


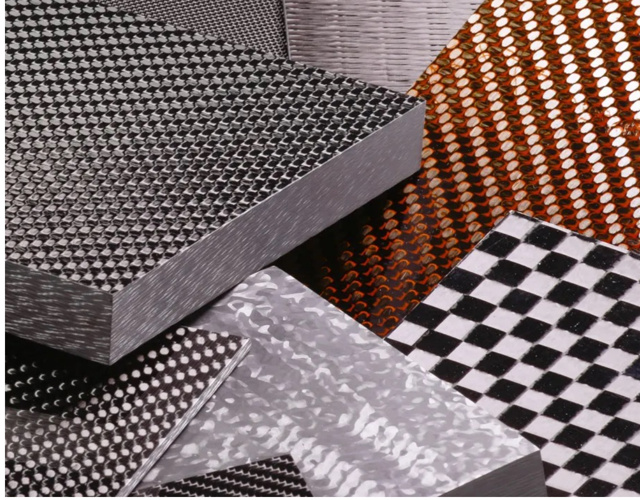

Materials Engineering I
Ingénierie des matériaux II
(MSE 214 & 215)

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WHY SHOULD WE CARE ABOUT MATERIALS?

The History of Humanity is Tied to Materials

Stone Age
Till ~3000 BC

Copper Age*
Till ~2000 BC

Bronze Age
Till ~1200 BC

Iron Age
Till ~550 BC

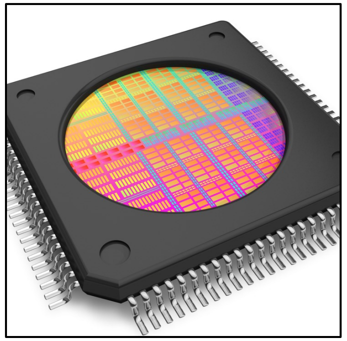
Glass Age*^

Steel Age*^

Aluminium Age*^

Plastic Age*^

Silicon Age^



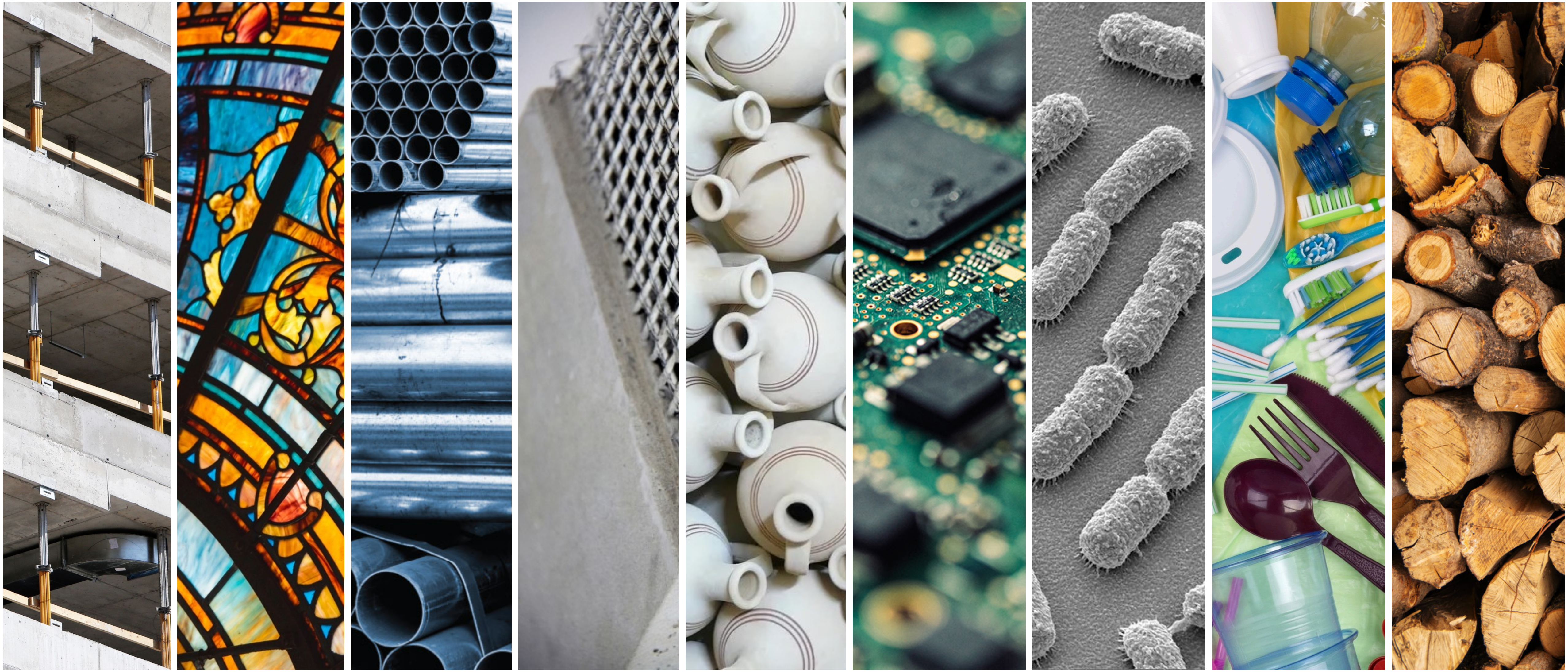
Graphene Age?

Designer Materials Age?

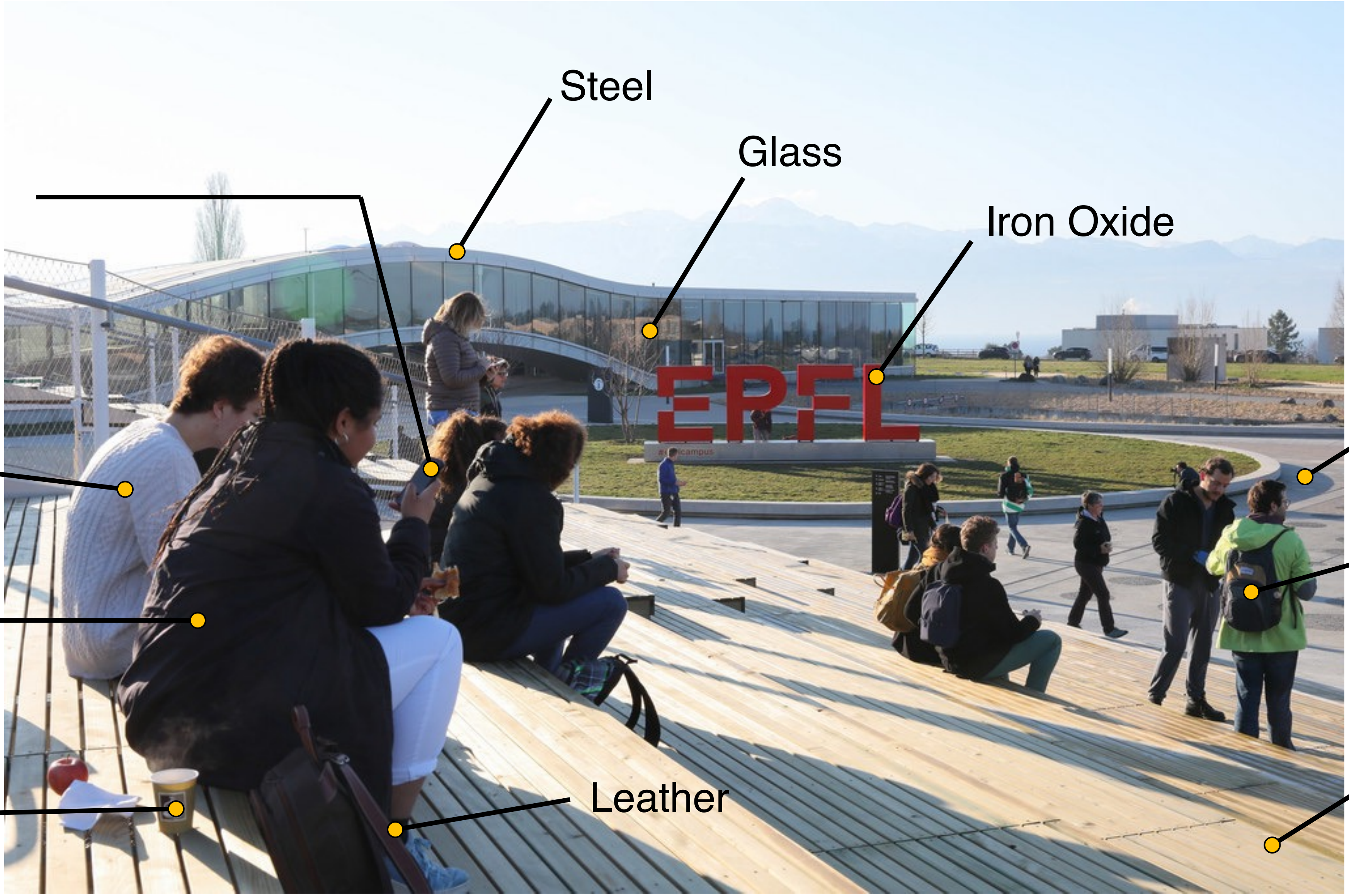
_____ Age?

^ Concurrent * Not universally accepted

The Materials of Today

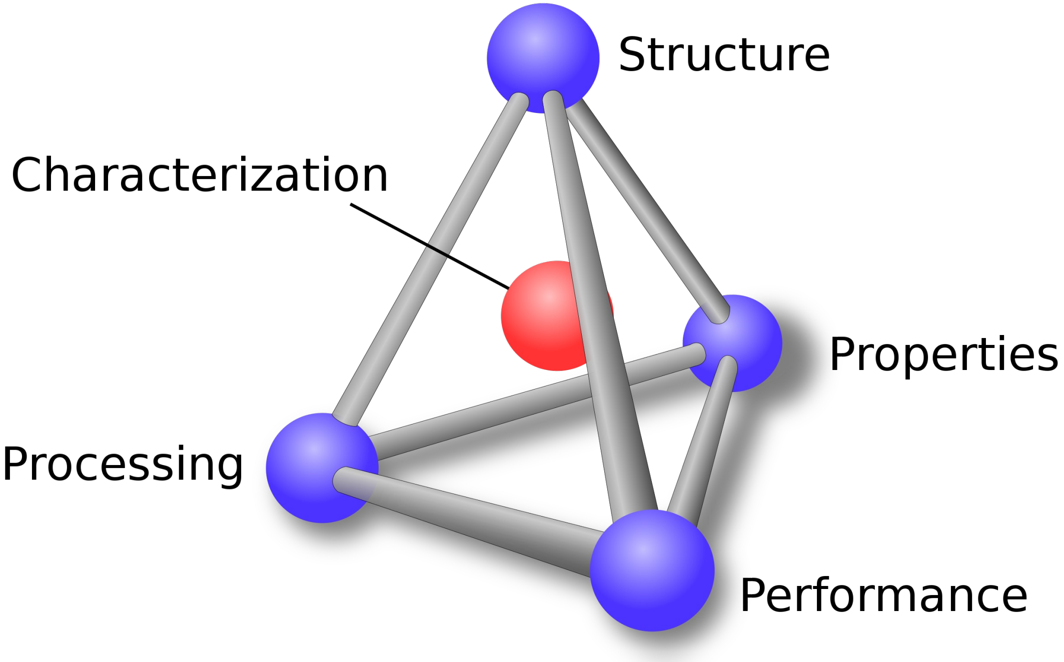


Materials: Everything Everywhere All at Once

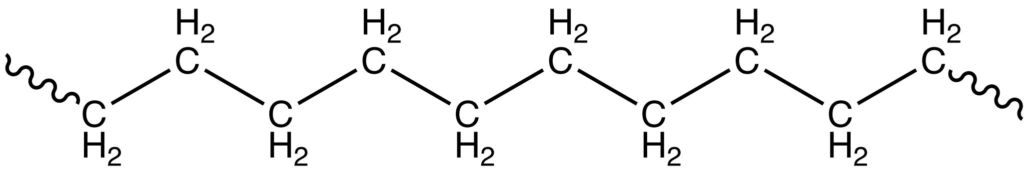


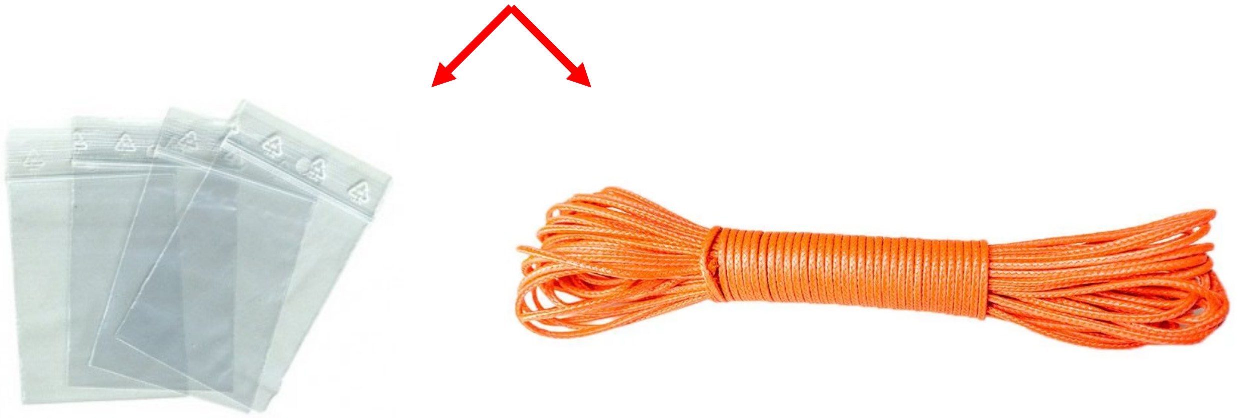
Materials Engineering

Main Learning Objective(s)



Polyethylene → $(C_2H_4)_n$





Understand how materials are used and why they behave in the ways that they do

Main Learning Objective(s)

Polymer	T_g (˚C)	T_m (˚C)
Poly(1-butene)	–24	171
Poly(butyl acrylate)	–54	No melting point
Poly(methyl methacrylate)	105	No melting point
High density polyethylene	–125	130
Polyvinylcarbazole	227	320
Polyethylene terephthalate	67	260

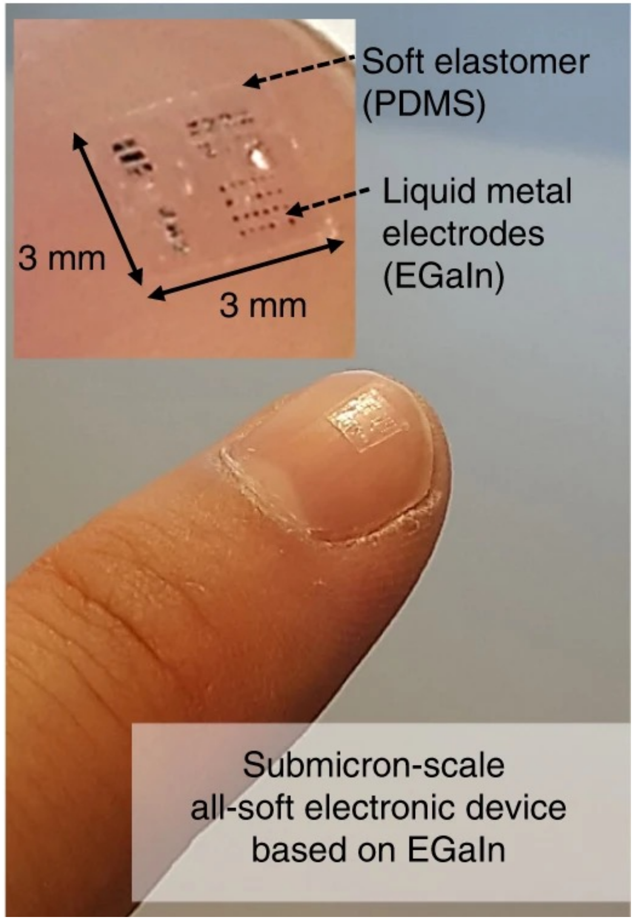
Which material can I use for long term storage of boiling water?

(Liner for a boiler)

Identify the optimal material for your application!

