Lecture 8: Molding & Plastics

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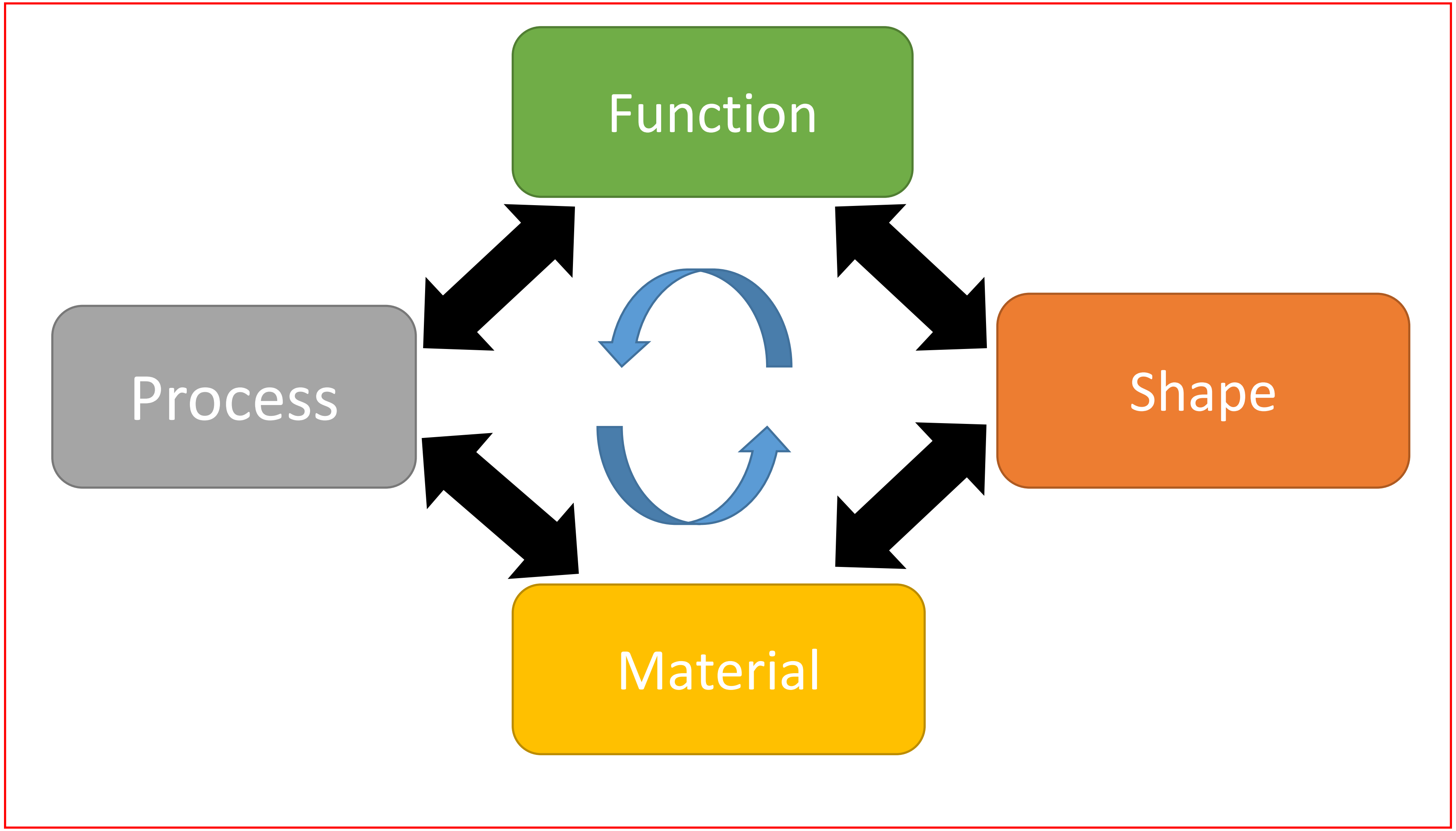
EPFL

‘A PART’



Is there a magic combination where only one process/ one material is needed?

Learning objectives

1. **Plastics** / review of their properties
2. **Manufacturing of plastics**
3. A few words about composites

Exercise

- Can you name a product in your daily life that **does not have** any plastic?

Discussion: Why are plastics so successful?

- **Economical:** cheaper than glass, wood, metal or glass
- **Lightweight**
- **Chemically stable:** does not react to environment: no corrosion, etc.
- **Easy-to-recycle**
- **Durable and safe**
- **Easy to manufacture**
- **Row materials are easy to handle/transport**

But...

- **Easy-to-recycle...** However today only 80% of the plastics are **not** recycled...
- **Not infinitely recyclable**...
- **(majority) comes from non-renewable resources**...
- **Durable...** So much that it does not degrade easily in the environment
- **Cheap...** Adverse effect? Overused?
- **Toxicity**...

A hot debate!

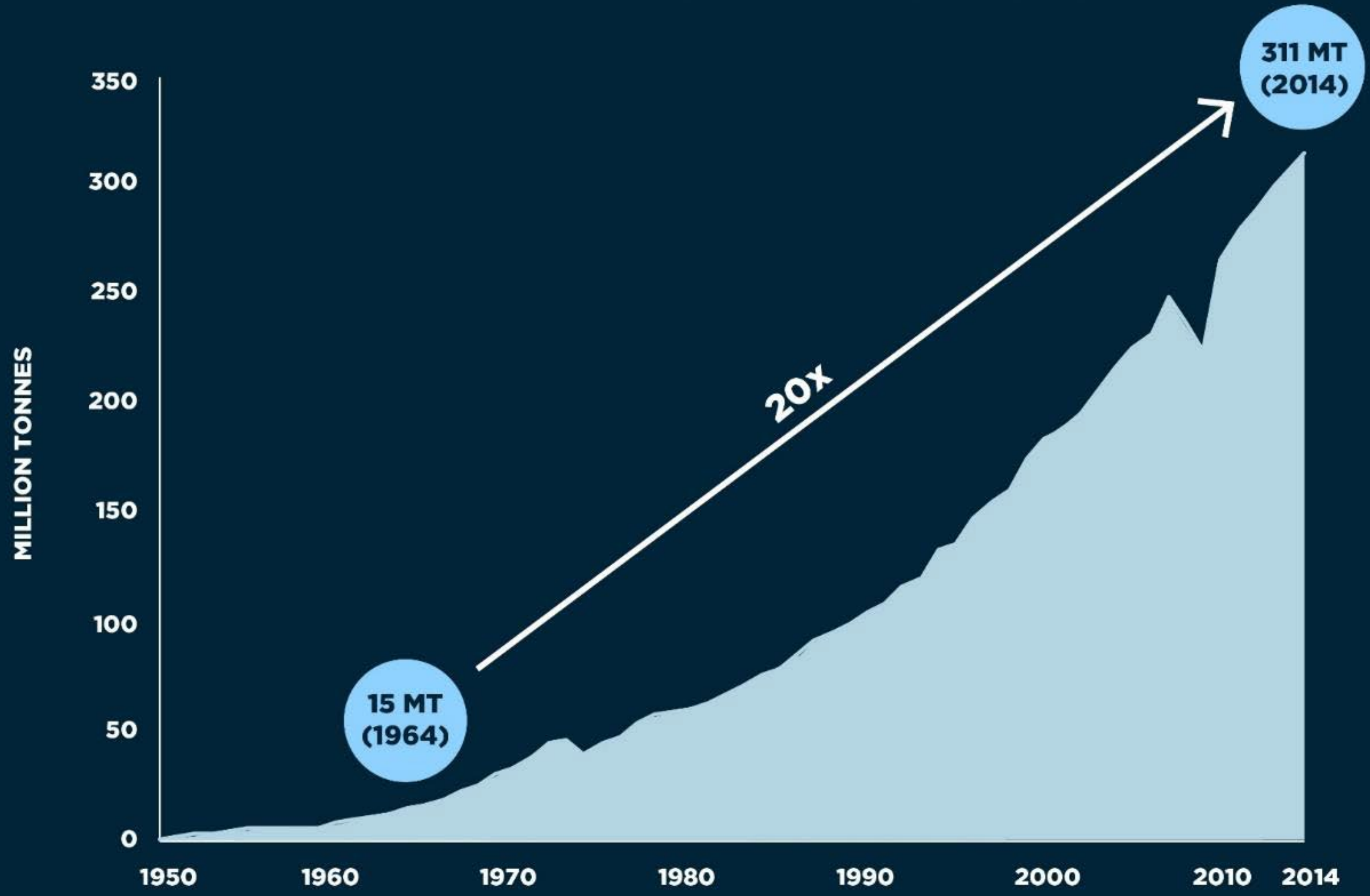
So, what do we do?

'Myminifactory.com'

VS

'Huffington Post' – (Greenland)

PLASTICS PRODUCTION INCREASED TWENTY-FOLD OVER THE LAST 50 YEARS



WORLD ECONOMIC FORUM, ELLEN MACARTHUR FOUNDATION, MCKINSEY & COMPANY,
A NEW PLASTICS ECONOMY: RETHINKING THE FUTURE OF PLASTICS (2016)
ELLENMACARTHURFOUNDATION.ORG/PUBLICATIONS

NOTE: Production from virgin petroleum-based feedstock only (does not include bio-based, greenhouse gas-based or recycled feedstock)
SOURCE: PlasticsEurope, Plastics – the Facts 2013 (2013); PlasticsEurope, Plastics – the Facts 2015 (2015).

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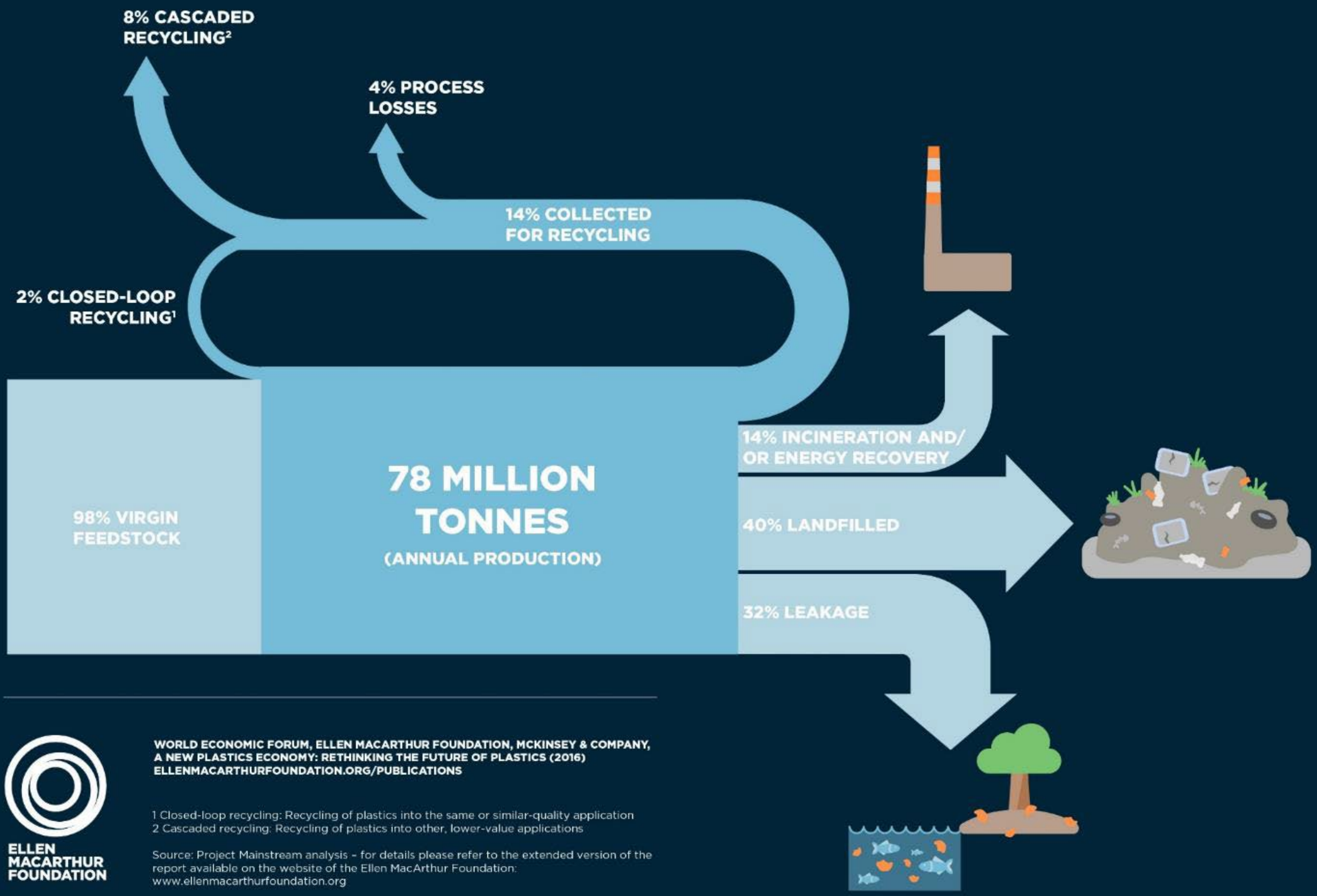
TODAY, PLASTIC PACKAGING MATERIAL FLOWS ARE LARGELY LINEAR



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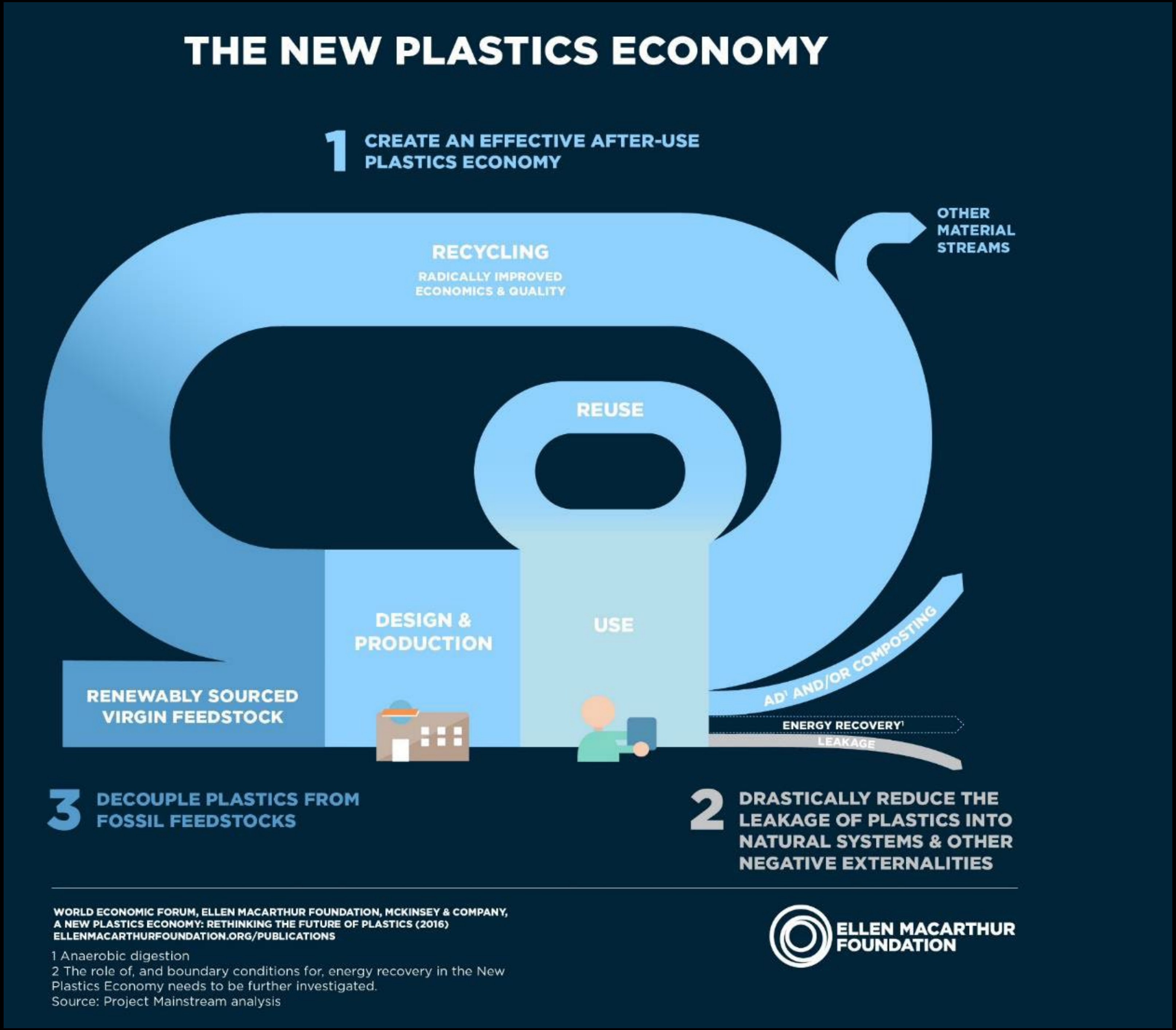
1 Closed-loop recycling: Recycling of plastics into the same or similar-quality application
2 Cascaded recycling: Recycling of plastics into other, lower-value applications

Source: Project Mainstream analysis – for details please refer to the extended version of the report available on the website of the Ellen MacArthur Foundation: www.ellenmacarthurfoundation.org

Future model?



What are plastics?

- Plastics families...
- Key material properties
- Mechanical properties

Recommanded excellent overview video about ‘plastics’ (National Geographic)
https://youtu.be/ggh0Ptk3VGE

Plastics main families

- **Polyamides (PA)** or (nylons) – fibers, toothbrush bristles, tubing, fishing line and low-strength machine parts
- **Polycarbonate (PC)** – compact discs, eyeglasses, riot shields, security windows, traffic lights and lenses
- **Polyester (PES)** – fibers and textiles
- **Polyethylene (PE)** –supermarket bags and plastic bottles
- **Polypropylene (PP)** – bottle caps, drinking straws, yogurt containers, appliances, car fenders (bumpers)
- **Polystyrene (PS)** – foam peanuts, food containers, plastic tableware, ...

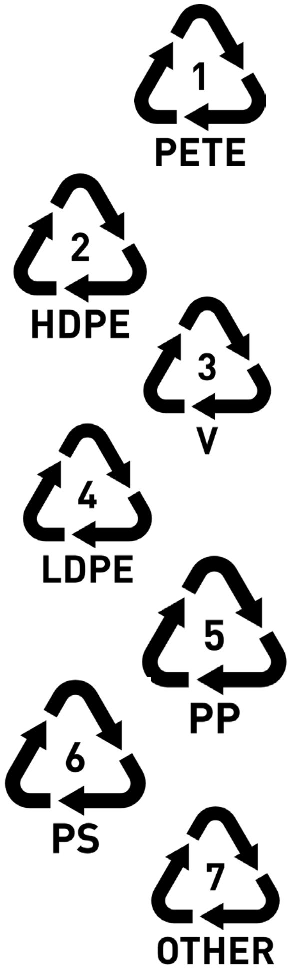
Plastics main families

- **Polyurethanes (PU)** – cushioning foams, thermal insulation foams,etc.
- **Polyvinyl chloride (PVC)** – plumbing pipes and guttering, electrical wire/cable insulation, etc.
- **Polyvinylidene chloride (PVDC)** – food packaging,
- **Acrylonitrile butadiene styrene (ABS)** – electronic equipment cases (e.g. computer monitors, printers, keyboards) and drainage pipe.
- **Polyactic acid (PLA)** – ‘biodegradable’ in theory, but not really in practice, needs specific conditions not naturally found… plastics used for some medical applications (stens, suture points, etc.), *3D-printing.* Do not resist to well to fire and poses problems during recycling when mixed with other plastics (different recycling pathway – class 7).

Plastics main families

- **Polyepoxide (epoxy)** – ex. adhesive,
- **Polymethyl methacrylate (PMMA)** (acrylic) – contact lenses, glazing (trades names: Perspex, Plexiglas, Oroglas),...
- **Polytetrafluoroethylene (PTFE),** or Teflon – heat-resistant, low-friction coatings
- **Acetal (Polyoxymethylene; POM**) - low-friction plastic – Gears.

Plastics families by recycling tags…



1. Polyethylene terephthalate (PET or PETE)
2. High-density polyethylene (HDPE)
3. Polyvinyl chloride (PVC)
4. Low-density polyethylene (LDPE)
5. Polypropylene (PP)
6. Polystyrene (PS)
7. Other types of plastics (ex. PLA)

Recycling codes

1 PETE	2 HDPE	3 PVC	4 LDPE	5 PP	6 PS	7 OTHER
polyethylene terephthalate	high-density polyethylene	polyvinyl chloride	low-density polyethylene	polypropylene	polystyrene	other plastics, including acrylic, polycarbonate, polyactic fibers, nylon, fiberglass
soft drink bottles, mineral water, fruit juice containers and cooking oil	milk jugs, cleaning agents, laundry detergents, bleaching agents, shampoo bottles, washing and shower soaps	trays for sweets, fruit, plastic packing (bubble foil) and food foils to wrap the foodstuff	crushed bottles, shopping bags, highly-resistant sacks and most of the wrappings	furniture, consumers, luggage, toys as well as bumpers, lining and external borders of the cars	toys, hard packing, refrigerator trays, cosmetic bags, costume jewellery, audio cassettes, CD cases, vending cups	an example of one type is a polycarbonate used for CD production and baby feeding bottles

Some selection criteria...

