1 Organic Chemistry & Soft Matter Research

Table of Contents

1. **Organic Chemistry & Soft Matter Research (2 h)**
2. **The Nature of the Covalent Bond (7 h)**
   - 2.1. Carbon as the Basis of Organic Chemistry
   - 2.2. Atomic Orbitals and Hybridisation
   - 2.3. Formation of Single Bonds
   - 2.4. Formation of Multiple Bonds
   - 2.5. Electron Delocalization & Resonance Structures
3. **Molecular Structure and Nomenclature (3 h)**
   - 3.1. Basic Rules of Nomenclature
   - 3.2. Isomerism
4. **Mechanisms of Organic Reactions (15 h)**
   - 4.1. Reaction Thermodynamics & Kinetics
   - 4.2. Reaction Types and Intermediates
   - 4.3. Nucleophilic Substitutions (S_N1, S_N2)
   - 4.4. Elimination Reactions (E1, E2, $E1_{CB}$)
   - 4.5. Nucleophilic Reactions on Carbonyl Groups (S_{AE}, A_N)
   - 4.6. Electrophilic Additions on Double Bonds (A_E)
   - 4.7. Electrophilic Substitutions on Aromatic Systems (S_E)
   - 4.8. Radical Substitutions and Additions (S_R, A_R)
   - 4.9. Orbital-Controlled Reactions
5. **Polymer Chemistry (6 h)**
   - 5.1. Introduction to Polymer Science
   - 5.2. Step-Growth Polyreactions
   - 5.3. Chain-Growth Polymerizations
   - 5.4. Living and Controlled Polymerizations
   - 5.5. Molecular Weight Determination
6. **Organic and Polymer Materials (3 h)**
   - 6.1. Industrial Chemistry
   - 6.2. Polymer Materials & Sustainability
   - 6.3. Surfactants
   - 6.4. Organic Dyes and Semiconductors

Organic Compounds & Polymer Materials

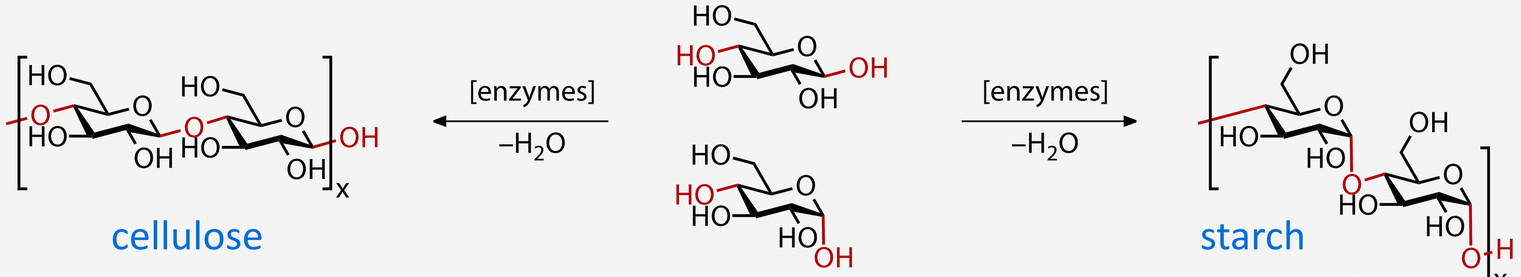
The Role of Organic Chemistry for Everyday Life

lipids

carbohydrates

proteins

Examples of Natural Polymers: Polysaccharides

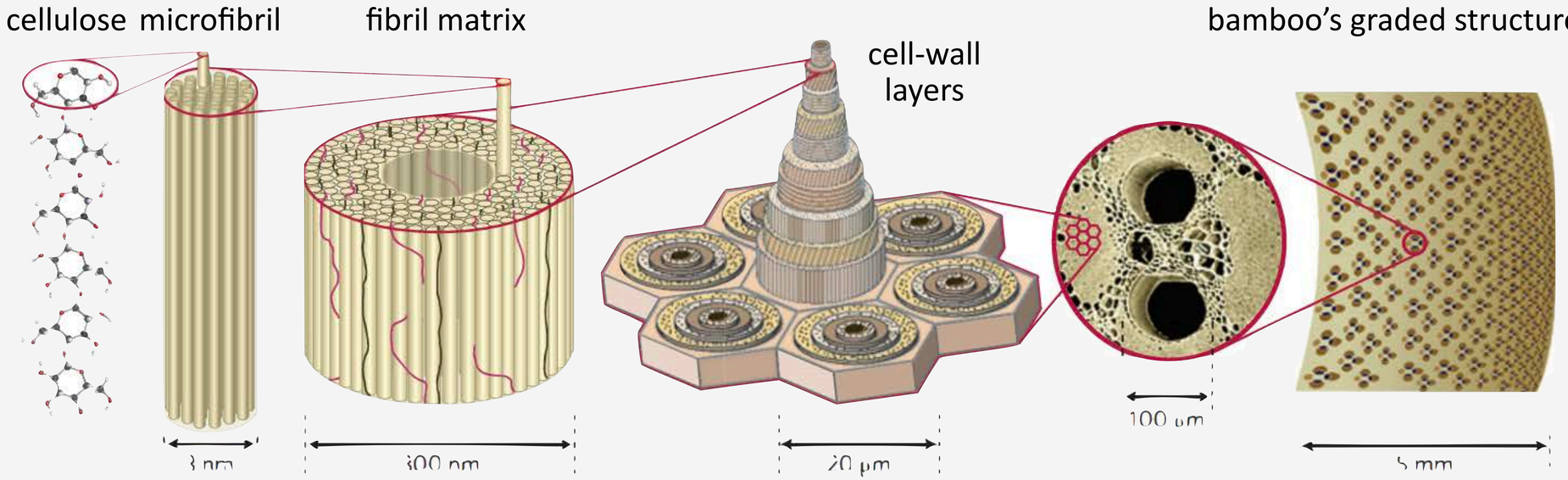


cellulose

10^{12} t/a

starch

$2.8 \cdot 10^{9}$ t/a



- **biomaterials: hierarchical structures on different length scales for optimized performance**

Examples of Natural Polymers: Peptides

- **Primary Structure**

  defined macromolecule from 20 amino acids

- **Secondary Structure**

  3D form of local segments (α-helices, β-sheets) as the result of defined patterns of hydrogen bonds

- **Tertiary Structure**

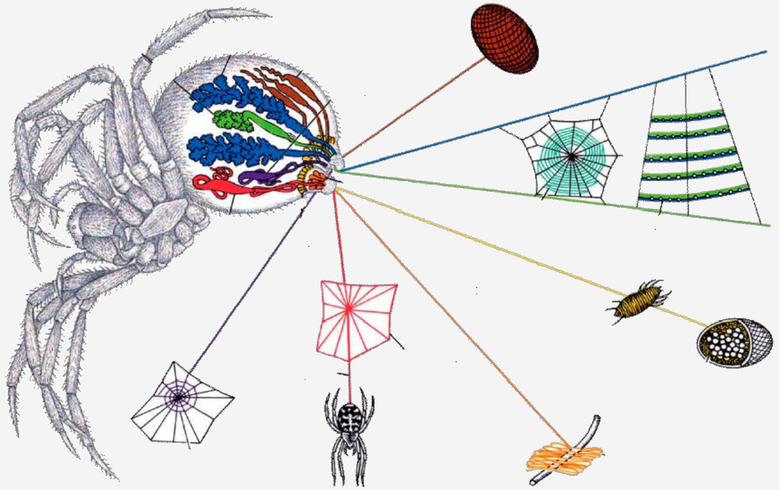
  geometric shape of the protein as result of supramolecular interactions between the amino acid side chains (hydrogen bonds, S–S bonds, electrostatic and van der Waals interactions)

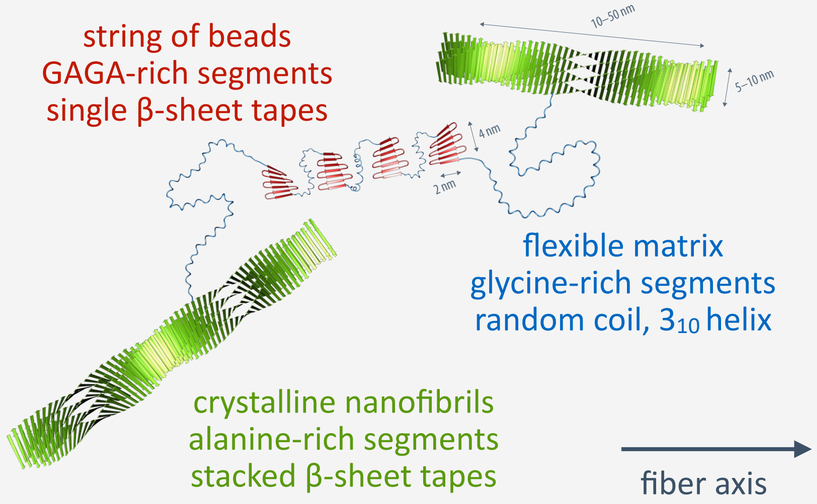
- **Quaternary Structure**

  aggregation of multiple proteins into multi-unit complex

- **proteins are defined macromolecules formed by concatenation of amino acid repeat units**

Nanostructure and Properties of Spider Dragline Silk





Material	Strength σ_{max} / GPa	Toughness 10^3 kJ m^{-1}	Stiffness GPa	Energy at Break kJ kg^{-1}	Extensibility ε_{max} / %
Spider Silk	1.1	160	10	100	27
Nylon	1	80		15	18
Kevlar	3.6	50	100	30	3
Steel	1.5	6	200	1	1
Rubber			0.001	10	1000

- **spider silk's high specific toughness due to hierarchical structures on different length scales**

Scheibel, *Polymer* **2008**, *49*, 4309.

