Manufacturing Technologies

Lecture 1 – Introduction and materials selection

Prof. Yves Bellouard
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EPFL

Contact

- **Pour me contacter** / yves.bellouard@epfl.ch
- **Bureaux**
  - La plupart du temps: Neuchâtel / MC A1 288 (Microcity)
  - De temps en temps: Lausanne **(sur rendez-vous, mercredi matin)** / ME B2 433 / ME B2 425
  - Limited mobility until end of March

- Utiliser de préférence l'email pour me contacter. J'essaierai de vous répondre dans les meilleurs délais. Mon bureau est sur Neuchâtel, mais je serai en général le mercredi matin également sur le campus de Lausanne.

- N'hésitez pas à contacter les assistants du cours également (voir page suivante pour les emails de contacts) en me mettant en copie.

Vos assistants 2025

- **Martin** Lentz / martin.lentz@epfl.ch
- **Antoine** Duret / antoine.duret@epfl.ch
- **Camar** Cheyto / camar.cheyto@epfl.ch

Etudiants-assistants:

- **Samm** De Bruyn / samm.debruyn@epfl.ch
- **Alexandre** Van Nam Dao / alexandre.dao@epfl.ch

Les assistants et les étudiants-assistants seront présents à partir de 15h00 et jusqu'à 17h00, les mercredis.

Les étudiants-assistants vous aideront pour réaliser vos expériences aux DLLs. Plus d'informations concernant ces expériences vous seront fournies durant le semestre.

Format du cours / Evaluation

- Les transparents seront en **anglais**…
- Le cours est donné en **français**…
- **Six questionnaires durant le semestre**
  - Une semaine sur deux
  - **10%** de la note finale / (moyenne des *quatre* meilleurs questionnaires)
- **Examen écrit**
  - **40%** de la note finale
- **Projet intégré à faire en cours ('reverse engineering')**
  - **50%** de la note finale répartie comme suit:
    - *40% - rapport*
    - *10% - 5 min vidéo tutorielle courte.*
- **Quatre heures** hebdomadaires sur 14 semaines

> ***Cours** / 13h15 – 15h00 in **PO 01***
> ***Exercices** / **Project** / 15h15 –17h00 in **PO 01***

Les transparents sont en anglais, mais le cours est donné en français (à l'exception des deux séances de cours du Prof. Subramanian). Le but est de vous préparer au mastère et à vous encourager à lire en anglais.

Pour l'examen, celui-ci est divisé en deux parties.

Une première partie qui comptera pour **50%** de la note finale est un projet de 'reverse engineering' que nous ferons tout au long du semestre. Le principe de ce projet et les conditions sont décrites dans un autre document. La note du projet est divisée comme suite: **40%** pour le rapport et **10%** pour une vidéo-tutoriel en relation avec l'objet étudié. Le rapport sera écrit en anglais (mais la qualité de l'anglais ne sera pas notée, sauf pour ceux qui ont choisi de suivre le module d'anglais). La vidéo-tutoriel peut être soit en anglais, soit en français. Nous vous recommandons de la faire en anglais pour vous préparer au mastère, mais ce n'est pas une obligation et le choix de la langue n'aura pas d'incidence sur la note.

La second partie qui elle comptera pour **50%** de la note finale est un examen sous forme d'un questionnaire Moodle en fin de semestre (**40%**) et un contrôle continu sous forme de quiz (**10%**). A noter que pendant l'examen en fin de semestre, les notes personnelles de cours et les exercices sont permis, ainsi qu'un calculateur de poche. Les quiz, au nombre de six, seront également fait sur Moodle. *La note des quiz est la moyenne des quatre meilleurs quiz du semestre.* La présence physique en classe est obligatoire et ces quiz ne peuvent pas être fait à distance.

Le cours comprend quatre heures hebdomadaires, divisées en deux. Les premières deux heures au Polydôme sont le cours proprement dit et les deux suivantes sont une semaine sur deux, les exercices, et une semaine sur deux le projet (en alternance).

Support pour le cours

- **Moodle** / Mise-à-jour avant le cours de la semaine
- **Ouvrages conseillés:**
  - **Materials Selection in Mechanical Design** / M.F. Ashby / Elsevier / Lien bibliothèque EPFL
  - **Manufacturing Engineering & Technology** / M.C. Shaw, P.K. Wright, S. Kalpakjian / Pearson Ed / Lien bibliothèque EPFL
- Beaucoup de resources sur Internet (Youtube // How things are made? etc.) – **Soyez curieux !**

L'ensemble de l'information sur le cours se trouve sur le Moodle. Pour en profiter pleinement, il est conseillé de le consulter à partir d'un PC portable ou d'une tablette, plutôt que d'un téléphone portable.

Deux ouvrages sur le sujet sont conseillés à titre informatif et peuvent être trouvés à la bibliothèque de l'EPFL. A ce jour, il n'y a pas d'ouvrage qui suive exactement le contenu du cours.

Nous recommandons également de consulter les nombreux sites sur internet et en particulier, les clips sur YouTube décrivant différents procédés de fabrication. Par exemple, la série 'How things are made?' est, en général, très bien faite. Bien sûr vous devez exercer votre esprit critique par rapport à ces informations.

Tout au long de semestre, nous fournirons des liens pour illustrer certains procédés que nous décrirons pendant le cours.

Overall planning for the class

MICRO-301 - Manufacturing Technologies Course **2025**

Lecturers	**Prof. Yves Bellouard (YB) / Prof Vivek Subramanian (VS)**	
TAs	*Antoine Duret, Martin Lentz, Camar Cheyto*	Lecture given in French
Etudiants assistants	*Samm de Bruyn, Alexandre Van Nam Dao*	Lecture given in English

Room	PO 01	**13h15 - 15h00**		**15h15 - 17h00**	
#	**Date**	**Lecture content**	**Lecturer**	**Suggested exercises**	**Revese engineering project**
1	19-Feb	Introduction	YB	*Exercise I*	Learning objectives
2	26-Feb	Surfaces	YB	*Exercises II-IV*	
3	05-Mar	Laser manufacturing	YB	*Quiz I*	Session 1
4	12-Mar	Metal forming	YB	*Exercises V-IX*	
5	19-Mar	Casting and molding	YB	*Quiz II*	Session 2
6	26-Mar	Conventional machining	YB	*Excercises X-XIII*	
7	02-Apr	Unconventional machining process	YB	*Quiz III*	Session 3
8	09-Apr	Polymers and related processing methods	YB	*Exercises XIV-XV*	
9	16-Apr	Manufacturing economics and process monitoring	YB	*Quiz IV*	Session 4
	23-Apr	Pâques			
10	30-Apr	Assembly processes	YB	*Exercises XVI-XXI*	
11	07-May	Electronics integration	VS	*Quiz V*	Session 5
12	14-May	Multiscale integration / packaging	VS	*Exercises XXII-XXIV*	
13	21-May	Introduction to additive manufacturing	YB	*Quiz VI*	Session 6
14	29-May	Sustainability and life cycle analysis	YB		Session 7
15	05-Jun	**Deadline for submitting the report**			

Updated 18/02/2025

English course (Optional)

- Barbara Althaus
- Kristin Andrikopoulos

A unique opportunity not only to improve your English skills while applying in a technological context!

Engage in a discussion over sustainability in manufacturing

La suite de vos études s'effectuera en anglais et donc la maîtrise de cette langue est un atout pas seulement pour vos études, mais également pour votre vie professionnelle future.

L'idée de ce module est de donner une chance à ceux qui souhaiterait le faire, d'améliorer leur anglais écrit et oral dans un contexte de conversation technique.

C'est un module à part, qui ne fait pas partie du cursus MT en tant que tel. Vous recevrez à l'issue de ce module un certificat de capacité linguistique que vous pourrez valoriser dans votre curricula.

Importance of manufacturing in Switzerland and beyond…

- High number of jobs in the country **(~ 20 %** is more or less related to it)
- **'Swiss expertise'**
- Strong push worldwide (initiatives in Europe, USA, Asia, …)
- ***This is not 'old science'*** – Hot research topic…

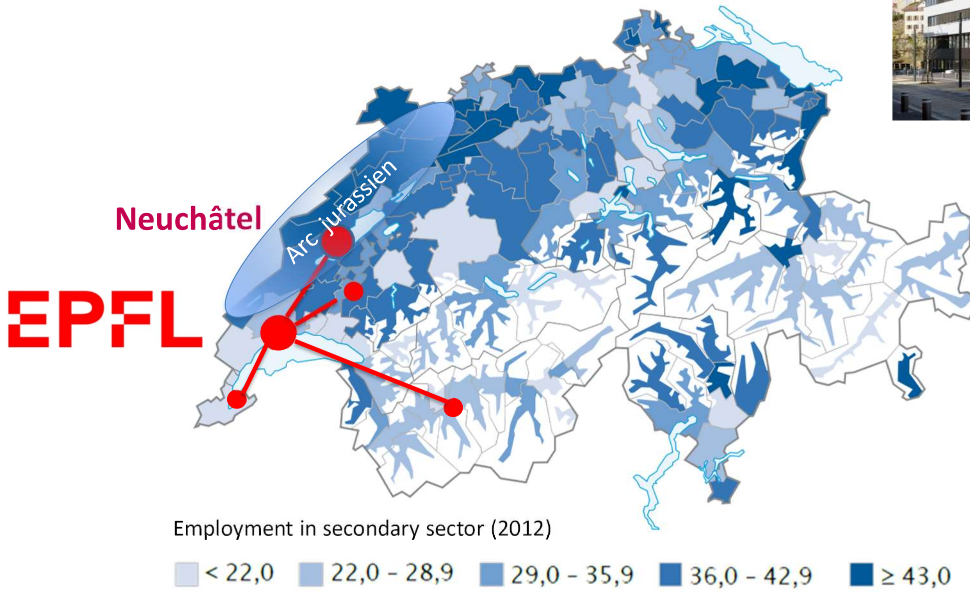
As an introduction, we would like to stress the importance of manufacturing for the Swiss economy where it represents a significant part of the GDP as well as an important number share of the job market.

Switzerland has a long tradition in this field. In microengineering, it somehow originated from the watchmakers and expanded into other fields such as Medtech and fine mechanics in general.

With the recent political push for renewing local productions as opposed to delocalizing it in low labor-cost markets, there has been a regain of interest for the topic and, in particular, for novel methods related to advanced manufacturing, such additive manufacturing.

It is not an 'old' science topic, but a vibrant one, with large amount of ongoing initiatives worldwide.

Major manufacturing groups active in watchmaking and Medtech >75% of jobs in highly specialized SMEs



Source: Federal Office of Statistics, February 2015

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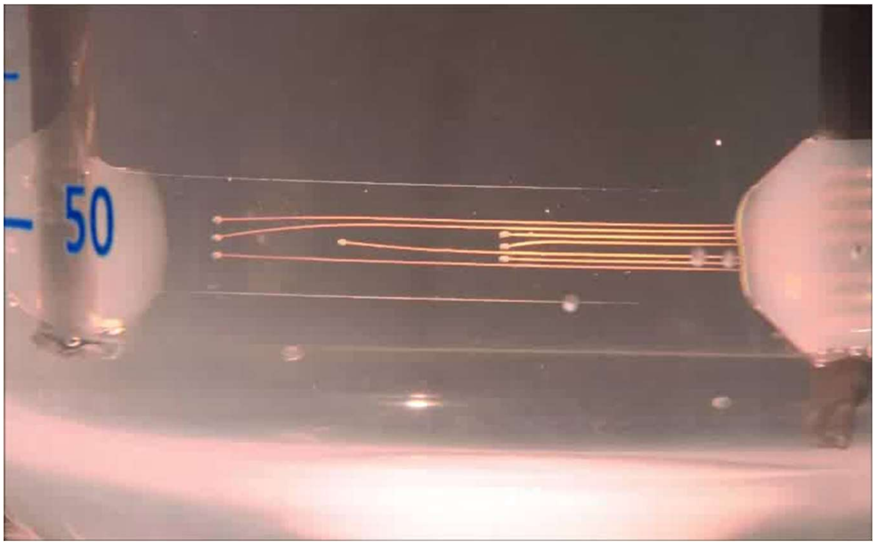
This is a map of Switzerland showing the geographical distribution of the secondary sector work force. The biggest share is specifically located in the Jura arc, notably around the canton de Neuchâtel.

