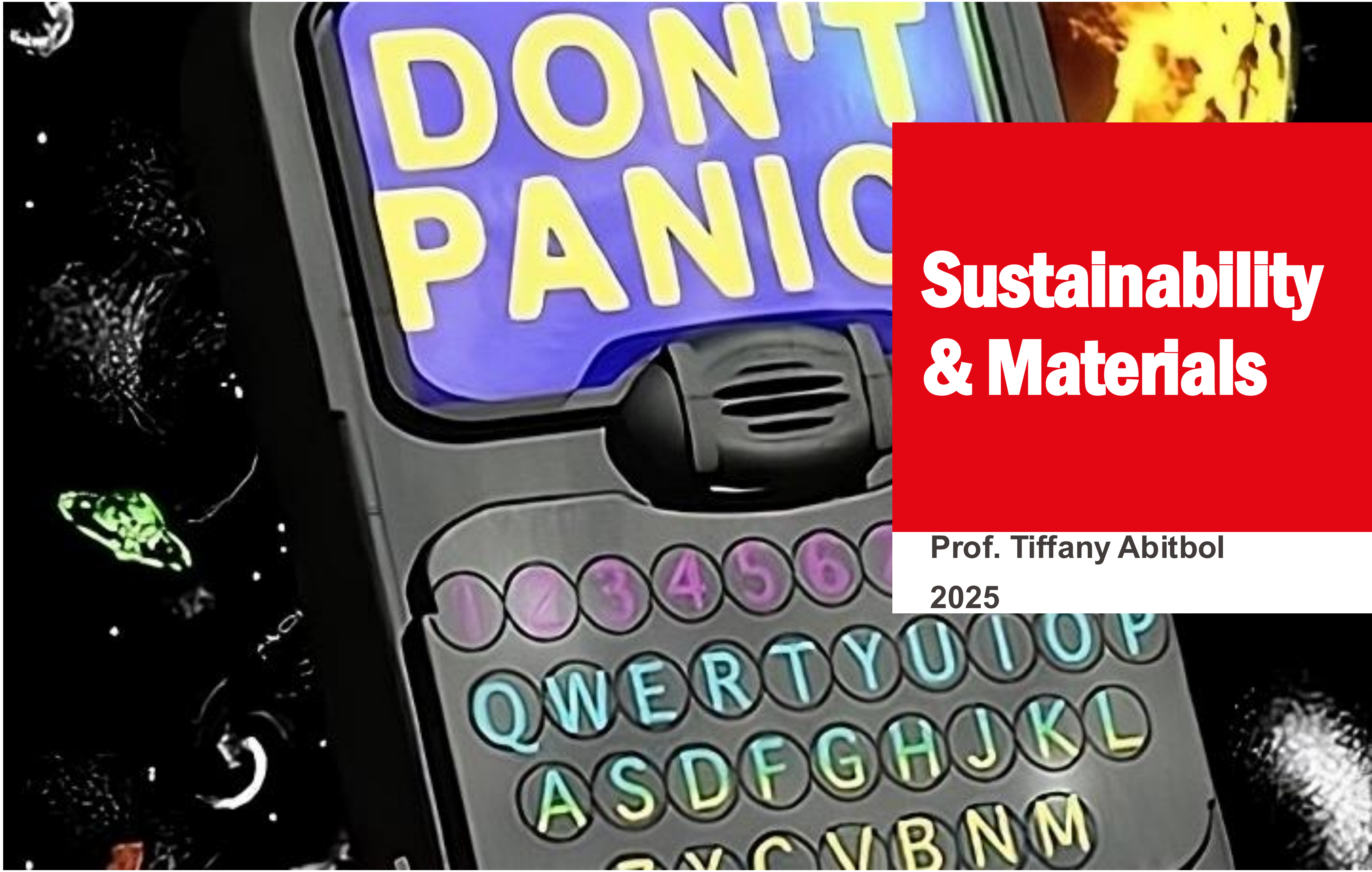
EPFL

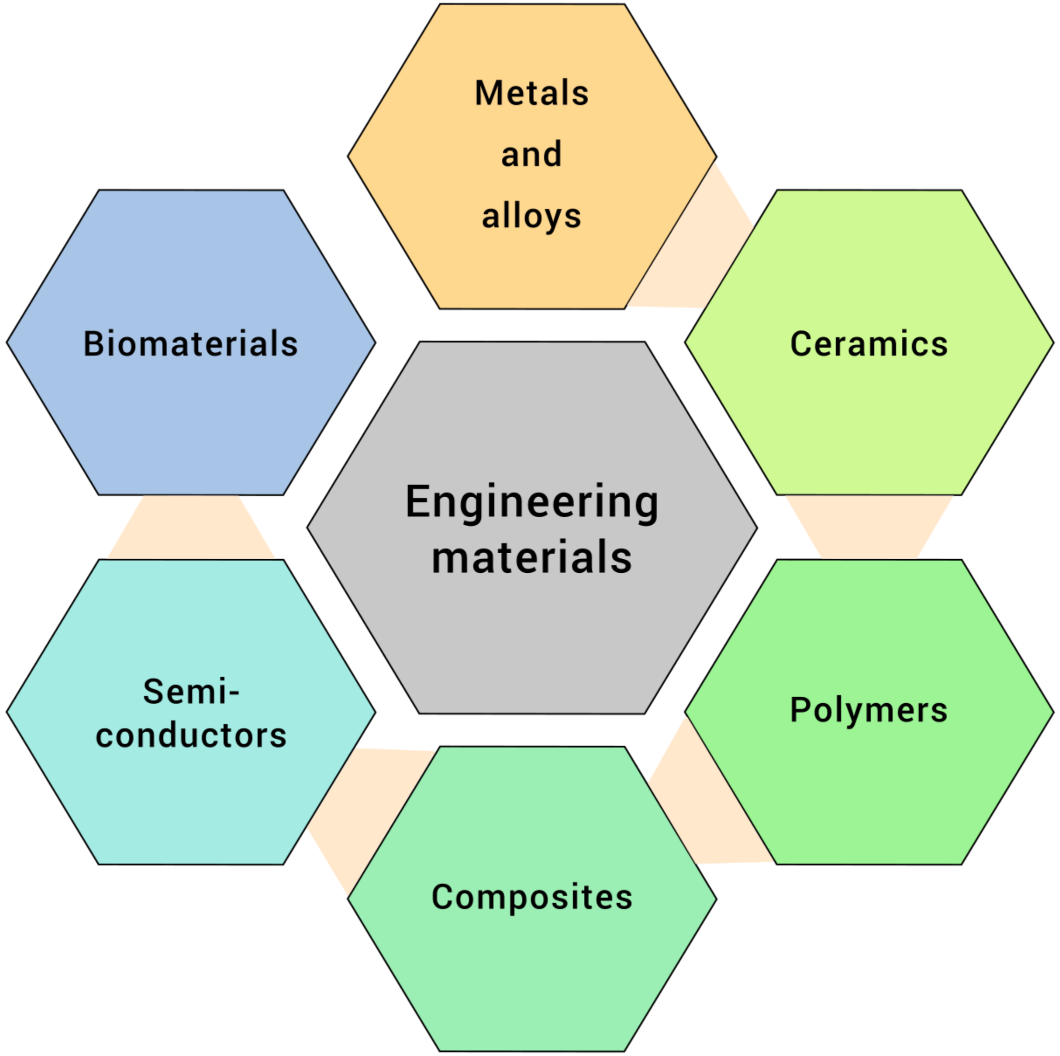


Sustainability & Materials

Prof. Tiffany Abitbol

2025

Engineering materials categories (variable)

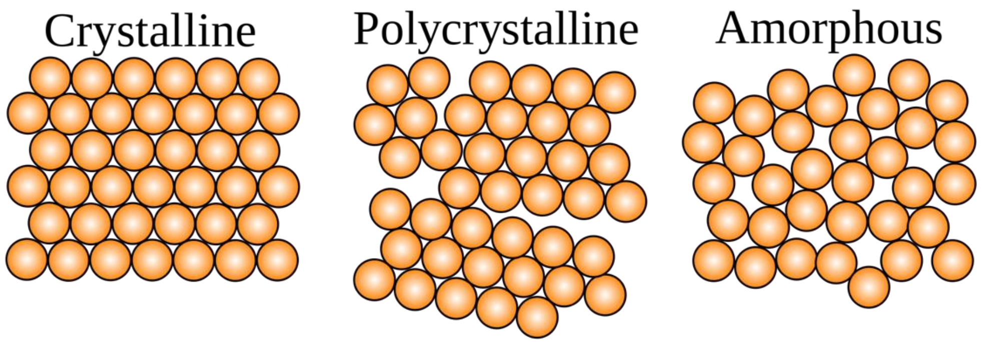


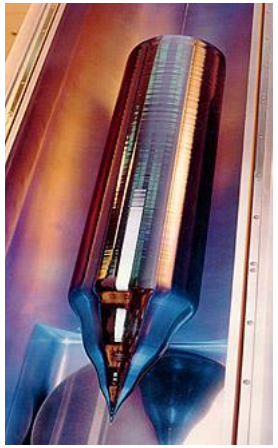
Focus: Ceramics

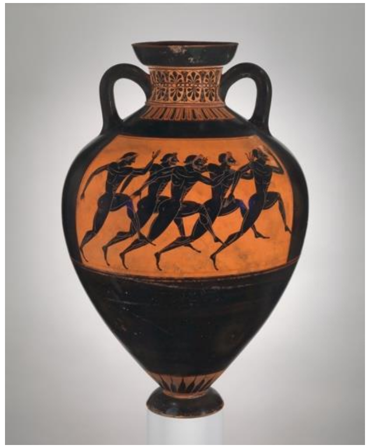
[Materials science classifications]

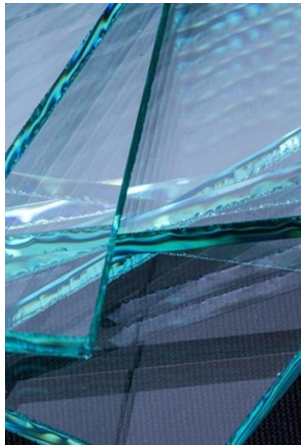
Ceramics

- Non-metallic
- Inorganic
- Ionic and/or covalent bonds
- Mostly made by heat processing: heating and cooling
- Crystalline or semicrystalline except glass, which is amorphous
- Examples: alumina, silica, titania, boron nitride, etc.,

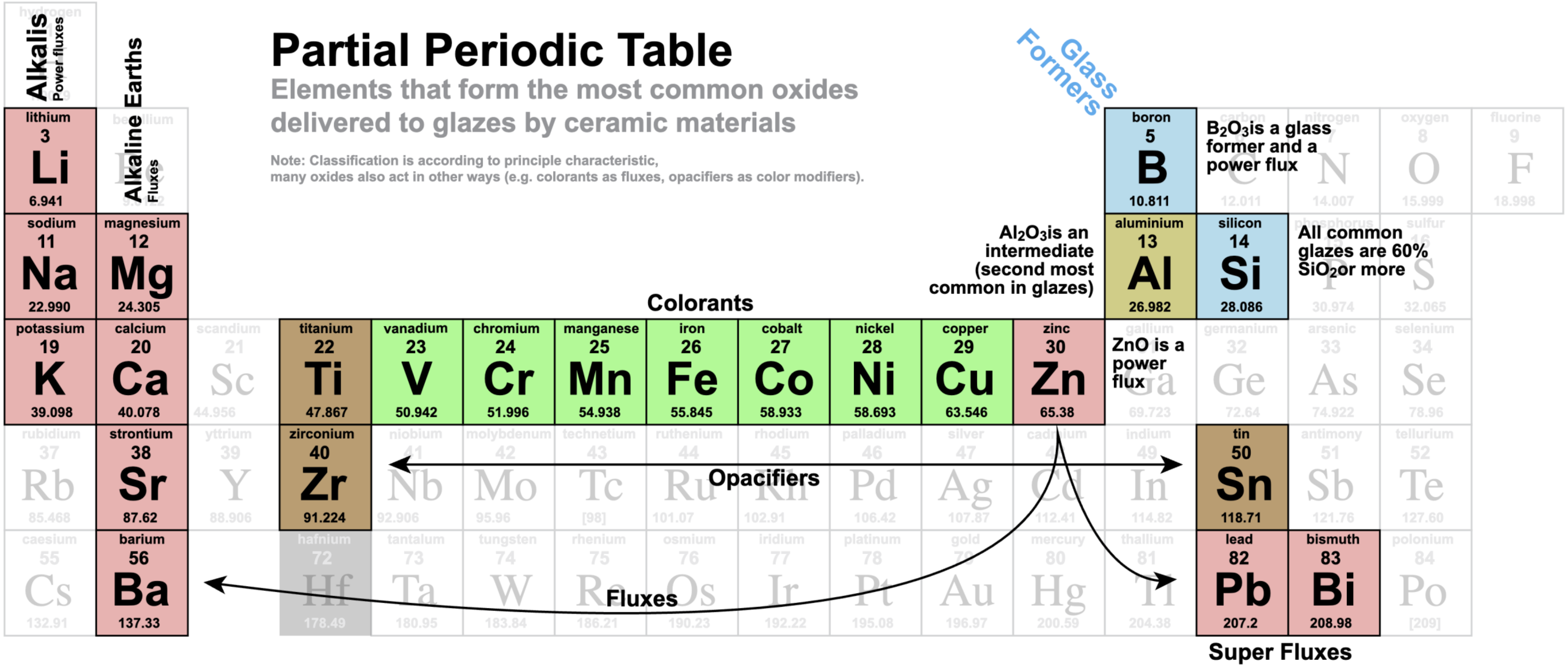








Traditional ceramics



Ceramics

- Considered one of the greatest and earliest successes of humankind – control of fire
- Among the 1st objects manufactured
- From Greek “keramos” meaning burned earth
- Characteristics – long service life, low density, chemically inert, corrosion resistant, electromagnetic response, non-toxic, heat and fire resistant, sometimes electrical resistance or porosity