	1 PETE Polyethylene Terephthalate (PET)	2 HDPE High Density Polyethylene	3 V Polyvinyl Chloride (PVC)	4 LDPE Low Density Polyethylene	5 PP Polypropylene	6 PS Polystyrene (PS)
Clarity	Clear	Hazy Translucent	Clear	Translucent	Translucent	Clear
Moisture Barrier (MTVR)	Good	Excellent	Good	Very Good	Excellent	Poor
Oxygen Barrier	Good	Poor	Good	Poor	Poor	Poor
Distortion Temperature	155°F	160°F	150°F	110°F	200°F	170°F
Rigidity	High	Moderate	High	Low	Moderate	High
Stress Crack Resistance	Excellent	Fair	Excellent	Good	Excellent	Fair
Cold Resistance	Good	Excellent	Fair	Excellent	Poor	Poor
Impact Resistance	Good	Excellent	Good	Excellent	Fair	Poor
Alcohol Resistance	Good	Good	Excellent	Good	Good	Fair
Alkalis Resistance	Poor	Good	Excellent	Good	Good	Fair
Solvent Resistance	Good	Poor	Good	Poor	Poor	Poor
Oil Resistance	Fair	Good	Good	Good	Good	Poor
Acid Resistance	Fair	Good	Good	Good	Good	Fair

Part design related properties

(Source: siglanplastics)

(Source: engineeringlearn.com)

Two families of plastics

- **Thermoplastics** → Can be remolded! (below Tm, above Tg)
  - No chemical changes upon heating
  - 'Reformable chemical bonds'
  - *Ex. Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC)*

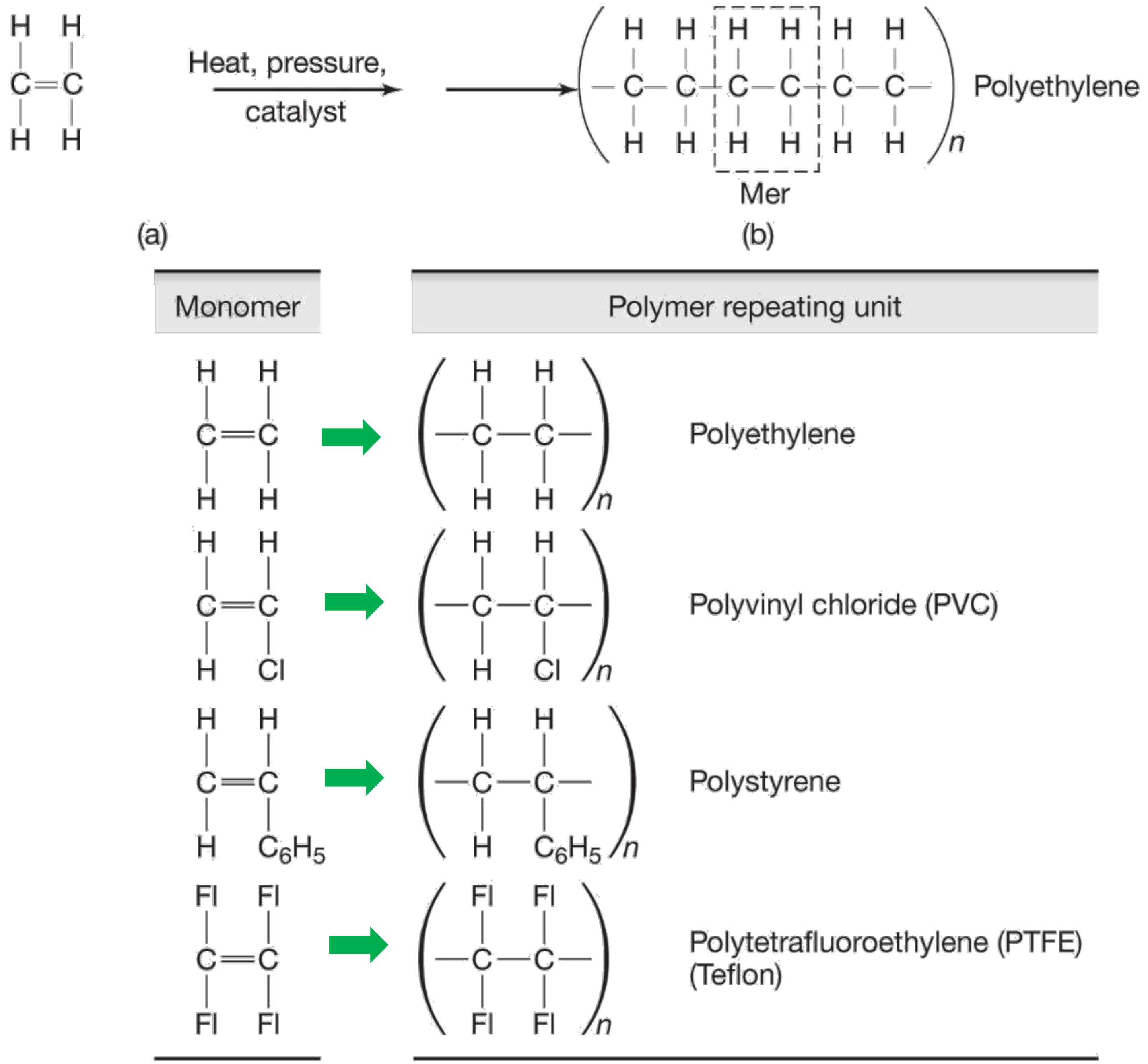
- **Thermosets** → Can be put into form only once!
  - Irreversible chemical reaction
  - Irreversible hardening ('curing') / cannot be reused
  - Better suited for high-temperature applications
  - Decompose above the melting point
  - *Example: epoxy resin, polyimides (mask for cleanroom), polyurethanes*

Polymers // Elastomers

Polymers (The thermoplastics and thermosets of engineering)	Acrylonitrile butadiene styrene	ABS
	Cellulose polymers	CA
	Ionomers	Ionomers
	Epoxies	Epoxy
	Phenolics	Phelonics
	Polyamides (nylons)	PA
	Polycarbonate	PC
	Polyesters	Polyester
	Polyetheretherkeytone	PEEK
	Polyethylene	PE
	Polyethylene terephalate	PET or PETE
	Polymethylmethacrylate	PMMA
	Polyoxymethylene (Acetal)	POM
	Polypropylene	PP
	Polystyrene	PS
	Polytetrafluorethylene	PTFE
	Polyvinylchloride	PVC

Elastomers (Engineering rubbers, natural and synthetic)	Butyl rubber	Butyl rubber
	EVA	EVA
	Isoprene	Isoprene
	Natural rubber	Natural rubber
	Polychloroprene (Neoprene)	Neoprene
	Polyurethane	PU
(Subclass of polymers)	Silicone elastomers	Silicones

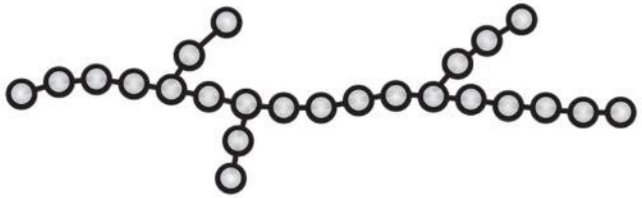
Viscoleastic, weak intermolecular forces, ***low Young's modulus***, high failure strain, ***amorphous***…



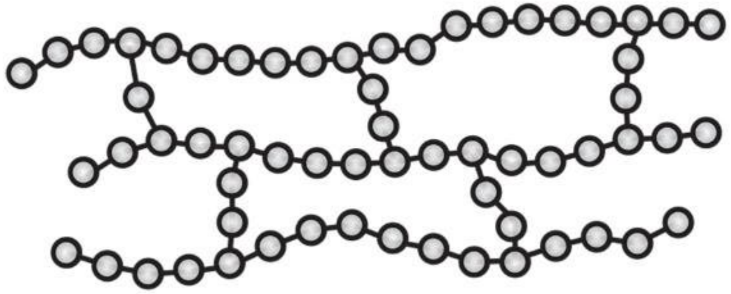
Basic chemical structures (plastics)

‘A **polymer** is a substance or material consisting of very large molecules called macromolecules, composed of many repeating subunits.’ (def. Britannica)

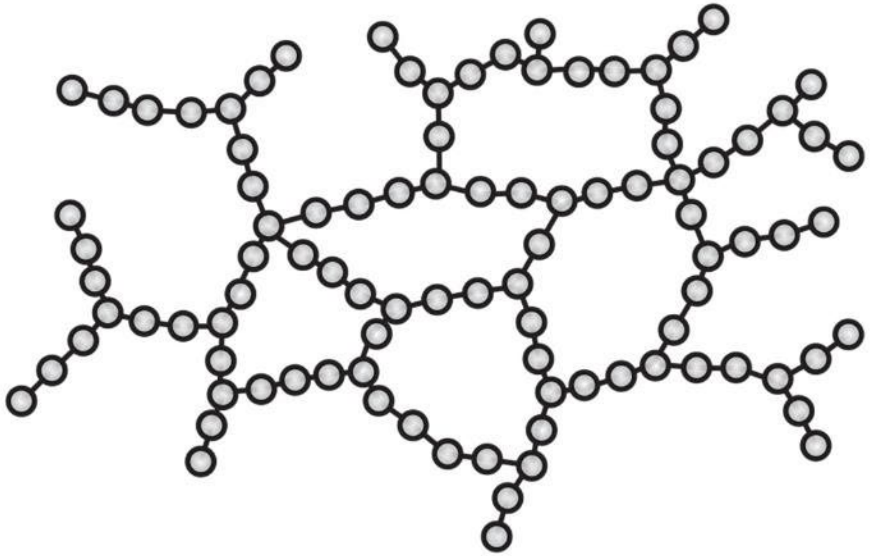
Linear
ex. Thermoplastics
(acrylics, nylons,
polyethylene, and polyvinyl
chloride)



Branched
(ex. Polyethylene)

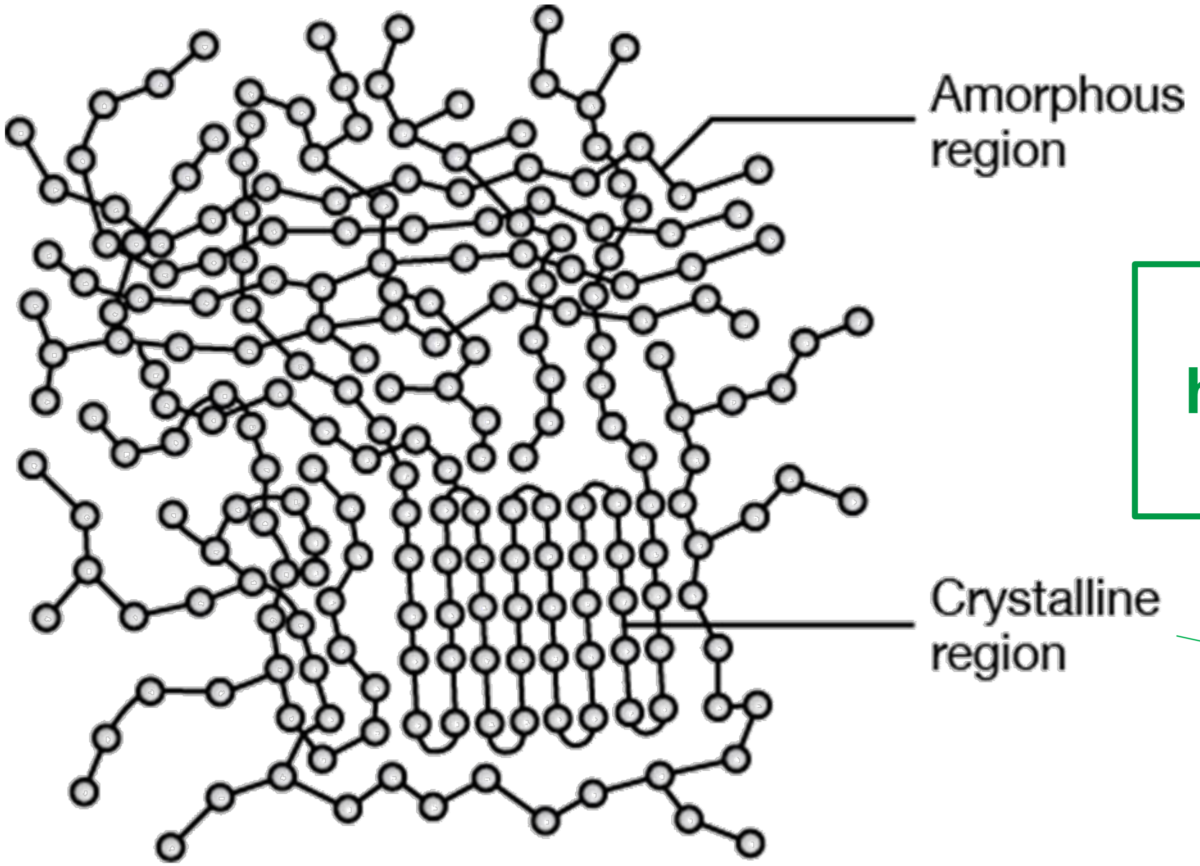


Cross-linked
(ex. rubbers, elastomers)



Network (highly cross-linked)
(ex. Thermosetting plastics, epoxies,
phenolics)

Crystallinity in a polymer



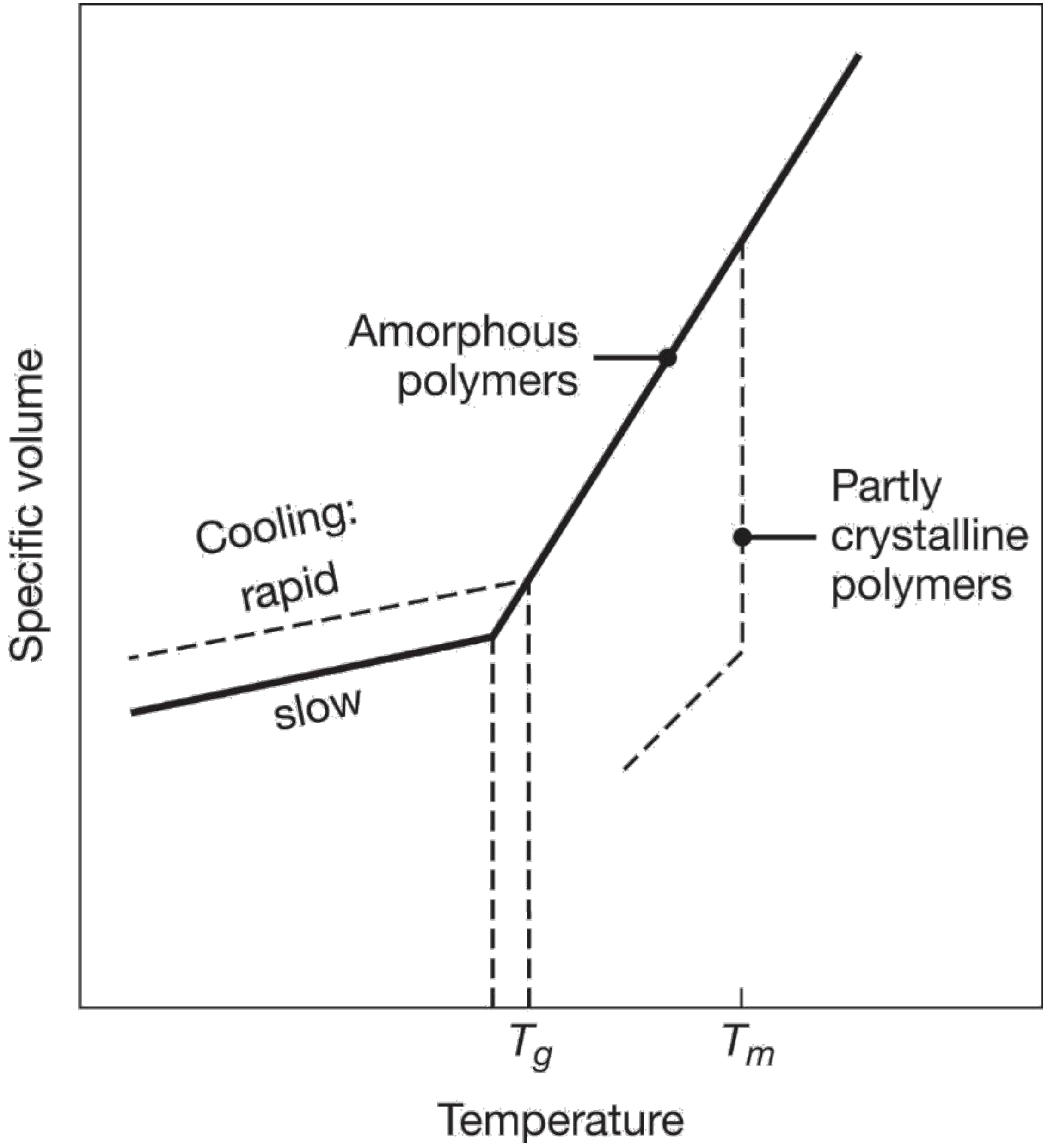
'less organized'

The **higher** the crystallinity = the **harder**, **stiffer**, and **less ductile** is the material.

'more organized'

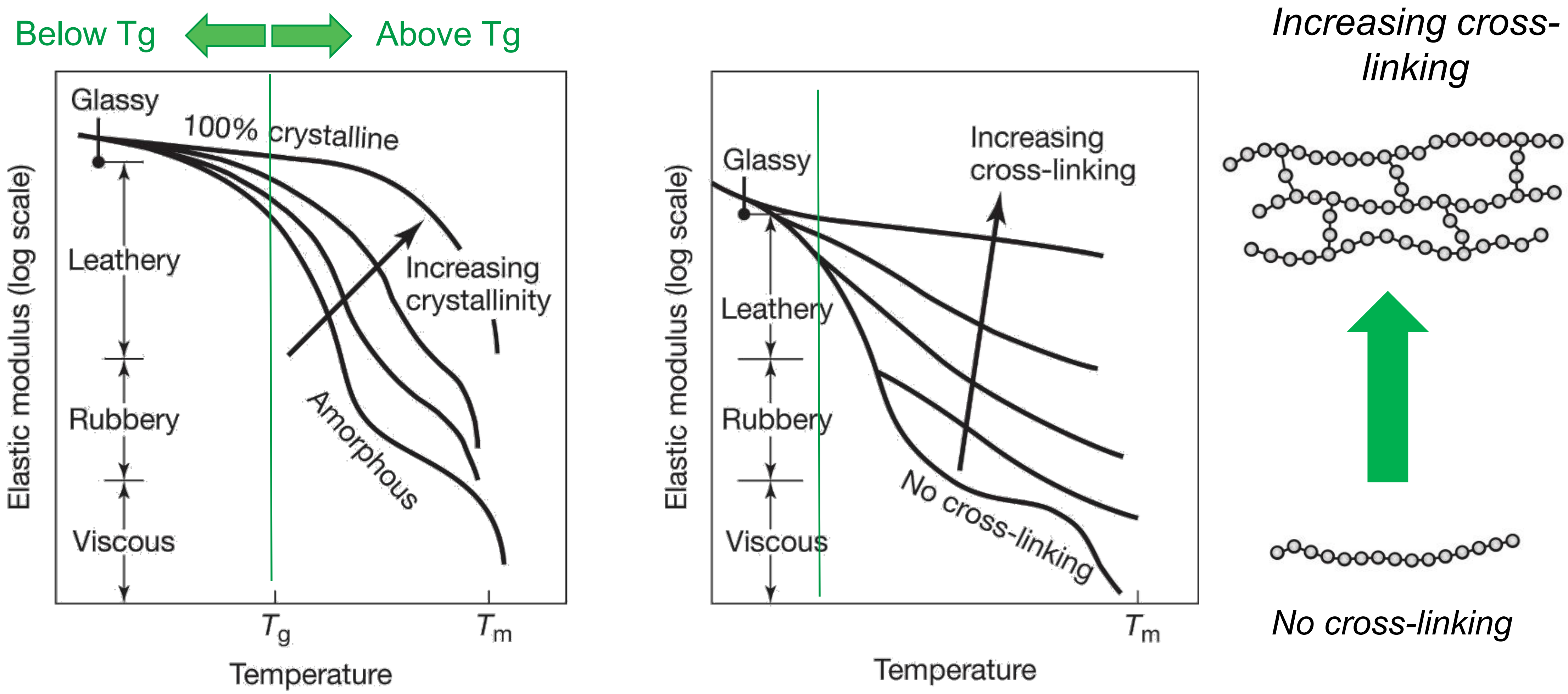
Tg / Tm

- **Tg /** ‘Glass-transition’ temperature
- **Tm /** Melting-point
- Note that some plastics do not have a clearly defined melting point
- Thermodynamics phase change point of view: second order transformation (i.e. no discontinuity in physical properties)



***Tg** defines the limit towards a sharp change in physical properties of the plastic.*
***Tg** depends on the cooling velocity*

Temperature behavior of polymers as a function of degree of crystallinity and cross-linking