Note that 75% of high-skilled workers in this sector are in highly specialized SMEs.

A few illustrative examples of manufacturing research @ EPFL

Mastering 'undeformable material' deformation …

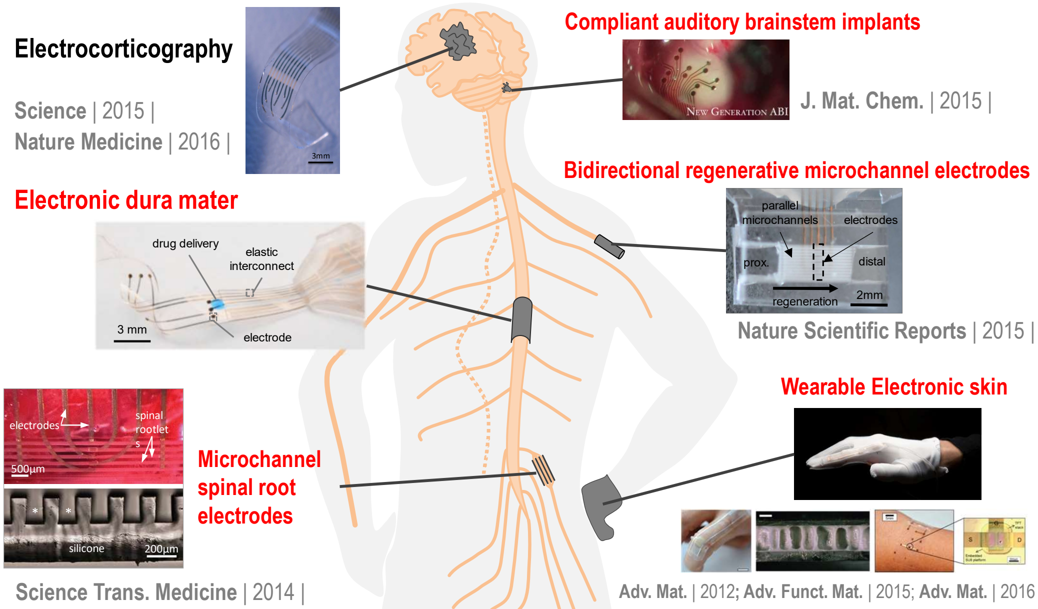


Prof. S. Lacour's lab

This is a sampling of the research in manufacturing being done at EPFL where the goal is to find a combination of soft materials and metals that can withstand high deformation, while maintaining an electrical contact.

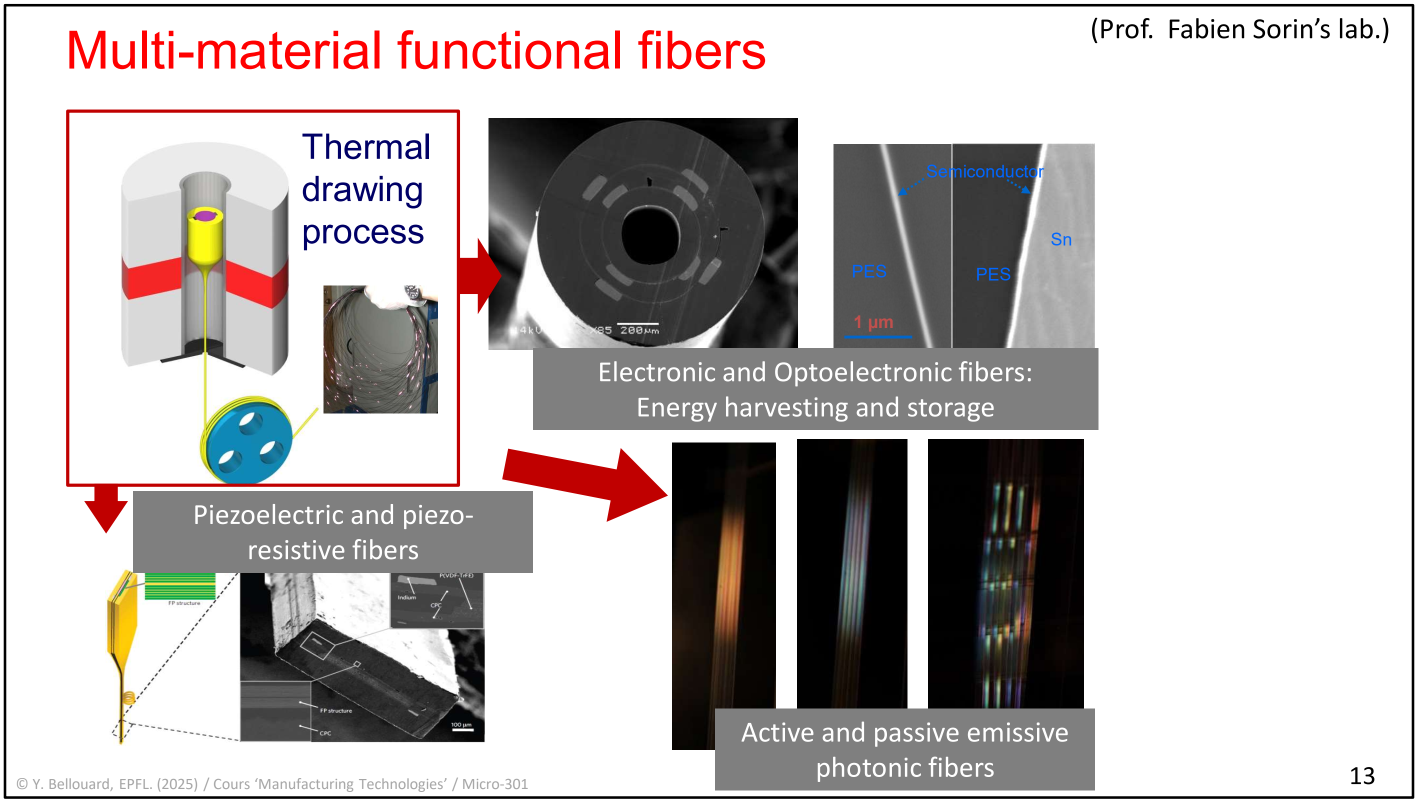
This specific research is done in the laboratory of Prof. Stéphanie Lacour.

... enables new field of soft bioelectronic Interfaces

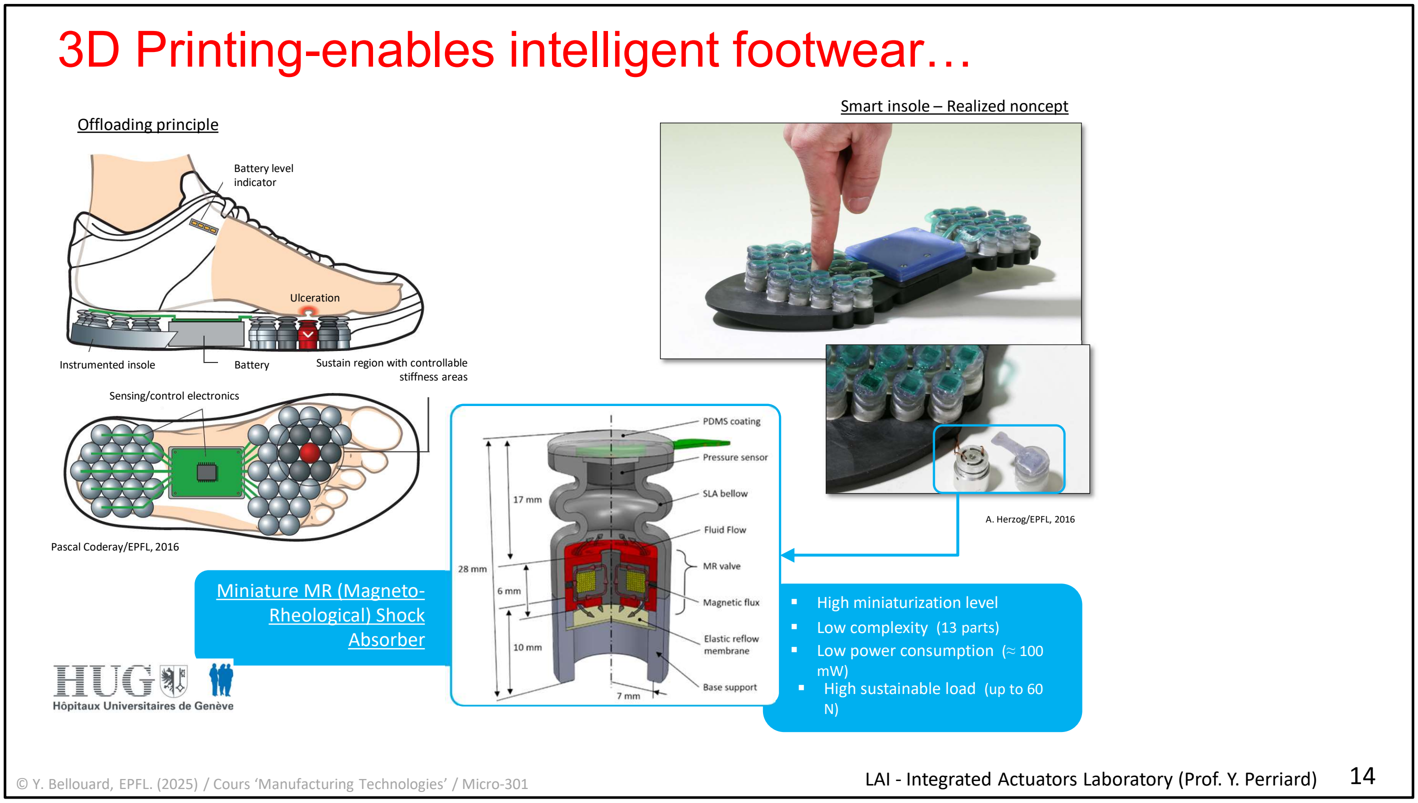


(Profs. S. Lacour's lab / & Courtine's lab) 12

Mastering the processing of metal/soft materials interfaces enables a variety of applications for implantable devices in the human body that may help restoring lost functions as illustrated here.