[Decarbonizing ceramics_2022]

Ceramics

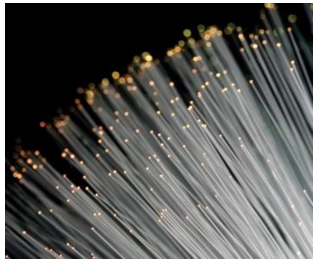
- 1st pieces reported ca. 24,000 years ago
- Many uses today: promising for aerospace and high temperature structural applications, information storage and optical devices, oral prosthetics, water purification, bone void fillers, CO_2 adsorbents, etc.,
- Value of global ceramics market was approx. 230 billion in 2018, and growing due to constant growth in the construction industry, technological advancements in nanotechnology, 3D printing, and ceramics in health

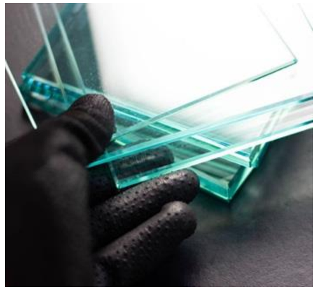
Decarbonizing ceramics_2022

Main uses – Ceramics

Ceramics

Glasses





- Optical fibers
- Glasses
- Household

Clay products

- Pottery
- Whitewares
- Bricks and tiles

Refractories

- Refractory bricks for high T (furnaces)

Abrasives

- Sandpaper
- Polishers
- Cutlery

Cements

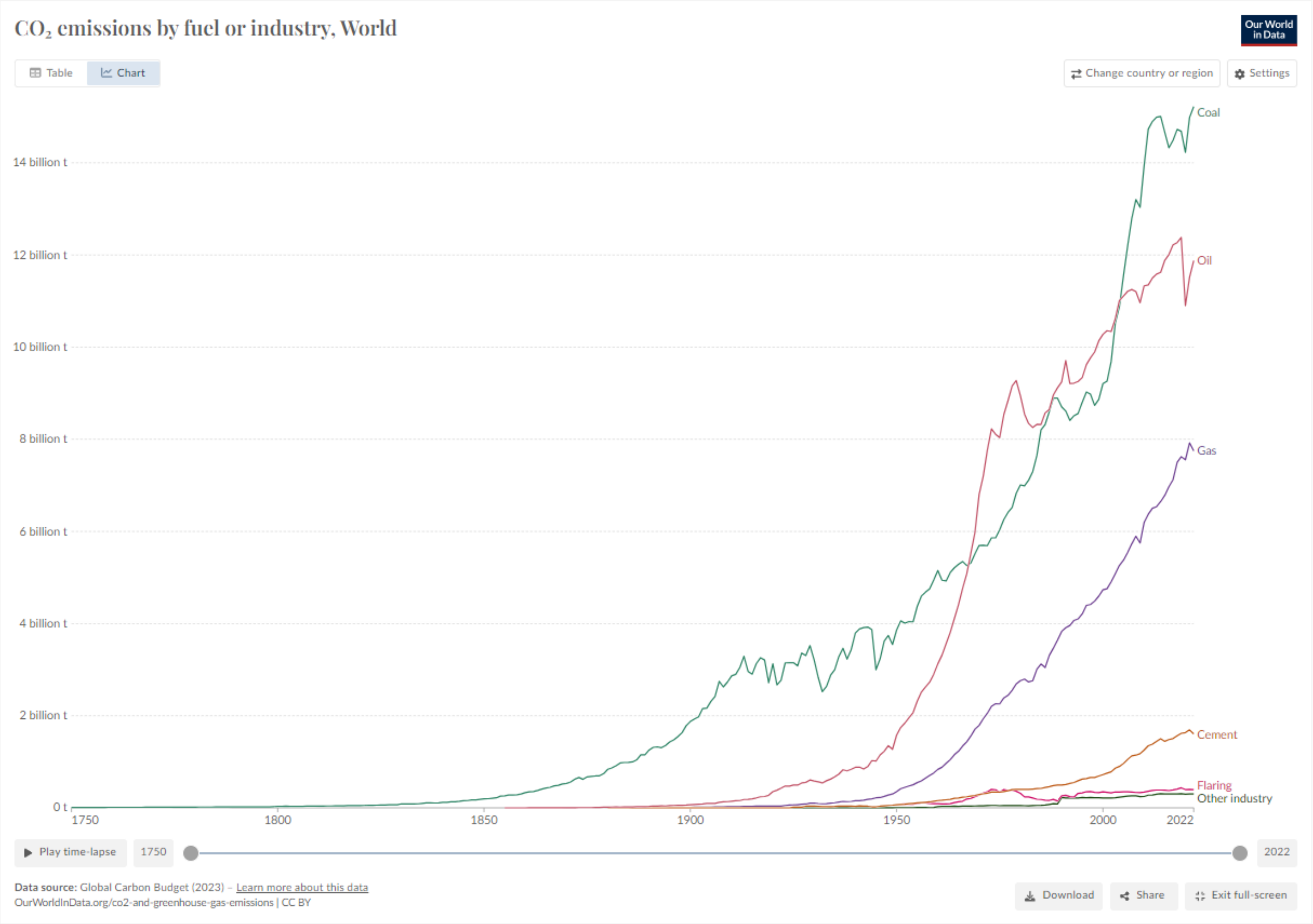
- Constructions
- Composites

Advanced ceramics

- Electronics
- Turbines
- Batteries

Environmental cost of ceramics

- In EU: production of refractories, wall and floor tiles, and bricks and roof tiles emit around 19 Mt CO_2
- Globally: brick manufacture is responsible for 2.7% of annual carbon emission; cement (considered a ceramic in this course's context) is responsible for 5-8% of annual emissions



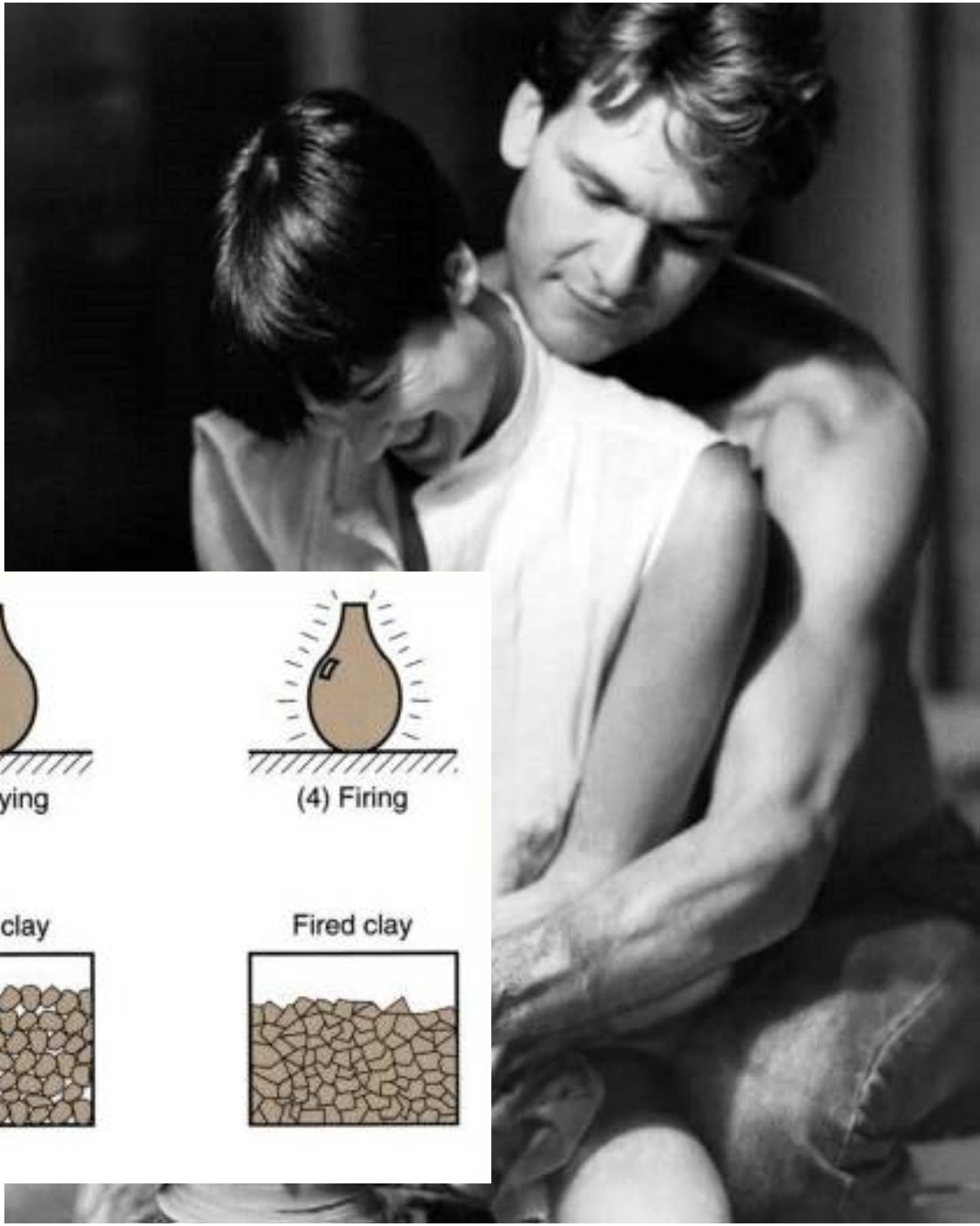
[Decarbonizing ceramics_2022]