The Role of Organic Chemistry for Technology

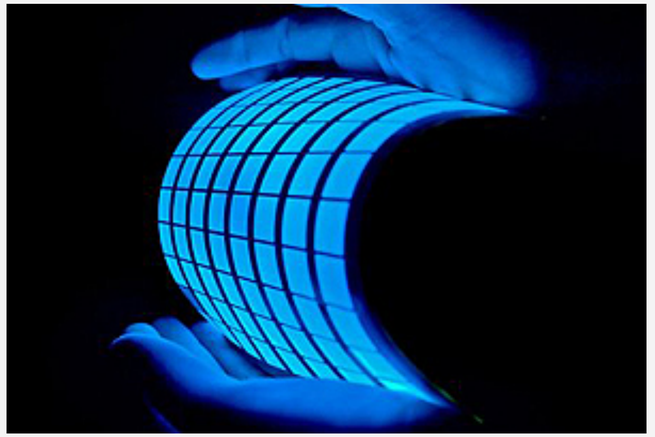
oil industry

refinery industry

base and fine chemicals

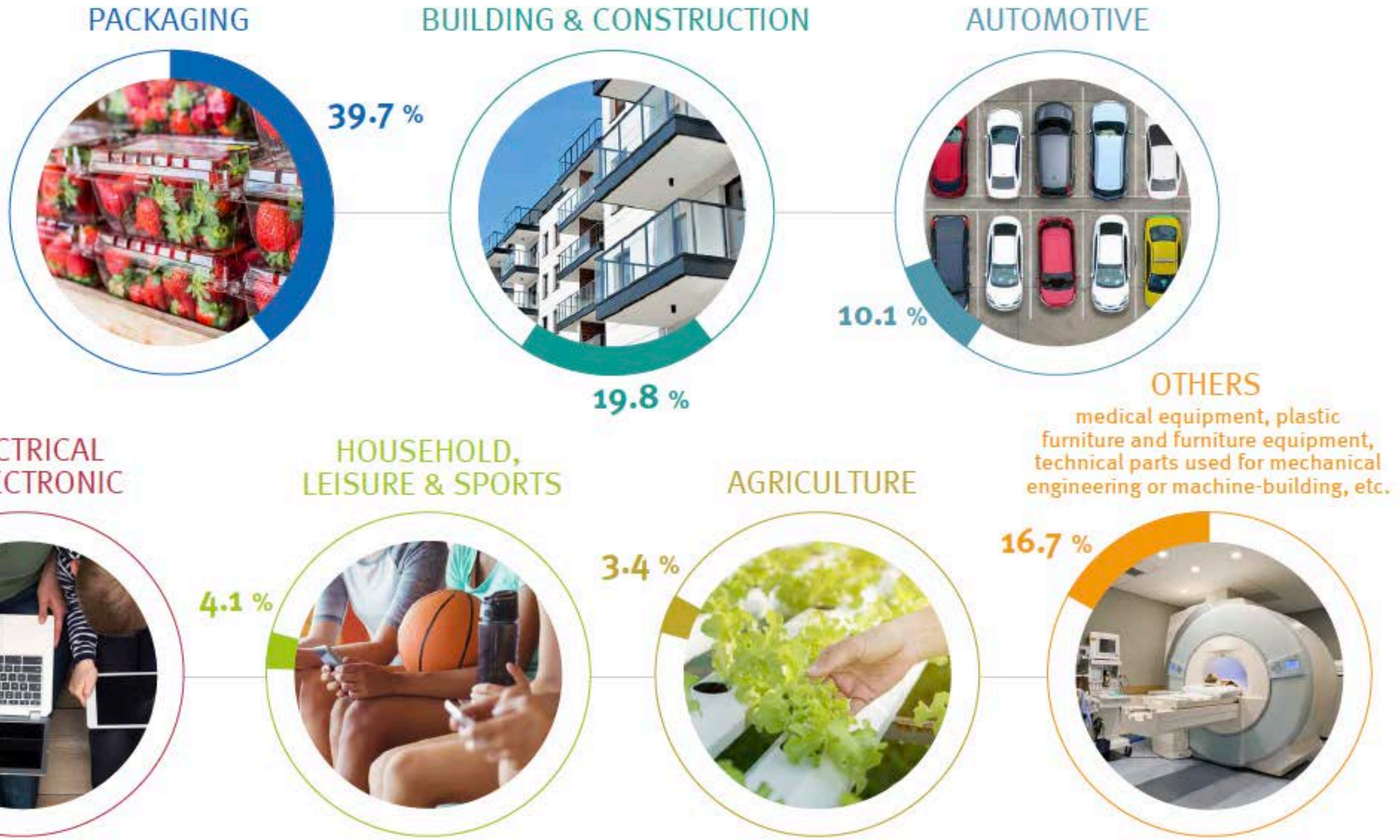
crop protection

pharmaceutics



new materials

Major Applications of Plastics



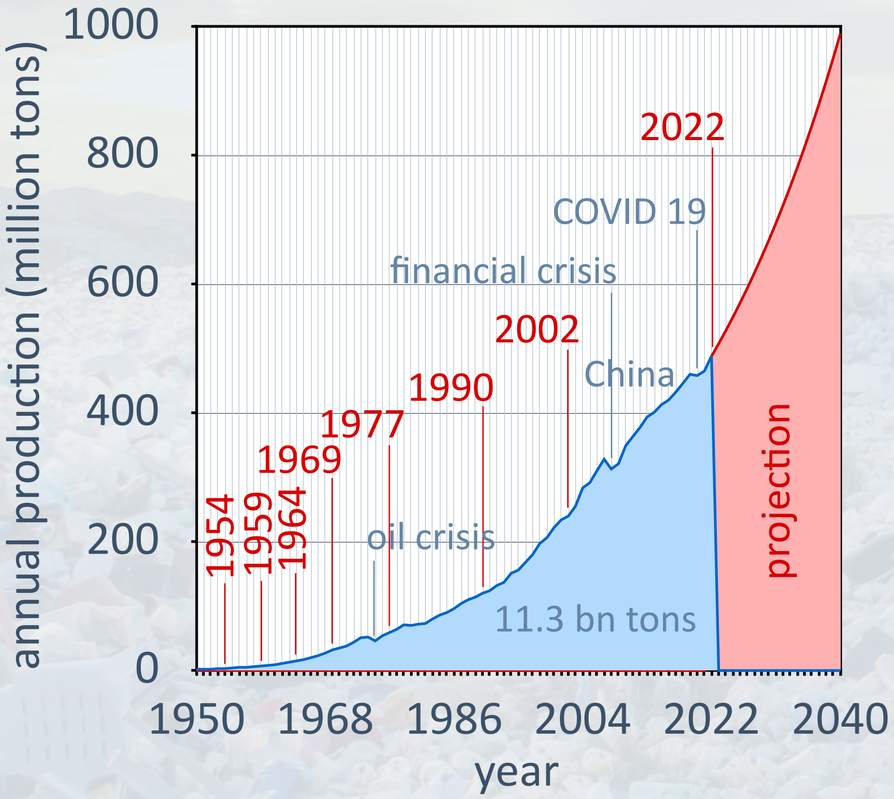
Sustainability Challenges of the Plastics Industry

- **This is not a regular landfill but the Thilafushi waste disposal site, a beach on the Maldives !**

