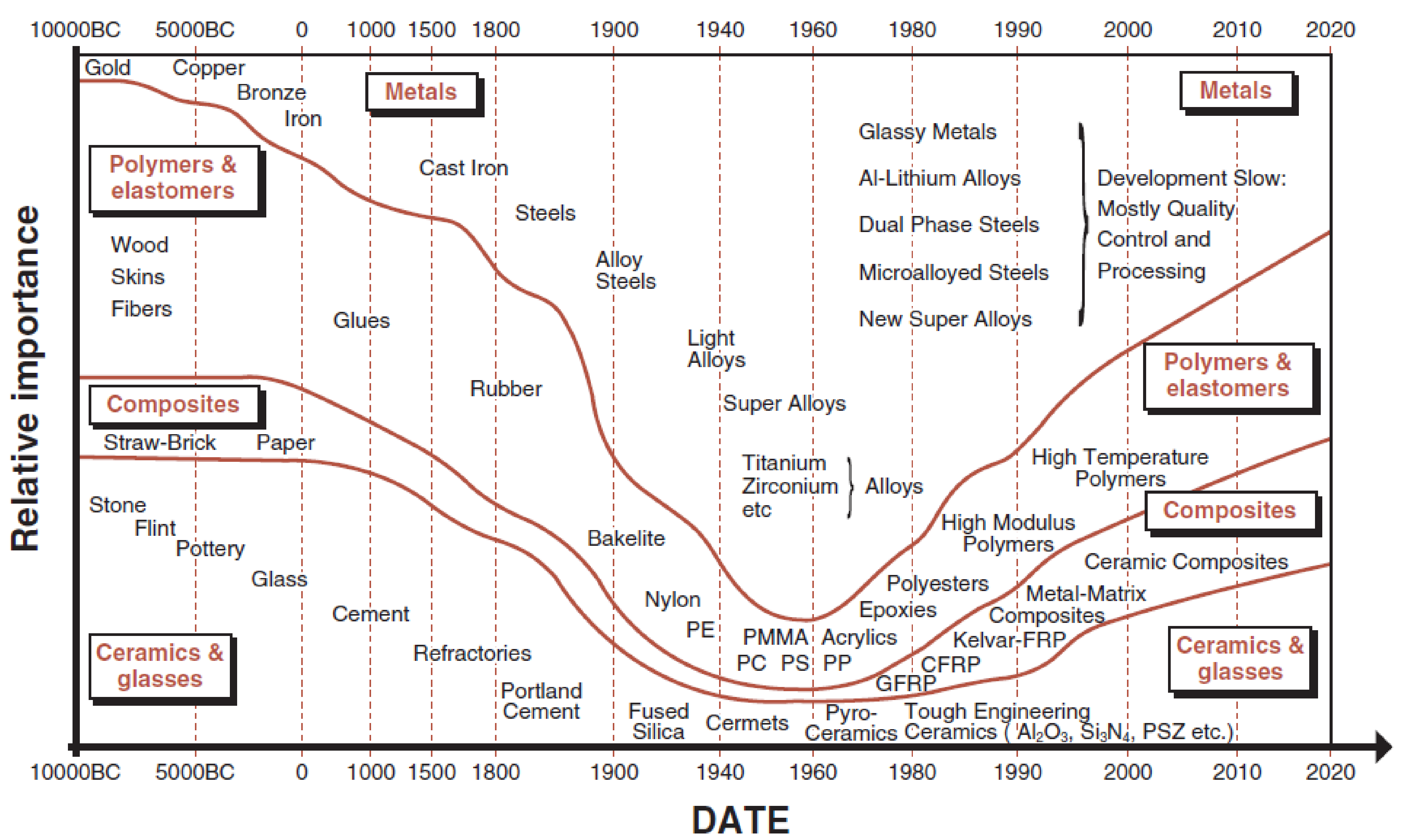
There are more than 500000 unique materials available to us