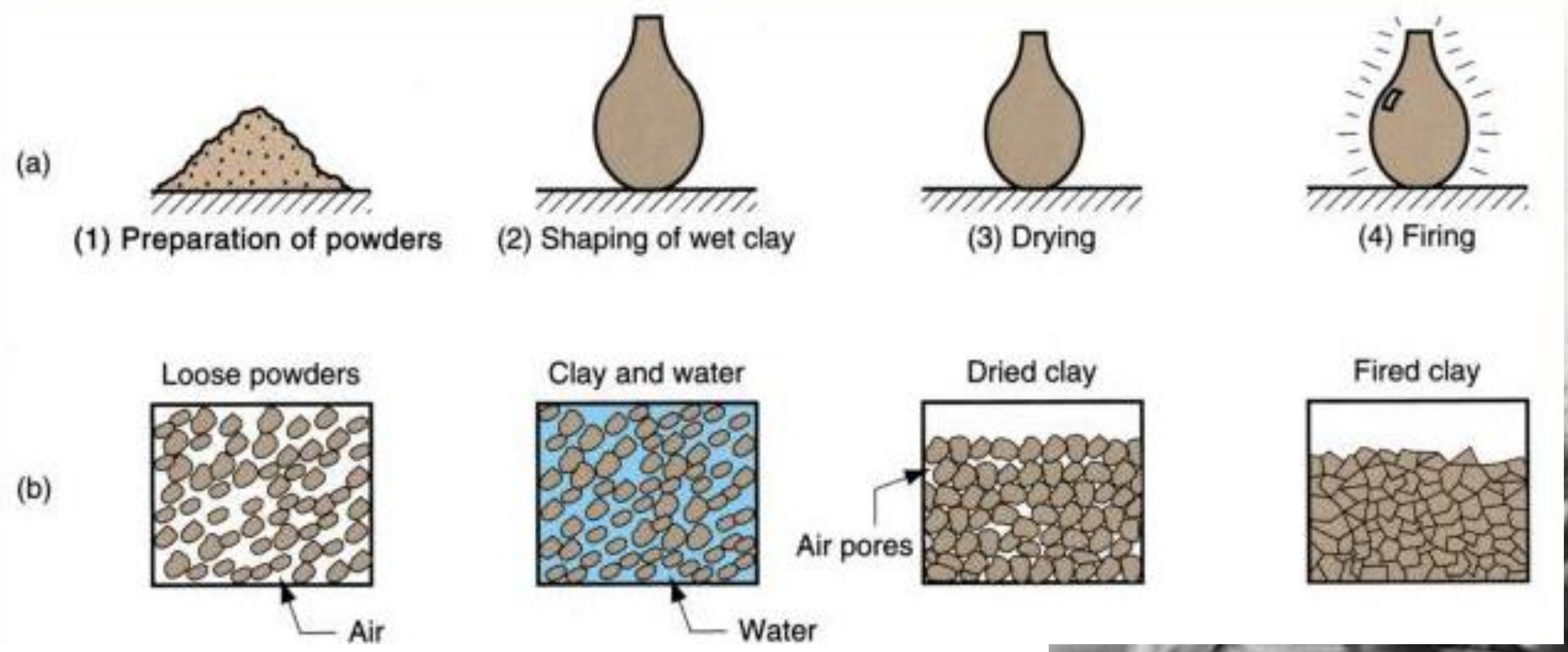
[Projecting future carbon emissions from cement_2023]

Traditional ceramics

Processing ceramics

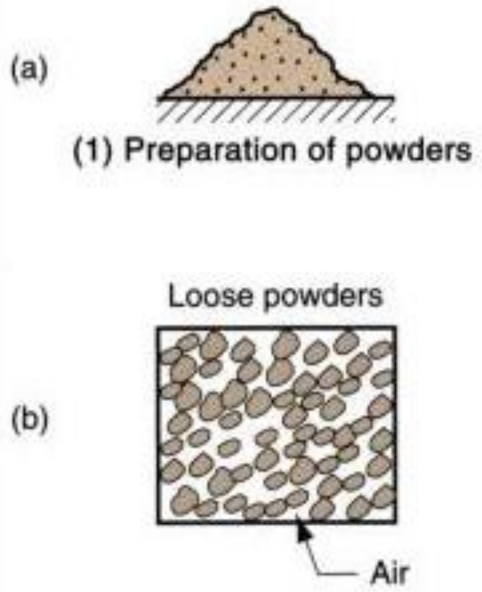
- Traditional ceramics are made from naturally occurring minerals
- Mineral extraction has the usual consequences: habitat destruction, soil erosion, water pollution
- Open pits and quarries common

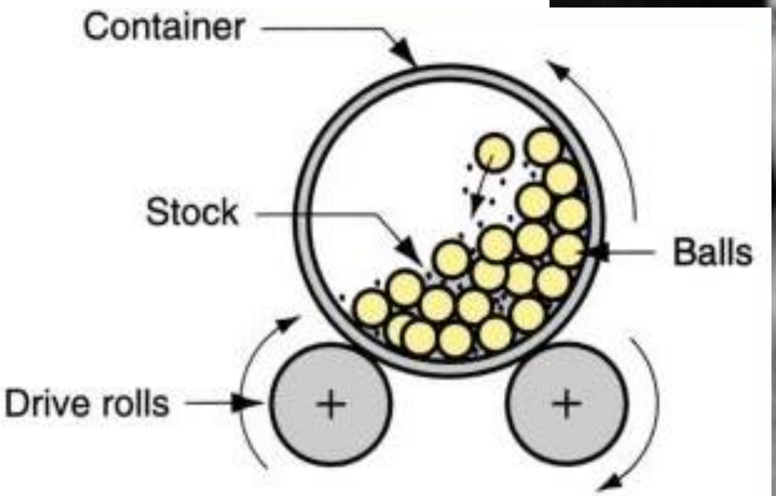




Powders

Processing ceramics

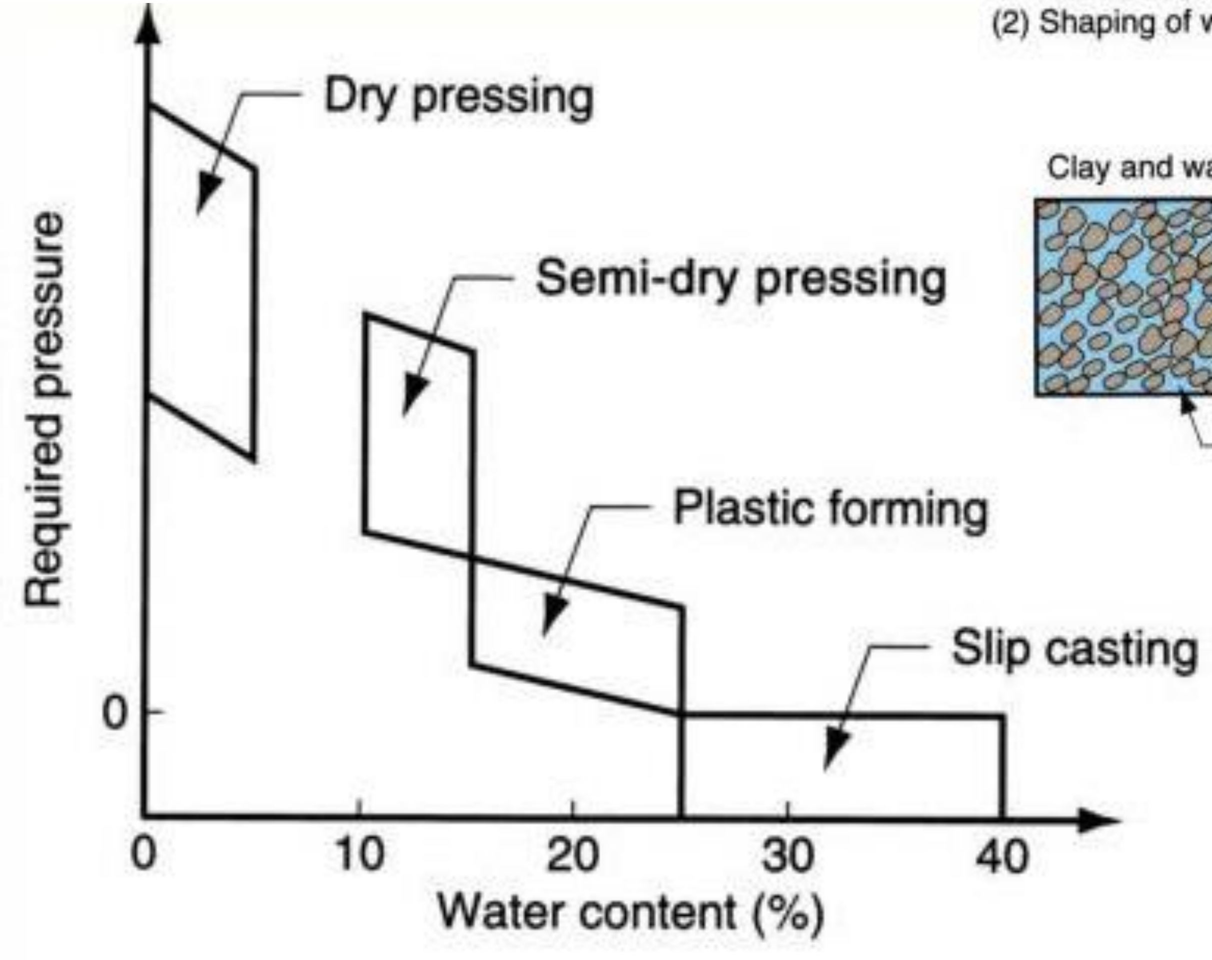


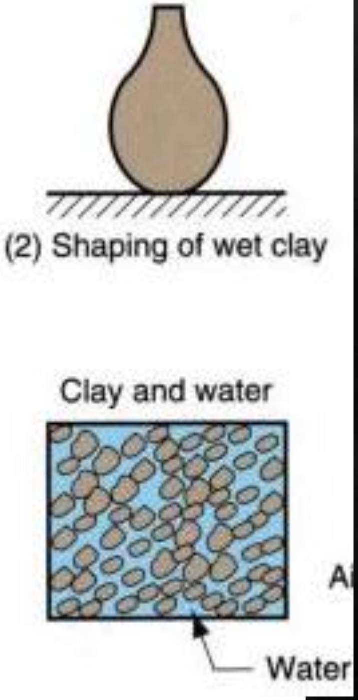


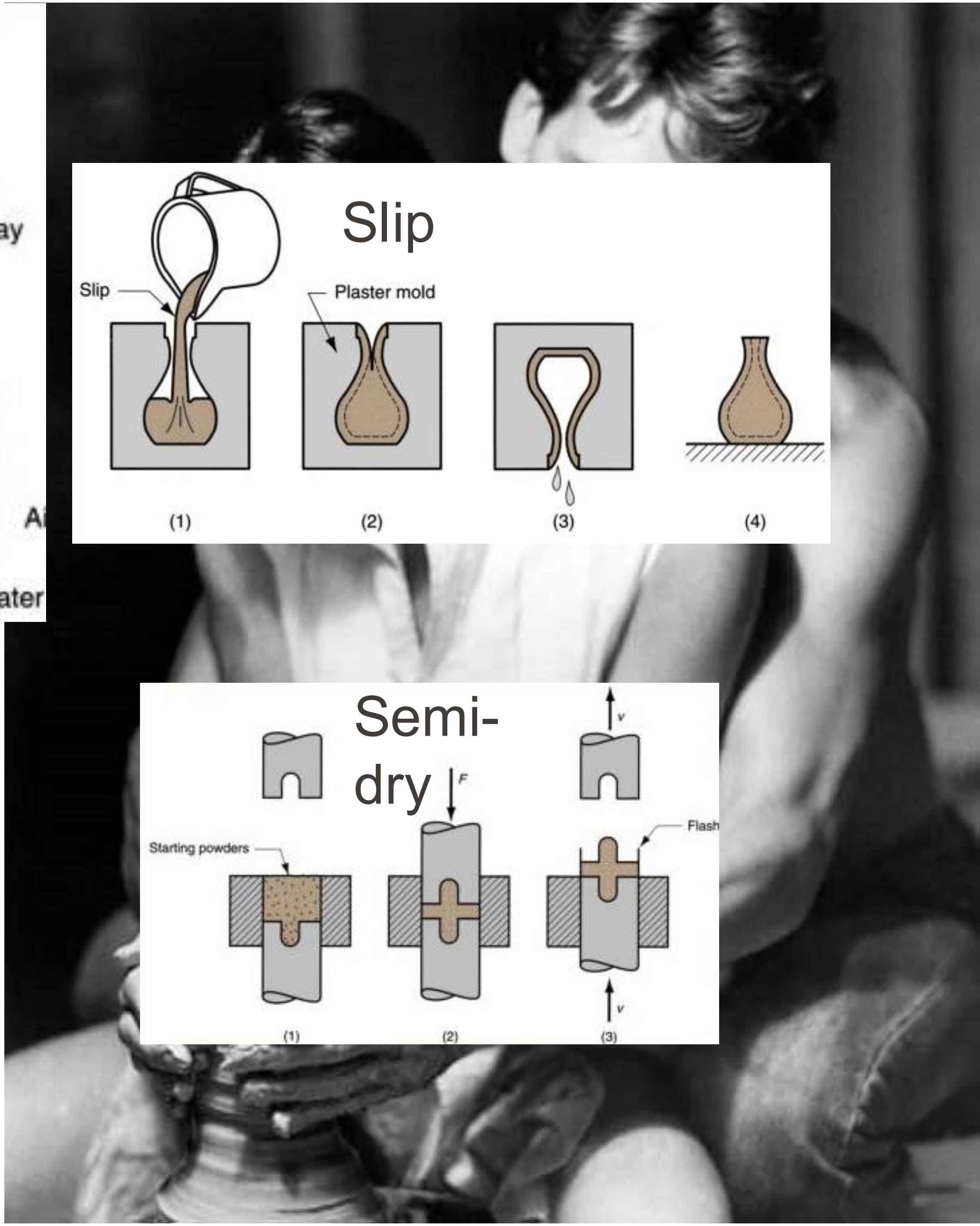
- Starts with a powder
- Powder usually made by ball crushing and then grinding, which is very energy intensive!