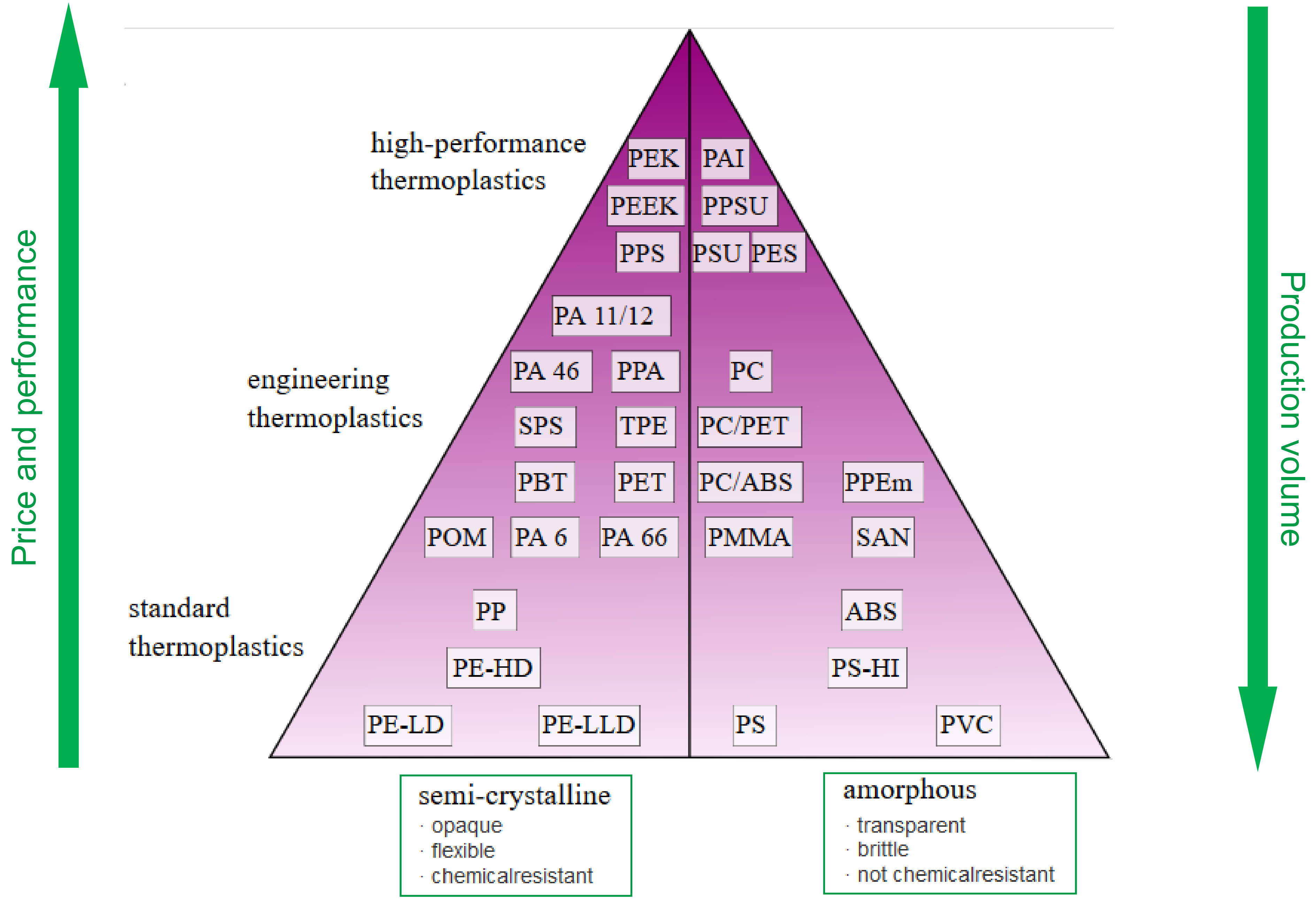


‘Glass’-transition / melting temperature

Material	T_g (°C)	T_m (°C)
Nylon 6,6	57	265
Polycarbonate	150	265
Polyester	73	265
Polyethylene		
High density	−90	137
Low density	−110	115
Polymethylmethacrylate	105	–
Polypropylene	−14	176
Polystyrene	100	239
Polytetrafluoroethylene (Teflon)	−90	327
Polyvinyl chloride	87	212
Rubber	−73	–

For comparison:

Melting point of aluminum – 660°C
Glass-transition of:
SiO_2 ~ 1200°C
Sodalime glass ~ 500-600°C
Sapphire ~ 2030°C

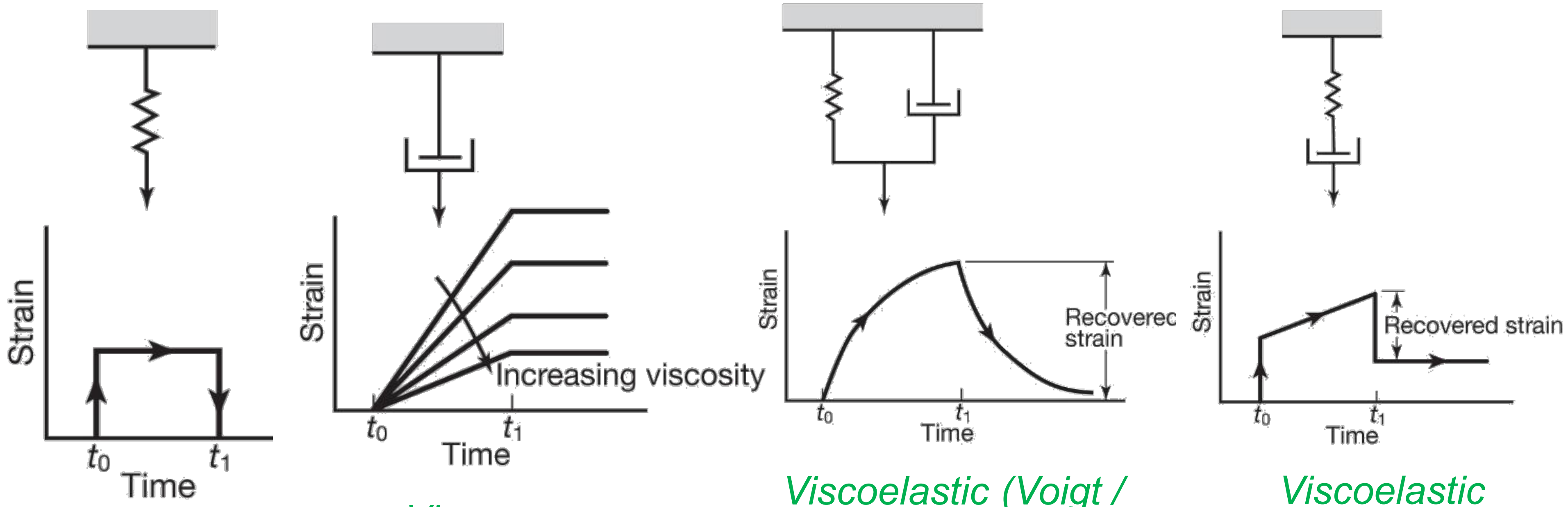


Price and performance
Production volume
high-performance thermoplastics
engineering thermoplastics
standard thermoplastics
PEK
PAI
PEEK
PPSU
PPS
PSU
PES
PA 11/12
PA 46
PPA
PC
SPS
TPE
PC/PET
PBT
PET
PC/ABS
PPEm
POM
PA 6
PA 66
PMMA
SAN
PP
ABS
PE-HD
PS-HI
PE-LD
PE-LLD
PS
PVC
semi-crystalline
· opaque
· flexible
· chemicalresistant
amorphous
· transparent
· brittle
· not chemicalresistant

(Source: Wiki)

Polymers strain behavior models

'Assume a load is applied at t_0 then release at t_1'



Elastic

Viscous

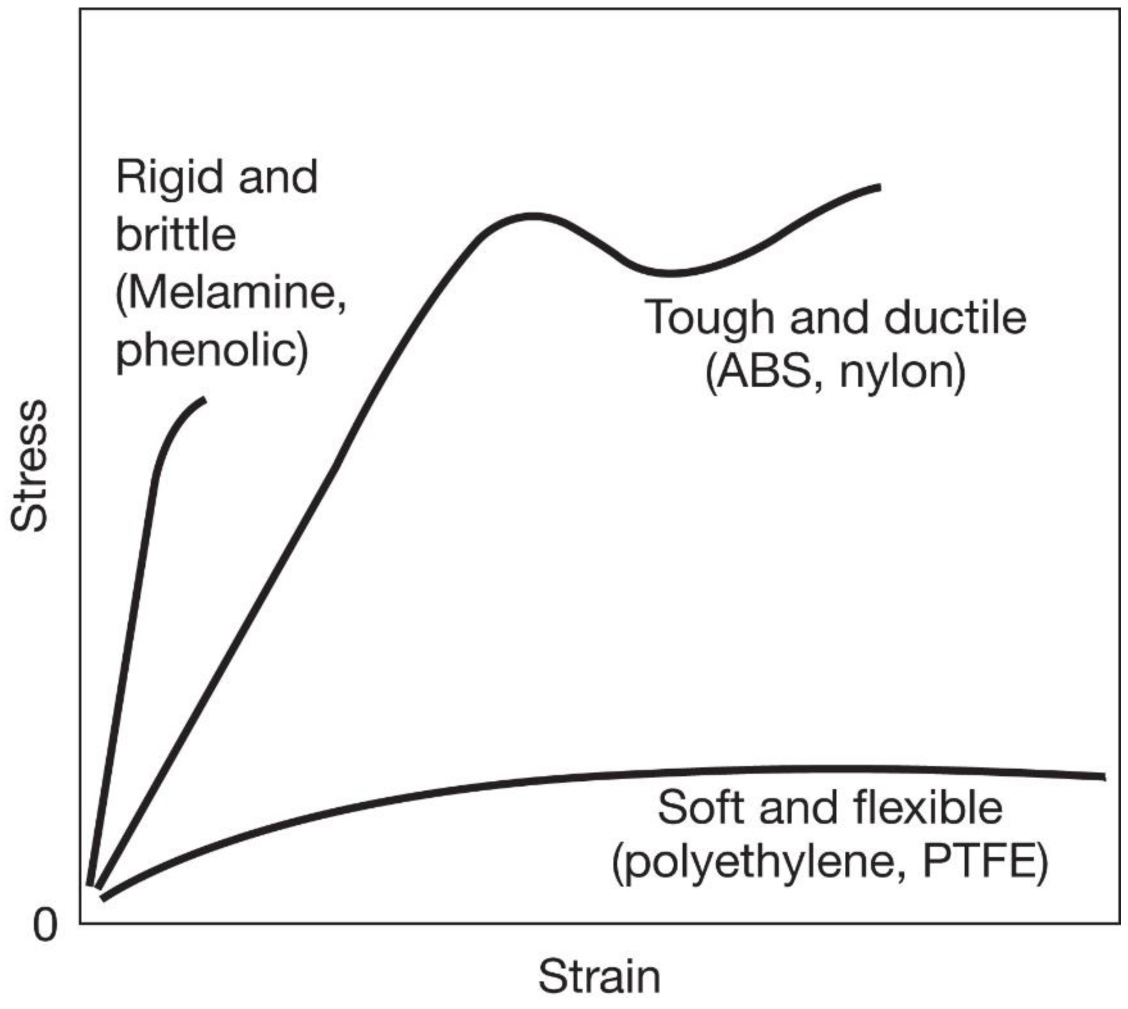
Viscoelastic (Voigt / Kelvin model)

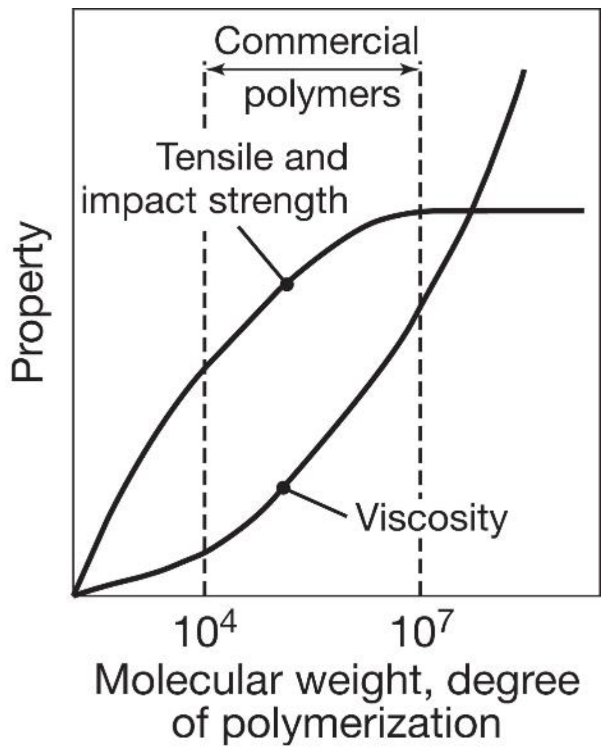
Viscoelastic (Maxwell model)

Typically observed below Tg

Typically observed above Tg

Mechanical properties
Typical behaviors





'The higher the degree of polymerization, the higher the tensile and impact strength and the highest the viscosity'

Temperature dependent properties

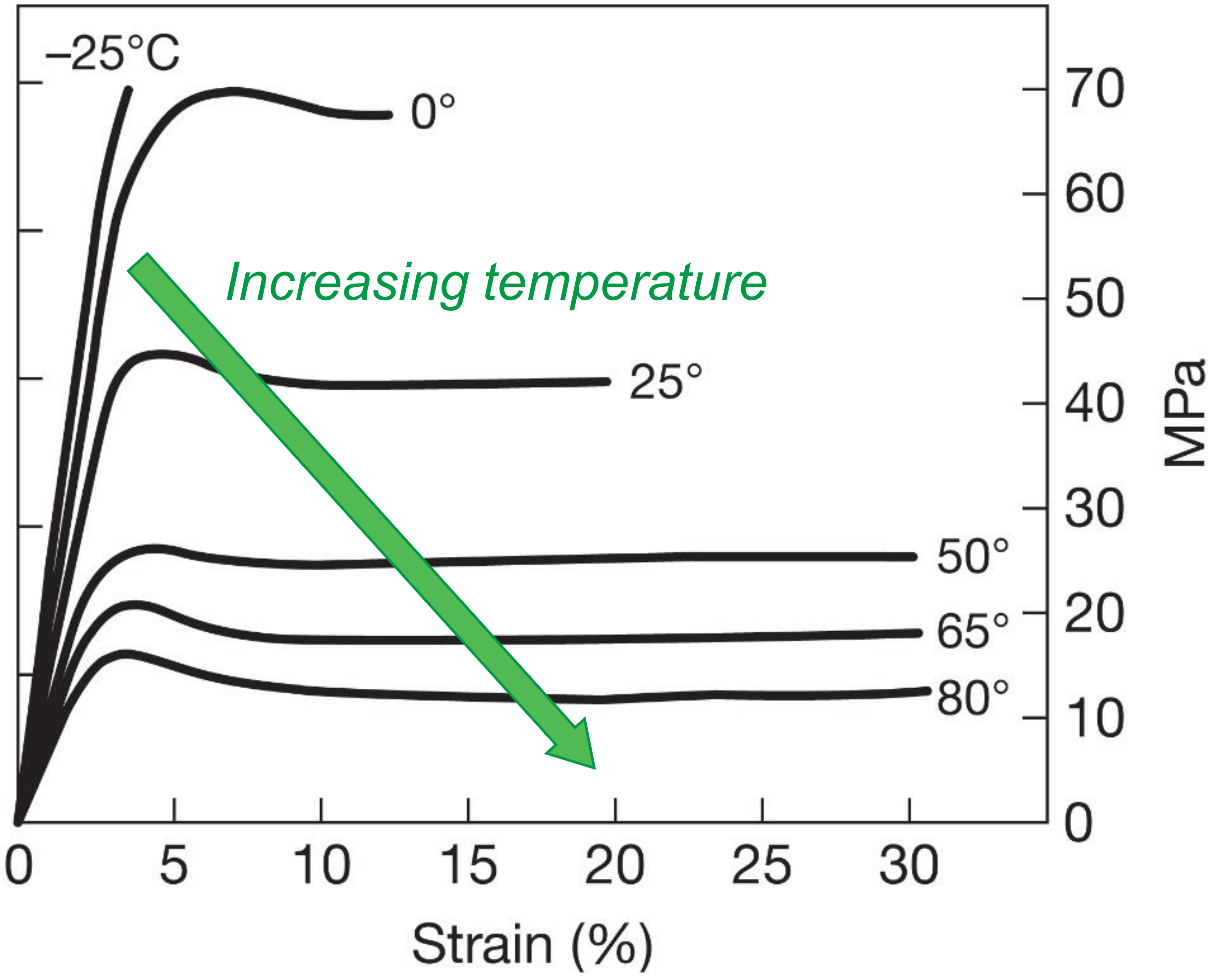
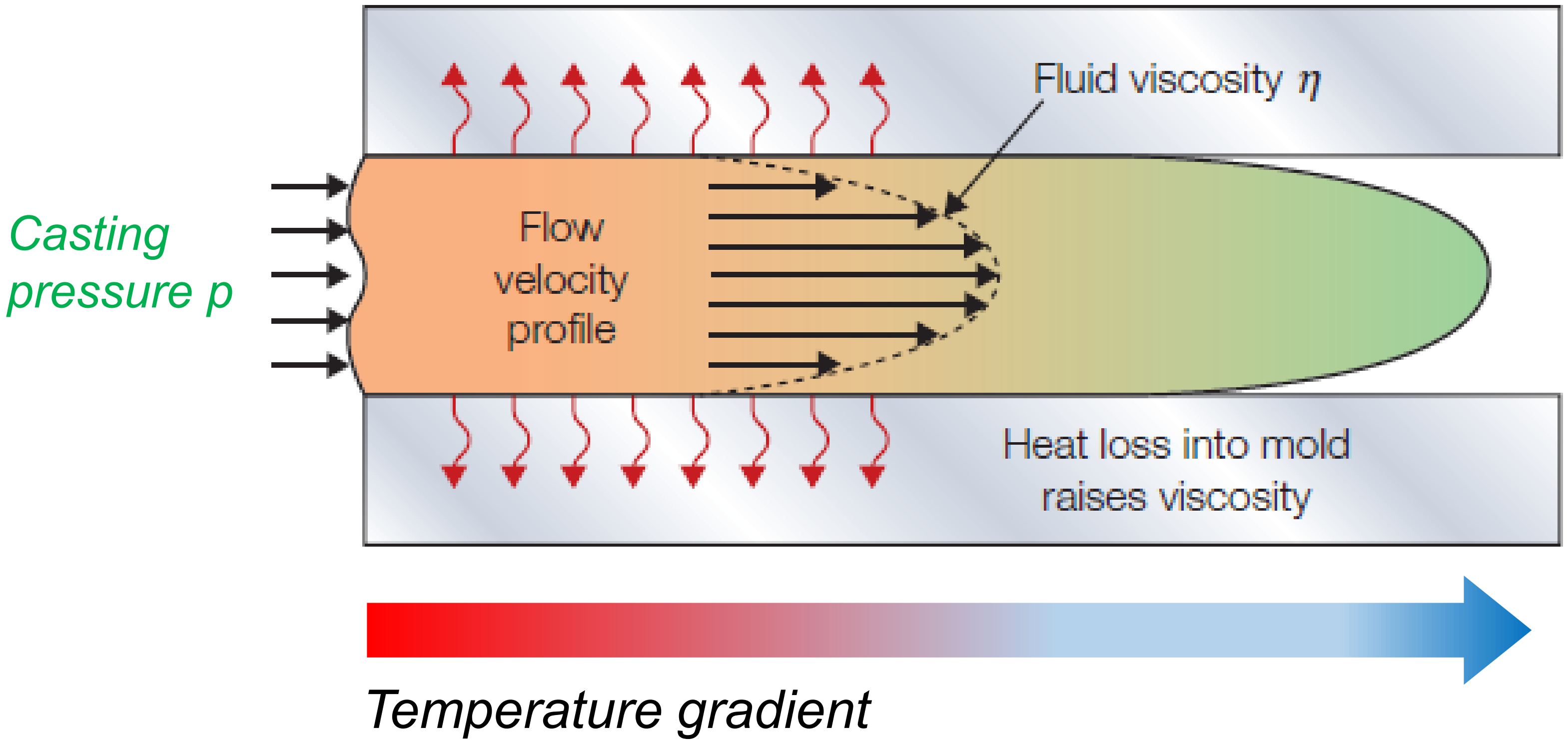


Illustration for a thermoplastics (cellulose acetate)



Determine the process conditions for the injection (temperature, injection rate)

Typical use of plastics

Design requirement	Typical applications	Plastics
Mechanical strength	Gears, cams, rollers, valves, fan blades, impellers, pistons	Acetals, nylon, phenolics, polycarbonates, polyesters, polypropylenes, epoxies, polyimides
Wear resistance	Gears, wear strips and liners, bearings, bushings, roller-skate wheels	Acetals, nylon, phenolics, polyimides, polyurethane, ultrahigh-molecular-weight polyethylene
Friction		
High	Tires, nonskid surfaces, footwear, flooring	Elastomers, rubbers
Low	Sliding surfaces, artificial joints	Fluorocarbons, polyesters, polyethylene, polyimides
Electrical resistance	All types of electrical components and equipment, appliances, electrical fixtures	Polymethylmethacrylate, ABS, fluorocarbons, nylon, polycarbonate, polyester, polypropylenes, ureas, phenolics, silicones, rubbers
Chemical resistance	Containers for chemicals, laboratory equipment, components for chemical industry, food and beverage containers	Acetals, ABS, epoxies, polymethylmethacrylate, fluorocarbons, nylon, polycarbonate, polyester, polypropylene, ureas, silicones
Heat resistance	Appliances, cookware, electrical components	Fluorocarbons, polyimides, silicones, acetals, polysulfones, phenolics, epoxies
Functional and decorative features	Handles, knobs, camera and battery cases, trim moldings, pipe fittings	ABS, acrylics, cellulosics, phenolics, polyethylenes, polypropylenes, polystyrenes, polyvinyl chloride
Functional and transparent features	Lenses, goggles, safety glazing, signs, food-processing equipment	Acrylics, polycarbonates, polystyrenes, polysulfones, laboratory hardware
Housings and hollow shapes	Power tools, housings, sport helmets, telephone cases	ABS, cellulosics, phenolics, polycarbonates, polyethylenes, polypropylene, polystyrenes