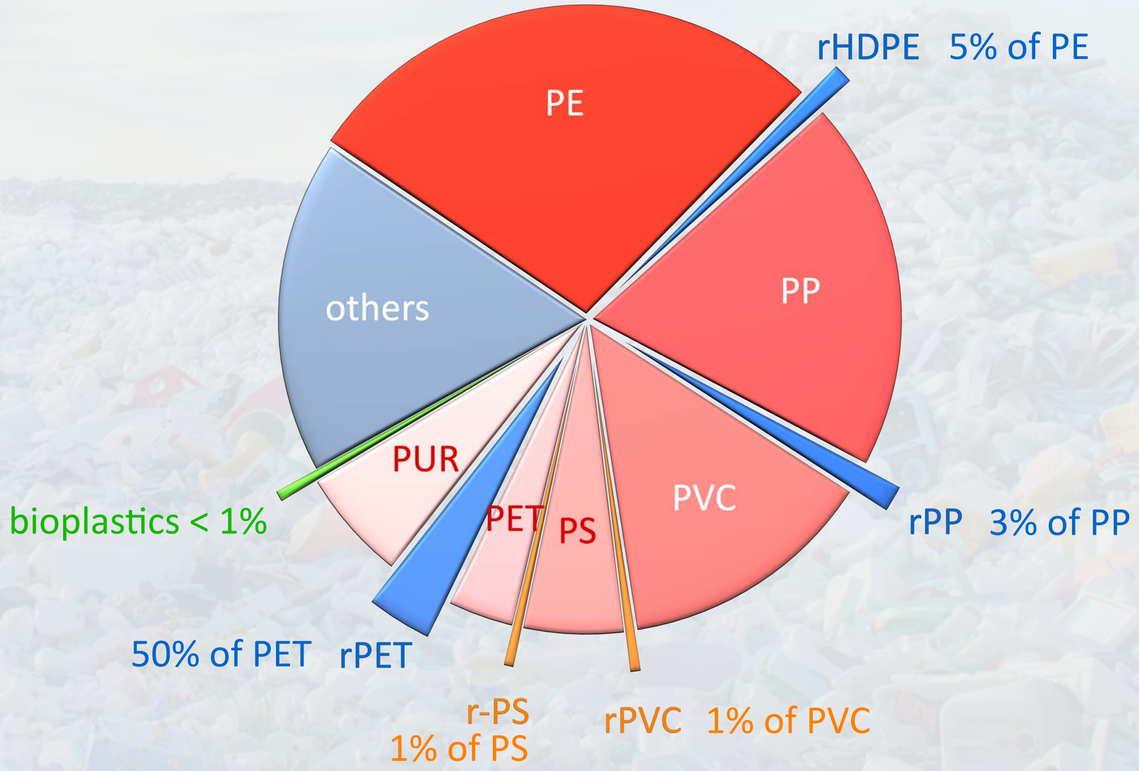
Image © Mohamed Abdulraheem

Global Plastics Production & Recycling

global plastics production 1950–2022



global plastics production 2022 488 Mt total

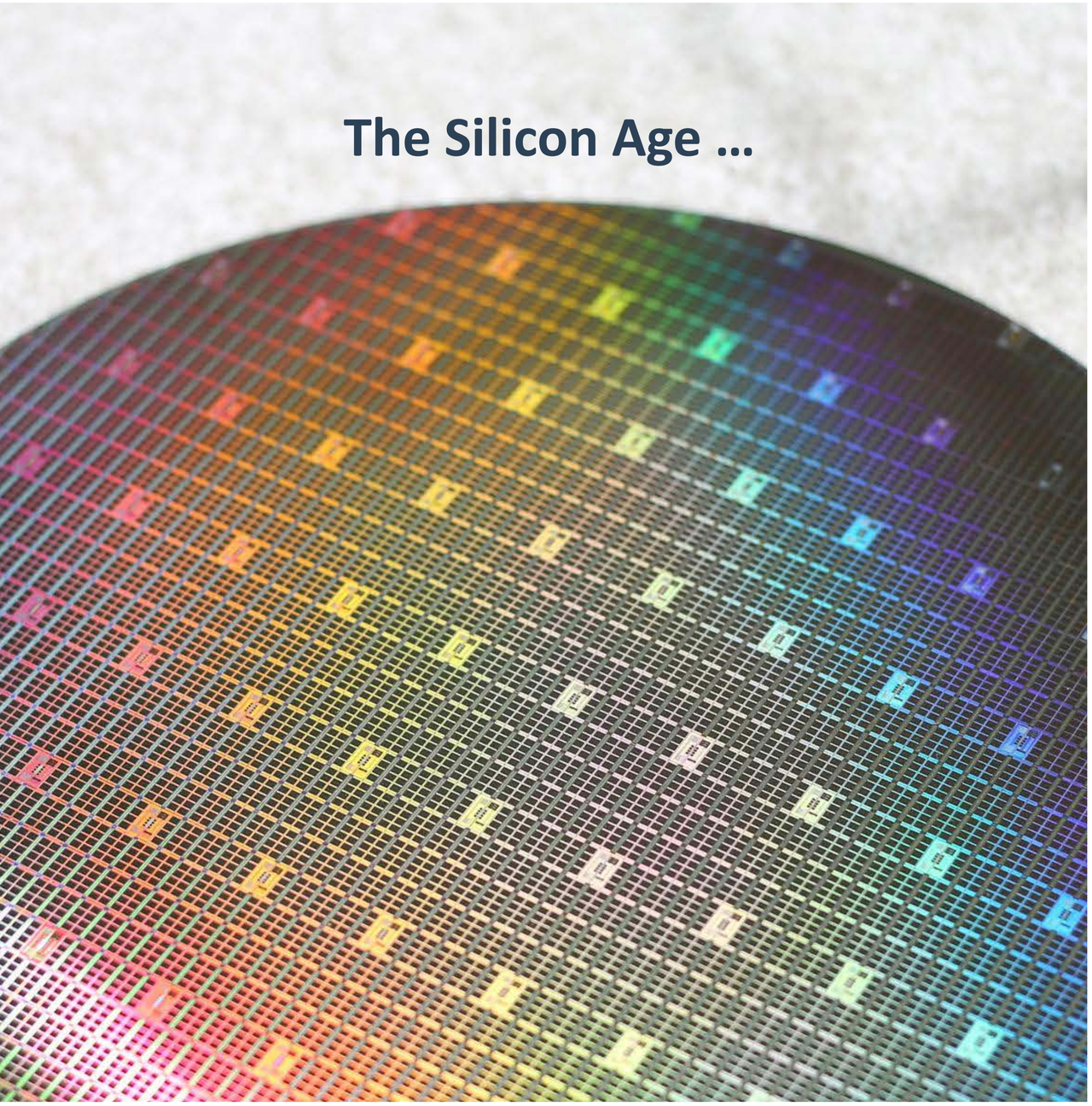


- just **9% of all plastics recycled**, only **three open-loop** and **two closed-loop** recycling streams
- **50% incinerated, 36% landfill**, of which half is mismanaged; overall **30% leaked into environment**

Global Plastics Outlook, OECD Report **2022**; Tan, *Commun. Earth Environ*. **2025**, *6*, 257.

So Which Epoch Do We Want to Be Known For ?