Shaping

Processing ceramics





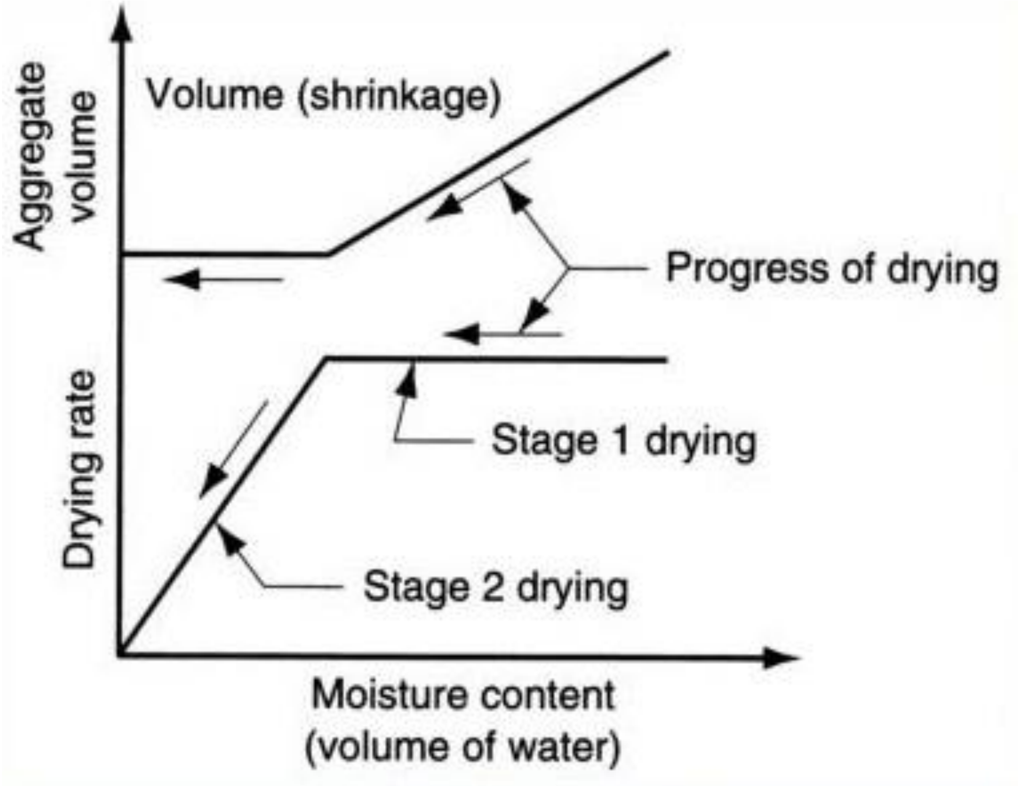


- Water is needed for shaping only/plasticity
- High pressures required for semi-dry/dry shaping

EPFL

Drying – 2 stages

Processing ceramics

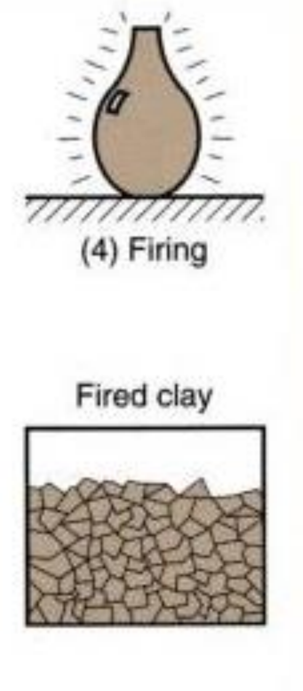


- Stage 1: fast and constant rate to evaporate surface water (prone to shrinkage)
- Stage 2: enough water has been removed so particles are in contact (no shrinkage)

Firing

Processing ceramics

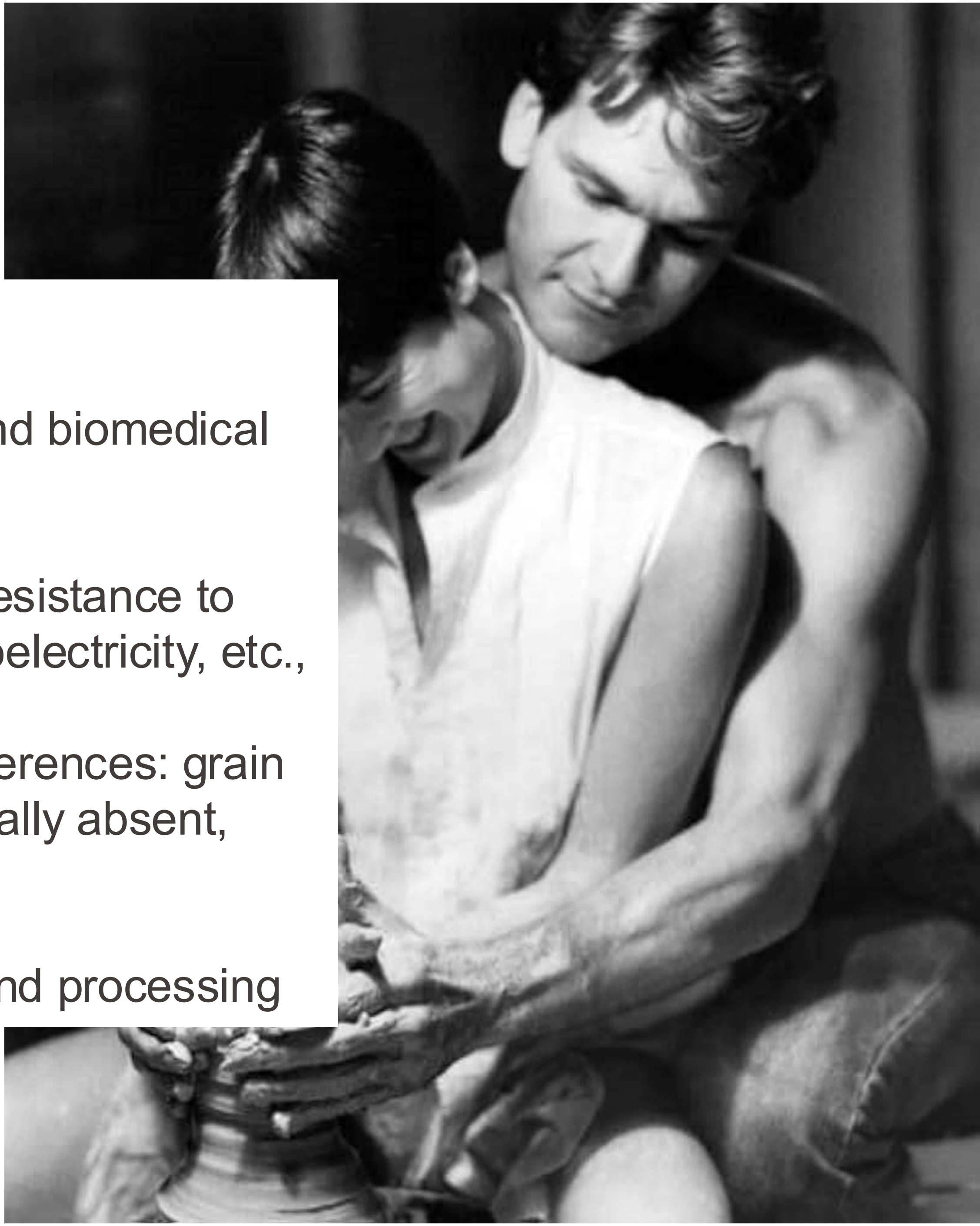
- Heat treatment to *sinter* – form bonds between particles, occurring with densification
- Performed in kiln
- Biggest impact to emissions, related to use of fossil fuels to heat the kiln and process emissions from carbonate raw materials which emit CO_2 when heated
- If glaze is applied, the ceramic is fired again!



EPFL

Advanced ceramics

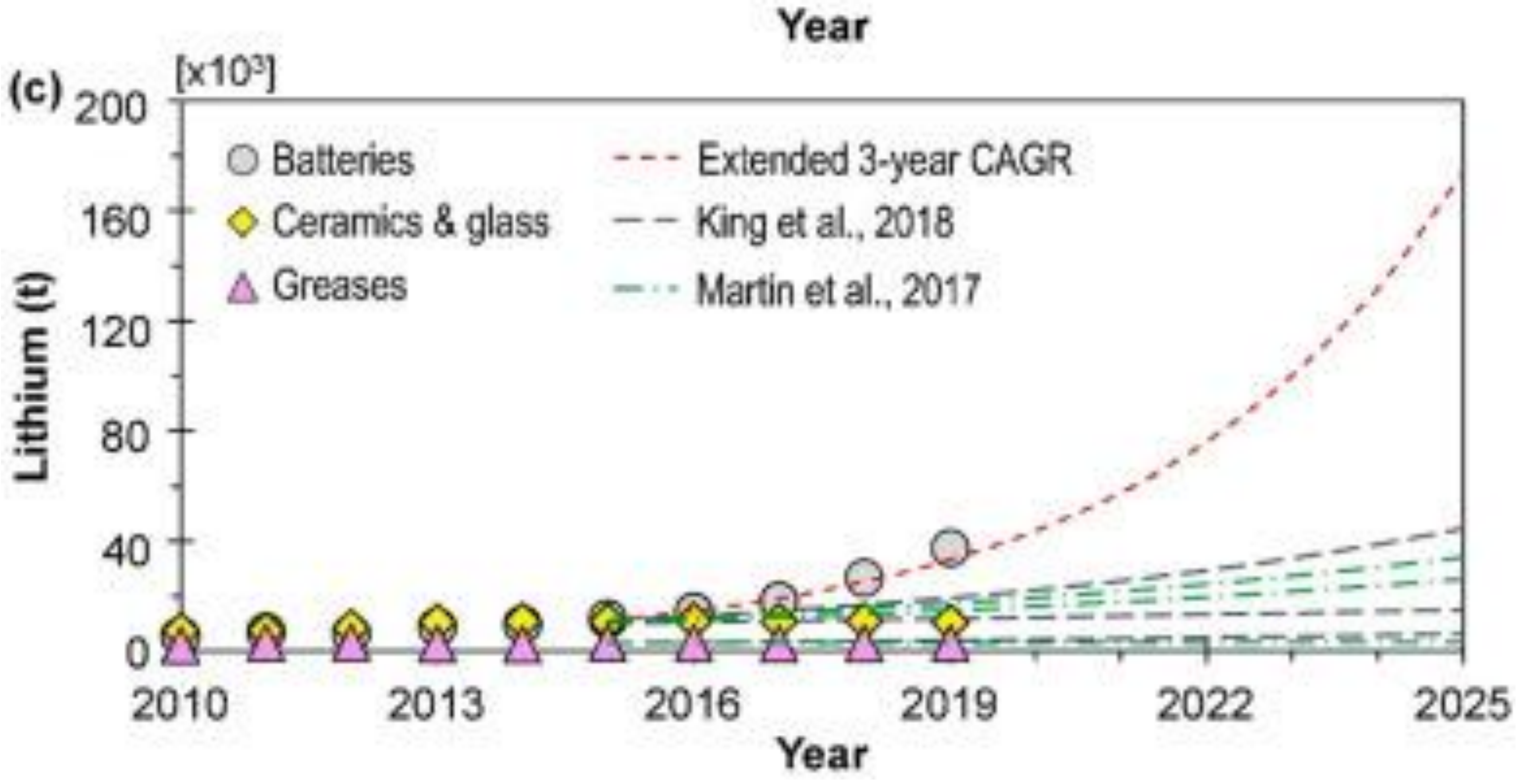
- Made from manmade raw materials
- Developed to meet industrial, technological, and biomedical needs
- Exhibit exceptional properties: high strength, resistance to wear, electrical insulation or conductivity, piezoelectricity, etc.,
- Same general processing steps with some differences: grain size can be controlled chemically, water is usually absent, etc.,
- Emissive hot spots depend on raw materials and processing



Advanced ceramics roadmap

Lithium connection?