Properties

Material	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Poisson's ratio, ν
Thermoplastics:				
ABS	28–55	1.4–2.8	75–5	–
ABS, reinforced	100	7.5	–	0.35
Acetal	55–70	1.4–3.5	75–25	–
Acetal, reinforced	135	10	–	0.35–0.40
Acrylic	40–75	1.4–3.5	50–5	–
Cellulosic	10–48	0.4–1.4	100–5	–
Fluorocarbon	7–48	0.7–2	300–100	0.46–0.48
Nylon	55–83	1.4–2.8	200–60	0.32–0.40
Nylon, reinforced	70–210	2–10	10–1	–
Polycarbonate	55–70	2.5–3	125–10	0.38
Polycarbonate, reinforced	110	6	6–4	–
Polyester	55	2	300–5	0.38
Polyester, reinforced	110–160	8.3–12	3–1	–

For comparison:

Aluminum (alloys)
– UTS ~ 600 Mpa
- Young's modulus ~76 GPa

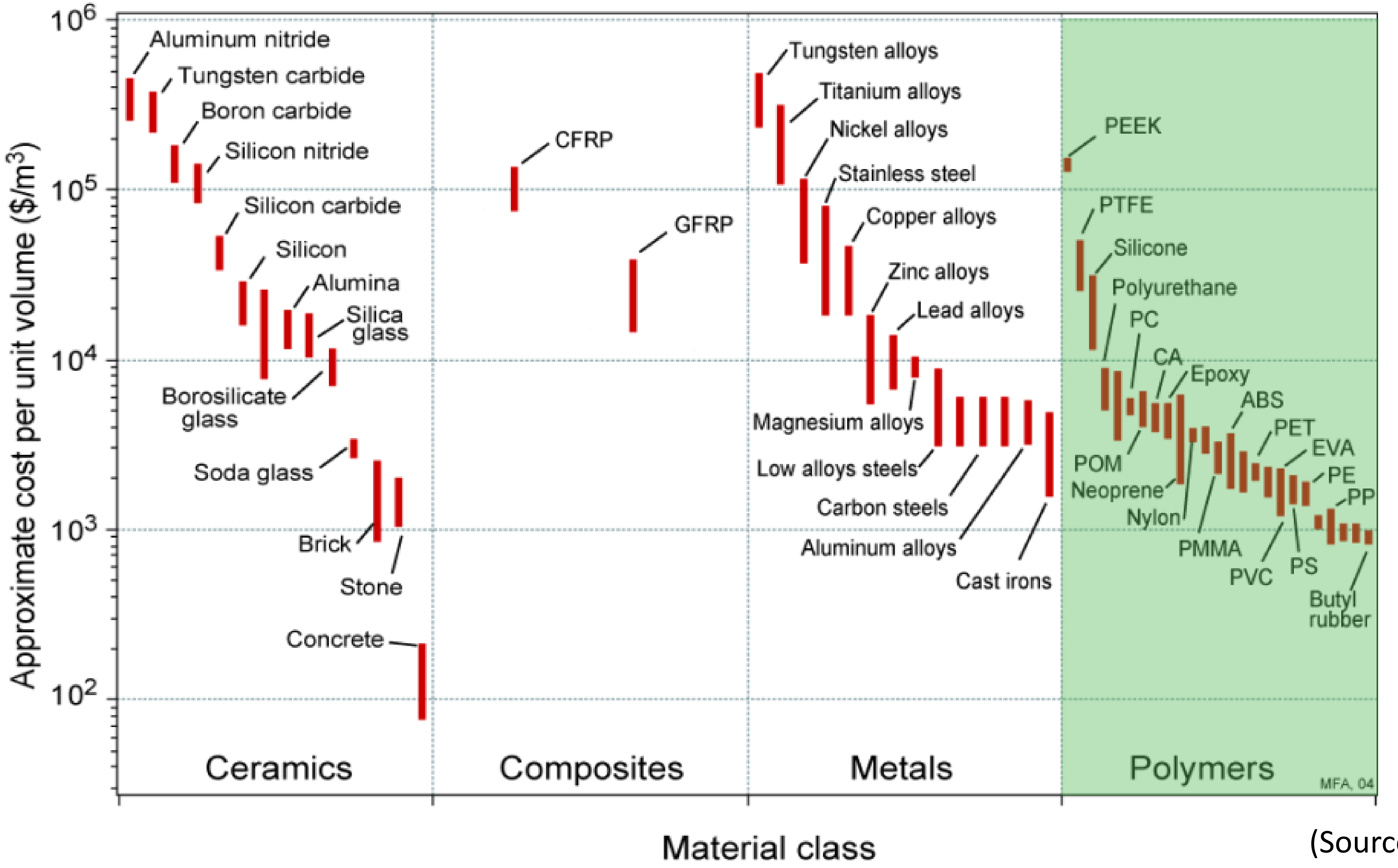
Properties (II)

Material	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Poisson's ratio, ν
Polyethylene	7–40	0.1–1.4	1000–15	0.46
Polypropylene	20–35	0.7–1.2	500–10	–
Polypropylene, reinforced	40–100	3.5–6	4–2	–
Polystyrene	14–83	1.4–4	60–1	0.35
Polyvinyl chloride	7–55	0.014–4	450–40	–
Thermosets:				
Epoxy	35–140	3.5–17	10–1	–
Epoxy, reinforced	70–1400	21–52	4–2	–
Phenolic	28–70	2.8–21	2–0	–
Polyester, unsaturated	30	5–9	1–0	–
Elastomers:				
Chloroprene (neoprene)	15–25	1–2	100–500	0.5
Natural rubber	17–25	1.3	75–650	0.5
Silicone	5–8	1–5	100–1100	0.5
Styrene-butadiene	10–25	2–10	250–700	0.5
Urethane	20–30	2–10	300–450	0.5

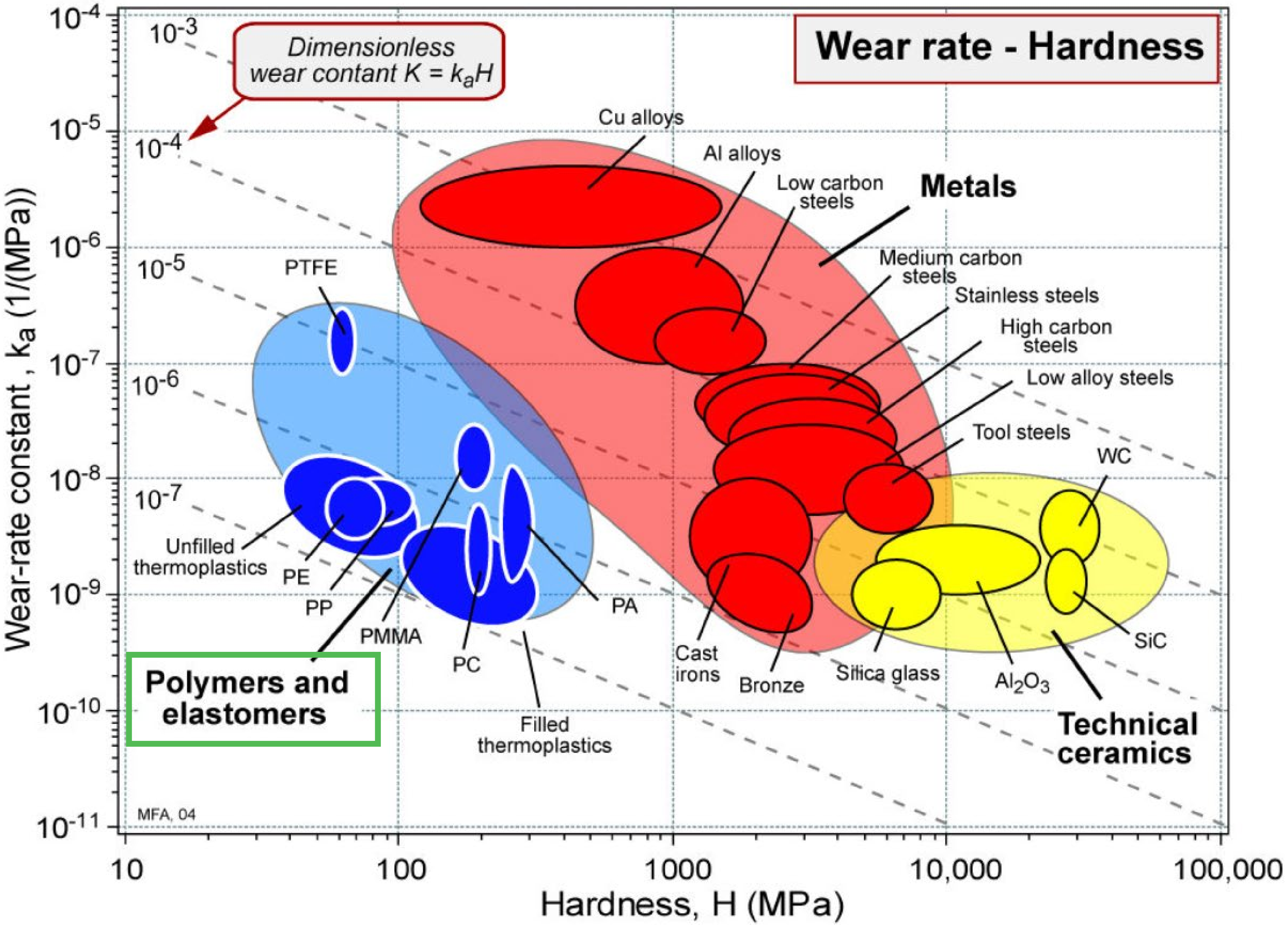
Some orders of magnitude and key characteristics

- Young modulus ~ 1 GPa
- Strength ~ 1 MPa to 100 MPa
- Can have Low friction < 0.1
- Operating temp. < 300°C
- **High CTE** (among the highest) >= 10^{-4} /°C
- Poor thermal conductivity: typ. 0.1 to 1 W/m.K // Low to very low diffusivity
- Very high electrical resistance (insulator)
- Very high damping coefficient (= high internal friction)

Plastic economics



(Source: Granta Design)



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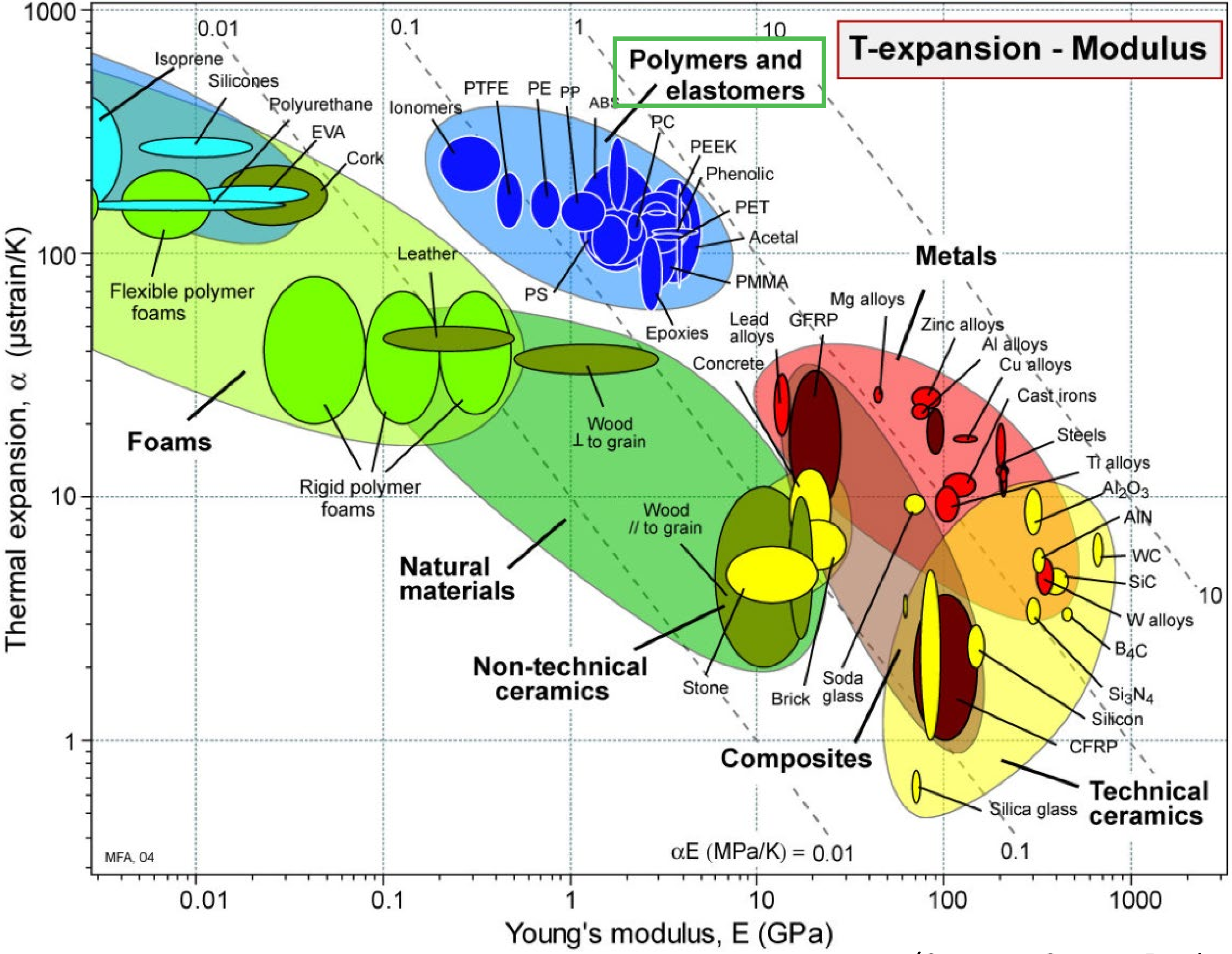

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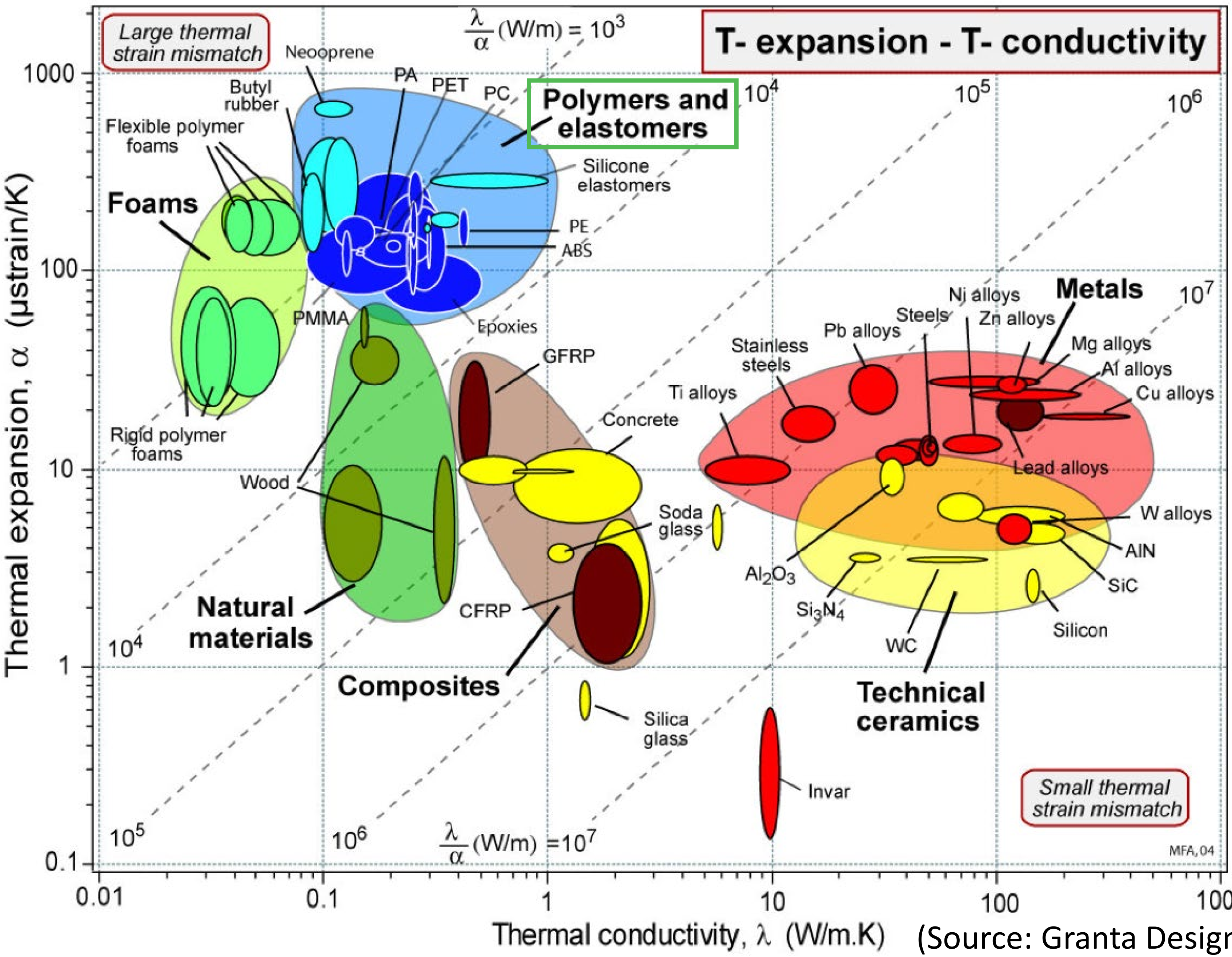

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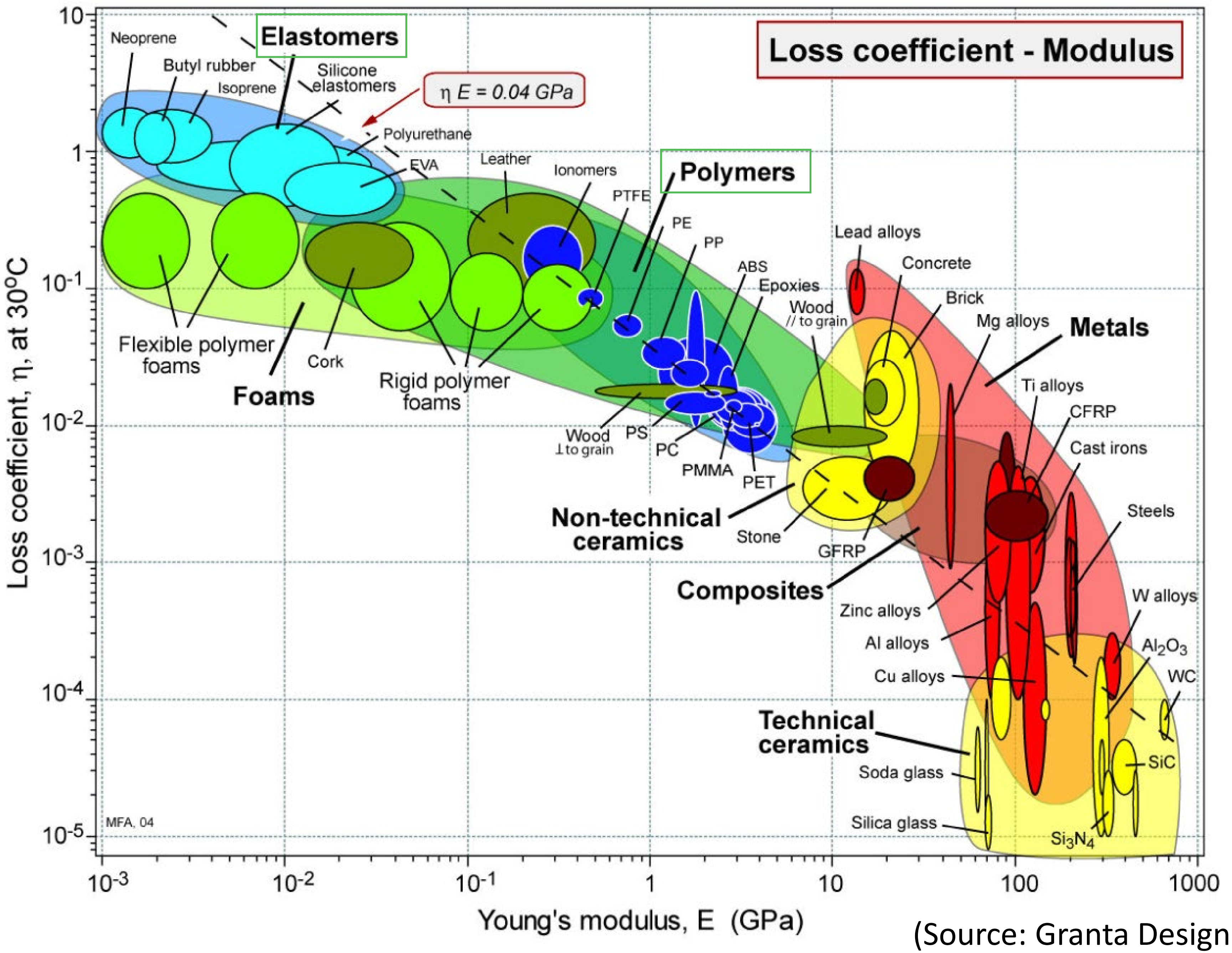