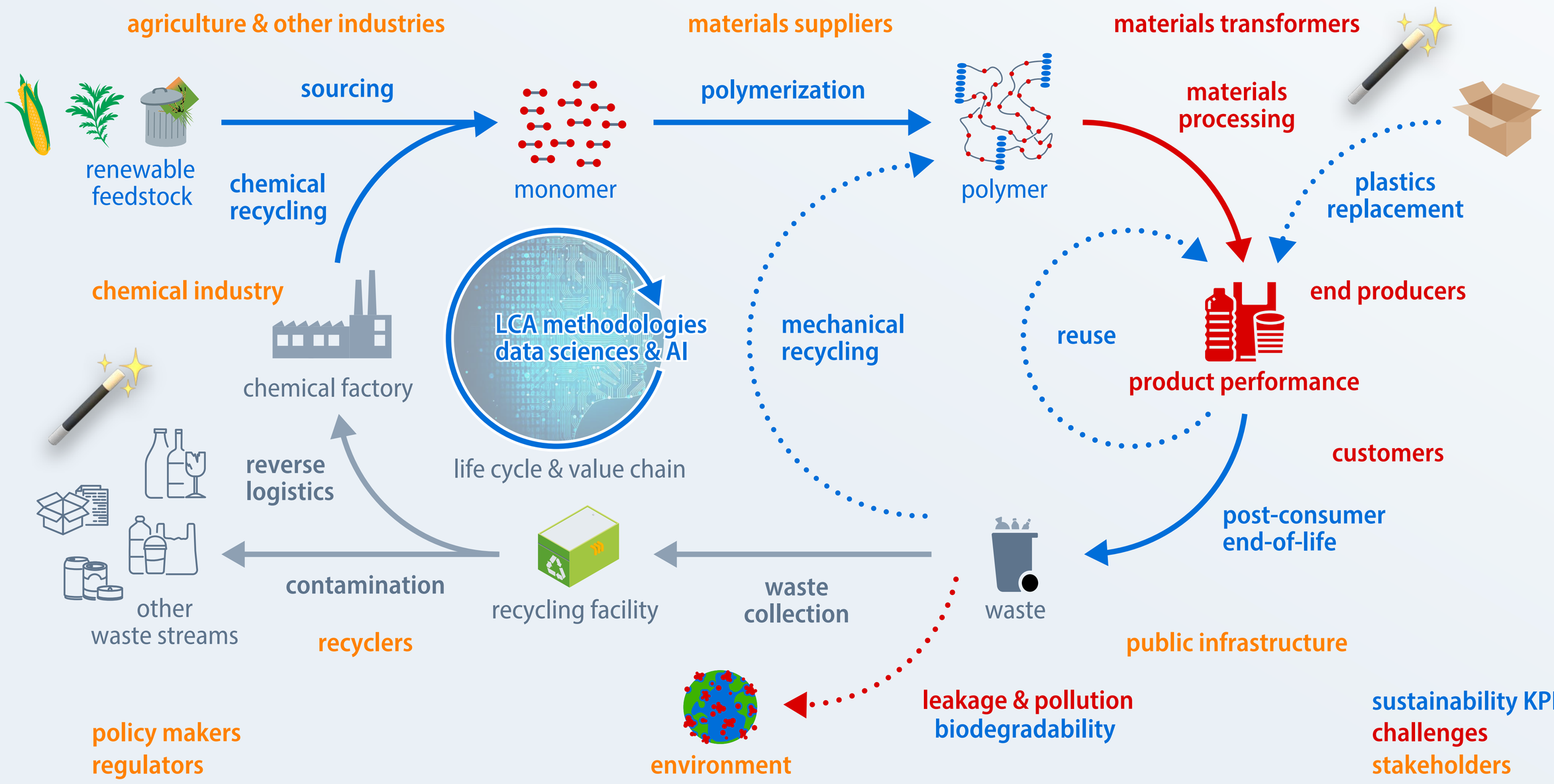
The Silicon Age …



… or the Plastic Age ?

© Mohamed Abdulraheem

Materials Challenges on the Way to a Circular Plastics Economy

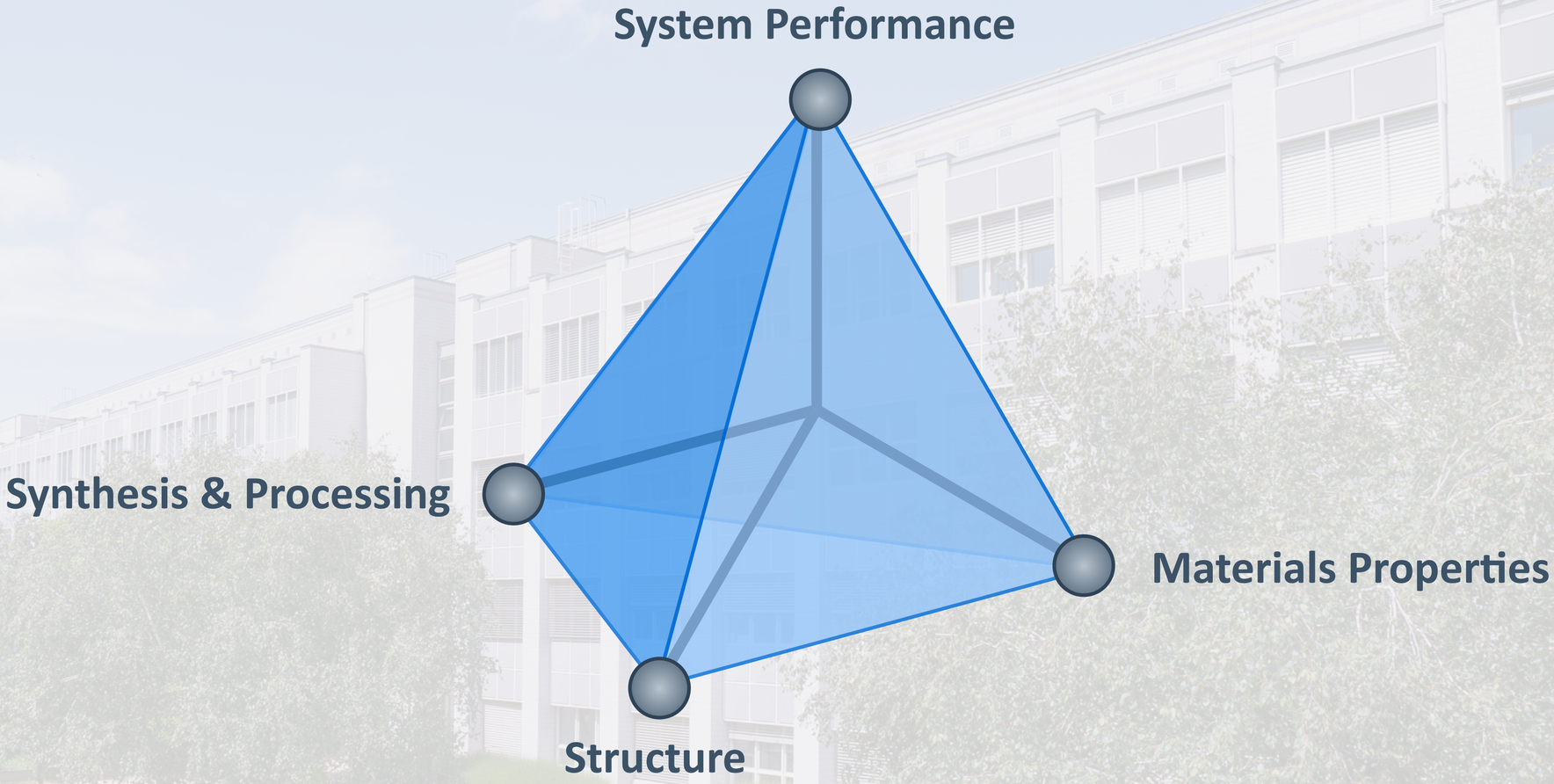


Awareness for the Plastic Waste Crisis Is Growing

Soft Matter at the Institute of Materials

“Everything is Made of Something”

- materials science is in many ways a foundational discipline for all other fields of science & engineering

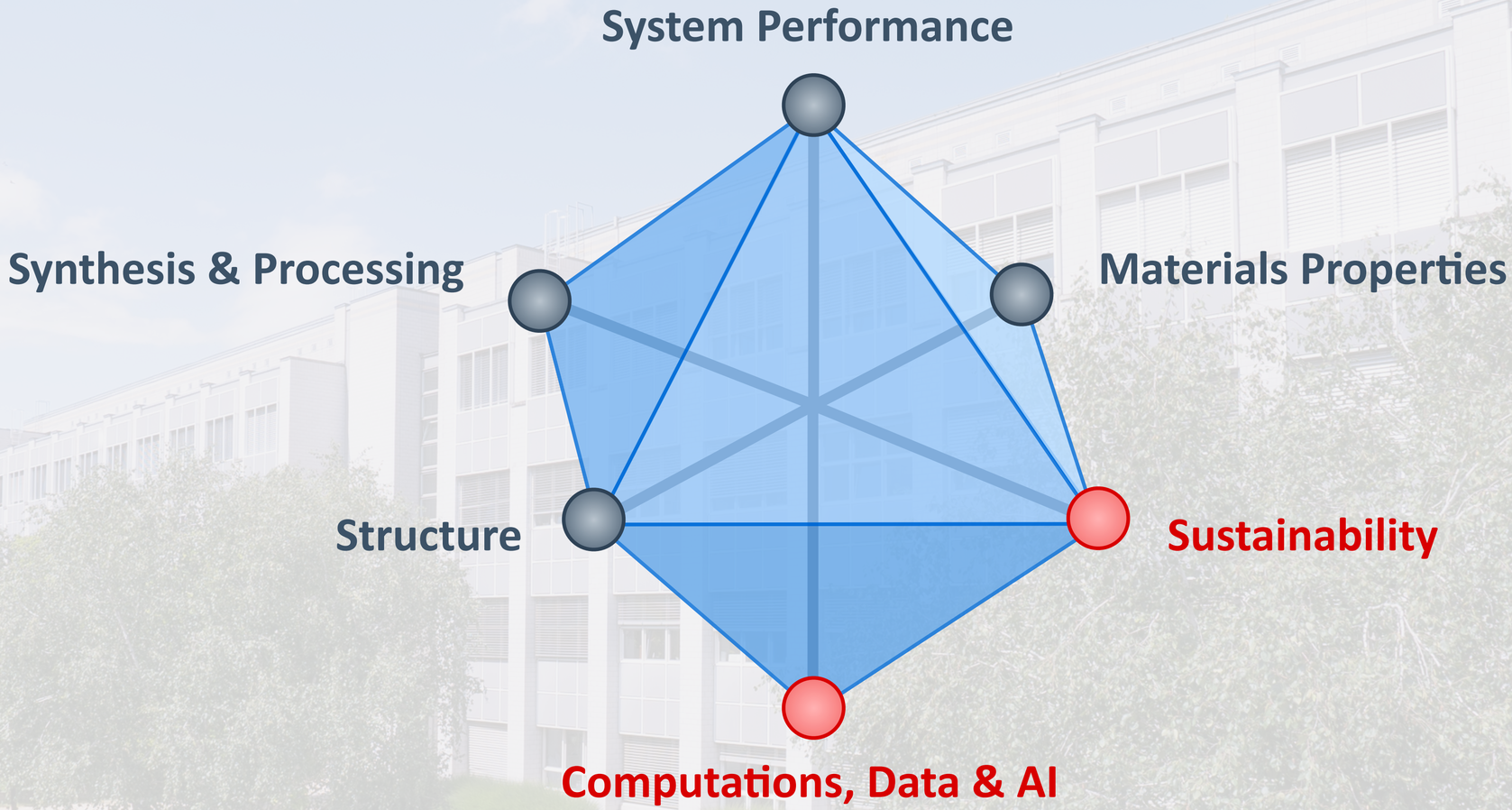


- **diversity and interdisciplinarity are inherent and paramount to the field of materials science, which is also populated by researchers from physics, chemistry, biology, and engineering**