- Lithium is used in advanced ceramics due to its ability to enhance certain properties: low thermal expansion, high strength and toughness, melting point reduction, improved optical properties, enhanced electrical properties, light weight

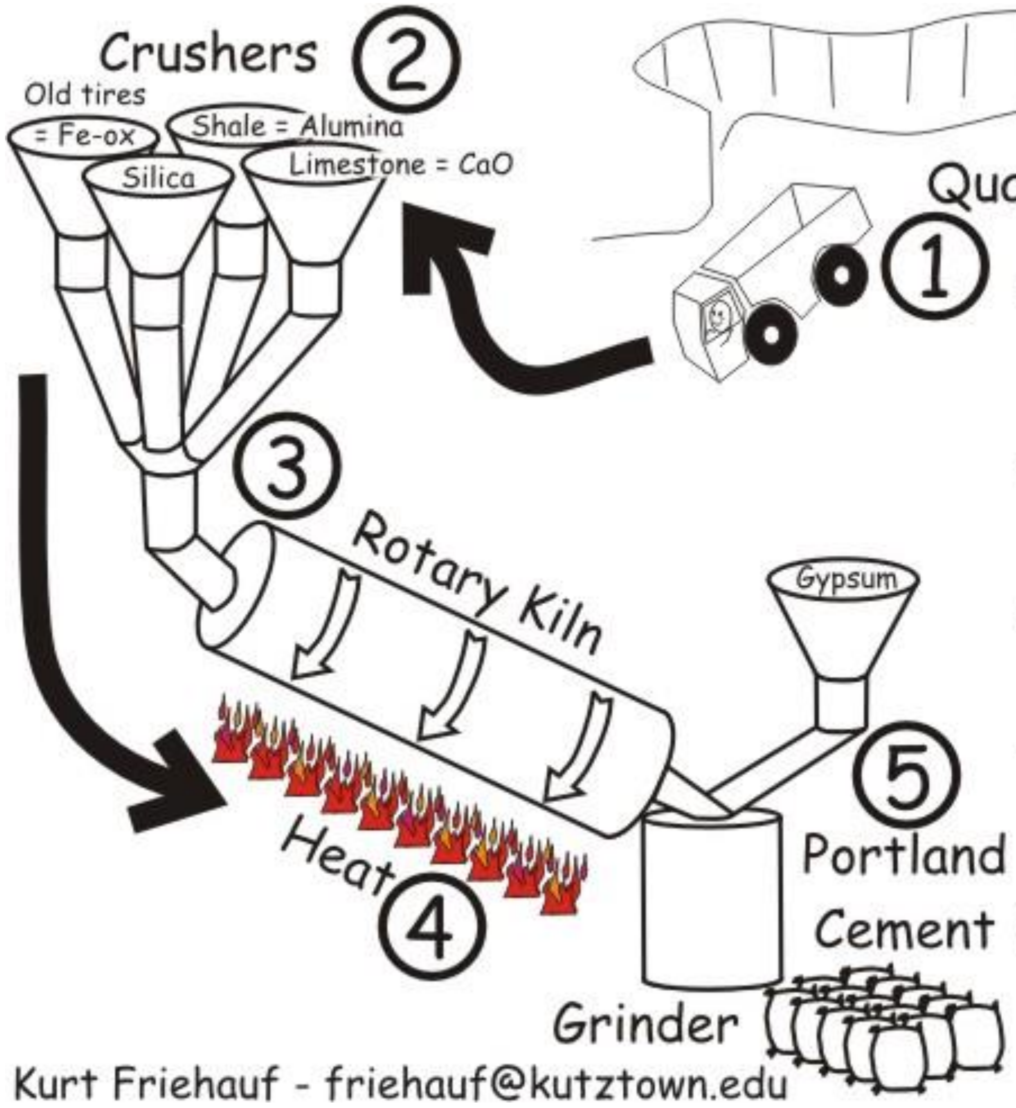


- Cathode material in bateries
- Now batteries, but before 2015, ceramics and glass was the main industry using lithium

Decarbonizing ceramics_2022

How cement is made

$CaCO_3$ (limestone) + heat -> CaO (lime) + CO_2

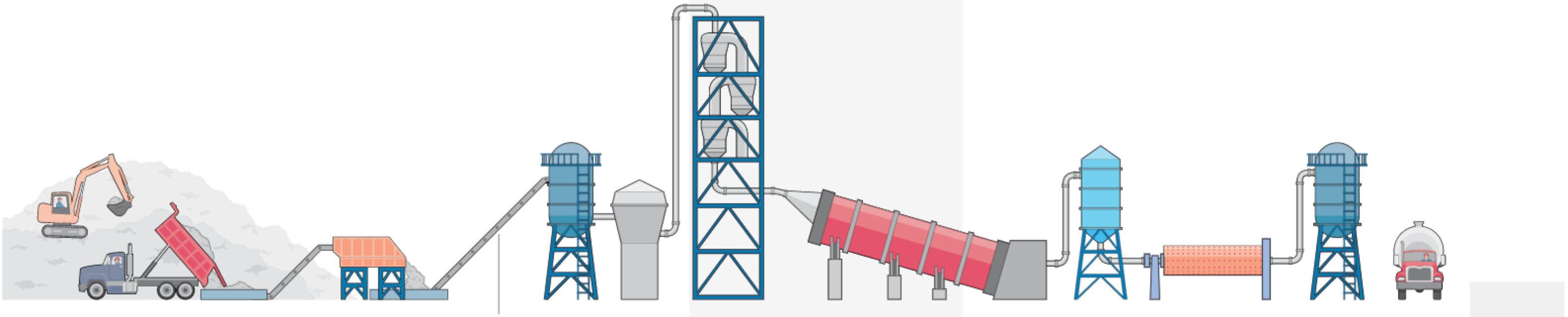


1. Limestone, shale, silica, and iron oxides are quarried from the ground. (Some limestones already contain enough silica).
2. Rock materials are run through a crusher that turns rock into smaller pieces.
3. Crushed limestone + silica + shale + iron oxides are mixed together and run through a rotary kiln.
4. Rotary kiln continuously mixes ingredients and "calcines" limestone so that CO_2 is driven off, forming clinker.
5. Clinker is ground to fine powder and mixed with gypsum (helps moderate how fast the cement "sets), then bagged for sale.

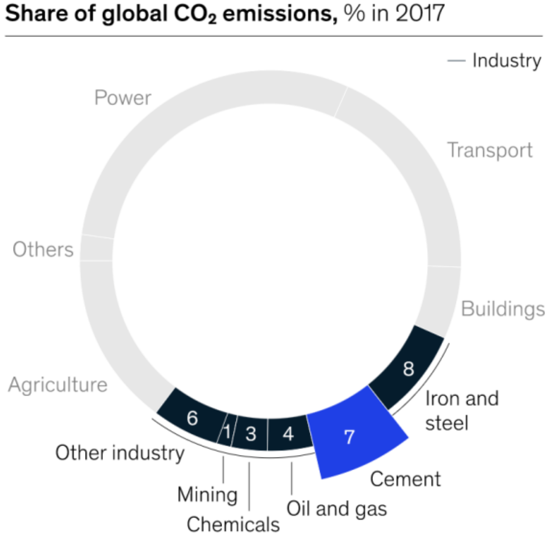
Cement manufacture

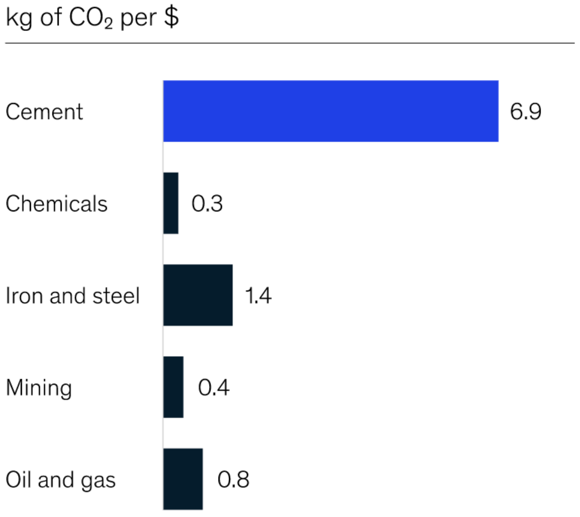
Cement

https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement



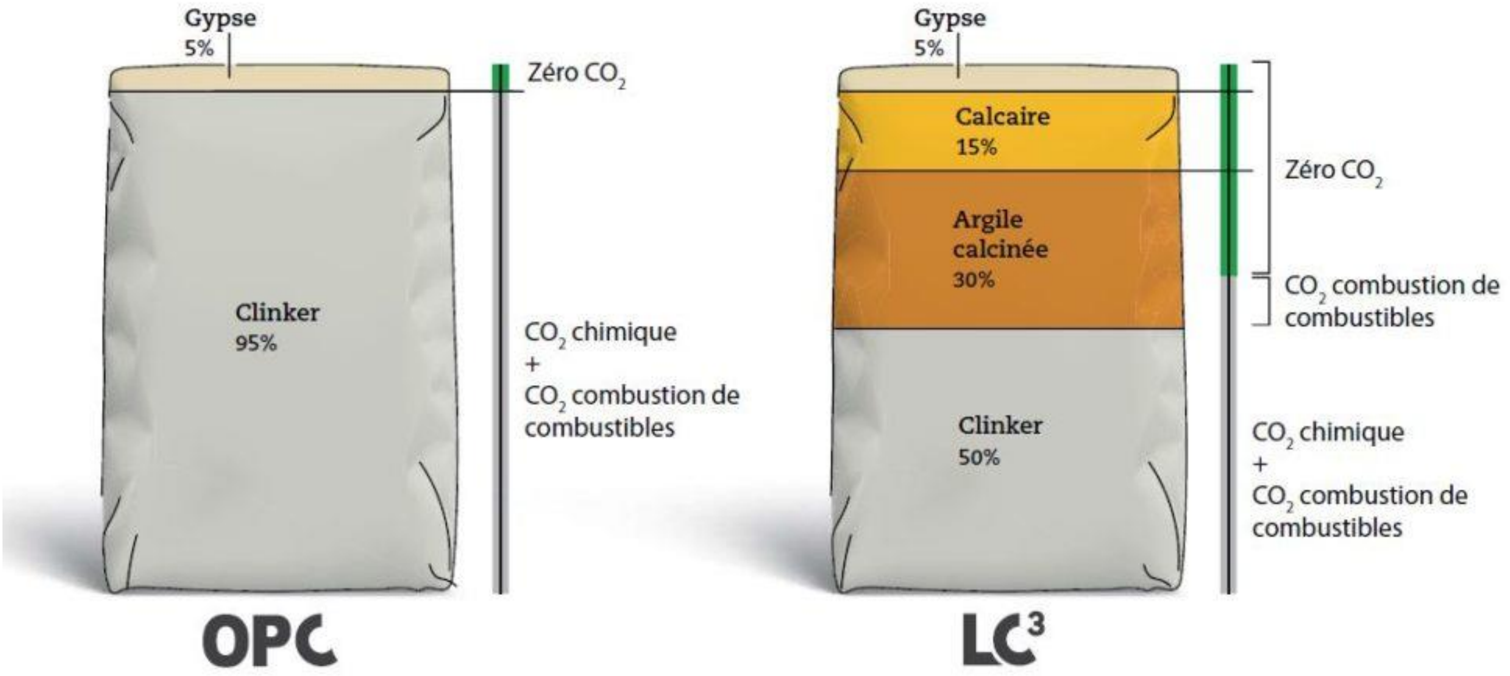
	Raw materials, energy, and resources			Clinker and cement manufacturing					
	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]	Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process; 319 Fossil fuels	28	49	22	925





- The cement industry alone is responsible for about a quarter of all industry CO_2 emissions, and it also generates the most CO_2 emissions per dollar of revenue
- About two-thirds of those total emissions result from calcination, the chemical reaction that occurs when raw materials such as limestone are exposed to high temperatures.