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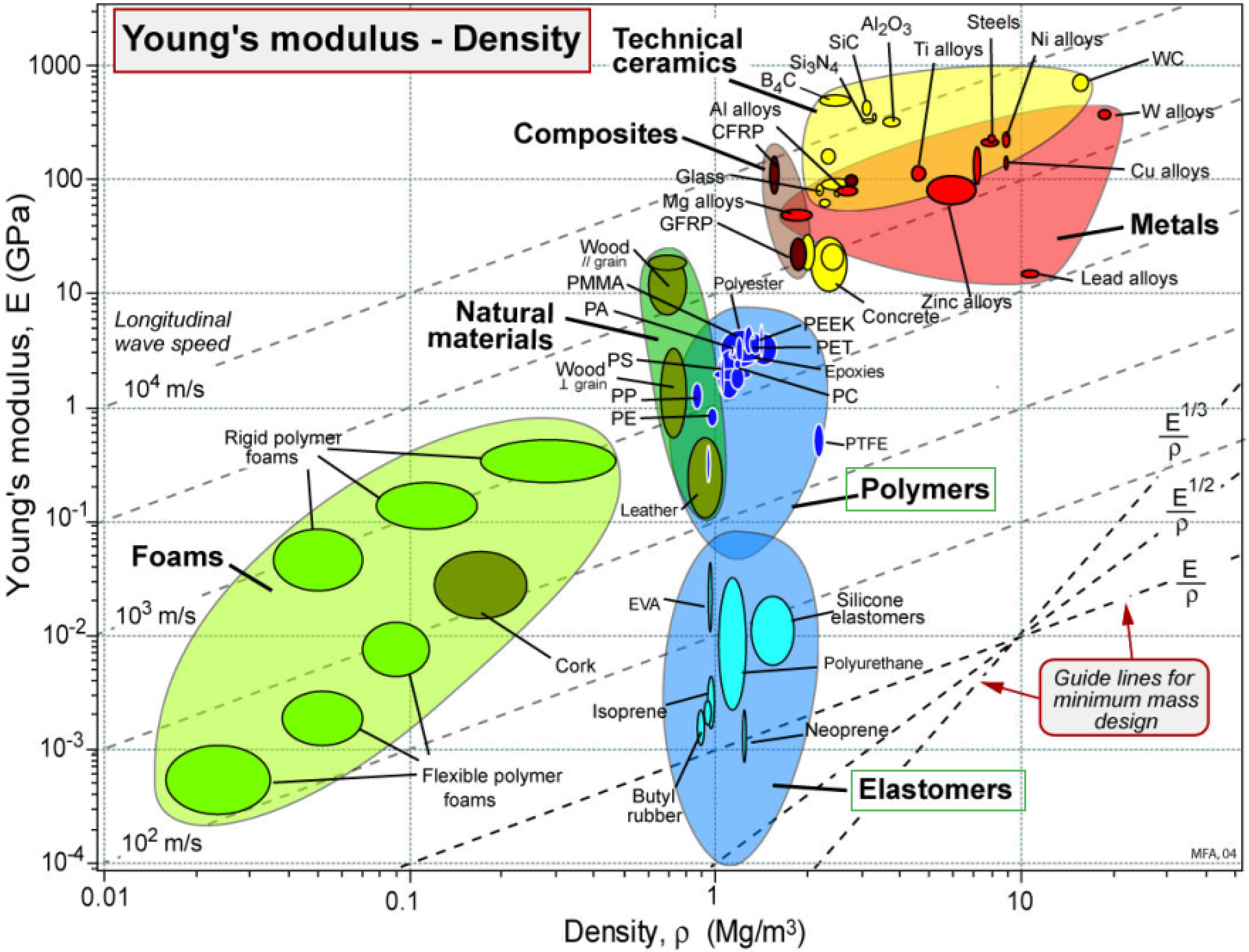
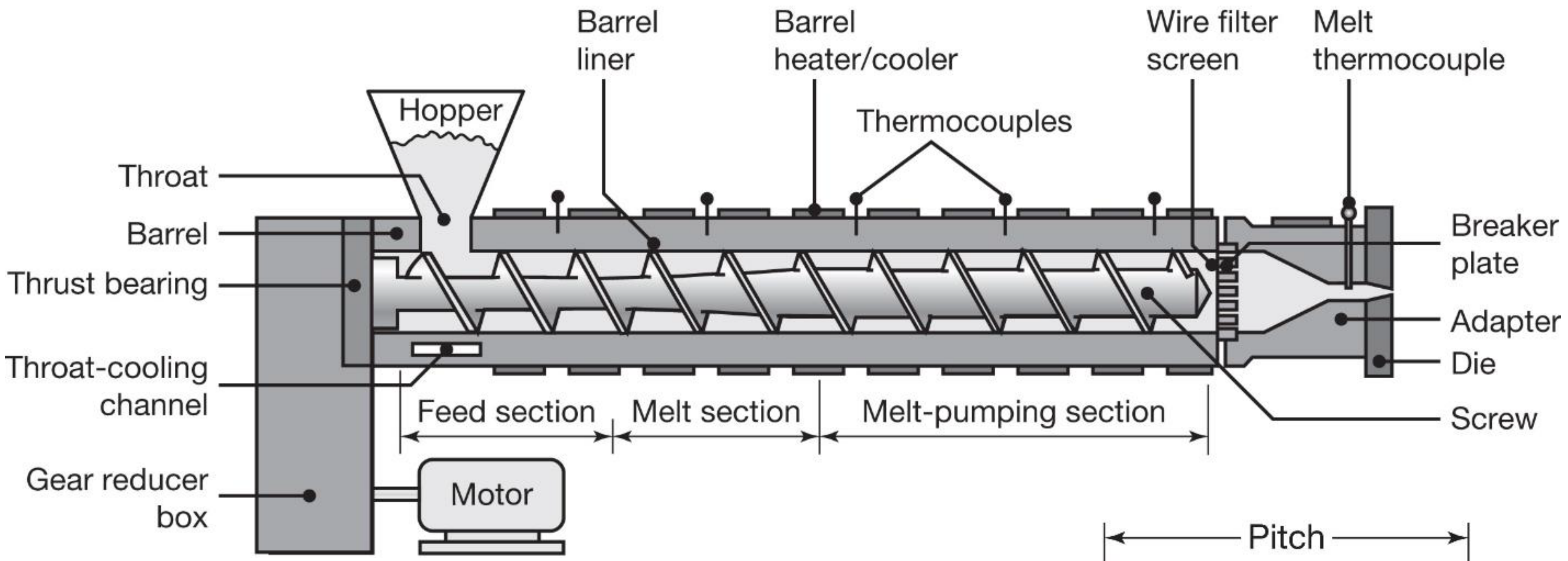

Young's modulus - Density
Technical ceramics
Composites
Metals
Natural materials
Polymers
Foams
Elastomers
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
SiC
Al_2O_3
Steels
Ni alloys
Ti alloys
Si_3N_4
B_4C
WC
W alloys
Al alloys
CFRP
Cu alloys
Glass
Mg alloys
GFRP
Lead alloys
Zinc alloys
Concrete
Wood // grain
PMMA
PA
Polyester
PEEK
PET
Epoxies
PC
PS
Wood ⊥ grain
PP
PE
PTFE
Leather
Rigid polymer foams
Cork
Flexible polymer foams
EVA
Silicone elastomers
Polyurethane
Isoprene
Neoprene
Butyl rubber
$\frac{E^{1/3}}{\rho}$
$\frac{E^{1/2}}{\rho}$
$\frac{E}{\rho}$
Guide lines for minimum mass design
Young's modulus, E (GPa)
Density, ρ (Mg/m³)
0.01
0.1
1
10
1000
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
MFA, 04

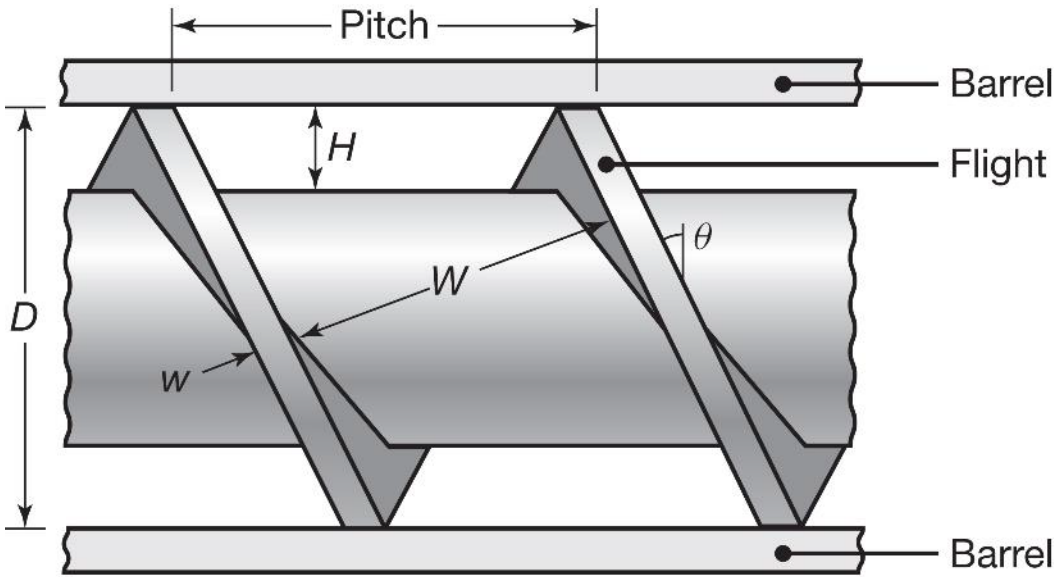
Manufacturing of plastics

Process	Characteristics
Extrusion	Long, uniform, solid or hollow, simple or complex cross sections; wide range of dimensional tolerances; high production rates; low tooling cost
Injection molding	Complex shapes of various sizes and with fine detail; good-dimensional accuracy; high production rates; high tooling cost
Structural foam molding	Large parts with high stiffness-to-weight ratio; low production rates; less expensive tooling than in injection molding
Blow molding	Hollow thin-walled parts of various sizes; high production rates and low cost for making beverage and food containers
Rotational molding	Large hollow shapes of relatively simple design; low production rates; low tooling cost
Thermoforming	Shallow or deep cavities; medium production rates; low tooling costs
Compression molding	Parts similar to impression-die forging; medium production rates; relatively inexpensive tooling
Transfer molding	More complex parts than in compression molding, and higher production rates; some scrap loss; medium tooling cost
Casting	Simple or intricate shapes, made with flexible molds; low production rates
Processing of reinforced plastics	Long cycle times; dimensional tolerances and tooling costs depend on the specific process

→ Rapid prototyping: 3D Printing!

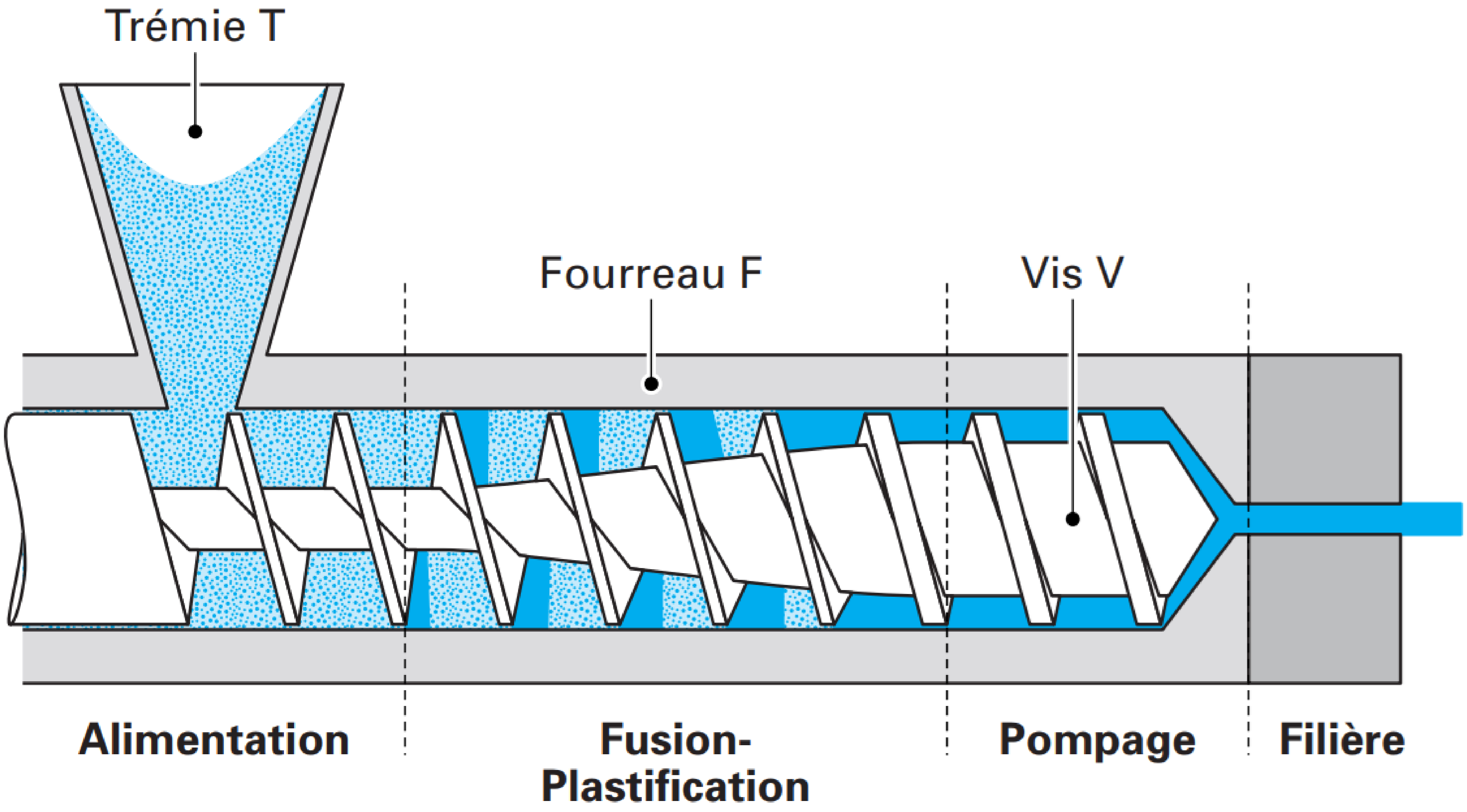
Plastic extrusion





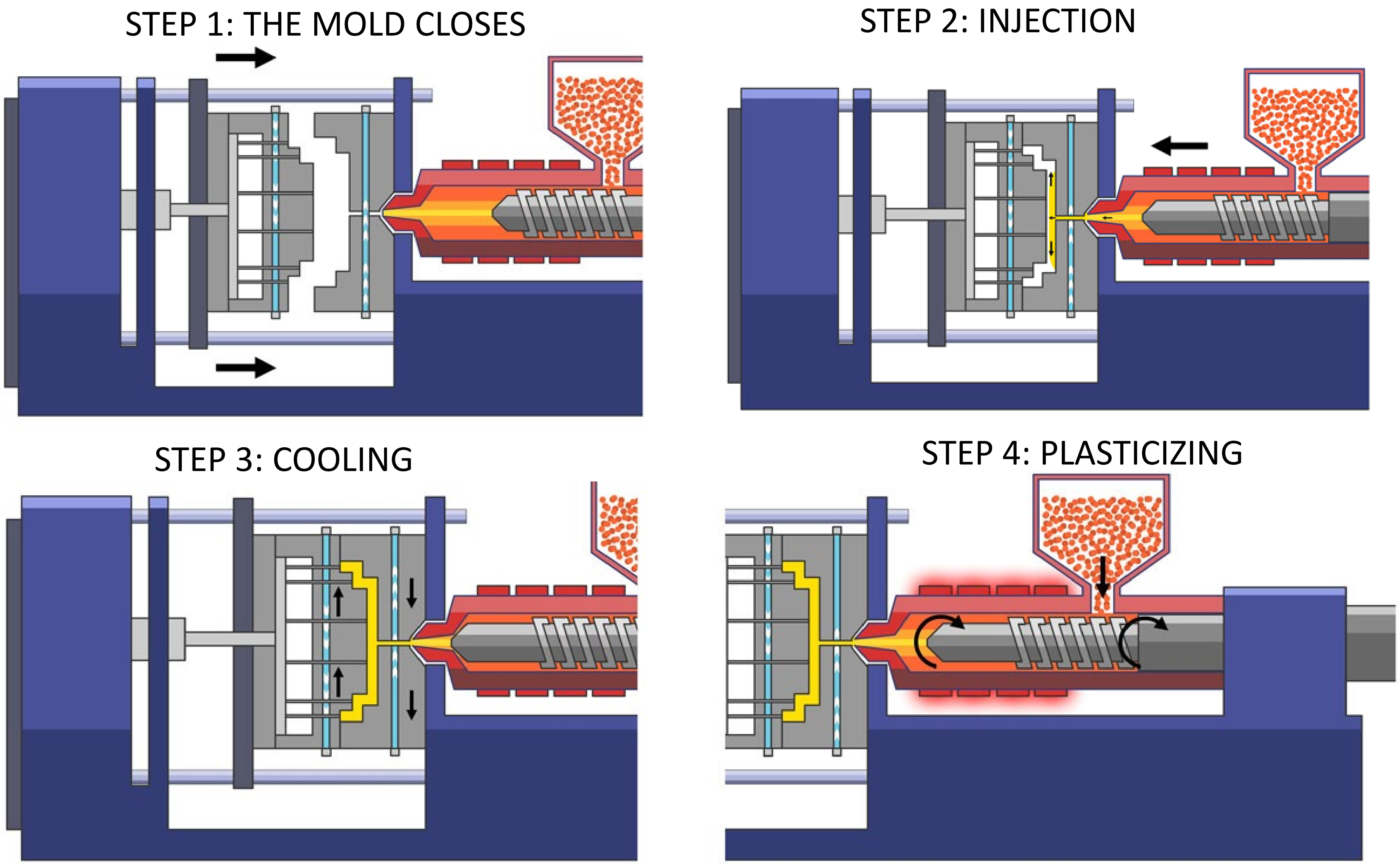
Key idea: *Prevent non-uniform melting of the plastic and progressively melt and homogenize the plastic for injection.*

Extrusion des plastiques



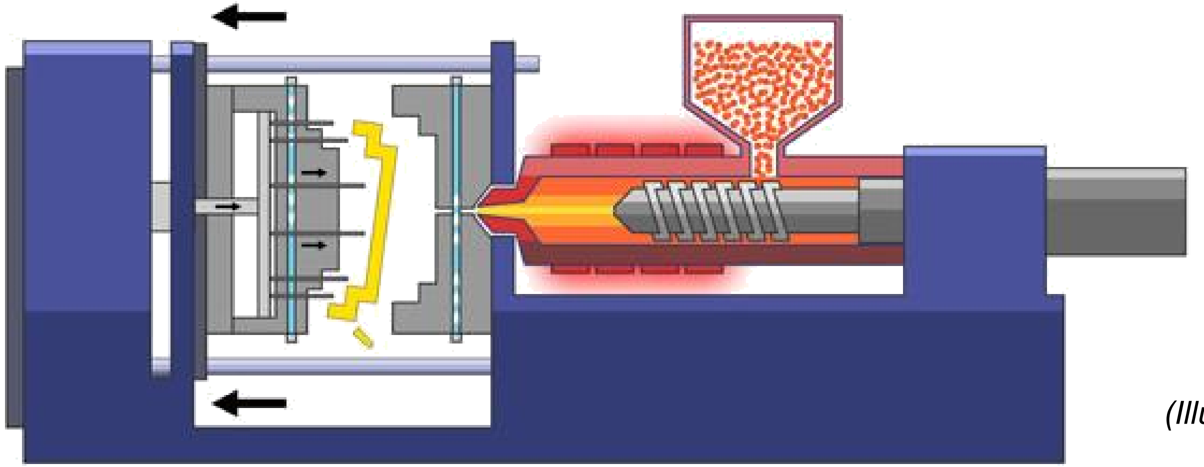
(Source: Techniques de l'Ingénieur, AM3650, B. Vergnes, S. Puissant)

Injection molding: Process steps (I)

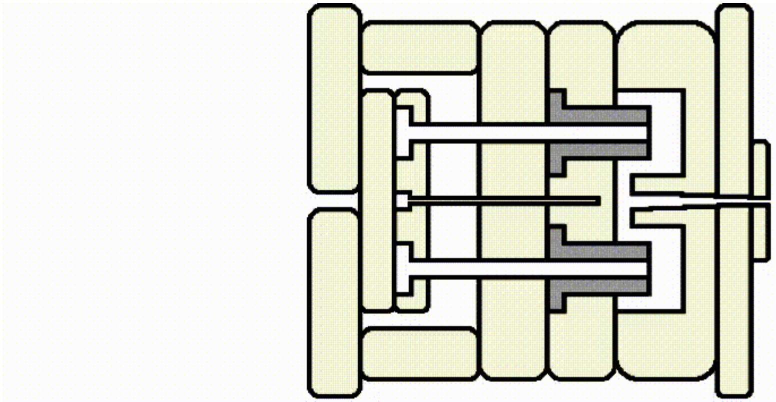


(Illustrations AirePlastics)

Process steps (end)



(Illustrations AirePlastics)