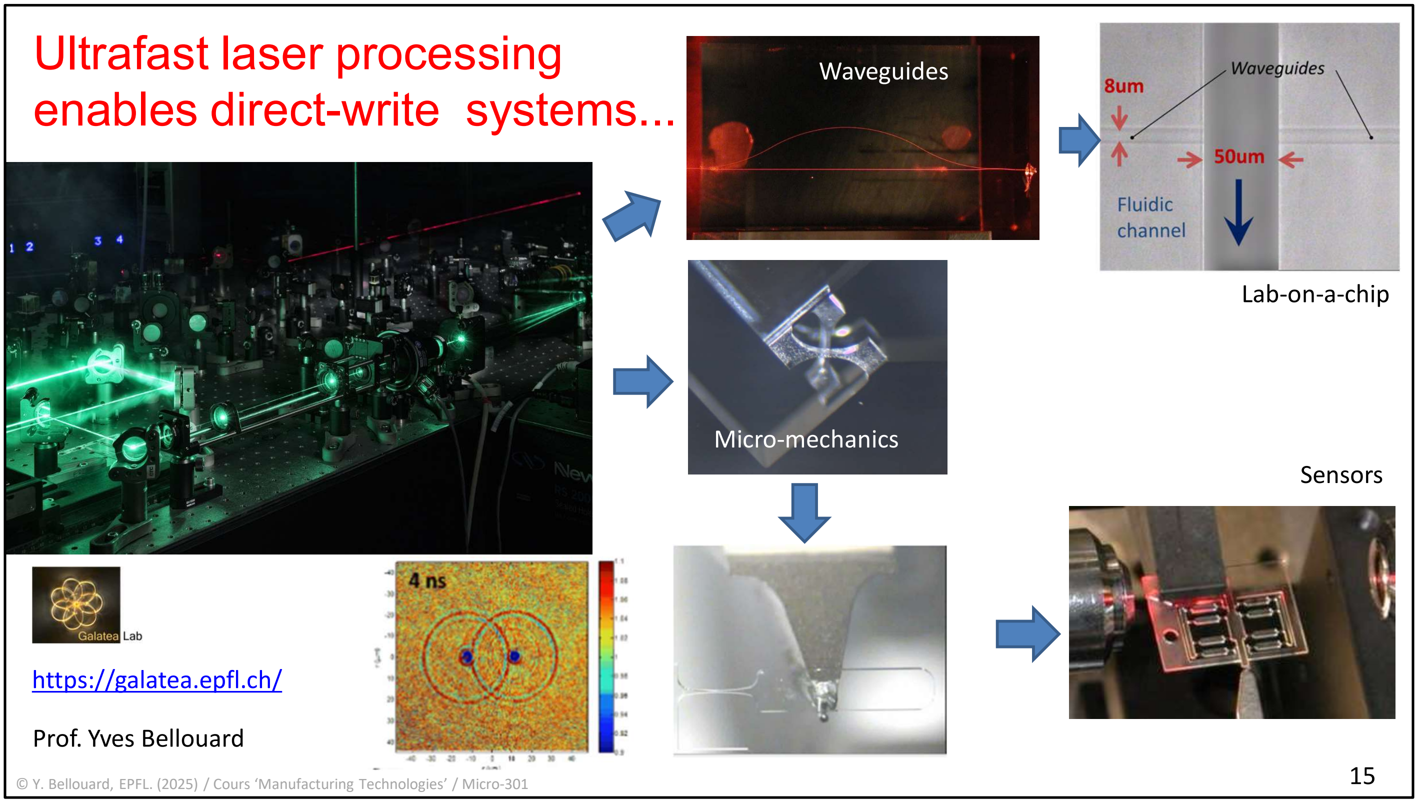


Thermal drawing is a common process used for pulling fibers out of a melt. In the lab of Prof. Fabien Sorin, they investigate an extension of this process, so that more complex devices can be produced, like for instance fibers combining different materials to achieve more specific functions.



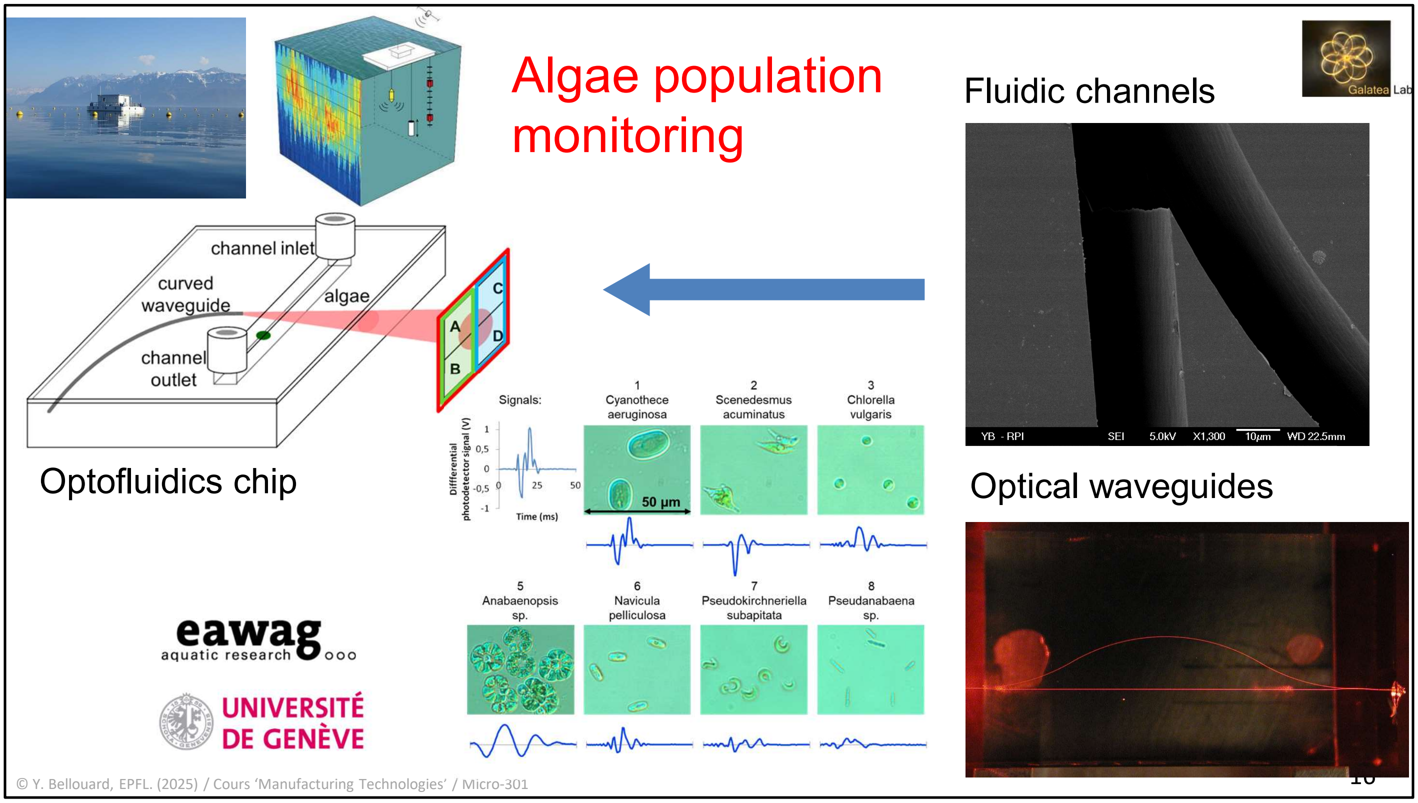
This is an example of research in mechatronics, where additive manufacturing enables new possibilities and new design options.

In this example, studied in the laboratory of Prof. Yves Perriard, 3D-printing helps producing a complex structure with some compliance and that integrated the actuator and sensing element in it. This shoe integrates many of these elements to help preventing overpressure on ulceration for diabetic patients who are otherwise no longer able to feel the pain.



These are a few examples of the research done in the Galatea Lab that I am heading at EPFL (https://galatea.epfl.ch/).

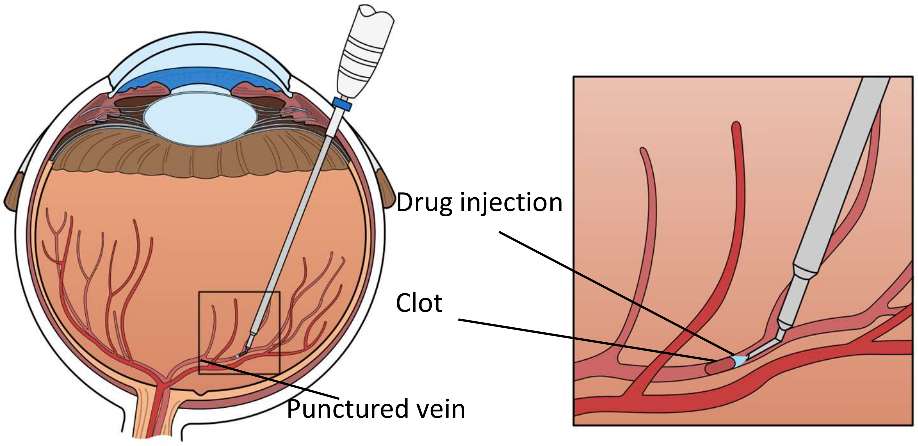
We studied femtosecond laser-matter interaction with the objectives of finding new applications in micro-manufacturing and in microengineering in general. In particular, we are interested in the monolithic integration of optical, fluidics and/or mechanical functions in a same substrate.

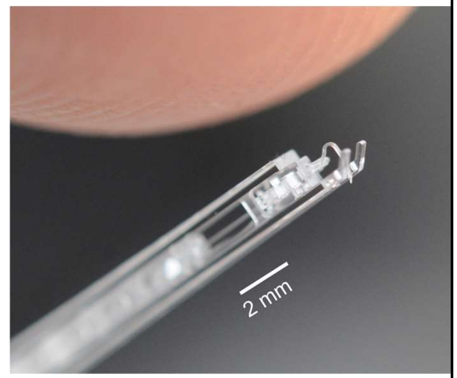


An illustration on how the field ultrafast laser manufacturing can be used in real life. Here, the application is a 'lab-on-a-chip' device that is used to monitor and identify algae species present in the Geneva Lake.

The importance of this research is to help biologists to understand the impact of climate change on the lake ecology and its long-term evolution.

Illustration: Retinal vein canulation





Hôpital ophtalmique Jules-Gonin

FEMTOprint
3D printing for glass microdevices

INSTANT-LAB

Galatea Lab

Another illustration of the use of three-dimensional laser processing in the context of medical applications.

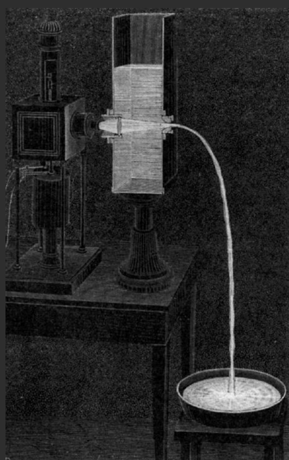
The microdevice is used to investigate future procedures to cure retinal vein clot that are currently uncured or rarely cured, due to the complexity of the disease. This disease is severe and most often leads to blindness.

The micro-needle is planned to be used as a means to inject drugs in the vein, so that the clot is washed away.

Manufacturing is an enabler for product innovations…

From a concept…

… to a mass product



(Colladon 1842)

(Fiber drawing tower, ORC, Univ. of Southampton)

Finding new manufacturing processes enables innovations!

This is very important to realize the connection between manufacturing and innovations.

Here is an example illustrating this idea. The concept of guiding light through a 'light-pipe' dates from 1842 and was demonstrated by injecting light in a water fountain dripping out of a bucket.