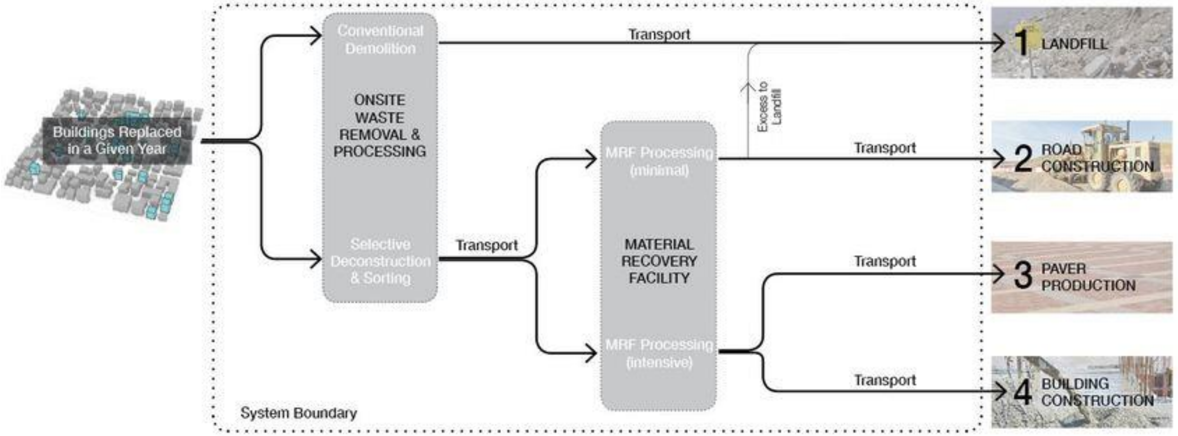
Decarbonizing cement : EPFL connection (LMC)



- Replaces half of clinker with calcined clay and ground limestone, neither of which releases CO_2 when heated the way limestone does
- Clay is heated to lower temperatures, reducing fuel needed and emissions
- Lower temperatures mean that cleaner energy, like electricity can be used

LC3 - more sustainable cement

End of life – Ceramics and Glasses

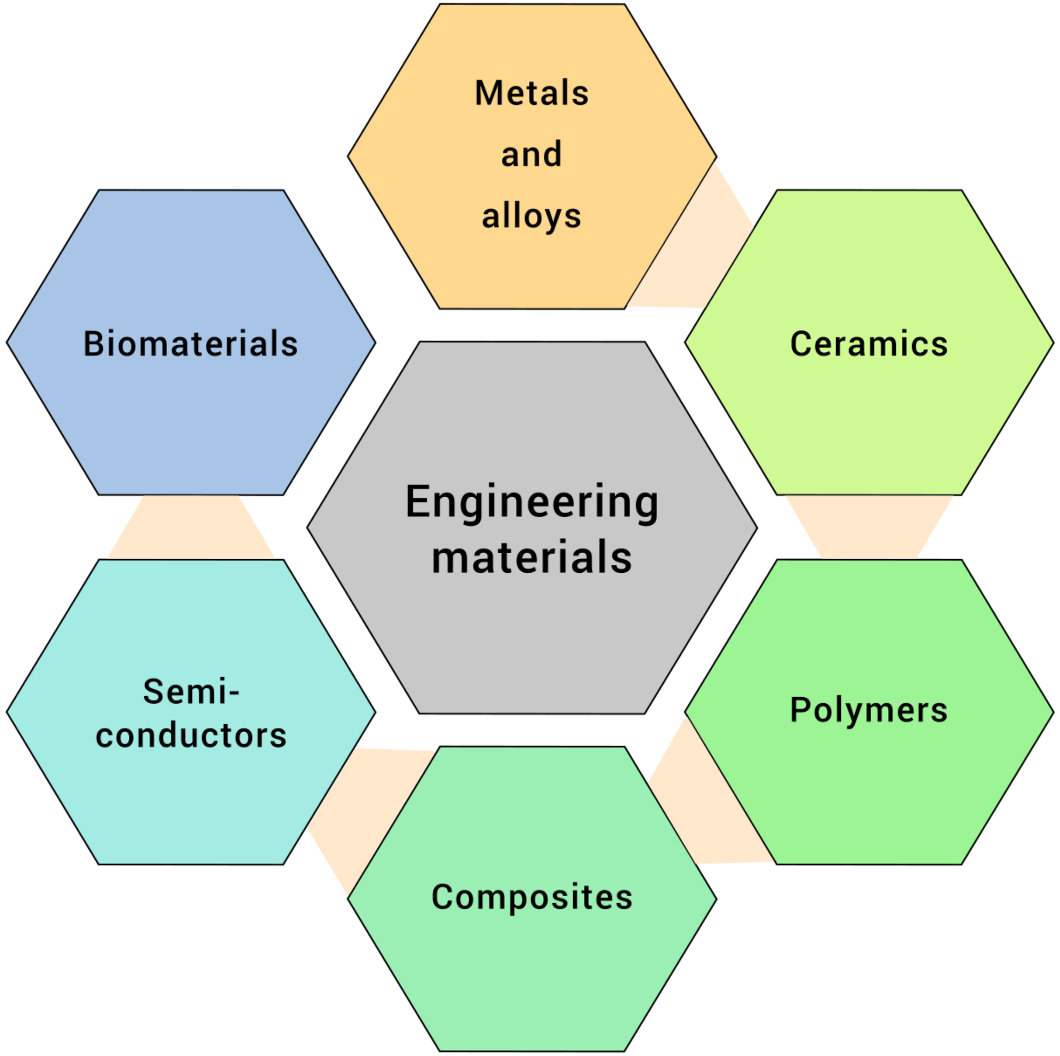


Concrete

- About 60% of what is crushed can be used for downcycling processes (recovery of materials with a more limited range of uses than the original material).
- These fragments can be used as base materials for structures such as roads.

[Recycling concrete]

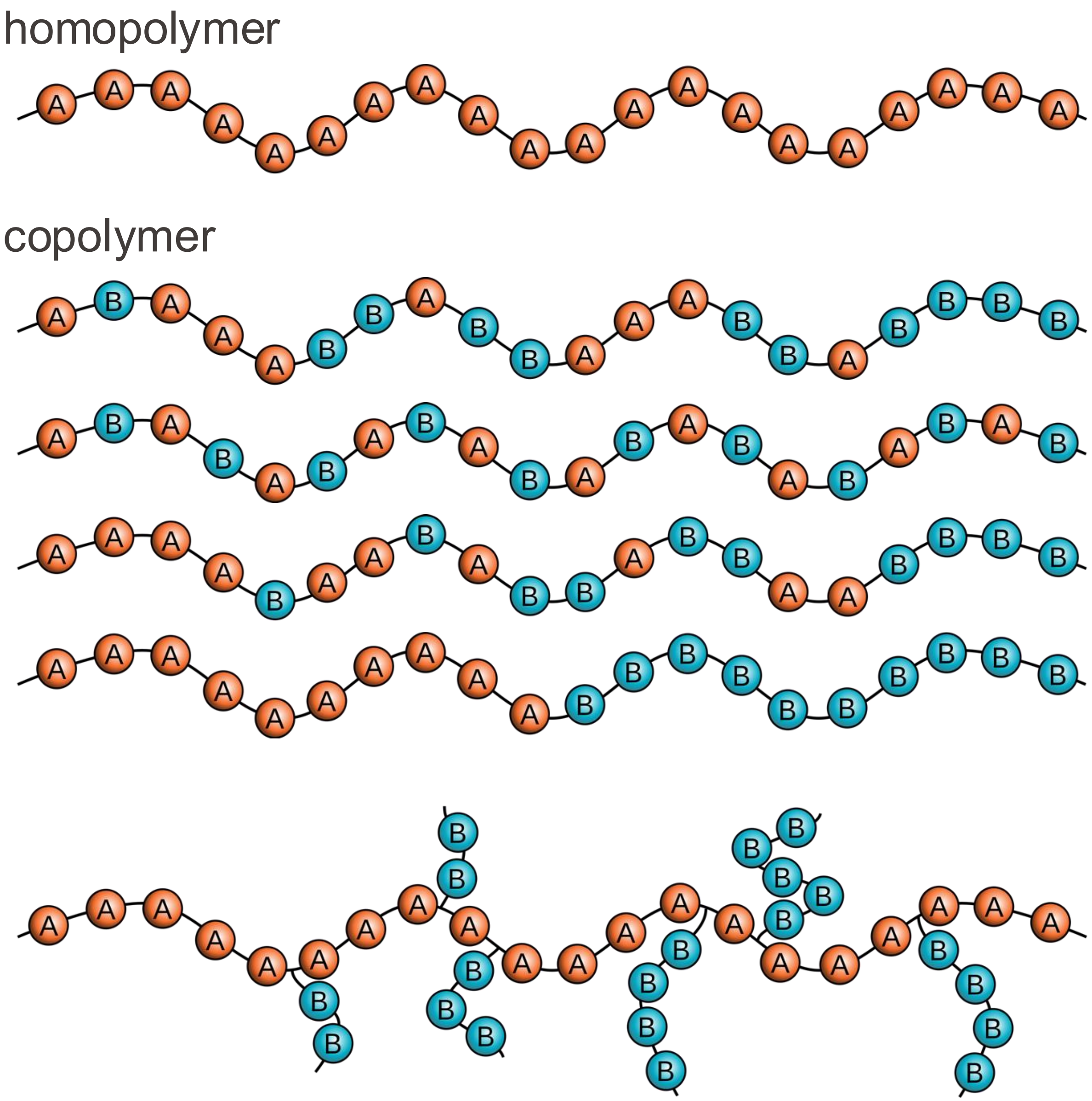
Engineering materials categories (variable)



Focus: Plastics

Materials science classifications

Generic definition of a polymer



- Covalently linked repeat units, building up into a long molecule, *aka* a macromolecule or a polymer
- Can be nature-derived, semi-synthetic or synthetic
- Often defined by chain length
- Versatile chemistry and chain length translates to versatile properties (crystallinity, viscosity, thermal, mechanical, etc.,)

EPFL

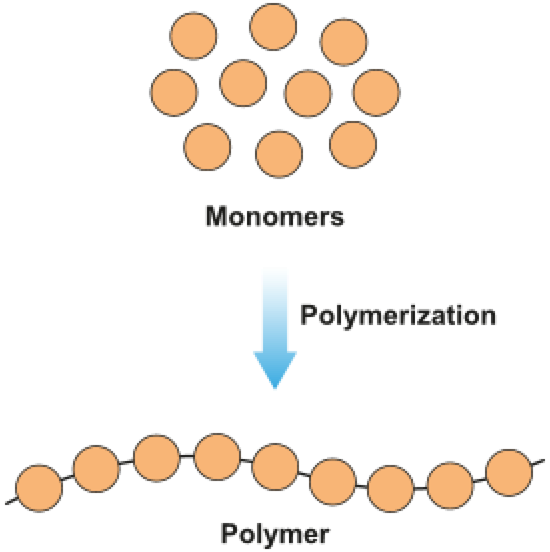
Polymer definition

Hermann Staudinger
"Father of Macromolecular Chemistry"
1953 Chemistry Nobel Prize

"…Heinrich Wieland, 1927 Nobel laureate in chemistry, wrote to Staudinger, "Dear colleague, drop the idea of large molecules; organic molecules with a ***molecular weight higher than 5000 do not exist****. Purify your products, such as rubber, then they will crystallize and prove to be low molecular compounds!"*

1920
"In a paper entitled "Über Polymerisation," Staudinger presented several reactions that form high molecular weight molecules by linking together a large number of small molecules. During this reaction, which he called "polymerization," individual repeating units are joined together by covalent bonds."