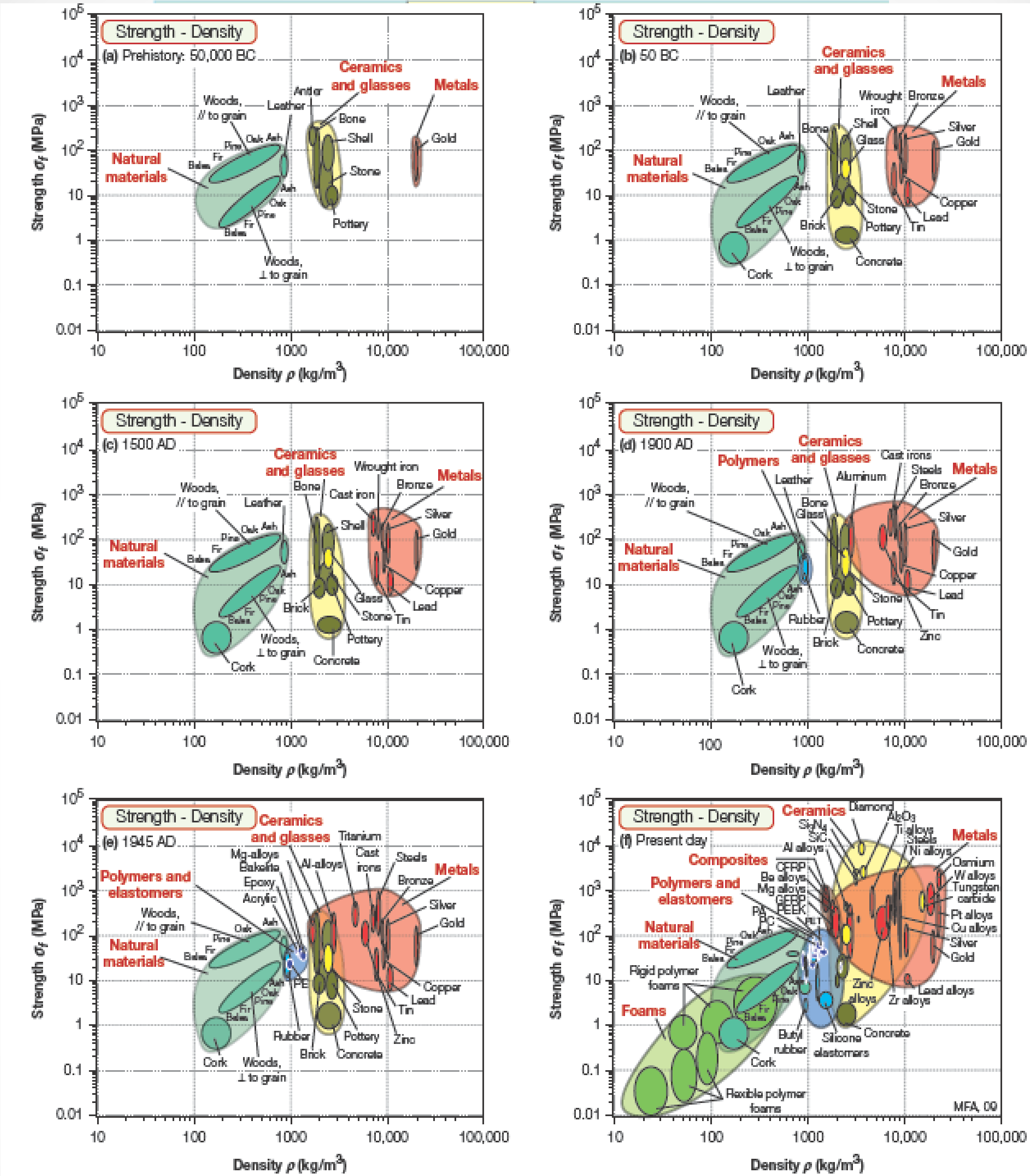
Normally the choice of materials is dictated by the design
e.g. Turbine blades necessitate light, strong and wear resistant materials

Sometimes the new product is suggested or made possible by a new material
e.g. High purity glass enabled optical fibers

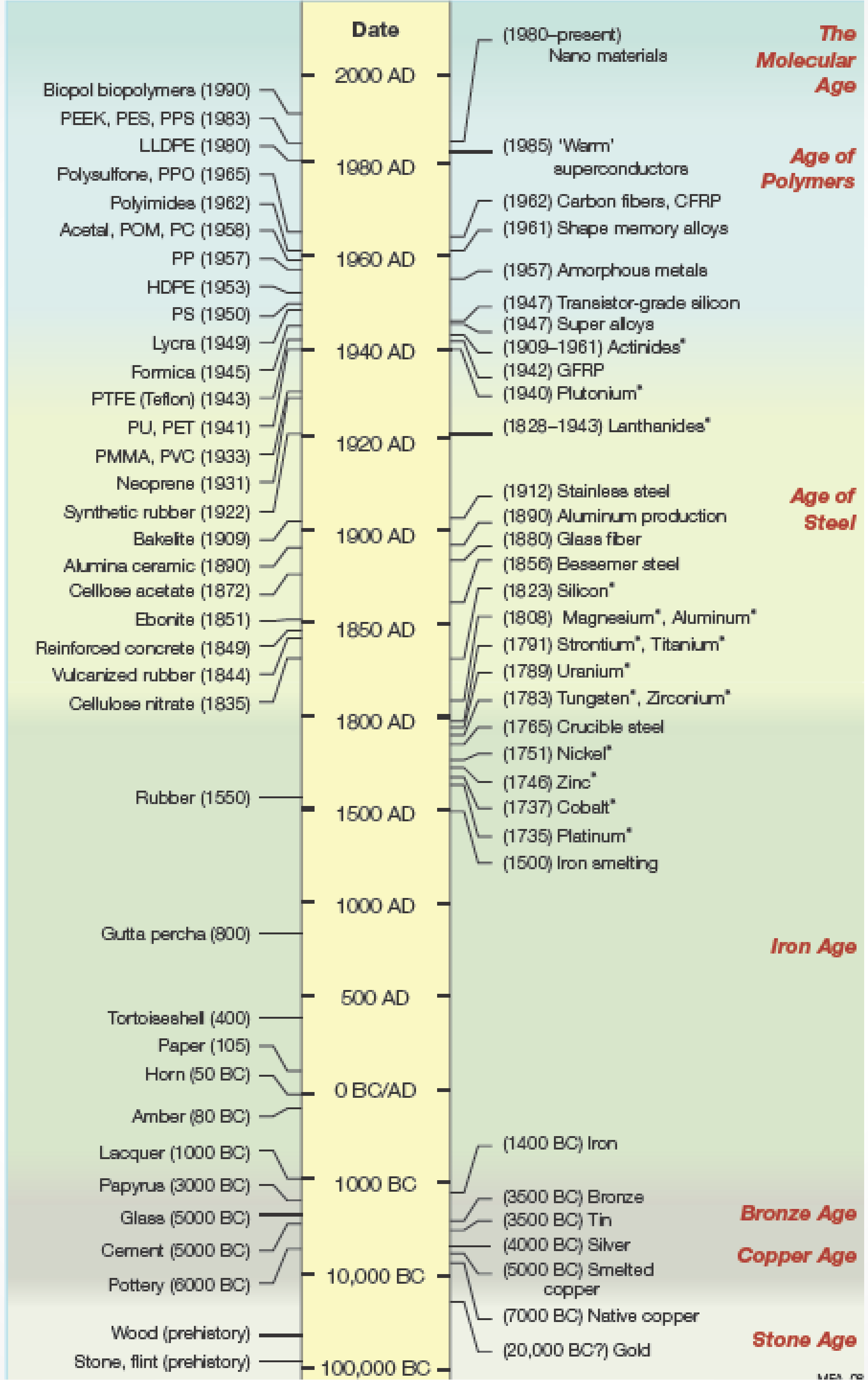
The vast number of materials developed in the modern ages enable designers be as imaginative and open minded as possible for innovative designs based on a wide range of material properties

