# Scope of the next sessions

You have a large knowledge in Materials Science, Materials Processing and Mechanical Engineering.

Efficient Materials selection, however, needs also a systematic methodology and a data base including information on materials properties, materials processes, eco efficiency, cost etc.

The next two sessions we will introduce you to translation, screening, and ranking procedures and you will practice with case studies one of the software packages available on the market.

In the remaining sessions you will get an in depth introduction to surface and coating processes, hybrid design etc. and will use the software only occasionally.

Don’t be bored, because

50% class room, and 50% computer room exercises

Little “advanced materials science and advanced mechanics” – learn a method and give your colleagues from other sections a chance!

And start the course with the attitude to train yourself on a useful tool in materials selection

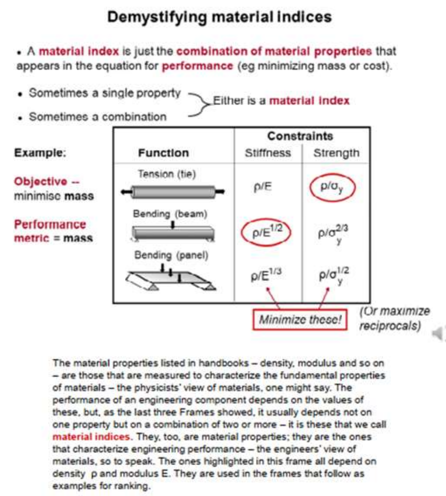
# introduction

Prerecorded video lecture content

Annotated lecture slides in pdf

Written exercises (check lecture instructions)

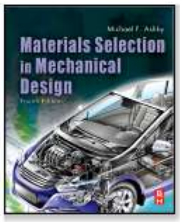
Computer exercise with prerecorded video instructions with solutions in pdf



# General texts on materials selection in design:


- Budinski, K.G., & Budinski, M.K. (2010) *Engineering materials, properties and selection* (9th ed.), Prentice Hall, ISBN 978-0-13-712842-6.
  *(A well established materials text that deals well with both material properties and processes).*
- Callister, W.D. (2010) *Materials science and engineering: An introduction* (8th ed.). John Wiley & Sons, ISBN 978-0-470-41997-7
  *(A well-established text taking a science-led approach to the presentation of materials teaching)*
- Shackelford, J.F. (2009) *Introduction to materials science for engineers* (7th ed.). Prentice Hall, ISBN 978-0-13-601260-4.
  *(A well-established materials text with a design slant)*
- Farag, M.M. (2008) *Materials and process selection for engineering design* (2nd ed.). CRC Press, Taylor and Francis, ISBN 9-781-420-06308-0.
  *(A materials science approach to the selection of materials)*
- Dieter, G.E. (1999) *Engineering design, a materials and processing approach* (3rd ed.). McGraw-Hill, ISBN 9-780-073-66136-0.
  *(A well-balanced and respected text focusing on the place of materials and processing in technical design)*
- Charles, J.A., Crane, F.A.A., & Furness, J.A.G. (1997) *Selection and use of engineering materials* (3rd ed.), Butterworth-Heinemann, ISBN 0-7506-3277-1.
  *(A materials science rather than a design-led approach to the selection of materials)*

# literature

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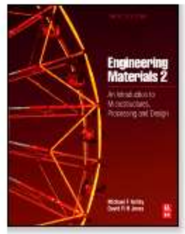
Butterworth-Heinemann Title
ISBN: 978-1-85617-663-7

**Materials Selection in Mechanical Design, 4th Edition**

By Michael F. Ashby

664 pages
Trim Size 7 1/2 X 9 1/4 in
Copyright 2011
USD 89.95, Softcover, Reference

**Available:** In Stock

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**Engineering Materials 2, 3rd Edition**

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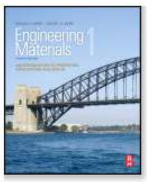


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**Engineering Materials 1, 4th Edition**

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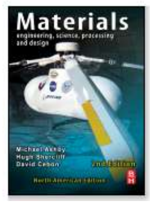


**Materials 2/e with Online Testing, 2nd Edition**

engineering, science, processing and design (with Elsevier Online Testing)
By Michael F. Ashby, Hugh Shercliff & David Cebon

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USD 125.00, Hardcover, Reference

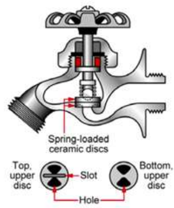
# exam simulation (planned)



## 2. Ceramic valves for taps.

Taps drip because the rubber washer is worn or the brass seat is pitted by corrosion, or both. Ceramics wear well, and they have excellent corrosion resistance in both pure and salt water. Many household taps now use ceramic valves.

The sketch shows how they work. A ceramic valve consists of two disks mounted one above the other, spring-loaded so that their faces are in contact. Each disk has a diameter of 20 mm, a thickness of 3 mm and weighs about 10 grams. In order to seal well, the mating surfaces of the two disks must be flat and smooth, requiring high levels of precision and surface finish; typically tolerance < 0.02 mm and surface roughness < 0.1 µm. The outer face of each has a slot that registers it, and allows the upper disc to be rotated through 90º (1/4 turn). In the “off” position the holes in the upper disc are blanked off by the solid part of the lower one; in the “on” position the holes are aligned. A production run of $10^5 – 10^6$ is envisaged.




2.1 Please list all functions and constraints:

**Function:** a) ........................................

**Constraints:** b) ........................................
c) ........................................
d) ........................................
e) ........................................
f) ........................................
g) ........................................
h) ........................................

**Free variables:** ........................................



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE Exercise “Typical exam questions”, “Material Selection’ Name: ..................... Prename: .....................

2.2 Write down the typical evaluation steps and comment them.

........................................

2.3 Please find appropriate production processes of such valves under the constraints mentioned above? (see Appendix):

........................................

Comments: ........................................

# exam simulation (planned)



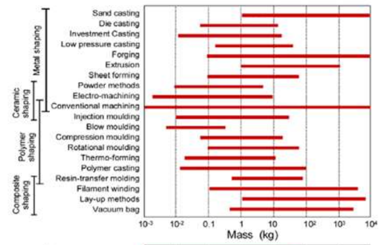
**Table 2: Process – Shape Matrix**

| Group | Process | Circular prismatic | Non-circular prismatic | Flat sheet | Dished sheet | 3-D solid | 3-D hollow |
|---|---|---|---|---|---|---|---|
| Metal shaping | Sand casting | ☑ | ☑ | | | ☑ | ☑ |
| Metal shaping | Die casting | ☑ | ☑ | | | ☑ | ☑ |
| Metal shaping | Low pressure casting | ☑ | ☑ | | | ☑ | ☑ |
| Metal shaping | Forging | ☑ | ☑ | | | ☑ | |
| Metal shaping | Extrusion | ☑ | ☑ | | | | |
| Metal shaping | Sheet forming | ☑ | ☑ | ☑ | ☑ | | |
| Metal shaping / Ceramic shaping | Powder methods | ☑ | ☑ | | | ☑ | |
| Metal shaping / Ceramic shaping | Electro-machining | ☑ | ☑ | ☑ | | ☑ | |
| Metal shaping / Ceramic shaping | Conventional machining | ☑ | ☑ | ☑ | ☑ | ☑ | |
| Polymer shaping | Injection molding | ☑ | ☑ | | | ☑ | |
| Polymer shaping | Blow molding | | | | ☑ | | |
| Polymer shaping | Compression molding | | | ☑ | ☑ | ☑ | |
| Polymer shaping | Rotational molding | | | | ☑ | | |
| Polymer shaping | Thermo-forming | | | | ☑ | | |
| Polymer shaping | Polymer casting | ☑ | ☑ | | | ☑ | |
| Polymer shaping / Composite shaping | Resin-transfer molding | ☑ | ☑ | ☑ | ☑ | ☑ | |
| Composite shaping | Filament winding | ☑ | ☑ | | ☑ | | |
| Composite shaping | Lay-up methods | | | ☑ | ☑ | ☑ | |
| Composite shaping | Vacuum bag | | | ☑ | ☑ | | |



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE Exercise “Typical exam questions”, “Material Selection’ Name: ..................... Prename: .....................

**Table 3: Process – Mass Range Matrix:**



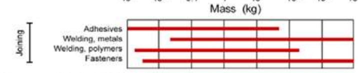
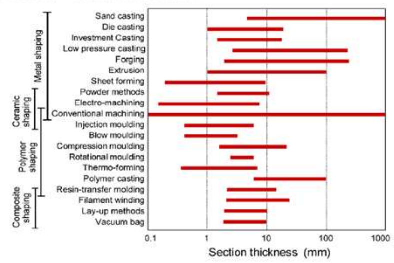




**Table 4: Process – Section Thickness Matrix:**



# One Course / Two Lecturers

## Prof. Dr. Johann Michler:

**Education:**

1999 **Ph.D.** thesis at the Department of Materials Science, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland

1995 **Dipl.-Ing.** (Engineering Diploma), in **Materials Science** at the Technical University of Erlangen-Nürnberg, Germany

**Positions:**

since 2007 Head of „Laboratory for Mechanics of Materials and Nanostructures " at Empa, Thun

## Dr. Sébastien Vaucher:

**Education:**

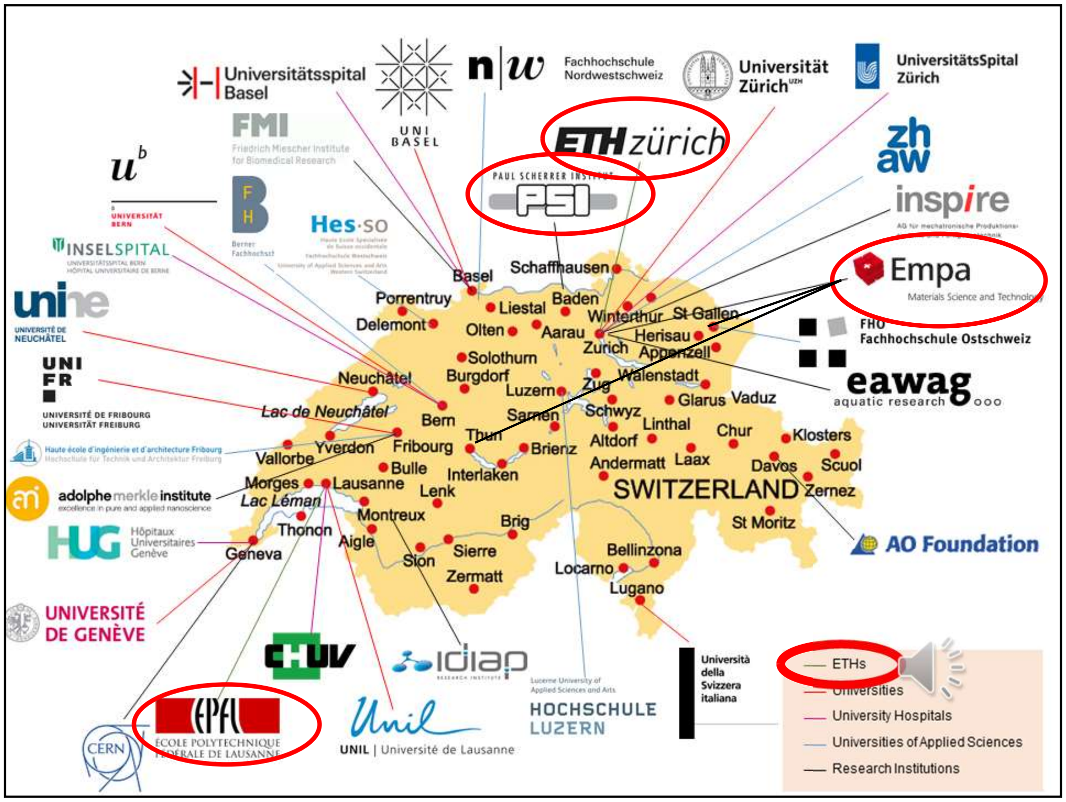
1998 **Ph.D.** thesis at the University of Neuchâtel,

1993 **Diploma** in chemistry at the University of Neuchâtel,

**Positions:**

2001-2021: Member of the Advanced Non-Organic Composites Group at EMPA, Thun developing in-situ analytical tools to explore the effect of microwave field on powdered complex inorganic materials.


WELCOME
Prof. Dr Johann Michler
Empa, Materials Science and Technology, Thun, Switzerland
G
A
F
Zürich
Bern
Interlaken
Thun
I


Universitätsspital Basel
UNI BASEL
FMI Friedrich Miescher Institute for Biomedical Research
n|w Fachhochschule Nordwestschweiz
Universität Zürich
UniversitätsSpital Zürich
ETH zürich
PAUL SCHERRER INSTITUT PSI
zh aw
inspire
Empa Materials Science and Technology
FHO Fachhochschule Ostschweiz
eawag aquatic research
u b UNIVERSITÄT BERN
Berner Fachhochschule
Hes·so
INSELSPITAL
unine UNIVERSITÉ DE NEUCHÂTEL
UNI FR UNIVERSITÉ DE FRIBOURG UNIVERSITÄT FREIBURG
Haute école d'ingénierie et d'architecture Fribourg Hochschule für Technik und Architektur Freiburg
adolphe merkle institute excellence in pure and applied nanoscience
HUG Hôpitaux Universitaires Genève
UNIVERSITÉ DE GENÈVE
CHUV
idiap
Unil UNIL | Université de Lausanne
HOCHSCHULE LUZERN
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Aarau
Winterthur
St Gallen
Zurich
Herisau
Appenzell
Solothurn
Burgdorf
Zug
Walenstadt
Neuchâtel
Luzern
Glarus
Vaduz
Lac de Neuchâtel
Bern
Sarnen
Schwyz
Linthal
Chur
Klosters
Thun
Altdorf
Vallorbe
Yverdon
Fribourg
Brienz
Andermatt
Laax
Davos
Scuol
Bulle
Interlaken
Morges
Lausanne
Lenk
Zernez
Lac Léman
Montreux
Brig
St Moritz
Thonon
Aigle
Geneva
Sion
Sierre
Bellinzona
Zermatt
Locarno
Lugano
ETHs
Universities
University Hospitals
Universities of Applied Sciences
Research Institutions

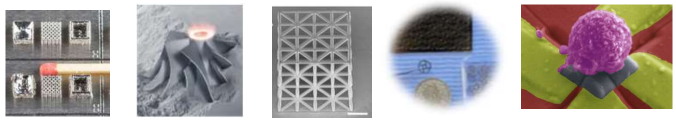
# Empa Sites

Dübendorf
St. Gallen
Zürich
Bern
Chur
Lausanne
Thun
Bellinzona

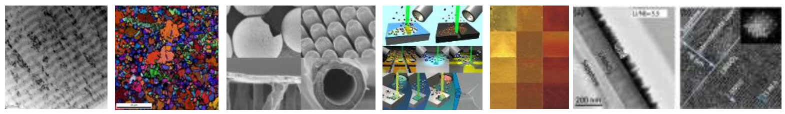
# Advanced Manufacturing@ EMPA in Thun

Empa
Materials Science and Technology

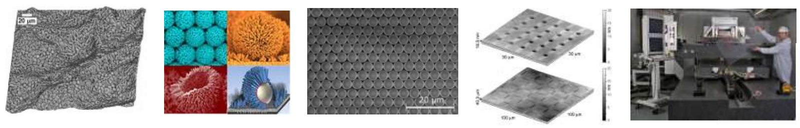
Additive manufacturing & Microfabrication: SLM, EBM, 2PP, UV-LIGA, FEBID



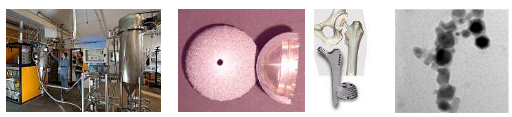
Thin films and coatings: Electroplating, PVD, ALD & CVD

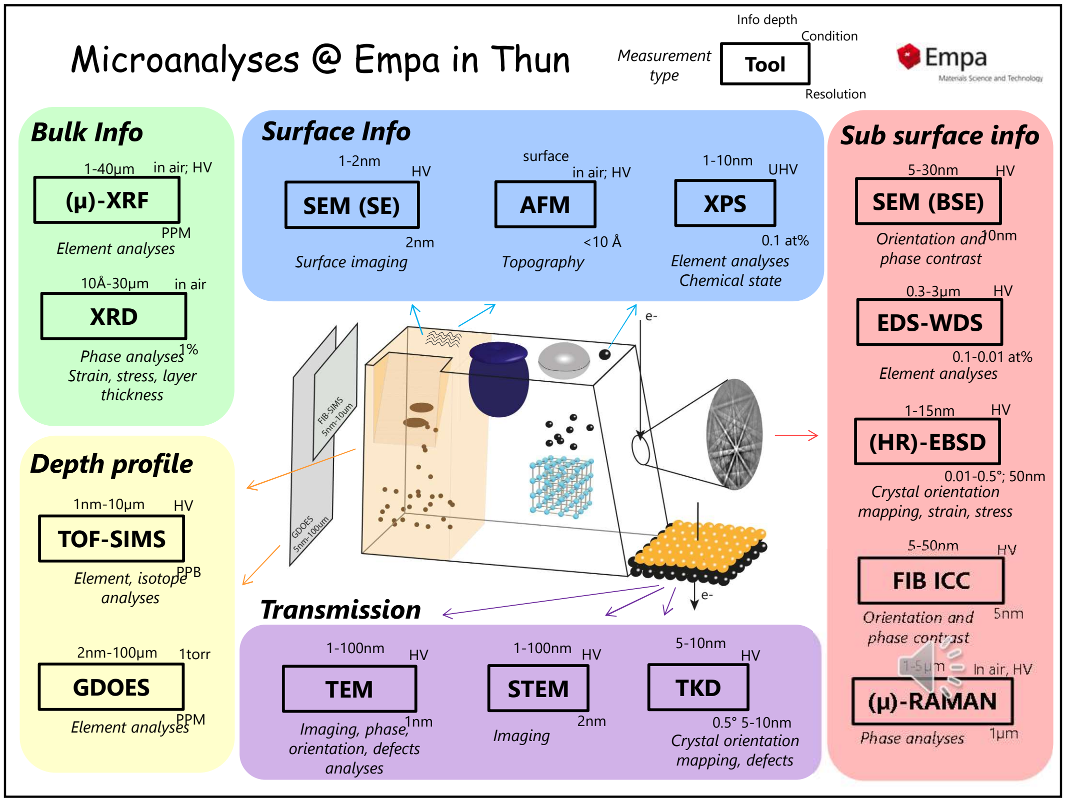


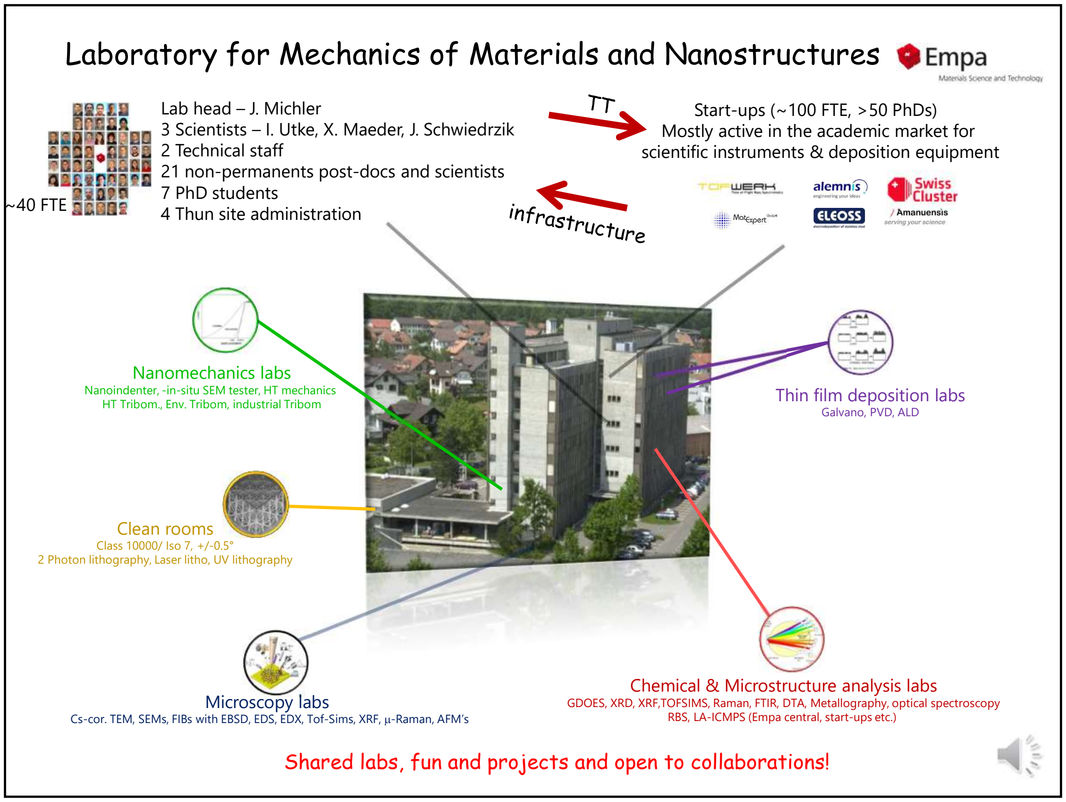
Surface pattering (Laser, UV, electron & ion beams)



Materials Technology (Composites, Nanopowder)

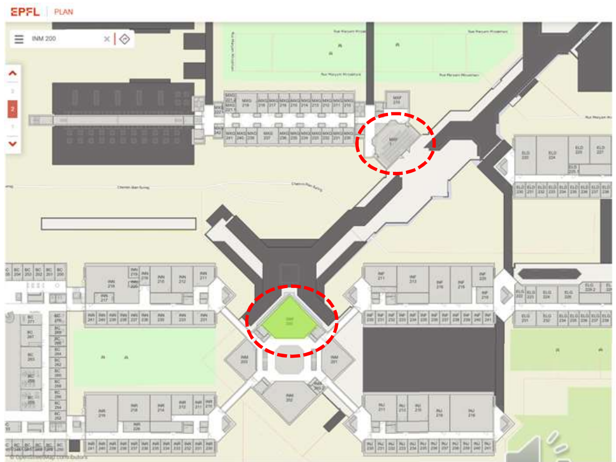



Microanalyses @ Empa in Thun
Info depth
Condition
Measurement type
Tool
Resolution
Empa
Materials Science and Technology
Bulk Info
1-40µm in air; HV
(µ)-XRF
PPM
Element analyses
10Å-30µm in air
XRD
1%
Phase analyses
Strain, stress, layer thickness
Depth profile
1nm-10µm HV
TOF-SIMS
PPB
Element, isotope analyses
2nm-100µm 1torr
GDOES
PPM
Element analyses
Surface Info
1-2nm HV
SEM (SE)
2nm
Surface imaging
surface in air; HV
AFM
<10 Å
Topography
1-10nm UHV
XPS
0.1 at%
Element analyses
Chemical state
FIB-SIMS 5nm-10um
GDOES 5nm-100um
e-
e-
Transmission
1-100nm HV
TEM
1nm
Imaging, phase, orientation, defects analyses
1-100nm HV
STEM
2nm
Imaging
5-10nm HV
TKD
0.5° 5-10nm
Crystal orientation mapping, defects
Sub surface info
5-30nm HV
SEM (BSE)
10nm
Orientation and phase contrast
0.3-3µm HV
EDS-WDS
0.1-0.01 at%
Element analyses
1-15nm HV
(HR)-EBSD
0.01-0.5°; 50nm
Crystal orientation mapping, strain, stress
5-50nm HV
FIB ICC
5nm
Orientation and phase contrast
1-5µm In air, HV
(µ)-RAMAN
1µm
Phase analyses


Laboratory for Mechanics of Materials and Nanostructures
Empa
Materials Science and Technology
~40 FTE
Lab head – J. Michler
3 Scientists – I. Utke, X. Maeder, J. Schwiedrzik
2 Technical staff
21 non-permanents post-docs and scientists
7 PhD students
4 Thun site administration
TT
infrastructure
Start-ups (~100 FTE, >50 PhDs)
Mostly active in the academic market for
scientific instruments & deposition equipment
TOFWERK
alemnis
Swiss Cluster
Amanuensis
ELEOSS
Nanomechanics labs
Nanoindenter, -in-situ SEM tester, HT mechanics
HT Tribom., Env. Tribom, industrial Tribom
Thin film deposition labs
Galvano, PVD, ALD
Clean rooms
Class 10000/ Iso 7, +/-0.5°
2 Photon lithography, Laser litho, UV lithography
Microscopy labs
Cs-cor. TEM, SEMs, FIBs with EBSD, EDS, EDX, Tof-Sims, XRF, µ-Raman, AFM's
Chemical & Microstructure analysis labs
GDOES, XRD, XRF,TOFSIMS, Raman, FTIR, DTA, Metallography, optical spectroscopy
RBS, LA-ICMPS (Empa central, start-ups etc.)
Shared labs, fun and projects and open to collaborations!

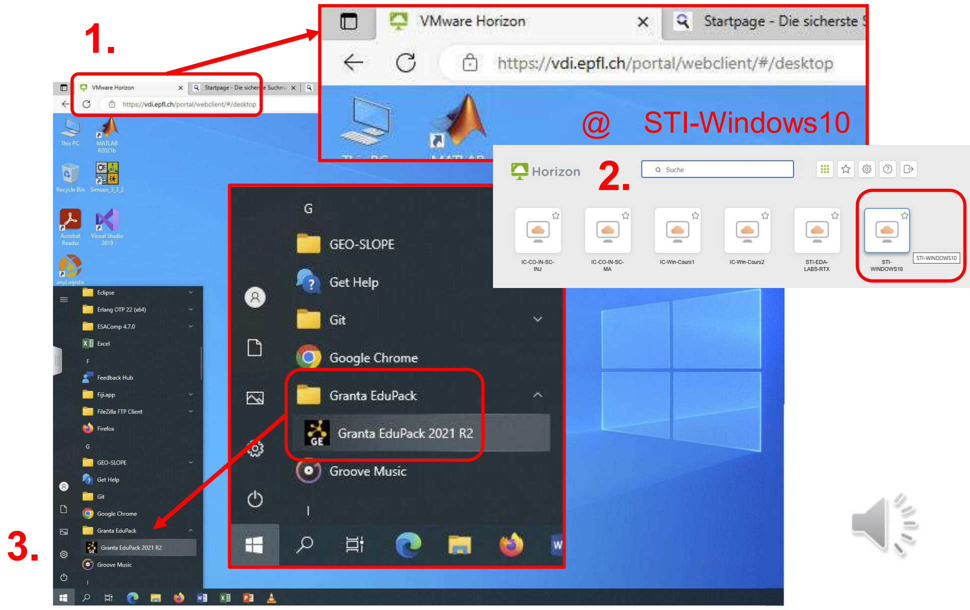
# Documentation

INM200,    MXF014



and/or on your own computer via virtual infra !

