ADVANCED
&
EXOTIC MATERIALS

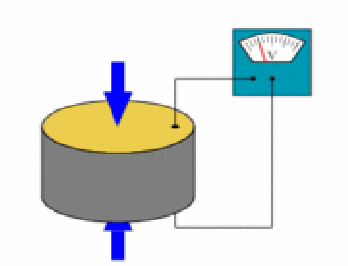
Smart Materials Structures and Systems
Laboratory
IIT Kanpur

Smart Materials

Smart materials are those which posses ability to change their physical properties in a specific manner in response to specific stimulus input.

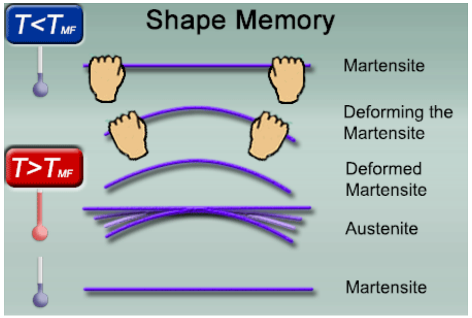
Commonly used smart materials are:-

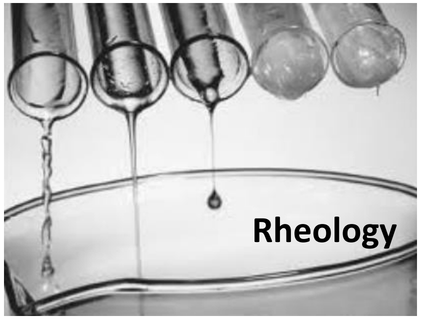
1. **Piezoelectric -** Generate s electric charge in response to applied mechanical stress and vice versa.
2. **Magnetostrictive** – Change in dimension of ferromagnetic material in magnetic field and vice versa.
3. **Phase-Transition dependent -** "Remembers" its original shape and after being deformed returns to its original shape when heated.
4. **Electro/Magneto Rheological Materials –** Change in viscosity in response to electric/magnetic field.



Piezoelectricity
Image: Wikipedia

Terfenol-D





Smart Materials Structures and Systems Laboratory
IIT Kanpur

Bio-materials

- Substances (excluding food & drugs) introduced into a **living body** with the aim of **improving** or replacing a **diseased**, damaged or lost tissue or whole **organ**.

Examples – Biomedical applications

- ✓ Joint replacements
- ✓ Bone plates
- ✓ Bone cement
- ✓ Artificial ligaments and tendons
- ✓ Dental implants for tooth fixation
- ✓ Heart valves
- ✓ Vascular grafts
- ✓ Stents
- ✓ Skin repair devices (artificial tissue)
- ✓ Cochlear replacements
- ✓ Contact lenses
- ✓ Surgical sutures for wound closure
- ✓ Pins and screws for fracture stabilisation

Metals as bio-materials

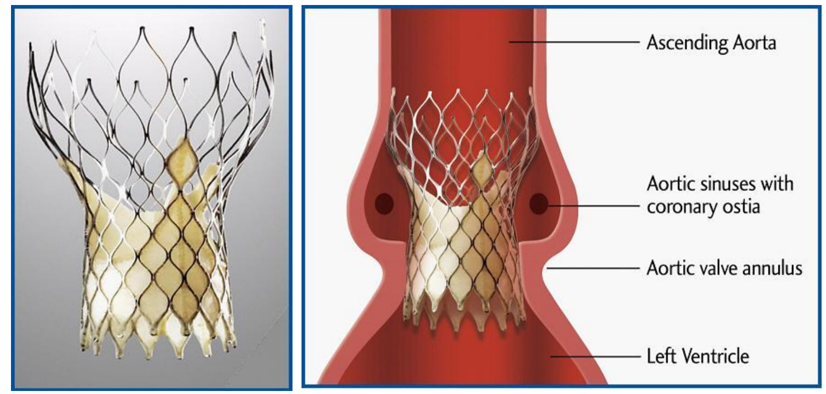
Metals : Co-Cr alloys, Stainless steel, Gold , Ti alloys, Vitallium (Co-Cr-Mo), Amalgams(Hg-Ag-Sn)
Shape memory alloys - Nitinol(Ni-Ti alloy) and Cu-Zn-Al.

Usages : Orthopedics, dentistry, stent, etc.