Evolution of Engineering Materials





Strength - Density
(a) Prehistory: 50,000 BC
Natural materials
Ceramics and glasses
Metals
Woods, // to grain
Leather
Antler
Bone
Shell
Stone
Pottery
Gold
Woods, ⊥ to grain
Strength - Density
(b) 50 BC
Cork
Concrete
Brick
Wrought iron
Bronze
Silver
Copper
Lead
Tin
Glass
Strength - Density
(c) 1500 AD
Cast iron
Strength - Density
(d) 1900 AD
Polymers
Aluminum
Cast irons
Steels
Rubber
Zinc
Strength - Density
(e) 1945 AD
Polymers and elastomers
Titanium
Mg-alloys
Bakelite
Epoxy
Acrylic
Al-alloys
PE
Strength - Density
(f) Present day
Ceramics
Composites
Foams
Diamond
Al alloys
CFRP
Be alloys
Mg alloys
GFRP
PEEK
PA
PC
Ti alloys
Ni alloys
Osmium
W alloys
Tungsten carbide
Pt alloys
Cu alloys
Zinc alloys
Zr alloys
Lead alloys
Rigid polymer foams
Flexible polymer foams
Butyl rubber
Silicone elastomers
MFA, 09
Strength σ_f (MPa)
Density ρ (kg/m^3)


Date
2000 AD
1980 AD
1960 AD
1940 AD
1920 AD
1900 AD
1850 AD
1800 AD
1500 AD
1000 AD
500 AD
0 BC/AD
1000 BC
10,000 BC
100,000 BC
Biopol biopolymers (1990)
PEEK, PES, PPS (1983)
LLDPE (1980)
Polysulfone, PPO (1965)
Polyimides (1962)
Acetal, POM, PC (1958)
PP (1957)
HDPE (1953)
PS (1950)
Lycra (1949)
Formica (1945)
PTFE (Teflon) (1943)
PU, PET (1941)
PMMA, PVC (1933)
Neoprene (1931)
Synthetic rubber (1922)
Bakelite (1909)
Alumina ceramic (1890)
Celllose acetate (1872)
Ebonite (1851)
Reinforced concrete (1849)
Vulcanized rubber (1844)
Cellulose nitrate (1835)
Rubber (1550)
Gutta percha (800)
Tortoiseshell (400)
Paper (105)
Horn (50 BC)
Amber (80 BC)
Lacquer (1000 BC)
Papyrus (3000 BC)
Glass (5000 BC)
Cement (5000 BC)
Pottery (6000 BC)
Wood (prehistory)
Stone, flint (prehistory)
(1980–present) Nano materials
(1985) 'Warm' superconductors
(1962) Carbon fibers, CFRP
(1961) Shape memory alloys
(1957) Amorphous metals
(1947) Transistor-grade silicon
(1947) Super alloys
(1909–1961) Actinides*
(1942) GFRP
(1940) Plutonium*
(1828–1943) Lanthanides*
(1912) Stainless steel
(1890) Aluminum production
(1880) Glass fiber
(1856) Bessemer steel
(1823) Silicon*
(1808) Magnesium*, Aluminum*
(1791) Strontium*, Titanium*
(1789) Uranium*
(1783) Tungsten*, Zirconium*
(1765) Crucible steel
(1751) Nickel*
(1746) Zinc*
(1737) Cobalt*
(1735) Platinum*
(1500) Iron smelting
(1400 BC) Iron
(3500 BC) Bronze
(3500 BC) Tin
(4000 BC) Silver
(5000 BC) Smelted copper
(7000 BC) Native copper
(20,000 BC?) Gold
The Molecular Age
Age of Polymers
Age of Steel
Iron Age
Bronze Age
Copper Age
Stone Age