# How to access the software



# Time Schedule: 2025

- Lectures every 2nd week:
- 4 Hour courses (including exercises)
  from $9^{15}$ am to 1 pm.
- Final written exam: 2 hours

# Time & Content Schedule

| Lecture Day | Titles | Responsible |
|---|---|---|
| 1 | Introduction to topic, The design process, How to use the software “EduPack Granta/Ansys” | Michler |
| 2. | Material properties and charts, Selection Strategies, Materials Indices | Michler |
| 3. | How to select materials,;<br>Solving multiple constraints/objectives, Economics, Environmental concerns, Coselection of shape | Michler |
| 4. | Process selection, Materials Processing of Ceramics, Metals, Polymers, Hybrids, Surface and coating processes | Michler |
| 5. | Designing of hybrid materials | Vaucher |
| 6. | Material Selection applied to Musical Instruments<br>Tasks/exercises for all students (group work) | Vaucher |
| 7. | Exercise of examination examples | All |

# table of content

# A closer look at Materials Property Charts

How to read them, how to use them,
Guide lines, Selection lines
Slope of selection lines
Materials Index, Shape, …

Copyright: Most slides in this course are based on slides from:

Ashby, EduPack 2008, Granta Design
Caceres, Edupack supporting lectures 2008,Granta Design

or adapted from:

Materials Selection in Mechanical Design, Third Edition, 2005, by Michael F. Ashby, Butterworth-Heinemann

Materials: Engineering, Science, Processing and Design, 2007 by Michael F. Ashby, Hugh Shercliff, David Cebon, Butterworth-Heinemann

# Material properties: modulus

Definition:
Young's modulus,
shear modulus,
bulk modulus

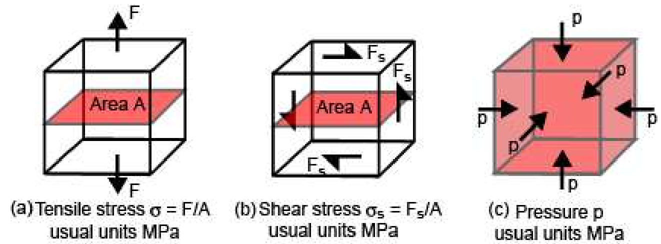



*Figure 2. (a) Tensile stress,. (b) Shear stress. (c) Hydrostatic pressure*

Range:
0.1 MPa (foams) to 1000GPa (diamond)

Origin:

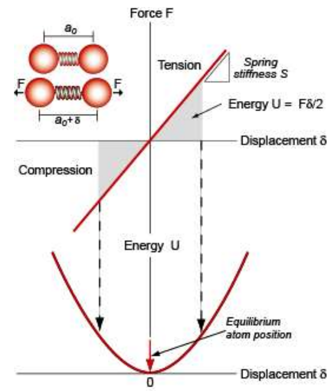



*Figure 3. Stretching or compressing an atomic bond raises its energy. Its resistance to stretch is its stiffness, S.*

| Bond type | Examples | Bond Stiffness S (N/m) | Young's Modulus E (GPa) |
|---|---|---|---|
| Covalent | Carbon-carbon bond | 50 – 180 | 200 – 1000 |
| Metallic | All metals | 15 – 75 | 60 – 300 |
| Ionic | NaCl | 8 – 24 | 32 – 96 |
| Hydrogen bond | Polyethylene | 6 – 3 | 2 – 12 |
| Van der Waals | Waxes | 0.5 - 1 | 1 - 4 |

Importance:
deflections, energy absorption, elastic instability

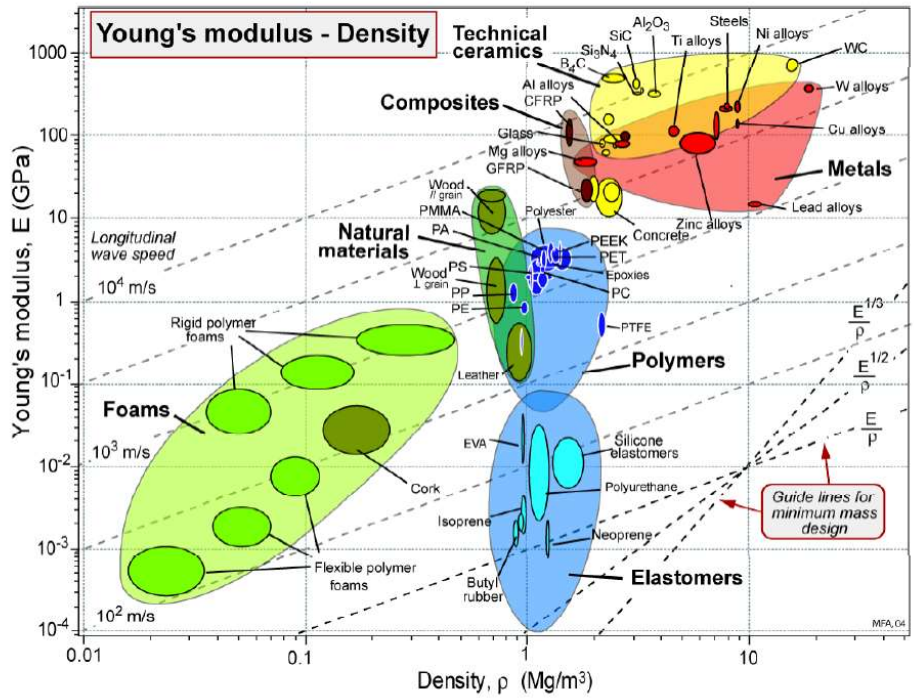
# Material properties: modulus

**Why the differences?**

- ***Atom size and weight***
- ***Spring constant for various bond types***

**Manipulating properties**

- ***Making composites***
- ***Making foams***

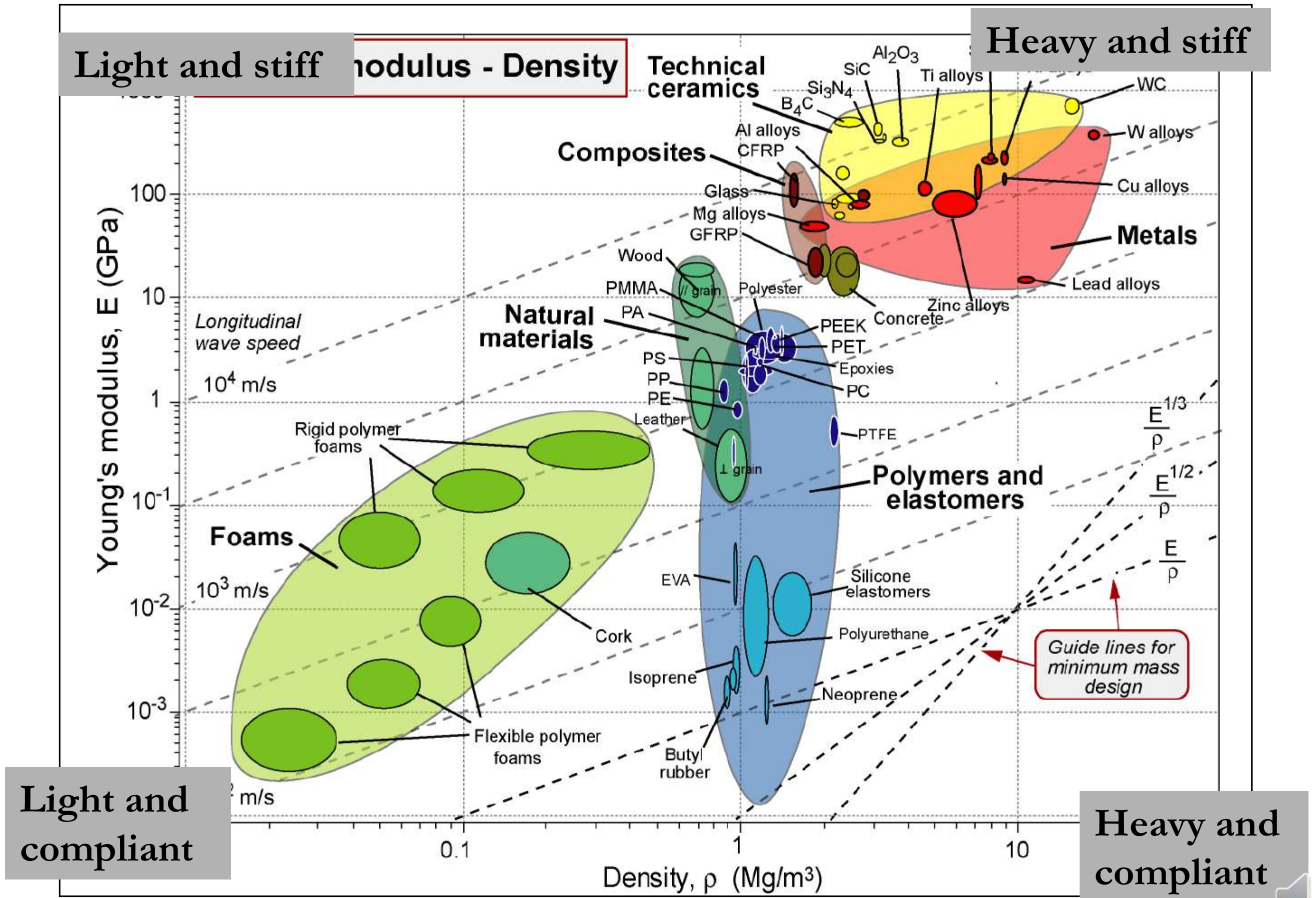


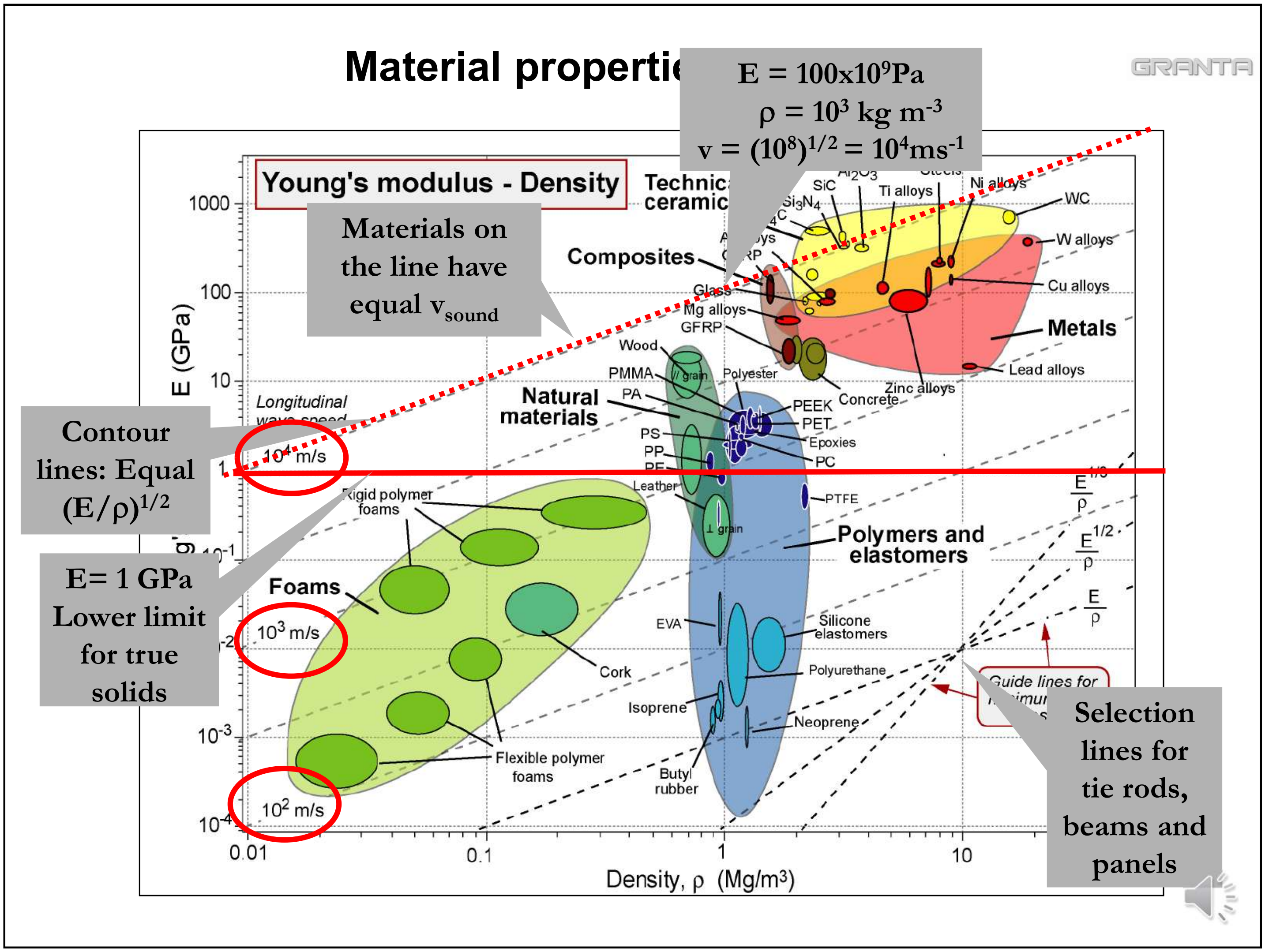

This chart guides selection of materials for light, stiff, components. The moduli of engineering materials span a range of $10^7$; the densities span a range of 3000. The contours show the longitudinal wave speed in m/s; natural vibration frequencies are proportional to this quantity. The guide lines show the loci of points for which

- $E/\rho = C$ (minimum weight design of stiff ties; minimum deflection in centrifugal loading, etc)
- $E^{1/2}/\rho = C$ (minimum weight design of stiff beams, shafts and columns)
- $E^{1/3}/\rho = C$ (minimum weight design of stiff plates)

The value of the constant C increases as the lines are displaced upwards and to the left; materials offering the greatest stiffness-to-weight ratio lie towards the upper left hand corner.

# Material properties: modulus

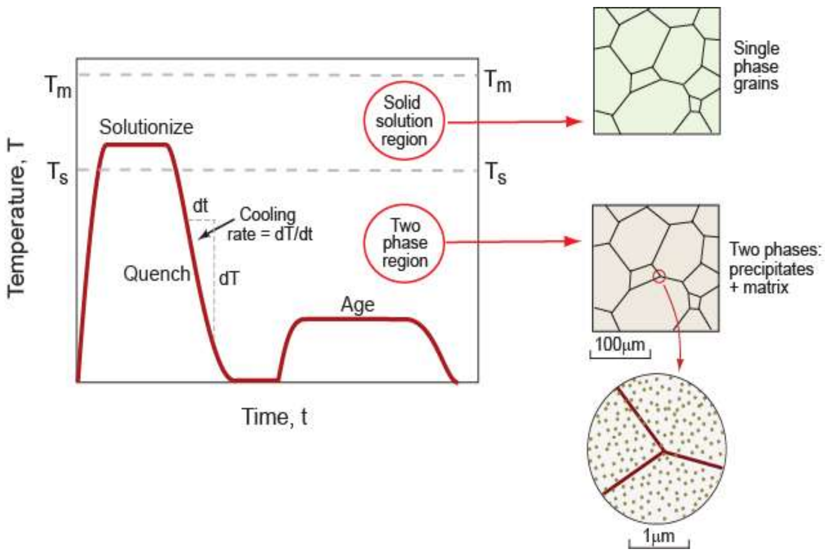



Material properti
GRANTA
E = 100x10^9Pa
ρ = 10^3 kg m^-3
v = (10^8)^1/2 = 10^4ms^-1
Young's modulus - Density
Materials on the line have equal v_sound
Contour lines: Equal (E/ρ)^1/2
E= 1 GPa Lower limit for true solids
Selection lines for tie rods, beams and panels
Composites
Metals
Natural materials
Foams
Polymers and elastomers
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
Density, ρ (Mg/m3)
E (GPa)
Guide lines for

## Property control by chemistry and microstructure

GRANTA

*Metals:* Precipitation hardening




*Examples:*

*Heat-treatable Al alloys*
(age hardening)

*Carbon & alloy steels*
(quench and temper)

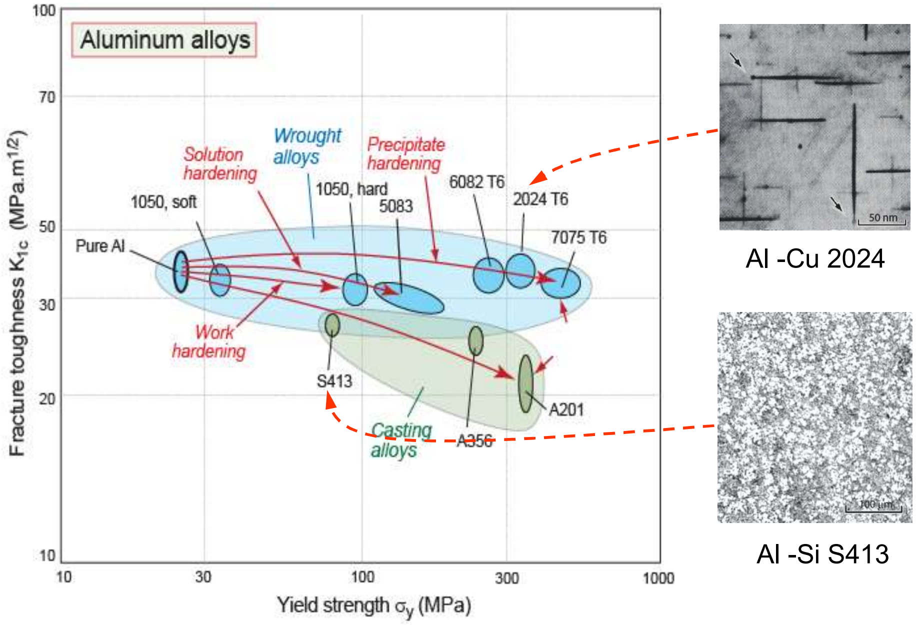
**Precipitation hardening** is most effective when fine-scale second phase particles are dispersed throughout every grain. – this microstructure is achieved by **heat treatment.** The science behind the evolution of precipitates requires a basic understanding of *phase diagrams* and *phase transformations* – taking alloying elements into solution, quenching to avoid the formation of coarse two-phase distributions, with controlled low temperature, solid-state transformation of fine-scale precipitates.

Two prominent examples are: age hardening of Al alloys, quenching/tempering of steels.

Property charts again offer a neat graphical illustration of the consequences of these heat treatments.

## Control by chemistry and microstructure

Aluminum alloys: precipitation, solution and work hardening




A common trade-off in processing for higher yield strength is the consequential evolution of **fracture toughness**, the resistance to crack propagation – hence charts showing this pairing are of interest.

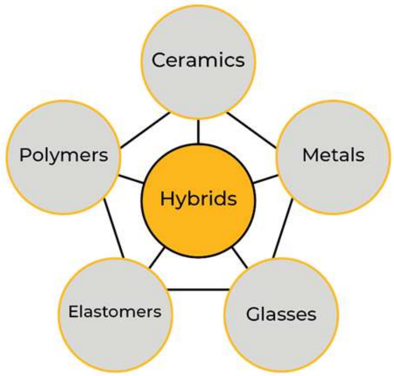
The figure shows the composition and process trajectories for commercial Al alloys.

For **wrought alloys** the chart illustrates that the hardening mechanisms all increase strength with minimal impact on fracture toughness. The relative effectiveness of the different mechanisms is apparent – the strongest are the age hardened aerospace alloys.

We can then annotate the figures with typical micrographs – here a TEM image of the needle shaped precipitates in 2024 alloy (noting the nm length scale).

The figure also shows data for **casting alloys –** alloying + heat treatment again raises strength, but with a corresponding decrease in toughness. This can be correlated with the coarser microstructure formed on casting (2$^{nd}$ micrograph), and the presence of brittle second phases such as Si in casting alloys. (By zooming in, we could easily illustrate the effectiveness of chemical additions to modify the Si for greater toughness, as in Na-modified Al-Si casting alloys).

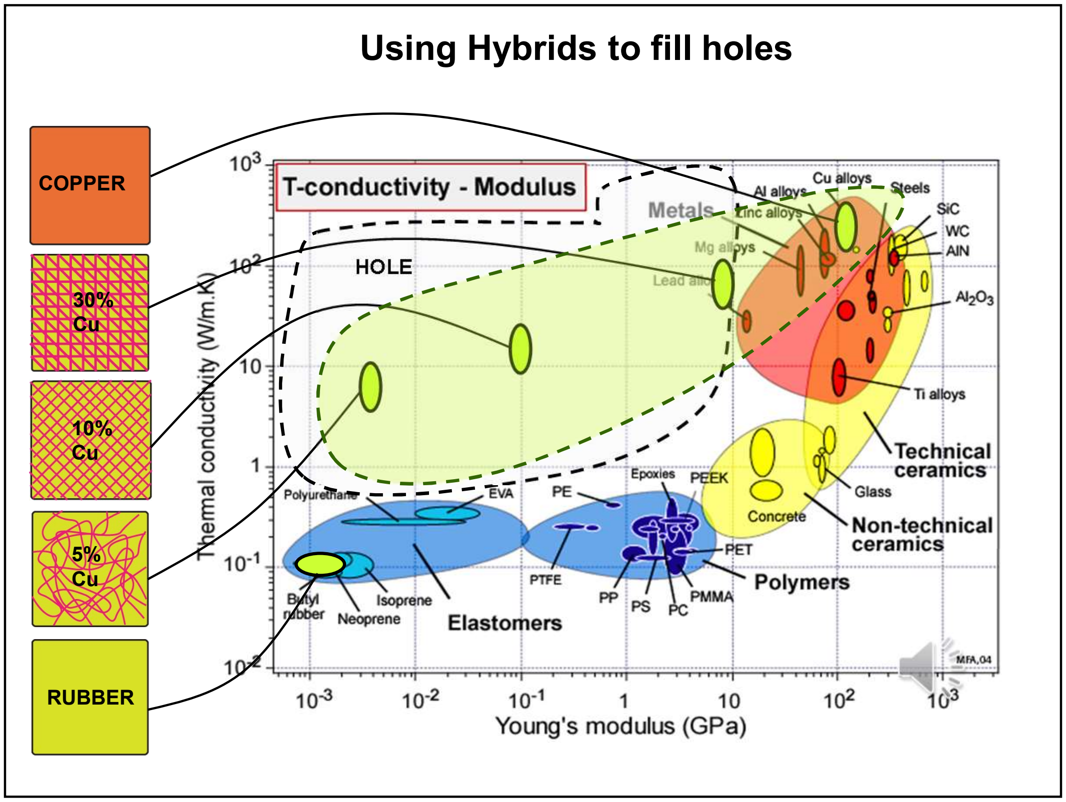
## control by hybridisation – making hybrid/composite materials




**Design variables:**
- Choice of materials
- Volume fractions
- Configuration
- Connectivity
- Scale

***Hybrids***

This image summarizes the families of materials, with examples, that make up hybrids: Metals Polymers, Elastomers, Ceramics and Glasses. A number of design variables will determine the properties of the resulting hybrid material. Mainly composition, microstructural parameters and architecture.




***The Design-driven approach***

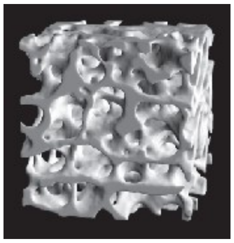
Here is an example of a section with an enormous hole. How could materials be created to fill it? The traditional routes of materials science are not much help: alloy development cannot lower Young's modulus of metallic conductors much below 10 GPa; and making new polymer compositions or blends cannot increase the thermal conductivity above about 1 W/m.K.

The answer is to make **hybrids**: mixtures of two materials in a configuration and relative fraction that gives both low modulus and high conductivity.

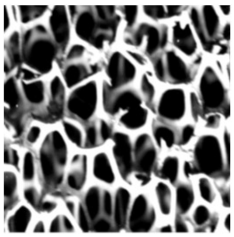
## Control of modulus by architecture

GRANTA

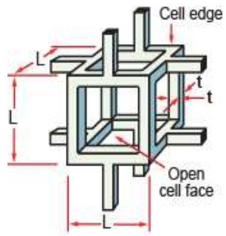
*Foams:* "solid – air hybrids"

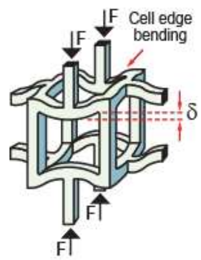


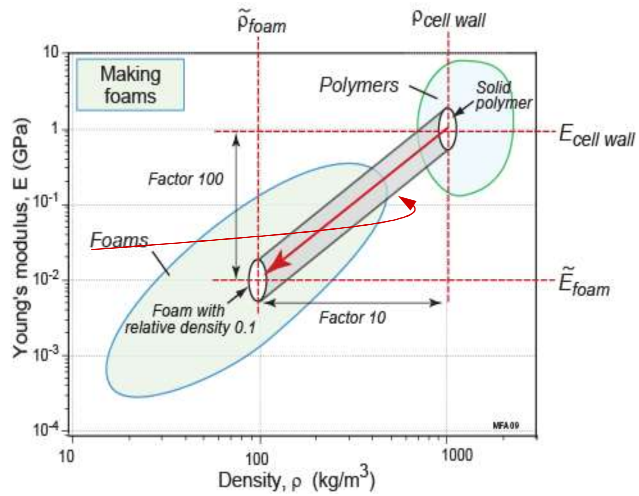
Ceramic foam



Metal foam




$$\frac{\tilde{E}_{foam}}{E_{solid}} = \left(\frac{\tilde{\rho}_{foam}}{\rho_{solid}}\right)^2$$

Modulus and density are also manipulated by **architecture** – by making *hybrids* of more than one bulk material.

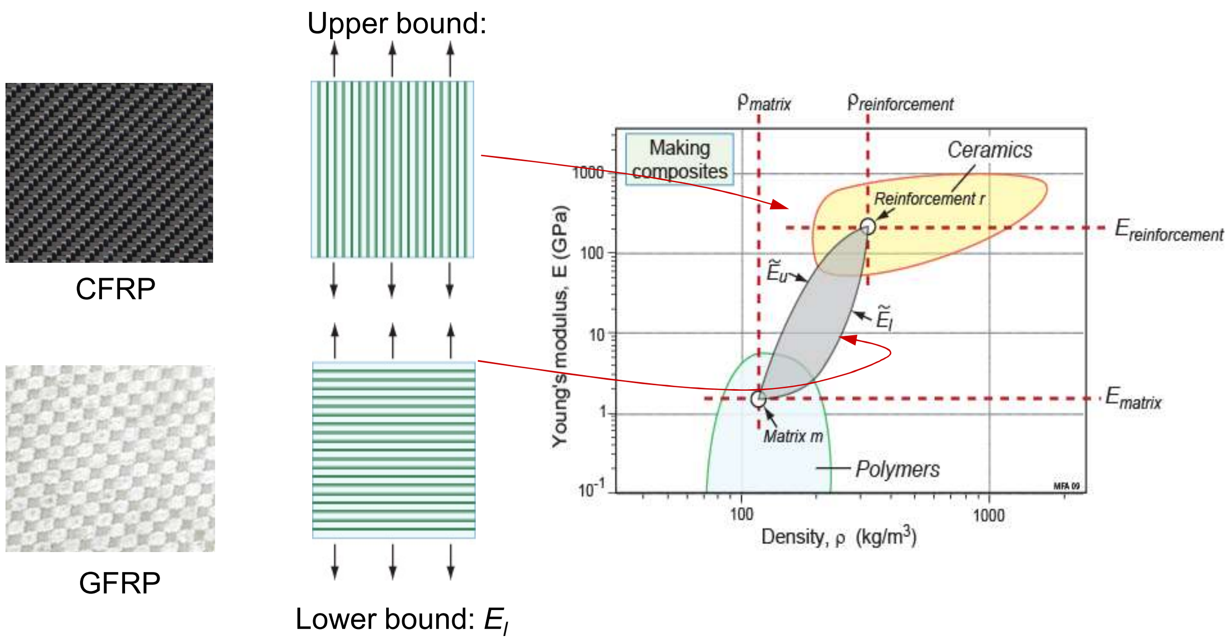
The first example is **foams** – porous solids, or a hybrid of solid and air.

The density is easily explained – the air is effectively weightless, so the *relative density* (the proportion of the foam that is solid) determines the density of the foam, given the density of the slid in the foam.

Interpreting the modulus requires some simple solid mechanics. In many foams, the overall displacement imposed is accommodated internally by *bending* the solid edges of the cells. This leads to simple scaling laws, suggesting for example that a foam which is 10% solid will have a modulus 100$^{th}$ that of the solid in the cell walls. Here is an example of a "trajectory" on a property chart – foaming a solid moves the resulting properties downwards to the left on a characteristic slope (of 2, for the model illustrated).

## Control of modulus by architecture

*Composites:* "solid – solid hybrids"

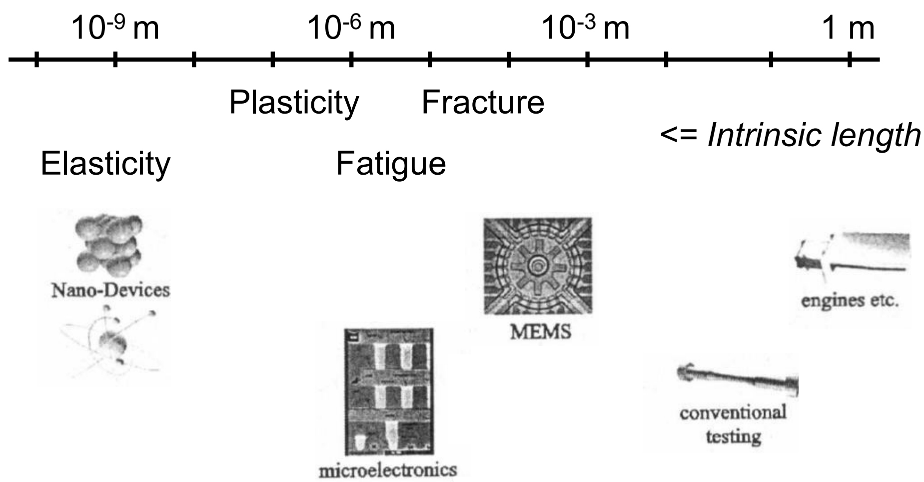



The second example is **composites** – hybrids of two solids.

Density is again straightforward – mixing two fractions of different density materials leads to a composite denisty given by a linear rule of mixtures.

Simple stress-strain analysis produces two familiar *bounds* for the modulus – upper and lower limits on the property, between which the actual value must fall. These bounds can also be interpreted graphically as a "lozenge" of property space between the bulk values for the two constituents.

## Control by size effects

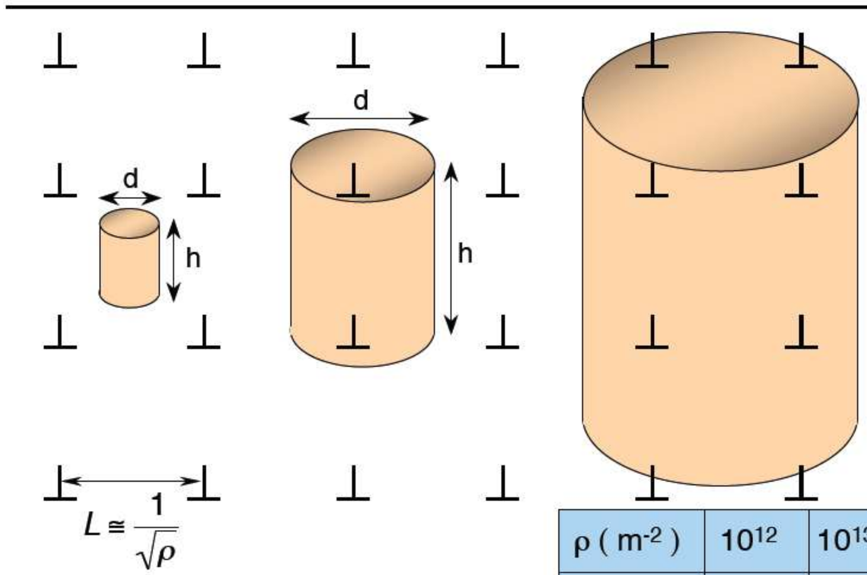



Object dimensions < intrinsic length scale => mechanical properties differ from the macroscale

O. Kraft, C. Volkert (2001) Adv. Eng. Mater. 3, 99

The material properties of thin films and small structures, with typical dimensions in the range of microns or below, can not simply be extrapolated from the properties of bulk samples. This is due to two major effects: First, samples used for bulk mechanical testing usually have dimensions which are much larger than the microstructural features, such as grains or particles, whereas in thin films the geometrical and micro- structural dimensions are typically on the same order of magnitude. Second, mechanical behavior is controlled by certain fundamental length scales. A few examples for length scale effects on mechanical properties are illustrated in the figure. Elastic properties are determined by the atomic bonds, with lengths in the range of 0.1nm. Plasticity in metals involves the motion of dislocations, which are hindered when they try to pass between obstacles more closely spaced than about 100 nm. During fatigue in metals, complicated dislocations structures are formed, with typical dimensions of a few micrometers. And in brittle materials, fracture is initiated at defects with a critical size of several tens of micrometers. As a result, it is expected that the mechanical properties of a material will fundamentally change as the sample dimensions become smaller than these various intrinsic lengths.