Fractured fore-arm

Stainless steel implant

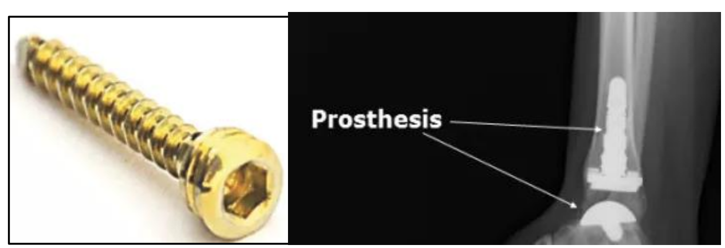
Ref: www.boneandspine.com



Self-expanding Nitinol stent in aortic heart valve

(Ref: www.heartlungdoc.com)

Hip implant stem - Vitallium/ Ti



Stainless steel screws

Ref: www.boneandspine.com

Amalgam filling

(Ref: www.dunadental.hu)

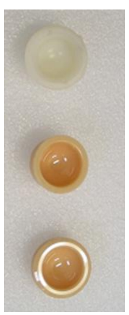
Polymers as bio-materials

Polymers : Silicones, Polyethylene(UHMWPE-ultra-high molecular weight PE), polyurethanes, polymethylmethacrylate (PMMA or bone cement - fill space b/w bone & implant).

Usages : Orthopedics, artificial tendons, vascular grafts, facial and soft tissue reconstruction

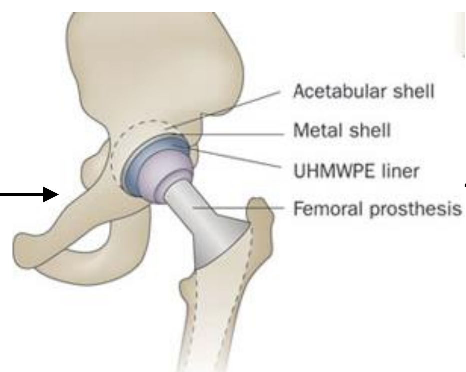
Resorbable polymers : Polylactic acid (PLA),polyglycolic acid for suture, scaffolds for building tissues.

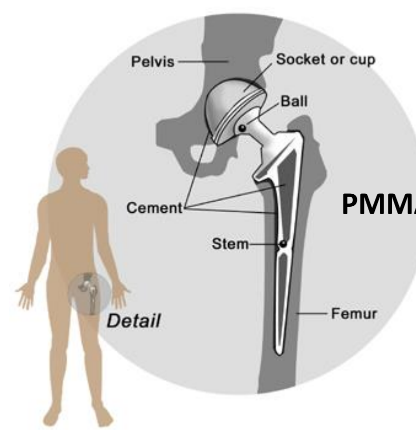
Hydrogel : pHEMA (Polyhydroxyethylmethacrylate) – wound dressing, retinal implant, contact lens



UHMWPE liner

Femoral prosthesis





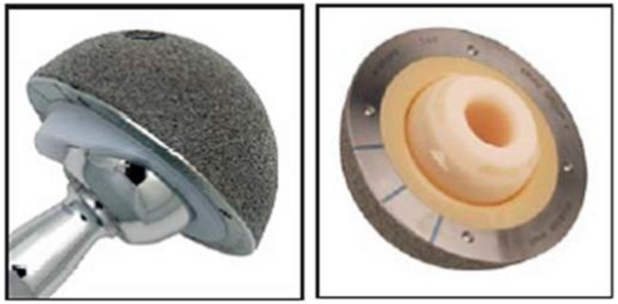
PMMA as cement

UHMWPE lining on femoral prosthesis

Image: http://emedicine.medscape.com/

Ceramics as bio-materials

Ceramics: Alumina, calcium phosphate (bone grafting), synthetic hydroxyapatite (promote bone ingrowth), pyrolytic carbon (lining on blood contacting prosthesis)



Alumina on UHMWPE

Ceramic as bearing

Image: http://emedicine.medscape.com/

Aerogels

- Aerogel is a material that is around **90-98 % porous**.
- They are produced by extracting the liquid component of a gel through supercritical drying.
- The air molecules trapped inside the gel would act as **insulators**, and its **heat conductivity** is close to **zero**.

Aerogel kept b/w Flower and Bunsen burner
Image: Wikipedia

Applications

- Capturing **space dust** from comets (NASA STARDUST mission -1999).
- **Insulating** material in **spacesuits** of NASA astronauts since 1960s.

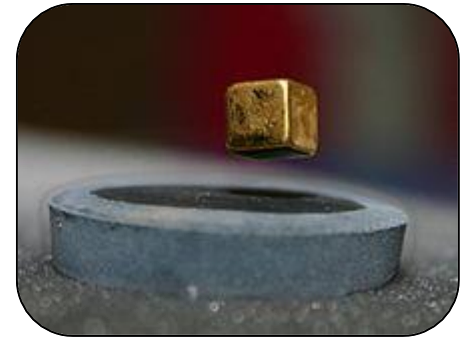
Potential applications

- **Thermal barrier** – extreme cold region clothes such as for Siachen (requires around 500 grams of gel to coat a jacket).
- **Thermal insulators** for cryogenic fuel tank of rockets.
- **Acoustic insulators**, building and pipeline insulation.

Superconductors

- ✓ An element , intermetallic alloy or compound that will **conduct electricity without resistance** below a characteristic critical temperature (T_C).
- ✓ Costly due to cryogenic requirements.