The development of the number and class of materials throughout history were driven by the desire for greater performance

In prehistory the weapons which represented the peak of technology, were made of wood and flint

Development of thermochemistry and metallurgy allowed copper, bronze and iron swords until the middle ages

Invention of cast iron established the dominance of metals in engineering

In mid 20^{th} century, “engineering materials” meant metals

Although ceramics and polymers have developed to a great extent since 1950, steel is the most widely used structural material in the world today

General Properties of Metals

Steel, aluminum, magnesium, zinc, cast iron, copper, lead, etc

- High electrical conductivity
- High heat conductivity
- Ductile
- Easily deformed
- High thermal shock resistance
- Suitable for structural and load bearing applications
- Alloys utilized for development of high performance metals

General Properties of Ceramics

Bricks, glass, refractory and abrasive ceramics

- Low electrical conductivity
- Low heat conductivity
- Brittle
- High wear resistance in high temperature applications
- Corrosion resistance
- Generally used as insulators and load bearing structures
- Advanced ceramics are utilized in integrated circuits and optical applications due to the improvements on optical and electrical properties
- Biocompatible materials

General Properties of Polymers

Elastomers, plastics, and adhesives

- Produced by polymerization of organic molecules into large molecular structures
- Low electrical conductivity
- Low thermal resistance
- Low strength
- Light materials

General Properties of Composites

Comprised of two or more materials

- Carbon fiber reinforced polymer, polymer fiber reinforced HA
- Light
- Strong
- High fracture toughness
- High thermal shock resistance

In old times materials selection process from a relatively small group of materials relied on the experience of the designer

In modern ages when the development rate of new materials is the highest in history, a systematic procedure is used instead that is robust, allows computer implementation and compatible with other established tools of engineering design

The methodology that will be discussed in materials selection and design course guides the engineer through obstacles faced using material and process attributes given in material and process selection charts

The initial survey for potential candidate materials is simplified to a great extent using this systematic procedure

It is important in the early stage of design, to examine the full materials menu, not rejecting options merely because they are unfamiliar

Examples to the evolution of materials in products

Competitive design requires the innovative use of new materials and the clever exploitation of their special properties, both engineering and aesthetic

Basic Definitions

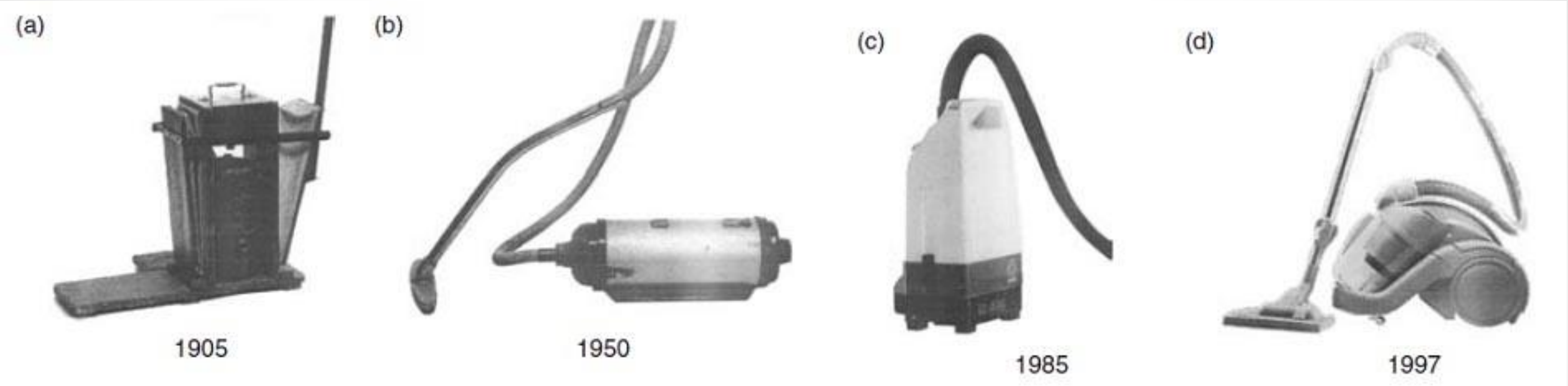
Original design: Design involving a new idea or working principle (e.g. the ballpoint pen)

a. New materials enable new products (high purity glass – optic fibers)
b. New product requires the development of a new material (space vehicle – light, heat resistant composites)