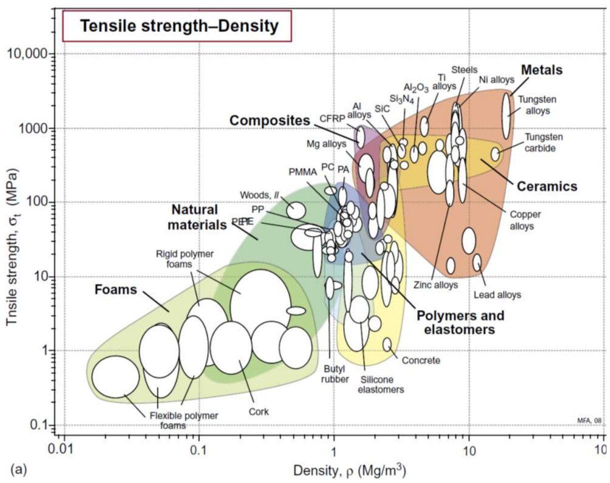
## Control by size effects

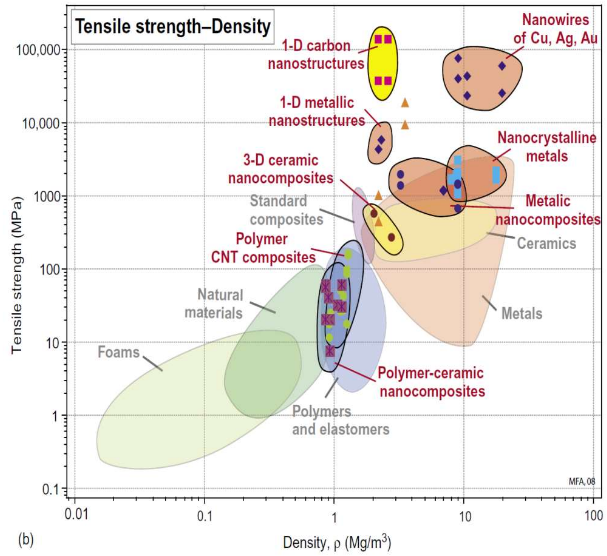



| $\rho$ ($m^{-2}$) | $10^{12}$ | $10^{13}$ | $10^{14}$ |
|---|---|---|---|
| $L$ ($\mu m$) | 1.0 | 0.3 | 0.1 |

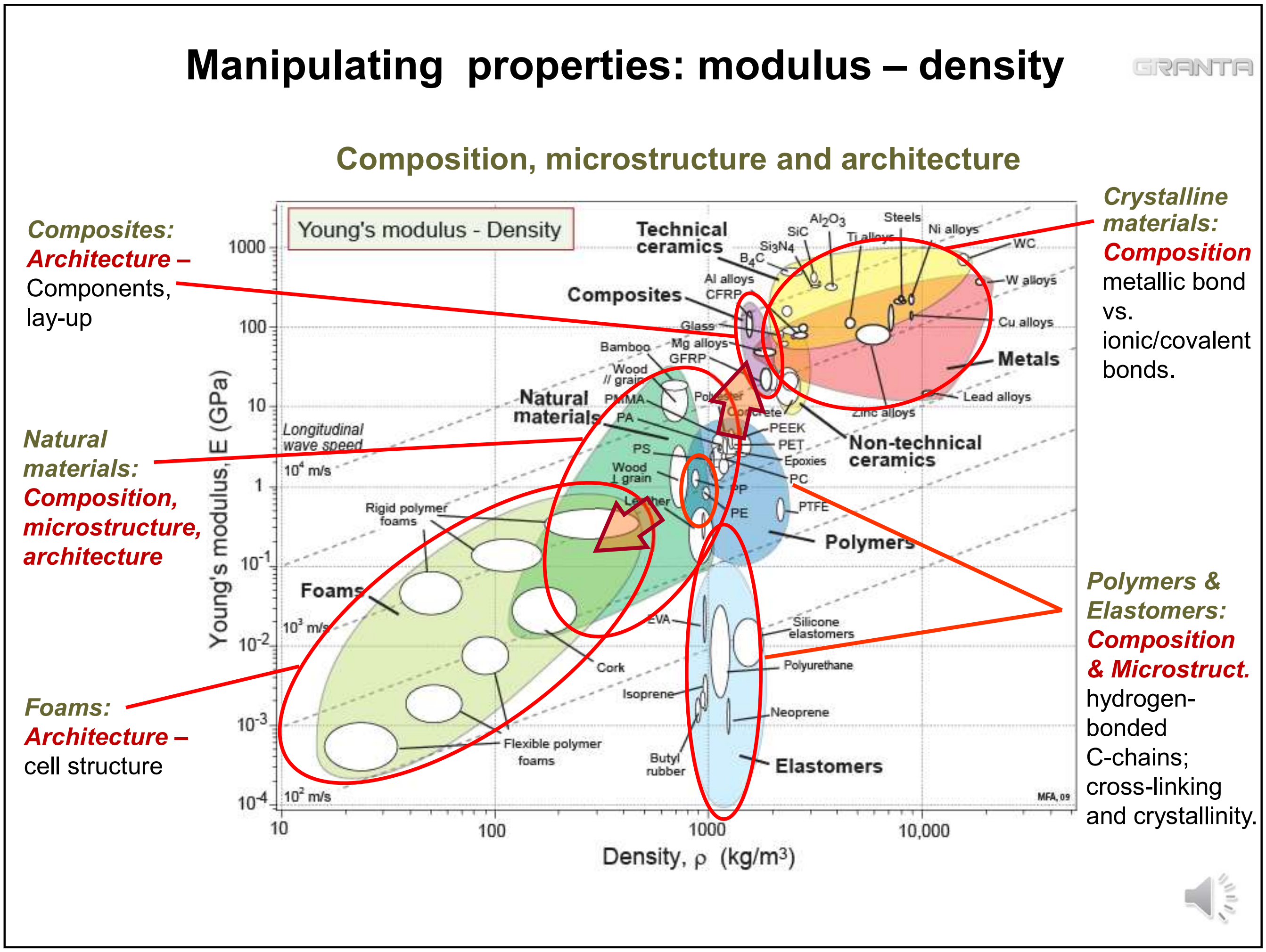
In this example we consider a micron-sized cylindrical sample with different sizes. Dislocations are carriers of plastic deformation in crystals. Depending on synthesis and processing conditions dislocations appear with different dislocation densities. Dislocation densities can be converted into an average dislocation interdistance. Is the sample large compared to the dislocation interdistance then the sample will exhibit mechanical properties similar to a bulk sample as dislocations can interact and multiply in a similar fashion during deformation. If the sample is very small then no dioslocation is contained in the sample and during deformation dislocations need to be nucleated which requires stresses approaching the theoretical strength. At intermediate sizes the mechanical properties vary depending on the exact dislocation configuration that varies from sample to sample.

## Control by size effects




At small length scales such as sub-100nm size in metals the tensile approaches the theoretical limit of E/10, means a tenth of the Young's modulus




***What controls the differences?***

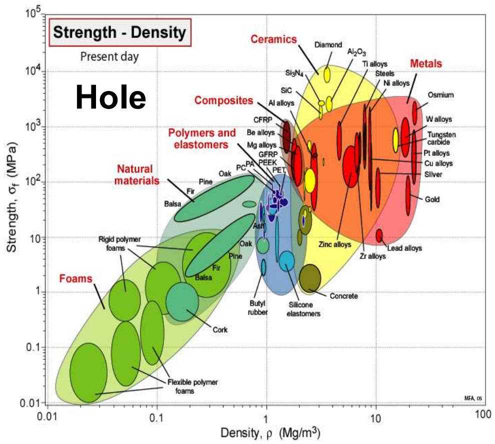
Returning to the chart, we find **composites** falling between the polymers (matrix) and ceramics (glass and carbon fibres). And polymer **foams** fall below and to the left of the solids of which they are made. Finally, note the position of **natural materials**, governed by a bit of everything: complex polymers, with both cellular and fibrous architectures.

Designers might just take all this as "given data". But by "drilling down" into the origin of the properties, we not only understand the physical world around us, but can turn the problem around and ask how we engineers and scientists can manipulate properties. For modulus and density, composition largely dictates the outcome – only architecture enables completely new combinations of properties to be developed.

The potential for innovation afforded by making composite materials (and other "hybrid" combinations of materials, such as sandwich panels") is a good motivator for students – expensive composites often emerging from high performance applications (e.g. sports goods).

## Case study: Control by architecture and size effects

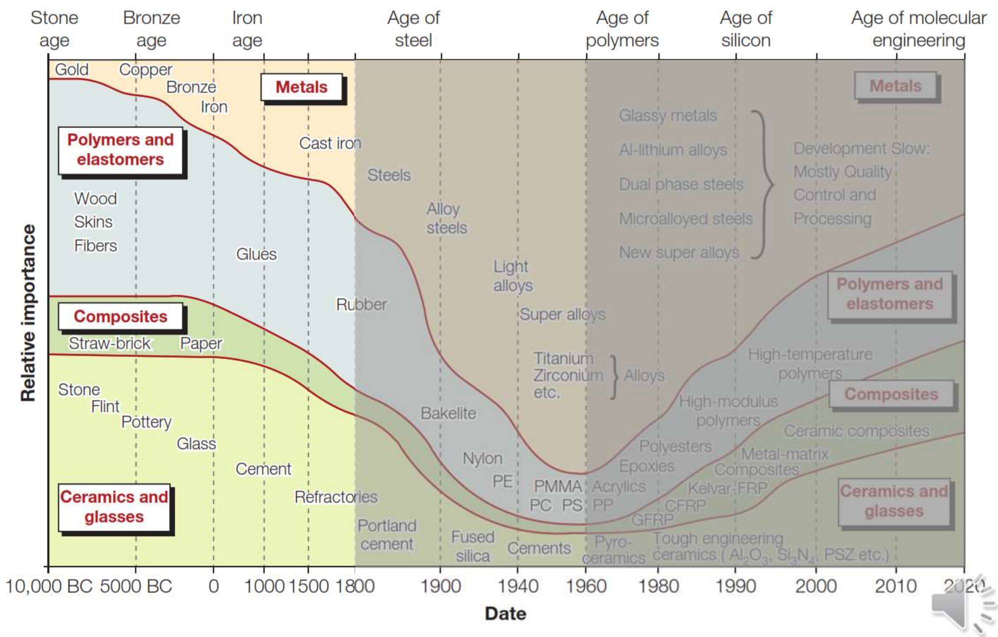
GRANTA



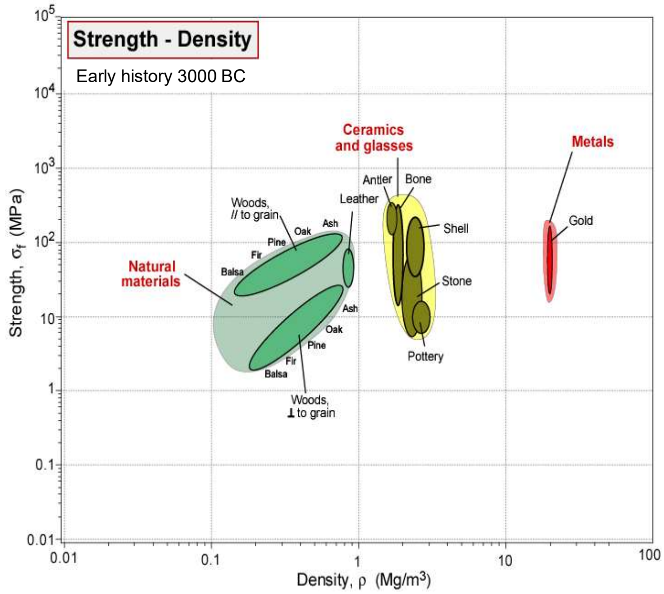

- History of structural materials
- Holes in material property space
- architecture design
- size effects & architecture

We'll look into a research topic related to microlattices to fill white spaces in the property maps. We'll combine architecture with a mechanical size effect.

# History of Materials in Relation to Importance



## Case study: Control by architecture and size effects

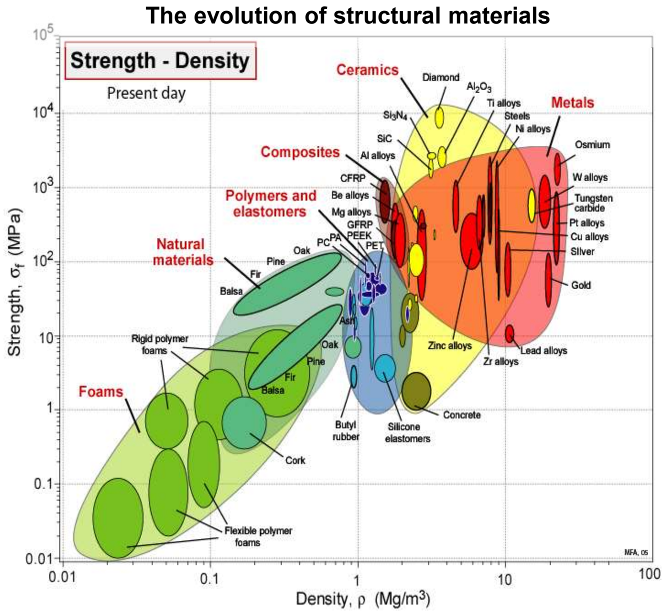



Egyptian Pyramids

It is worth looking back to see the way in which the filled parts of material property space have expanded over time. We take the $\sigma_y$ – $\rho$ section as an example.

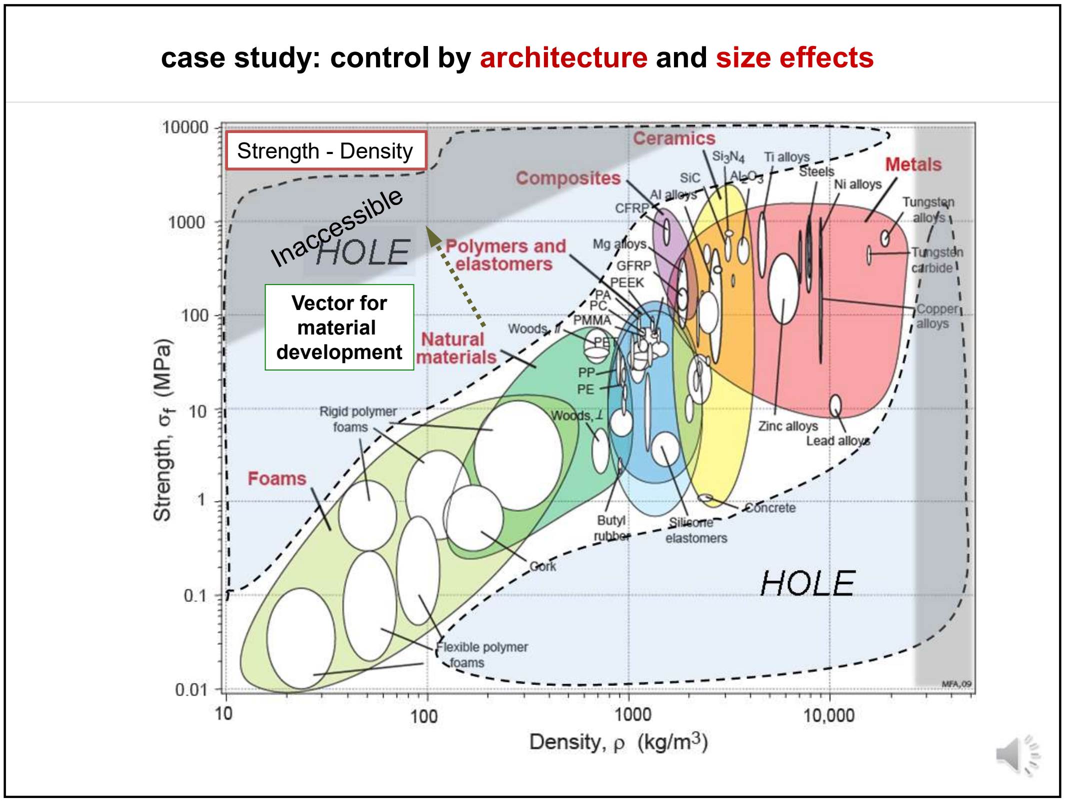
The materials of pre-history cover only a tiny fraction of this strength-density space.

**case study: control by architecture and size effects**




21st Century

By the time of the peak of the Roman empire, around 50 BC (b), the area occupied by metals has expanded considerably, giving Rome critical advantages in weaponry and defence. The progress thereafter was slow: 1500 years later not much has changed, although, significantly, cast iron now appears. Even 500 years after that expansion of the occupied area of the chart is small; aluminium only just creeps in. Then things accelerate. By 1945 the metals envelope has expanded considerably and a new envelope – that of synthetic polymers – now occupies a significant position. Between then and the present day the expansion has been dramatic. Much of the space is now filled and the filled area starts to approach fundamental limits (not shown here) beyond which it is not possible to go.



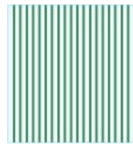

Holes in material property space

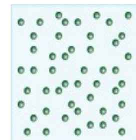
- The strength-density chart, for example, has unfilled areas – holes.
- If materials could be devised that lay in the hole in the upper left, it would allow lighter, stronger structures to be built.
- Is it possible, at least in principle, to fill them? What, in other words, are the ultimate limits?
- It is possible to assign approximate values to these., based on what is known of the strength of interatomic bonds and the atomic mass and volume of atoms, shown as inaccessible on the figure.
- Thus some unfilled parts of the Strength-Density space are accessible, others are not. The figure suggests that there remain some unfilled regions of this section that, in principle, could be filled.

## case study: control by architecture and size effects

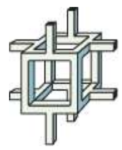
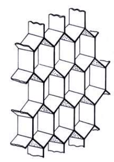
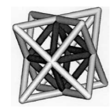
**Familiar Architectures**

**Composites**
- *Unidirectional*
- *Quasi-isotropic*
- *Particulate*

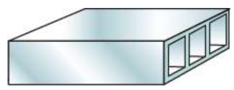
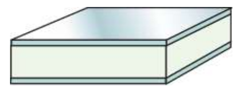




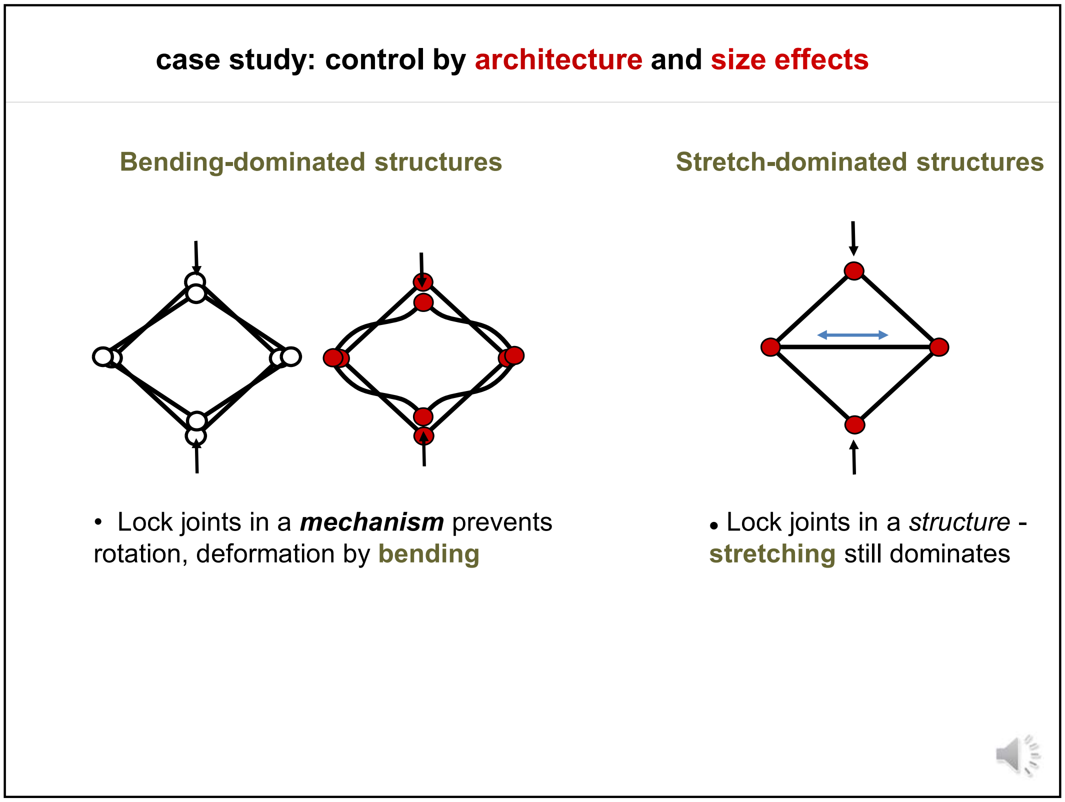
**Cellular structures**
- *Foams*
- *Honeycombs*
- *Triangulated lattices*

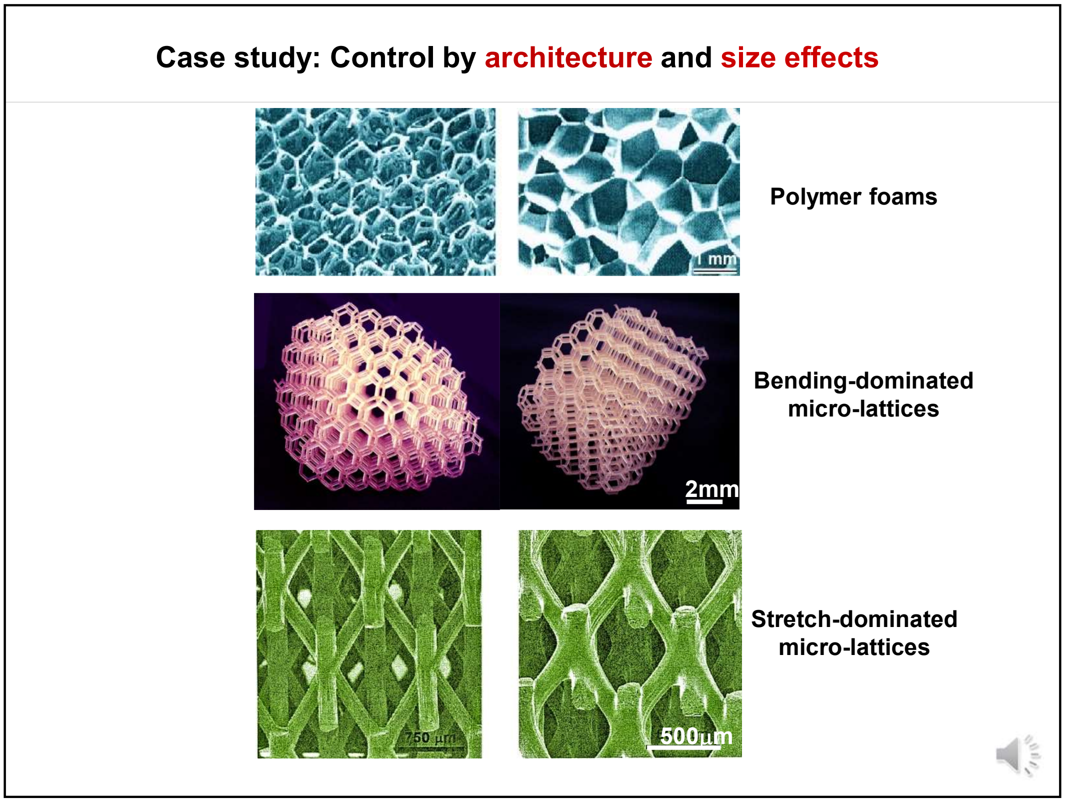
**Sandwich structures**
- *Symmetric sandwiches*

**Many more**




This frame explains the difference between bend and stretch-dominated structures. Stretch dominant structures are much stiffer and stronger that those that are bending dominated.




Foams and lattices, when on a small scale, can be thought of as “materials”, just as we think of wood as a material. Their mechanical properties – stiffness, strength, toughness etc – depend critically on the connectivity of the lattice.

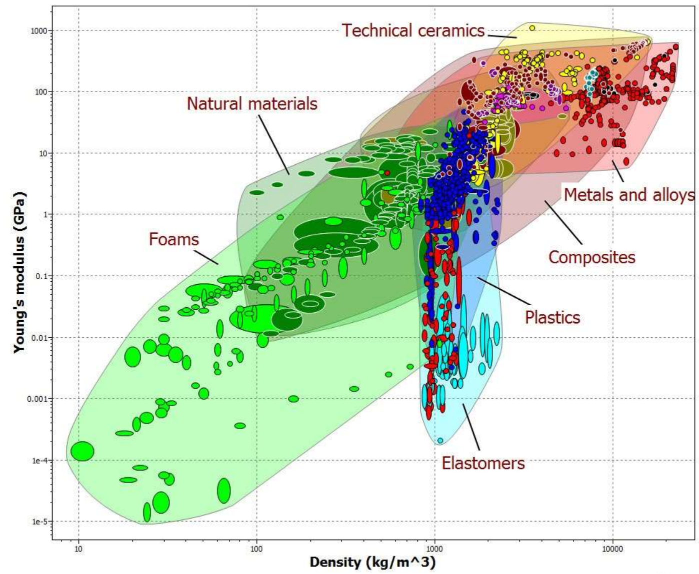
# Control by architecture and size effects


White areas = opportunity to expand the material property space.

Cellular metals with tailored:

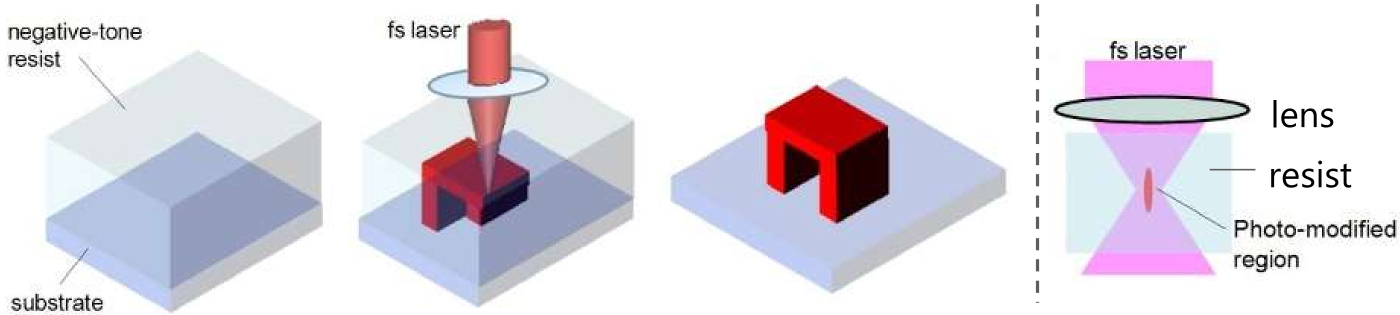
- ✓ Microstructure
- ✓ Geometrical constraints
- ✓ Design

Superposition of size effects



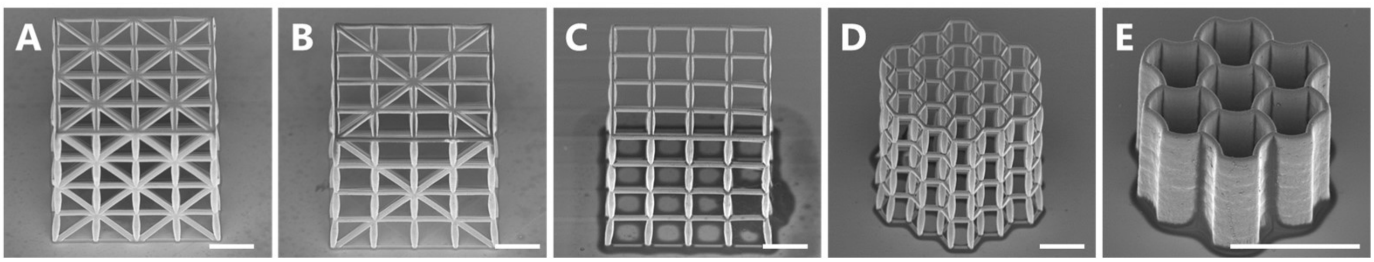
# fabrication of microlattices: architecture

- 3D laser lithography: 2 photon polymerization




(Adapted from: Nishiyama and Hirata, 2010)

- Micro-architectures



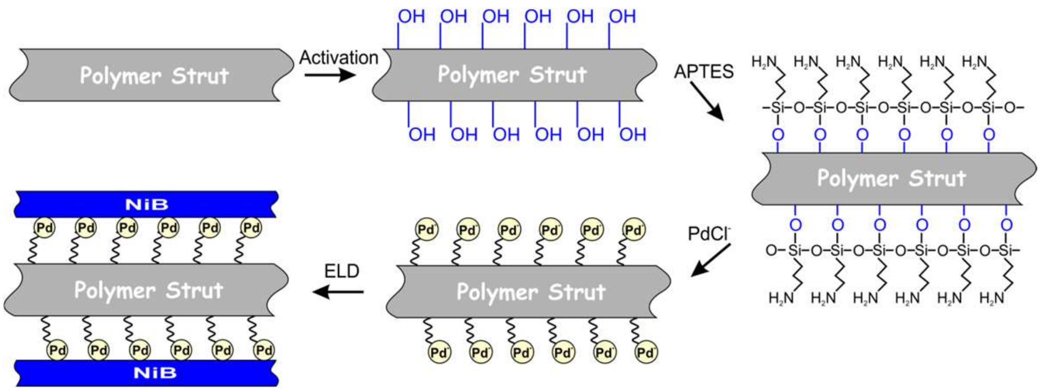

(Scale bars: 10 µm)

The slides illustrates a manufacturing process for polymer microlattices based on 2 photon polymerisation.