Example: Hg, Lanthanum-Barium-Copper Oxide, Niobium-Tin, Yttrium-Barium-Copper Oxide

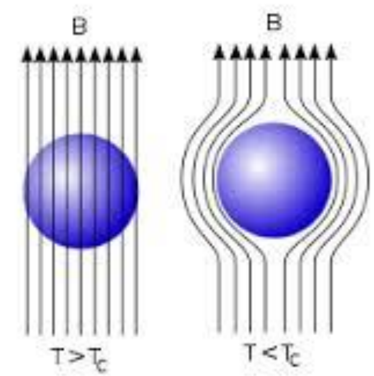


Superconductor(black) cooled by nitrogen and material being levitated

PROPERTIES OF SUPERCONDUCTORS

1. Meissner effect

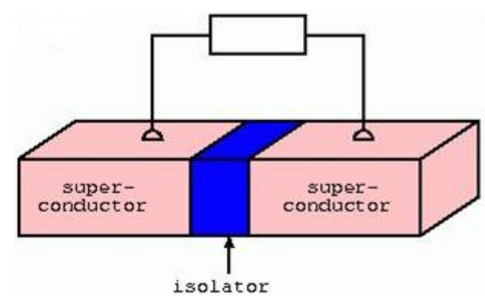
When superconducting material cooled below its T_C ,it becomes perfectly **diamagnetic** (all magnetic flux expelled out).



Meissner effect

2. Josephson effect

When 2 superconductors sheets are separated by small thin insulating material the **current** can **pass through without any voltage**.



Josephson effect

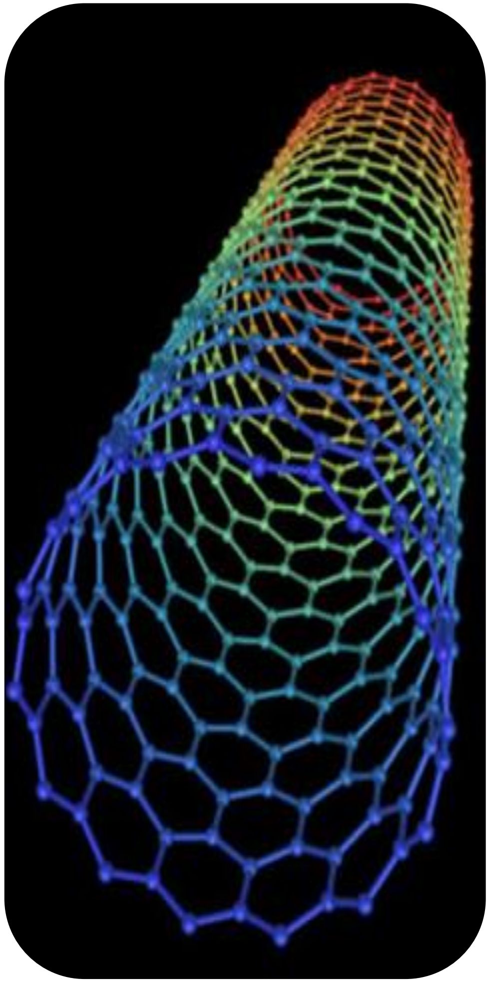
Applications

- Magnetic-levitation
- **SQUID's (**Superconducting Quantum Interference Device**)** are capable of sensing a change in a magnetic field over a billion times weaker than the force that moves the needle on a compass . With this technology, the body can be probed to certain depths without the need for the strong magnetic fields associated with MRI's.

Image: Wikipedia

Carbon Nanotubes (CNT)/ Fullerene

- Discovered in 1991.
- Composed of **carbon atoms linked in hexagonal shapes**, with each carbon atom **covalently bonded** to three other carbon atoms.
- Carbon nanotubes have **diameters** as small as **1 nm** and lengths up to several centimeters.
- Carbon nanotubes are the **strongest and stiffest materials** yet discovered in terms of tensile strength and elastic modulus respectively.
- CNT are at least **100 times stronger than steel**, but only one-sixth as heavy.
- Extremely **high thermal conductivity** (≈ 10 times of copper) and **electrical conductivity** (≈100 times of copper).
- Combining **carbon nanotubes** with other materials into **composites** can be used to **reinforce** and build **lightweight** structures.