Adaptive or developmental design: Adaptive design takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle
(polymers replacing metals in household appliances)
The motive for redesigning it may be to enhance performance, to reduce cost, or to adapt it to changing market conditions

Variant design: Design involving a change of scale or dimension or detailing without a change of function or the method of achieving it (e.g. the scaling up of boilers, large boats being made of steel instead of composite)

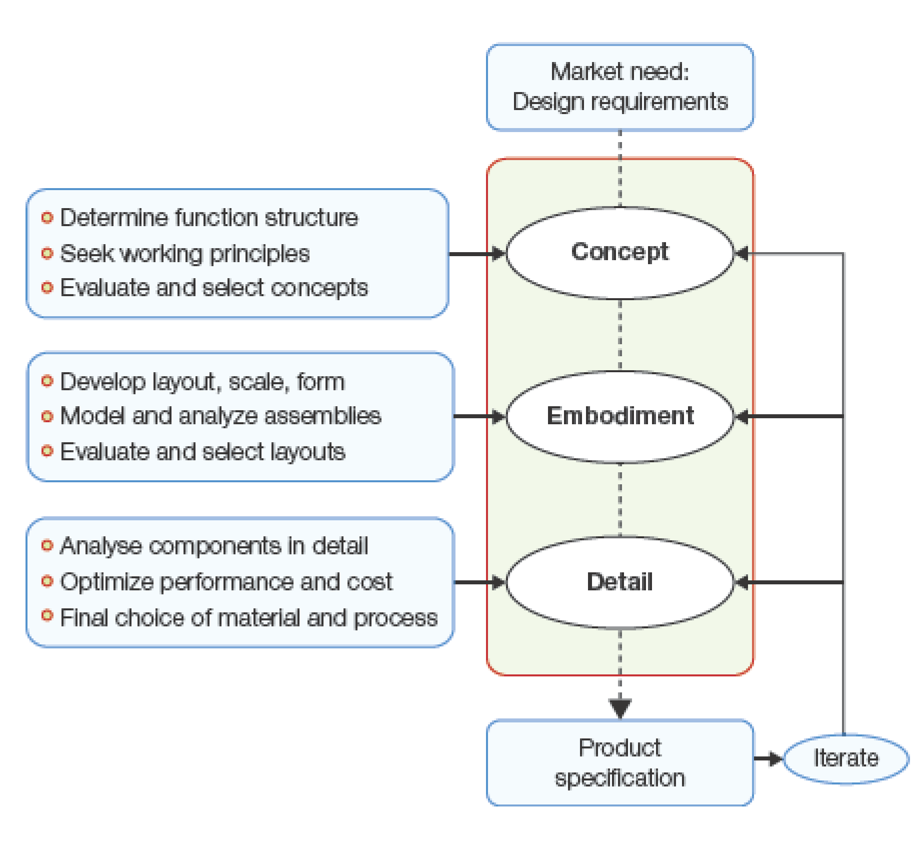
Vacuum cleaner – Original, adaptive and variant designs



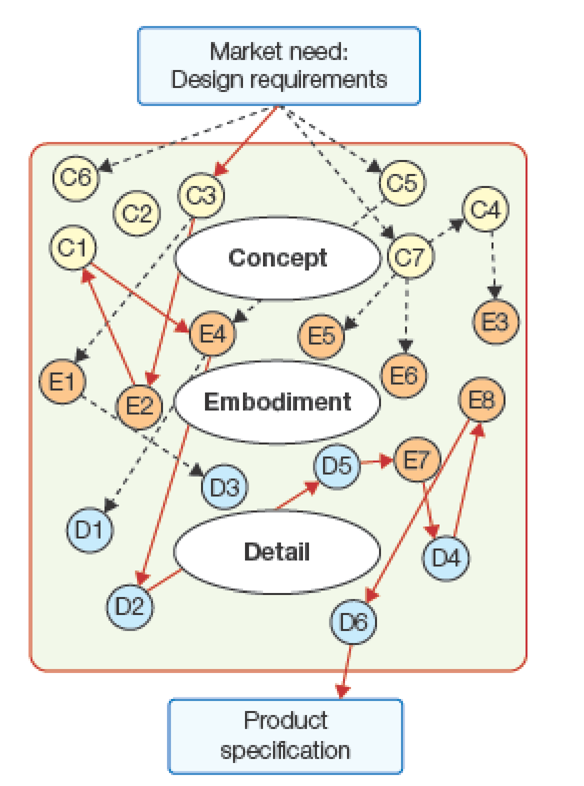
Cleaner and date	Dominant materials	Power (W)	Weight (kg)	Approximate cost*
Hand powered, 1900	Wood, canvas, leather	50	10	£240–$380
Cylinder, 1950	Mild steel	300	6	£96–$150
Cylinder, 1985	Molded ABS and polypropylene	800	4	£60–$95
Dyson, 1995	Polypropylene, polycarbonate, ABS	1200	6.3	£190–$300