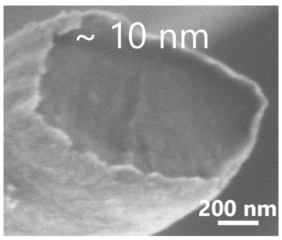
M. Mieszala et al. (2017) Micromechanics of Amorphous Metal/Polymer Hybrid Structures with 3D Cellular Architectures: Size Effects, Buckling Behavior, and Energy Absorption Capability, Small 13, p.1602514

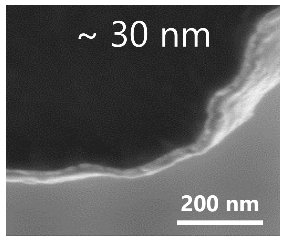
## metallisation of microlattices: size effect

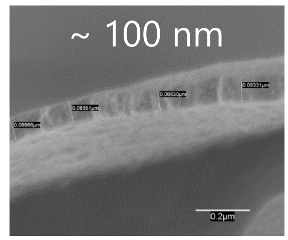
NiB electroless deposition on polymer template




Deposition time controls NiB thickness



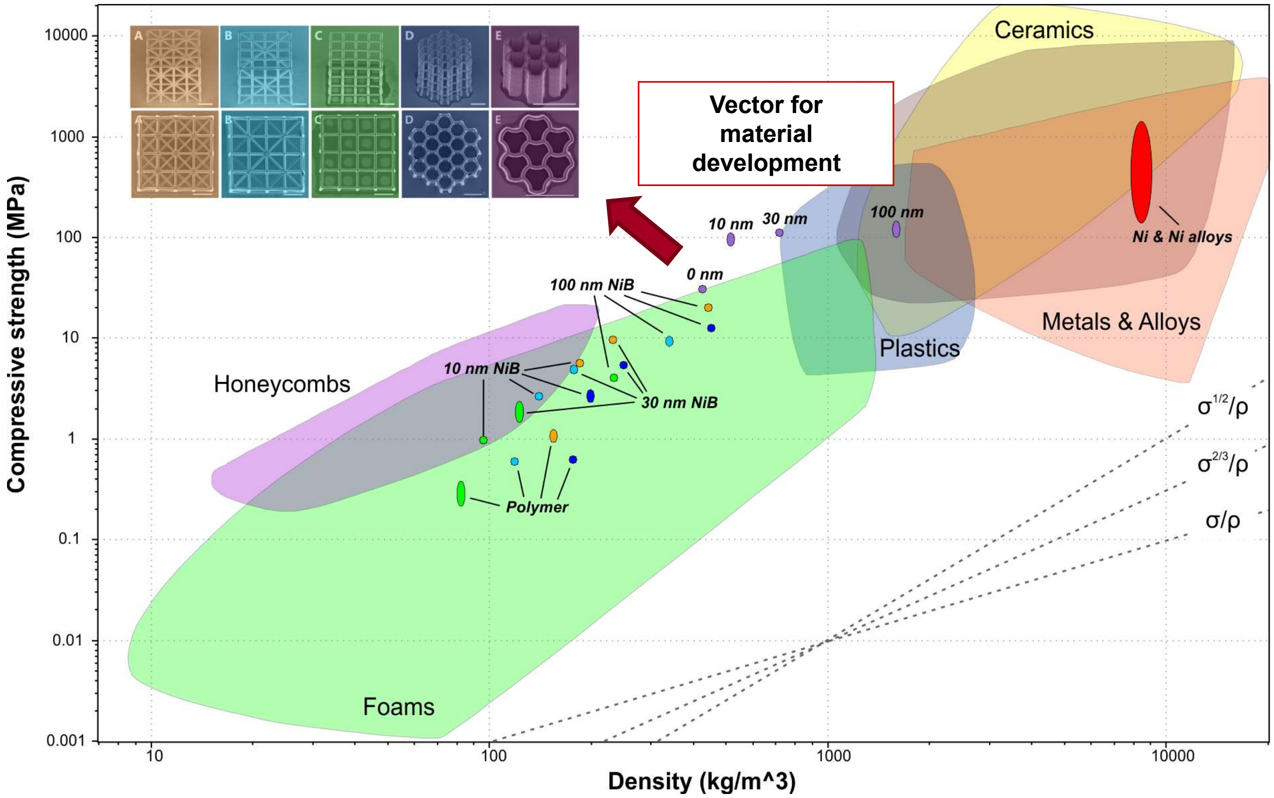




On the polymer microlattice a thin metal coating is deposited. The coating is 100nm or thinner and therefore we expect the strength of the metal to be close to the theoretical strength thus reinforcing the polymer microlattice.

M. Mieszala et al. (2017) Micromechanics of Amorphous Metal/Polymer Hybrid Structures with 3D Cellular Architectures: Size Effects, Buckling Behavior, and Energy Absorption Capability, Small 13, p.1602514

## size effect and architecture

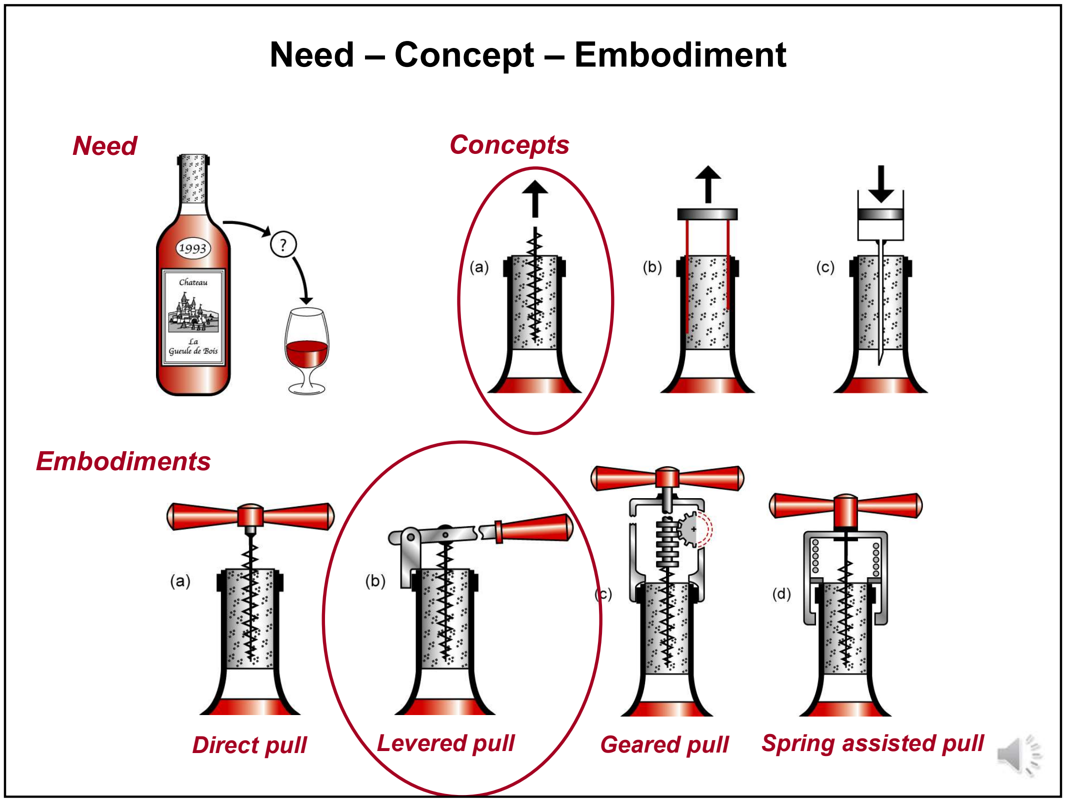



Depending on the geometry some metal coated polymer microlattices fill the white space in the map

## So what?

- **Multi-dimensional material-property space**
  - **Only part-filled** by monolithic materials
  - True for **mechanical, thermal, electrical, magnetic** and **optical** properties
- **Material development strategies**
  - **Classical** (classical alloy development, polymer chemistry….)
  - **"Nano" (sub-micron) scale** (exploiting scale-dependence of properties)
  - **Architecture & hybridisation**
- **The strategy:**
  - Map out the filled areas
  - Explore the ultimate boundaries
  - Explore ways of filling the empty space.
  - Hybrids, exploiting potential of novel configurations, have potential for this

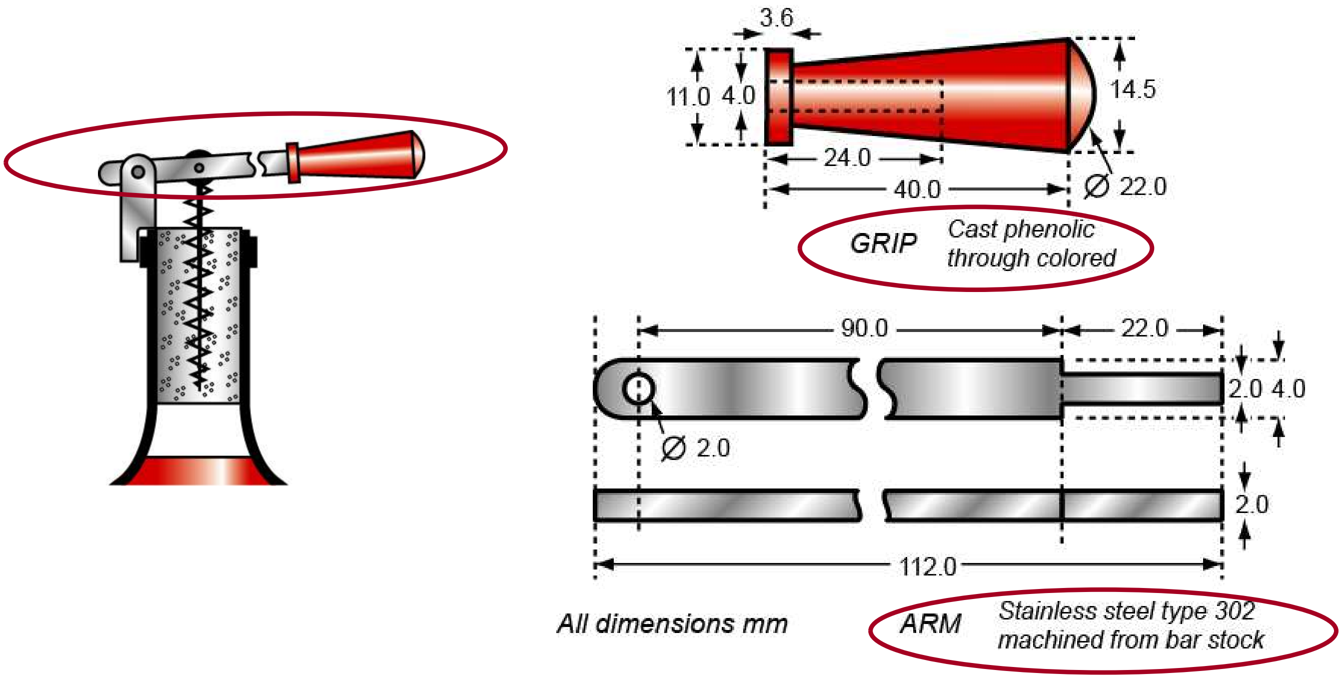
# table of content



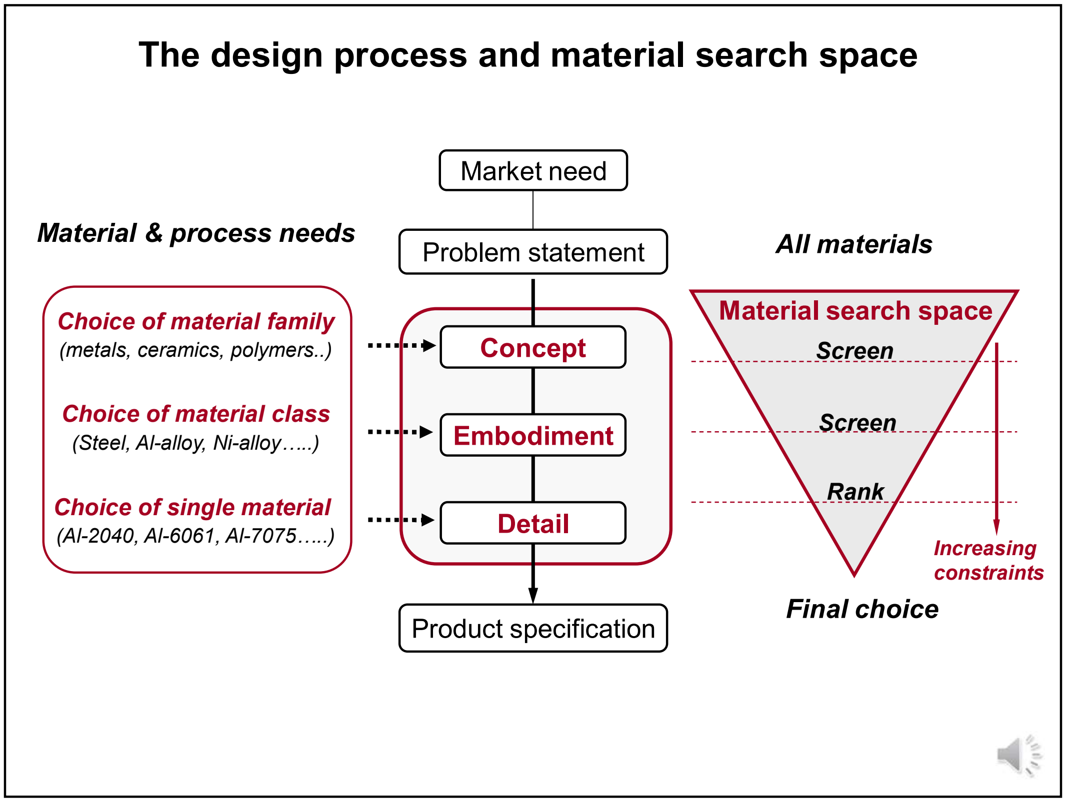

Here is an example of the **design process** at work. By storing wine in a corked bottle, a need is created – that of a device to remove the cork when you want to drink it. Three concepts are shown at the top left: (a) a tensile force is exerted on the cork using a threaded screw,(b) shear tractions are applied to the cork via thin elastic blades, and (c) a pressure is applied below the cork by forcing air into the bottle. (All three concepts have been developed into products and are marketed.)

The lower row shows four embodiments of just one of these – the tensile pull. At (a) is direct pull, and (b) is levered pull, at (c) is geared pull and at (d) is spring-assisted pull.

# Embodiment -- Detail



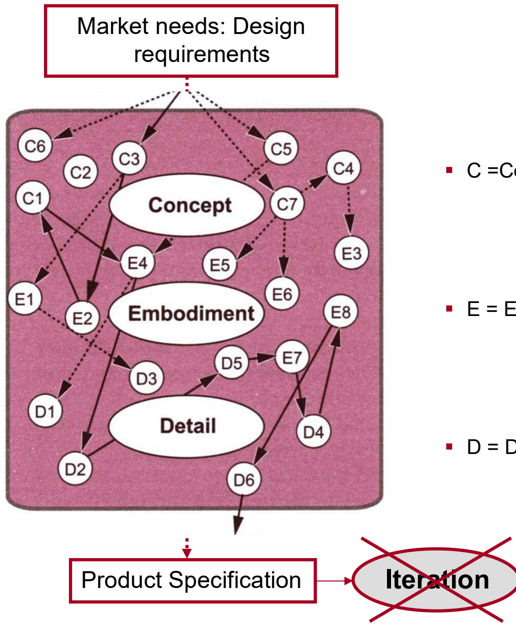

Here we show the **detailed design** stage for the lever and grip of the cork screw design ringed in red on the previous frame.



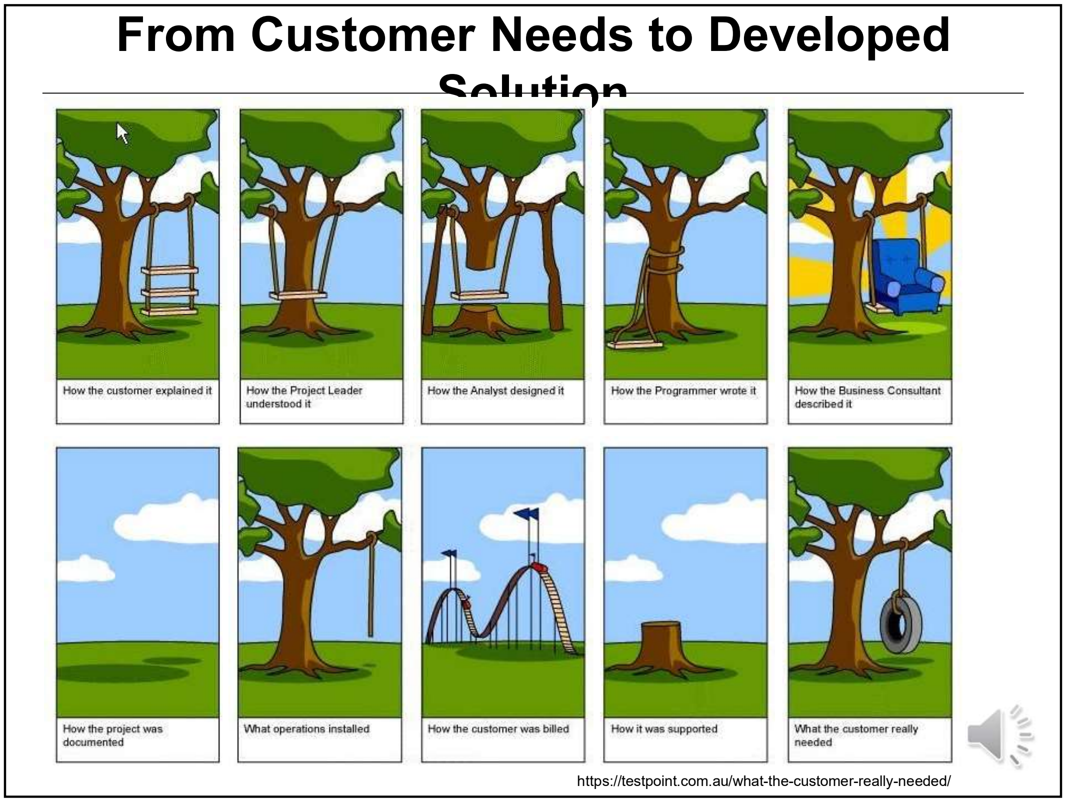

Design starts with the identification of a **market need**. **Concepts** (general working principles) are identified to fill the need. The most promising of these are developed into sketches or diagrams indicating configuration, lay-out and scale ("**embodiment**"). One or more of these is selected for **detailed** development, analyzing performance, safety and cost. The output is a design enabling the construction of a prototype that, after testing and development, goes to manufacture.

Material information enters all stages of the design. At the concept stage the design is fluid and all materials are candidates. Here the need is the ability to scan the entire Materials Universe, but at a low resolution. As the design goals and the requirements become sharper, the need becomes that for information about fewer materials but at a higher level of precision. In the final, detailed, stage when finite element, optimization and other analyses are undertaken, the need is for data for just one or a very few materials at the highest precision. The screening process narrows the initially wide material search space containing all materials (triangle on the right) ultimately leading to a final single choice.

# The Design Process in Reality




- C =Concepts
- E = Embodiments
- D = Details




***How the customer explained it.*** The customer usually has no clue what he really needs. He thinks he does, but he can also think of extra features he'll never use. He'll demand them up front, because he's afraid he won't get them added later.

***How the project leader understood it.*** The guy in charge of the project usually gets some critical detail wrong. It's often wrong in a way that makes it useless, but it snowballs from there into comedy.

***How the analyst designed it.*** The analyst has to decide how to fix the leader's misunderstanding of the project. A common "fix" is to break something else to work with our existing design.

***How the programmer wrote it.*** Programmers are notorious for not understanding the essential features of a project. They implement things quite literally, sometimes.

***How the business consultant described it.*** Marketing folks are the engineers' nightmares. They sell the customer on the glowing, cushy features of this project, paying no attention to the truth or practicality of the situation.

***How the project was documented.*** Documentation is usually an afterthought, or an I-thought. As in, I thought someone else was writing it.

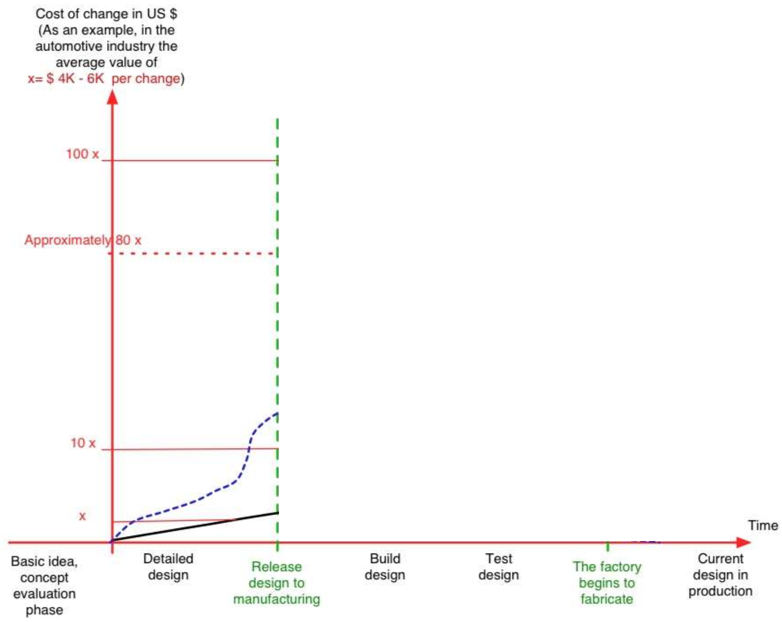
***What operations installed.*** Sometimes we spend months getting certain features to work, only to find out later that those features were never installed at the customer site because A) they didn't work, B) the installer didn't understand how it worked, or C) someone was afraid the fixes were no good.

***How the customer was billed.*** Yeah, software is expensive. We get to charge for all our clueless machinations.

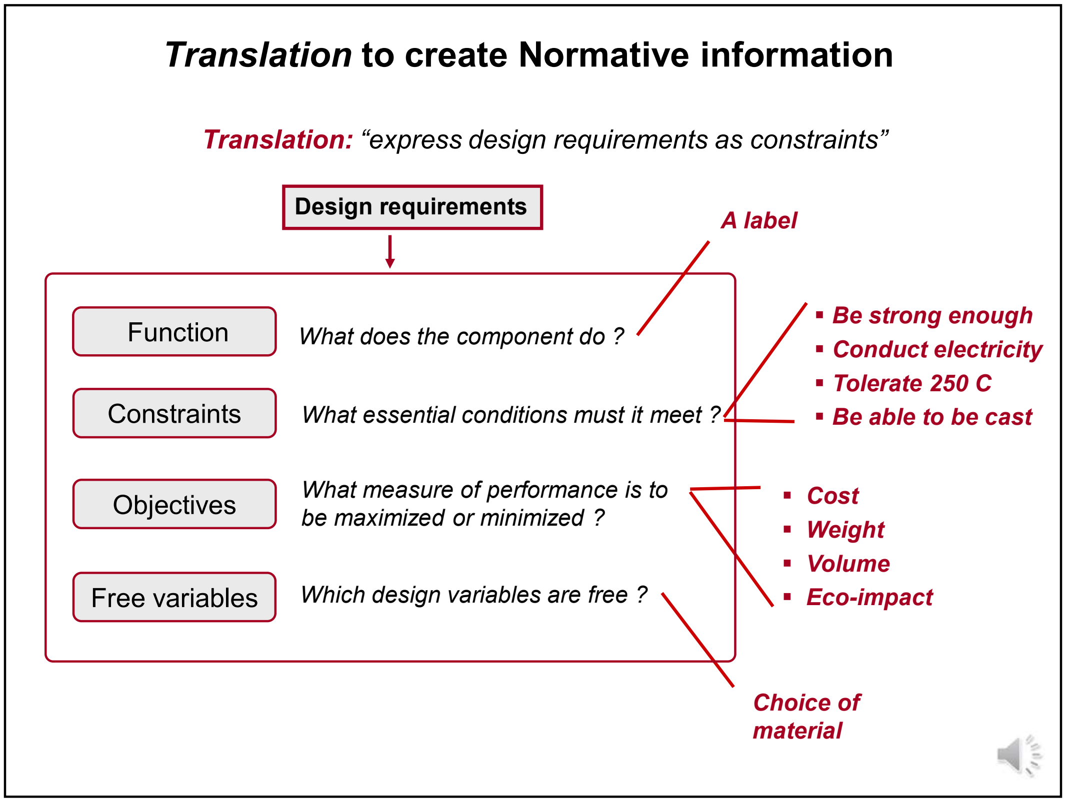
***How it was supported.*** "Is this feature causing the customer to call tech support? Perhaps we should remove it." Eventually, you end up with the basic stub of the project.

***What the customer really needed.*** It would be so much easier if we could ever get to this simple starting point. But we never do…

# Cost of Changes from Idea to Production




http://www.cimwareukandusa.com/All_IE655/IE655_Media/CostOfEngChanges.jpg



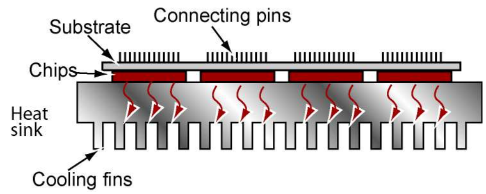

We need a procedure develop the normative information. The first step is that of **translating** the design requirements into a specification for materials selection. This frame outlines how this is done. The steps are summarized here.

- Identify the **function** of the component for which the material is sought.
- Identify and list the **constraints** it must meet: its ability to carry loads safely, satisfy limits on thermal or electrical properties and so forth.
- Finally, identify the **free variables** – those that the designer is free to change: usually dimensions or shape, and, of course, the choice of material.

From this analysis emerges the inputs to the next two key steps in selection: screening and ranking. The following frames give examples of translation and screening.

## Translation: a heat sink for power electronics

*Power micro-chips get hot. They have to be cooled to prevent damage.*




***Design requirements***

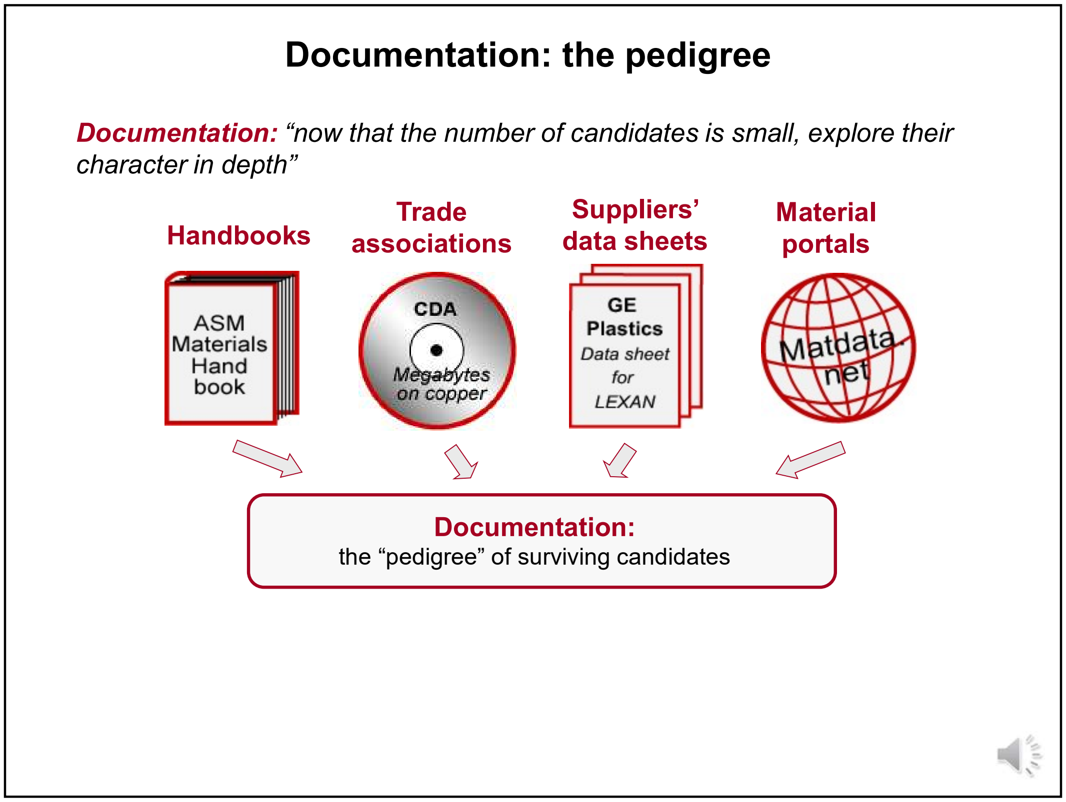
Keep chips below 200 C without any electrical coupling.

⇨

***Translation***

| | |
|---|---|
| Function | Heat sink |
| Constraints | **1. Max service temp > 200 C** |
| | **2. "Good electrical insulator"** |
| | **3. "Good thermal conductor"** |
| | **(or T-conduction > 25 W/m.K)** |
| Free variable | ***Choice of material*** |

Here is an **example of translation**. The chip-array in a high-powered computer consumes only a few watts, but it is very small, so the power density is high, and it all ends up as heat. The heat has to be pumped out to stop the array overheating. Heat sinks have to meet demanding specifications, some of which are listed on the left of this frame. These – translated into limits for material properties -- constrain the choice of material. Any material that does not meet the constraints is unacceptable.