Materials Science and Engineering for Micro Engineering

Materials as a foundation for the engineering of (micro)devices



Nat. Commun. 2020, 11, 1002

Considerations when building a device:

- What materials?
- Material properties?
- Material performance?
- Material compatibility?
- Manufacturability?
- Cost / availability?
- Material lifecycle?

→ Requires an understanding of Materials Science and Engineering

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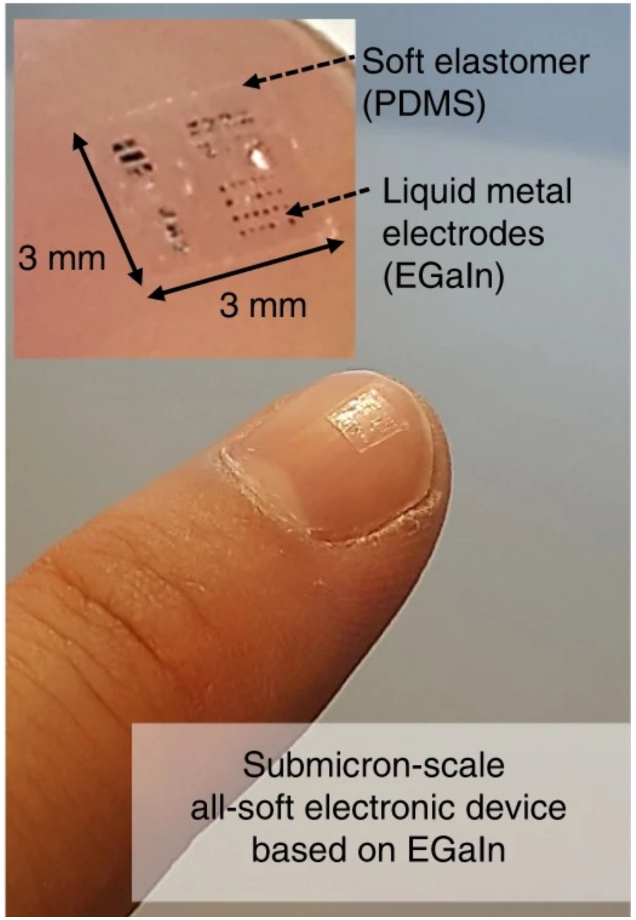
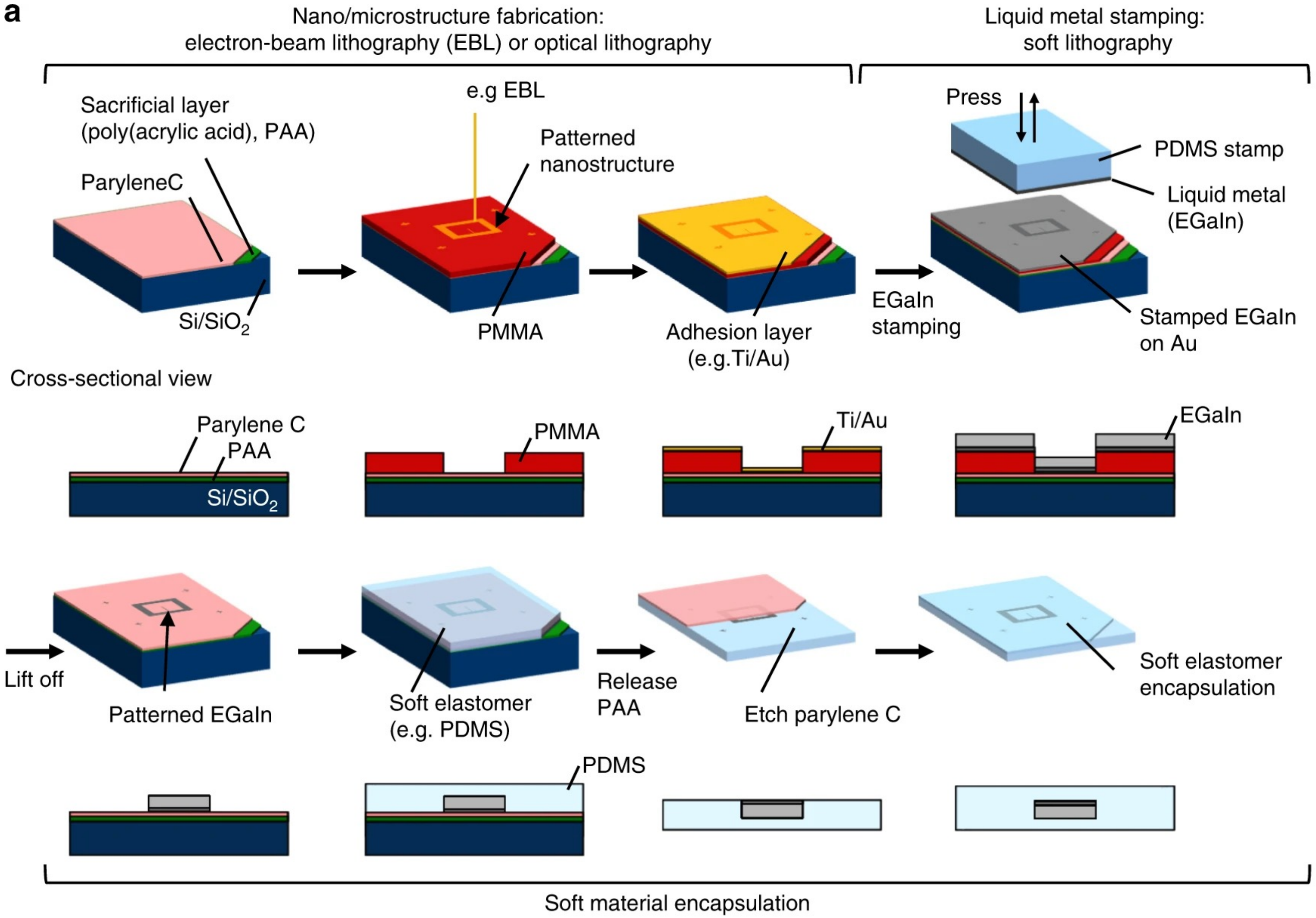
Materials Science and Engineering for Micro Engineering

Materials as a foundation for the engineering of (micro)devices



Nat. Commun. 2020, 11, 1002



MSE 214 and 215 Course Structure

Daryl W. Yee
Polymers and Metals
(MSE 214)

Pierre-Etienne Bourban
Composites
(MSE 214)

Practical
(MSE 215)

Michael Stuer
Ceramics
(MSE 215)

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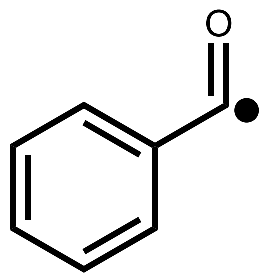
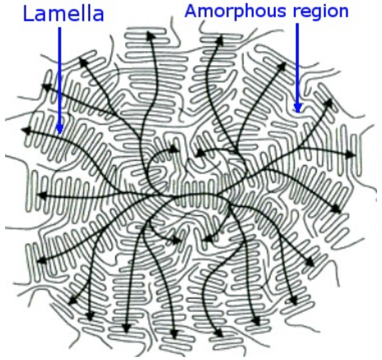
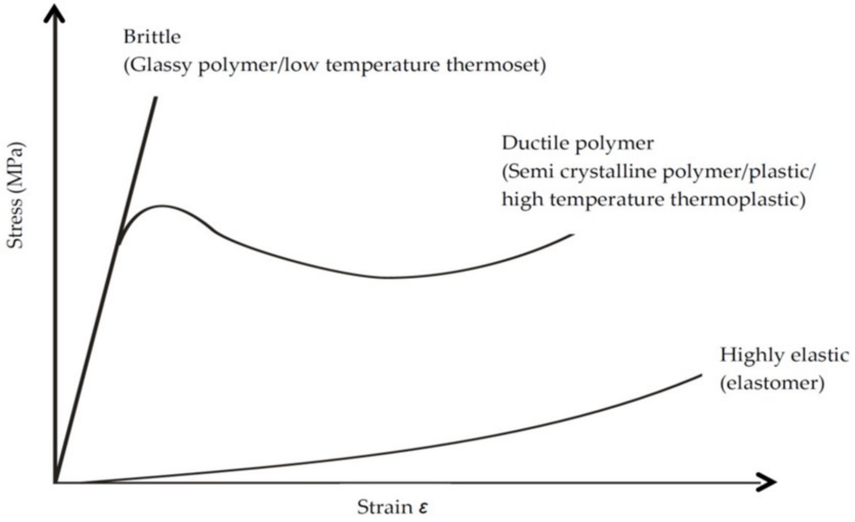
MSE 214 – Polymers (English; ~6 Lectures)

Goal: Basic understanding of polymer science and processing

1) What are polymers?
2) How are polymers made (synthesis)?
3) What is the microstructure of polymers?
4) How are polymer parts made (manufacturing)?
5) What are the properties of polymers?
6) How do I control the properties of polymers?
7) How do I pick the right polymer for my needs?



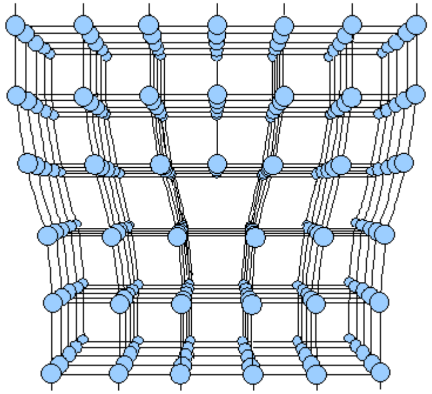


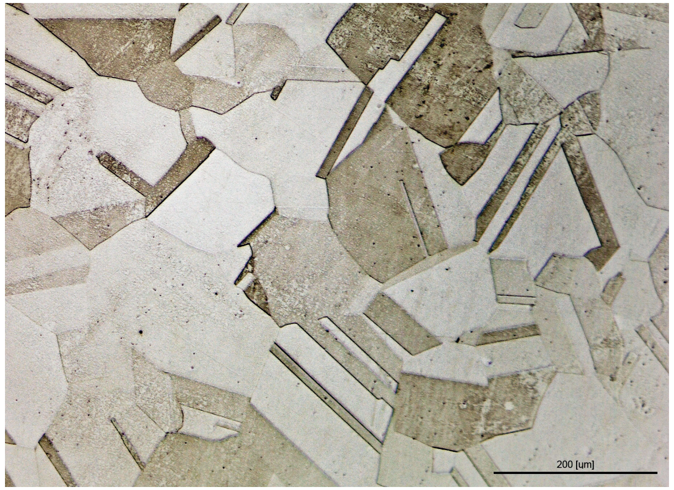


MSE 214 – Metals (English; ~5 Lectures)

Goal: Basic understanding of metallurgy

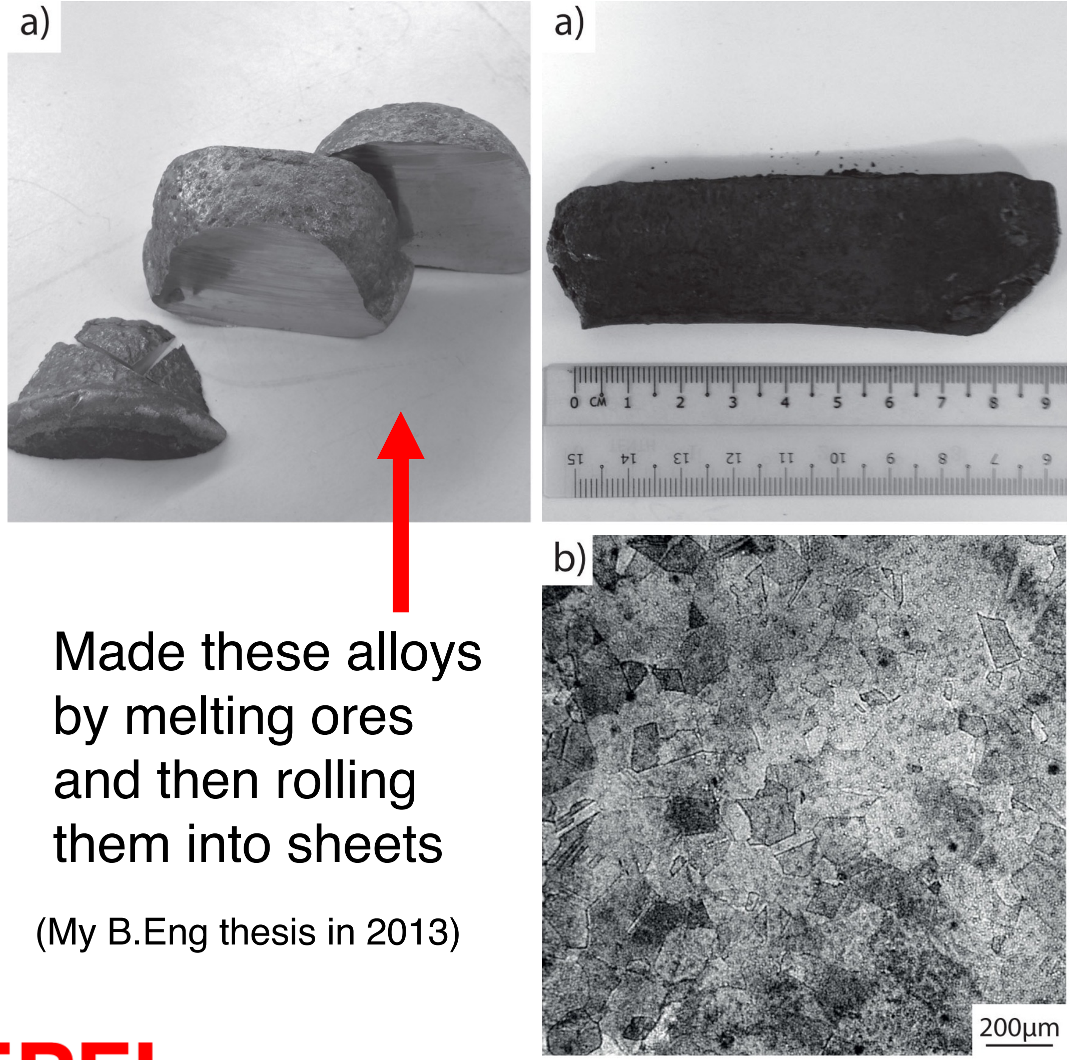
1) What are metals?
2) Metals and phase diagrams
3) What is the microstructure of metals?
4) How are metal parts made (manufacturing)?
5) What are the properties of metals?
6) How do I control the properties of metals?
7) How do I pick the right metal for my needs?





My experience with metals and polymers

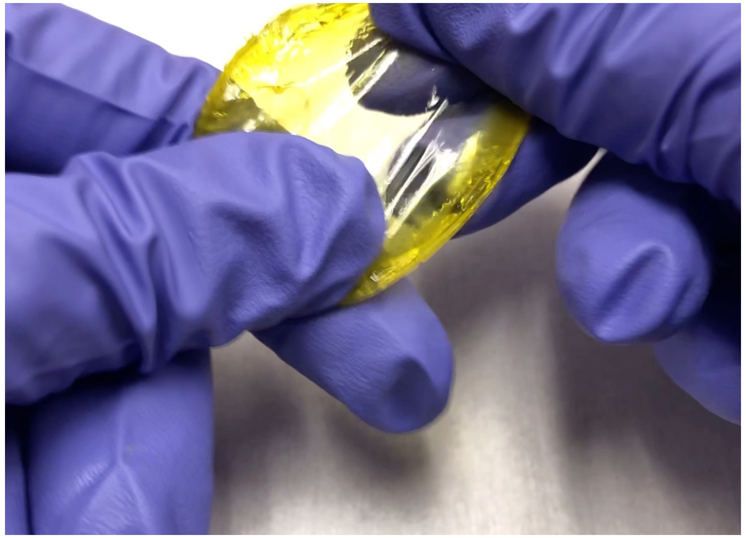
Trained as a metallurgist a long time ago!