"My colleagues were very skeptical about this change, and those who knew my publications in the field of low molecular chemistry asked me why I was neglecting this interesting field and instead ***was working on a very unpleasant field and poorly defined compounds, like rubber and synthetic polymers****. At that time the chemistry of these compounds often was designated, in view of their properties, as Schmierenchemie ('grease chemistry')."*

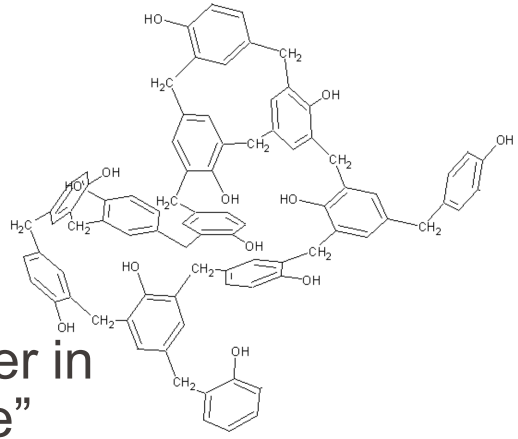


[Staudinger Polymer Science]

Celluloid

- Late 19th century
- John Wesley Hyatt in response to $10,000 reward for ivory substitute
- Celluloid = partially nitrated cellulose (“guncotton”) + camphor
- 1st semi-synthetic plastic
- Thermoplastic
- (Launching the age of man-made plastics)

Bakelite



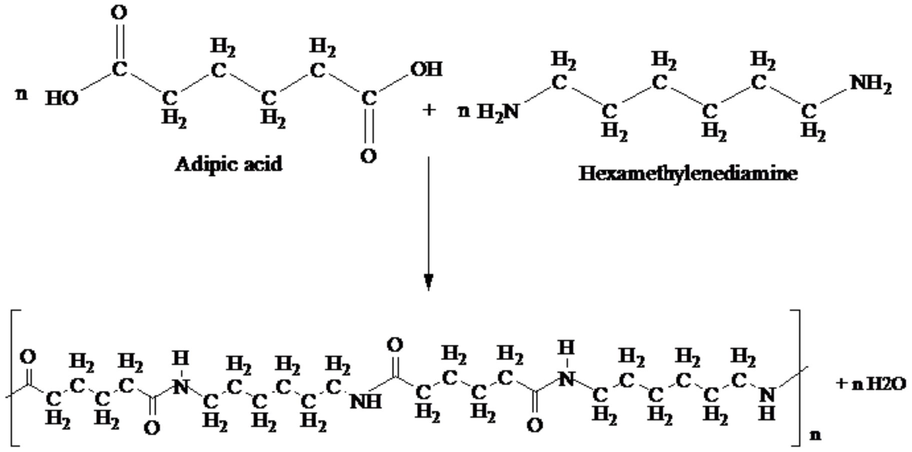
- World's first fully synthetic polymer in 1907, heralding the "Polymer Age"
- "Insoluble in all solvents, does not soften. I call it Bakalite (sic)"
- Moldable
- Thermoset

"Von Baeyer had reported that when he mixed phenol, a common disinfectant, with formaldehyde, it formed a hard, insoluble material that ruined his laboratory equipment, because once formed, it could not be removed. Kleeburg reported a similar experience, describing the substance he produced as a hard amorphous mass, infusible and insoluble and thus of little use."

[Bakelite]

Nylon

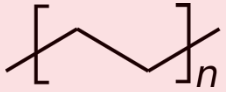
- Wallace Carothers at Dupont (US)
- Nylon developed in 1930s
- Condensation polymerization
- Thermoplastic
- High strength, rigidity, good heat and chemical resistance
- Highly used, e.g., automotive, textile fibers, etc.,



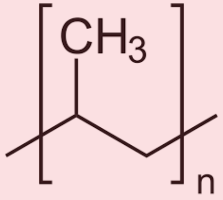
Nylon 6,6

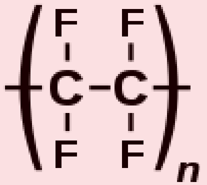
Examples of common synthetic polymers

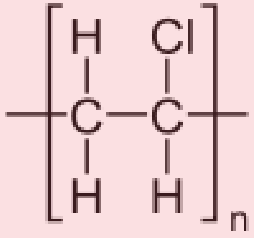
ADDITION POLYMERS

#1
PE


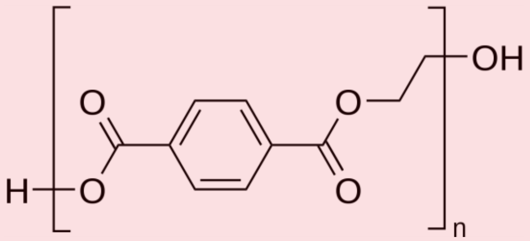
packaging

#2
PP
packaging


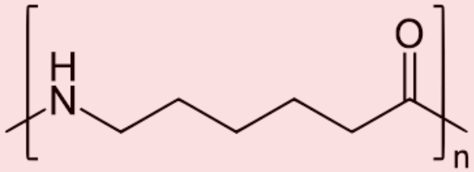
Teflon


#3
PVC
pipes


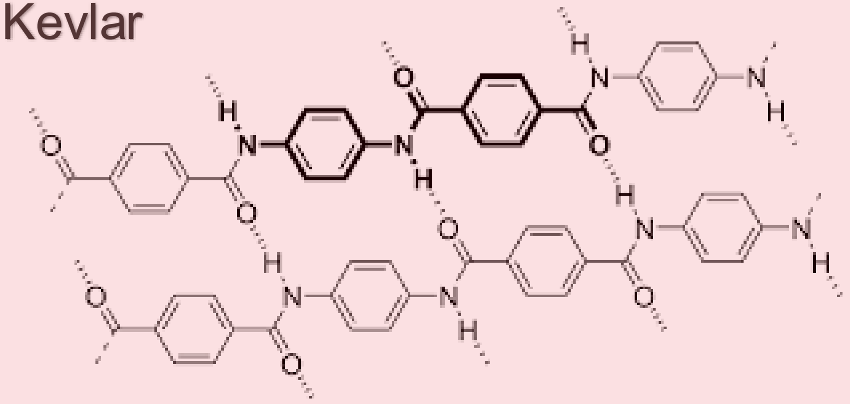
CONDENSATION POLYMERS

PET


Polyester
Carbonated drinks

Nylon 6,6


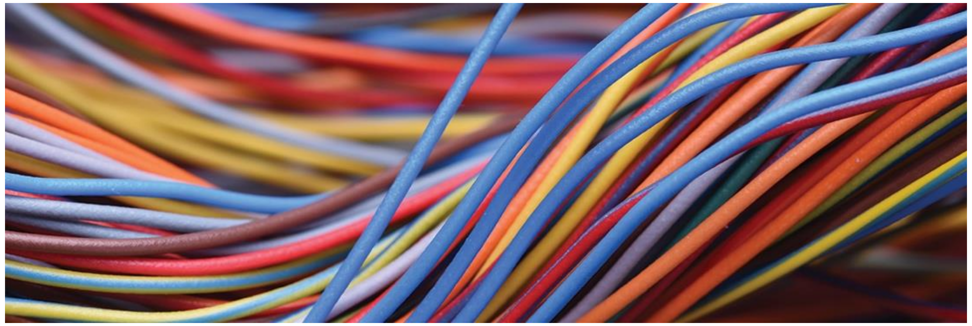
Polyamide
Textiles

Kevlar


aromatic polyamide
Engineering materials

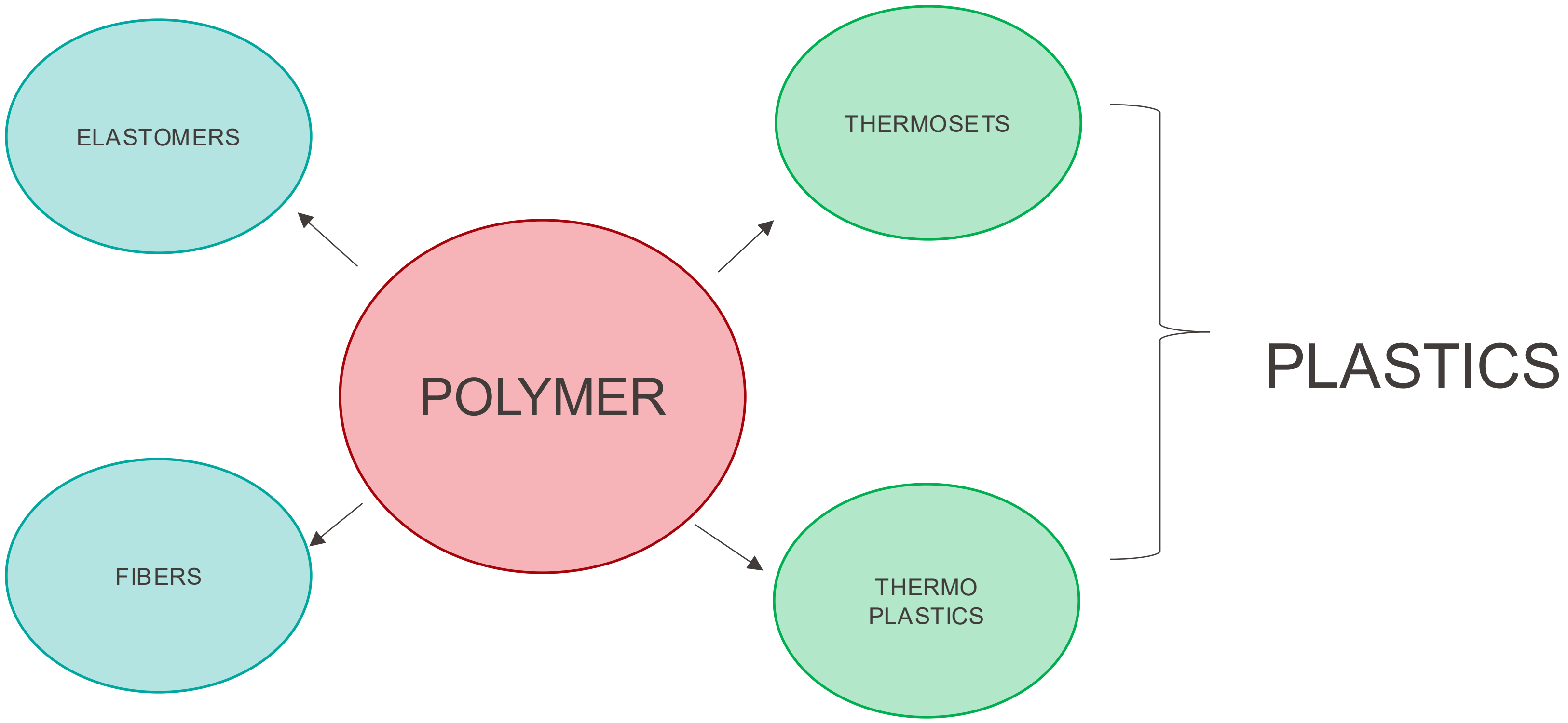
General characteristics of plastics

- Cheap & versatile
- Excellent strength to weight ratio
- Highly processible
- Non-reactive – inert, not easily corroded, BUT can be degraded and broken down into microplastics by UV-light, abrasion
- Good insulators
- Tailorable appearance and properties
- Life cycle & end of life complex for synthetic polymers



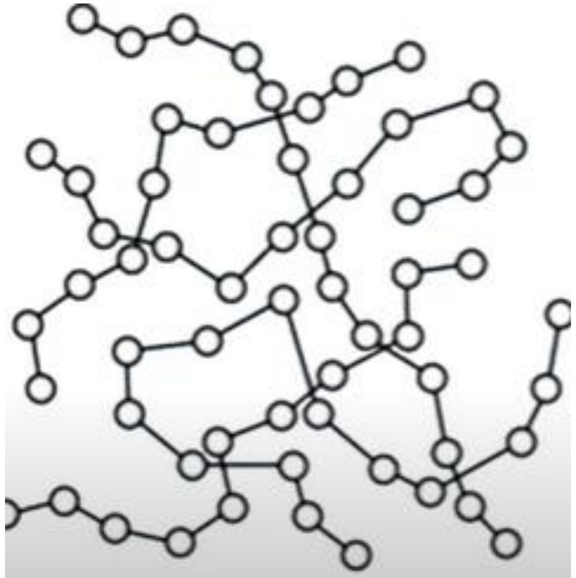
Polymer vs. plastic

- *Polymer is from Greek for “of many parts”*
- *Plastic is from “Plastikos”, Greek for pliable*