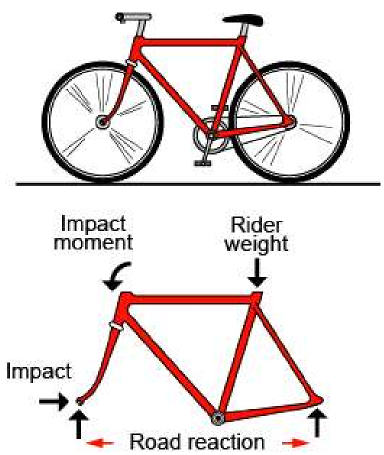

**Documentation** provides the additional information and knowledge that cannot be adequately captured in a record for a material, usually because it is of the sort that is not contained in the structured databases required for screening and ranking. Examples are: detailed data on wear, corrosion and oxidation; case studies ("experience") in the use of materials; failure analysis; design guide-lines and – often – details of supply and availability. Each record in the CES EduPack database contains a limited amount of documentation. More is found by searching the sources listed on this frame.

# table of content

# Analysis of design requirements

*Express design requirements as* ***constraints*** *and* ***objectives***

**Bike frame**




Design requirements

- Function — *What does the component do ?* — ***A label***
- Constraints — *What essential conditions must be met ?*
- Objectives — *What is the criterion of excellence ?*
- Free variable — *What can be varied ?* — ***Choice of material***

**Must be**

- ***Stiff enough***
- ***Strong enough***
- ***Tough enough***
- ***Able to be welded***

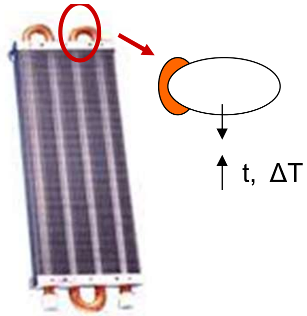
**Minimize**

- ***Cost***
- ***Weight***
- ***Volume***
- ***Eco-impact***

This frame is a reminder of the step of translation, expressing design requirements in terms of function, constraints, **objectives** and free variables. An objective is a criterion by which the excellence of choice is to be judged. Thus the most desirable choice from among those materials that meet all the constraints might be the cheapest one – the objective is that of minimizing cost. It might be the lightest one – the objective is then that of minimizing mass. Other common objectives are those of minimizing volume and of minimizing the environmental impact associated with the choice.

## Simple one-property indices

**Conduction**




**Thermal management**

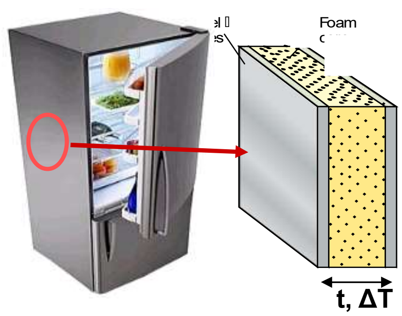
**Heat flux** $J = \lambda \dfrac{\Delta T}{t}$ **W/m²**

*Thermal conductivity*

**Heat exchanger:**
maximize heat flux for given ΔT
Choose material with ***largest*** T- conductivity, **λ**

***Index***

**Insulation**




**Thermal insulation:**
minimize heat flux for given ΔT
Choose material with ***smallest*** T- conductivity, **λ**

A **material index** is a metric of excellence for the component. Frequently, the index for is a single property. Here are three examples.

The pressure vessel has a given radius R and wall thickness t, and must carry a pressure p. It is impossible to be sure it has no cracks. The safest pressure vessel is the one that can tolerate the longest crack, c, without failing. The equation shows that this is the one made of the material with the largest fracture toughness $K_{ic}$. It is the index for the problem.

The heat sink must conduct heat from the chips to the cooling fins. The best material is the one that conducts the most heat for a given temperature difference, ΔT. The equation shows that this is the one with the largest thermal conductivity λ. It is the index for the problem.

The fridge insulation must minimize the heat flux into the fridge. The best material is the one that, for a given thickness t, leads to the smallest heat flux. The equation shows that this is the one with the smallest thermal conductivity λ (or largest thermal resistivity 1/ λ).

# Advanced ranking: modelling performance

**The method:**

1. **Identify function, constraints, objective and free variables**
   (list simple constraints for screening).

2. **Write down equation for objective** -- the "performance equation".

If the performance equation involves a free variable (other than the material):

- Identify the constraint that limits it.
- Use this to eliminate the free variable in performance equation.

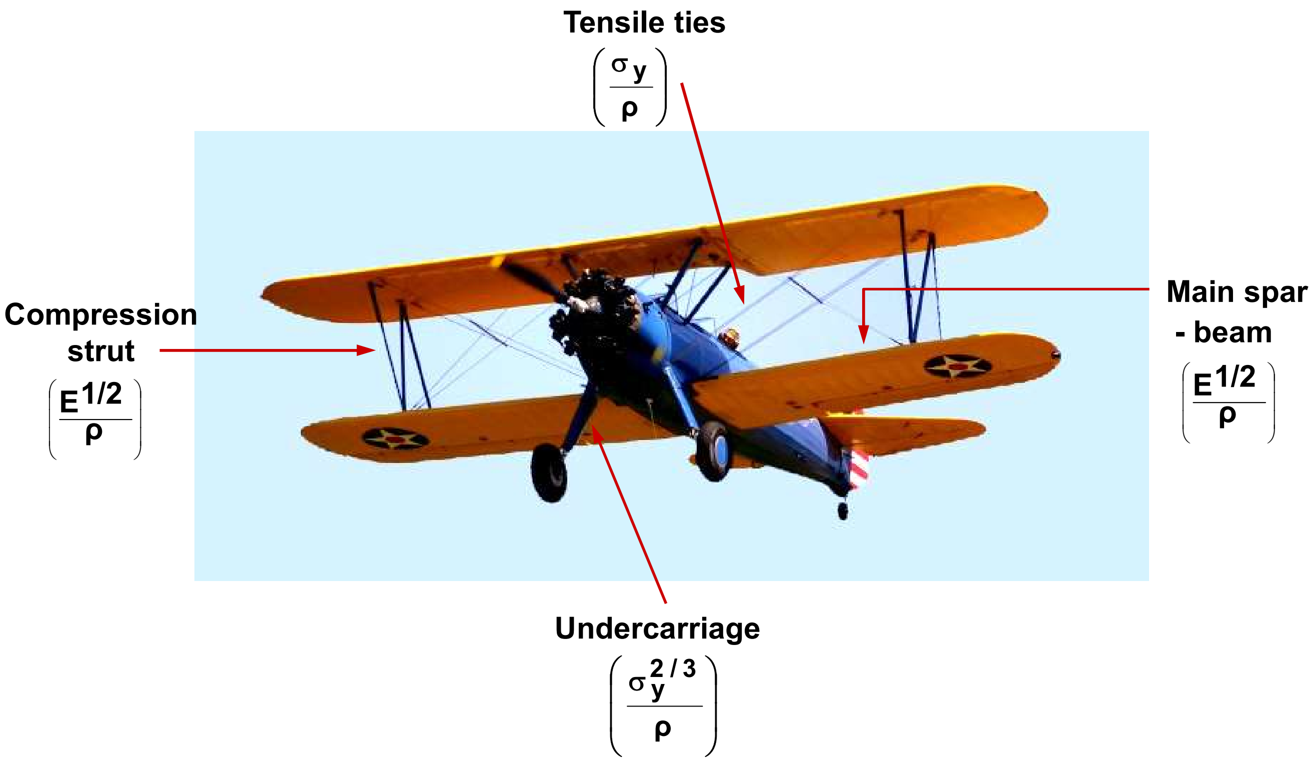
3. **Read off the combination of material properties that maximises performance -- the material index**

4. **Use this for ranking**

This frame summarizes and extends the steps in using an objective for ranking. They are summarized under the headings 1, 2, 3 and 4 on this frame, omitting, initially, the red box in the middle.

Now for the extension – **the red box**. Sometimes the equation for the objective contains a free variable other than the choice of material – the next two frames give examples. If the volume V of material in the CD case of the last frame had **not** been defined as fixed, it would have been a **free variable**, one we could have varied to minimize the cost of the case. But changing V has other consequences, limited by other constraint such as a requirement for adequate stiffness. Then the constraint must be identified, setting a limit on V. Once that is established, the method continues as before.

# Minimum weight design




**E = Young's modulus** **$\rho$ = Density** **$\sigma_y$ = Yield strength**

The marked components of this plane perform different functions. The ties carry tension, the struts carry compression (they act as columns) and the spars carry bending moments – they are beams. They are chosen to be as light as possible: thus the objective is to minimize mass.

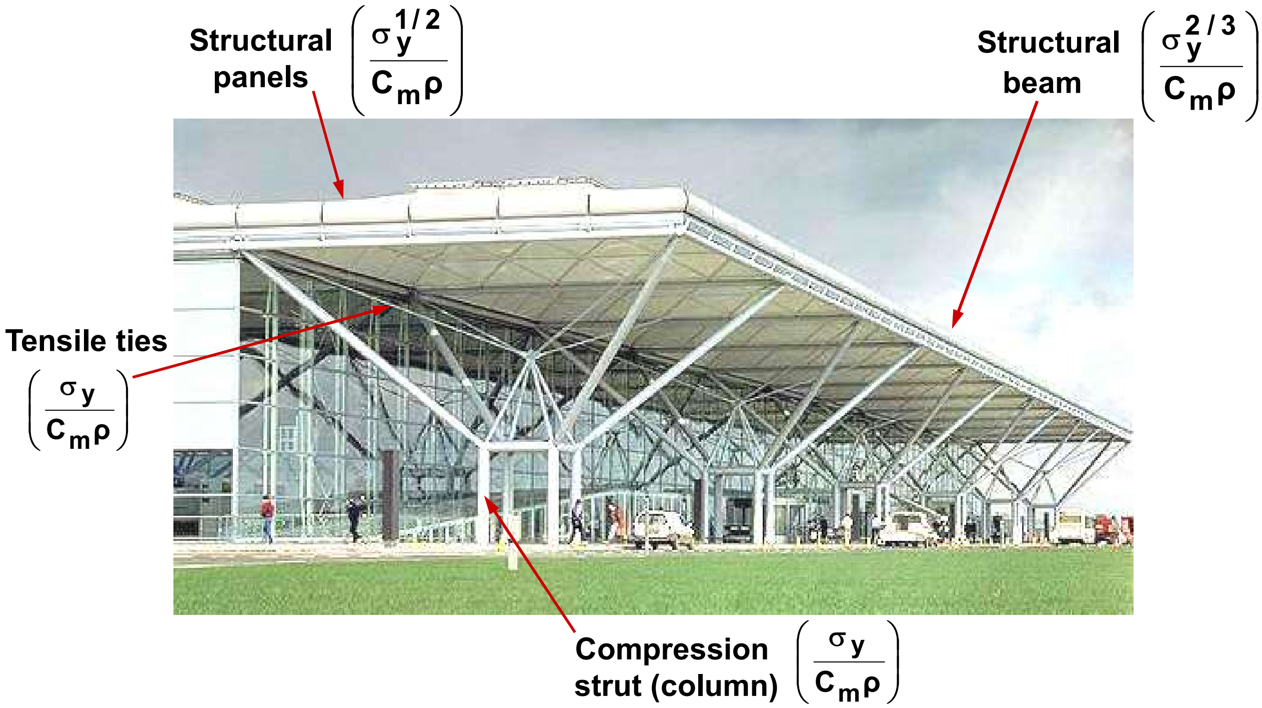
The mass of a **tensile tie** of prescribed strength depends two material properties – yield strength and density – in the combination $\sigma_y / \rho$; it is the material index for this component.

The mass of a **strut** that must carry a compressive load without buckling elastically is proportional to the material group $E^{1/2} / \rho$ so this becomes the material index.

The mass of a **beam,** loaded in bending, with restriction on elastic deflection is also proportional to $E^{1/2} / \rho$ so the index here is the same as that for the strut.

Thus the index depends on the mode of loading (tension, compression, bending) and on the requirement for stiffness or strength.

# Minimum cost design




$C_m$ = Material cost / kg $\rho$ = Density $\sigma_y$ = Yield strength

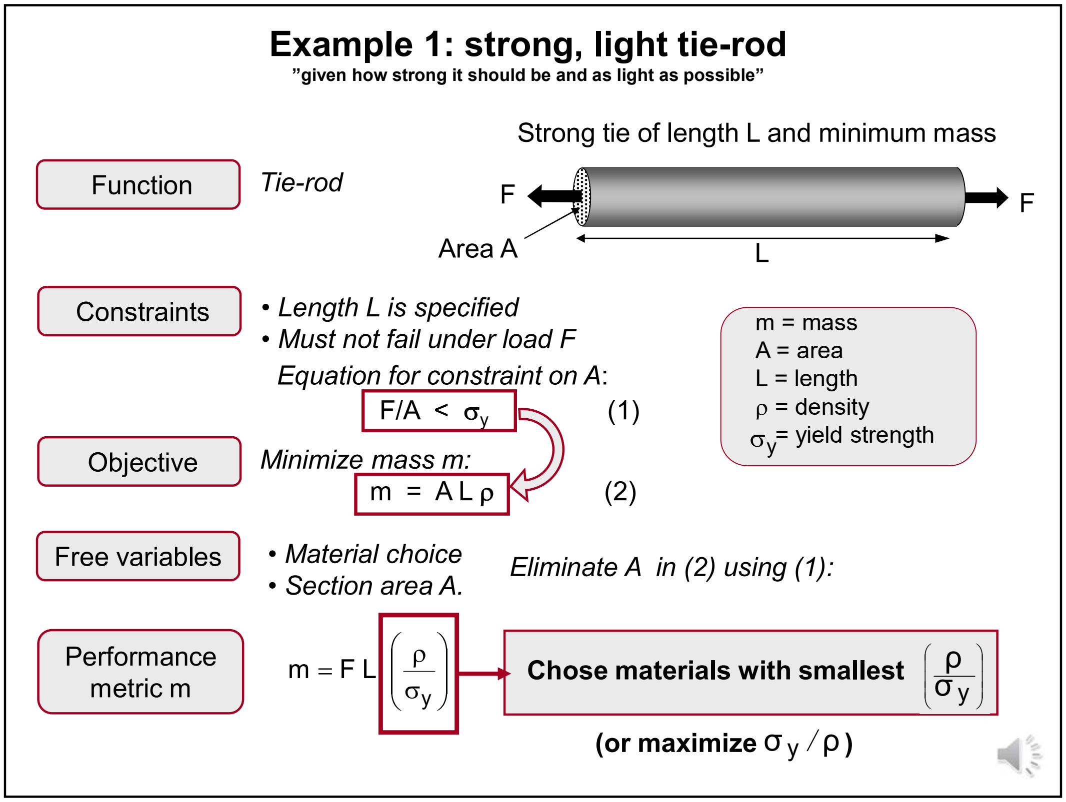
The marked components of this building, like those of the plane, perform different functions. The ties carry tension, the struts carry compression (they act as columns) and the beams carry bending moments. They are chose to be as cheap as possible: thus the objective is to minimize cost.

The cost of a **tensile tie** of prescribed strength depends two material properties – yield strength and density – in the combination $\sigma_y / C_m \rho$ ; it is the material index for this component.

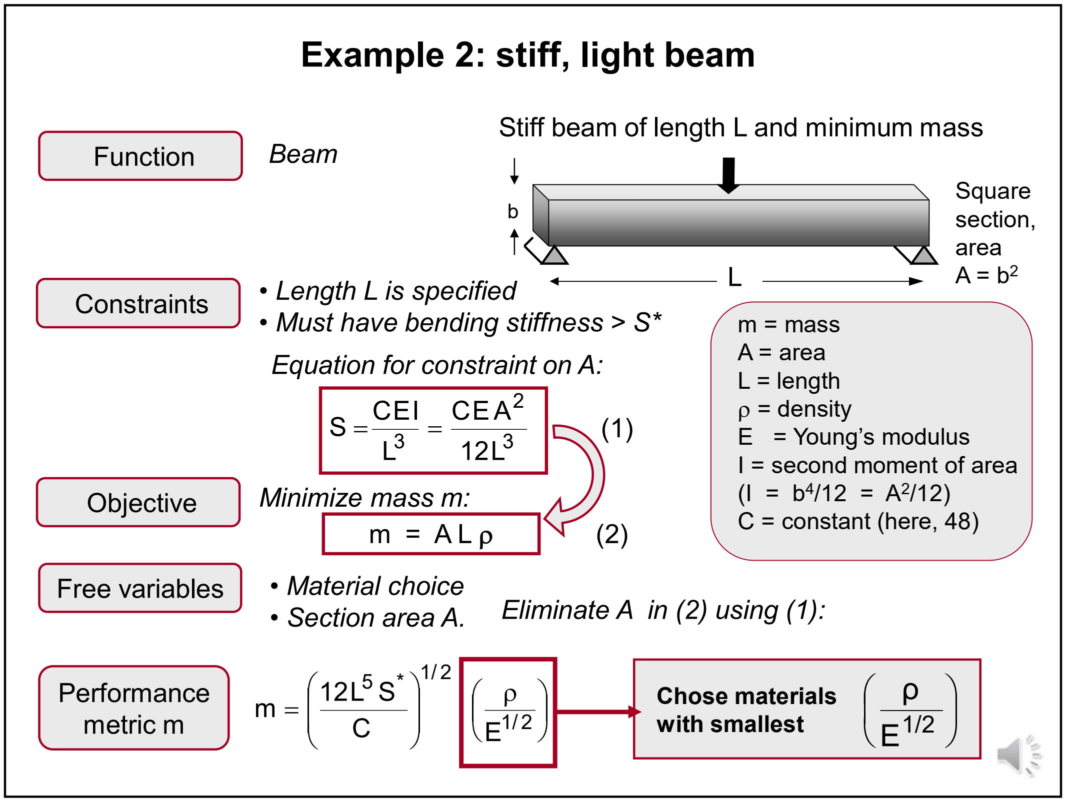
The cost of a **strut** that must carry a compressive load without buckling elastically is proportional to the material group $E^{1/2} / C_m \rho$ so this becomes the material index.

The cost of a **beam,** loaded in bending that must not yield plastically is proportional to the combination $\sigma_y^{2/3} / C_m \rho$ so that it the index.

Thus the index depends on the mode of loading (tension, compression, bending) and on the requirement for stiffness or strength.



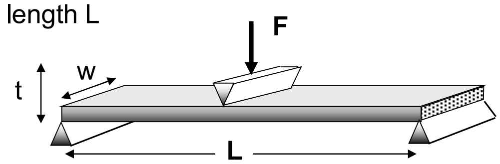

This and the next frame work through examples illustrating how to derive **material indices** when there is a free variable in addition to the choice of material; many more appear in later frames. Here we have the simplest of components – a tie rod. Its length L is defined. It must carry a prescribed tensile load F without failure (a constraint) and at the same time be as light a possible (an objective). The frame shows the steps, following the method of the last frame. Materials satisfying all the other constraints (such as operating temperature, corrosion resistance and so forth) and that have a low value of the index $\rho/\sigma_y$ (or, equivalently, a high value of $\sigma_y/\rho$) are the best choice. If the constraint had been on stiffness rather than strength, the index becomes $\rho/E$ (E is Young's modulus).




The most usual mode of loading of engineering structures is bending: wing-spars of aircraft, ceiling and floor joists of buildings, golf club shafts, oars, skis, ….all these structures carry bending moments; they are **beams**. The requirement here is for a beam of specified stiffness and minimum mass. The frame lays out the steps, leading to the index $\rho/E^{1/2}$ ; it differs from the index for a light stiff tie-rod because the mode of loading is bending, not tension. Later frames show how these indices are used to rank materials.

## Example 3: stiff, light panel

**Function** — *Panel* with given width w and length L




**Objective** — *Minimise mass*, m, where

$$m = AL\rho = w\,t\,L\rho$$

**Constraint** — *Stiffness* of the panel S:

$$S = \frac{CEI}{L^3}$$

I is the second moment of area:

$$I = \frac{w\,t^3}{12}$$

m = mass
w = width
L = length
ρ = density
t = thickness
S = stiffness
I = second moment of area
E = Youngs Modulus

**Free variables**
- *Material choice.*
- *Panel thickness t.* Combining the equations gives:

$$m = \left(\frac{12\,S\,w^2}{C}\right)^{1/3} L^2 \left(\frac{\rho}{E^{1/3}}\right)$$

**Chose materials with smallest** $\left(\frac{\rho}{E^{1/3}}\right)$

A **panel** is a flat sheet of given length and width: a table top, for instance. It differs from a beam in that the width of the beam is a free variable, whereas the width of the panel is prescribed. Otherwise the method, given in this frame, is the same. It leads to the index $\rho/E^{1/3}$.

# Demystifying material indices

- A **material index** is just the **combination of material properties** that appears in the equation for **performance** (eg minimizing mass or cost).

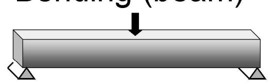
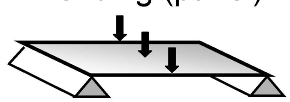
- Sometimes a single property
- Sometimes a combination

} Either is a **material index**

**Example:**

**Objective --** minimise **mass**

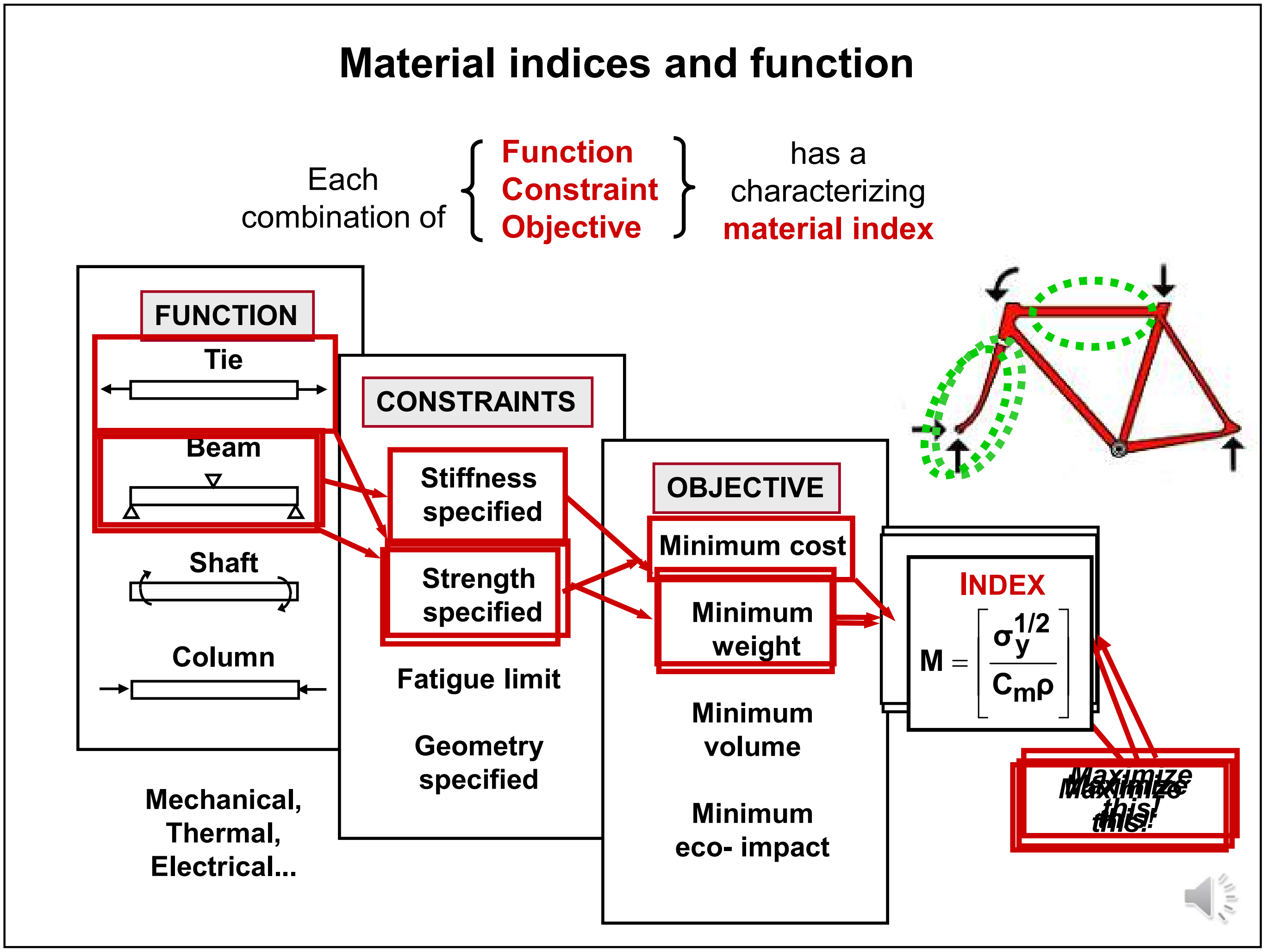
**Performance metric** = **mass**

| **Function** | **Constraints** Stiffness | Strength |
|---|---|---|
| Tension (tie)  | $\rho/E$ | $\rho/\sigma_y$ |
| Bending (beam)  | $\rho/E^{1/2}$ | $\rho/\sigma_y^{2/3}$ |
| Bending (panel)  | $\rho/E^{1/3}$ | $\rho/\sigma_y^{1/2}$ |

*Minimize these!*

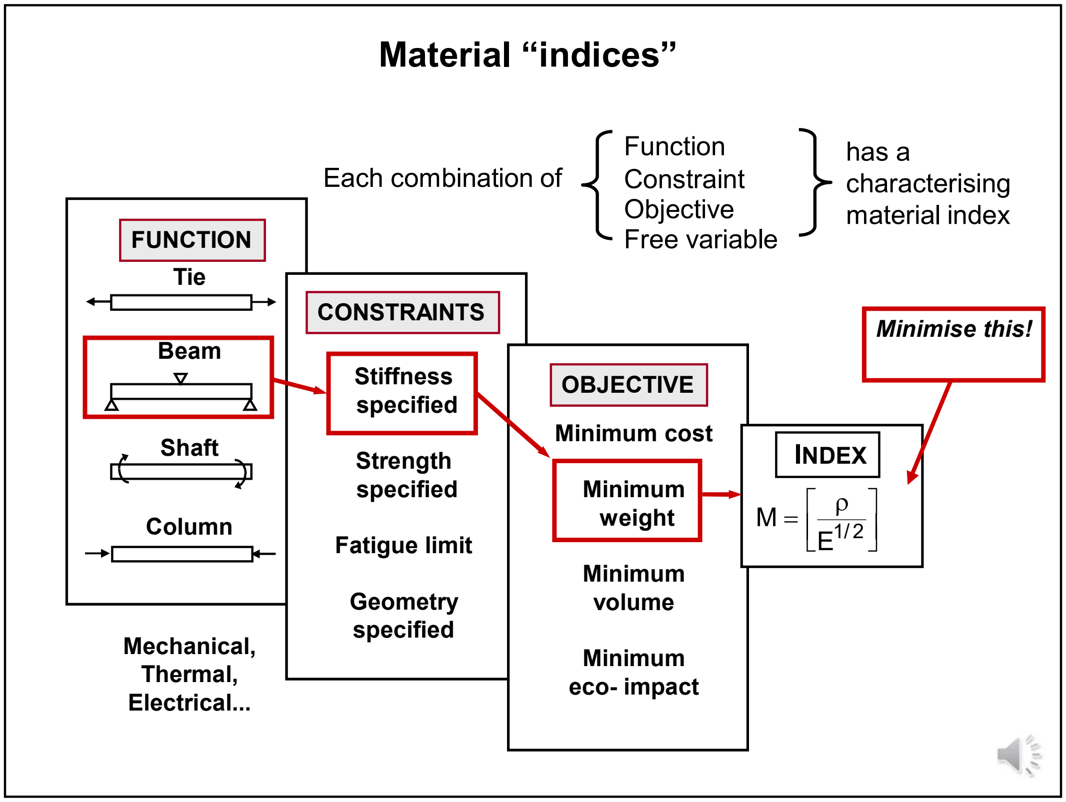
*(Or maximize reciprocals)*

The material properties listed in handbooks – density, modulus and so on – are those that are measured to characterize the fundamental properties of materials – the physicists' view of materials, one might say. The performance of an engineering component depends on the values of these, but, as the last three Frames showed, it usually depends not on one property but on a combination of two or more – it is these that we call **material indices**. They, too, are material properties; they are the ones that characterize engineering performance – the engineers' view of materials, so to speak. The ones highlighted in this frame all depend on density $\rho$ and modulus E. They are used in the frames that follow as examples for ranking.




Any combination of function, objective, constraint and free variable leads to a **material index**. The frame illustrates how indices arise from different combinations.

There are many such indices. They are listed in Appendix B of the Text "Materials Selection in Mechanical Design" and in CES Help.




Any combination of function, objective, constraint and free variable leads to a **material index**. The frame illustrates this, selecting the light stiff beam used in the previous frame. There are many such indices. They are listed in Appendix B of the Text "Materials Selection in Mechanical Design".

# Exercise – 20min!

**1 Material indices for elastic beams with differing constraints** (Figure 1). Start each of the four parts of this problem by listing the function, the objective, the constraints and the free variable. You will need the equations for the deflection of a cantilever beam with a square cross-section $t$ x $t$. The two that matter are that for the deflection $\delta$ of a beam of length $L$ under an end load:

$$\delta = \frac{FL^3}{3EI}$$

and that for the deflection of a beam under a distributed load $f$ per unit length:

$$\delta = \frac{1}{8}\frac{fL^4}{EI}$$

where $I$ is given in Table 2. For a self-loaded beam $f = \rho A g$ where $\rho$ is the density of the material of the beam, $A$ its cross-sectional area and $g$ the acceleration due to gravity.