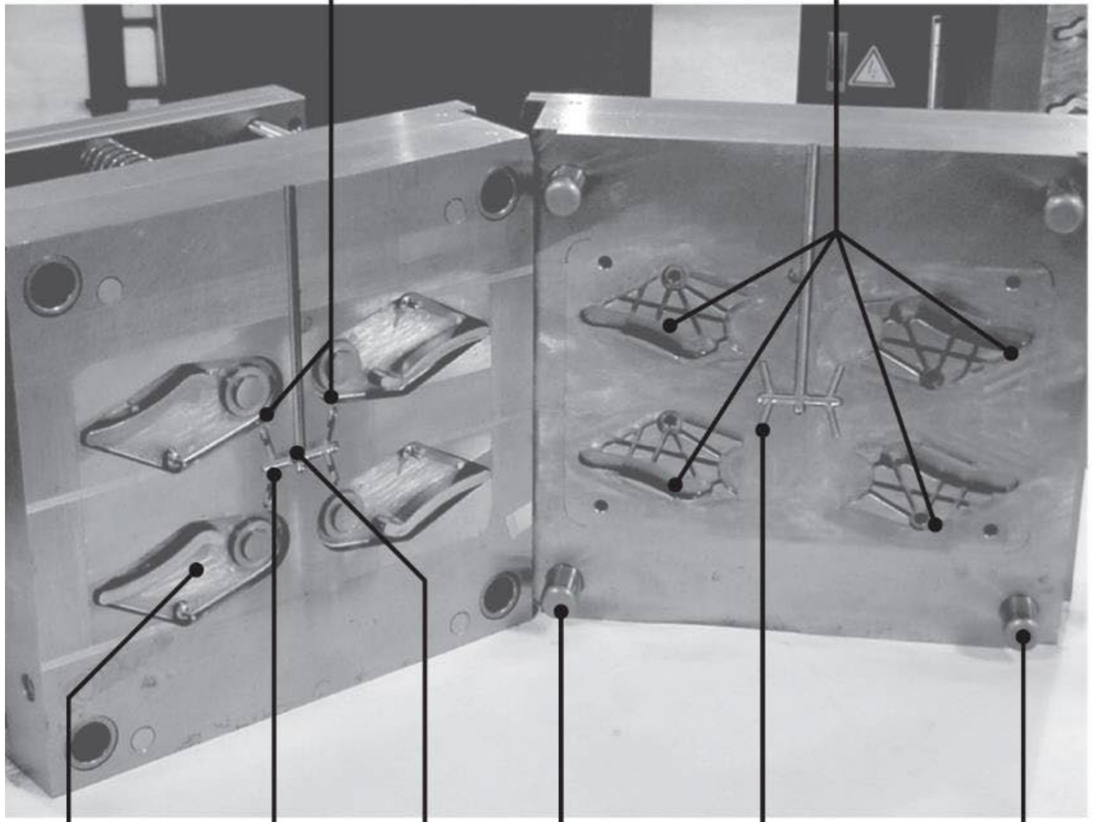


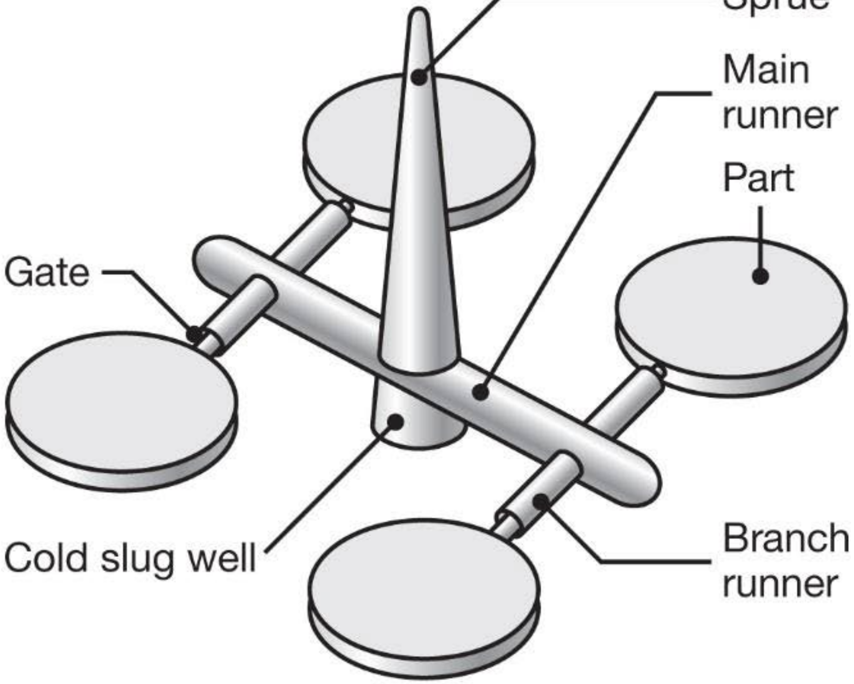
(Source: Ekmul.fr)

Excellent video explaining injection molding: (source Bill Hamack, Univ. of Illinois):
https://youtu.be/WPW-yvKCbr0

Example of industrial plastic injection machine

Terminology

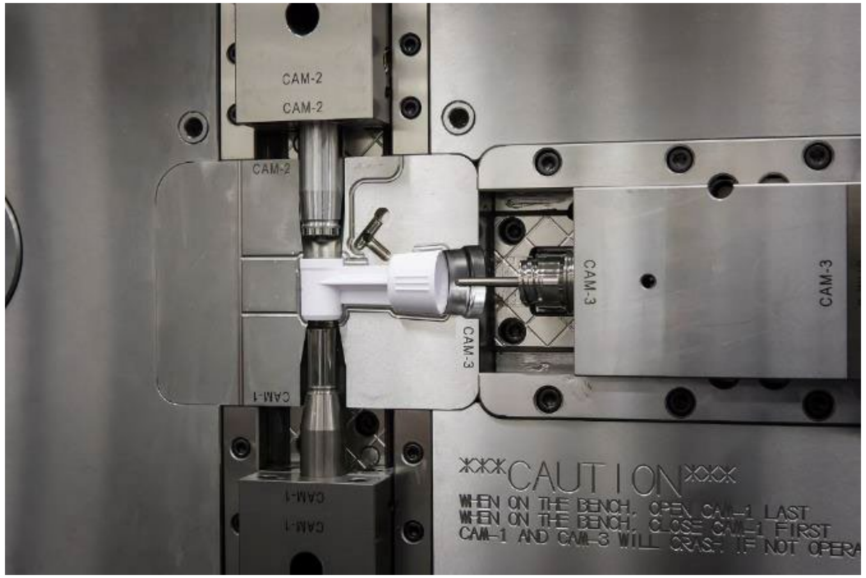


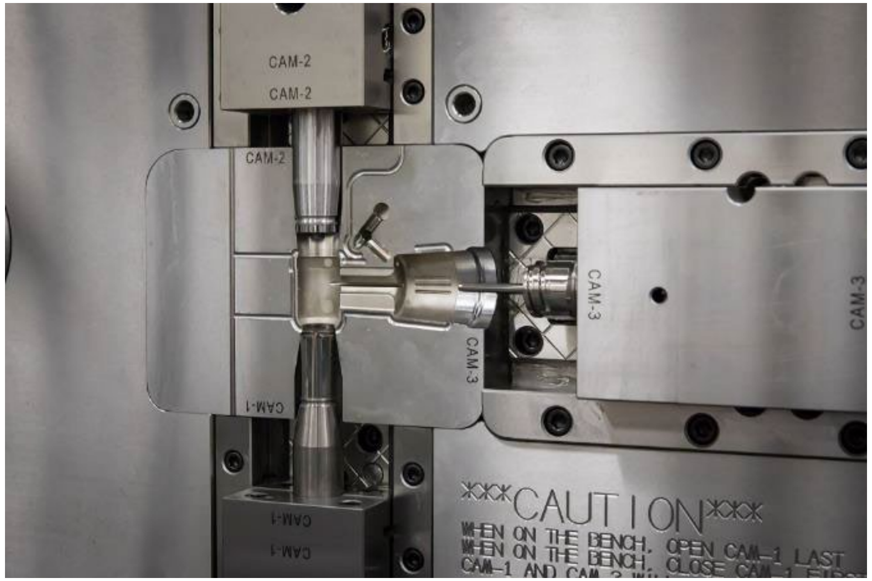


Sprue - 'Carotte'
Cold slug well – 'Piège de solidification'
Main runner – 'Canal d'alimentation principal'
Branch runner – 'Canal secondaire'
Gate – 'Point d'entrée de l'infiltration'

Molds: Illustrations

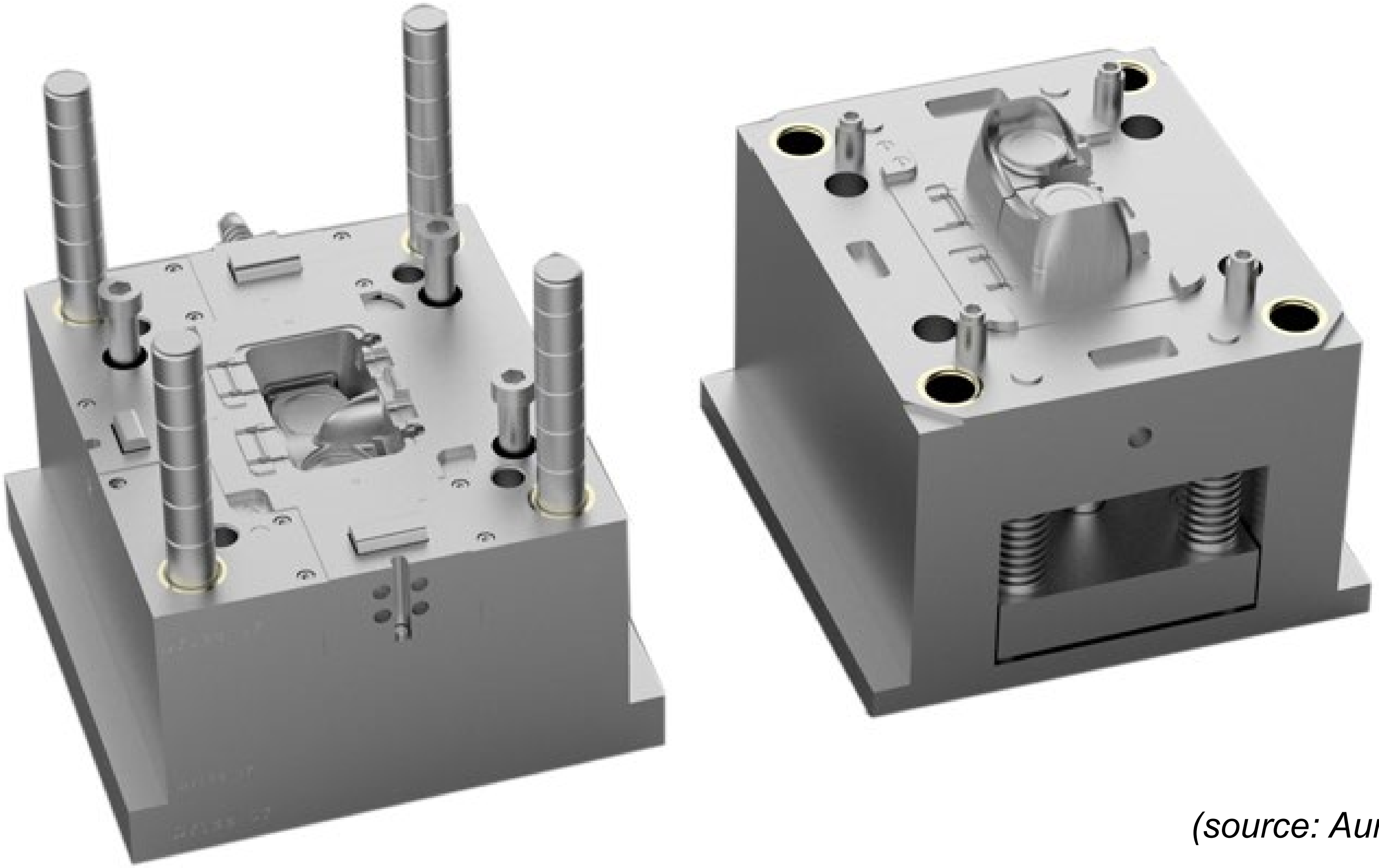
(source Akromold)





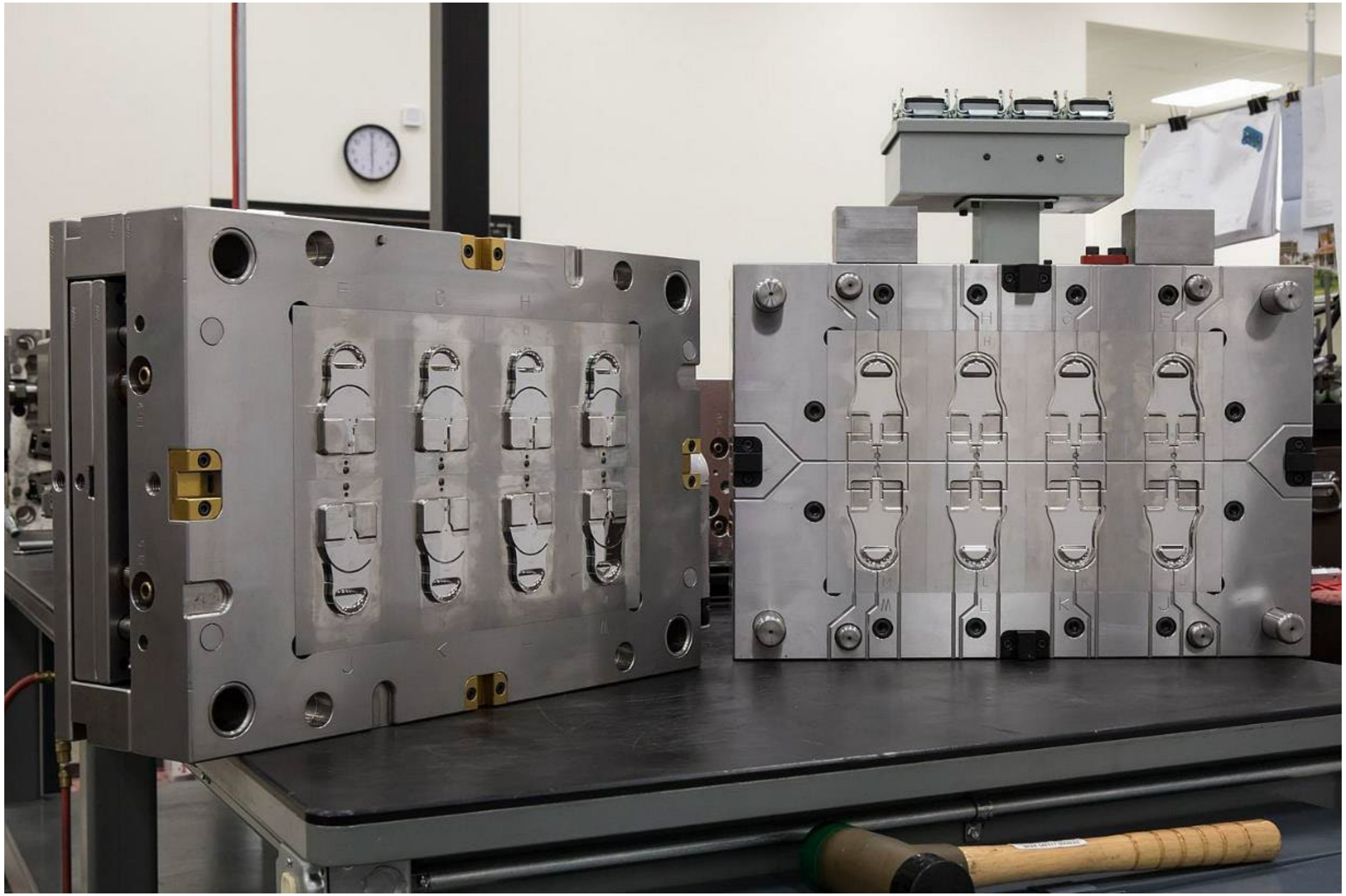
(source Moldtech Inc)

Molds examples



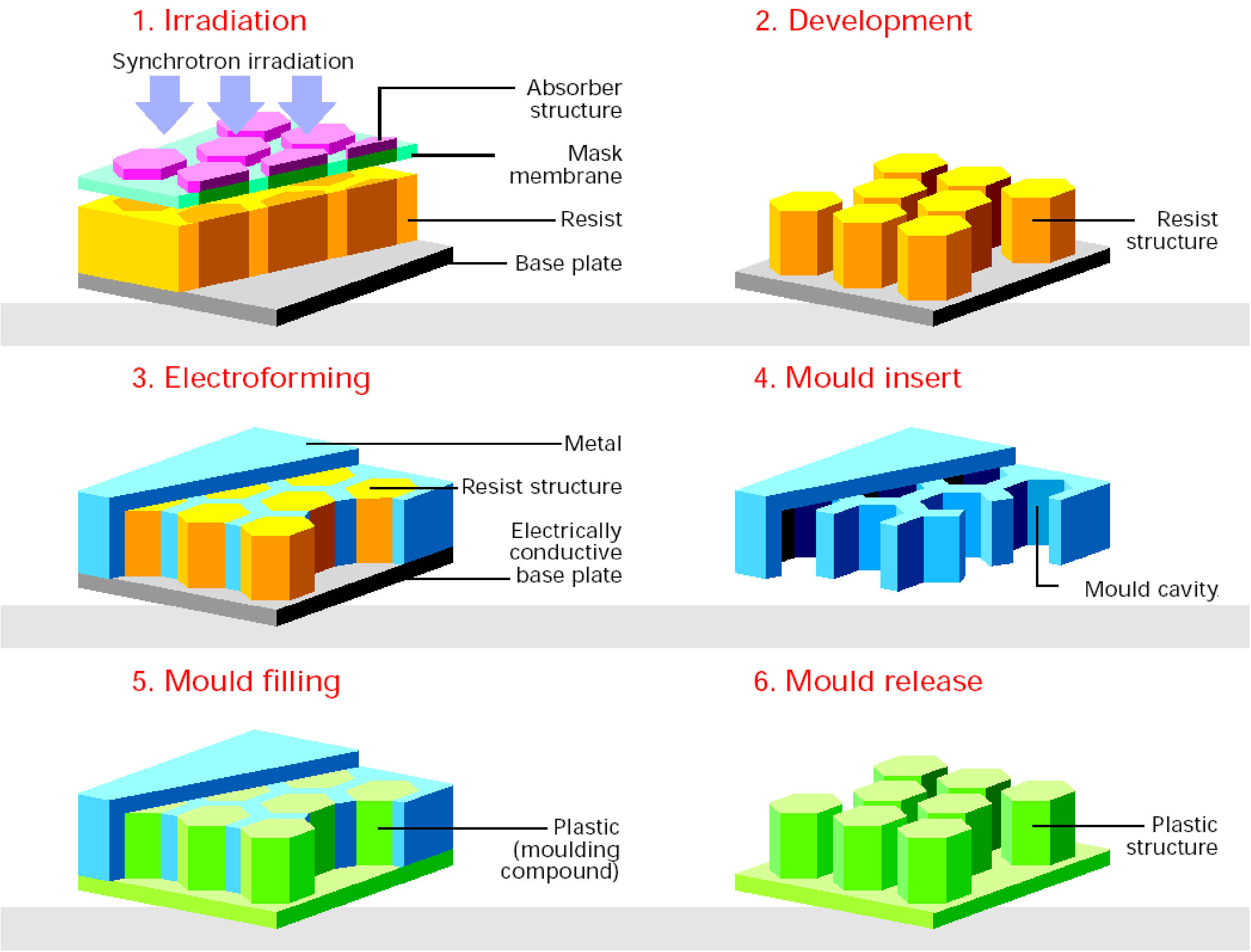
(source: Aurorahelmets)

Molds examples



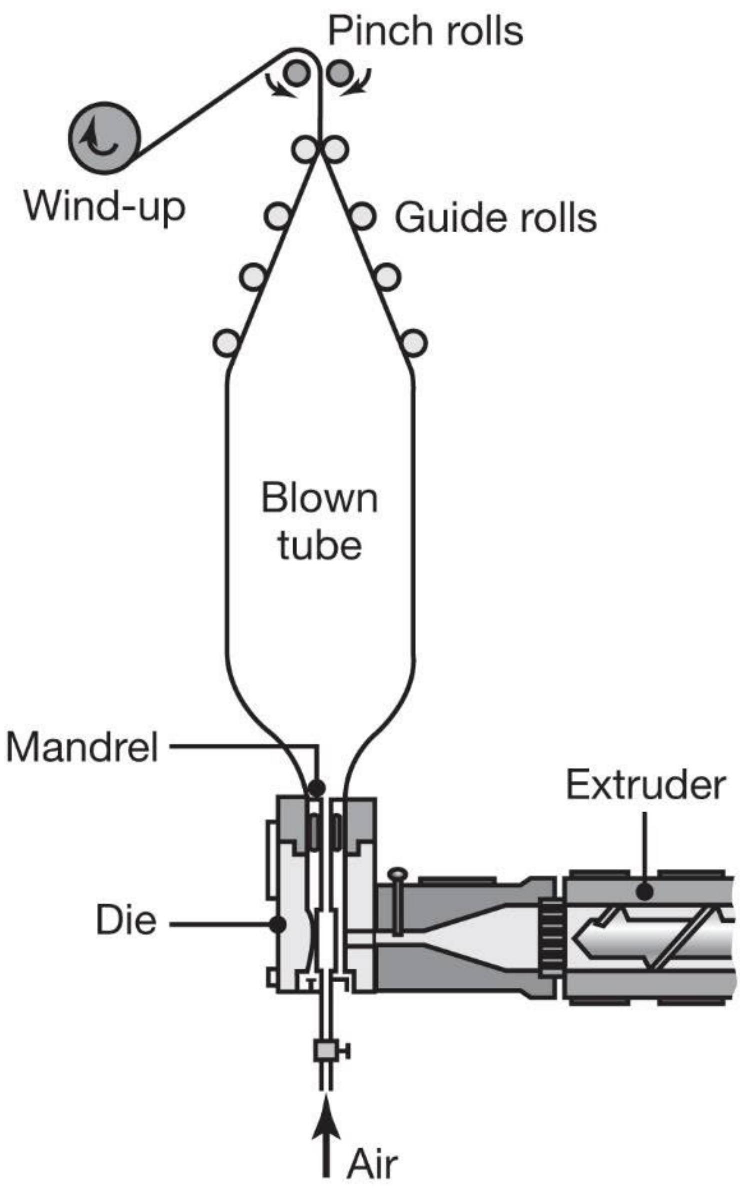
(source Moldtech Inc)

LIGA/ UV LIGA technology as a mould for replicas



(Source KIT)

Illustration of other use: thin film production (plastic bags)



Schematic illustration of production of thin film and plastic bags from a tube produced by an extruder, and then blown by air.