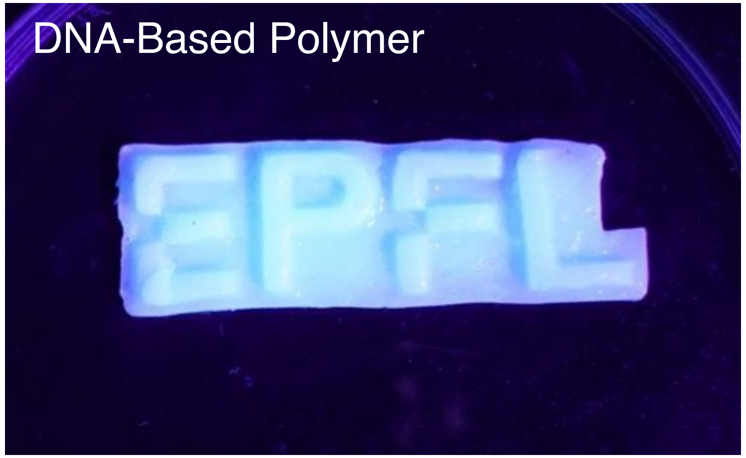


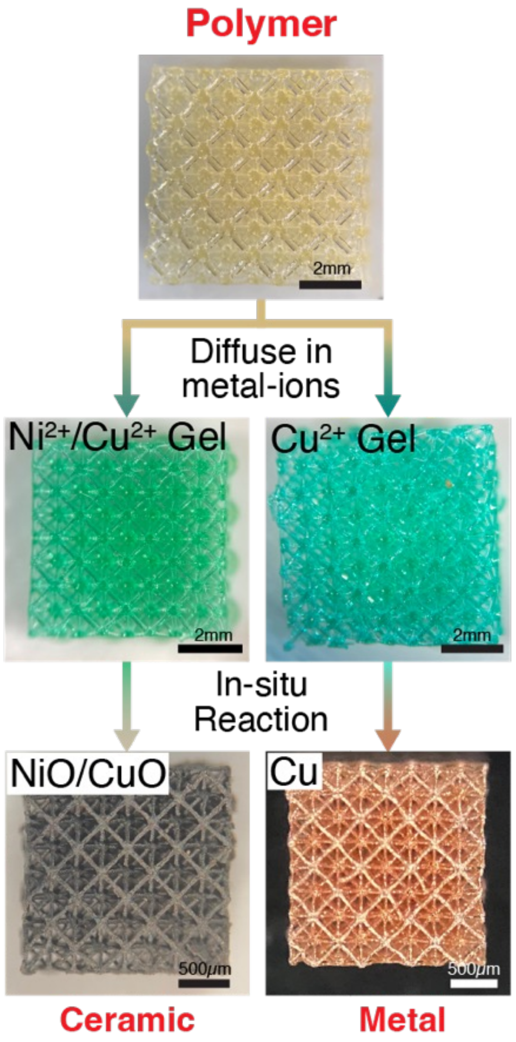
Made these alloys by melting ores and then rolling them into sheets

(My B.Eng thesis in 2013)

10+ years later, now a polymer scientist!

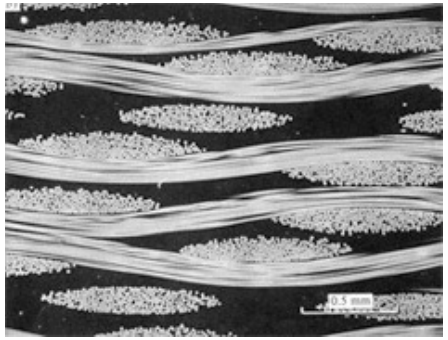




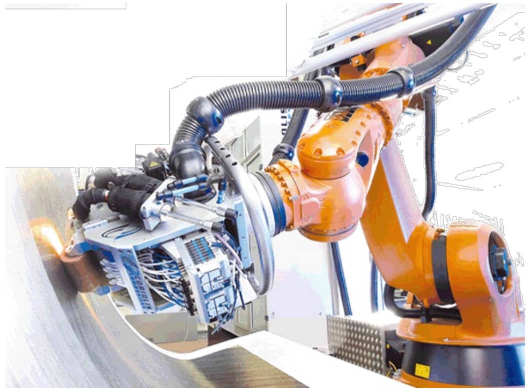


MSE 214 – Composites (French; 2 Lectures)

Pierre-Etienne Bourban



Hull & Clyne, 1992



Coriolis Composites

Reuters

Composite Materials

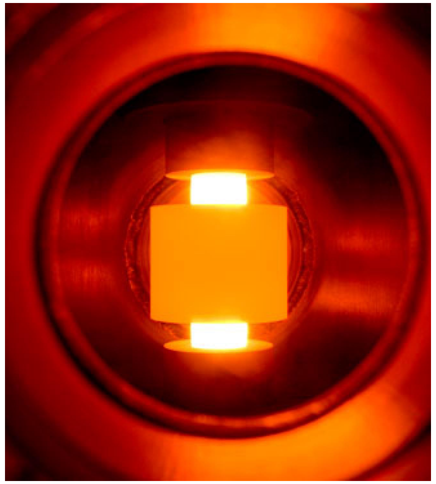
- Fibers, matrices
- Implementation processes
- Micromechanics and anisotropy
- Nanocomposite applications
- Biocomposites
- Self-healing composites

Reference:

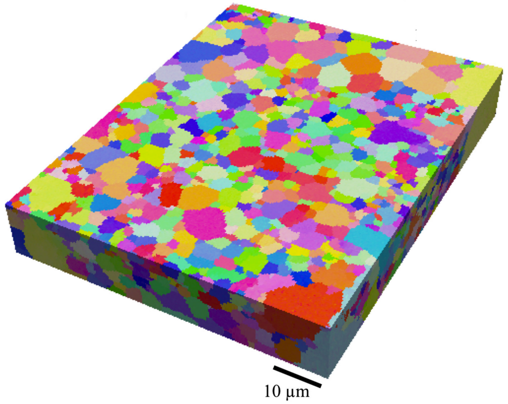
1. Traité des Matériaux, vol. 15 " Matériaux composites à matrice organique"

MSE 215 – Ceramics (French; ~7 Lectures)

Michael Stuer



University of Arizona



Zhong et al. J. Amer. Ceram. Soc. 2019. 102

PI Ceramic

Implementation of Ceramics

- Introduction — Properties of ceramics
- Characterization of powders
- Raw materials and powder synthesis
- Processing/modification of powders
- Shaping and debinding
- Sintering and finishing of ceramics

Reference:

1. Les Traité des Matériaux, vol. 16 "Céramiques et Verres"

MSE 215 – Practical (French)

Pierre-Etienne Bourban

Implementation (Mise en oeuvre (MEO))

MEO. Metals	MEO. Polymers	MEO. Ceramics
TPA	TPB	TPC
Heat treatments, Hardening	3D printing	Atomization, Dispersion of powders

Properties (Propriétés (Pro))

Material Selection	Pro. Thermal	Pro. Mechanical	Pro. Optical
TPD	TPE	TPF	TPG
Selection of materials, Edupack	Expansion, Internal stresses	Stiffness, Toughness	Wave transmission

Tentative Outline

Schedule subject to change.

Week	Date	Lecture (0915-1000 / 1015-1100)	Exercise (1115-1200)
1	10.09.25	Introduction (to Polymers)	-
2	17.09.25	Making Polymers (I)	Introduction
3	24.09.25	Making Polymers (II) + Microstructure	Making Polymers
4	01.10.25	Properties (I)	Microstructure
5	08.10.25	Composites (I) – Prof. Bourban	Composites
6	15.10.25	Properties (II) + Processing (I)	Properties
7	22.10.25	Break	Break

Tentative Outline

Schedule subject to change.

Week	Date	Lecture (0915-1000 / 1015-1100)	Exercise (1115-1200)
8	29.10.25	Processing (II) + Sustainability	Processing
9	05.11.25	Composites (II) – Prof. Bourban	Composites
10	12.11.25	Introduction to Metals	Polymer Sustainability
11	19.11.25	Phase Diagrams (I)	Introduction Metals
12	26.11.25	Phase Diagrams (II) + Properties (I)	Phase Diagrams
13	03.12.25	Properties (II)	Properties
14	10.12.25	Manufacturing + Sustainability	
15	17.12.24	Review	

MSE 214: Organizational Information

- **Study Materials:**
  - Lecture notes
  - Exercises

(Exercise solutions will be made available on Moodle after the exercise session)

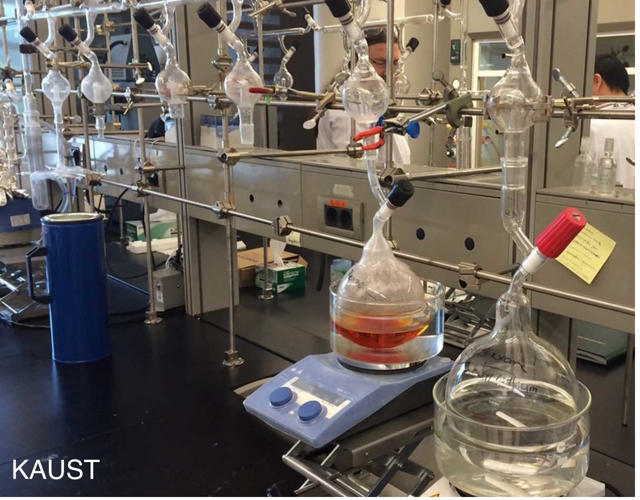
- **Lectures:**
  - AAC006
  - AAC231

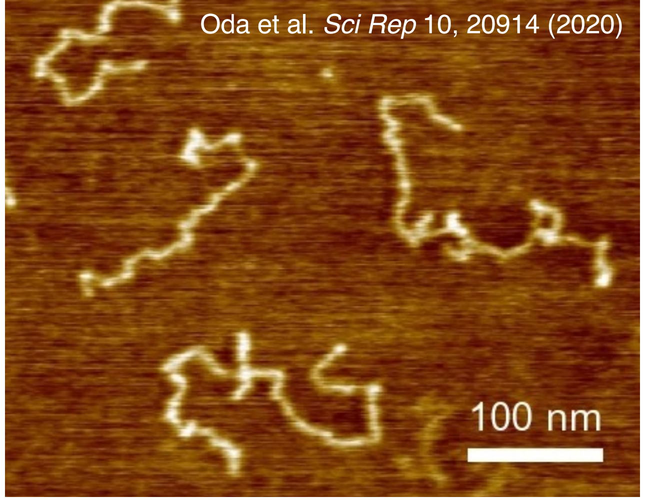
- **Exercise sessions:**
  - AAC006, AAC231
  - 8 assistants
  - Try to spread between the two locations
  - Work on exercise and ask for support.
  - Ask about the exercises and/or the study materials

MSE 214: Course Evaluation

Written exam in the exam period (combined polymers and metals)

- Bring a calculator
- *Likely* distribution: 42.5% polymers, 42.5% metals, 15% composites
- 1 A4 sheet of paper (front and back) with a handwritten summary of equations, definitions, and notes will be allowed at the exams
- You are free to write on an electronic device and then print it out on an A4 sheet of paper.
- No electronic devices will be permitted at the exam
- Information sheets will be checked before the exam. Sheets that do not adhere to the handwritten rule will be confiscated.





Materials Engineering I (MSE 214)

Lecture 1: Introduction to Polymers

EPFL

Week 1 Learning Objectives

- **Understand what a polymer is**
  - Terms: monomer, repeat unit, polymer, degree of polymerization, molecular weight, dispersity
- **Know how to classify polymers (I)**
  - Composition, architecture, polymerization mechanism, chemical reaction, properties
- **Understand the definition and impact of molecular weight**
- **Determine molecular weight and dispersity of a polymer sample**

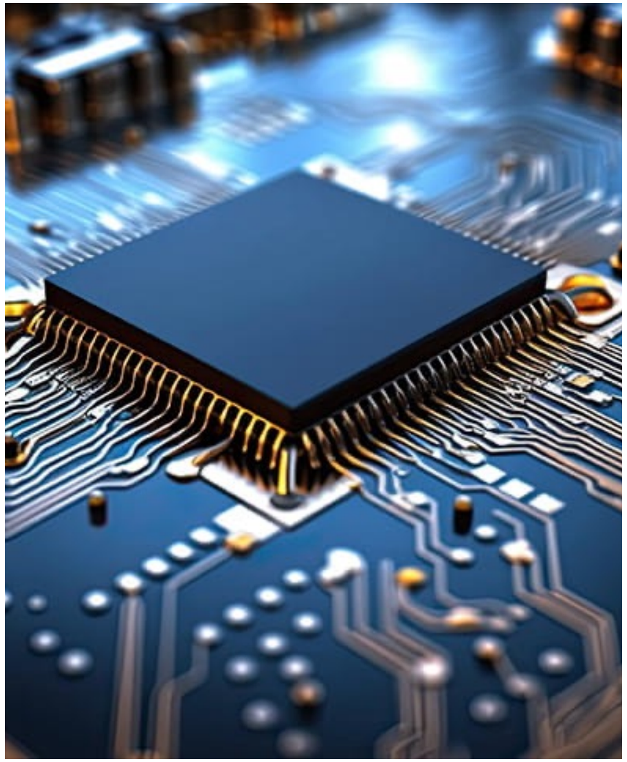
Polymers are complex and messy materials!

WHY SHOULD WE CARE ABOUT ~~MATERIALS~~ POLYMERS?

Almost everything you see is a polymer or uses a polymer to make

- Polyester
- Polyacrylate
- Nylon
- Cotton

- Polyethylene
- Polyethylene terephthalate (PET)
- Polypropylene
- Polycarbonate

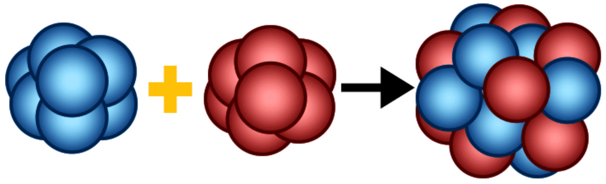


- Polyimide
- Polyepoxides
- Parylene
- SU8
- Polymethylmethacrylate

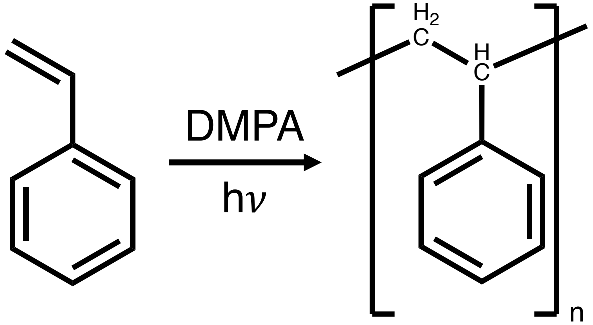
- Cellulose
- Lignin
- DNA
- Proteins

What do we mean by "Make"? — Synthesis v.s. Processing v.s. Manufacturing

Synthesis



E.g. Styrene → Polystyrene

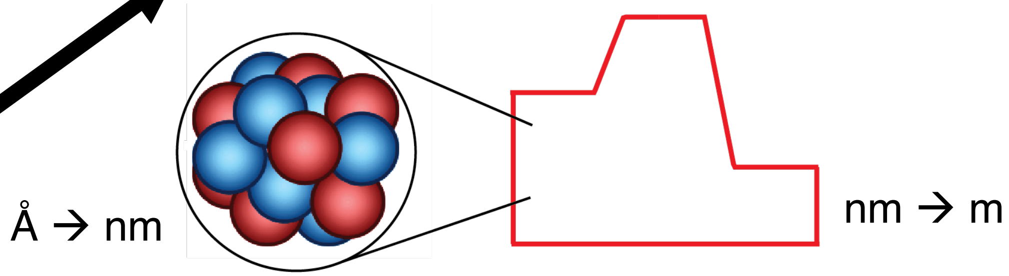


- Reactants transformed into products via chemical reactions
- Products include the desired material
- Mostly control composition