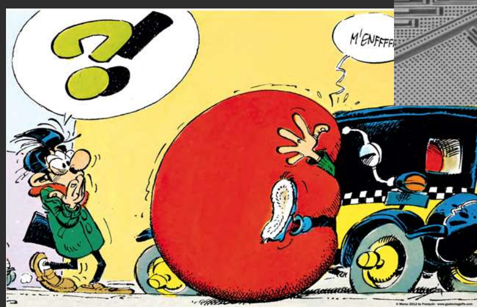
To guide light, one needs two media, a higher index one embedded into a lower index one. It is not until the discovery of fiber drawing and glass doping that it was possible to produce such element that would guide light permanently.

Innovation in fiber drawing have triggered the invention of the optical fiber, which has revolutionized today's world.

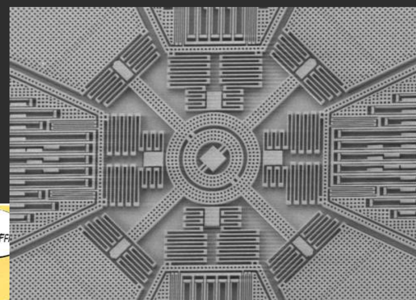
(The illustration of fiber drawing tower is taken from a lab at the Univ. of Southampton.)

Manufacturing is an enabler for product innovations…

From a concept…



(Franquin, 70s, Dargaud)



… to a product

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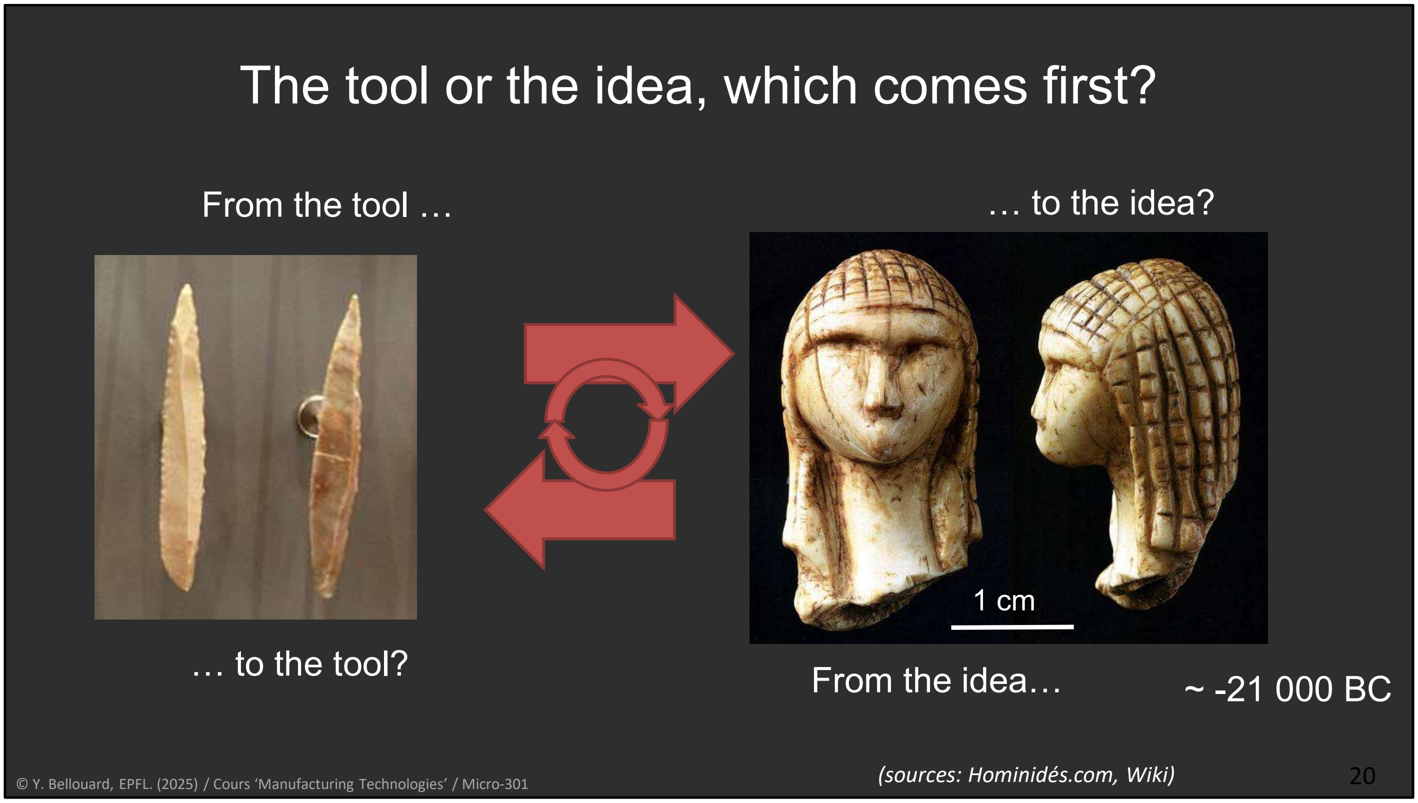
While the concept of airbag is relatively old (from the 60-70s), it took some time before a successful airbag could be demonstrated.

The main issue being that it requires sensing means capable of measuring acceleration with a sufficiently fast time response in order to trigger the inflation of the balloon.

If ones wants to measure acceleration, it needs a proof-mass that will move due to the force applied on it as result of the acceleration being experienced by the system (Newton's law). If we can sense the motion of this proof-mass, it can convert it into an acceleration measurement.

The enabling manufacturing process here have been the clean room processes (so called MEMS) that have made the miniaturization of a proof-mass possible, down to scale where the time response becomes sufficiently short for reacting on time to a violent change of acceleration, like what is happening during a car crash.



It is important to realize that there is an intimate relation between a process and a function, and likewise a tool and an idea.

Philosophically, one can ask about what came first: the tool or the idea?

As an 'prehistorical' illustration here, is it the flint that triggered the idea of making this little figurine (from -25000 BC, 'Vénus de Brassempouy in France) or rather, is it the idea of making such an object that did enable the making of new tools?

We will never know and probably, it is both... Having new tools trigger innovations, and likewise, the will to create something enable the design / invention of new tools.

The point here is to appreciate the importance of the intimate relation between an object and its manufacturing process used to produce it.

Course overall learning objectives

- **Understand** how process, design, and materials are closely linked together and interdependent
- **Learn about** existing manufacturing processes
- **Understand** the underlying physical principles and evaluate process limitations
- **Be able** to make a proper choice for a manufacturing process for a given problem

The course objectives are multiple:

- The **first one** is to understand the **strong interdependency between process, design and materials**. As it will be outlined further, the three go hands-in-hands. One cannot make a good design if he/she does not comprehend well manufacturing *and* materials issues.

- The **second one** is to be aware of the most common processes used nowadays. Manufacturing processes are numerous. Although it would be too ambitious to pretend that we will review them all, we will review the most common ones, illustrative for the class of manufacturing processes they represent. The main focus will be on understanding the *underlying physics* between these processes. Hence, the objective is not to dive into too specific technical details that can easily be found on the web, but rather to develop a critical understanding of these processes.

- The **third objective** is to lay down the conditions for making an educated choice when selecting a given manufacturing process. *This is the most important objective*. These days, finding information on processes is easy and can be overwhelming. More difficult is to sort what is truly relevant and to develop a critical thinking for choosing the most relevant processes for a given manufacturing problem.

Emphasis on physical processes...

- Understanding **physical processes** behind manufacturing enables you to:

  - ✓ *Be aware* of the theoretical limits of a given process
  - ✓ *Be able to have a critical look* at what manufacturers propose / cost related to manufacturing
  - ✓ *Develop a generic understanding* of manufacturing
  - ✓ *Activate prior knowledge* acquired in the bachelor phase

The course aims at emphasizing the necessity of understanding fundamental principles rather than technicalities behind a given manufacturing process.

Doing so, we expect the student to be able to critically assess at what manufacturers propose and to understand the intrinsic limit of a given process as well as their potential benefits.

As the topic is rapidly evolving and as the number of processes very large, the aim is to develop a *generic* understanding that can be applied to an ensemble of possible cases. In short, to develop a methodology for assessing and solving a manufacturing problem.

From a learning perspective, studying manufacturing technologies is also a formidable opportunity for applying prior knowledge acquired during the bachelor phase and to activate it in practical cases.

Today's learning objectives

- Appreciate how **design / materials / process** are **interlinked**
- An introduction on **material selection process**
- Learn about **Ashby plots** as one method for **selecting material**

This first introductory lecture focuses on the materials, and more specifically on a material selection process.

Our objective is to define a methodology for choosing a material for a given situation.

In particular, we would like to make this choice, not based on *a priori* knowledge (which can be deceptive or biased), but based on *factual information* and according a systematic *quantitative methodology* free of possible bias.

Furthermore, we also aim at defining a method that allows for optimizing the choice made, while scanning a set of possible materials candidates.

One approach, which has been quite successful so far, is the use of the Ashby plots that we will review in the next slides.

Bottles…

Plastic… Metal… Glass…

(Source Wisegeek)

(Source SIGG)

(Source DIYhomedecorguide.com)

Why choosing these materials?

We are familiar with three common types of bottles, made of three family of materials that are the *plastics*, the *metals* and the *glass*.

A first question that we can ask ourselves would be the rationale for choosing one material versus another.

In other words, on which criteria should I decide for one of the three materials mentioned above?

This simple question helps us to emphasize the importance of defining specifications and, more broadly, of posing the right boundary conditions for a given problem.

Many possible (and valid) reasons…

- … reusable and durable (metal)
- … recyclable (polymers, glass, metal)
- … One-time use (polymers, glass)
- … inert (ex. for chemistry) (polymers, glass)
- … long term storage (glass)
- …. elegant (ex. perfumes, etc.) (glass)
- … cost
- … optical properties (etc.)

Comes from product specifications 'Cahier des charges'

The selection for one bottling material versus another can be motivated by multiple reasons.

The slide above lists a few possible examples.

All these are valid reasons that ultimately will define the object specifications, or in French, 'Le cahier des charges'.

By defining precisely these requirements, we narrow down the choice of possible materials that may fulfill the selected criteria.

How SIGG bottles are made?

https://youtu.be/J_Rnf_aKd-0

SIGG bottle are iconic objects from the Swiss manufacturing history.

It has a long history and illustrates well that a project that seems apparently simple may involve multiple processes for its making. Each of this process is defined to address all the requirements of the future object, which in this case are (among others): durability, robustness, safety for the consumer, health-safe and appealing appearance.

How plastics bottles are made?