(a) Show that the best material for a cantilever beam of given length $L$ and given (i.e. fixed) square cross-section ($t \times t$) that will deflect least under a given end load $F$ is that with the largest value of the index $M = E$, where $E$ is Young's modulus (neglect self-weight). (Figure 1a.)

(b) Show that the best material choice for a cantilever beam of given length $L$ and with a given section ($t$ x $t$) that will deflect least under its own self-weight is that with the largest value of $M = E/\rho$, where ρ is the density. (Figure 1b.)

(c) Show that the material index for the lightest cantilever beam of length $L$ and square section (not given, i.e., the area is a free variable) that will not deflect by more than δ under its own weight is $M = E/\rho^2$. (Figure 1c.)

(d) Show that the lightest cantilever beam of length $L$ and square section (area free) that will not deflect by more than $\delta$ under an end load $F$ is that made of the material with the largest value of $M = E^{1/2}/\rho$ (neglect self weight). (Figure 1d.)

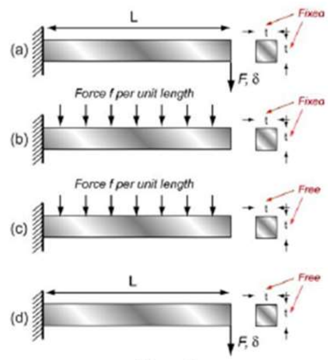
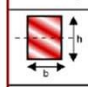
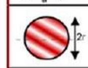
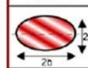
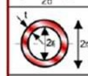
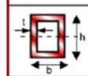
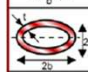
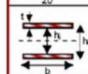
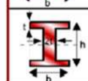
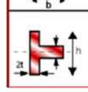



Figure 1

Functions required:

## 2. Moments of sections.

| Section shape | Area A m | Moment I m⁴ | Moment K m⁴ | Moment Z m⁴ | Moment Q m⁴ | Moment Zp m⁴ |
|---|---|---|---|---|---|---|
|  | $bh$ | $\frac{bh^3}{12}$ | $\frac{bh^3}{3}(1-0.58\frac{b}{h})$ (h > b) | $\frac{bh^2}{6}$ | $\frac{b^2h^2}{(3h+1.8b)}$ (h>b) | $\frac{bh^2}{4}$ |
|  | $\frac{\sqrt{3}}{4}a^2$ | $\frac{a^4}{32\sqrt{3}}$ | $\frac{\sqrt{3}a^4}{80}$ | $\frac{a^3}{32}$ | $\frac{a^3}{20}$ | $\frac{3a^3}{64}$ |
|  | $\pi r^2$ | $\frac{\pi}{4}r^4$ | $\frac{\pi}{2}r^4$ | $\frac{\pi}{4}r^3$ | $\frac{\pi}{2}r^3$ | $\frac{\pi}{3}r^3$ |
|  | $\pi ab$ | $\frac{\pi}{4}a^3b$ | $\frac{\pi a^3b^3}{(a^2+b^2)}$ | $\frac{\pi}{4}a^2b$ | $\frac{\pi}{2}a^2b$ (a<b) | $\frac{\pi}{3}a^2b$ |
|  | $\pi(r_o^2-r_i^2)$ $\approx 2\pi rt$ | $\frac{\pi}{4}(r_o^4-r_i^4)$ $\approx \pi r^3t$ | $\frac{\pi}{2}(r_o^4-r_i^4)$ $\approx 2\pi r^3t$ | $\frac{\pi}{4r_o}(r_o^4-r_i^4)$ $\approx \pi r^2t$ | $\frac{\pi}{2r_o}(r_o^4-r_i^4)$ $\approx 2pr^2t$ | $\frac{\pi}{3}(r_o^3-r_i^3)$ $\approx \pi r^2t$ |
|  | $2t(h+b)$ (h,b >> t) | $\frac{1}{6}h^3t(1+3\frac{b}{h})$ | $\frac{2tb^2h^2}{(h+b)}(1-\frac{t}{h})^4$ | $\frac{1}{3}h^2t(1+3\frac{b}{h})$ | $2tbh(1-\frac{t}{h})^2$ | $bht(1+\frac{h}{2b})$ |
|  | $\pi(a+b)t$ (a,b >> t) | $\frac{\pi}{4}a^3t(1+\frac{3b}{a})$ | $\frac{4\pi(ab)^{5/2}t}{(a^2+b^2)}$ | $\frac{\pi}{4}a^2t(1+\frac{3b}{a})$ | $2\pi t(a^3b)^{1/2}$ (b>a) | $\pi abt(2+\frac{a}{b})$ |
|  | $b(h_o-h_i)$ $\approx 2bt$ (h,b >> t) | $\frac{b}{12}(h_o^3-h_i^3)$ $\approx \frac{1}{2}bth_o^2$ | -- | $\frac{b}{6h_o}(h_o^3-h_i^3)$ $\approx bth_o$ | -- | $\frac{b}{4}(h_o^2-h_i^2)$ $\approx bth_o$ |
|  | $2t(h+b)$ (h,b >> t) | $\frac{1}{6}h^3t(1+3\frac{b}{h})$ | $\frac{2}{3}bt^3(1+4\frac{h}{b})$ | $\frac{1}{3}h^2t(1+3\frac{b}{h})$ | $\frac{2}{3}bt^2(1+4\frac{h}{b})$ | $bht(1+\frac{h}{2b})$ |
|  | $2t(h+b)$ (h,b >> t) | $\frac{t}{6}(h^3+4bt^2)$ | $\frac{t^3}{3}(8b+h)$ | $\frac{t}{3h}(h^3+4bt^2)$ | $\frac{t^2}{3}(8b+h)$ | $\frac{th^2}{2}\{1+\frac{2t(b-2t)}{h^2}\}$ |

# Exercise!

**1 Material indices for elastic beams with differing constraints** (Figure 1). Start each of the four parts of this problem by listing the function, the objective, the constraints and the free variable. You will need the equations for the deflection of a cantilever beam with a square cross-section $t$ x $t$. The two that matter are that for the deflection $\delta$ of a beam of length $L$ under an end load:

$$\delta = \frac{FL^3}{3EI}$$

and that for the deflection of a beam under a distributed load $f$ per unit length:

$$\delta = \frac{1}{8}\frac{fL^4}{EI}$$

where $I$ is given in Table 2. For a self-loaded beam $f = \rho A g$ where $\rho$ is the density of the material of the beam, $A$ its cross-sectional area and $g$ the acceleration due to gravity.

(a) Show that the best material for a cantilever beam of given length $L$ and given (i.e. fixed) square cross-section ($t$ x $t$) that will deflect least under a given end load $F$ is that with the largest value of the index $M = E$, where $E$ is Young's modulus (neglect self-weight). (Figure 1a.)

a) function — endloaded cantilever

objective — minimise deflection

constraints — $L$, square section shape $t \times t$, $F$

free variable — material only

$$\delta = \frac{FL^3}{3EI} = \frac{FL^3}{3E} \cdot \frac{12}{t^4} = \frac{4FL^3}{t^4} \cdot \frac{1}{E}$$

Minimise $\delta$ ⇒ Maximise $E$

# Exercise!



**1 Material indices for elastic beams with differing constraints** (Figure 1). Start each of the four parts of this problem by listing the function, the objective, the constraints and the free variable. You will need the equations for the deflection of a cantilever beam with a square cross-section $t$ x $t$. The two that matter are that for the deflection $\delta$ of a beam of length $L$ under an end load:

$$\delta = \frac{FL^3}{3EI}$$

and that for the deflection of a beam under a distributed load $f$ per unit length:

$$\delta = \frac{1}{8}\frac{fL^4}{EI}$$

where $I$ is given in Table 2. For a self-loaded beam $f = \rho A g$ where $\rho$ is the density of the material of the beam, $A$ its cross-sectional area and $g$ the acceleration due to gravity.

(d) Show that the lightest cantilever beam of length $L$ and square section (area free) that will not deflect by more than $\delta$ under an end load $F$ is that made of the material with the largest value of $M = E^{1/2}/\rho$ (neglect self weight). (Figure 1d.)

Fixed

d)

| | |
|---|---|
| Func | endloaded cantilever |
| Obj | minimise m |
| Const. | $\delta$, F |
| Free variable | A, choice of material |

$$\delta = \frac{FL^3}{3EI} = \frac{4FL^3}{Et^4}$$

$$\Rightarrow t^2 = A = \sqrt{\frac{4FL^3}{E\delta}}$$

$$m = \rho \cdot V = \rho \cdot L \cdot t^2$$

$$= \rho \cdot L \cdot \sqrt{\frac{4FL^3}{E\delta}}$$

$$= \frac{\rho}{\sqrt{E}} \cdot 2L^2 \sqrt{\frac{FL}{\delta}}$$

$\Rightarrow$ minimise m means maximise $\frac{E^{1/2}}{\rho}$

**Exercise 1:**

**The model.** The point of this problem is that the material index depends on the mode of loading, on the geometric constraints and on the design goal.

(a) The table lists the design requirements for part (a) of the problem.

| | |
|---|---|
| **Function** | • *End-loaded cantilever beam* |
| **Constraints** | • *Length L specified*<br>• *Section t x t specified*<br>• *End load F specified* |
| **Objective** | • *Minimize the deflection, δ* |
| **Free variables** | • *Choice of material only* |

The objective function is an equation for the deflection of the beam. An end-load $F$ produces a deflection δ of

$$\delta = \frac{FL^3}{3EI}$$

where $E$ is the modulus of the beam material and $I = t^4 / 12$ is the second moment of the area, so that the deflection becomes

$$\delta = 4\frac{FL^3}{t^4}\left(\frac{1}{E}\right)$$

The magnitude of the load $F$ and the dimensions $L$ and $t$ are all given. The deflection $\delta$ is minimized by maximizing:

$$M_1 = E$$

(b) The design requirements for part (b) are listed below:

| | |
|---|---|
| **Function** | • *Self-loaded cantilever beam* |
| **Constraints** | • *Length L specified*<br>• *Section t x t specified* |
| **Objective** | • *Minimize the deflection, δ* |
| **Free variables** | • *Choice of material only* |

The beam carries a distributed load, f per unit length, where

$$f = \rho\, g\, t^2$$

where $\rho$ is the density of the beam material and $g$ is the acceleration due to gravity. Such a load produces a deflection

$$\delta = \frac{3}{2}\frac{fL^4}{Et^4} = \frac{3}{2}\frac{gL^4}{t^2}\left(\frac{\rho}{E}\right)$$

(the objective function). As before, $t$ and $L$ are given. The deflection is minimized by maximizing

$$M_2 = E/\rho$$

| | |
|---|---|
| **Function** | • *Self-loaded cantilever beam* |
| **Constraints** | • *Length L specified*<br>• *Maximum deflection, δ, specified* |
| **Objective** | • *Minimize the mass, m* |
| **Free variables** | • *Choice of material only*<br>• *Section area $A = t^2$* |

The beam deflects under its own weight but now the section can be varied to reduce the weight provided the deflection does not exceed $\delta$, as in the figure. The objective function (the quantity to be minimized) is the mass $m$ of the beam

$$m = t^2 L \rho$$

Substituting for $t$ (the free variable) from the second equation into the first, gives

$$m = \frac{3}{2}\frac{gL^5}{\delta}\left(\frac{\rho^2}{E}\right)$$

The quantities $L$ and $\delta$ are given. The mass is minimized by maximizing

$$M_3 = E/\rho^2$$

(d) The design requirements for part (d) are listed below

| | |
|---|---|
| **Function** | • *End-loaded cantilever beam* |
| **Constraints** | • *Length L specified*<br>• *Maximum deflection, δ, specified*<br>• *End-load F specified* |
| **Objective** | • *Minimize the mass, m* |
| **Free variables** | • *Choice of material only*<br>• *Section area $A = t^2$* |

The section is square, but the dimension $t$ is free. The objective function is

$$m = t^2 L \rho$$

The deflection is, as in part (a)

$$\delta = 4\frac{FL^3}{t^4}\left(\frac{1}{E}\right)$$

Using this to eliminate the free variable, $t$, gives

$$m = 2\left(\frac{FL^5}{\delta}\right)^{1/2}\left(\frac{\rho}{E^{1/2}}\right)$$

The quantities $F$, $\delta$ and $L$ are given. The mass is minimized by maximizing

$$M_4 = E^{1/2}/\rho$$

From a selection standpoint, $M_3$ and $M_4$ are equivalent.

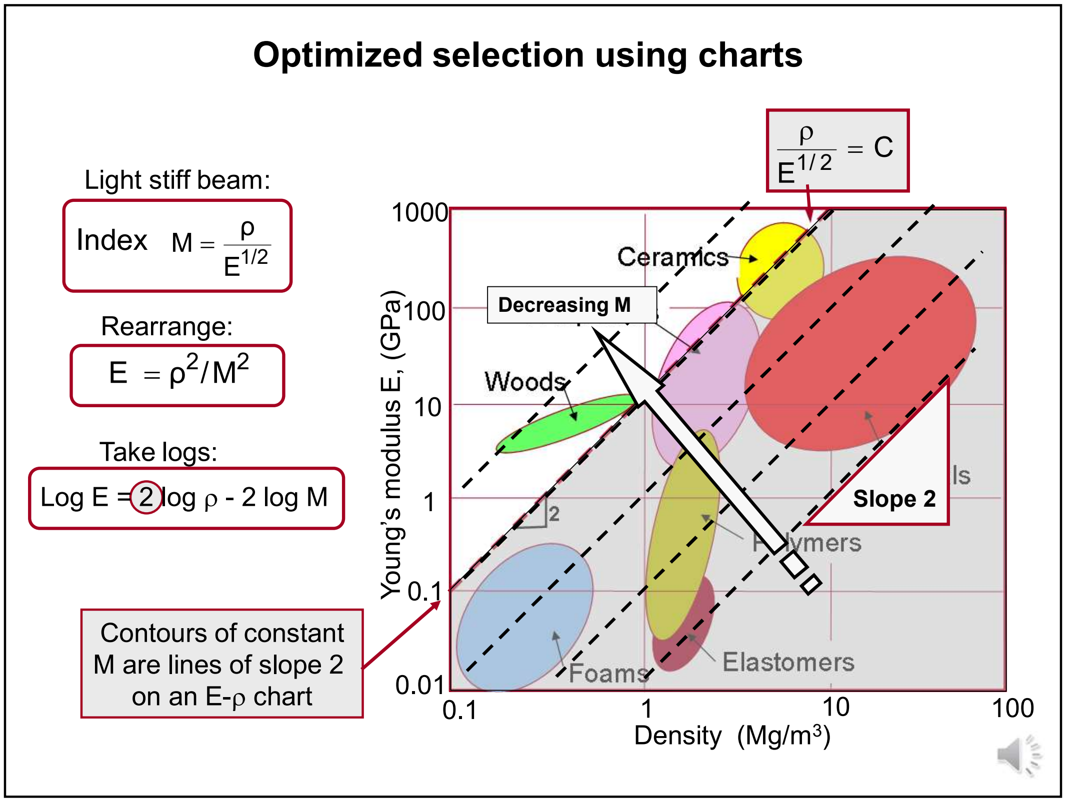
**The selection.** Applying the three indices to the CES Edu Level 1 or 2 database gives the top-ranked candidates listed below

| Index Material choice | Material choice |
|---|---|
| ***High*** $M_1 = E$ | • Metals: tungsten alloys, steels.<br>• Ceramics: SiC, $Si_3N_4$, $B_4C$ and AlN, but of course all are brittle. |
| ***High*** $M_2 = E/\rho$ | • Metals: aluminum, magnesium, titanium alloys and steels all have almost the same value of $E/\rho$<br>• Composites: CFRP<br>• Ceramics SiC, $Si_3N_4$, $B_4C$ and AlN |
| ***High*** $M_4 = E^{1/2}/\rho$ | • Metals: aluminum and magnesium alloys superior to all other metals.<br>• Composites: CFRP excels<br>• Ceramics: SiC, $Si_3N_4$, $B_4C$ and AlN |

## Materials indices: example of stiffness limited design

| FUNCTION and CONSTRAINTS | Maximize |
|---|---|
| **TIE (tensile strut)**<br>stiffness, length specified; section area free | $E/\rho$ |
| **SHAFT (loaded in torsion)** | |
| stiffness, length, shape specified, section area free | $G^{1/2}/\rho$ |
| stiffness, length, outer radius specified; wall thickness free | $G/\rho$ |
| stiffness, length, wall-thickness specified; outer radius free | $G^{1/3}/\rho$ |
| **BEAM (loaded in bending)** | |
| stiffness, length, shape specified; section area free | $E^{1/2}/\rho$ |
| stiffness, length, height specified; width free | $E/\rho$ |
| stiffness, length, width specified; height free | $E^{1/3}/\rho$ |
| **COLUMN (compression strut, failure by elastic buckling)**<br>buckling load, length, shape specified; section area free | $E^{1/2}/\rho$ |
| **PANEL (flat plate, loaded in bending)**<br>stiffness, length, width specified, thickness free | $E^{1/3}/\rho$ |
| **PLATE (flat plate, compressed in-plane, buckling failure)**<br>collapse load, length and width specified, thickness free | $E^{1/3}/\rho$ |
| **CYLINDER WITH INTERNAL PRESSURE**<br>elastic distortion, pressure and radius specified; wall thickness free | $E/\rho$ |
| **SPHERICAL SHELL WITH INTERNAL PRESSURE**<br>elastic distortion, pressure and radius specified, wall thickness free | $E/(1-\nu)\rho$ |

compare appendix
Ashby, “Materials Selection in
•Mechanical Design”

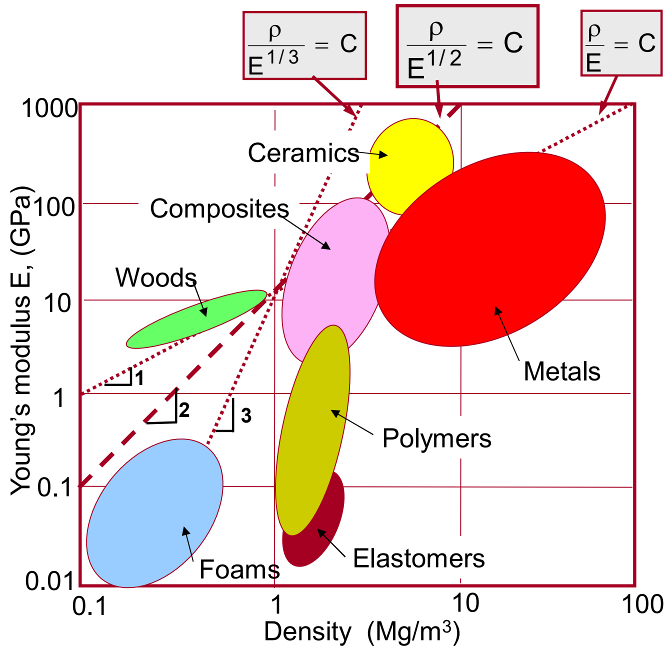


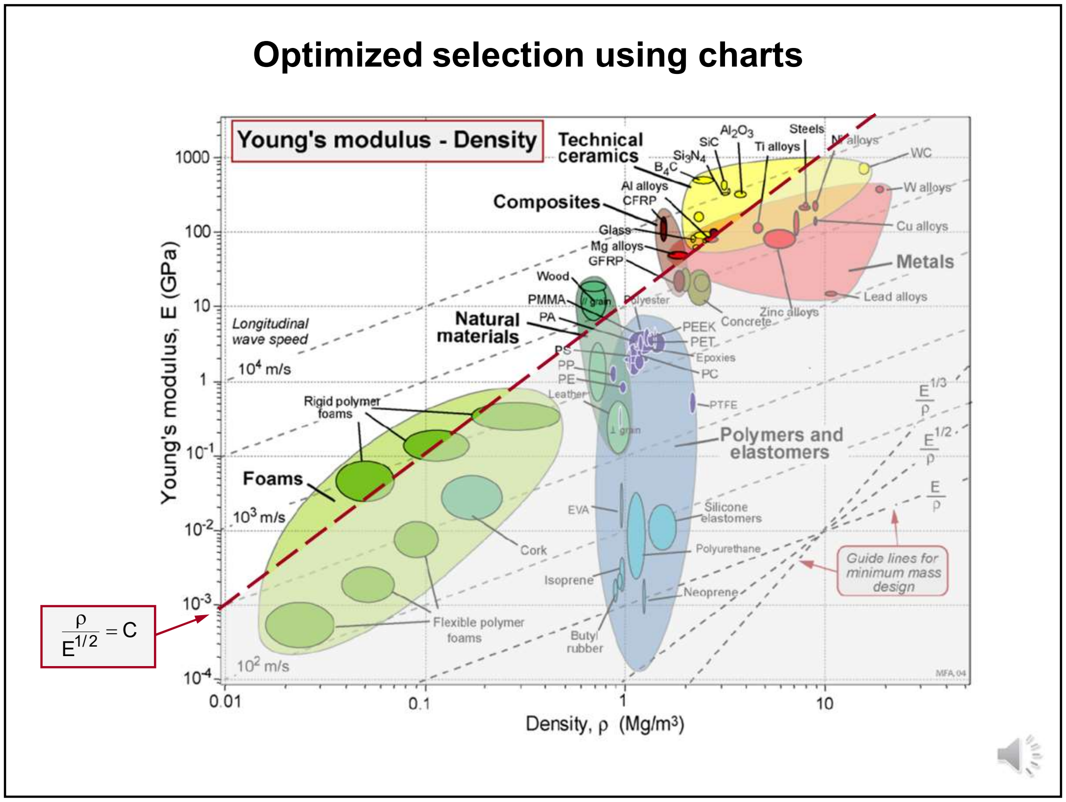

We take the index $M = \rho/E^{1/2}$ as an example (ρ is density and E is modulus). Rearranging and taking logs gives

$$Log(E) = 2Log(\rho) + 2\ Log(M)$$

The schematic shows the chart used in Unit 2; its axes are Log(E) and Log(ρ). The equation describes a **family of lines of slope 2**, each corresponding to a value of M. One such line is shown. Materials above the line have lower values of M than those below it; the ones above are the best choice. By moving the line upwards the number of materials above it decreases, narrowing the list of those that maximize performance. The other indices involving E and ρ can be shown on the same chart. The index $M = \rho/E$ appears as a line of slope 1; that for $M = \rho/E^{1/3}$ as a line of slope 3. They are used in the same way.

## Optimised selection using charts






This frame show **index-based selection** on a property chart. The selection can be done using a hard copy chart, as illustrated here. The EduPack software gives greater flexibility, allowing the selection line to be moved and additional constraints to be applied. It lists, in the Results window, the materials that meet all the selection criteria, and makes records for them immediately accessible. The list can be ranked by the value of any property used as a constraint or by the value of the index.

Here it is interesting to point out to students an interesting fact brought out by the method. Many components of aircraft are stiffness-limited – the wing spar is an example – and the objective here is to minimize mass. Materials texts often assert that, for aerospace, material with high specific modulus $E/\rho$ (low $\rho/E$ , the way we have done things here) are the best choice when stiffness is important. But aluminum and steel have the same value of specific stiffness, and steel is much cheaper that aluminum – so why are wing spars not made of steel? The answer is that they are loaded in bending, and then the correct criterion of choice is not $\rho/E$ but $\rho/E^{1/2}$ . By that criterion aluminum is much better than steel, as the chart shows.

# Outline

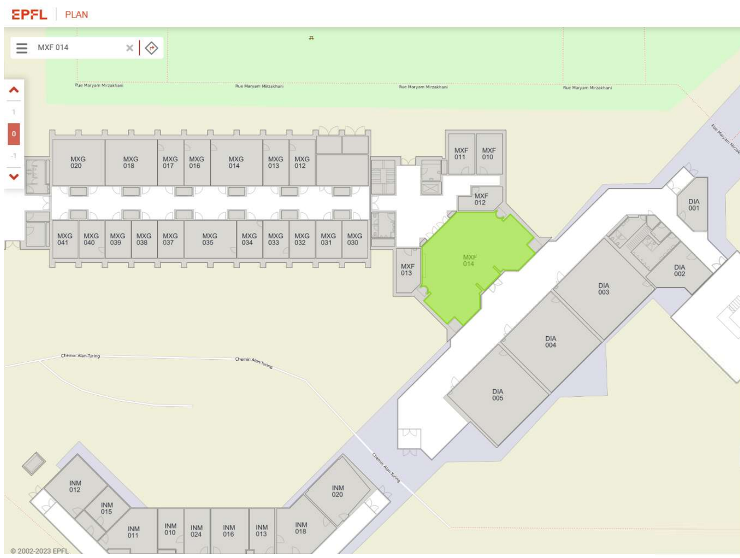
- **The EduPack and its use**
- ***Hands-on session 1, with exercises***



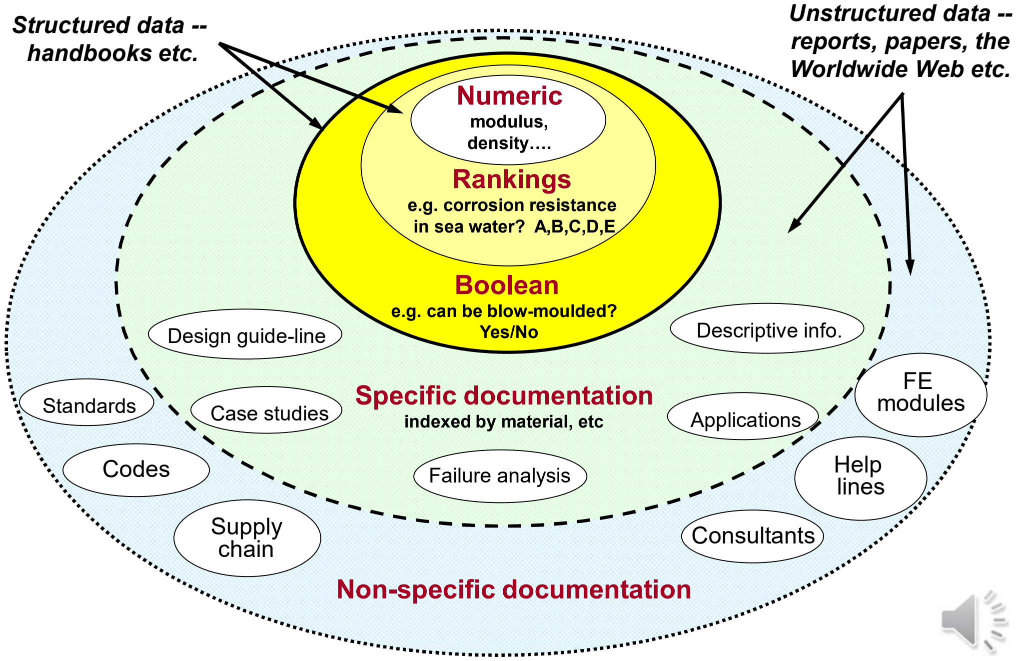

This is the first Unit of a course on **Material and Process Selection**. The Units link closely to the **Text** listed on this frame. The relevant chapters of the Text are listed on the Outline frame of each Unit. The methods developed in the course are implemented in the CES EduPack selection software, which is structured to evolve in pace with the student throughout a four-year engineering program. This first Unit introduces materials and processes, and the way in which information about them can be classified, stored, retrieved and explored. Each Unit ends with a set of examples for students to work through to develop facility with the software and understanding of methods.

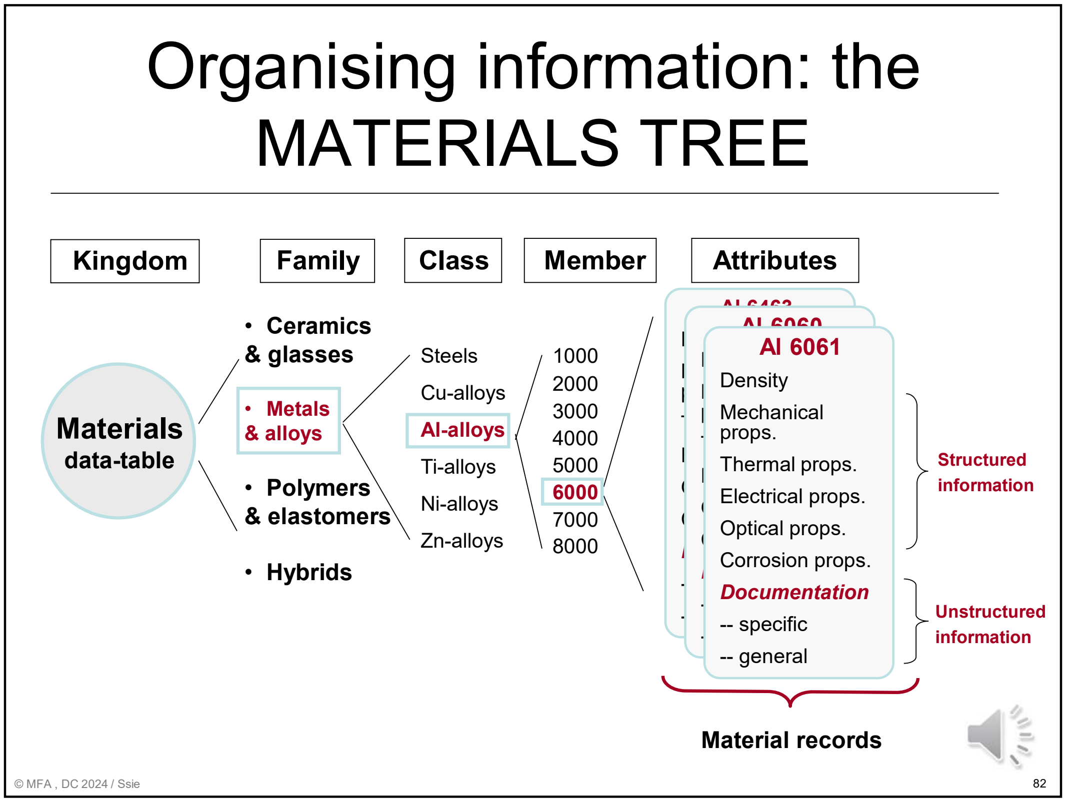
# Exercises:

in room MXF 014



# The nature of material (or process) data






Here we show a tree-like classification for materials, one typifying that used in handbooks and in the software described in a moment. The **kingdom** of materials contains the six **families** shown earlier. That for metals is partly expanded to show **classes**, each of which contains **sub-classes** (not shown) and – at the tips of the branches of the tree – **members**. Each member is characterized by a set of **attributes** – the numeric, non-numeric and supporting information that describes its properties and behavior. A listing of these attributes makes up a record for that material. Some of it is numeric and can be **structured** into tables. Some is in the form of text, images or graphs and cannot be organize in the same way. We refer to this as **unstructured data**.