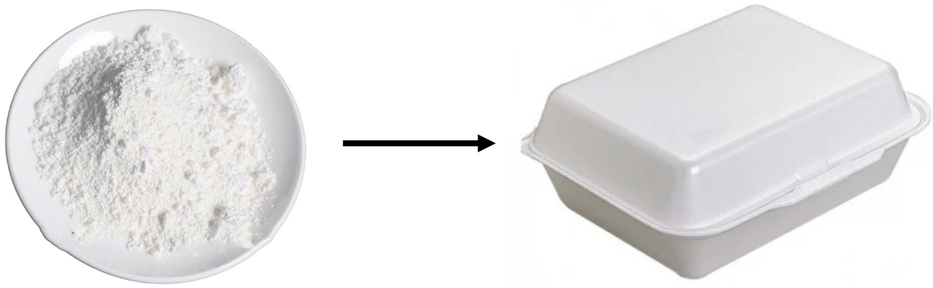
Processing

- Material modification
- Control microstructure and properties

Manufacturing



E.g. Polystyrene → Polystyrene

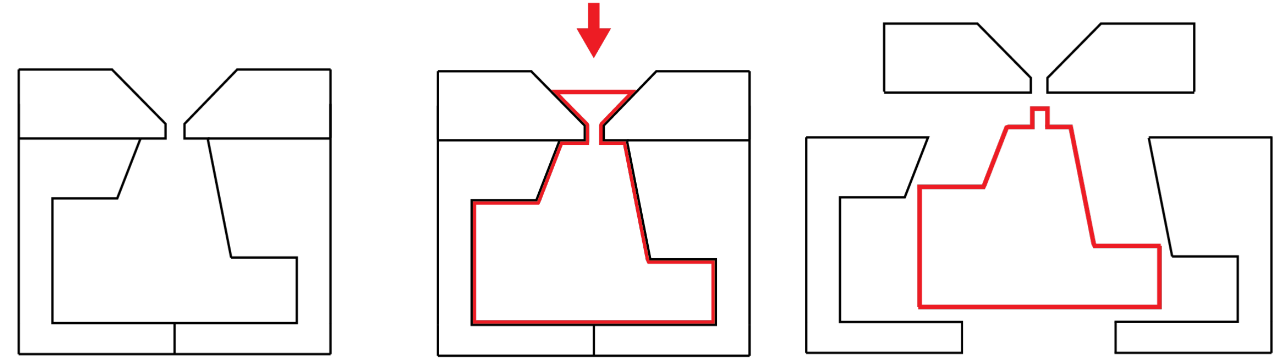


- Material transformed into finished product/part
- Shape the material
- Control microstructure and properties

*These examples are non-exhaustive

Polymer Manufacturing Categories

Formative



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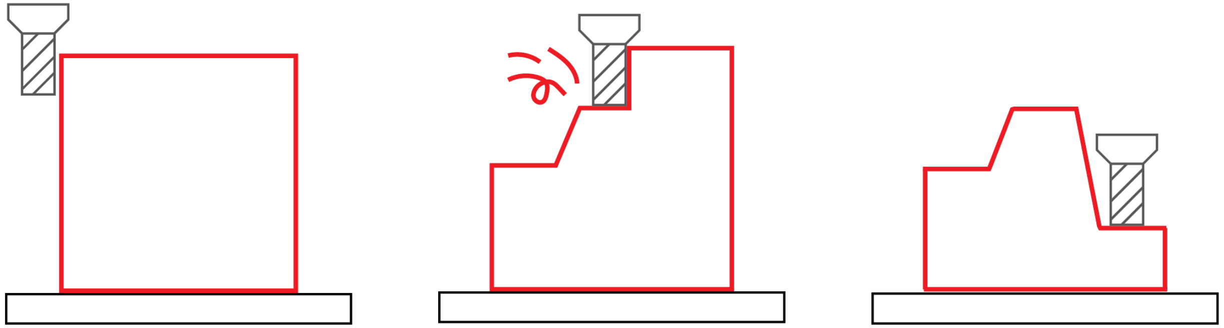
- Injection molding
- Blow molding
- Extrusion
- Fibre spinning
- Compression molding
- Thermoforming
- Spin coating

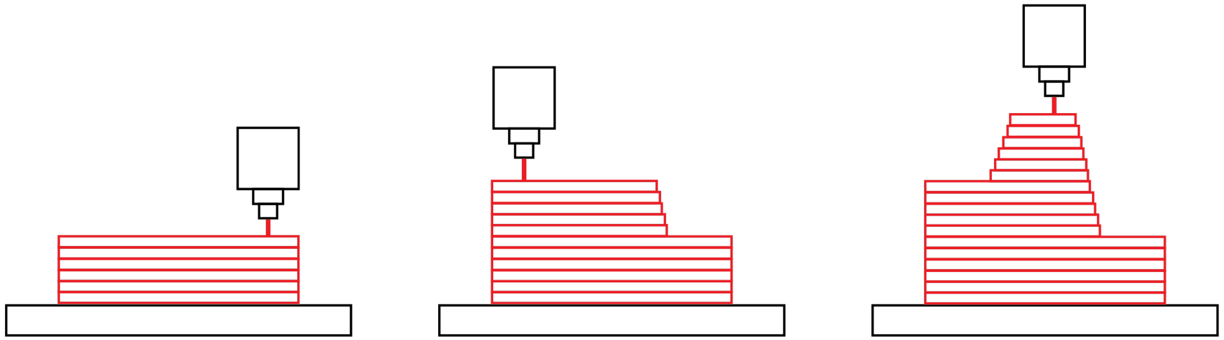
Subtractive



*

- CNC milling
- Laser cutting
- Stamping

Additive



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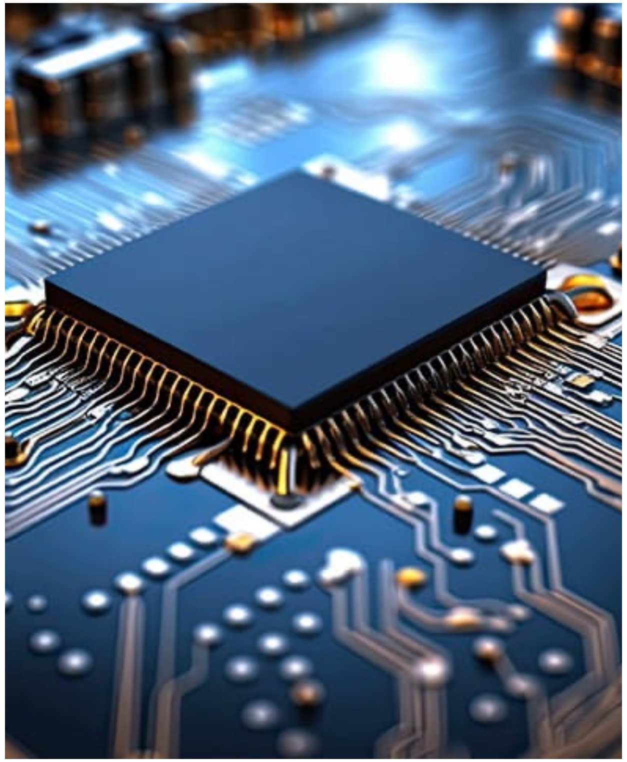
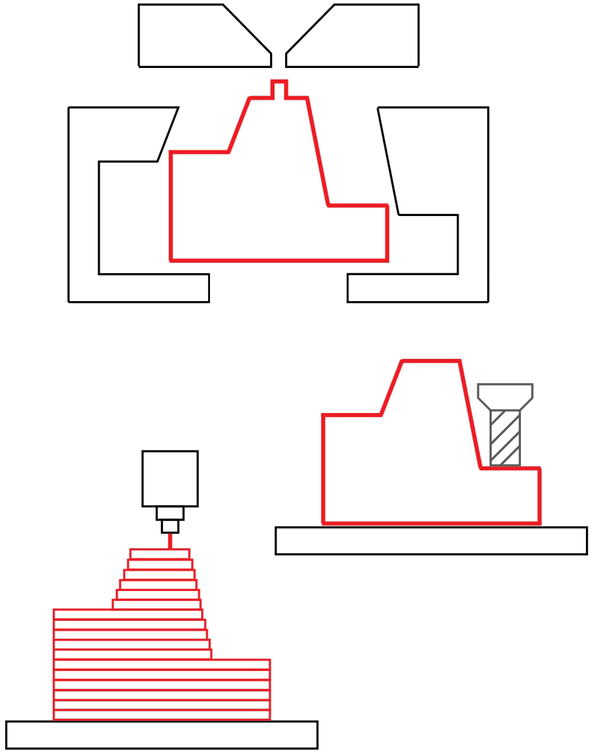
- Material extrusion
- Vat photopolymerization
- Material jetting
- Binder jetting
- Powder bed fusion
- Sheet lamination
- Deposition

WHY DO WE USE POLYMERS?

WHY DO WE USE THESE PARTICULAR POLYMERS?

WHY DO WE MANUFACTURE THEM IN THESE WAYS?

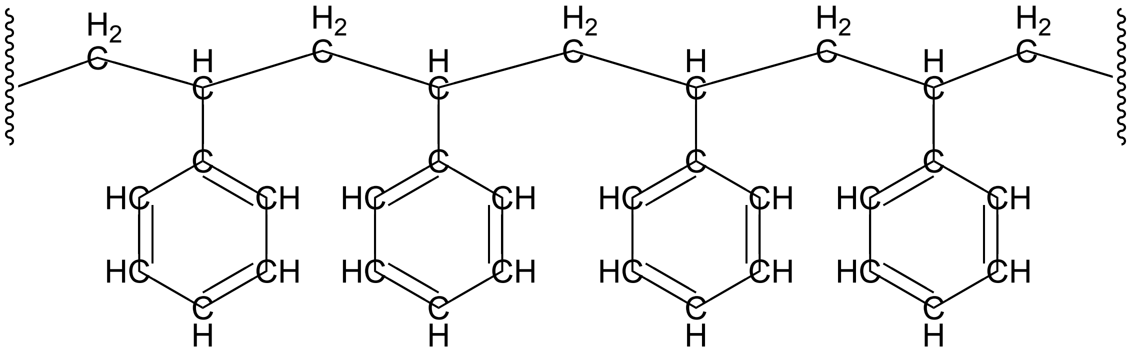
What are Polymers?

Greek: *Poly-*, “Many” + *-mer(os)*, “Part”

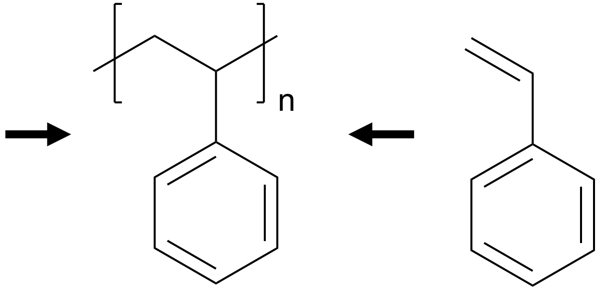
Polymers are large molecules that are composed of many repeating subunits

Styrofoam/Polystyrene

Expanded Structural Formula
Skeletal Structural Formula



Styrene



Polymer

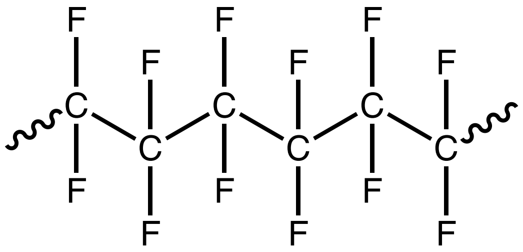
Monomer

Vertices: C ; 1 line = 1 bond ; H fills up rest
Everything other than C,H needs to be written explicitly

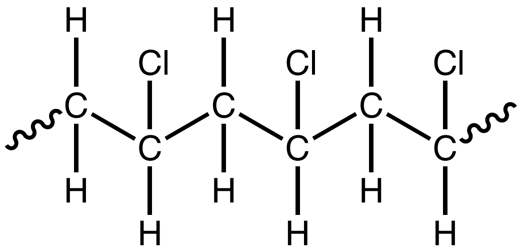
EPFL

What are Polymers?

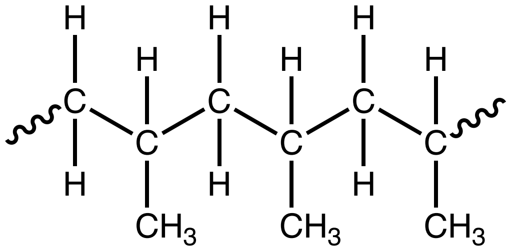
Teflon/PTFE
(Polytetrafluoroethylene)



PVC
(Poly(vinyl chloride))

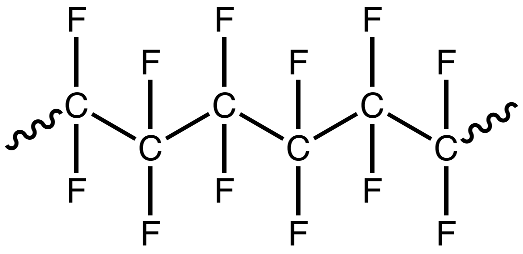


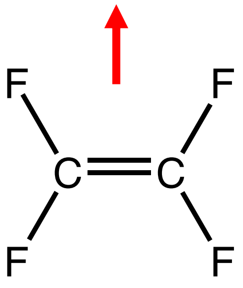
PP
(Polypropylene)



Polymers are made from Monomers

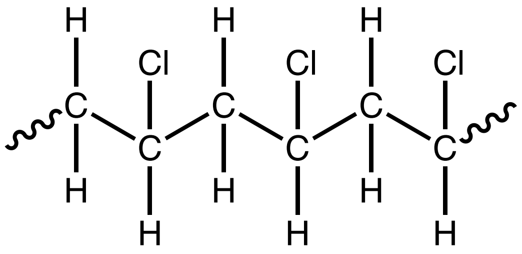
Teflon/PTFE
(Polytetrafluoroethylene)

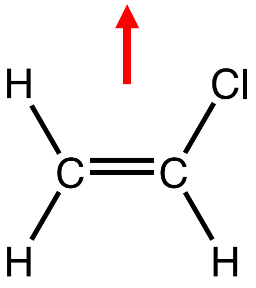




Tetrafluoroethylene

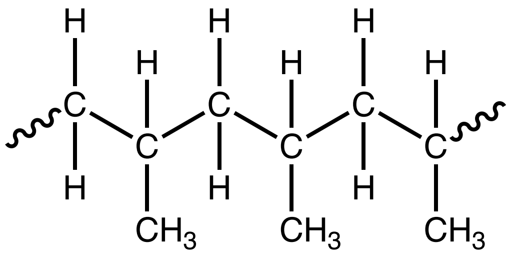
PVC
(Poly(vinyl chloride))

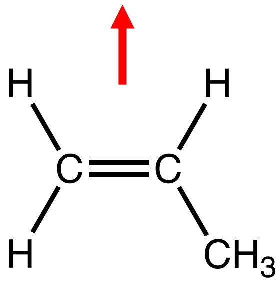




Vinyl chloride

PP
(Polypropylene)





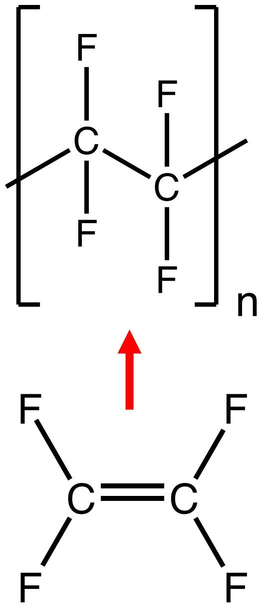
Propylene

Monomers (low molecular weight molecules) react together to form polymers

Polymer are sometimes named after the monomer: Poly(monomer)

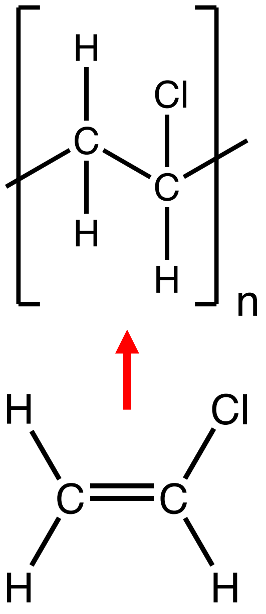
Polymers can be represented by their Repeating Unit

Teflon/PTFE
(Polytetrafluoroethylene)



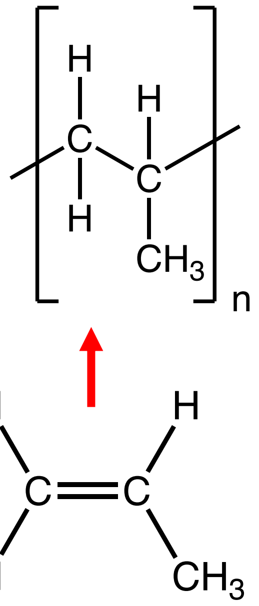
Tetrafluoroethylene

PVC
(Poly(vinyl chloride))



Vinyl chloride

PP
(Polypropylene)



Propylene

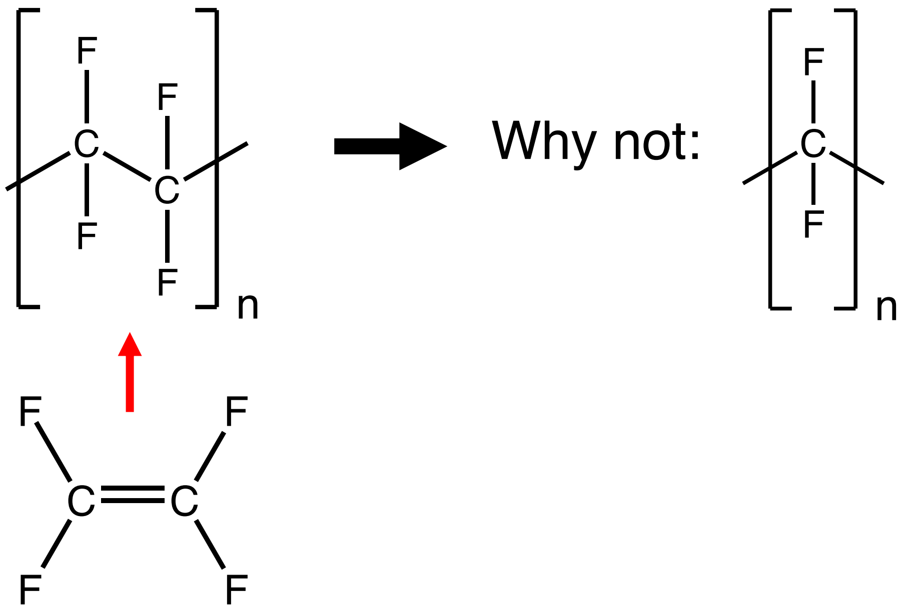
Polymers can be represented by their **repeating unit**.