The design flow chart

It is essential to define the need for design precisely—to formulate a need statement, often in this form: "A device is required to perform task X," expressed as a set of design requirements



Theory



Reality

Vacuum cleaner design steps

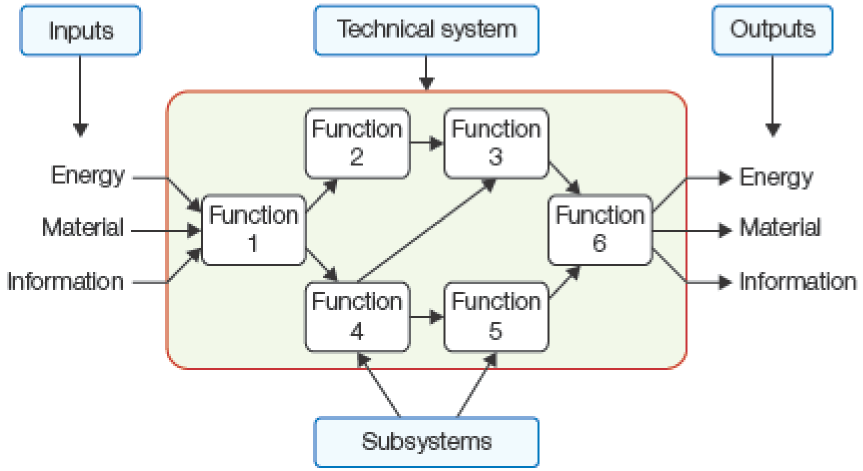
A device to remove dust from carpets

I. Conceptual design
   - To blow it out with compressed air
   - To draw it out electrostatically
   - To brush it out
   - To suck it out with a vacuum

II. Embodiment design
   - Design of pump, filter, tube, casing, controls, materials data
   - Flow rate calculation, layout diagrams, power, weight, processing

III. Detailed design
   - Stress analysis and air flow modeling
   - Details of each component, their materials and processes
   - Cost analysis, industrial design, eco-design

The function structure



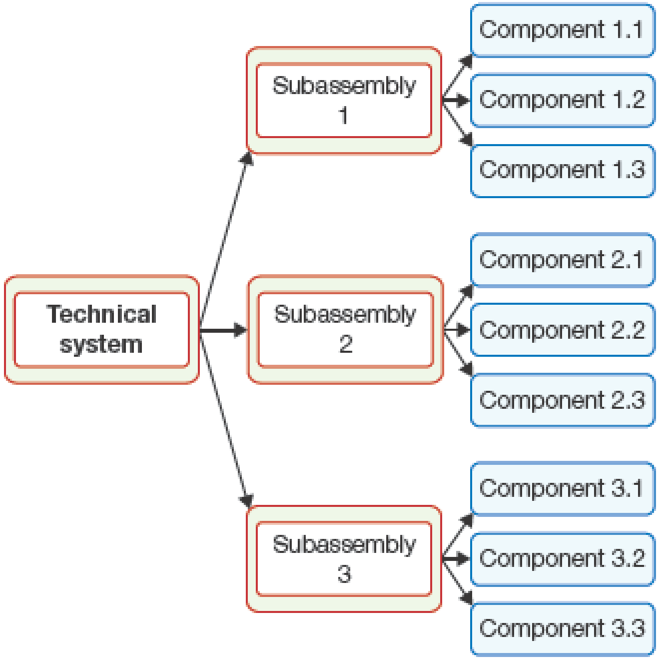
Analogy: the operative systems of a robot - engine, cpu, electrical signaling

The function structure is a systems approach to the analysis of a technical system, mainly for an original design

This approach helps structure thinking about alternative designs

The product is called a technical system

A technical system consists of subassemblies and components, put together in a way that performs the reauired task

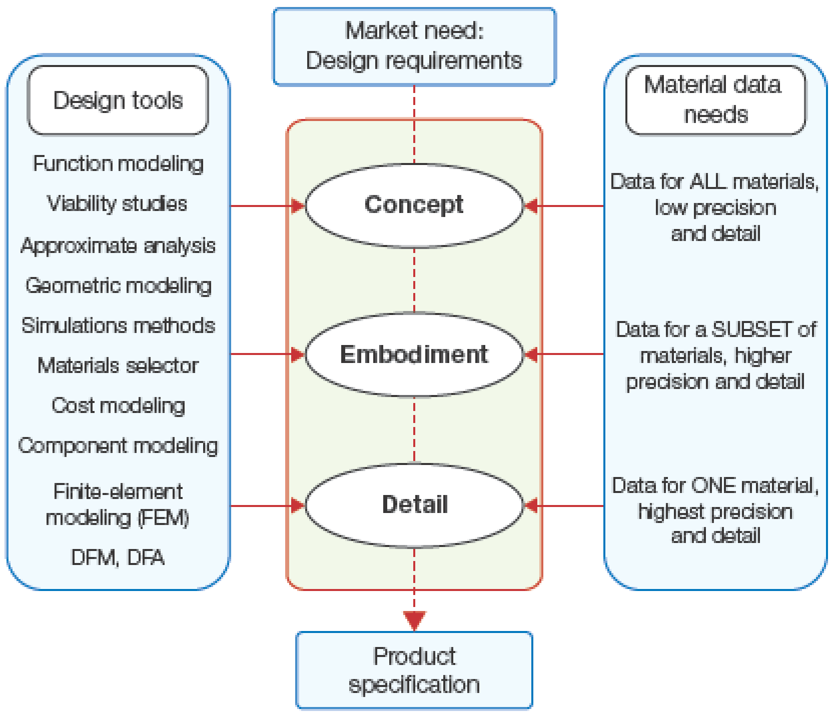


Analogy: the limbs of a robot - head, body, arms, legs, etc.