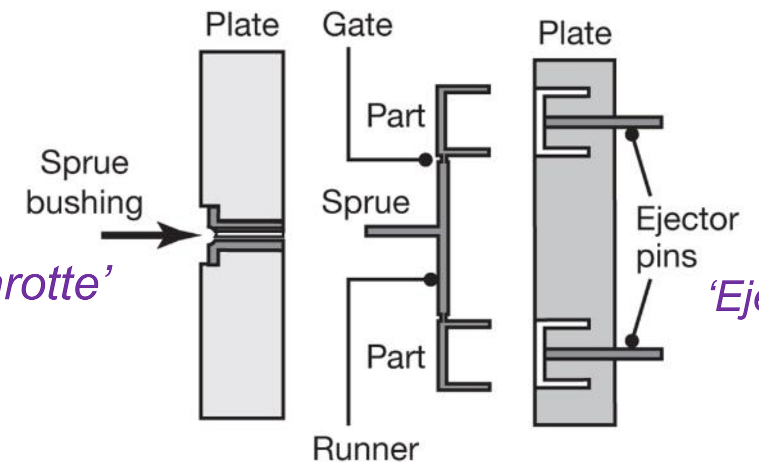
A blown-film operation.

Source: Courtesy of Windmoeller & Hoelscher Corp.

Mold fabrication and design rules

- High surface quality requirements (low roughness < 1 um) => EDM
- Cost are easily > 20kCHF
- Similarities with metal casting / molding + Cooling channels
- Manage issues related to demolding, shrinkage, etc.

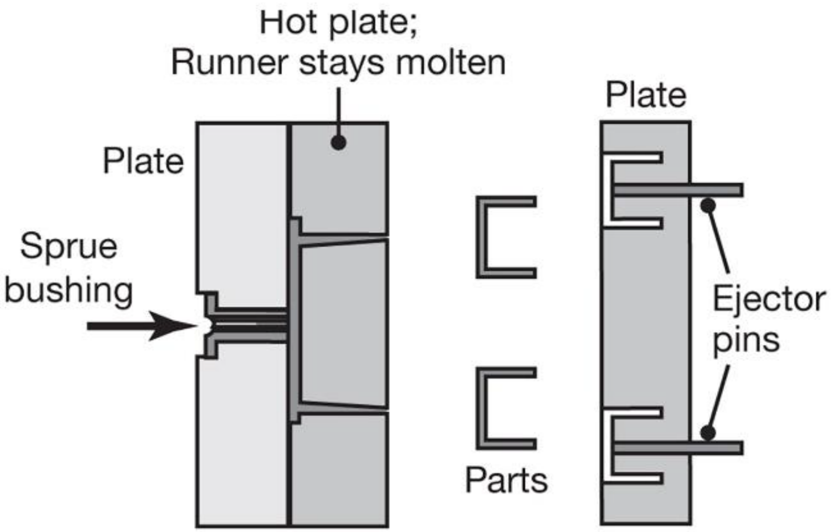
Molding principles



‘Tire-Carotte’

‘Ejecteurs’

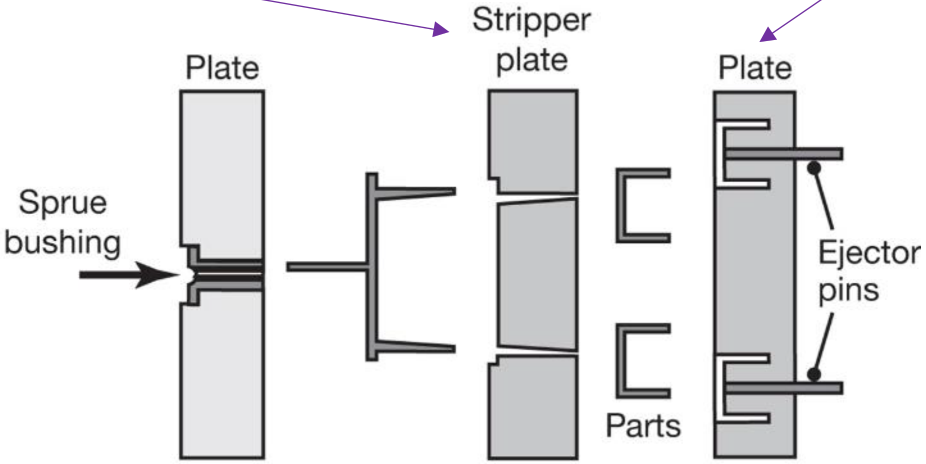
Two-plate mold



hot-runner mold

‘Rappel plaque d’éjection’

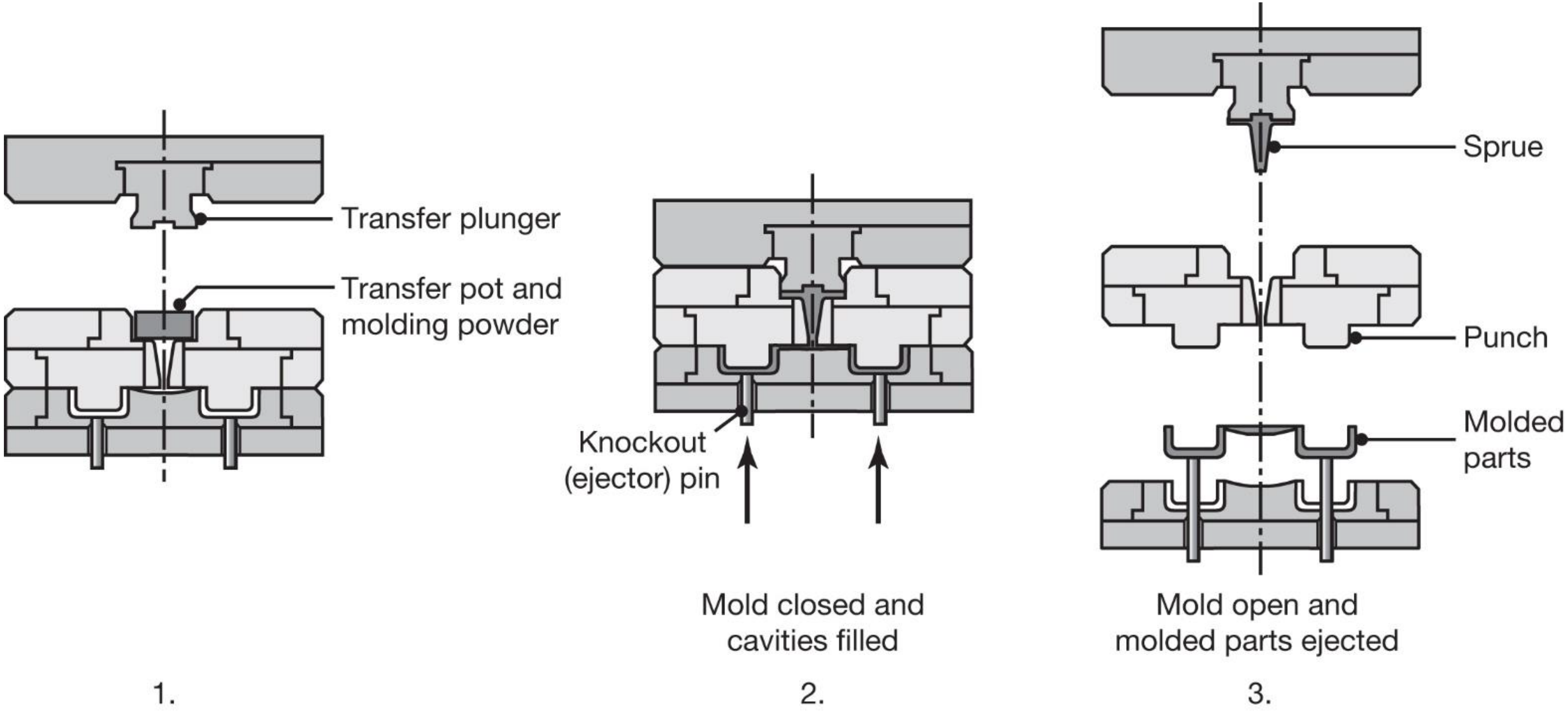
‘Plaque d’éjection’



three-plate mold

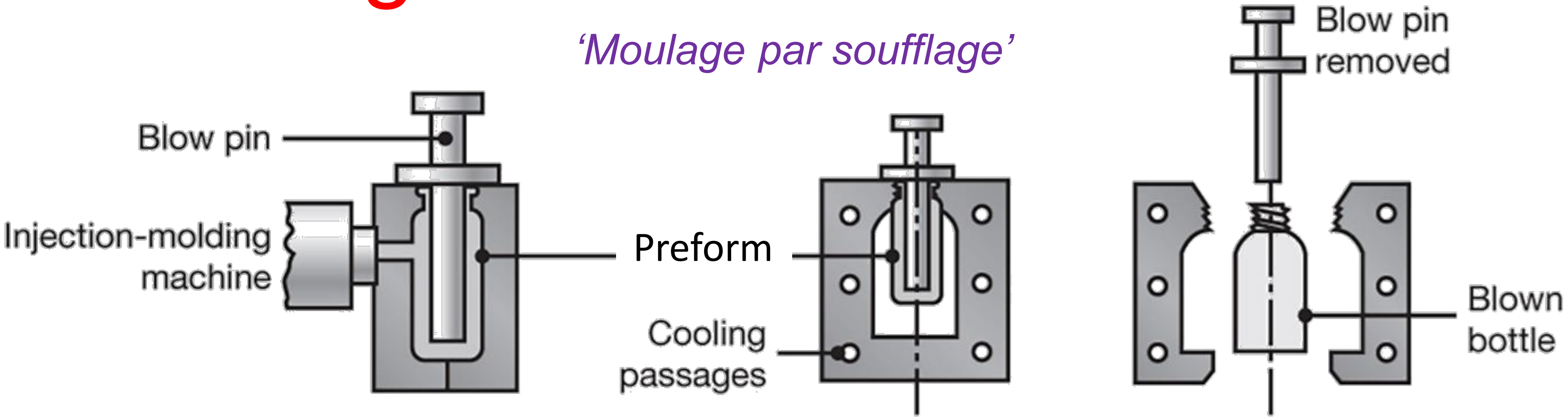
Typical goals are to limit post-operation after demolding (for instance, cutting the sprue).

Transfer molding of *thermosetting* plastics



Blow molding

'Moulage par soufflage'



Preform mold

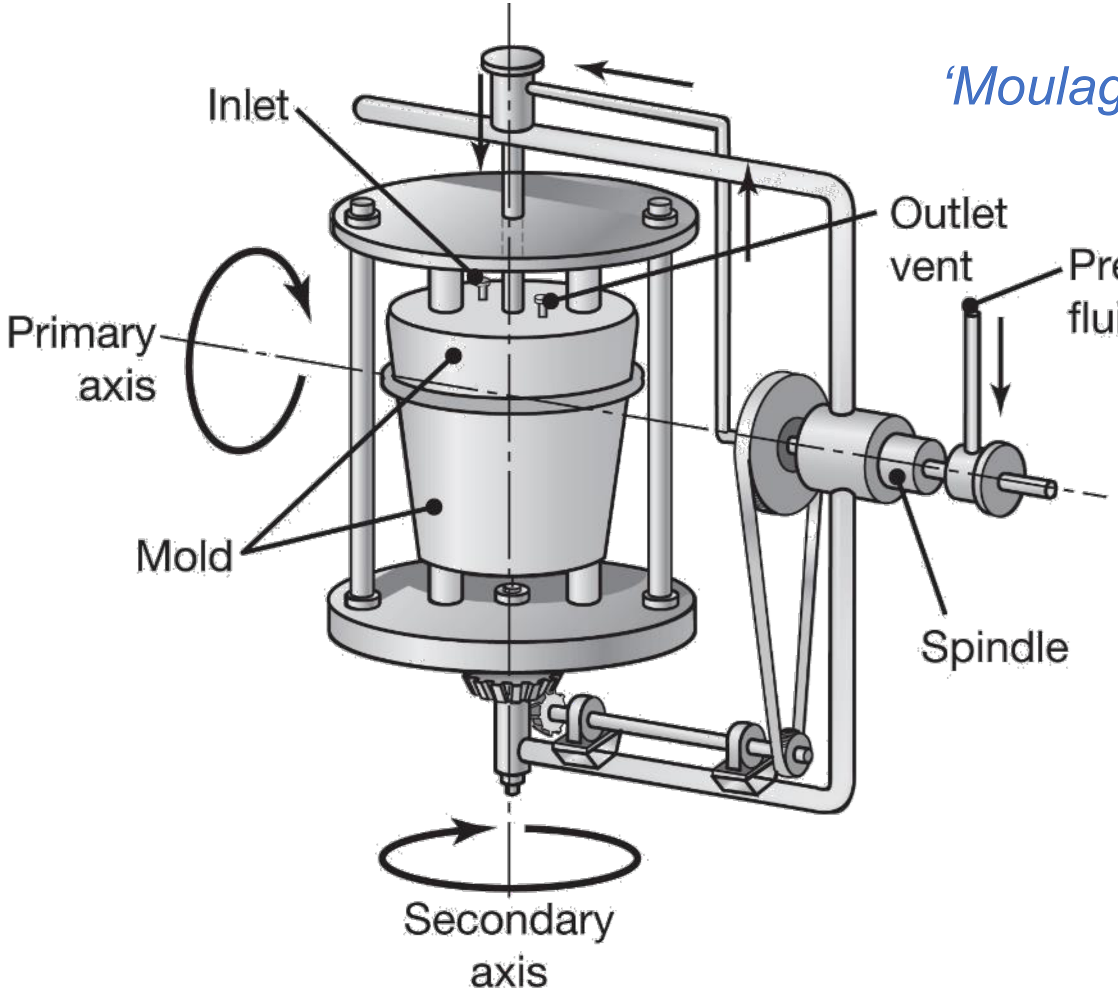
Parison transferred to blow mold

(Source: D. Schaefer)

Illustrative video of bottle manufacturing:
https://youtu.be/8QkxpQT967w

Typical mold (source: ekmul.fr)

Rotational molding

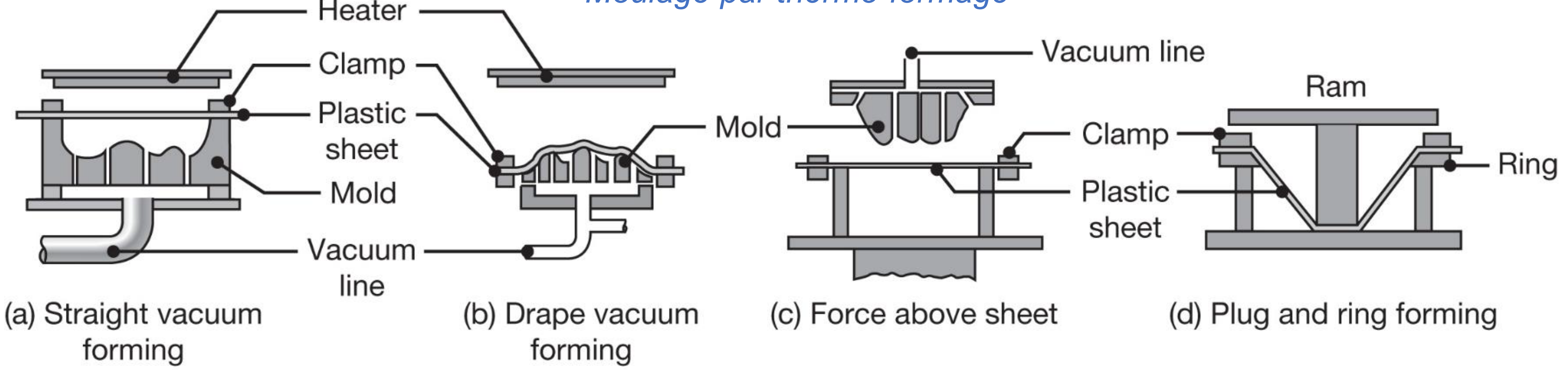


'Moulage par centrifugation'

Illustrative video: How Kayaks are made:
https://youtu.be/xc9pKiV5wag

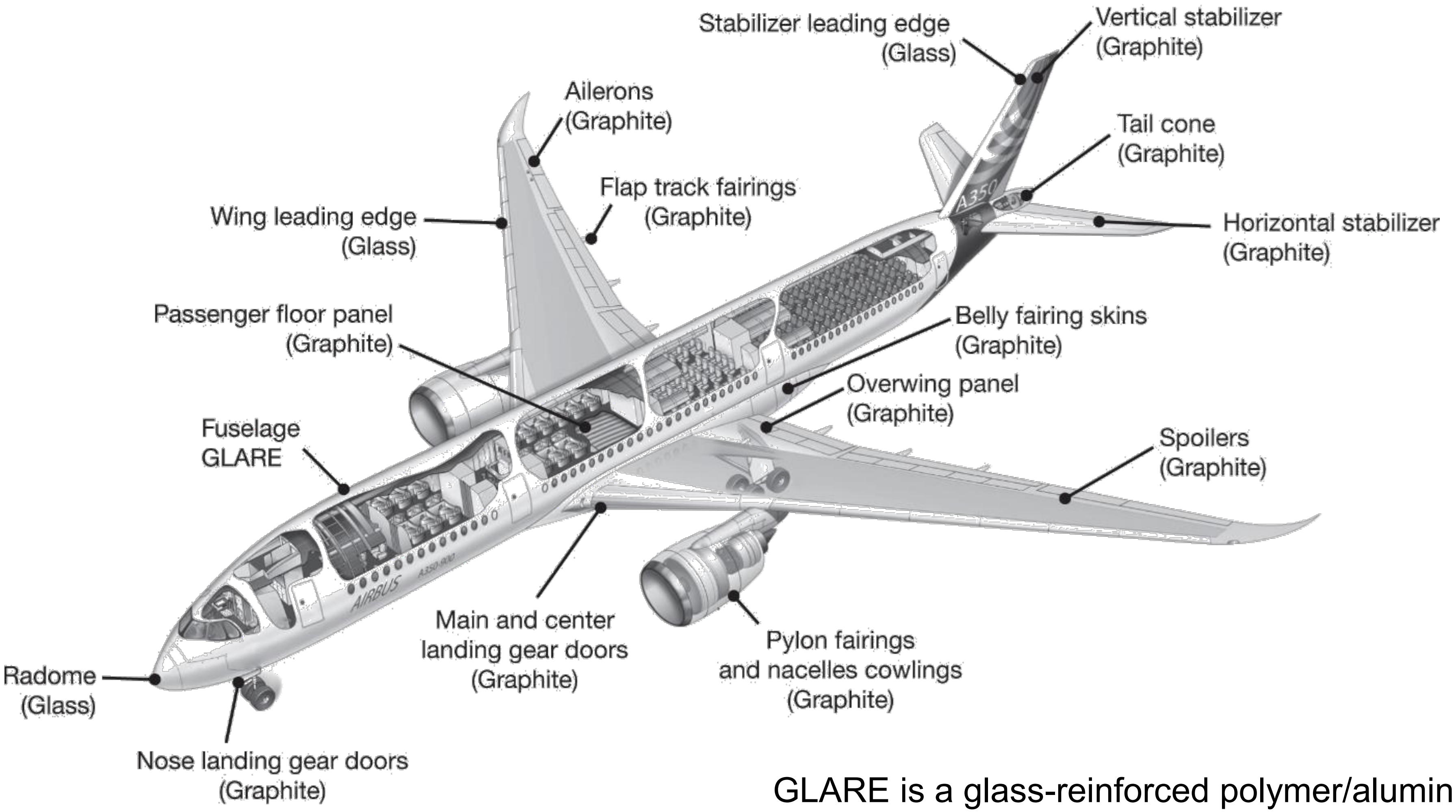
Thermoforming (shapes with thin sections)

'Moulage par thermo-formage'



- Various variations of the process
- Shapes with thin sections (food packages, masks, etc.)
- Illustrative videos:
  - (working principle) https://youtu.be/alq3RDZN4jo, https://youtu.be/GgWG6L-99V4
  - Industrial example: https://youtu.be/BqV_jsxD0UA