Repeating unit: smallest group of atoms whose repetition would produce the complete polymer chain (minus end groups)

Is this correct?

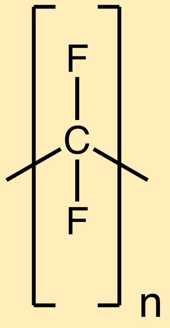
The Repeating Unit

Teflon/PTFE
(Polytetrafluoroethylene)



Tetrafluoroethylene

1. Tetrafluoroethylene (monomer) has 2 carbons → Polymer always has an even number of carbons.



suggests that you can get odd number of carbons. Not ideal.

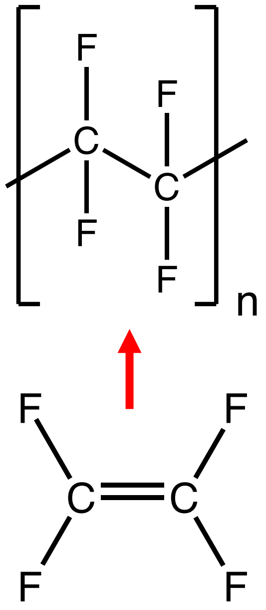
2. The choice of repeating unit is often linked to the monomer that was used

Polymers can be represented by their **repeating unit**.

Repeating unit: smallest group of atoms whose repetition would produce the complete polymer chain (minus end groups)

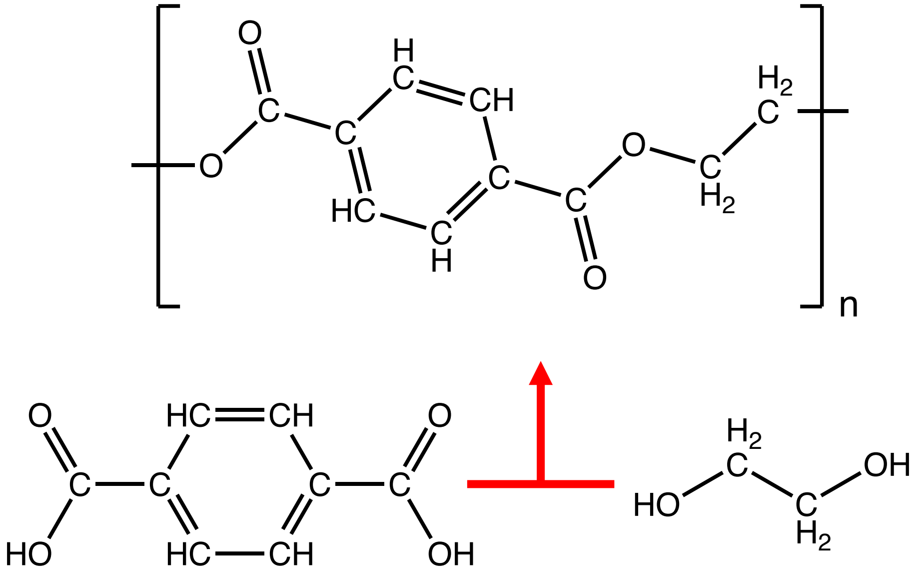
The Repeating Unit

Teflon/PTFE
(Polytetrafluoroethylene)



Tetrafluoroethylene

PET
(Poly(ethylene terephthalate))



Terephthalic acid

Ethylene glycol

The repeat unit and the monomer(s) can be **slightly or very** different

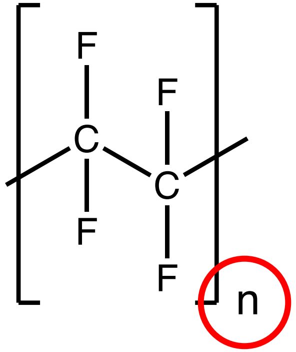
It is difficult to know how a polymer is made from their repeating unit

Polymer are sometimes named after the monomer: Poly(monomer)

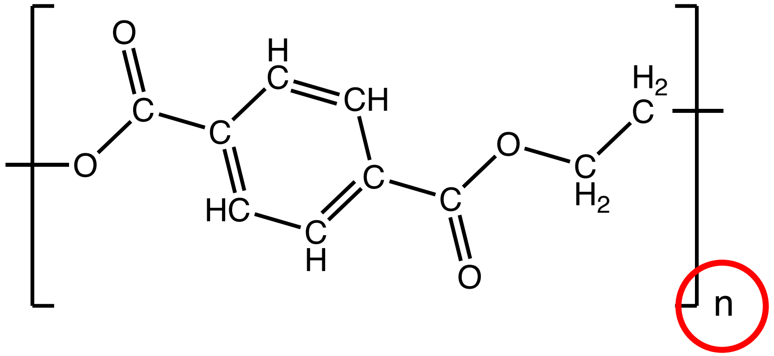
Polymers can be also named after their repeating unit: Poly(repeating unit)

Polymer Length and Degree of Polymerization

Teflon/PTFE
(Polytetrafluoroethylene)



PET
(Poly(ethylene terephthalate))



Polymer represented by [REPEAT UNIT] $_n$ → n tells us the length

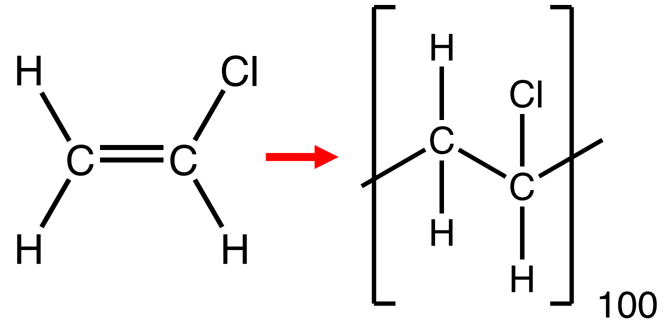
Degree of Polymerization (DP) = Average number of monomeric units in the polymer

For homopolymers (polymers made using one monomer): n = DP

For copolymers (polymers made using *x* different monomers): n = $\frac{\mathrm{DP}}{x}$

Degree of Polymerization (Example)

Homopolymer (n = DP)



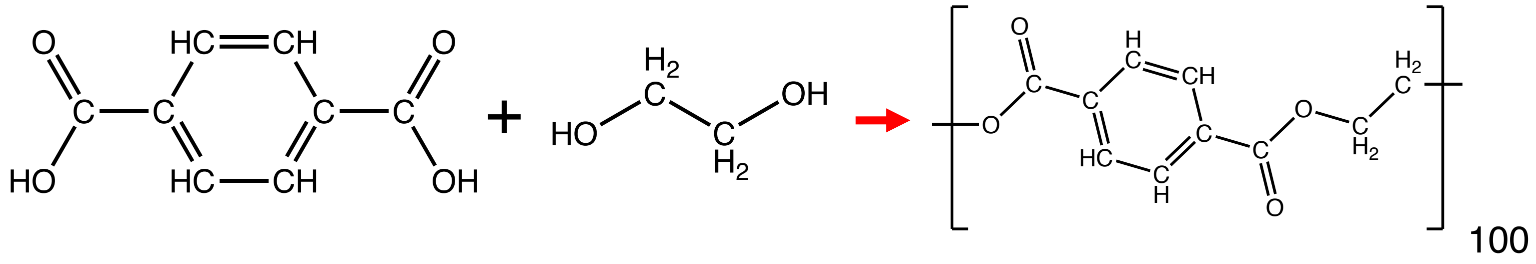
n = 100

# of monomers types = 1

# of monomers used to make the polymer = 100

# of monomeric units = 100
DP = 100

Copolymer (n = $\frac{\text{DP}}{x}$; x = # of comonomers)



n = 100

# of monomers types = 2

# of monomers used to make the polymer = 200

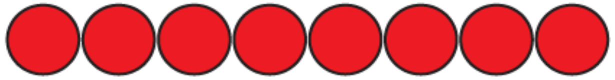
# of monomeric units = 200
DP = 200

How Do We Classify Polymers?

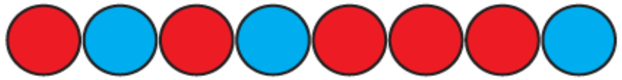
Multiple ways of classifying polymers — Depends on the information you want to convey

1. Composition: Number of monomer types

Single monomer type:
Homopolymer → PolyA



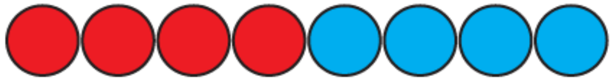
≥2 monomer types:
Copolymer → Poly(A-*co*-B)



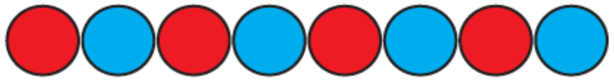
Convey information about the identity and property of the monomer(s):

If A has some property X
If B has some property Y

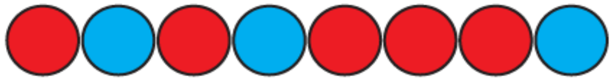
Poly(A-*co*-B) has properties X and Y *to some extent. Possible new property.*



Block Copolymer
Poly(A-*block*-B)



Alternating Copolymer
Poly(A-*alt*-B)



Statistical Copolymer
Poly(A-*stat*-B)

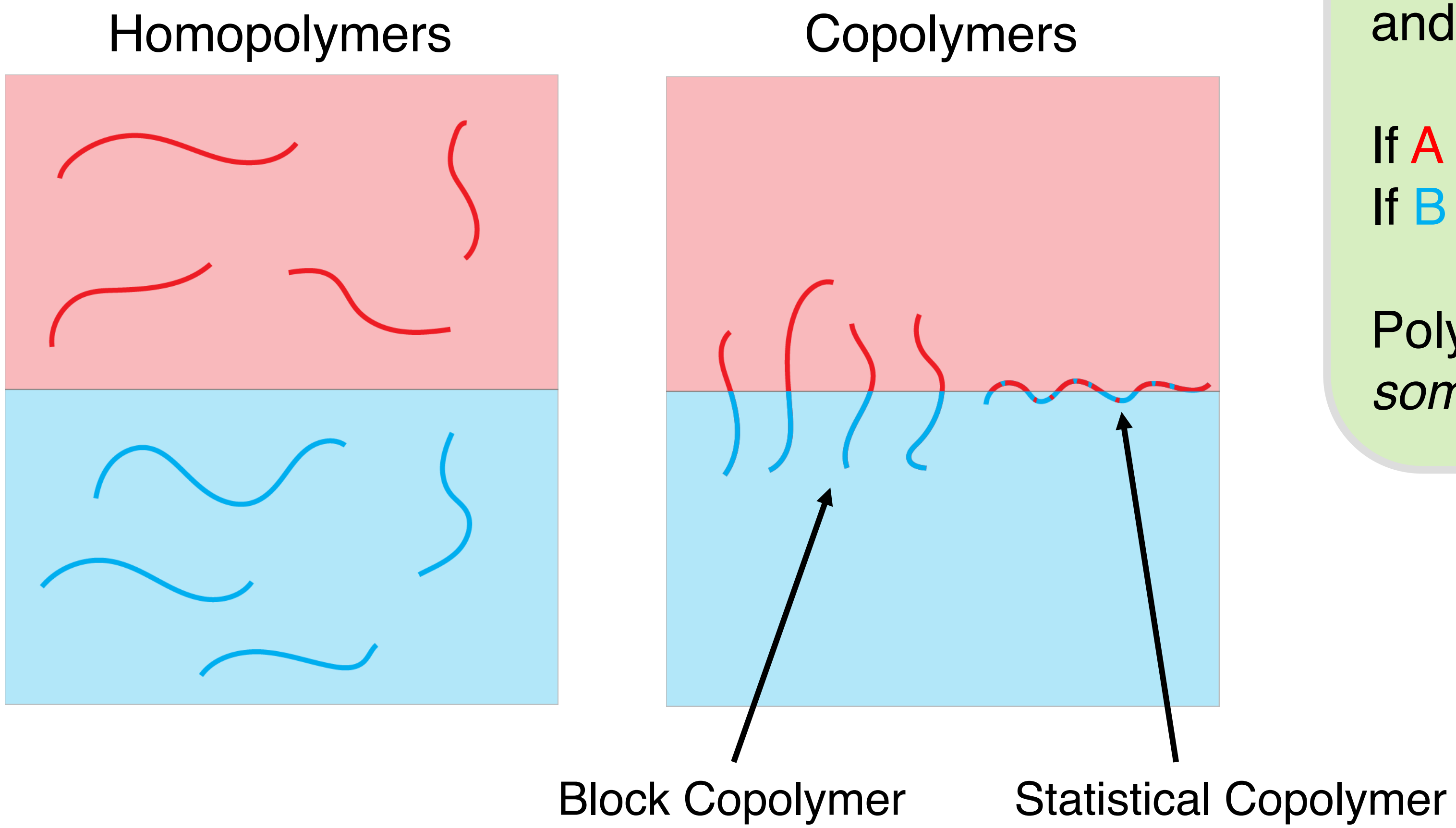
EPFL

Note: 3 monomer types can sometimes be called terpolymers and 4 monomer types, quaterpolymer

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

1. Composition: Number of monomer types



Convey information about the identity and property of the monomer(s):

If A has some property X
If B has some property Y

Poly(A-*co*-B) has properties X and Y *to some extent. Possible new property.*

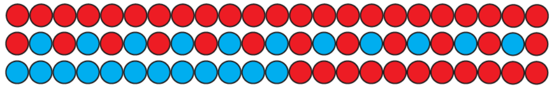
EPFL

How Do We Classify Polymers?