CNT

Image: Mstroeck

Materials Selection in Engineering Design

Smart Materials Structures and Systems
Laboratory
IIT Kanpur

Contents

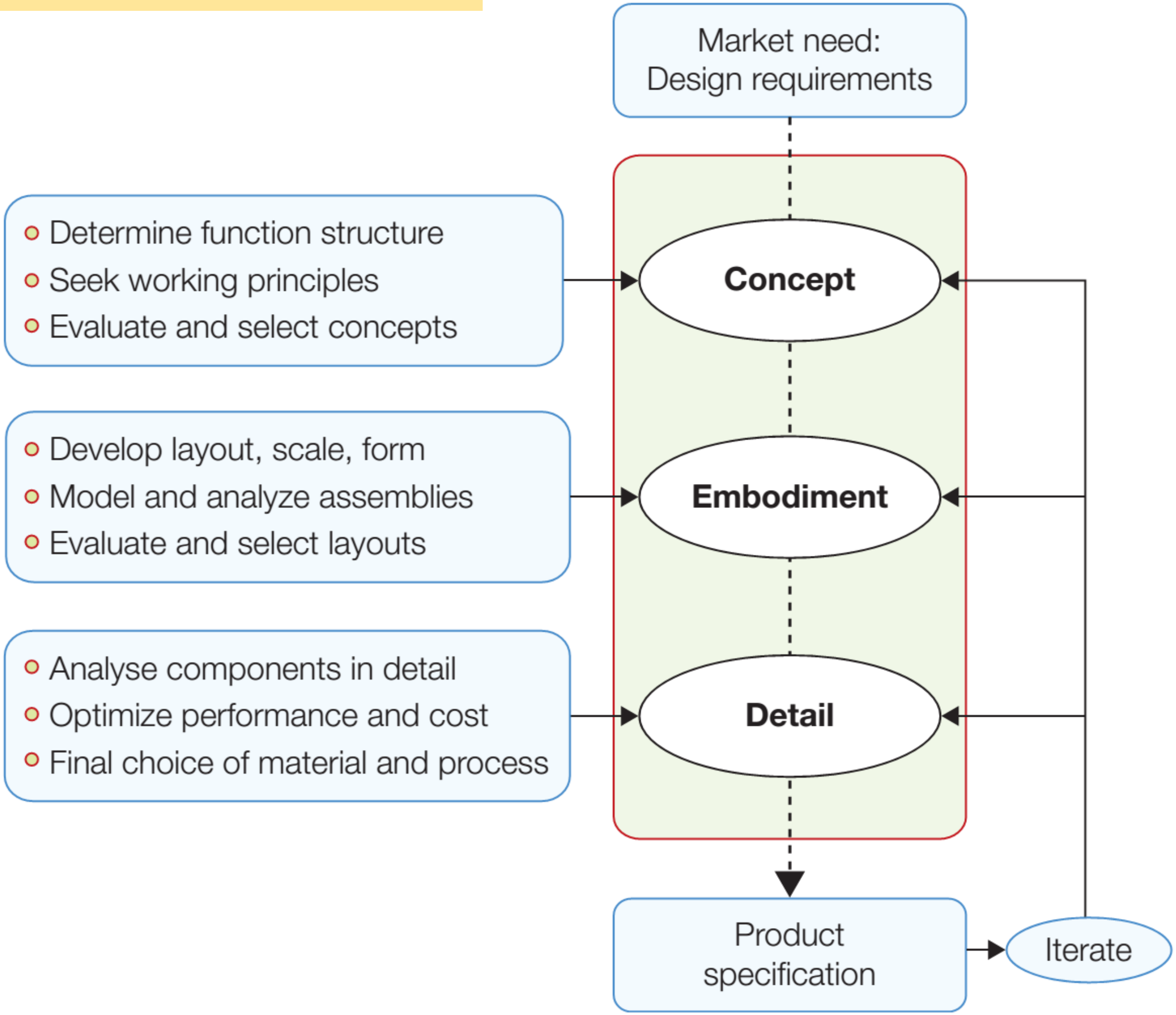
- ✓ Mechanical design
- ✓ Design flow chart
- ✓ Doubling time
- ✓ Resource availability
- ✓ Eco efficiency
- ✓ Ashby Chart

Basics

- **Mechanical Design** refers to the mechanical components that have mass, carry loads and other functionalities such as thermal/electromagnetic requirements and must be manufactured.

- **Design** refers to the selection of engineering materials based on a set of defined properties. It is an **iterative process.**

Design Flow Chart



Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

Selection Properties

1. Price and Availability
2. Density, Modulus, Damping, Yield Strength, Tensile Strength, Hardness, Fracture Toughness, Fatigue Strength, Thermal Fatigue Resistance, Creep Strength
3. Thermal, Optical, Magnetic & Electrical Properties
4. Oxidation, Corrosion, Friction, Abrasion & Wear
5. Ease of Manufacturing, Joining, etc.
6. Appearance, Texture, Feel, etc.