# Structured information e.g. for ABS*

**Acrylonitrile-butadiene-styrene (ABS) - $(CH2\text{-}CH\text{-}C6H4)_n$**

### General Properties

| | | | | |
|---|---|---|---|---|
| Density | 1.05 | - | 1.07 | Mg/m^3 |
| Price | 2.1 | - | 2.3 | US $/kg |

### Mechanical Properties

| | | | | |
|---|---|---|---|---|
| Young's Modulus | 1.1 | - | 2.9 | GPa |
| Elastic Limit | 18 | - | 50 | MPa |
| Tensile Strength | 27 | - | 55 | MPa |
| Elongation | 6 | - | 8 | % |
| Hardness - Vickers | 6 | - | 15 | HV |
| Endurance Limit | 11 | - | 22 | MPa |
| Fracture Toughness | 1.2 | - | 4.2 | $MPa.m^{1/2}$ |

### Thermal Properties

| | | | | |
|---|---|---|---|---|
| Max Service Temp | 350 | - | 370 | K |
| Thermal Expansion | 70 | - | 75 | $10^{-6}/K$ |
| Specific Heat | 1500 | - | 1510 | J/kg.K |
| Thermal Conductivity | 0.17 | - | 0.24 | W/m.K |

### Electrical Properties

| | |
|---|---|
| Conductor or insulator? | Good insulator |

### Optical Properties

| | |
|---|---|
| Transparent or opaque? | Opaque |

### Corrosion and Wear Resistance

| | |
|---|---|
| Flammability | Average |
| Fresh Water | Good |
| Organic Solvents | Average |
| Oxidation at 500C | Very Poor |
| Sea Water | Good |
| Strong Acid | Good |
| Strong Alkalis | Good |
| UV | Good |
| Wear | Poor |

\+ **Processes**

*Using the *EduPack* Level 2 DB



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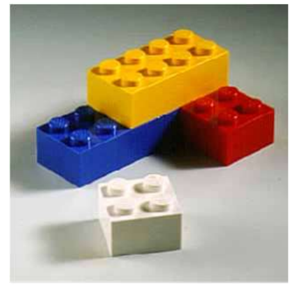
This is an example **structured data,** here for ABS. Numeric properties are reported as ranges (material properties have permitted range of values because of latitude in permitted compositions and methods of production). Non-numeric properties are shown as rankings: here, very poor, poor, average, good, very good. Ideally, structured data should contain no "holes" – missing data – because this compromises its use for selection. (The CES EduPack databases have no holes.) **Links** provide the connections to processes that can be applied to ABS.

# Unstructured information for ABS*

**What is it?** ABS (Acrylonitrile-butadiene-styrene ) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

**Design guidelines.** ABS has the highest impact resistance of all polymers. It takes color well. Integral metallics are possible (as in GE Plastics' Magix.) ABS is UV resistant for outdoor application if stabilizers are added. It is hygroscopic (may need to be oven dried before thermoforming) and can be damaged by petroleum-based machining oils.

ABS can be extruded, compression moulded or formed to sheet that is then vacuum thermo-formed. It can be joined by ultrasonic or hot-plate welding, or bonded with polyester, epoxy, isocyanate or nitrile-phenolic adhesives.



**Technical notes.** ABS is a terpolymer - one made by copolymerising 3 monomers: acrylonitrile, butadiene and syrene. The acrylonitrile gives thermal and chemical resistance, rubber-like butadiene gives ductility and strength, the styrene gives a glossy surface, ease of machining and a lower cost. In ASA, the butadiene component (which gives poor UV resistance) is replaced by an acrylic ester. Without the addition of butyl, ABS becomes, SAN - a similar material with lower impact resistance or toughness. It is the stiffest of the thermoplastics and has excellent resistance to acids, alkalis, salts and many solvents.

**Typical Uses.** Safety helmets; camper tops; automotive instrument panels and other interior components; pipe fittings; home-security devices and housings for small appliances; communications equipment; business machines; plumbing hardware; automobile grilles; wheel covers; mirror housings; refrigerator liners; luggage shells; tote trays; mower shrouds; boat hulls; large components for recreational vehicles; weather seals; glass beading; refrigerator breaker strips; conduit; pipe for drain-waste-vent (DWV) systems.

**The environment.** The acrylonitrile monomer is nasty stuff, almost as poisonous as cyanide. Once polymerized with styrene it becomes harmless. ABS is FDA compliant, can be recycled, and can be incinerated to recover the energy it contains.

*Using the *EduPack* Level 2 DB

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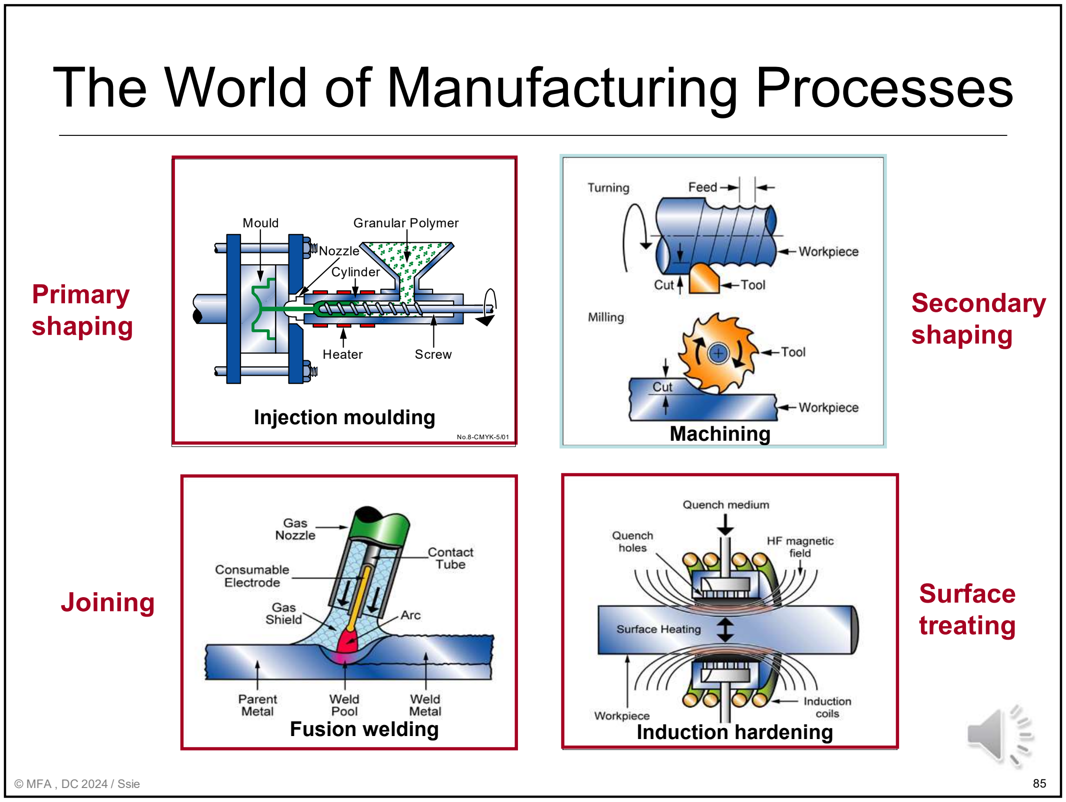
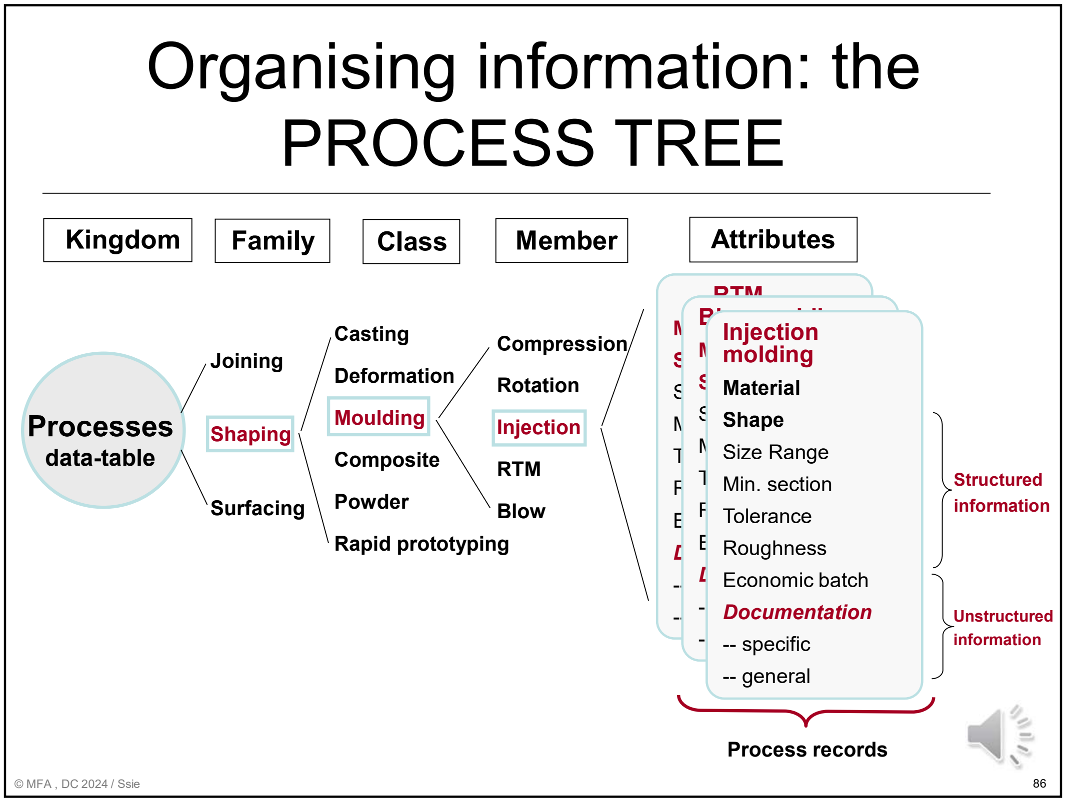
This is the other half of the story: **unstructured data**. It is text and image based, providing design guide-lines, environmental information, typical applications and warnings. The images captures much information: that ABS can be brightly colored and accept a high finish, that – since Lego is designed for small children – it is totally non-toxic and strong and wear resistant enough to survive the worst that children can do to it. All this is of primary use to the designer seeking a material for a new application.

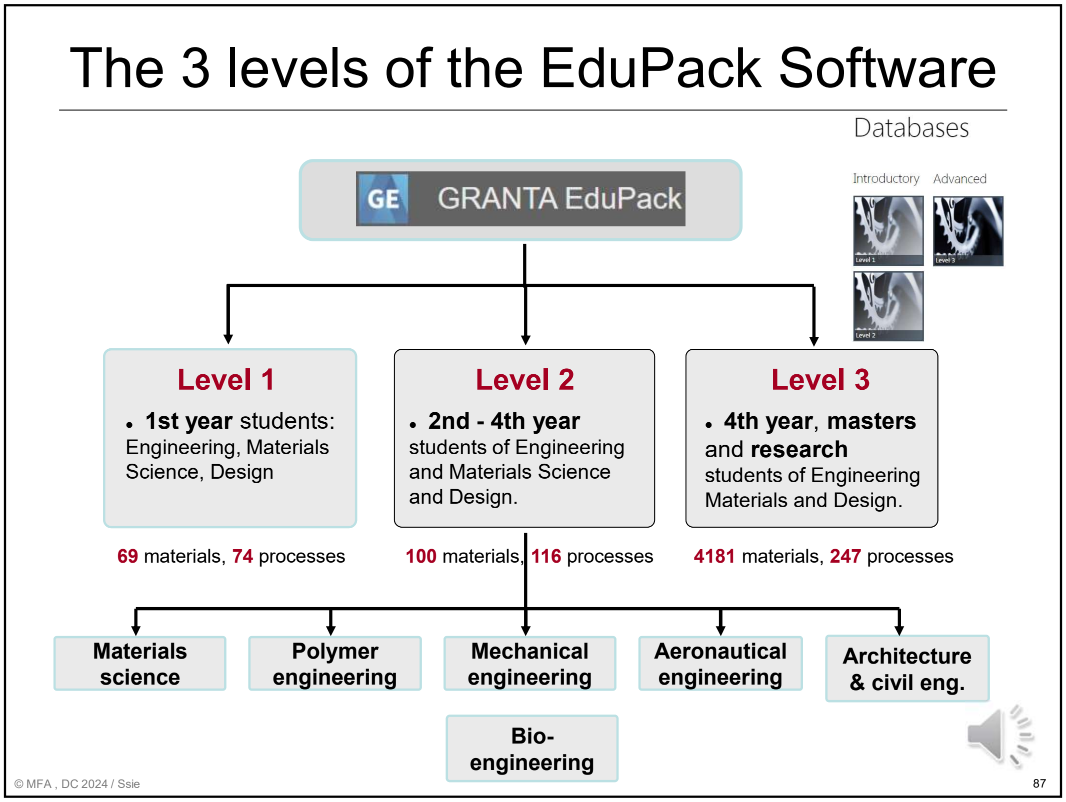



These schematics introduce the **three families** of manufacturing processes:

- those that **create shape**,
- those that **join** shapes together, and
- those that **coat, treat or finish** the surface.




Each material can be processed in a number of different ways. Here we digress for one frame to look at the **Process tree**, showing classification and data structure for manufacturing processes. To capture this information it is first necessary to structure data for processes. In the hierarchical structure shown here the kingdom of processes is divided into **families**. That for shaping is partly expanded to show **classes**: casting, molding and so on. In this schematic on of these – molding – is expanded to show **members**. Each member has certain **attributes**: the materials it can handle, the shapes it can make, their size, precision and cost. A list of these attributes makes up a record for the process. We return to processes in Unit 4, where their selection is discussed in detail.



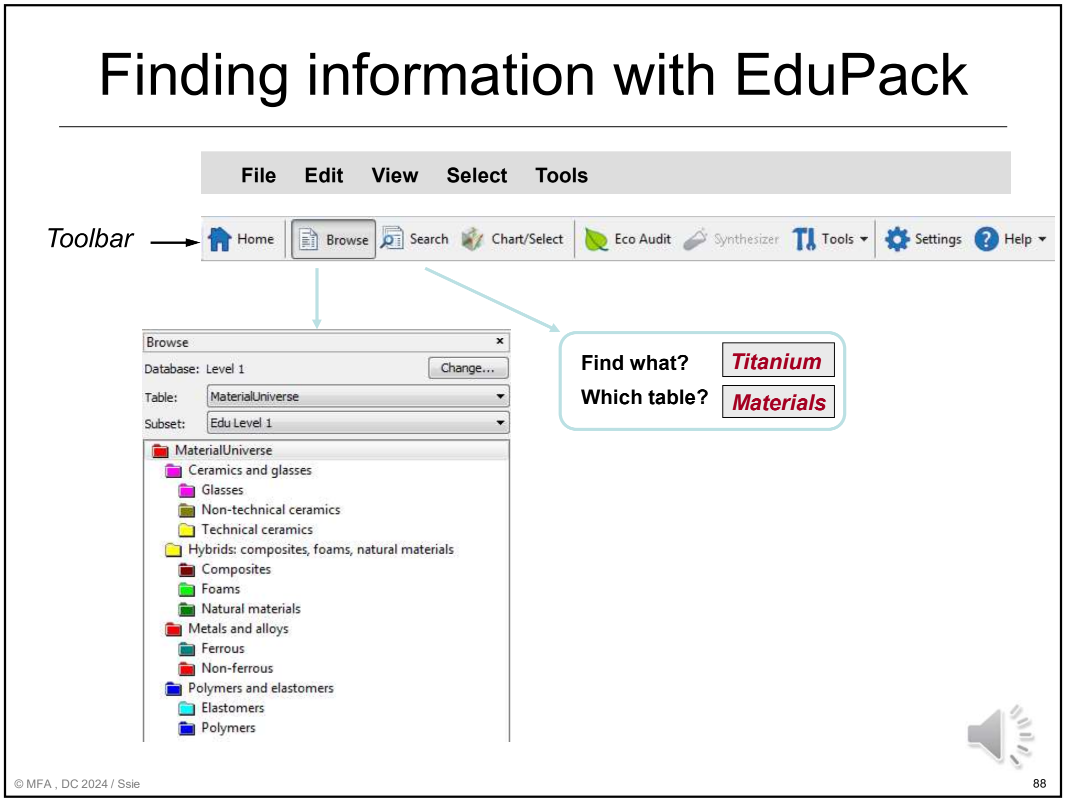

The software has 3 levels, allowing a progression from simple selection using a small number of materials, to advanced selection using very large databases of material and process attributes.

• **Level 1** is intended for an introductory course on materials. It contains records for 69 common structural materials and 74 processes drawn from all the families listed on earlier frames.

• **Level 2** has records for 100 materials and 115 processes with much more extensive data for each, including technical notes, design guidelines, environmental and economic notes. It allows more advanced teaching and projects.

• **Level 3** is much larger: over 3900 materials (with records for specific grades in specific states of heat treatment) and 240 processes. It allows real design problems to be tackled and solved.

All three levels provide supporting information through CES INDEPTH and WEBLINKS, introduced in Unit 3. The same selection engine accepts a range of other more specialized databases, including one for Eco design (it appears in Unit 6), the US Mil Handbook 5 (metals) and 17 (composites) data, and specialized databases for polymers, aerospace materials and more.

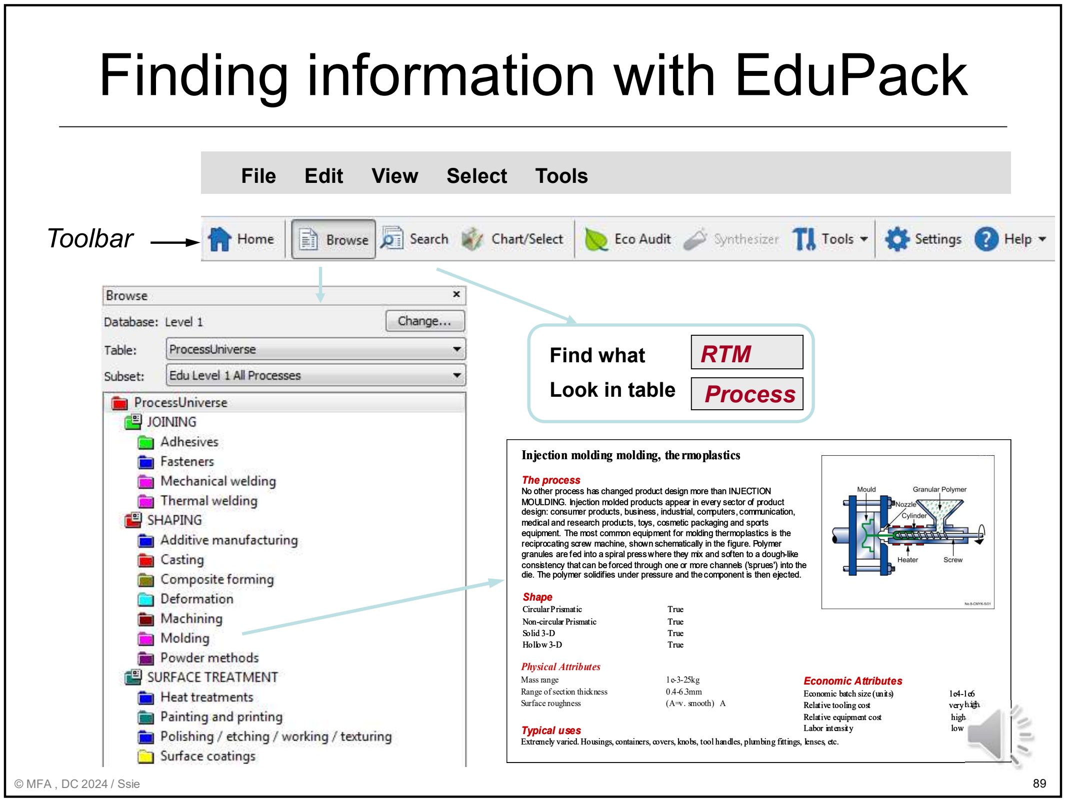



All three levels of the software use the same interface. This frame shows the principal tool bar and the function of two of its buttons (the others are described later).

• The **Browse** button lets you explore the contents of a data table by roaming through its "tree". When you click on the button, the first level of the tree (Families) appears. Each family can be expanded to show classes and members. Double clicking on a member opens its record.

• The **Search** button allows a full text search on part or all of the records in database, finding all records that contain a word or word-string entered by the user in the ***Find what***? box.

* (Resource book 1 of the EduPack gets students up to speed with the software quickly and efficiently.)

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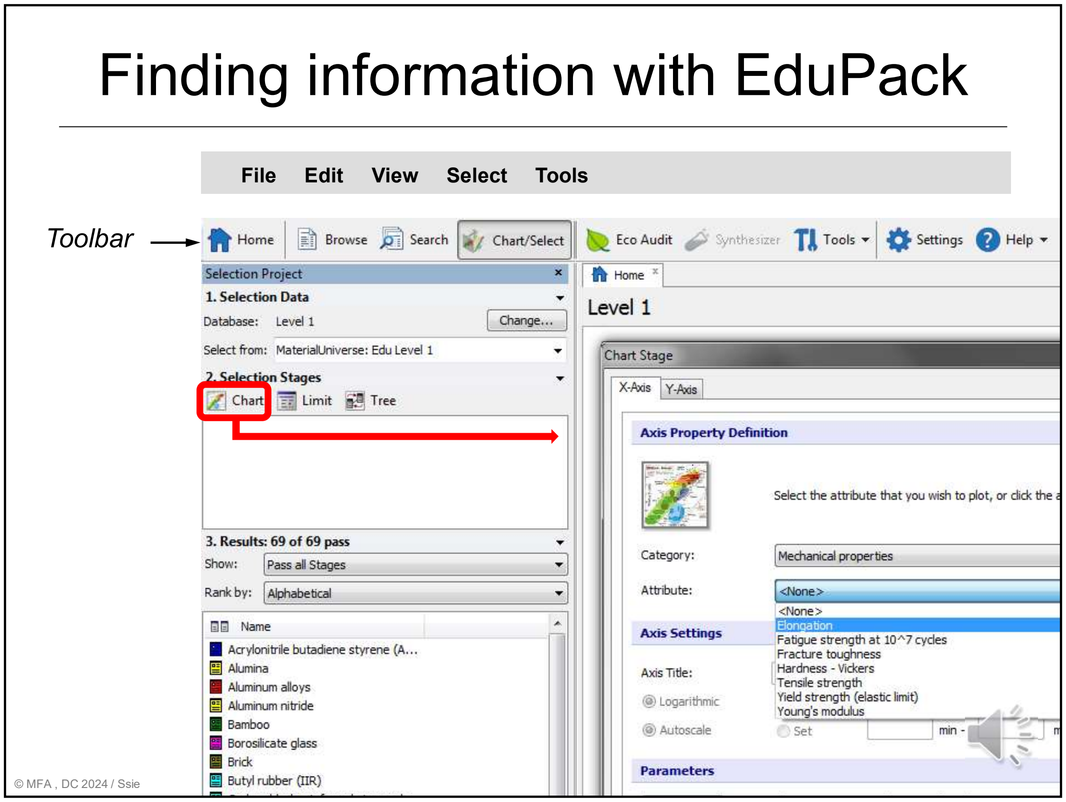
• The **Search** button allows a full text search on part or all of the records in database, finding all records that contain a word or word-string entered by the user in the ***Find what***? box.

* (Resource booklet 1 – a **Getting Started guide** – can be down loaded from the opening screen of the system. It allows students to get up to speed with the software quickly and efficiently.)

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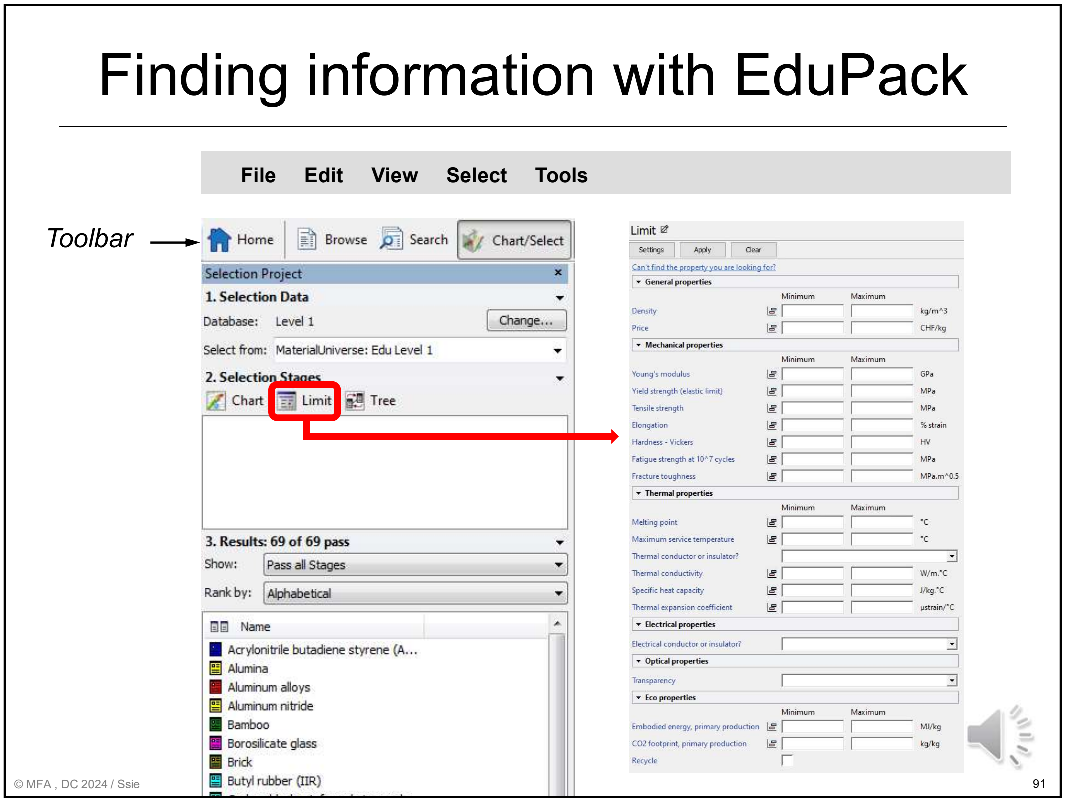


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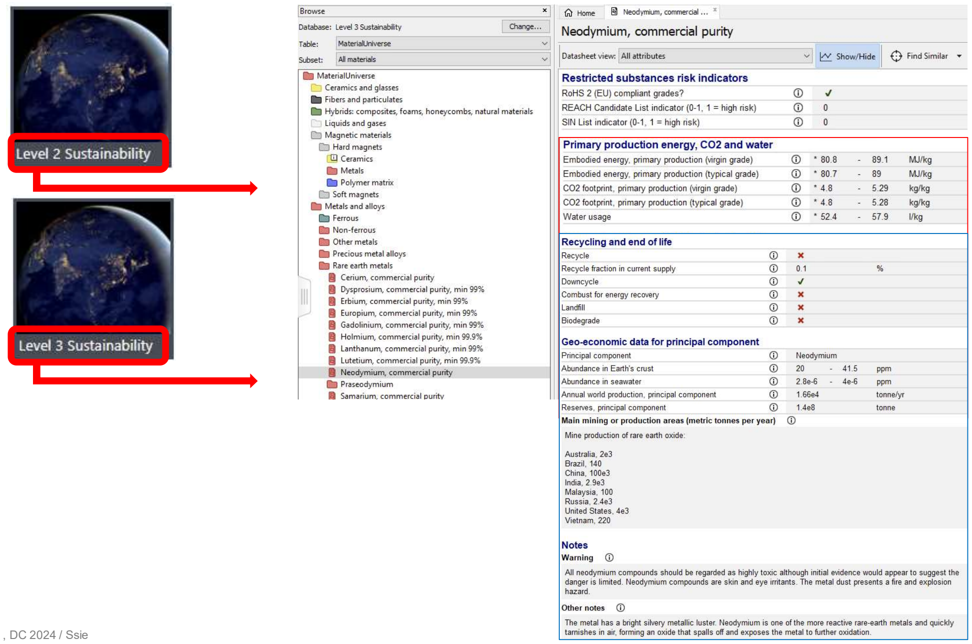
# Finding sustainability information







All three levels of the software use the same interface. This frame shows the principal tool bar and the function of two of its buttons (the others are described later).