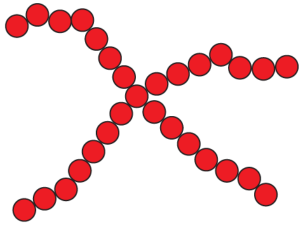
Multiple ways of classifying polymers — Depends on the information you want to convey

2. Architecture: Chain arrangement

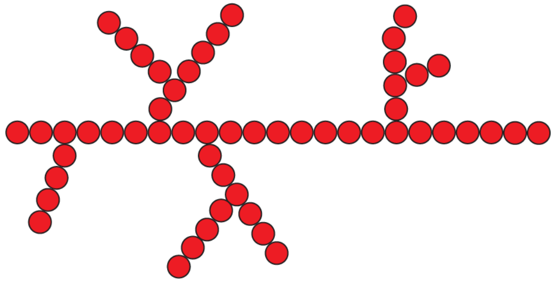
Linear polymer



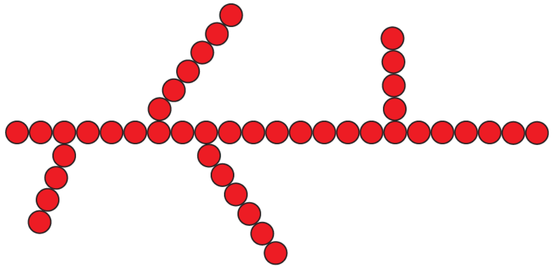
Star polymer



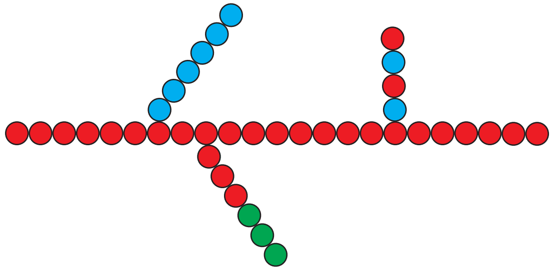
Branch polymer



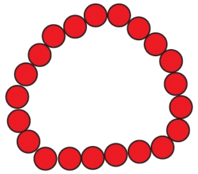
Comb polymer



Graft (co)polymer



Ring polymer

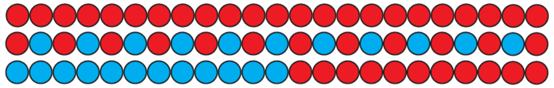


How Do We Classify Polymers?

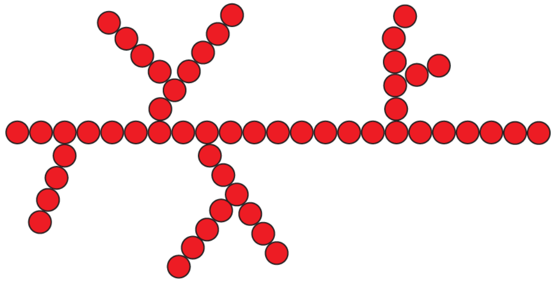
Multiple ways of classifying polymers — Depends on the information you want to convey

2. Architecture: Chain arrangement

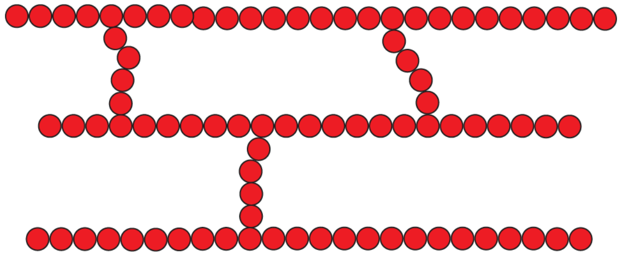
Linear polymer



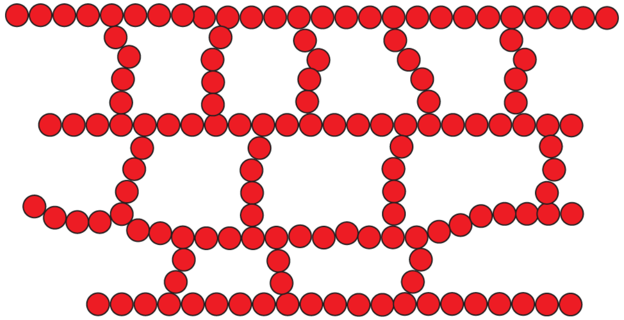
Branch polymer



Crosslinked polymer
(connected polymers)



Network polymer
(connected polymers)



Degree of crosslinking

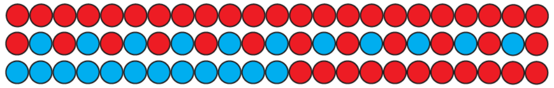
Common architectures: Linear, Branched, Crosslinked, Network
Crosslinked and Network are sometimes used interchangably

How Do We Classify Polymers?

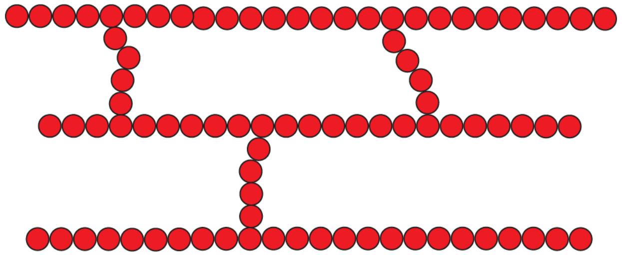
Multiple ways of classifying polymers — Depends on the information you want to convey

<u>2. Architecture: Chain arrangement</u>

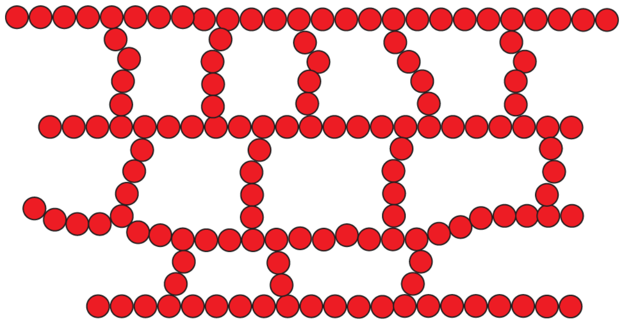
Linear polymer



Crosslinked polymer
(connected polymers)



Network polymer
(connected polymers)



Degree of crosslinking

What is crosslinking?
Crosslinks = Links between the chains!
Pull on one = pull on all connected

How does this affect polymer properties?

EPFL

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

2. Architecture: Chain arrangement

Conveys information about packing and topological effects

Low Density Polyethylene (LDPE)

High Density Polyethylene (HDPE)

Interaction between polyethylene chains are van der Waals forces → Van der Waals forces scale as $(\text{distance})^{-6}$ → Which packs better? → Which is harder to pull apart?

→ HDPE

LDPE

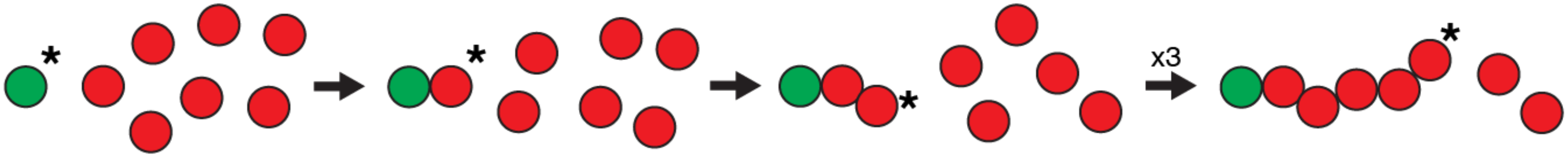
HDPE

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

3. Polymerization Mechanisms (There will be a whole lecture on these)

Chain-growth*: Polymer grows via the reaction of monomer(s) onto **active site(s)** on the polymer chain
Active site(s) regenerated at the end of each growth step



Addition of monomer is typically very rapid → Chain reaction

Important: Chain here does not refer to the formation of a polymer chain but to the **chain reaction** that takes place on formation of the active site.

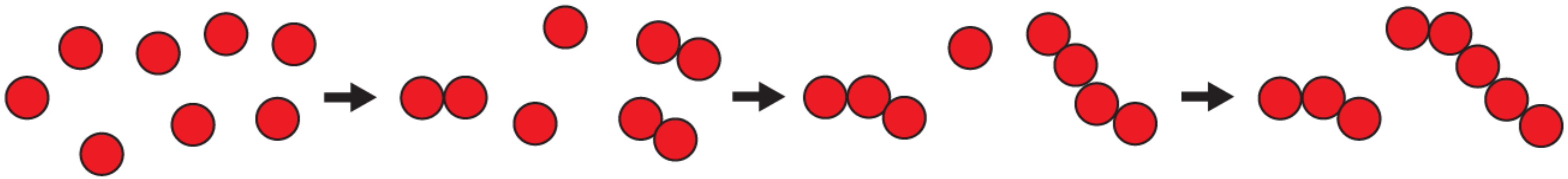
*Chain growth has been deprecated by IUPAC since 1994 but still very widely used today. More in next lecture.

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

<u>3. Polymerization Mechanisms (There will be a whole lecture on these)</u>

Step-growth*: Polymer grows via the reaction between any pairs of reactive species



Monomers consumed very early; Long polymer lengths require significant conversion

Important: (Macro)molecules of **all** sizes can react together!

Don't think of it as a step-by-step process since chain-growth also happens in steps
Easier to think of it as just a name

*Step growth has been deprecated by IUPAC since 1994 but still very widely used today. More in next lecture.

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

3. Polymerization Mechanisms (There will be a whole lecture on these)

Conveys information about the polymer synthesis

Polymerization game:

Chain-growth vs Step-Growth
Everyone is a monomer!

Form a polymer by making connections!

Chain-growth rules:

- Shake hands to form a bond!
- A select few start with the power to shake hands immediately. They can only use one hand, i.e. form one bond.
- Everyone else: Someone needs to shake your hand before you can shake someone else's, i.e. you can form two bonds.
- You have to look at each other to shake hands
- Form the biggest polymer in ___**s**
- Held hands cannot be un-held.

EPFL

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

<u>3. Polymerization Mechanisms (There will be a whole lecture on these)</u>

Conveys information about the polymer synthesis

Polymerization game:

Chain-growth vs Step-Growth
Everyone is a monomer!

Form a polymer by making connections!

Step-growth rules:

- Shake hands to form a bond!
- <u>Anyone can shake hands with anyone</u>
- <u>You have to look at each other to shake hands</u>
- <u>You cannot form 2 bonds with the same person</u>
- Held hands cannot be un-held
- Form the biggest polymer in ___**s.**
- Only shake a hand <u>if you can</u>

EPFL

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

3. Polymerization Mechanisms (There will be a whole lecture on these)

Conveys information about the polymer synthesis

Polymerization game:

Chain-growth vs Step-Growth
Everyone is a monomer!

Form a polymer by making connections!

Some observations from the game

Chain-Growth*	Step-Growth*
Reaction mixture contains of long polymers and monomers	Reaction mixture consists of **oligomers** of many sizes
Monomer concentration decreases steadily	Monomers disappear early, in favor of small oligomers
Easy to get long polymer	Not so easy to get long polymer

Oligomer: molecules consisting of a few repeating units

Why do we care about polymer length? Think about VDW forces

*Deprecated by IUPAC but still very very widely used. Taught here so you'll be familiar with the literature. More in next lecture.

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

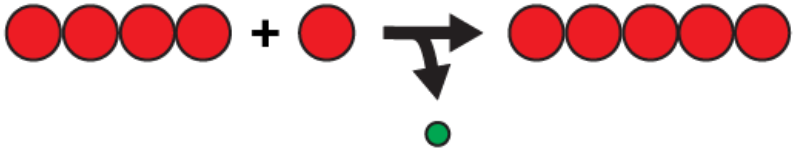
4. Chemical Reaction

Addition polymerization*: Polymer formed by addition reactions
No atoms lost during reaction

Note: not the same as polyaddition

Condensation polymerization*: Polymer formed by condensation reactions
Some atoms get kicked out during the reaction
Small molecule byproduct
Polymer is *condensed* w.r.t. to the monomers

Note: not the same as polycondensation



Conveys information about the polymer synthesis

*Deprecated by IUPAC but still very very widely used. Taught here so you'll be familiar with the literature. More in next lecture.

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How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