The analysis of a technical system as a breakdown into assemblies and components is mainly used in adaptive design

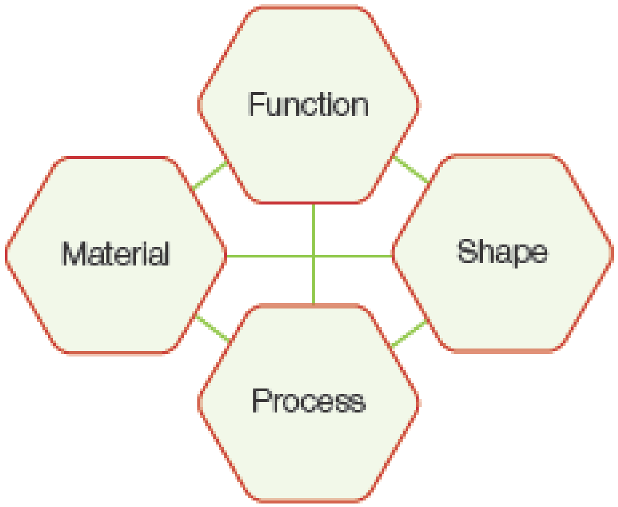
Material and process selection is at the component level

Design Tools enable the modeling and optimization of a design, easing the routine aspects of each phase
Function modelers suggest viable function structures
Configuration optimizers suggest or refine shapes
Geometric and 3D solid modeling packages allow visualization and create files that can be downloaded to numerically controlled prototyping and manufacturing systems



Information about materials is needed at each stage, but at very different levels of breadth and precision

The selection of material is tied in with function, process and shape



Function primarily influences material choice and shape

Material choice influences processes through the material's ability to be cast or molded or welded or heat-treated

Process determines shape; size; precision; and, of course, cost

Specification of shape may restrict the choice of material and process; but equally the specification of process may limit the material choice and the accessible shapes

The more sophisticated the design, the tighter the specifications and the greater the interactions

Design and Materials Selection Examples

A device is required to cut hard materials

with

- High elastic modulus
- High deformation resistance
- High fracture toughness

Candidate: High carbon steel

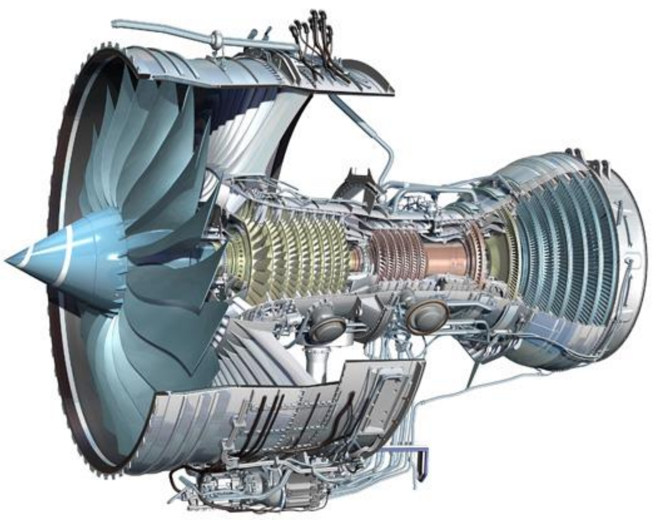
Handle requirements

- Easy manufacture
- Availability
- Light
- Aesthetic

Candidate: Wood

Design and Materials Selection Examples

A device is required to rotate in the Rolls-Royce turbofan engine with



- High stiffness
- High toughness
- High thermal shock resistance
- High wear, oxidation and corrosion resistance,
- Low density

Candidate: Ni alloys

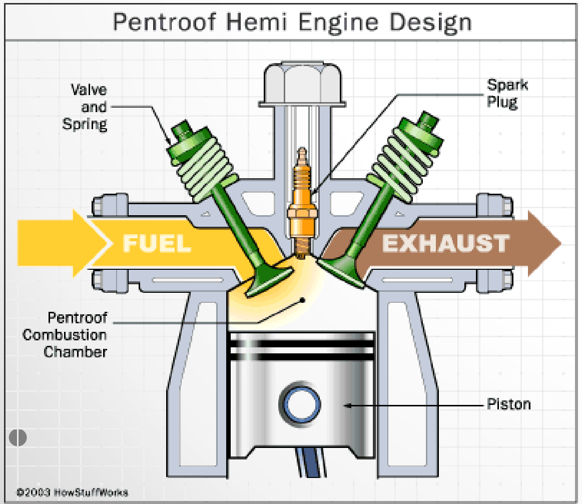
Design and Materials Selection Examples

A device is required to facilitate ignition in combustion engines

With

- Thermal shock resistance
- Wear, corrosion and oxidation resistance,
- Resistant to chemical attack by S and Pb