Relative Prices

Approximate Relative Price per Ton (mild steel = 100)

Material	Relative price
Platinum	12 m
Diamonds, industrial	10 m
Gold	9.6 m
Silver	290,000
CFRP (materials 70% of cost; fabrication 30% of cost)	20,000
Cobalt/tungsten carbide cermets	15,000
Tungsten	5000
Cobalt alloys	7000
Titanium alloys	2000
Nickel alloys	6000
Polyimides	8000
Silicon carbide (fine ceramic)	7000
Magnesium alloys	1000
Nylon 66	1500
Polycarbonate	1000
PMMA	700
Magnesia, MgO (fine ceramic)	3000
Alumina, Al_2O_3 (fine ceramic)	3000
Tool steel	500
GFRP (materials 60% of cost; fabrication 40% of cost)	1000
Stainless steels	600
Copper, worked (sheets, tubes, bars)	2000
Copper, ingots	2000
Aluminum alloys, worked (sheet, bars)	650
Aluminum ingots	550
Brass, worked (sheet, tubes, bars)	2000
Brass, ingots	2000
Epoxy	1000
Polyester	500
Glass	400
Foamed polymers	1000
Zinc, worked (sheet, tubes, bars)	550
Zinc, ingots	450
Lead, worked (bars, sheet, tube)	650
Lead, ingots	550
Natural rubber	300
Polypropylene	200
Polyethylene, high density	200
Polystyrene	250
Hard woods	250
Polyethylene, low density	200

Cont'd

Material	Relative price
Polyvinyl chloride	300
Plywood	150
Low-alloy steels	200
Mild steel, worked (angles, sheet, bars)	100
Cast iron	90
Soft woods	50
Concrete, reinforced (beams, columns, slabs)	50
Fuel oil	190
Cement	20
Coal	20

Note: *At April 2011 mild steel was $500/ton*

Reference: Engineering Materials 1: Ashby & Jones, 4th Ed.

Abundance of Elements

Crust		Oceans		Atmosphere	
Element	**Weight %**	**Element**	**Weight %**	**Element**	**Weight %**
Oxygen	47	Oxygen	85	Nitrogen	79
Silicon	27	Hydrogen	10	Oxygen	19
Aluminum	8	Chlorine	2	Argon	2
Iron	5	Sodium	1	Carbon as carbon dioxide	0.04
Calcium	4	Magnesium	0.1		
Sodium	3	Sulphur	0.1		
Potassium	3	Calcium	0.04		
Magnesium	2	Potassium	0.04		
Titanium	0.4	Bromine	0.007		
Hydrogen	0.1	Carbon	0.002		
Phosphorus	0.1				
Manganese	0.1				
Fluorine	0.06				
Barium	0.04				
Strontium	0.04				
Sulphur	0.03				
Carbon	0.02				

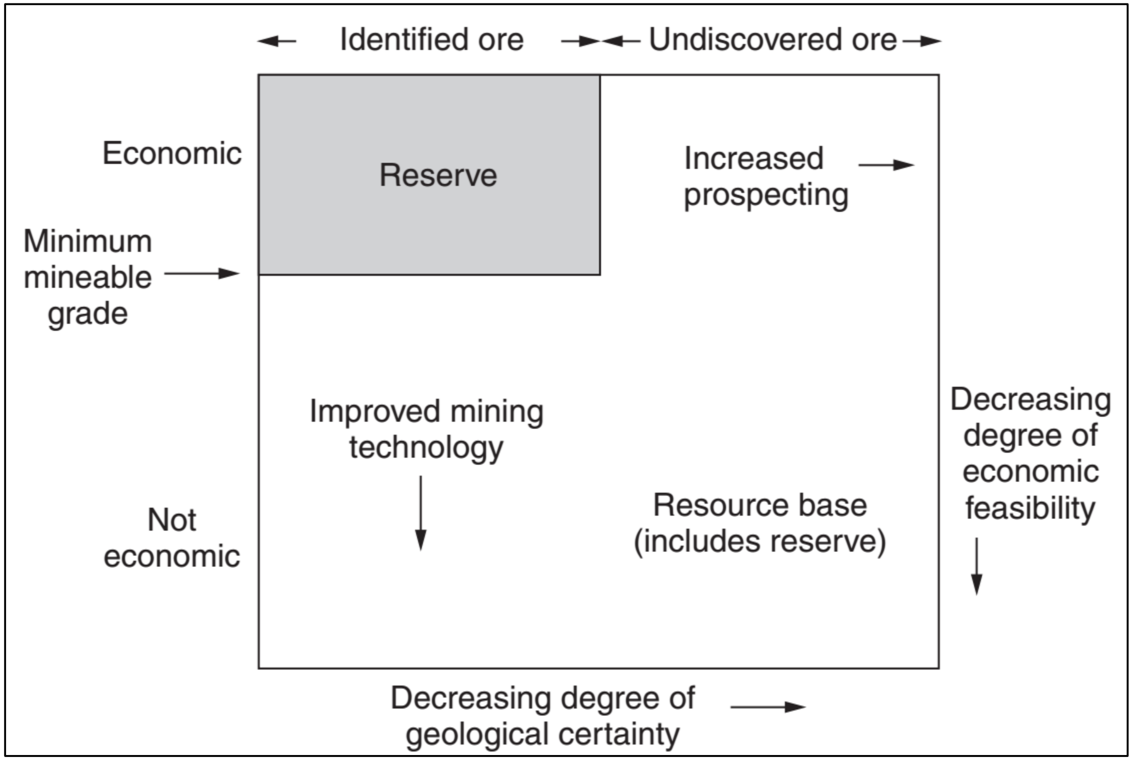
Note: *The total mass of the crust to a depth of 1 km is* 3×10^{21} *kg; the mass of the oceans is* 10^{20} *kg; that of the atmosphere is* 5×10^{18} *kg.*

Reference: Engineering Materials 1: Ashby & Jones, 4th Ed.