3. Polymerization Mechanisms

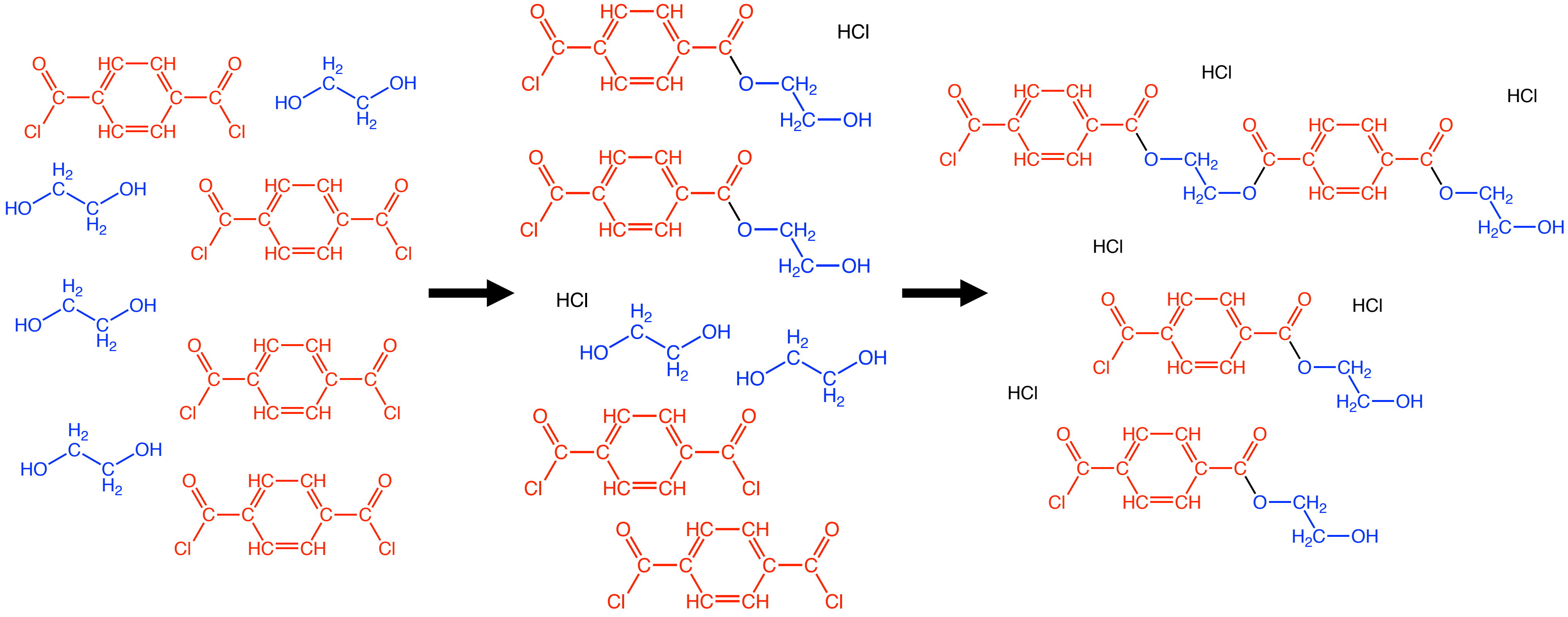
Chain-growth*

Step-growth*

4. Chemical Reaction

Addition polymerization*

Condensation polymerization*



Polymerization can be step-growth **and** condensation

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

<u>3. Polymerization Mechanisms</u>

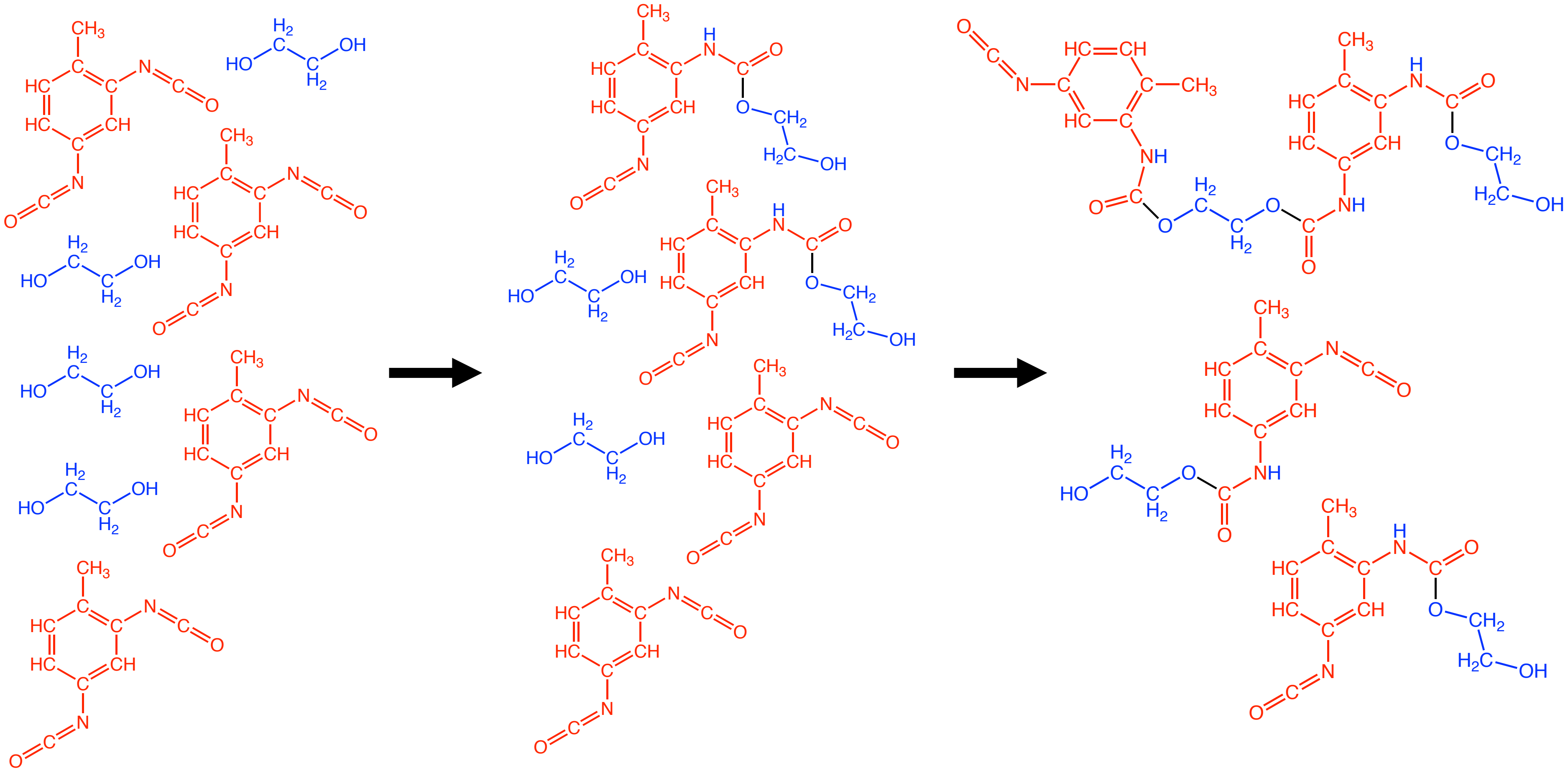
Chain-growth*

Step-growth*

<u>4. Chemical Reaction</u>

Addition polymerization*

Condensation polymerization*



Polymerization can be step-growth **and** addition

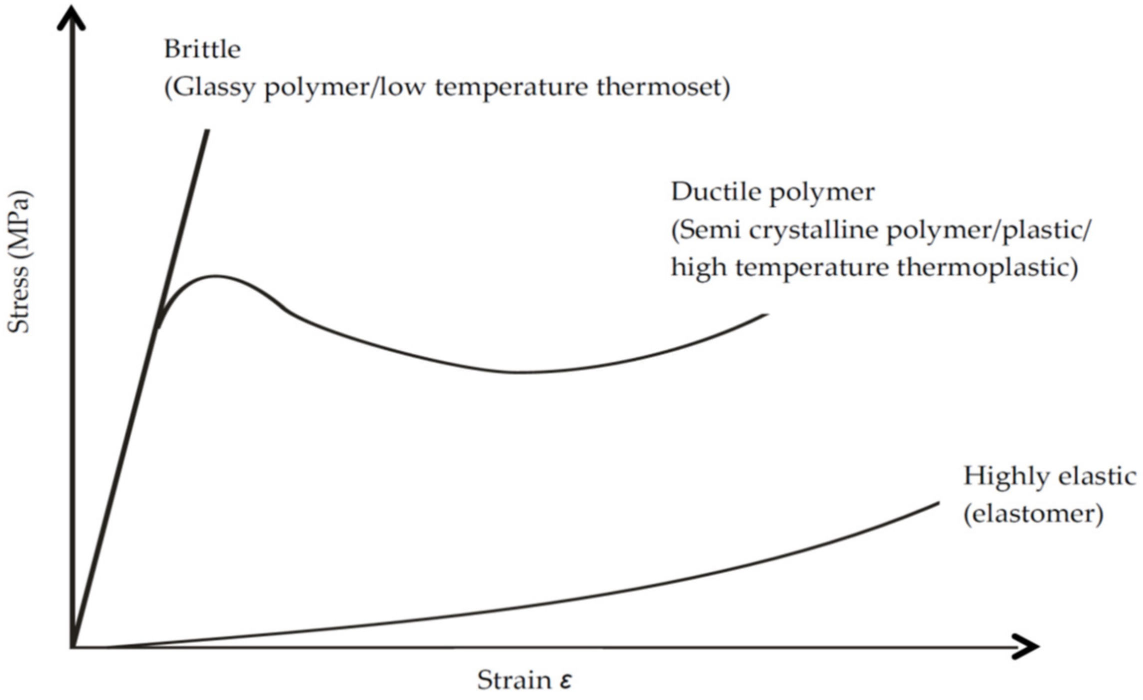
Step-growth <u>not always</u> Condensation and Chain-growth <u>not always</u> Addition

How Do We Classify Polymers?

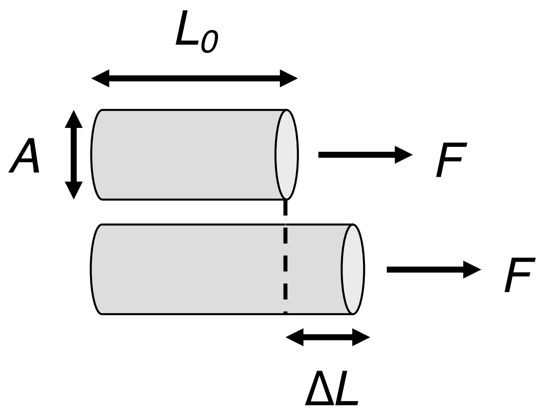
Multiple ways of classifying polymers — Depends on the information you want to convey

<u>5. Physical Properties</u>

Mechanical



Haque et al. *Energies* 2021, 14, 2758



Engineering Stress: $\sigma = \frac{F}{A}$

Engineering Strain: $\varepsilon = \frac{\Delta L}{L_0}$

Young's Modulus: $E = \frac{\sigma}{\varepsilon}$

E is only for elastic deformation!

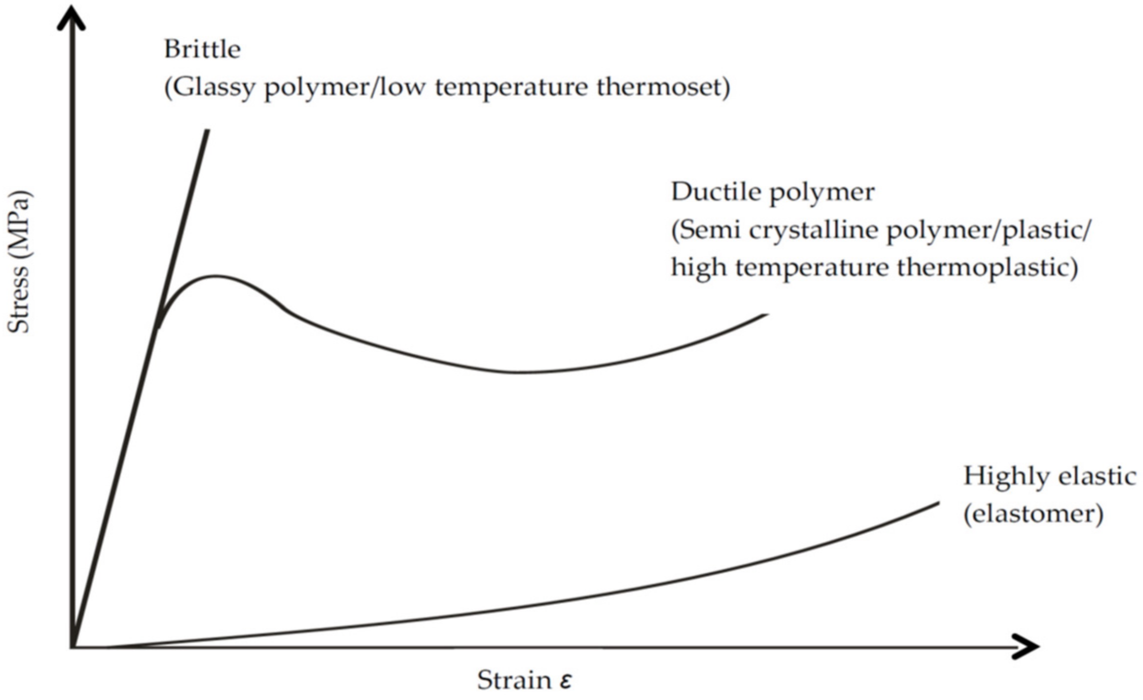
Measured in the linear elastic region of the stress-strain curve

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

5. Physical Properties

Mechanical



Haque et al. *Energies* 2021, 14, 2758

Partially adapted from Teo et al. *ACS Biomater. Sci. Eng.* 2016, 2, 454

Polymer	*E* (MPa)	(Stress at Failure) (MPa)	Strain at Break
LDPE	200 – 400	8 – 12	6 – 6.5
HDPE	600 – 1400	20 – 32	1.8 – 10
Nylon 66	1700 – 2000	80 – 85	0.12 – 3
PDMS	360 – 870	2.24	4.3 – 6.4
Rubber	4	28	7
Epoxy Resin	3000 – 6000	35 – 100	0.01 – 0.06
Carbon Steel	190000 – 210000	276 – 1882	0.1 – 0.32

Polymers are considered soft materials / matter

Huge contrast to metals!

How Do We Classify Polymers?

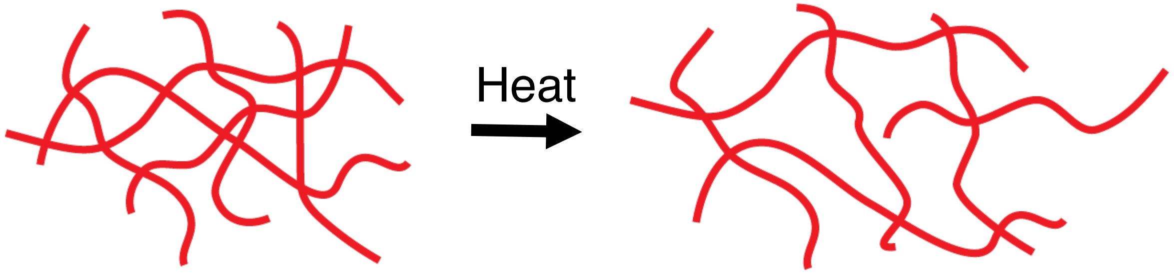
Multiple ways of classifying polymers — Depends on the information you want to convey

5. Physical Properties

Thermal 

 Crosslink point

Thermoplastics



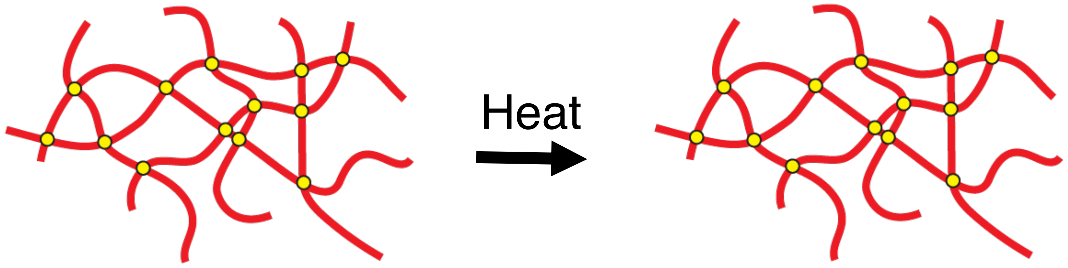
Weak intermolecular forces between chains

Significant chain movement with heat

Polymers soften and flow upon heating*

Can be reshaped with heat

Thermosets



Strong covalent bonds between chains

Minimal chain movement with heat

Polymers do not flow upon heating

Cannot be reshaped with heat

EPFL

*Note how I did not use ”melt”. Melt has a very specific meaning in materials science. More in another lecture.

How Do We Classify Polymers?

Multiple ways of classifying polymers — Depends on the information you want to convey

1. Composition: Number of monomer types

2. Architecture: Monomer arrangement

3. Polymerization Mechanisms

4. Chemical Reaction

5. Physical Properties

.

.

.

→

Polymers are complex materials

No universal classification!

The classifications are often interdependent on each other

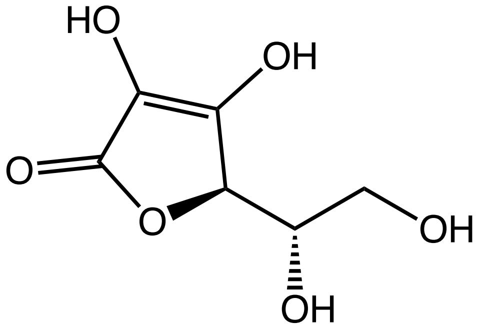
What Makes Synthetic Polymers Different from Other Materials?

Alumina (Ceramic)

Molecular formula: Al_2O_3
(101.96 g/mol)

Every molecule has the same molecular weight

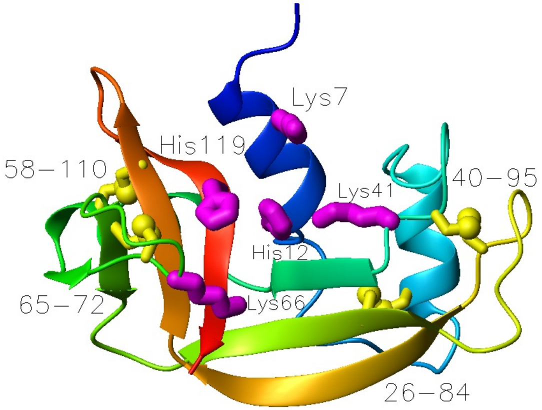
Vitamin C (Small Molecule)



Molecular formula: $C_6H_8O_6$
(176.12 g/mol)

Every molecule has the same molecular weight

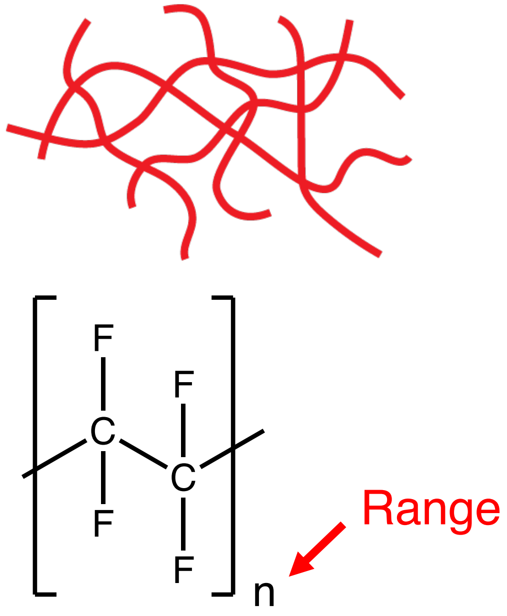
Ribonuclease A (Protein)



124 Amino Acids
(13.7 kg/mol)

Every protein chain has the same molecular weight

Synthetic Polymer



Mixtures of molecular weights

Synthetic polymers are mixtures

Synthetic Polymers are Mixtures

- Think back to the polymerization game: Do you think we can make the same polymer each time?

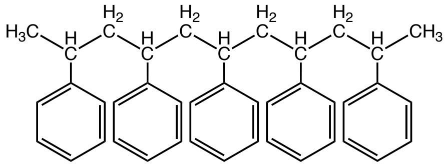
→ Statistical variations in the polymerization process

Mixtures of polymers of different molecular weights

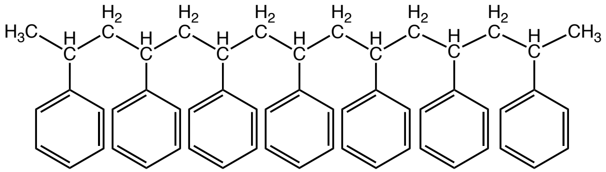
- Average molecular weight and the molecular weight distribution needed to characterize the polymer

A single molecular weight not sufficient
<u>Average</u> molecular weight needed ←

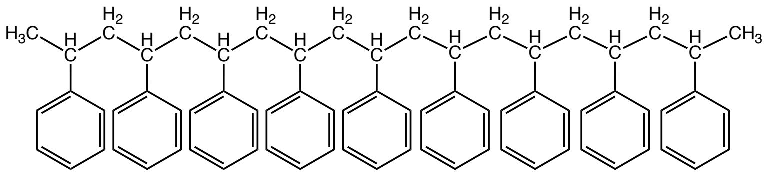
Consider this polystyrene sample of 3 different sizes



$(C_8H_8)_5 + C_2H_6$



$(C_8H_8)_7 + C_2H_6$



$(C_8H_8)_9 + C_2H_6$

How do we determine an average?