Candidate: alumina coated tungsten



The materials input does not end with the establishment of production

Products fail in service, and failures contain information

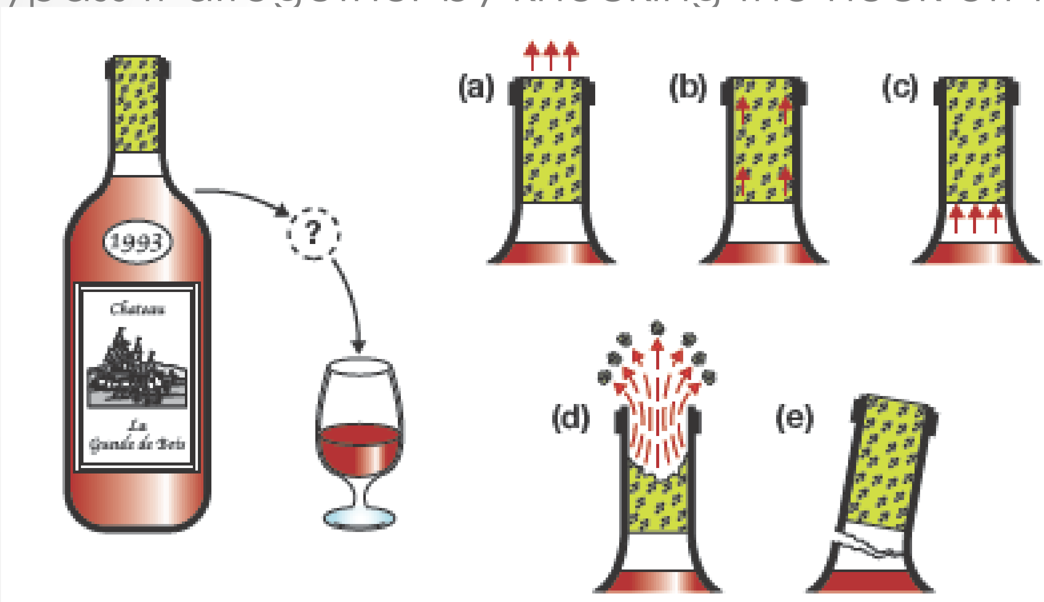
Often this points to the misuse of a material, one that redesign or reselection can eliminate

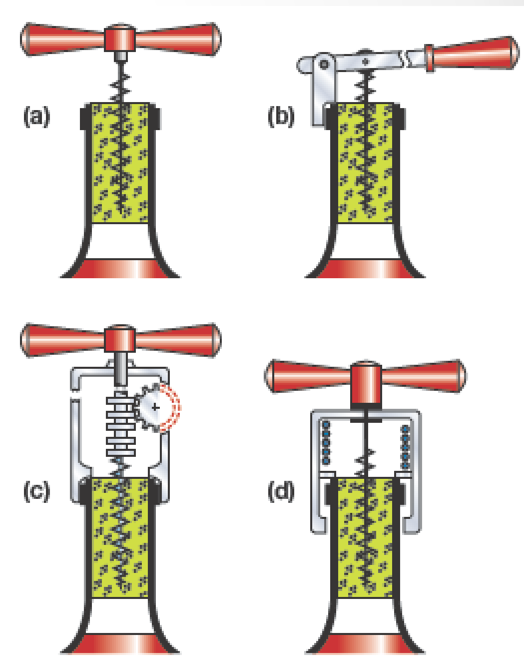
Failure analysis is a useful way to replace or improve a design

Many commercial ships failed catastrophically after World War II due to selection of welded steel with low fracture toughness

Example product – Cork opener

The market need – A device is required to allow access to wine in a corked bottle with convenience, at modest cost, and without contaminating the wine
Concepts - The devices act to remove the cork by axial traction (pulling); to remove it by shear tractions; to push it out from below; to pulverize it; and to bypass it altogether by knocking the neck off the bottle





Embodiments - Sketches for devices based on axial traction
The first is a direct pull; the other three use levered pull, geared pull, and spring-assisted pull

Example product – Cork opener

The embodiments identify the functional requirements for each component of the device, which might be expressed in statements such as

- A cheap screw to transmit a prescribed load to the cork
- A light lever to carry a prescribed bending moment
- A slender elastic blade that will not buckle when driven between the cork and the bottle neck
- A thin, hollow needle, stiff and strong enough to penetrate a cork

The functional requirements of each component are the inputs to the materials selection process which lead directly to the property limits and material indices
Detail - The final choice of material and process forms part of the detailed stage