Ashby, Shercliff, Cebon, *Materials: Engineering, Science, Processing and Design*, Elsevier, **2018**.

The Future of Materials Science

- materials science is evolving and needs to respond to societal and technological challenges

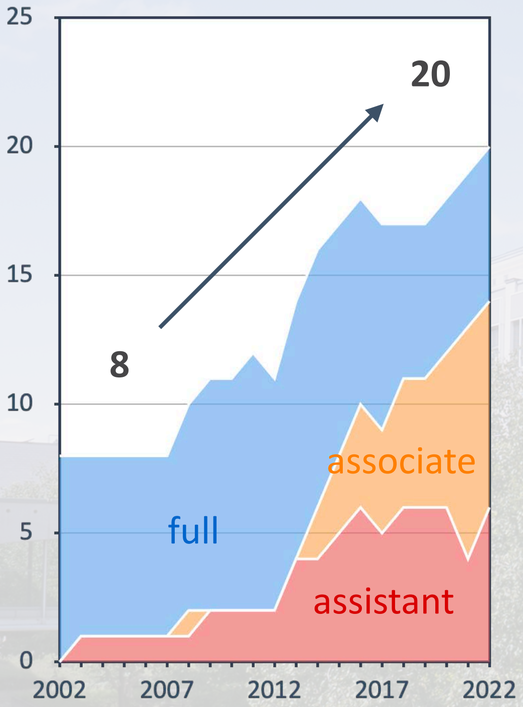


- **our vision of the future of materials science emphasizes the convergence of synthetic & biological worlds, and in particular the major role of sustainability and digital technologies**

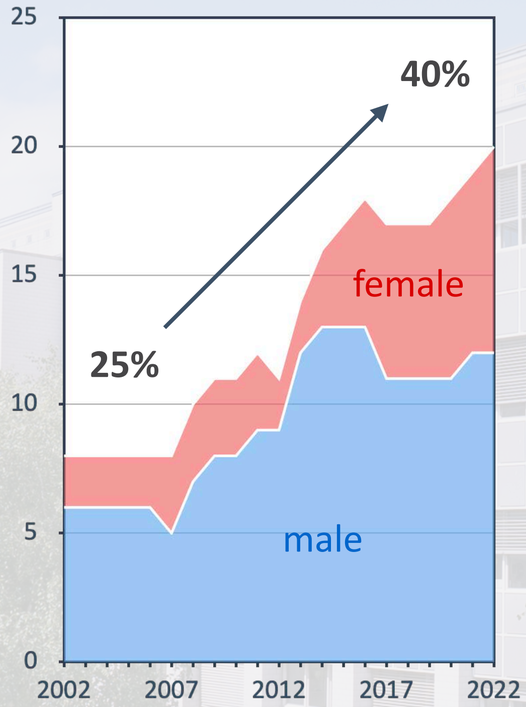
EPFL Institute of Materials

- materials science at EPFL is a diverse, well-balanced and thriving scientific community !

Faculty



Faculty Gender Balance



QS World University Rankings 2023 Materials Science

1	Massachussetts Institute of Technology	USA
2	Stanford University	USA
3	University of Cambridge	UK
4	Harvard University	UK
5	University of California, Berkeley (UCB)	USA
6	Nanyang Technological University, Singapore (NTU)	Singapore
7	University of Oxford	UK
8	**EPFL**	**CH**
9	Imperial College London	UK
10	Tsinghua University	China
11	ETH Zurich	CH
12	National University of Singapore (NUS)	Singapore
13	Georgia Institute of Technology	USA
14	California Institute of Technology	USA
15	Northwestern University	USA

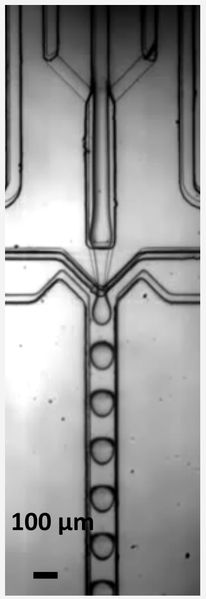
- **consistently ranking in the top 10 materials science departments since 2018 !**
- **world reputation in soft, construction, and quantum materials, as well as modeling & computations**

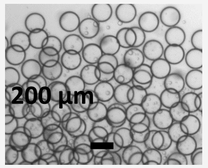
Soft Matter Activities at the Institute of Materials

Laboratory of Mechanical Metallurgy (LMM)	Andreas Mortensen
Laboratory of Construction Materials (LMC)	Karen Scrivener
Polymers Laboratory (LP)	Harm-Anton Klok
Tribology and Interfacial Chemistry Laboratory (TIC)	Stefano Mischler
Laboratory of Semiconductor Materials (LMSC)	Anna Fontcuberta
Laboratory of Organic and Macromolecular Materials (LMOM)	Holger Frauenrath
Supramolecular Nanomaterials & Interfaces Laboratory (SUNMIL)	Francesco Stellacci
Laboratory of Theory and Simulation of Materials (THEOS)	Nicola Marzari
Laboratory of Photonic Materials and Fibre Devices (FIMAP)	Fabien Sorin
Laboratory of Computational Science and Modelling (COSMO)	Michele Ceriotti
Laboratory of Thermomechanical Metallurgy (LMTM)	Roland Logé
Soft Materials Laboratory (SMAL)	Esther Amstad
Laboratory of Nanoscale Magnetic Materials & Magnonics (LMGN)	Dirk Grundler
In Situ Nanomaterials Characterization with Electron (INE)	Vasiliki Tileli
Laboratory for Processing of Advanced Composites (LPAC)	Véronique Michaud
Programmable Biomaterials Laboratory (PBL)	Maartje Bastings
Laboratory for Sustainable Materials (SUMA)	Tiffany Abitbol (PATT)
Laboratory for X-ray Characterization of Materials (CAM-X)	Marianne Liebi (PATT)
Dynamic Quantum Materials Laboratory (DQML)	Gregor Jotsu (PATT)
Mathematics for Materials (MATMAT)	Michael Herbst (PATT)

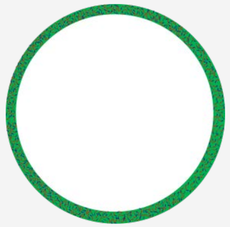
Soft Materials Laboratory (SMAL, Esther Amstad)

Capsules from Self-assembled Block Copolymers

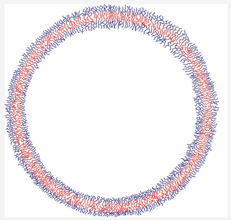




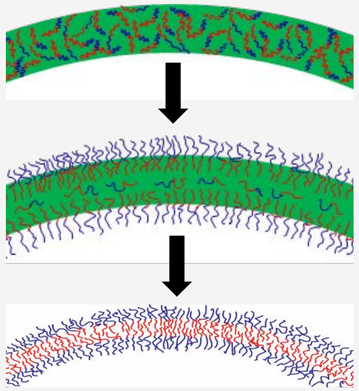
water/oil/water double emulsion



vesicle



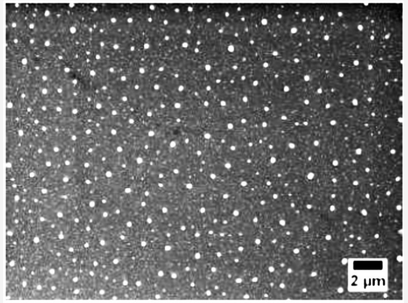
self-assembly upon drying



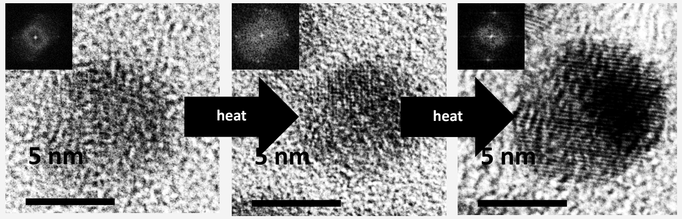
Early Stages of Crystallization

microfluidic spray drier

spray dried nanoparticles



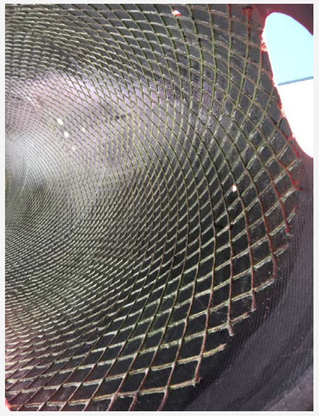
crystallization



- SMAL focuses on using polymers for compartmentalization and microstructure control