Let's use cities as an example:

Zürich: 700000
Morges: 14600
Lutry: 9000
Zermatt: 5800

Average population of the four cities:

$$\frac{700000 + 14600 + 9000 + 5800}{4} = 182350$$

Does this seem accurate? That the average city size is 180k?

The cities are treated as similar
→ Bias towards smaller cities

Does the average **person** live in a city with a population of 182350?

If you picked a person from random out of the four cities, it is more likely that they live in Zürich

Need to use weighted average!

$$\left(\frac{700000}{729400}\times 700000\right) + \left(\frac{14600}{729400}\times 14600\right) + \left(\frac{9000}{729400}\times 9000\right) + \left(\frac{5800}{729400}\times 5800\right) = 672234$$

The average person lives in a city of 672k

The cities are not treated as similar
→ Bias towards larger cities

Number Average and Weight Average Molecular Weight (M_n, M_w)

Number Average Molecular Weight (M_n)

$$M_n = \frac{\sum N_x M_x}{\sum N_x}$$

N_x is the number of moles of polymer whose weight is M_x

M_n is biased towards the low molecular weight fraction

Weight Average Molecular Weight (M_w)

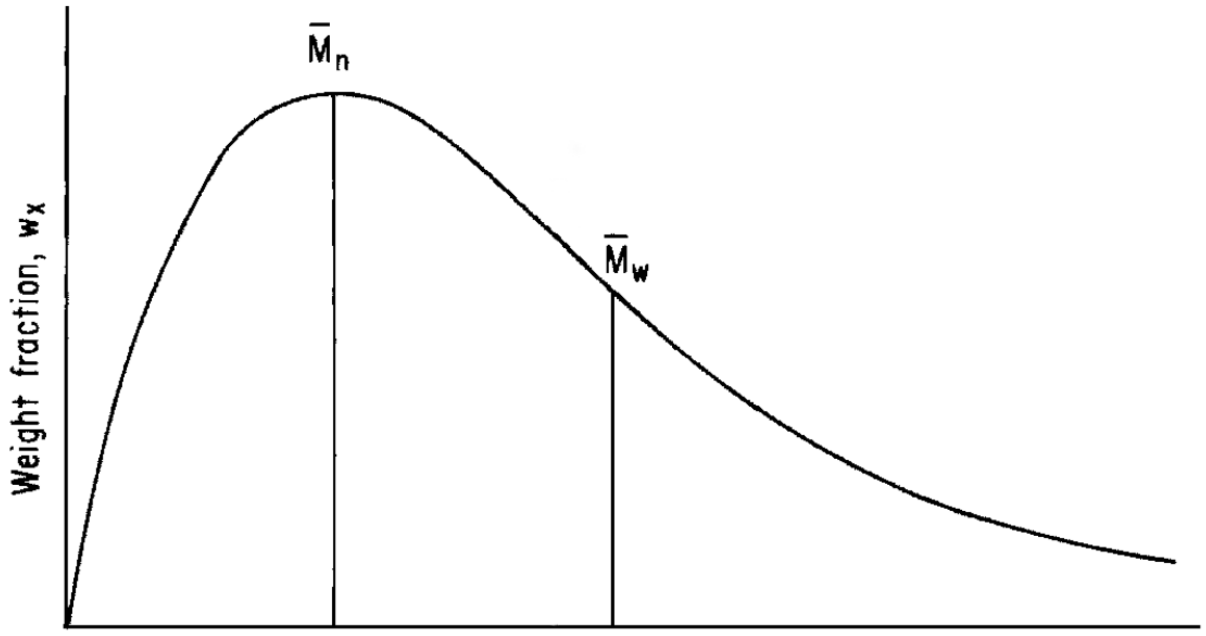
$$M_w = \frac{\sum N_x M_x^2}{\sum N_x M_x}$$

N_x is the number of moles of polymer whose weight is M_x

M_w is biased towards the high molecular weight fraction

Different characterization methods will give different types of molecular weights!

Distribution and Dispersity (Đ)



Adapted from Odian, 2004

Molecular weight, M_x

M_n is biased towards the low molecular weight fraction

M_w is biased towards the high molecular weight fraction

Dispersity* (Đ)

$$Đ = \frac{M_w}{M_n}$$

Đ is a parameter that measures the width of the molecular weight distribution of a polymer samples

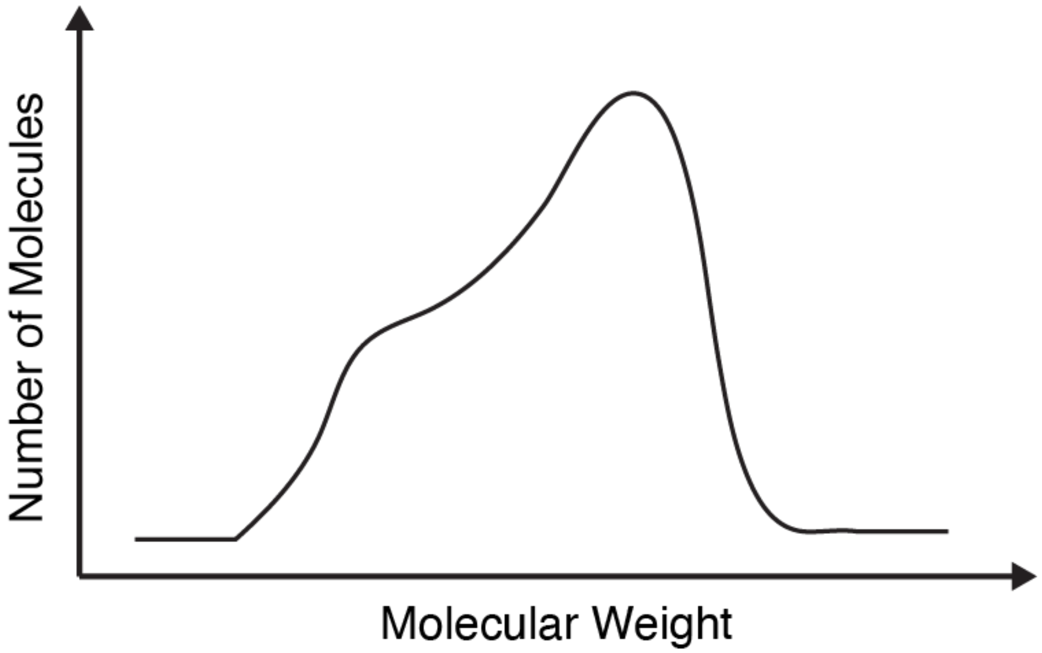
High dispersity = broad distribution
Low dispersity = narrow distribution

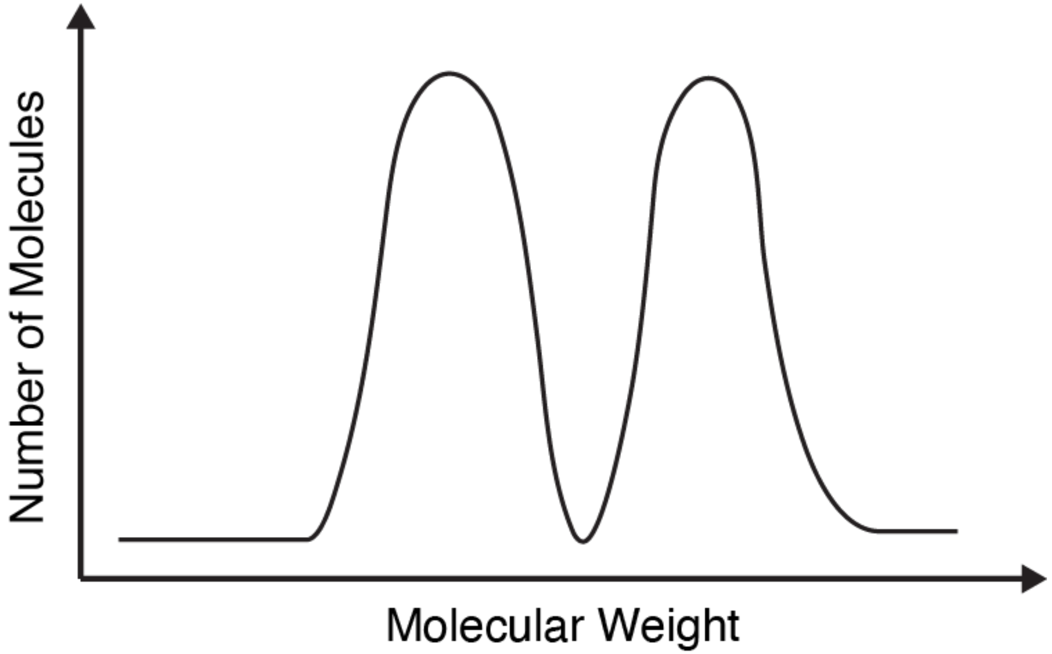
Đ cannot be smaller than 1

*Sometimes written as Polydispersity Index (PDI). This term has since been deprecated but can be found in older literature.

Distribution and Dispersity (Đ)

Average molecular weight alone is insufficient to characterize polymers.
Visualizing the complete distribution is important!





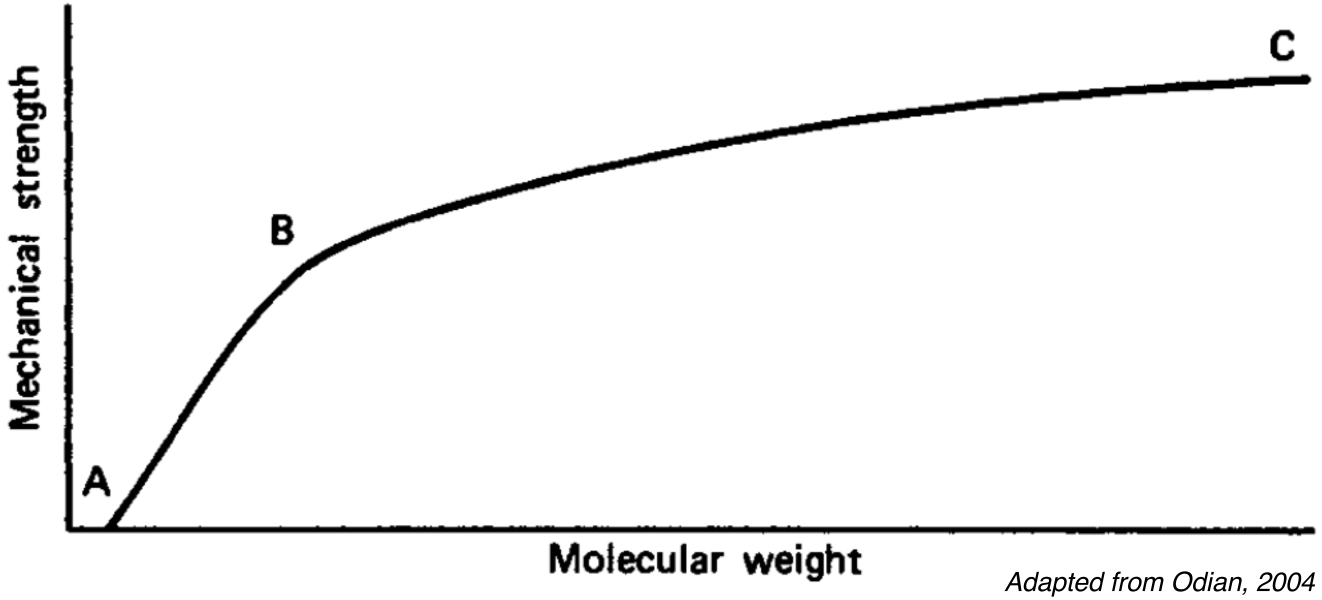
Just knowing M_n or M_w here alone would be misleading!

EPFL

Why should we care about molecular weight?

The properties of a polymer are a function of its molecular weight (and other things)

E.g. Mechanical Properties



Adapted from Odian, 2004

A. Minimal molecular weight for polymer to have appreciable strength

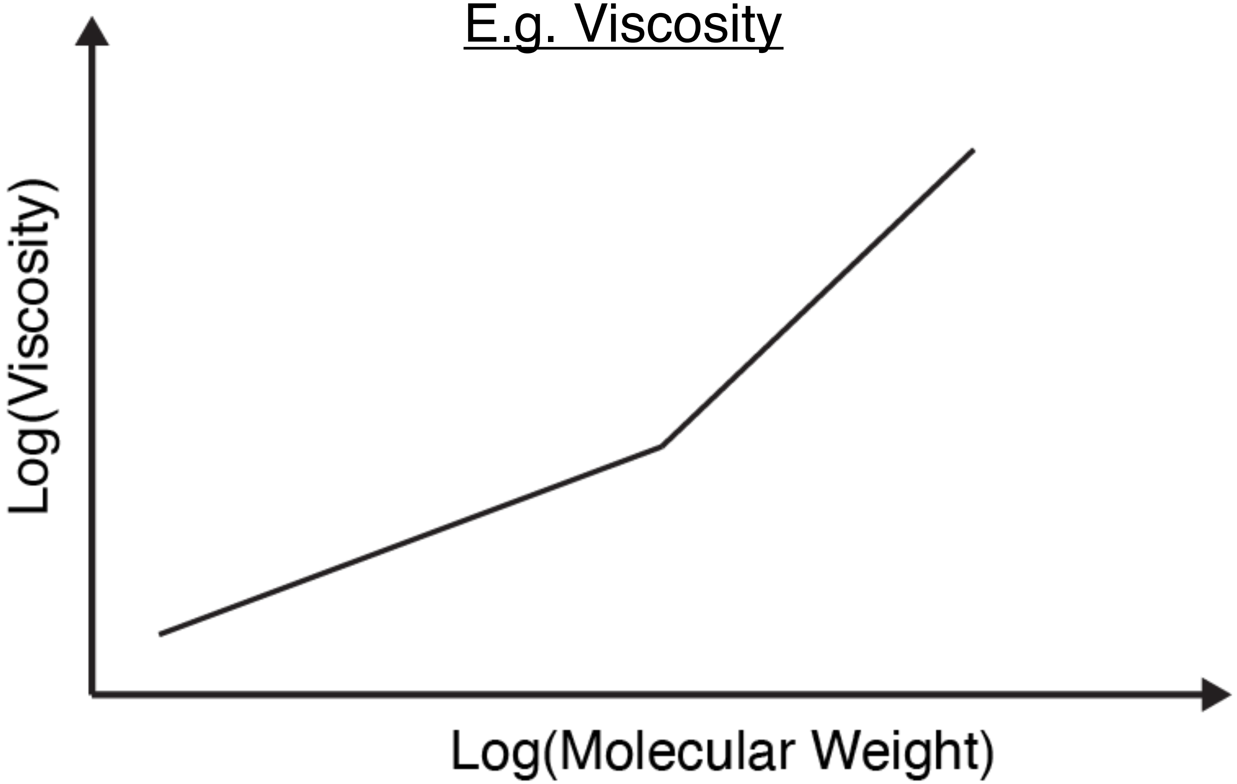
B. Above **A**, strength increases rapidly until a critical point **B** is reached.

C. Strength increases slowly past **B** until it reaches a limiting value **C**.

Why should we care about molecular weight?

The properties of a polymer are a function of its molecular weight (and other things)

E.g. Viscosity



Viscosity ∝ Molecular Weight

Viscosity impacts processability!

The ideal molecular weight is often not the manufactured molecular weight since compromises have to be made between properties and processability

Week 1 Learning Objectives

- **Understand what a polymer is**
  - Terms: monomer, repeat unit, polymer, degree of polymerization, molecular weight, dispersity
- **Know how to classify polymers (I)**
  - Composition, architecture, polymerization mechanism, chemical reaction, properties
- **Understand the definition and impact of molecular weight**
- **Determine molecular weight and dispersity of a polymer sample**

Polymers are complex and messy materials!