Resource Availability

- ✓ **Current reserve** is the known deposits that can be extracted profitably at today's price using today's technology.
- ✓ **Resource base** = Current reserve + (known & unknown deposits)

McElvey diagram



<u>Energy Consumed to extract (GJ/Tonne)</u>

Material	Energy
Aluminum	280
Plastics	85–180
Copper	140
Zinc	68
Steel	55
Glass	20
Cement	7
Brick	4
Timber	2.5–7
Gravel	0.2
Oil	44
Coal	29

Reference: Engineering Materials 1: Ashby & Jones, 4th Ed.

Doubling - Time

- Period of time required for a quantity to **double in size or value**.

- When the relative growth rate (not the absolute growth rate) is constant, the quantity undergoes ***exponential growth*** and has a constant Doubling time or period.

- **Example**: Applied to population growth, inflation, **resource extraction**, **consumption of goods**, compound interest, the volume of malignant tumors.

For a **constant growth rate of r%**, the formula for the **doubling time T_d** is given by

$$\boxed{T_d = \frac{ln(2)}{Growth\,rate} = \frac{log(2)}{\log(1+\frac{r}{100})} \approx \frac{70}{r}}$$

Availability

- Copper, Silver, Tungsten, Tin and Mercury are rarely available.
- Iron and Aluminium are the most widely available material.
- Steel consumption is doubling in every 20 years.
- Aluminium consumption is doubling in every 9 years.
- Polymer in every 4 years.

How to encounter shortages of materials?

- **Material Efficient Design**: *Use less amount of material*.

  For example, for a good surface property use cheap substrate and good surface finish

- **Substitution**: *Substitute rarer materials by the more available ones*.

  For example, Copper by Aluminium

- **Recycling**: *Use recyclable material like Aluminium*.

Eco-Efficiency

- Merges ecological and economic goals.
- Improving the productivity of energy and material inputs to reduce resource consumption and cut pollution per unit of output.
- A win-win approach that benefits both the bottom line and the environment.
- In 1989, ***Proctor & Gamble*** introduced **concentrated detergent powders**—called *Ultra detergents*—that took up half the volume of traditional detergents. The products **cleaned the same amount of clothes**, but were **more convenient** for consumers to handle, used 30 percent **fewer raw materials**, required **30 percent less packaging**, and substantially **cut the energy needed** to **transport** them to market.