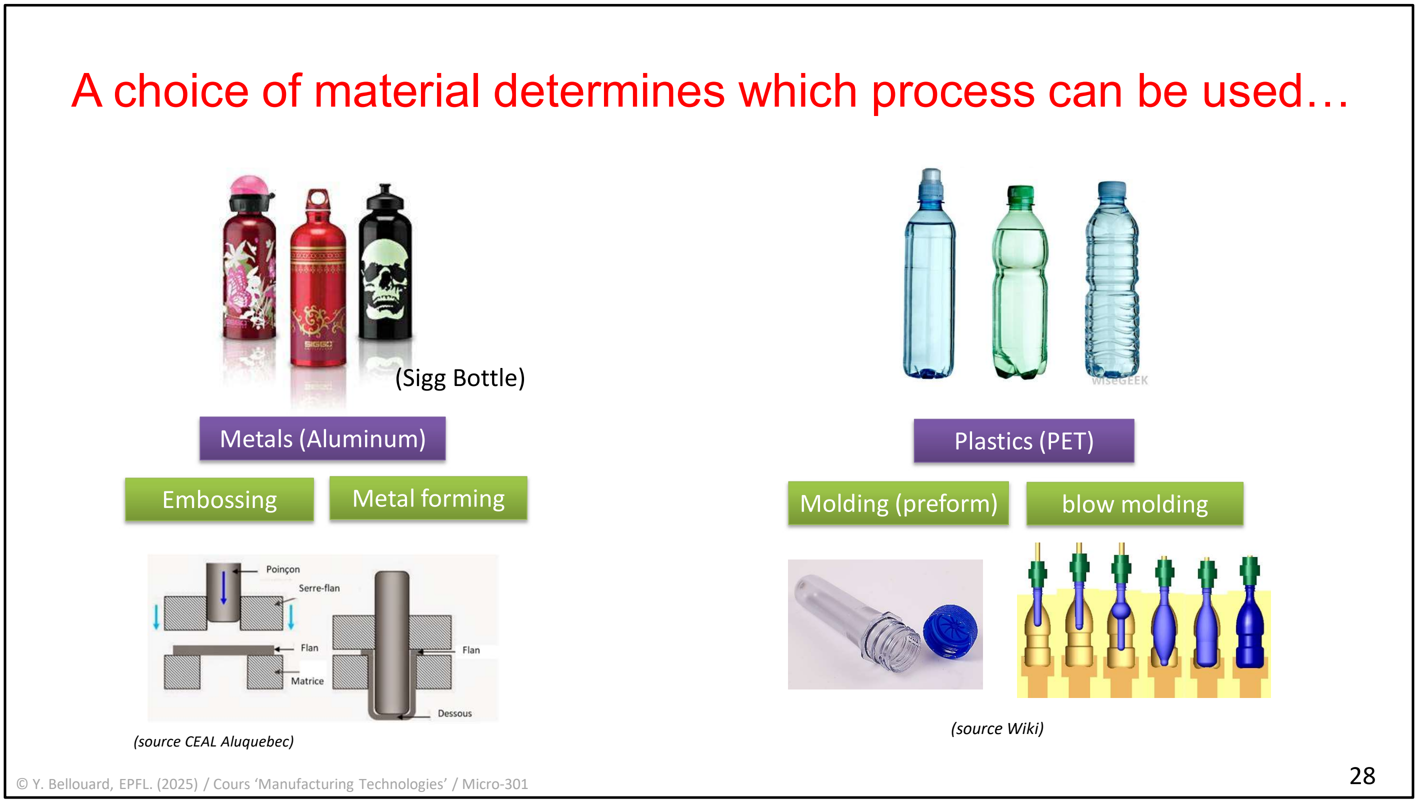
https://youtu.be/lWMZ1Pmh7uM

Another key example of manufacturing of commonly found objects in our daily life.

Here the requirements is to produce fast, diverse shapes, cheap objects, which initially are not intended to be kept.

It raises interesting sustainability debate in terms of energy consumption and long-term recyclability. The answers of this debate are complex.

We will discuss sustainability in the last lecture.



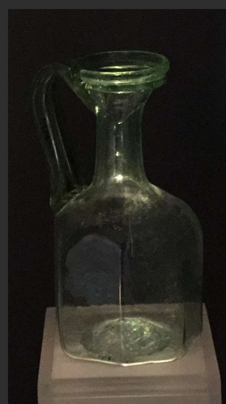
So, what is the best choice?

Metal versus *plastics*.

The answer is not trivial and depends on the **initial requirements** set for the object.

(source carionmineraux.com)

(source YB, Thessoliniki, 3rd c BC)



(source YB, Thessoliniki, 1 c. AD)

Glass: an historical note...

- Since when do we process glass?
  - Processing natural glass (Obsidian) < 11000 BC
  - Molding glass – Mesopotamia, probably ~ 1250 BC
  - Glass blowing (Phoenician? Roman around 1st century BC)

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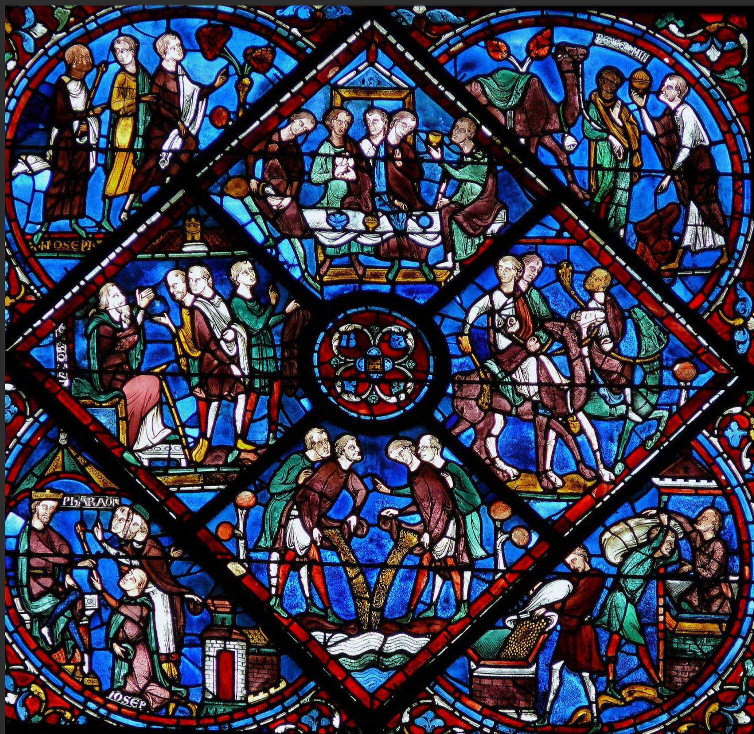
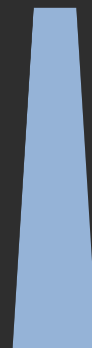
Let us make an historical parenthesis concerning glass.

As can be seen above this is one of the oldest processed materials, including in sophisticated shapes, just looking for instance at glass blowing processes mastered by the Romans in particular.

Although glass is an old material, there is a common, but erroneous, thinking that glass flows.



Does glass flow?



(Cathedral of Chartres,
~1200 AD, Picture from Mossot)

This thinking (more like an urban legend) originates from the observation of the cathedral glass.

Indeed, the stained glass are composed of small elements typically thicker at the base than at the top.

It was first thought that because these glass were old, they must have flowed gradually, and therefore leading to a larger base than the top.

While it sounds seducing at first as an explanation, it contains several assumptions that made questionable to start with.

It assumes that glass were flat and homogeneous in first place. However, the 'float' glass process that leads to perfectly flat glass was not mastered until the 19^{th} and 20^{th} centuries.

The second assumption is that it would have been viscous enough, so that gravity alone would have pulled down the glass material.

1/ The physics argument…

$$\log \eta = \log \eta_0 + \frac{B}{(T - T_0)}$$

Vogel-Fulcher-Tamman law

Assuming ultra-high viscosity still has a meaning, it would take about 10^{32} years! (age of the universe: ~ 10^{10} years)

…or hold the glass above 400 deg C, and for 800 yrs to see a flow, that would account for the bevel observed in the cathedral glasses.

Zanotto, "Do cathedral glasses flow?," American Journal of Physics 66, 392–395 (1998).

From a physics point of view, the 'viscosity of glass', which is a convenient representation that can be misleading, can be described by a Vogel-Fulcher-Tamman law.

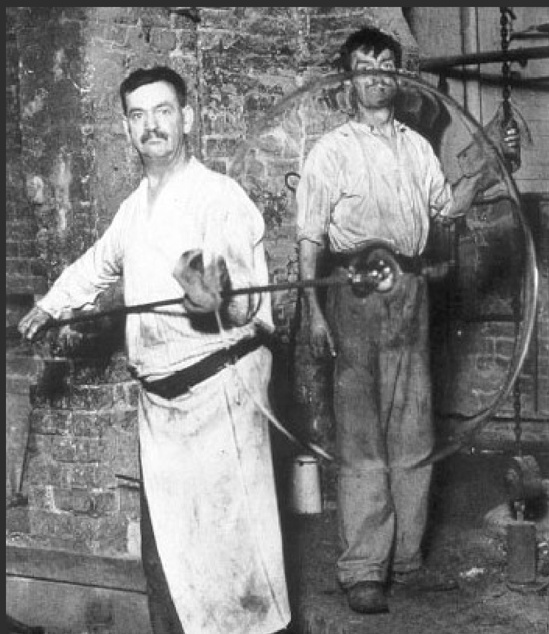
If we used this law and combine it with a viscous flow model, we find out that it would take more than the age of the universe for the glass to flow in a way to explain the Cathedral observations.

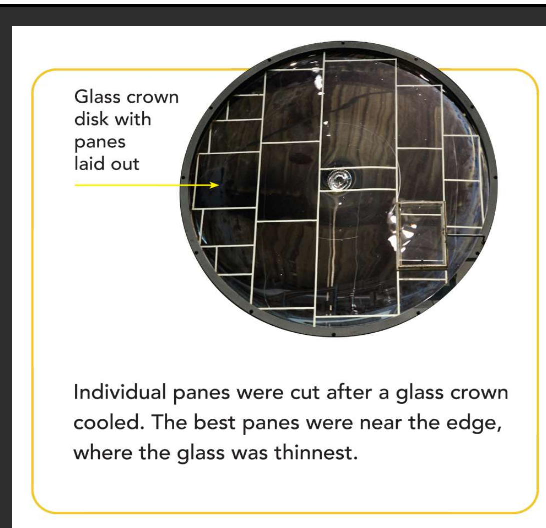
Likewise, to happen in the time scale considered here, it would have been necessary to hold the glass at a temperature above 400 deg C during 800 yrs...

Clearly, none of this happened.

If you are interested in this topic, the reference above provides some further details.

Crown glass process





(Source: Corning museum)

“Glass in Architecture and Decoration” by Raymond McGrath & A.C. Frost, 2nd Edition, London, 1961 [1937], p. 75

So, what may have happened and how cathedral glass may have been manufactured?

One possible explanation comes from the way glass were prepared in the past. A common approach was to use the Crown process that consisted in spinning the glass while hot, a bit like a pancake, so that it would expand in a disk of ever-increasing diameter.

As the process relies on centrifugal forces, the thickness is not homogeneous throughout the diameter.

One could then imagine that glass pieces cut from these disks where then assembled to form the stained-glass in a logical way, i.e. the thicker side facing down.

2/ The archeological argument: more ancient glass, why they did not flow, then?…

Roman cup (400 AD)
Antikensammlung München

Roman glass (between 351-400 AD), Cadiz, Spain

If you are not convinced that glass does not flow, here is another argument... If we assume middle-age glass would flow, then how to explain that even older ones, do not show any sign of flow?