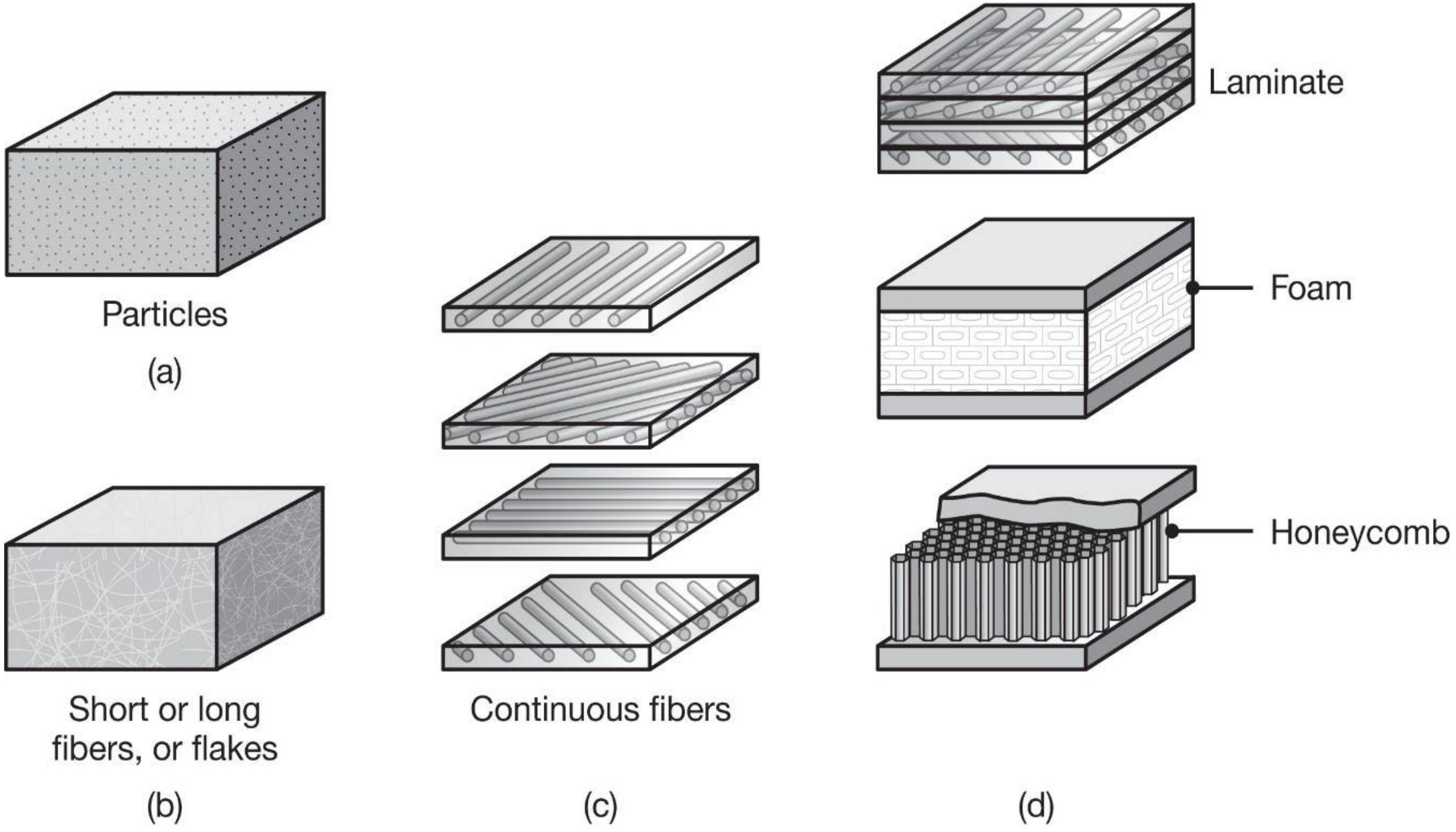
Composites in an airplane (A350)



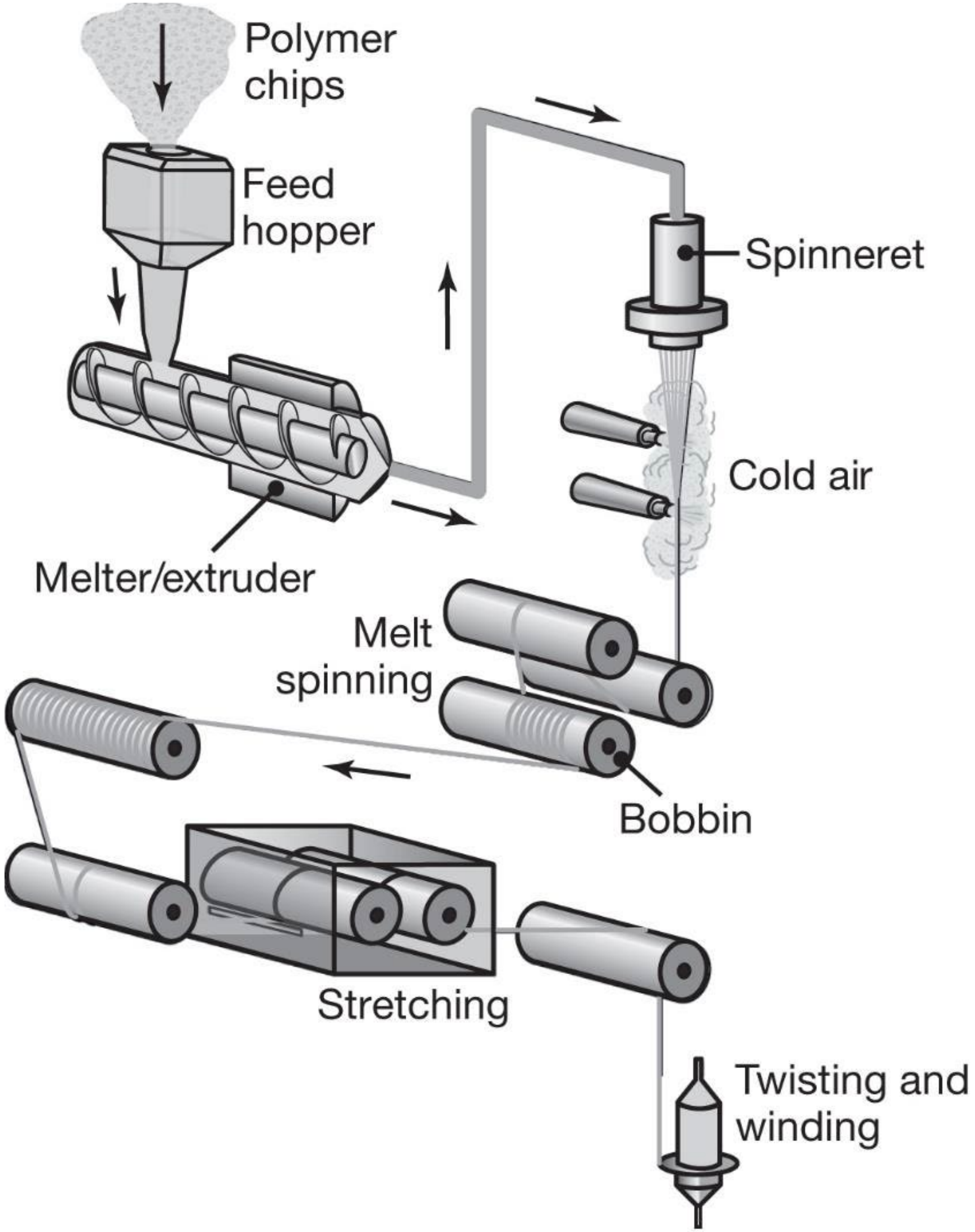
GLARE is a glass-reinforced polymer/aluminum laminate

Reinforcing plastics (Manufacturing of composites)

(a) Matrix with particles; (b) matrix with short or long fibers or flakes; (c) continuous fibers; and (d) and (e) laminate or sandwich composite structures using a foam or honeycomb core.



Production of polymer fibers

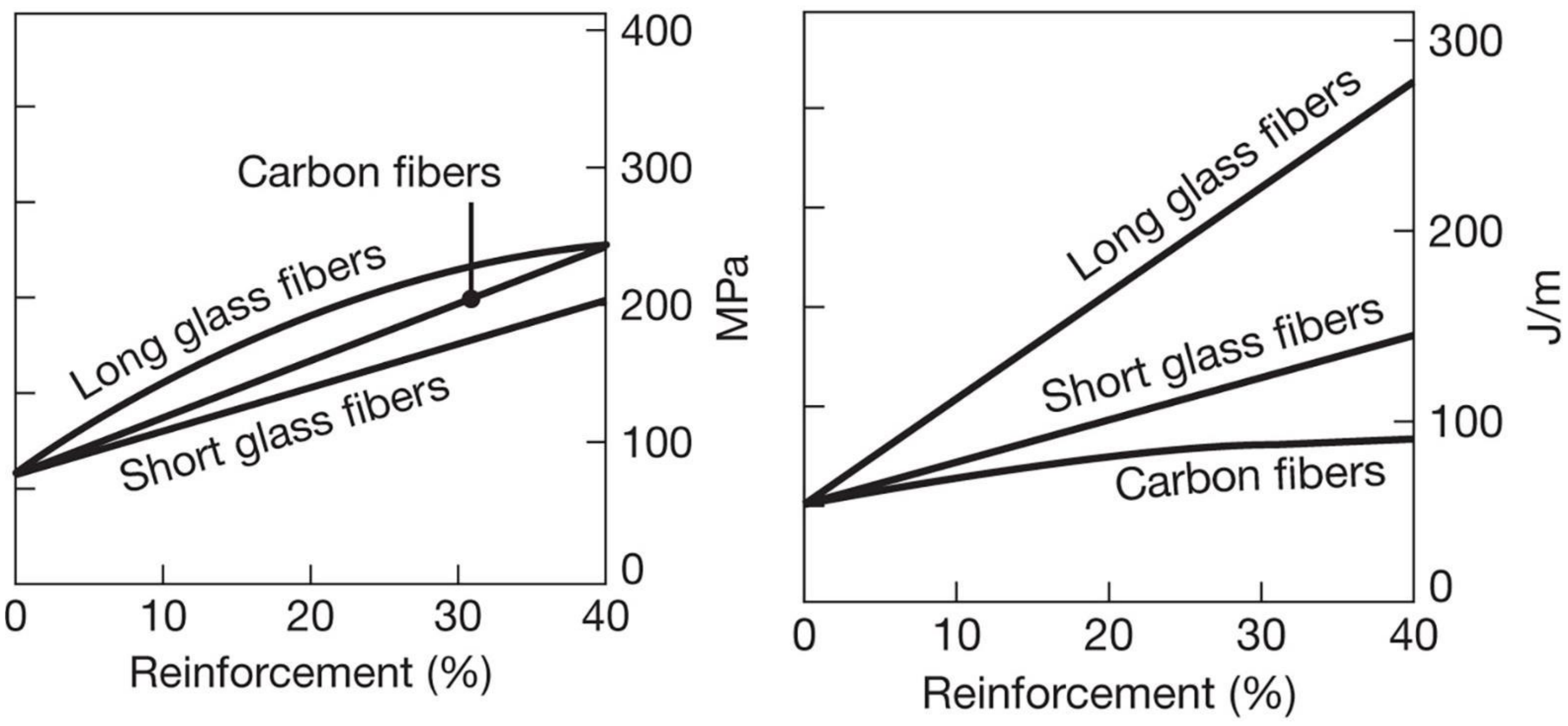


Reinforcing fiber materials

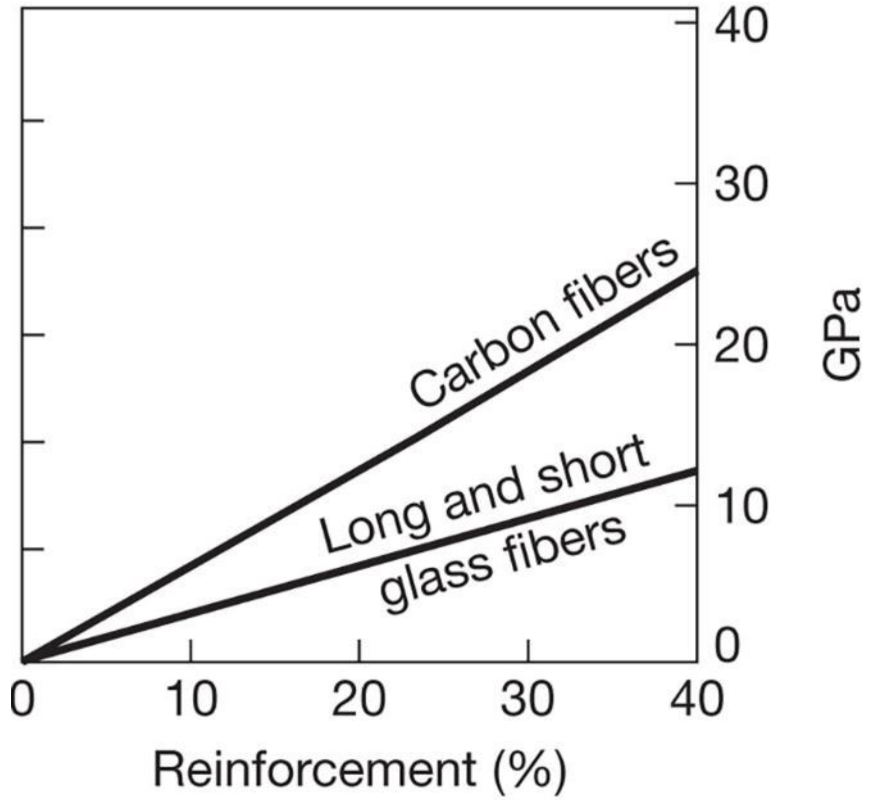
Type	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)	Relative cost
Boron	3500	380	2380	Highest
Carbon				
High strength	3000	275	1900	Low
High modulus	2000	415	1900	Low
Glass				
E-type	3500	73	2480	Lowest
S-type	4600	85	2540	Lowest
Kevlar				
29	2920	70.5	1440	High
49	3000	112.4	1440	High
129	3200	85	1440	High
Nextel				
312	1700	150	2700	High
610	2770	328	3960	High
Spectra				
900	2270	64	970	High
1000	2670	90	970	High
2000	3240	115	970	High
Alumina (Al_2O_3)	1900	380	3900	High
Silicon carbide	3500	400	3200	High

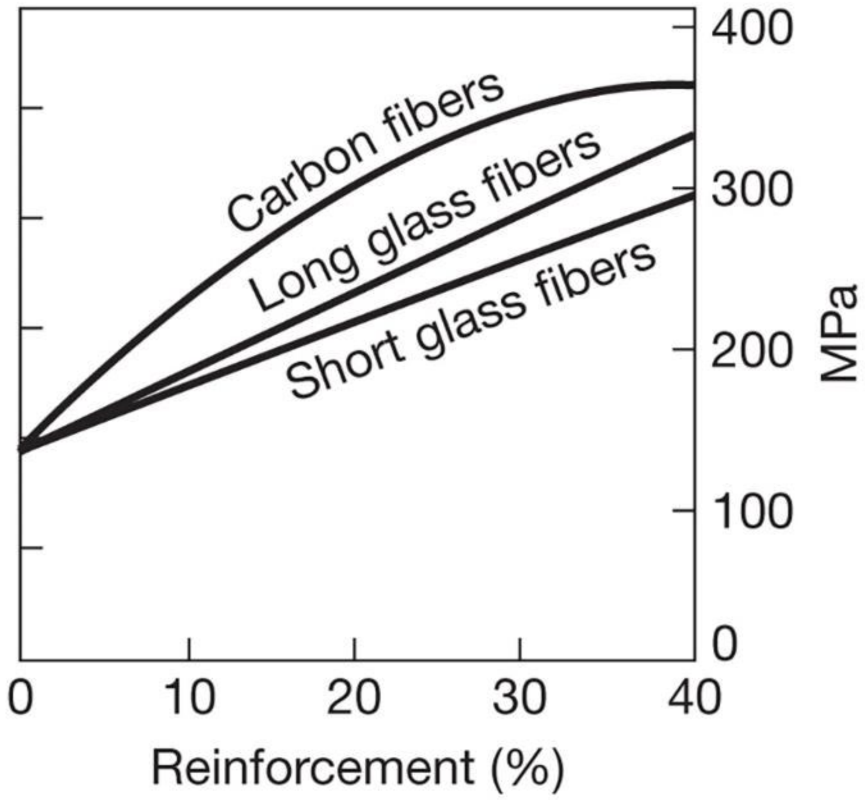
Note: These properties vary significantly depending on the material and method of preparation.

Mechanical properties improvements with reinforcement



Example with Nylon

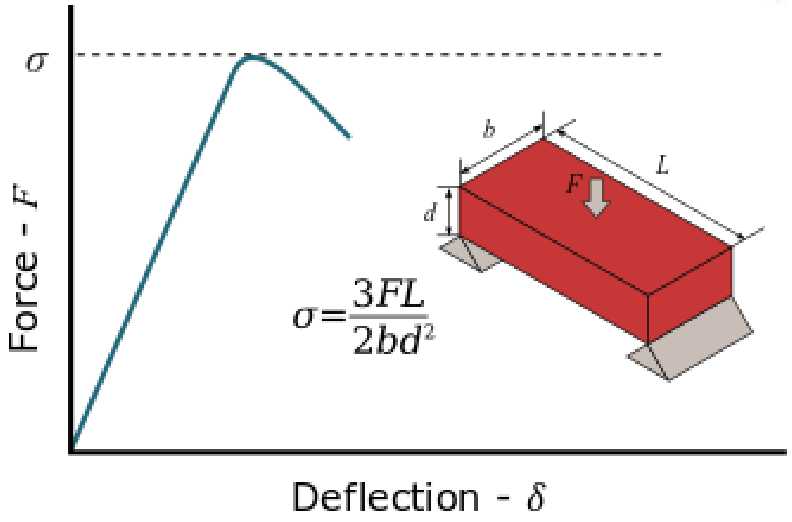




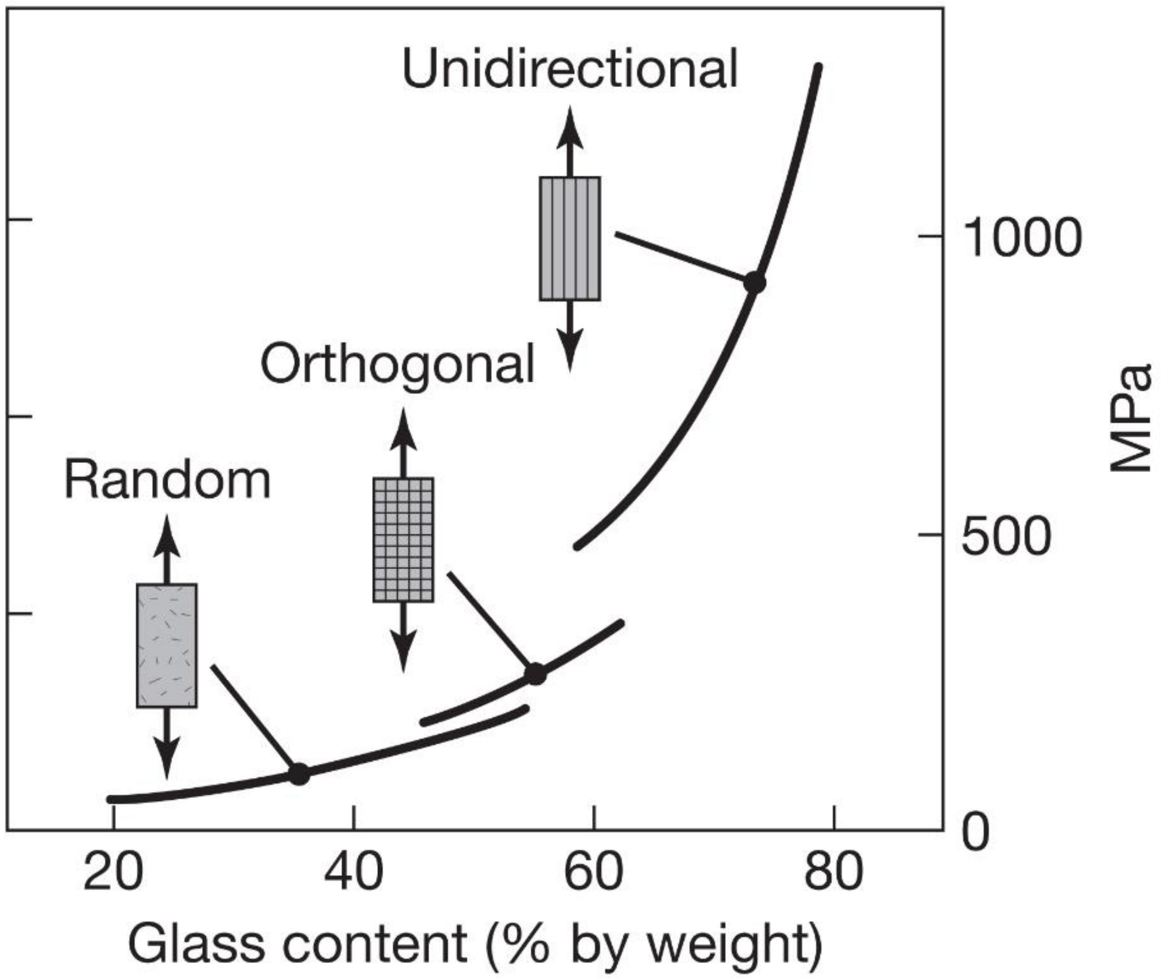
Flexural strength and flexural modulus

Unit force / Unit deflection

$$E_{bend} = (L^3 / 4bd^3)*F/y$$



Importance of directionality



Plastics production process as a function of production yield

Process	Equipment capital cost	Production rate	Tooling cost	Typical production volume, number of parts: 10	10^2	10^3	10^4	10^5	10^6	10^7
Machining	Med	Med	Low							
Compression molding	High	Med	High							
Transfer molding	High	Med	High							
Injection molding	High	High	High							
Extrusion	Med	High	Low	*						
Rotational molding	Low	Low	Low							
Blow molding	Med	Med	Med							
Thermoforming	Low	Low	Low							
Casting	Low	Very low	Low							
Foam molding	High	Med	Med							
Stereolithography	Med	Very low	None							
Fused-deposition modeling	Low	Very low	None							
Three-dimensional printing	Med	Very low	None							

*Continuous process

Low volume production

High volume production

Wrap-up: what should you remember?

- Difference between thermosets and thermoplastics
- Most common plastics and their typical usage
- Plastics manufacturing methods
- The concept of circular economy

Composites manufacturing...

- General description: https://youtu.be/ZotUR_GiVK8
- GE Fan blades: https://youtu.be/g8zt-qljYmM
- Illustration on high-end cars: https://youtu.be/504I_hJDFck

Credits

- *Illustrations source (when not mentioned): Kalpakjian, Manufacturing, Pearson,7th Edition.*