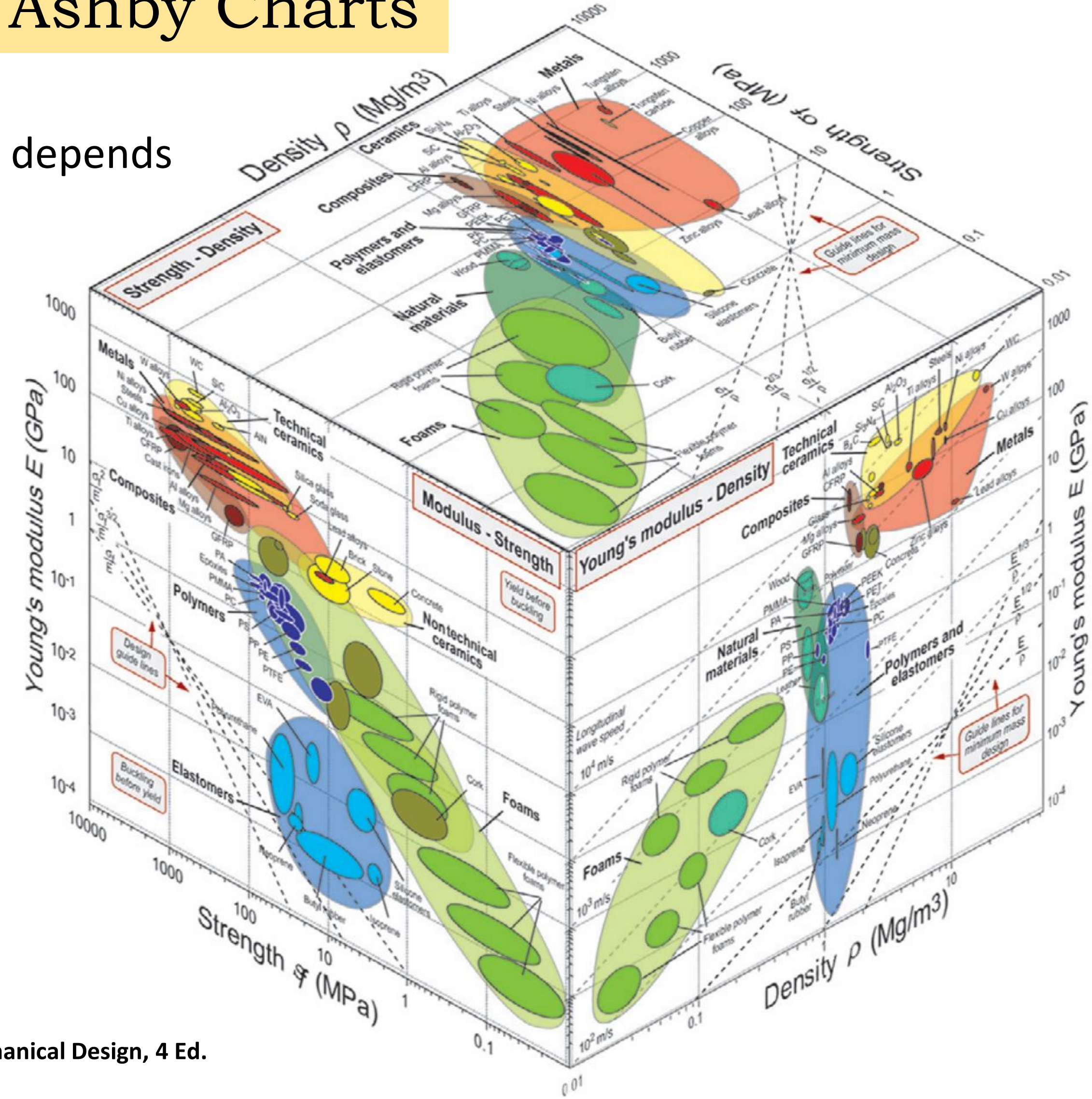
7 - Dimensions

1. **Reduce the material intensity of goods and services.**
2. **Reduce the energy intensity of goods and services.**
3. **Reduce toxic dispersion.**
4. **Enhance material recyclability.**
5. **Maximize sustainable use of renewable resources.**
6. **Extend product durability.**
7. **Increase the service intensity of goods and services.**

Greater the improvement in each of these dimensions -- and the more the dimensions -- the more eco-efficient a product or process is.

Material Property/Ashby Charts

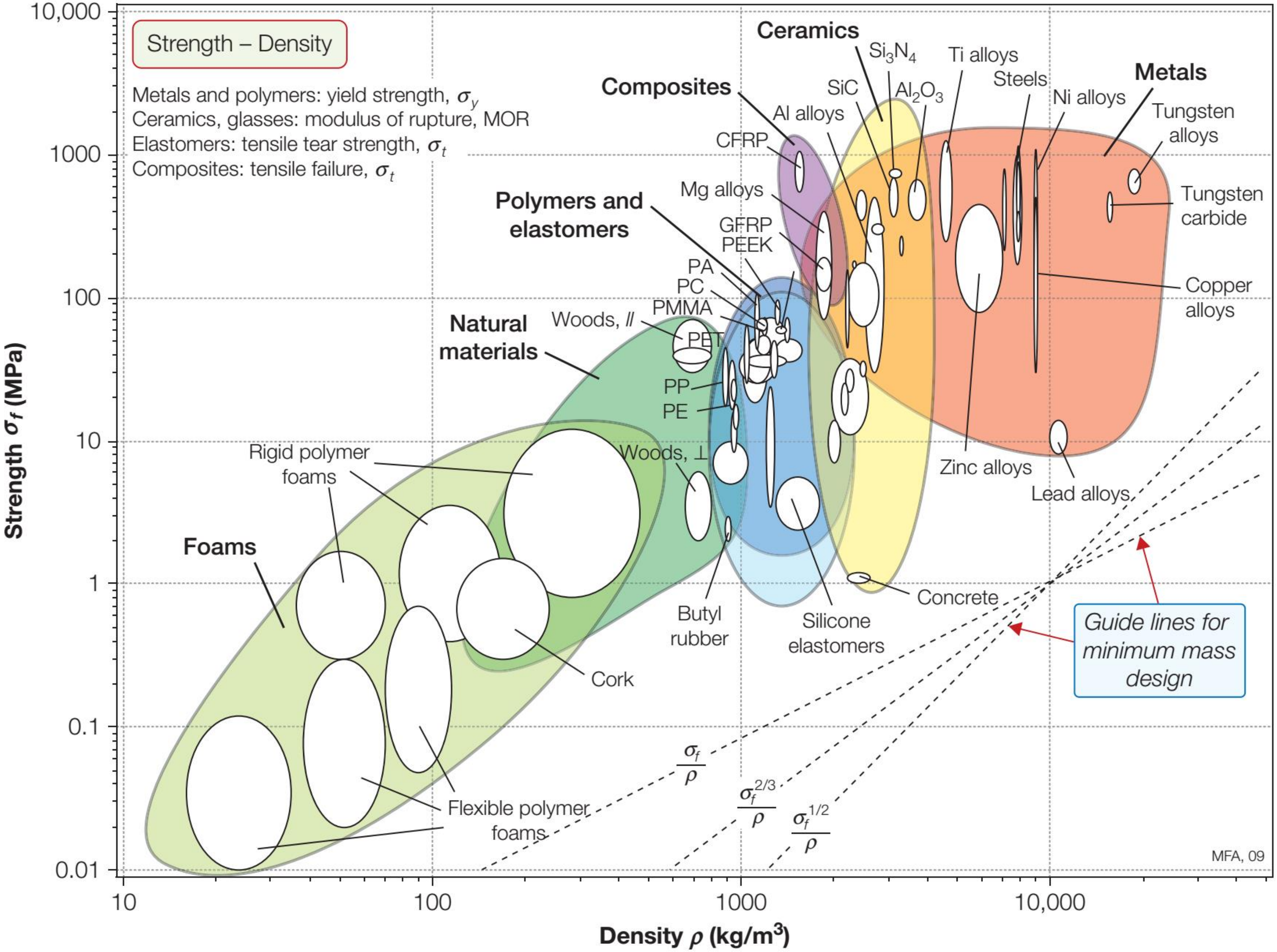
Performance of a component depends **not only on one** property.



Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

<u>One of a 3-dimensional slice: The Elastic modulus–strength–density</u>

2D Chart



Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

SMSS Smart Materials Structures and Systems Laboratory
IIT Kanpur

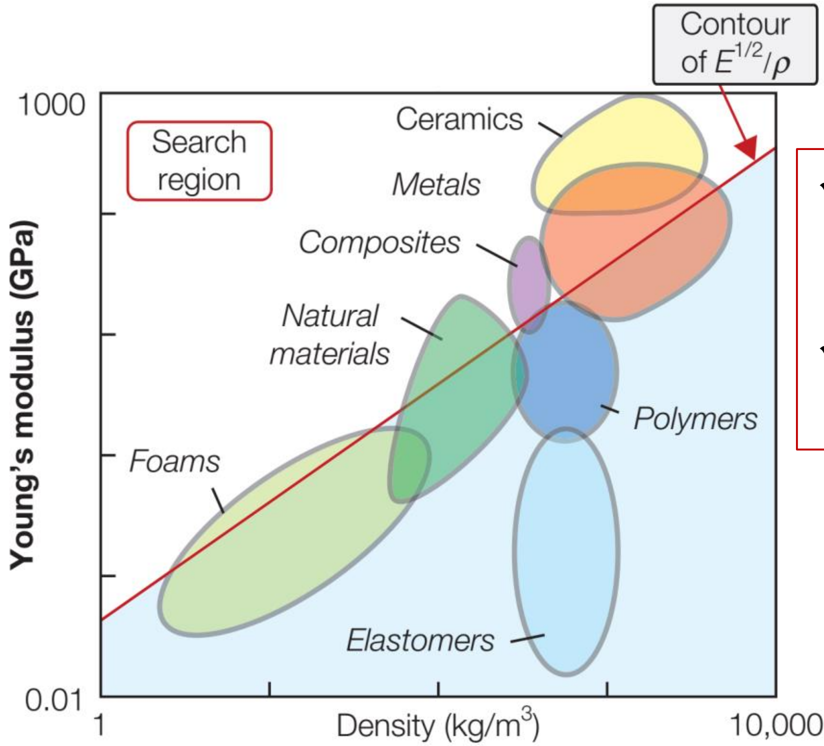
Material Selection for Cantilever Design

Smart Materials Structures and Systems
Laboratory
IIT Kanpur

Problem Statement: Select a **cost effective** material for a circular cross-section cantilever beam loaded at its end having **high stiffness** and **light weight.**

Solution:

Free variable : **Radius** of circular beam cross section & Material choice
Constraint: Maximum deflection and beam length



- ✓ **CFRP** is the best material in terms of performance, but **very expensive**.
- ✓ Hence, Wood is the **best choice** among the given materials.

$$PI = \frac{\sqrt{E}}{\rho}$$

- The **intercept** of the inclined line is **adjustable** to suit our needs but **slope** is **fixed** for a particular performance index.

Material	E (GPa)	Density (g/cm³)	($E^{1/2}/\rho$)	Cost ($/ton)
Steel	200	7.8	1.81	450
Wood	**16**	**0.8**	**5.0**	**450**
Concrete	50	2.8	2.53	300
Aluminium	69	2.7	3.08	2,000
CFRP	**200**	**1.6**	**8.84**	**200,000**

Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.