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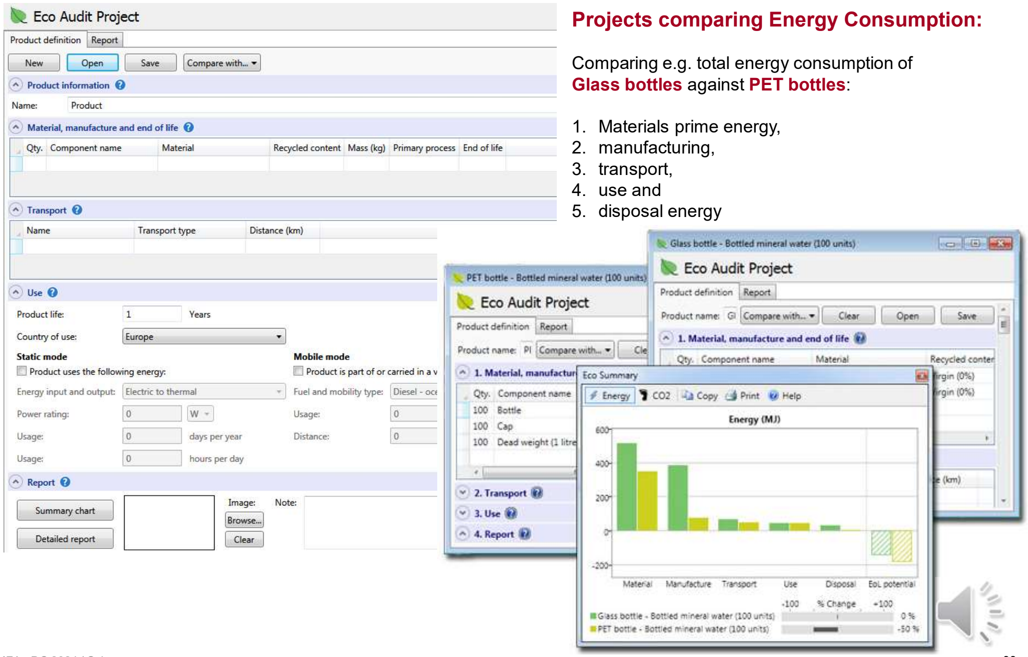
# Eco Audit Tool

**Projects comparing Energy Consumption:**

Comparing e.g. total energy consumption of **Glass bottles** against **PET bottles**:

1. Materials prime energy,
2. manufacturing,
3. transport,
4. use and
5. disposal energy

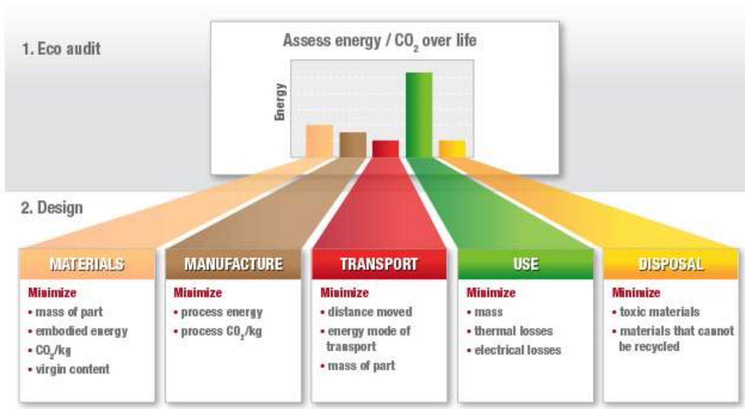


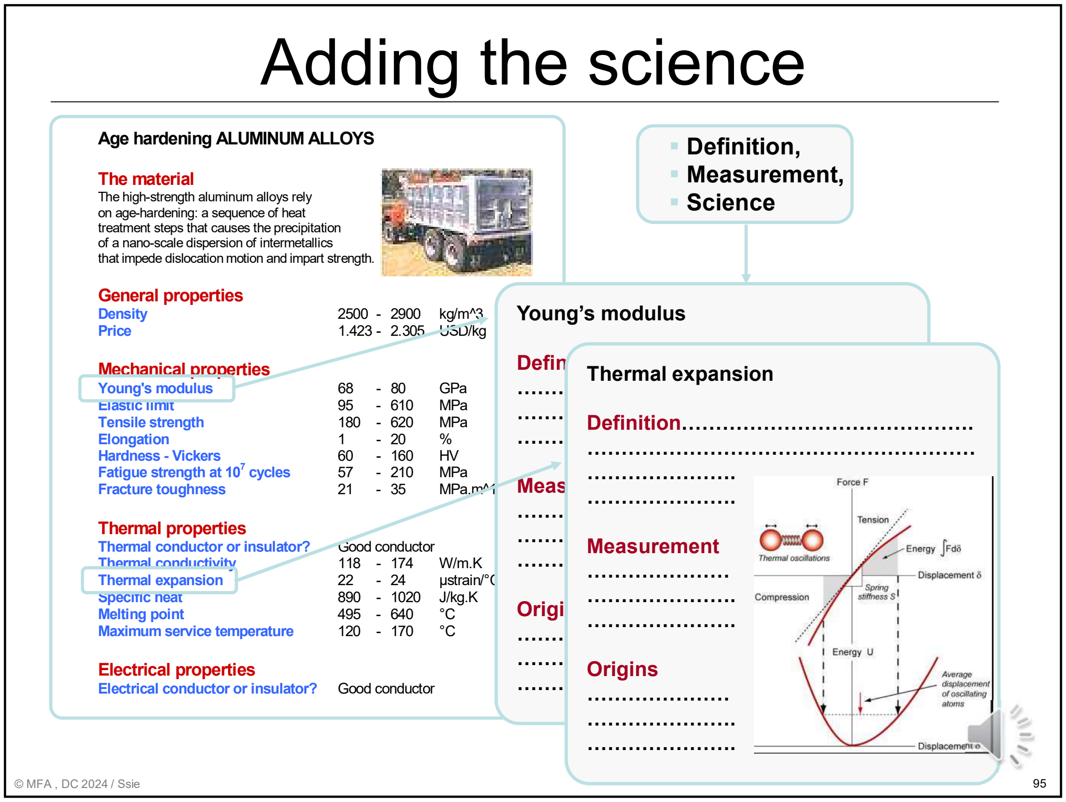
# Eco Audit Tool

**Optimisation**

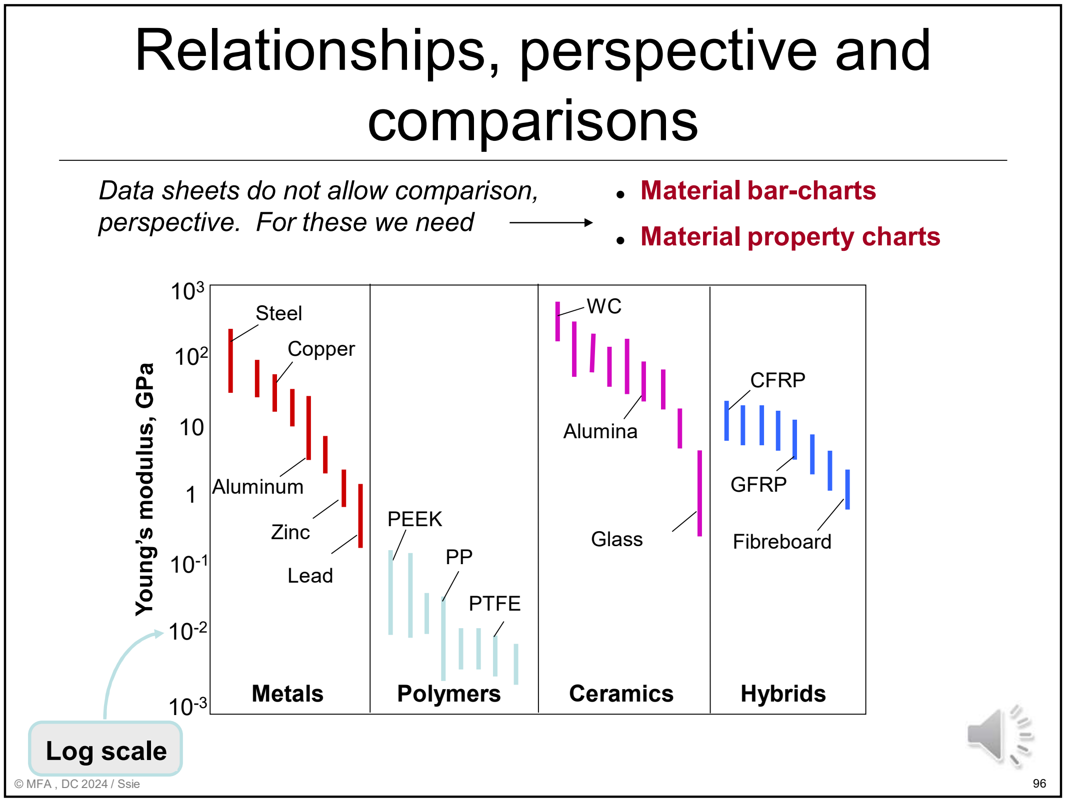
Minimize for:

1. Materials prime energy (e.g. mass, $CO_2$/kg),
2. Manufacturing (processing energy, $CO_2$/kg),
3. Transport (mass and distance moved),
4. Use (energy losses) and
5. Disposal



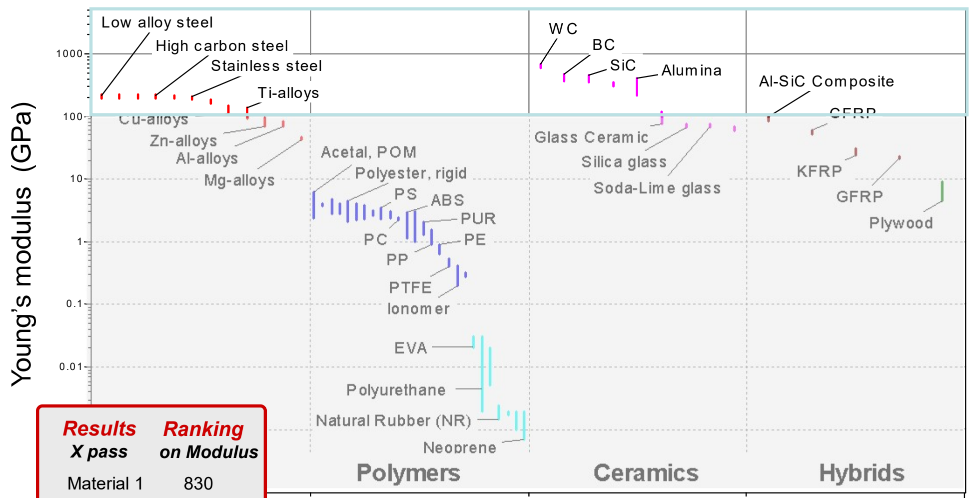



Each field name in a record for a material is linked to 3 or so pages of text and figures explaining how what it is, how it is measured and introducing the "**Materials Science**" behind the property.




Browsing or searching work well if you know which material or process you want. But they give no comparison or perspective of materials or processes in the database. The simplest way to compare materials is with **bar-charts**. Here each bar spans the range of the property (Young's modulus, E, in this schematic). It brings out the differences between material families, and – within a family – between its members.

# Bar-chart created with *EduPack* **(Level1**)

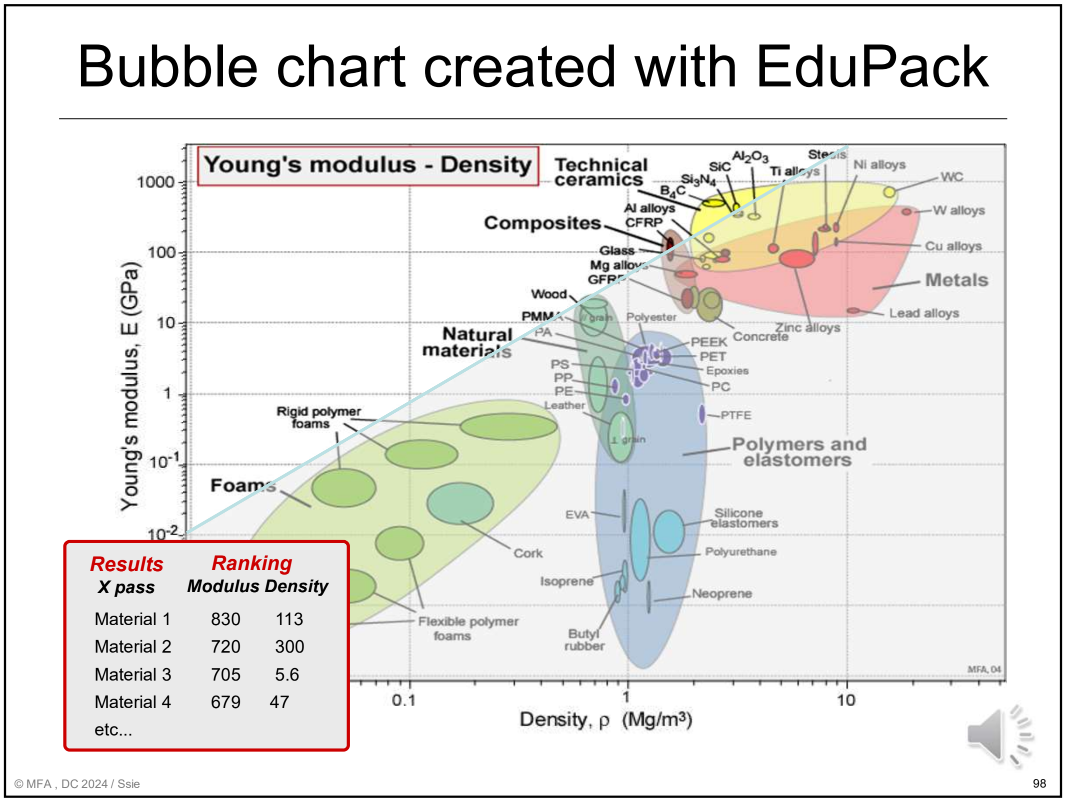



| ***Results*** ***X pass*** | ***Ranking*** ***on Modulus*** |
|---|---|
| Material 1 | 830 |
| Material 2 | 720 |
| Material 3 | 705 |
| Material 4 | 679 |
| etc... | |





Here is the same **bar-chart**, created using the CES EduPack software. The software allows the user to create bar-charts for any chosen property (or group of properties), to label the bars and to retrieve records for any material appearing on it. Bar-charts enable the simplest sort of selection – here it is possible to read-off materials that have a given value of E. Because CES contains all classes of material and all records are full (no missing data, or "holes"), none are overlooked in the selection.




A real **material property chart** with the same axes as the schematic of the last frame. Material families are enclosed in large bubbles, within which the material classes appear as smaller bubbles. Each occupies a characteristic area of the chart. This chart, made with the Level 1 CES database, has 64 materials plotted on it. A chart made with Level 3, with 2400 materials, has the same features.

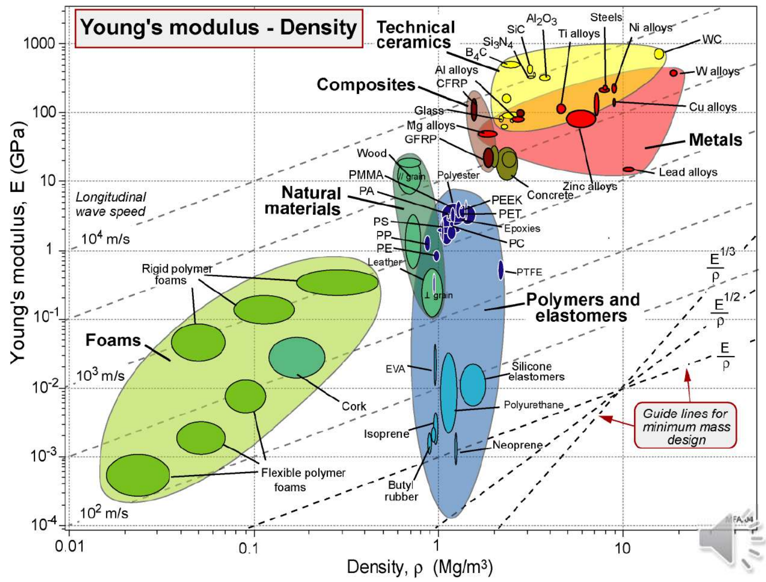
# Exploring the science:
# Mechanical properties

**Why the differences?**

- ***Atom size and weight***
- ***Bonds as (linear) springs***
- ***Spring constant for various bond types.***

**Manipulating properties**

- ***Making composites***
- ***Making foams***

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The charts can be used as a lead-in to ideas of materials science: the positions occupied by the families on the charts are explained through an understanding of inter-atomic bonding and crystal packing; other concepts of materials science explain their positions on the other charts. The notes attached to each field name introduce the property and its origins in more detail.

The Charts can be copied for teaching purposes without restriction from The Text, or downloaded from www.grantadesign.com.

The CES EduPack software allows any pair of properties to be plotted as a chart (even functions of properties can be plotted), giving enormous freedom to explore the world of materials visually.  This chart shows Young's modulus and density, as before.

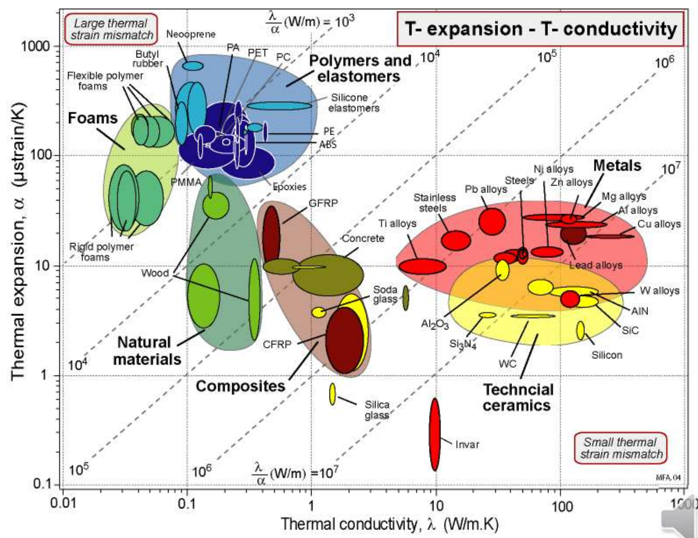
# Exploring the science:
## Thermal properties

**Why the differences?**

- ***Bonds as non-linear springs***
- ***10% expansion at melting point, so expansion goes inversely as Tm***
- ***Thermal energy as atom vibration, propagates as waves, scattered by obstacles***

**Manipulating properties**

- ***High conductivity: purity***
- ***Low conductivity, obstacles and foams***








A second example of the method, this time exploring **thermal properties**. These too have the feature that a given material family occupies a well-defined sub-region of the chart, often well separated from those occupied by other families. Again this provides a lead-in to the materials science, allowing a discussion of the mechanisms of conduction and the origins of thermal expansion.

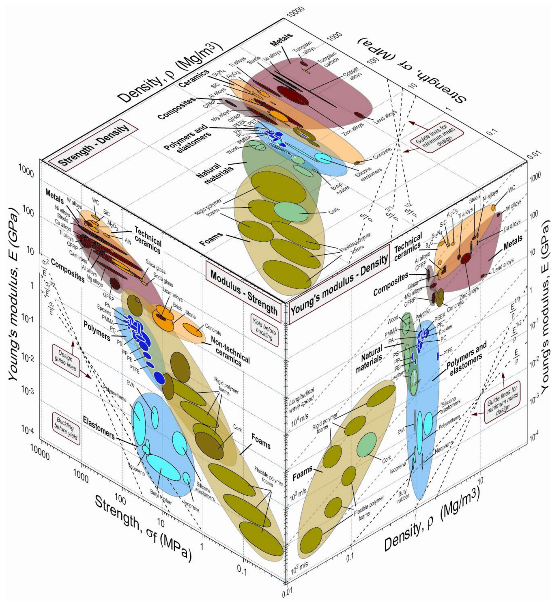
# Exploring the science: Space of materials

**Cube with properties leaves some spaces; Why?**

- ***Most of the properties have ranges***
- ***Pure materials are close (e.g. metals, ceramics)***

**How to fill "holes"?**

- ***Composites, Foams***
- ***Particles, Nanoparticles, Fibers (directional properties)***



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Why are metals and polymers, etc. there and not somewhere else?

Nature of atom size and weight

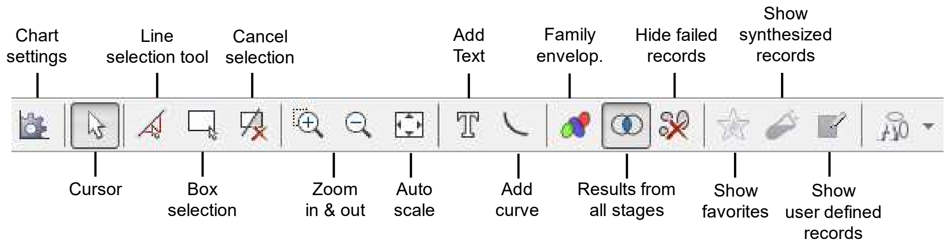
Bonds as (linear) springs; Spring constants for various

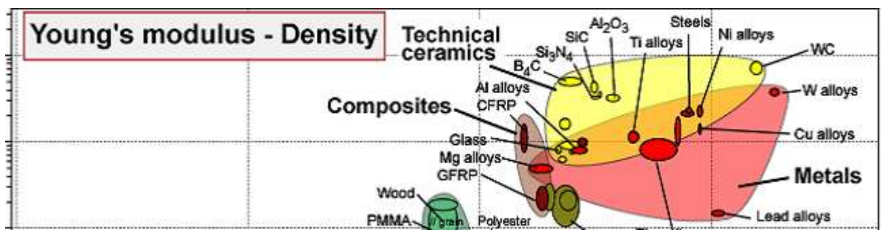
Manipulating properties -> Making composites, making foams

How to fill holes? Alloy development or other ways?

Even fibre and particles: -> Nanoparticles e.g. copper increase a factor of 10 (only) !

# The chart-management tool bar







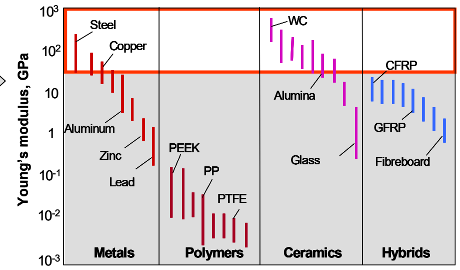
**The chart management tool bar** provides tools for

- Exploring the chart by zooming into selected areas of it
- Selection – applying a box or line selection, and removing it again
- Customizing the chart – adding text labels, adding envelopes round the families of materials, making materials that have failed other selection stages appear in grey or disappear altogether.

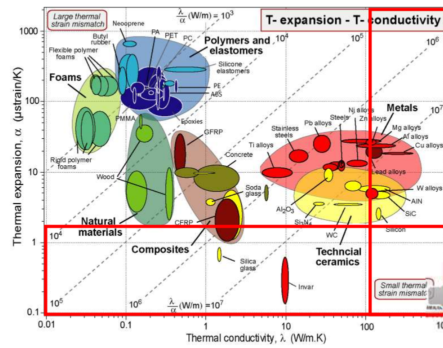
# Elementary selection

At this stage we have a **tool:**

- Materials with high stiffness?




- Materials with high thermal conductivity?

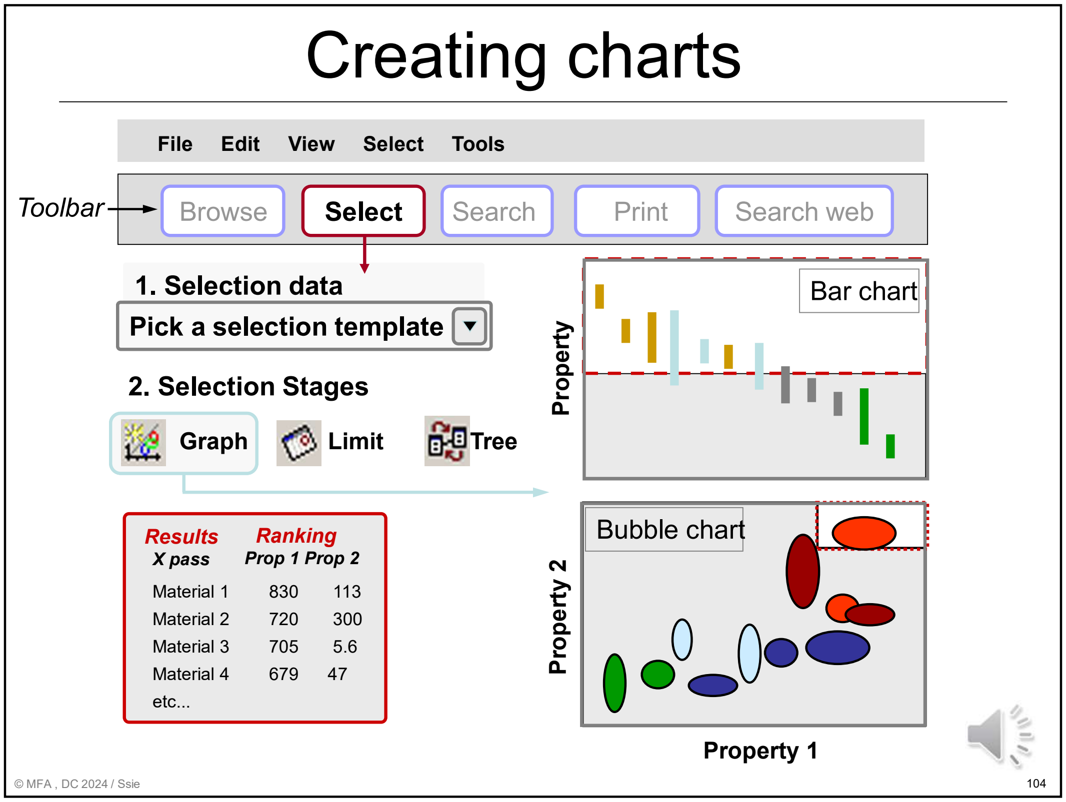



- Materials with low expansion?





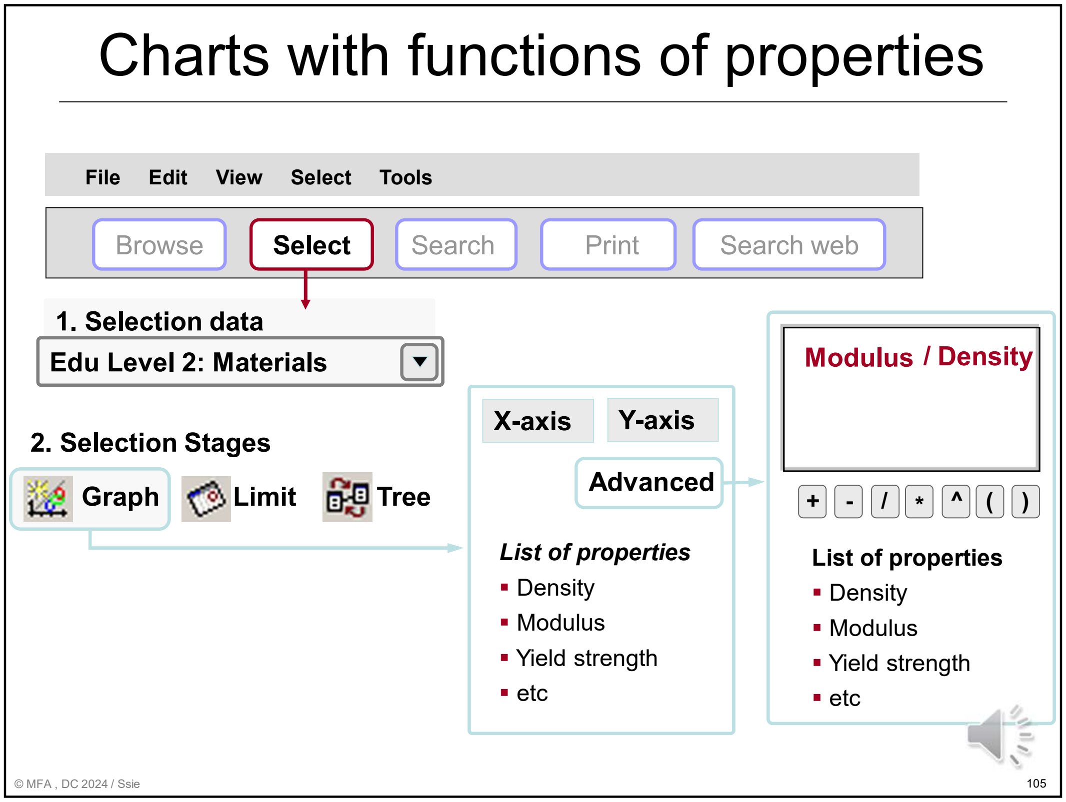
Even at this early stage the student has a **tool:** one allowing selection, from hard-copy charts like these, of materials with certain properties or combinations of properties. The charts also help develop a **perspective** of the materials world, building knowledge of where given material families and classes lie in material property space.




Charts like these are made using the **Select** button in the toolbar. Activating it leads to a dialog box asking you to choose what Level (1, 2 or 3) and which Universe (Materials or Processes) you want to plot. This brings up three options:

-  **Graph stage**
-  **Limit stage**
-  **Tree stage**

Select **Graph stage.** A dialog box then lets you select the properties you want to plot on the x and y-axes – one property for a bar-chart, two for a bubble chart. The chart appears with no labels; click on a bar or bubble to label it. Double click to show the record.




**Functions of properties**, such as Young's modulus / Density, are plotted by selecting the axis (x or y) for the function and using the Advanced option in the Graph stage dialog box to create it, as shown here. On closing the dialog boxes, the function of properties is plotted on the chosen axis.

# The main points

- **Visual presentation** of data as bar-charts and property (bubble) charts reveals relationships and allows comparisons
- **EduPack** allows a wide range of charts to be constructed
- **Box selection tool** allows elementary selection
- There are comprehensive **report-writing** facilities
- Databases can be **customized** to meet needs of projects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The central point of this Unit is the **visual presentation** of **materials data** and what can be learnt from it, both about the science of the material and about selection for design.