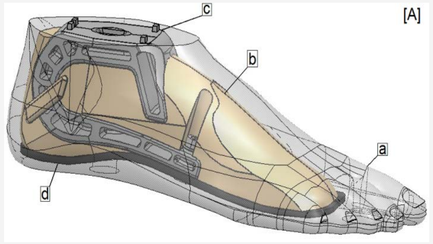
Laboratory of Advanced Composites (LPAC, Veronique Michaud)

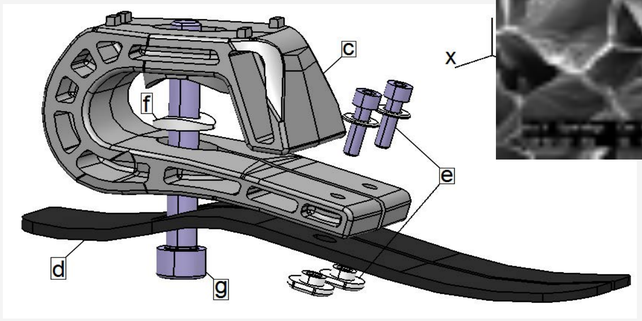
- LPAC focuses on the fundamentals of composite and hybrid materials processing



Flax Power Ribs (Bcomp)

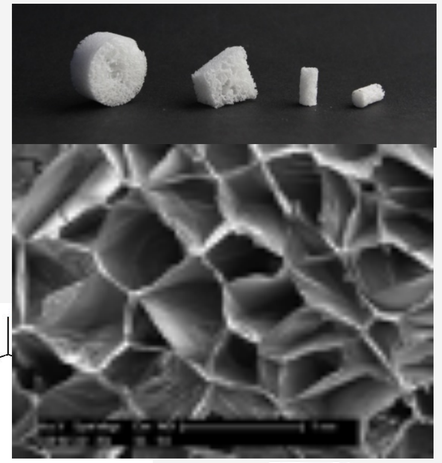
Textiles

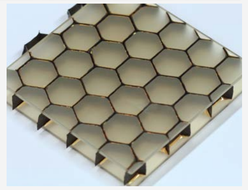




Agilis project: composites, injection molded polymers, foams

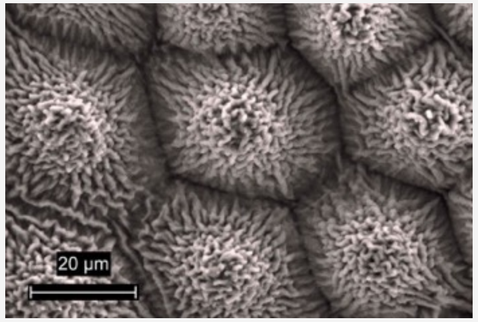
Biodegradable foams for medical applications

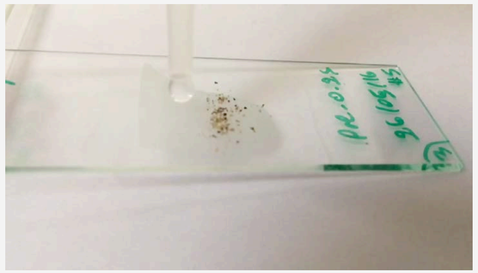




Sandwiches

Bioinspired self-cleaning and wear-resistant surfaces



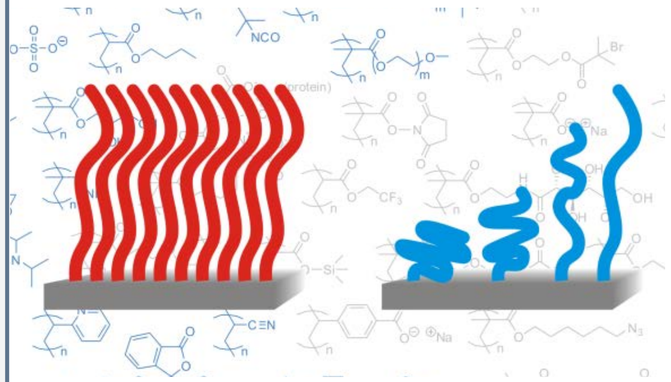


Synthetic yellow rose petal surface with pepper grains

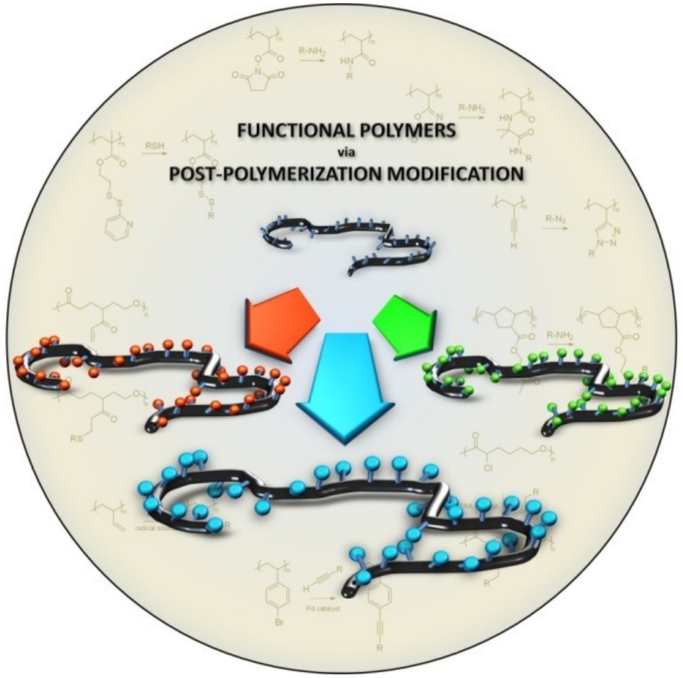
- **fundamentals of polymers and composite materials processing**
- **surface and interfaces (bioinspired surfaces, adhesion and bonding)**

Polymer Laboratory (LP, Harm-Anton Klok)

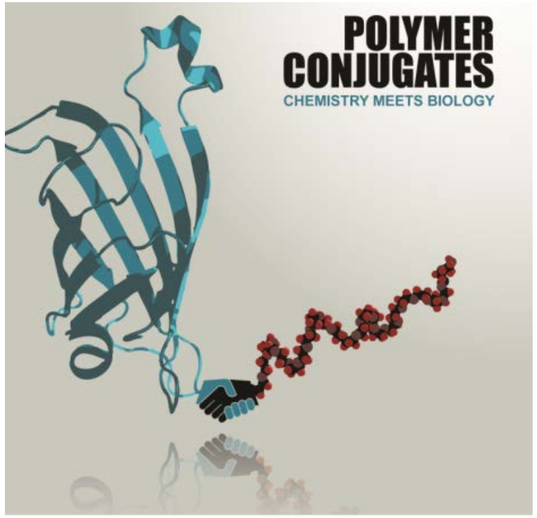
Polymer Surfaces & Interfaces



Precision Polymer Synthesis



Polymer Bioconjugates

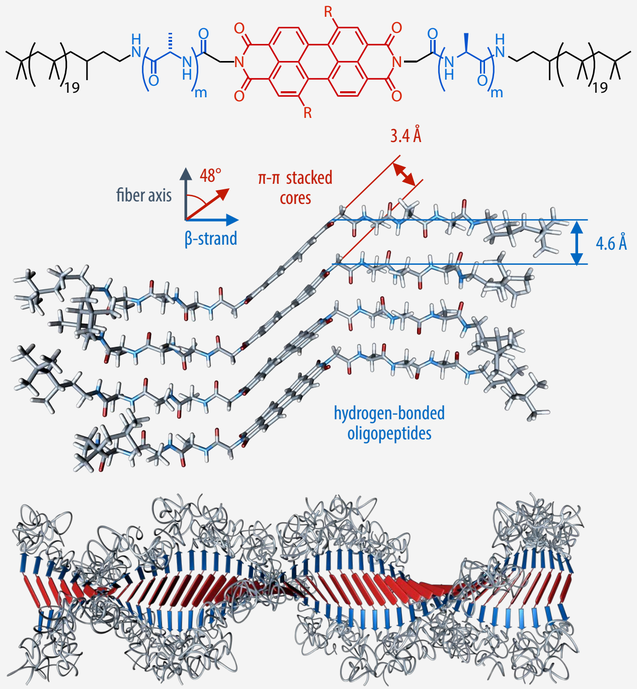


- peptide/protein-based polymer materials and hybrid materials for polymer therapeutics
- surface-initiated polymerization and polymer brushes for microarrays, chemical sensing