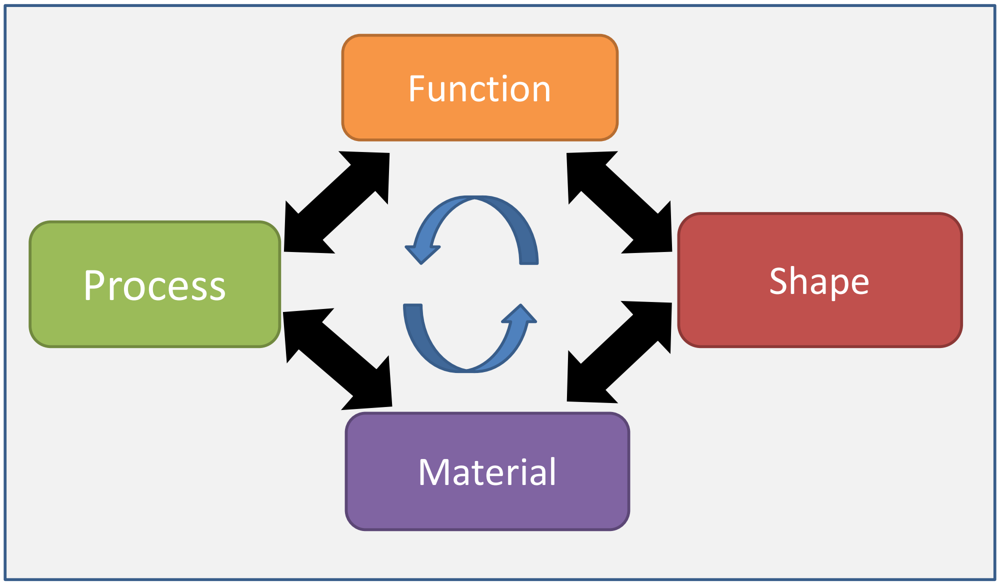
Just consider these two example of fine glass work from the Roman times.

If you are interested by the topic, you can visit the Corning – one of the world largest glass manufacturer – webpage.

https://home.cmog.org/
https://info.cmog.org/node/631

Let us go back to the course now...

‘A PART’



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As it will be shown several times during the lectures, process, shape, material and function are all inimically related in the genesis of an object, from its design to its fabrication.

In this lecture, we focus on the material and useful method to help making proper choices.

How do we choose a material for a given function?

- What criteria?
- What methodology?
- How to make an optimal choice?

Method based on M. F. Ashby plots

Relevant questions include the definition of selection criteria as well as the definition of a suitable methodology.

In what follows, we will consider the method proposed by Michael Ashby, an emeritus professor at Cambridge University.

https://en.wikipedia.org/wiki/Michael_F._Ashby

Materials properties versus function?

- Mechanical → *Young modulus, Elastic limit, Toughness, Damping (loss coefficient), etc.*
- Thermal → *Melting point, thermal conductivity, thermal expansion, heat conductivity*
- Electrical → *Resistivity, Dielectric properties, Breakdown voltage*
- Optical → *Refractive index, (absorptivity)*

The first important point is to relate materials properties and functions.

In other words, what is the relevant material parameters for a given function we would like the object to fulfil or a given properties it should have.

We can cluster material properties in categories, like for instance mechanical, thermal, electrical or optical. Note that we could also have considered chemical functions for instance.

For instance, if we are interested in the material mechanical properties, we will need to pay attention to the Young's modulus, the elastic limit, possibly the toughness, the damping properties, etc.

While if we consider thermal properties, logically we will want to know the material melting point, its thermal conductivity, maybe the thermal expansion coefficient or if this material will play a heat transfer role, its heat conductivity.

We can continue on for the various sub-categories.

The important message here, is that as a first step, one needs to identify what are the relevant material properties for a given function. This step is essential as it will help us identifying the most essential parameters for optimization in relation with a given object function.

Class	Property	Symbol and Units
General	Density	ρ (kg/m^3 or Mg/m^3)
	Price	C_m ($/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K (GPa)
	Yield strength	σ_y (MPa)
	Tensile (ultimate) strength	σ_{ts} (MPa)
	Compressive strength	σ_c (MPa)
	Failure strength	σ_f (MPa)
	Hardness	H (Vickers)
	Elongation	ε (–)
	Fatigue endurance limit	σ_e (MPa)
	Fracture toughness	K_{1c} (MPa.m$^{1/2}$)
	Toughness	G_{1c} (kJ/m^2)
	Loss coefficient (damping capacity)	η (–)
	Wear rate (Archard) constant	K_AMPa^{-1}
Thermal	Melting point	T_m (°C or K)
	Glass temperature	T_g (°C or K)
	Maximum service temperature	T_{max} (°C or K)
	Minimum service temperature	T_{min} (°C or K)
	Thermal conductivity	λ (W/m.K)
	Specific heat	C_p (J/kg.K)
	Thermal expansion coefficient	α (K^{-1})
	Thermal shock resistance	ΔT_s (°C or K)
Electrical	Electrical resistivity	ρ_e (Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_r (–)
	Breakdown potential	V_b (10^6 V/m)
	Power factor	P (–)
Optical	Refractive index	n (–)
Eco-properties	Embodied energy	H_m (MJ/kg)
	Carbon footprint	CO_2 (kg/kg)

Design related Material properties

(M.F. Ashby, Material selection in mechanical design, Elsevier, 2011)

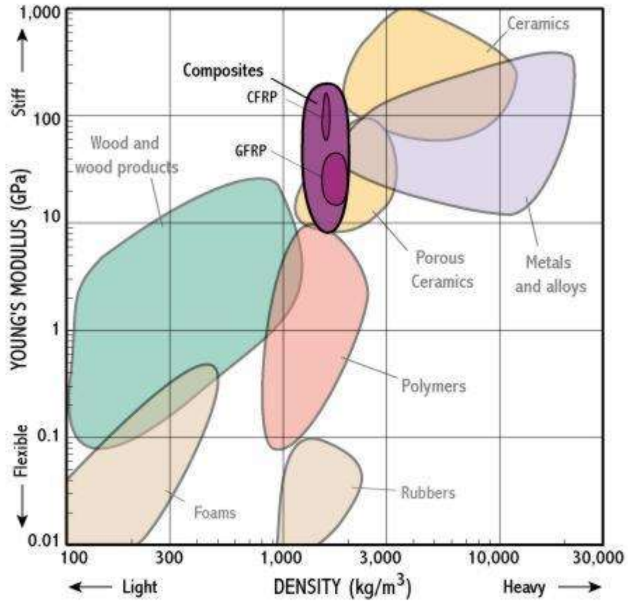
In this table, the properties of a material form the viewpoint of design are listed, along with the relevant units.

One thing to note is the number of materials data... And hence the importance of clustering them so that a proper selection is made, and the attention is paid to the most important ones.

Quiz?

- Highest Young modulus material?
- Heaviest material?
- Highest stiffness/weight ratio materials?
- Lowest stiffness/weight ratio materials?

Ashby's plot



(source Cambridge University)

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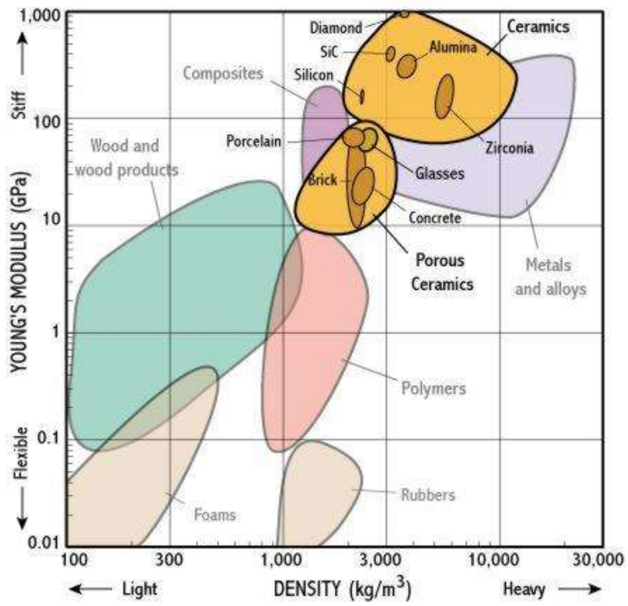
Ashby's method consists at representing on a log-log graph, the properties of materials in general, so that a global view at existing materials can be made.

On this log-log plots, two properties are represented, like for instance here, the density as a function of the Young's modulus.

On these graphs, materials are clustered by family.

Take a moment to examine how the various families of materials are located with respect to one-another.

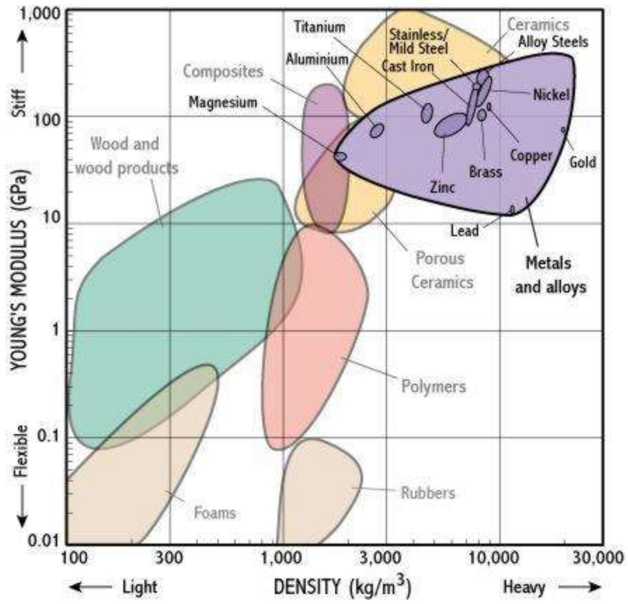
Ashby's plot



(source Cambridge University)

Here for instance, we notice that the highest possible Young's modulus are found for ceramics.

Ashby's plot



(source Cambridge University)

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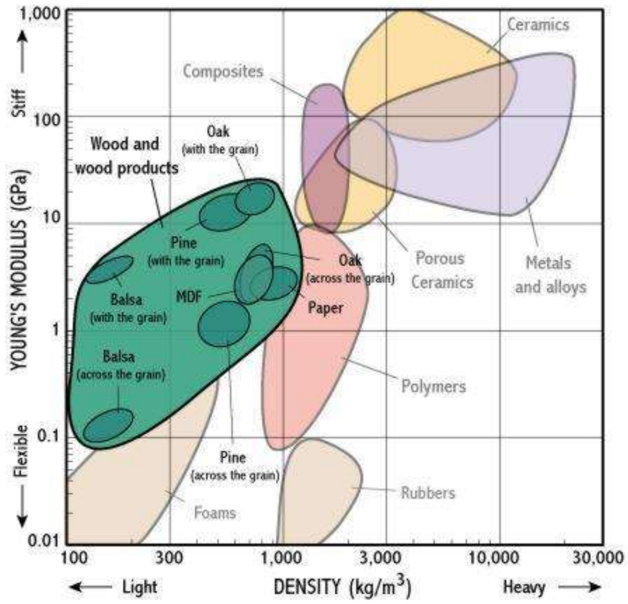
Among metals, the heaviest does not necessarily meant the strongest... Just compare gold with aluminum for instance.

Note the good ratio of Young's modulus versus density for magnesium, which alloys are ones of the most use metals for laptops....

Ashby's plot



(source Cambridge University)

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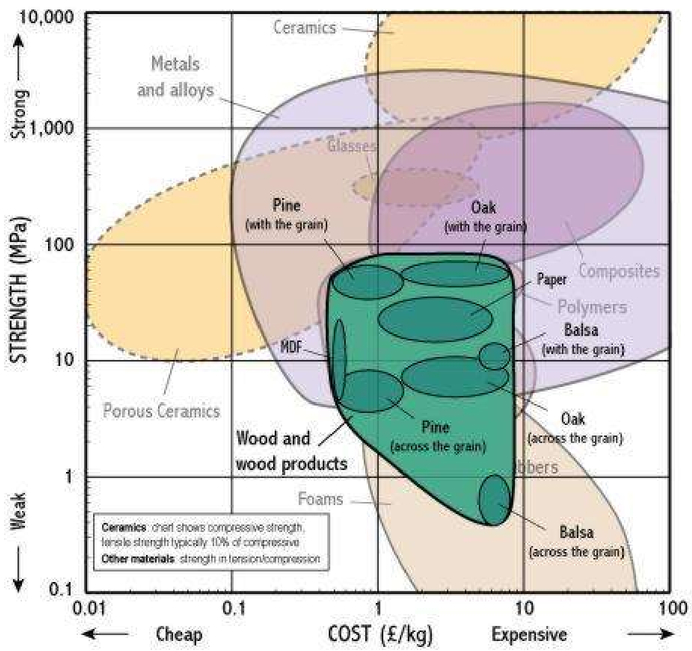
Natural materials can also be represented on these graphs, although they may have a complex structure.

You will notice that in general, wood products achieve better Young's modulus for a given density than any other materials.

Cost vs strength



(source Cambridge University)

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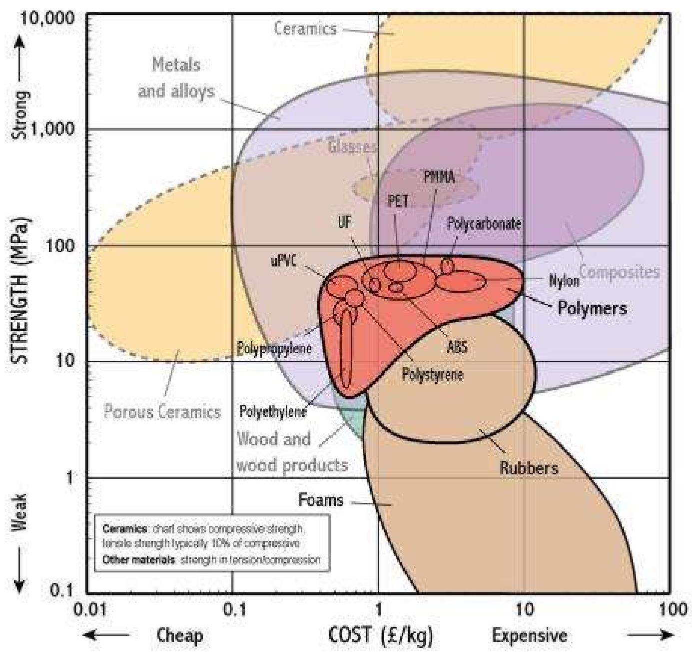
Ashby plots are also use for cost comparison...

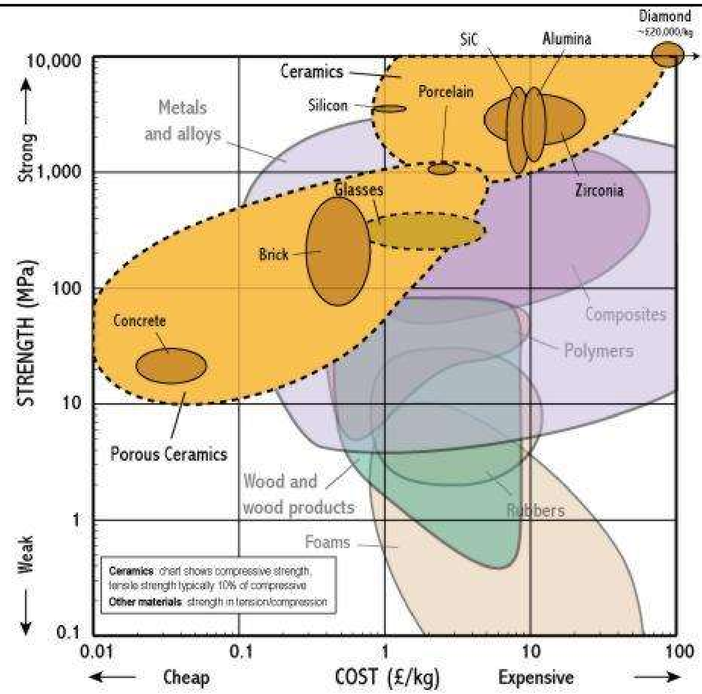
Here is an example comparing cost and strength. ('limite élastique').

Cost vs strength



(source Cambridge University)

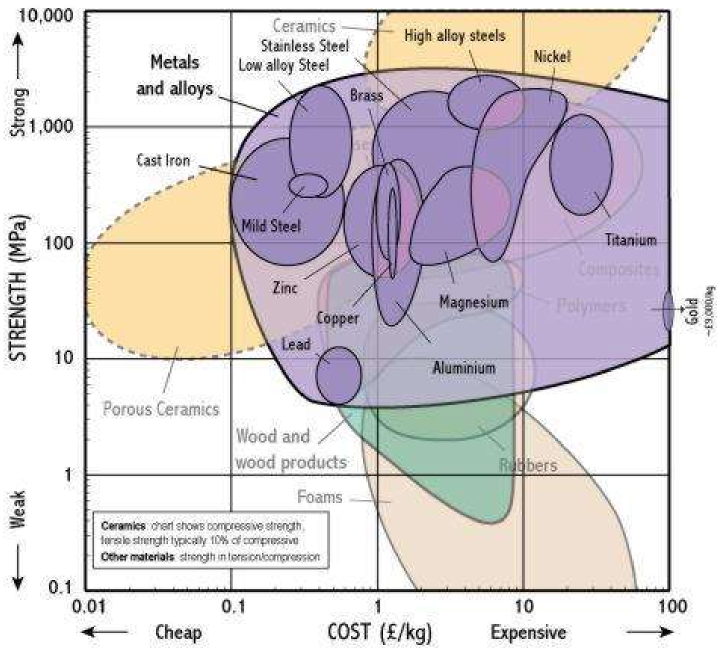
Cost vs strength



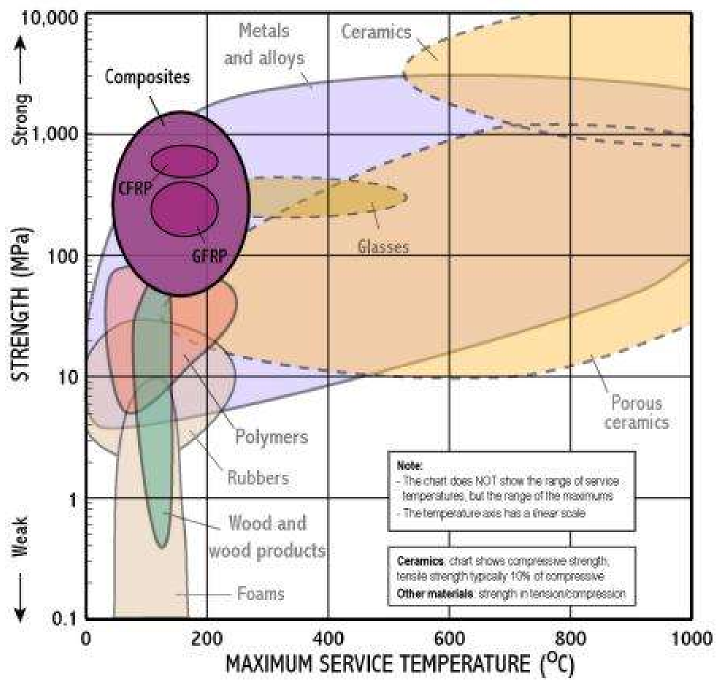
(source Cambridge University)

Note that one of the cheapest material/kg versus strength is the concrete, which substantially cheaper than the bricks. Concrete has been one of the widely used construction materials in modern times.

Cost vs strength



(source Cambridge University)

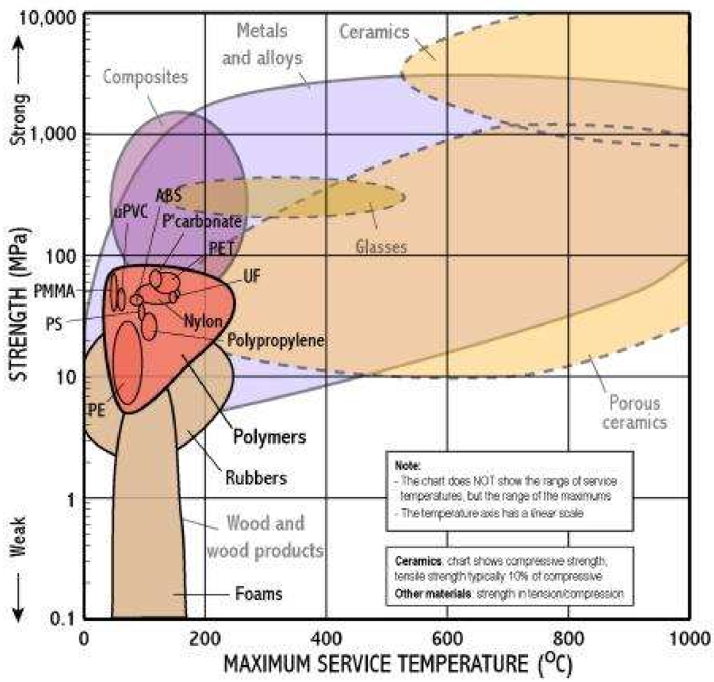


Strengh vs service temperature

(source Cambridge University)

In fact, many properties can be displayed according this principle. Note that in the case of temperature, it does not make sense to use a logarithmic scale.

Strengh vs service temperature



(source Cambridge University)

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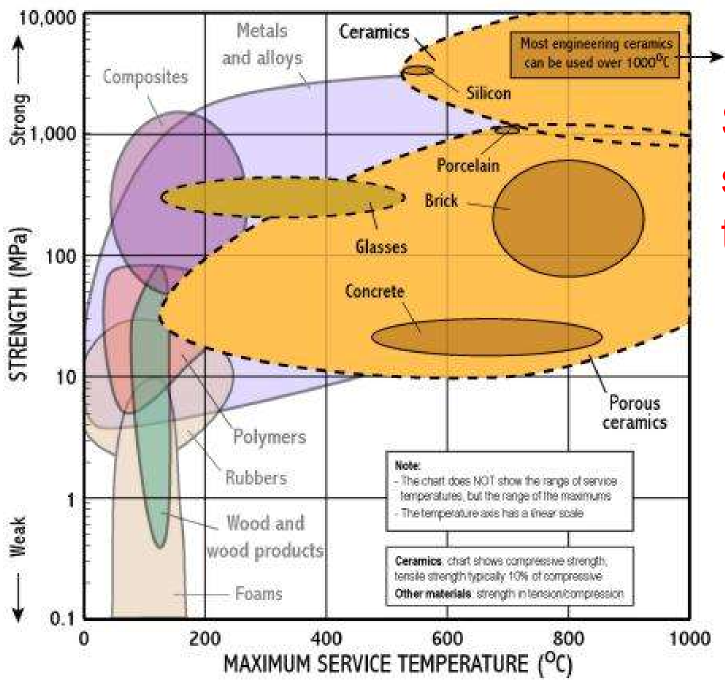
In fact, many properties can be displayed according this principle. Note that in the case of temperature, it does not make sense to use a logarithmic scale.