Laboratory of Macromolecular and Organic Materials

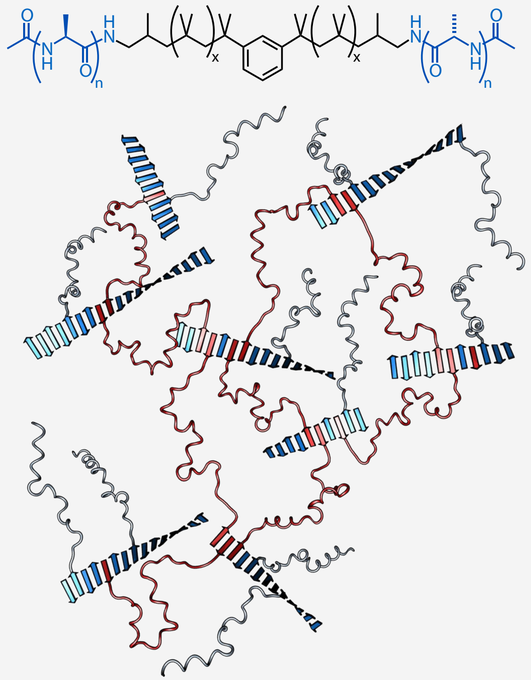
- **universal supramolecular approach** to control diverse functions in different materials classes

electronic properties



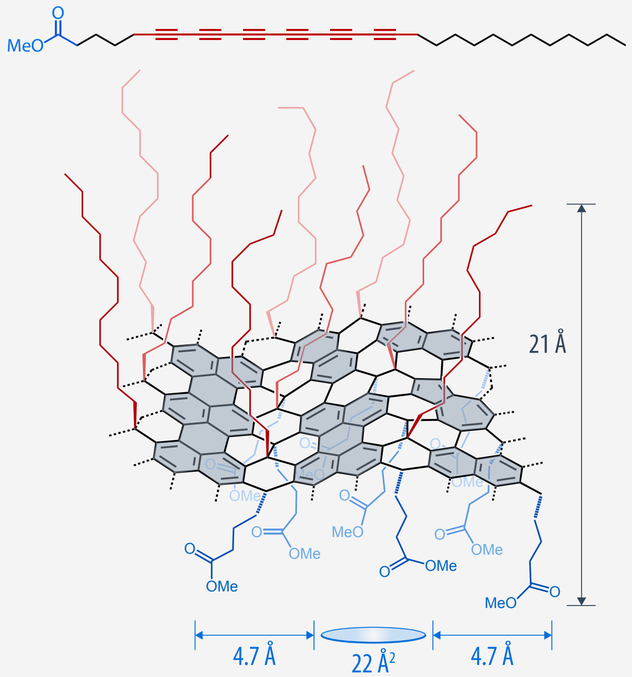
organic semiconductor nanostructures

mechanical properties



hierarchically structured supramolecular materials

chemical reactivity



carbon nanomaterials at room temperature

- **control of the balance of order and disorder across length scales to tailor structure and function**

From Molecular Design to Materials and Devices

molecular design & synthesis

synthetic chemistry,
NMR, MS, MALDI

physicochemical characterization

UV/vis/NIR, CD, fluorescence,
IR, Raman, ESR, DLS, CV

materials processing

extrusion, drawing, blowing,
injection molding, microfluidics

materials characterization

AFM, TEM, SEM, SAXS, WAXD
rheology, DMA, mechanical testing

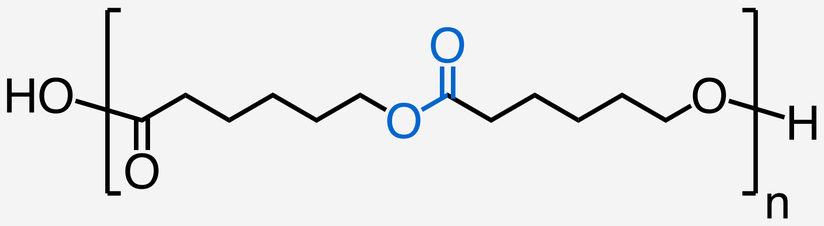
device fabrication

damping structures, railpads,
food containers, OFETs

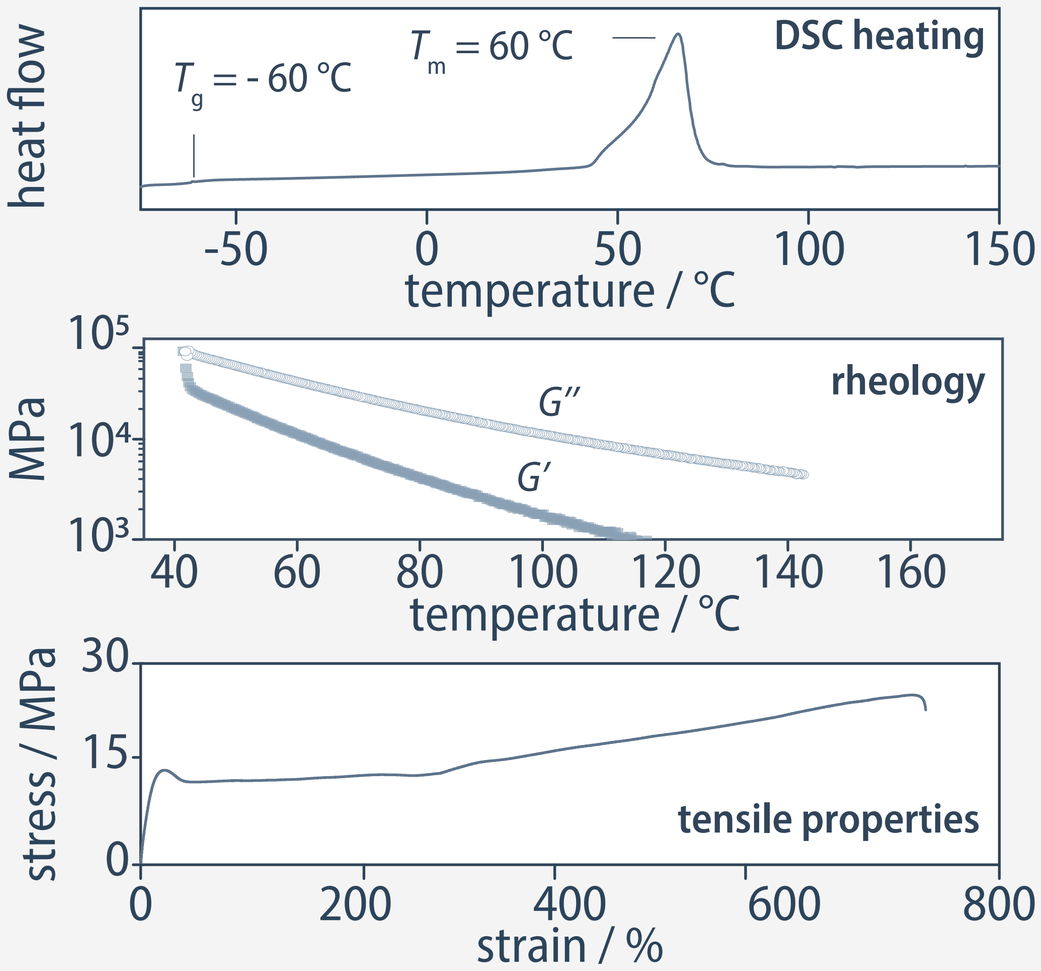
device testing & applications

damping, acoustics, barriers,
packaging, recycling, degradation

Poly(ε-caprolactone) (PCL) - A Biodegradable Aliphatic Polyester

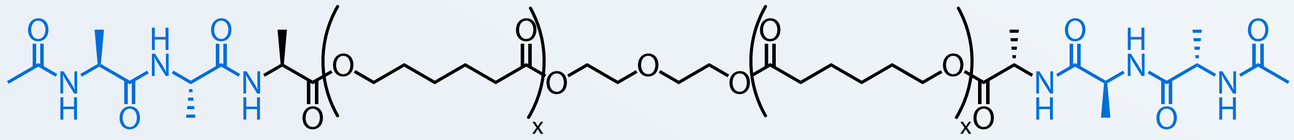


- polyethylene-like properties
- petroleum-based or bio-based
- hydrolytically cleavable ester groups
- FDA-approved
- implantable biomaterial
- biodegradable