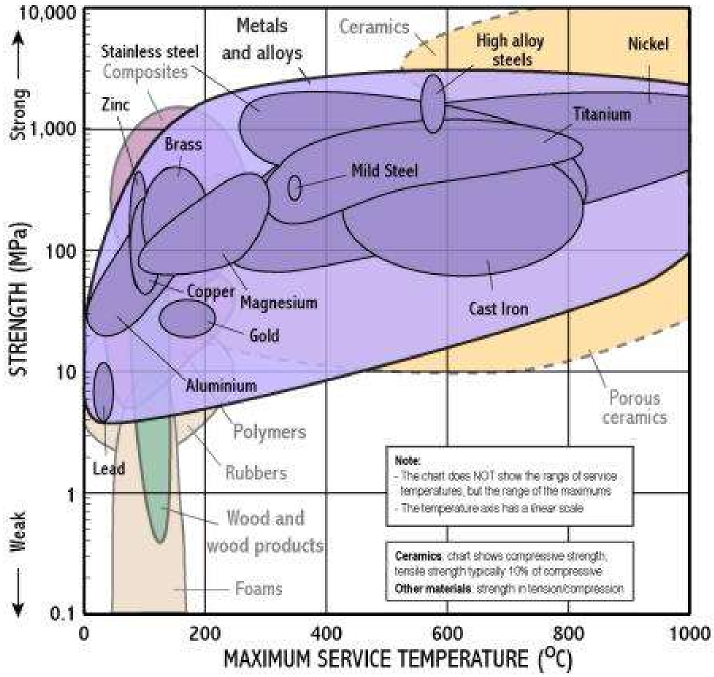
Strengh vs service temperature

(source Cambridge University)

In fact, many properties can be displayed according this principle. Note that in the case of temperature, it does not make sense to use a logarithmic scale.

Note that ceramics can survive high service temperatures...

Strengh vs service temperature



(source Cambridge University)

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In fact, many properties can be displayed according this principle. Note that in the case of temperature, it does not make sense to use a logarithmic scale.

Many other plots...

- Young's modulus - Density
- Young's Modulus - Cost
- Strength - Density
- Strength - Toughness
- Strength - Elongation
- Strength - Cost
- Strength - Max service temperature
- Electrical resistivity - Cost
- Recycle Fraction - Cost
- Etc…

There are many possible combination of graphs as listed above. We provide in the Moodle some example of tables that have been compiled by the company Grant-a-Design, spin-off of Michael Ashby's group at Cambridge.

Ashby's method

- **'Translation':** *express design requirements as constraints & objectives*
- **'Screening':** *eliminate materials that cannot do the job*
- **'Ranking':** *find the materials that do the job best*
- **'Supporting information':** *explore pedigrees of top-ranked candidates*

Ashby's method consists in four logical steps. Quite intuitive, this method has the merit of defining unbiased steps, so that material selection is made without a priori thinking and in a systematic manner.

The **first step** – in fact the most important one, is to translate design requirements in terms of constraints and objectives.

For instance, if I say, 'I would like the material to be strong', then I need to translate that first, into a physical properties (elastic limit for instance), and second, into acceptable numbers.

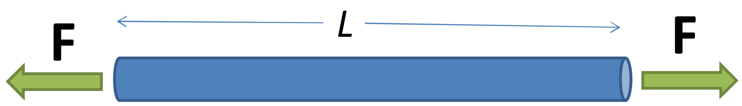
The **second step** is to do a screening by looking through Ashby maps, which ones are the ones that can be excluded.

The **third step** is to rank the possible candidates. Most of the time, there is not just one possible material that could do the job, but many. Ranking can be based on various additional criteria.

The **fourth step** is to gather all the information potentially useful for the selected material.

Illustration

What *material parameters* should we optimize to *minimize the mass* of a tie of length L and achieve the *maximum strength* in tension?



Objective function: 'minimize the mass' and 'maximize strength'
Design parameter: length of the tie (L)
Free parameter: Area (A)

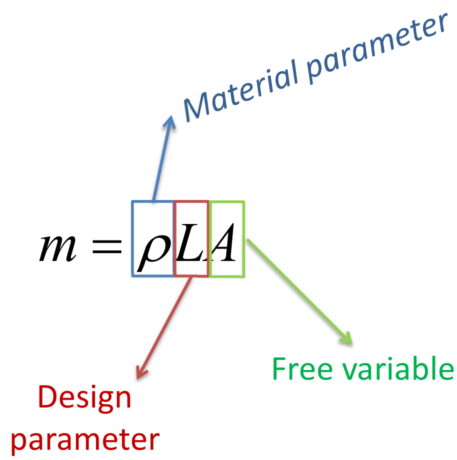
Let us know consider a very simple example for a material selection and optimization process.

Most important in these types of exercises is to identify the important words related to physical parameters, which will be used to define the problem.

There are two here: '*minimize the mass*' and '*maximum strength*'. Somehow, as an optimization problem here, we expect to be looking at the ratio between the two.

Methodology: pose the problem

- **Step 1:** Pose the problem
  - 'Minimizing mass'



$$m = \rho L A$$

As we would like to minimize the mass, let us express the mass definition in term of a relevant material parameter, since this is what we are trying to optimize.

Mass is defined by its density and its volume.

Methodology: pose the problem

- **Step 1** (follow): Define the problem
  - Maximum strength in tension

$$\sigma = \frac{F}{A} \rightarrow F_{\max} = \boxed{\sigma_{\max}}\boxed{A}$$

Free variable

Material data

- **Step 2:** Eliminate free variables to define an objective function

$$\frac{m}{F_{\max}} = \boxed{\left(\frac{\rho}{\sigma_{\max}}\right)}\boxed{L}$$

Design parameter

Material data

Likewise, strength in tension can be directly related to the force applied on the tie and the cross-section.

There the strength is the material data.

If now I define an objective function which is to minimize the mass and to maximize the force, I can come up with an expression where the ratio between density and elastic limit appears.

This ratio contains only material data and can therefore be optimized from the viewpoint of material selection.

Define an optimization problem

- Minimizing mass while achieving the highest strength is equivalent to looking for a material that maximizes:

$$C = \left(\frac{\sigma_{\max}}{\rho} \right)$$

(in which C is a constant)

- In an log-log Ashby plot, this is a family of straight line of slope 1.

$$\log(\sigma_{\max}) = \log(\rho) + \log(C)$$

The ratio will define a constant. Clearly there are several possible combinations of elastic limit versus density ratio that would satisfy this condition.

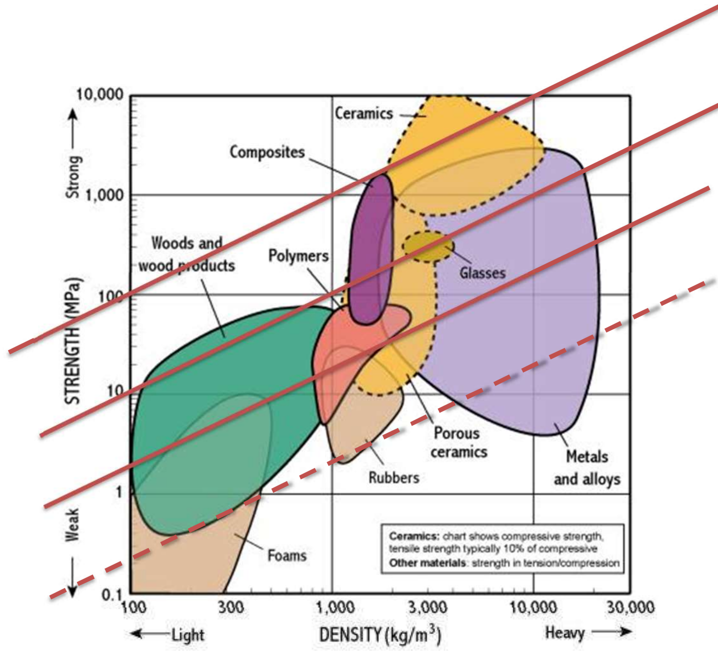
On a log-log plot, this ratio will simply be a straight of slope 1 in this case.

Visualize on a Ashby's material selection plot

$$C_1 = \left(\frac{\sigma_{max}}{\rho}\right)$$

$$C_2 = \left(\frac{\sigma_{max}}{\rho}\right)$$

$$C_3 = \left(\frac{\sigma_{max}}{\rho}\right)$$

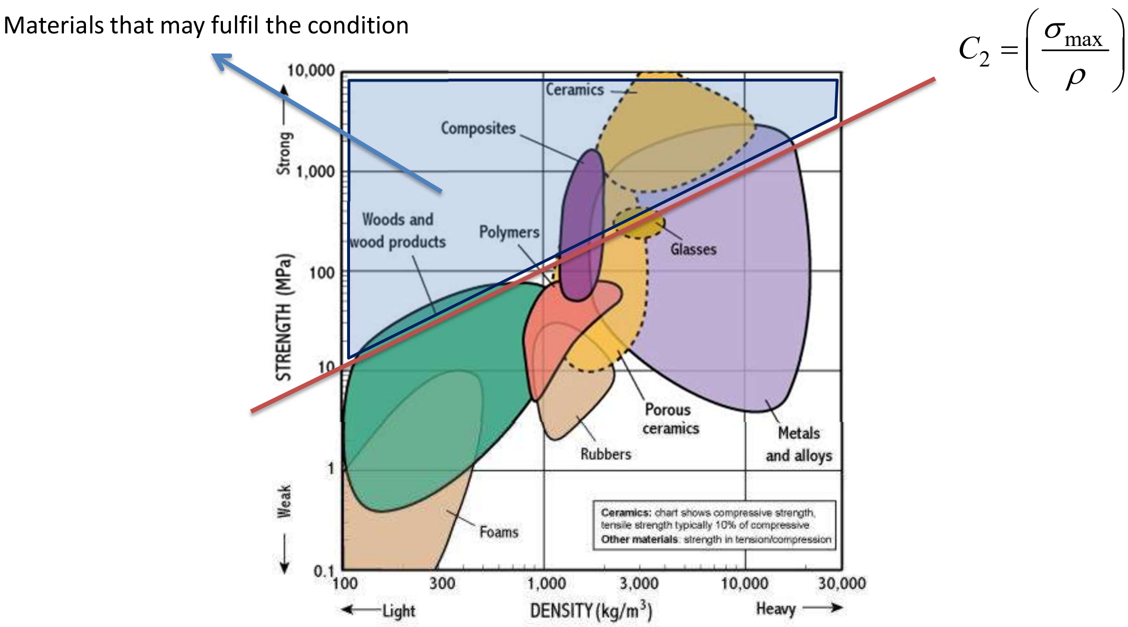


(source Cambridge University) 57

The following step is then to plot these lines on the corresponding Ashby plot.

In this example, we show several lines for given, chosen constants. The choice of this constant will depend on additional designed requirements. Like for instance a desired minimum performance.

Visualize on a Ashby's material selection plot



(source Cambridge University)

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Let us consider one of these lines.

The candidate materials that would satisfy the condition strictly are on the line, and the ones that fulfill the condition or do better in term of optimization define a domain above the curve in this case.

Mutliple solutions to a given problem: ex. Bamboo vs steel

Steel scaffolding

Bamboo scaffolding

Hong Kong (source LABC, UK)

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In the some part of world, steel is widely used for scaffolding, while other countries (in warmer climate) tend to use bamboo for scaffolding.

Final remarks on Ashby's opmitization approach

- The final selection will be triggered by additional considerations, such as:
  - A minimum Young modulus
  - Manufacturability / Sustainability
  - Durability
  - Cost
  - Etc.

→ *A multi-parameters optimization problem with multiple possible solutions!*

Here, we have just looked only at one specific **requirement** that we have optimized. Hence, only a small part of a wider problem.

The final selection of the material will be triggered by additional considerations that comes from other design **requirements**.

'Lexique manufacturing'

English (UK) > French

- Metal embossing: *Emboutissage profond*
- Metal forming: *Mise en forme des métaux / formage*
- Molding (Moulding): *Moulage*
- Blow molding (Blow moulding): *Moulage par soufflage*
- Scaffold / Scaffolding: *Echaffaudages*