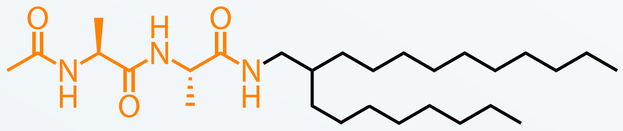


- **PCL has limited engineering applications due to poor thermal, rheological & mechanical properties**

Supramolecular Modification of High Molar Mass Sustainable Polyesters

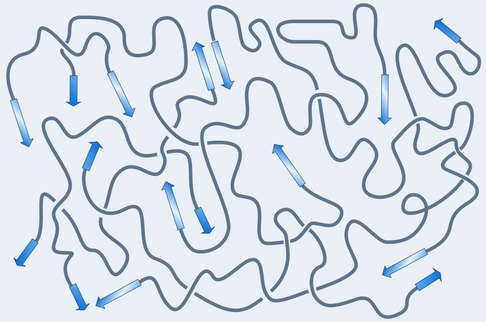


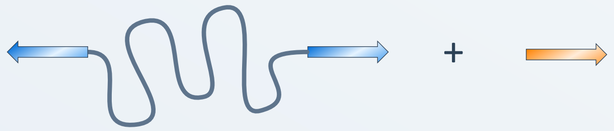
mPCL



A

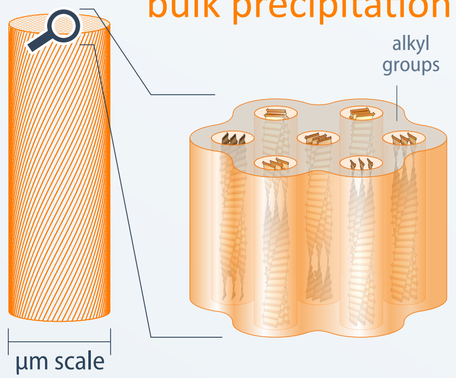
poor aggregation



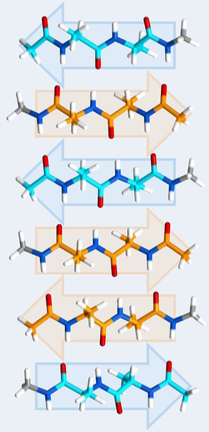


co-assembly of **mPCL** & **A**
nanophase separation
hierarchical structure formation

bulk precipitation

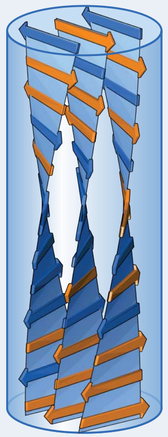


hydrogen bonding



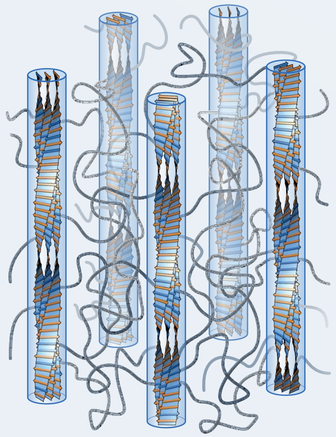
β sheet tapes

β sheet stacking



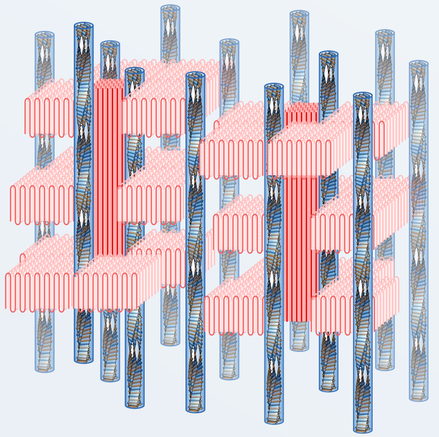
nanofibrils

polymer bridging



nanofibril network

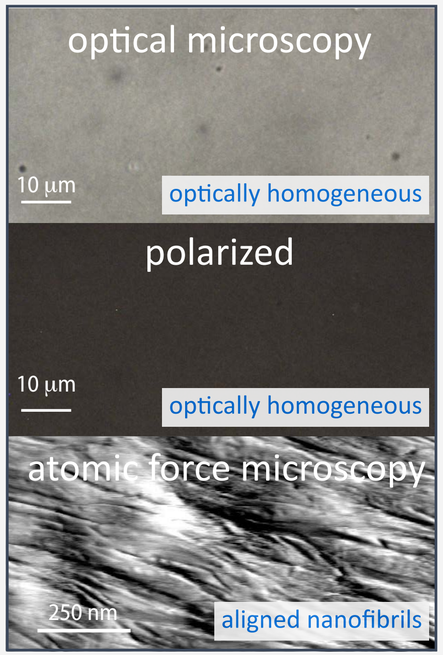
melt deformation

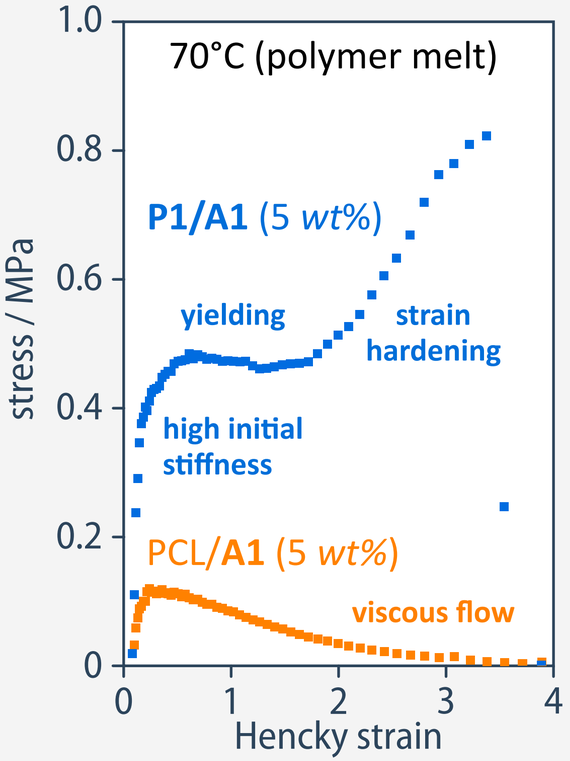


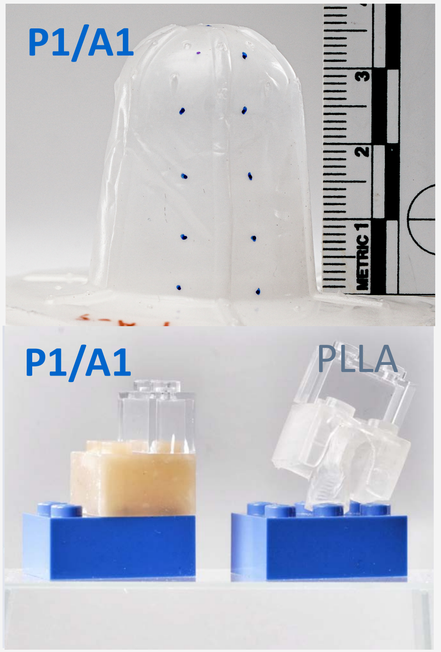
shish kebab microstructure

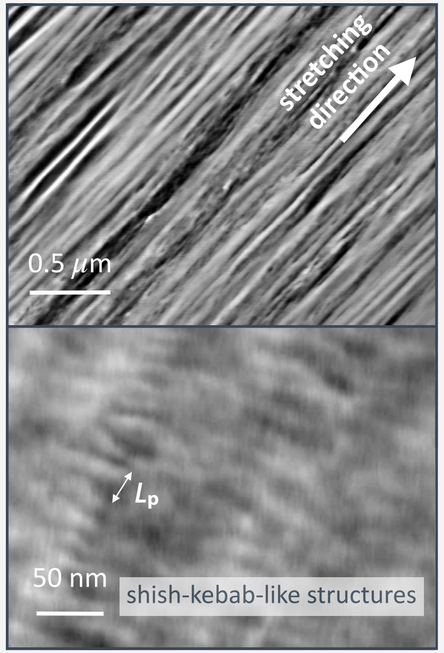
Supramolecular Modification for Tailored Melt Properties and Product Performance

new nanofibril phase regime → **tailored melt strength & elasticity** → **new / improved processing options** → **materials orientation**









cross-linking reinforcement → **melt deformation strain hardening** → **processing at high deformation** → **high draw ratios fibrillar crystals**

Learning Outcomes

- organic chemistry is the basis for polymer science and soft matter research
- soft matter research has significantly increased in relevance in our department
- relevance will further increase with focus on sustainable materials