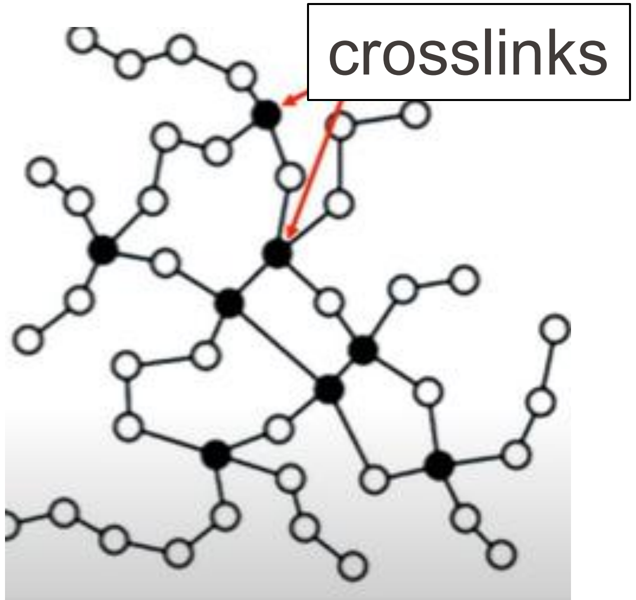
Thermoplastics vs. Thermosets

THERMOPLASTICS



- Weak intermolecular bonds
- Softens when heated
- Hardens when cooled
- Reversible

THERMOSETS

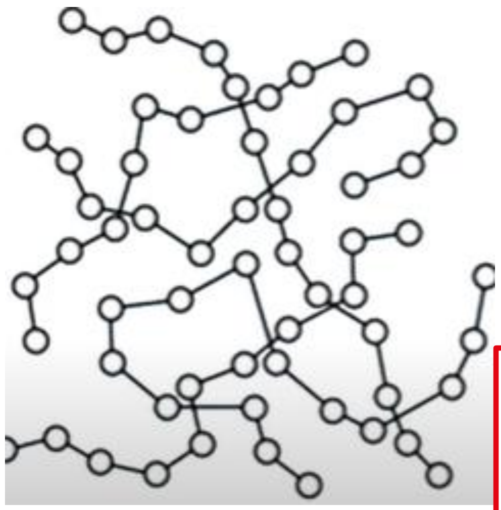


- Strong covalent bonds ("crosslinks")
- Rigid, prevents melting when heated
- Cannot be reshaped or remolded

thermoplastics vs thermosets
https://www.youtube.com/watch?v=4fTtrKPySm0

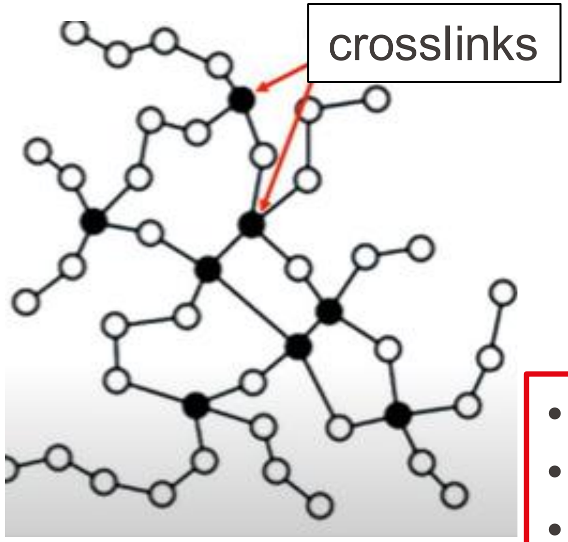
Thermoplastics vs. thermosets

THERMOPLASTICS



- Remoldable
- Recyclable
- High strength
- Shrink resistance
- Flexibility

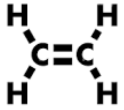
THERMOSETS



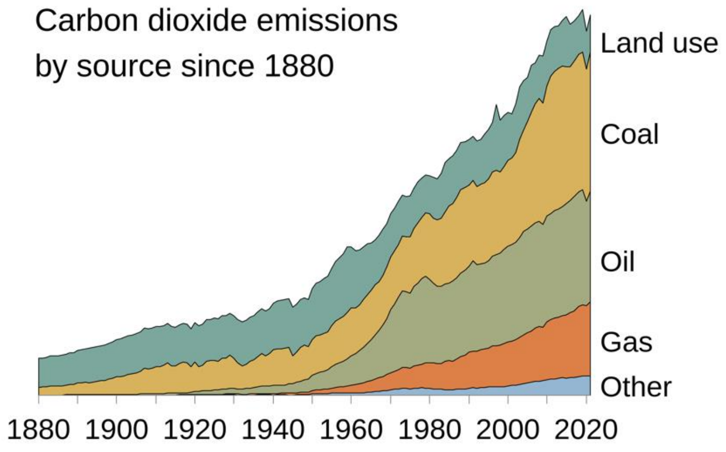
- Heat resistant
- Corrosion resistant
- High strength
- Mechanical creep resistance
- High specific strength (strength to weight ratio)

[thermoplastics vs thermosets]

Plastic resources



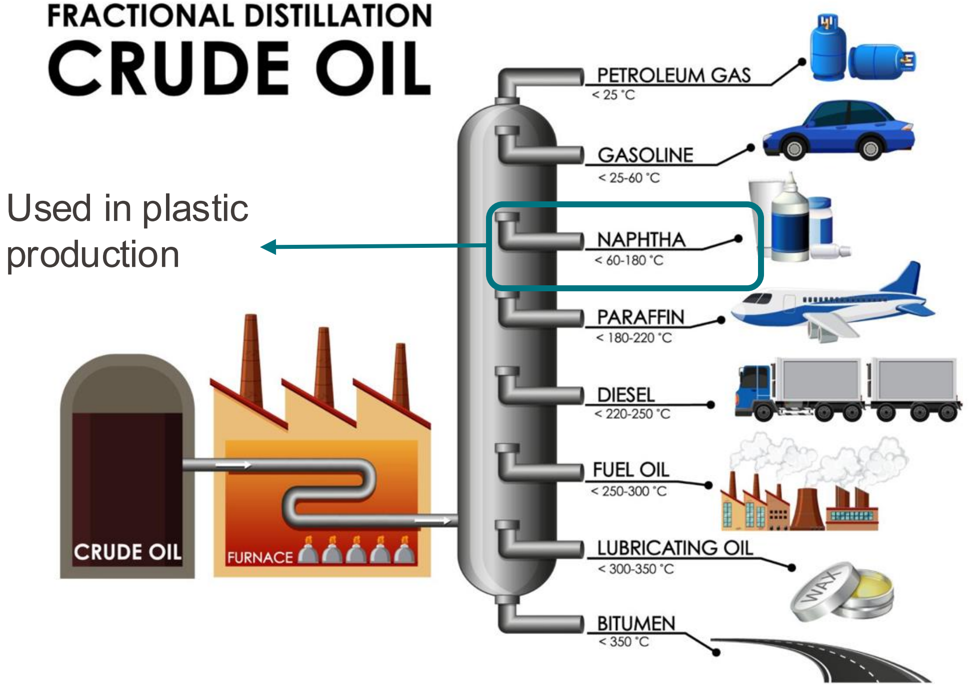
ethylene



- Most plastic in use today comes from hydrocarbons derived from crude oil, natural gas, and coal – fossil fuels
- Crude oil is a combination of hundreds of different hydrocarbons
- Fractional distillation is used to separate them into their various components
- Higher molecular weight hydrocarbons are then selected and further processed (cracking) to yield lower molecular weight alkenes and alkanes (e.g., decane cracking)

$C_{10}H_{22} \rightarrow C_8H_{18} + C_2H_4$ → ethylene → polymers

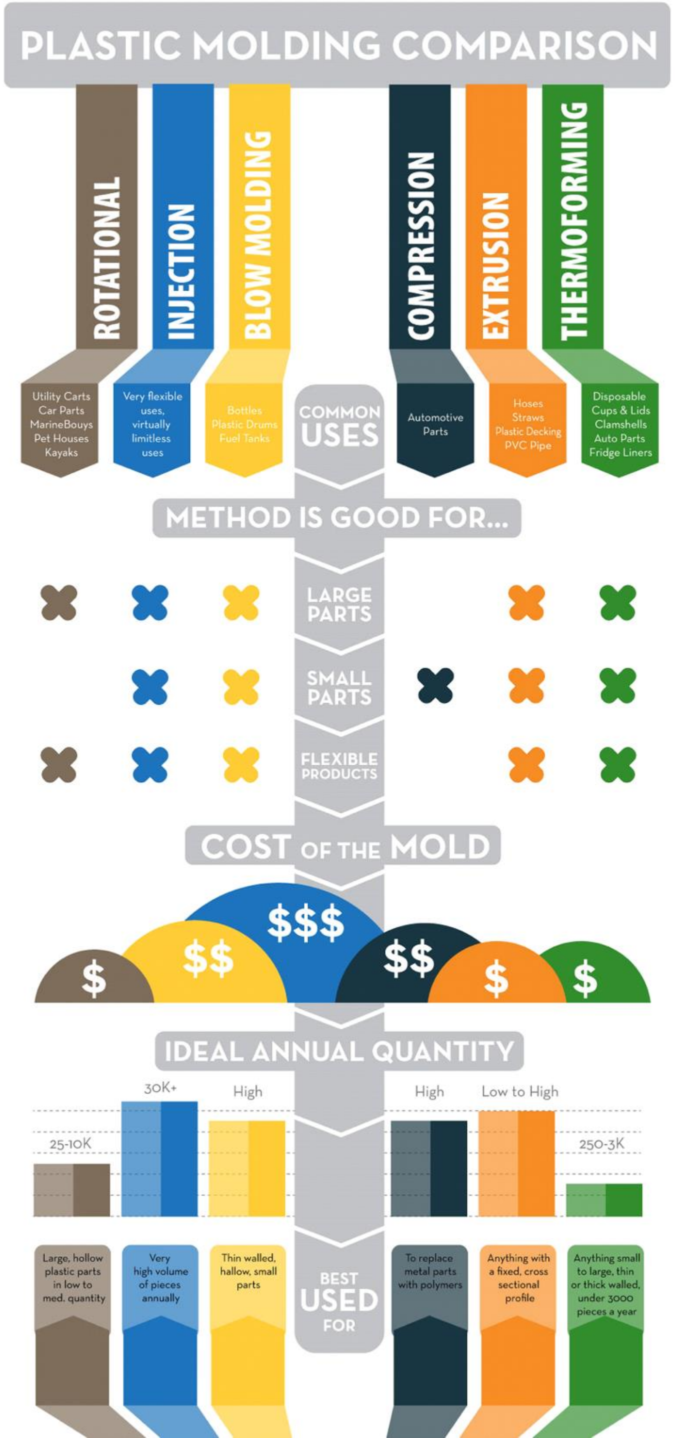
C_8H_{18} → octane → fuel



EPFL

Plastic processing

- Rotational molding
- Injection molding
- Blow molding
- Compression molding
- Extrusion molding
- Thermoforming



- *Neoprene*
- *Nylon*
- *Teflon*
- *Lycra*
- *Kevlar*

Plasticene

A NEW GEOLOGICAL AGE…(last 60-70 years!)

n. & adj. (2011) an era in Earth's history, within the Anthropocene, commencing in the 1950s, marked stratigraphically in the depositional record by a new and increasing layer of plastic (Stager, 2011, attributed to Matt Dowling). The history and etymology of plasticene in this sense is not related to the word *plasticene*, a common early spelling (for example, Cooper, 1901) of the popular molding clay, plasticine.

A Plasticene Lexicon, Marine Pollution Bulletin,Volume 150, 2020, 110714, ISSN 0025-326X, https://doi.org/10.1016/j.marpolbul.2019.110714.

EPFL

Useful and ubiquitous

Plastics everywhere

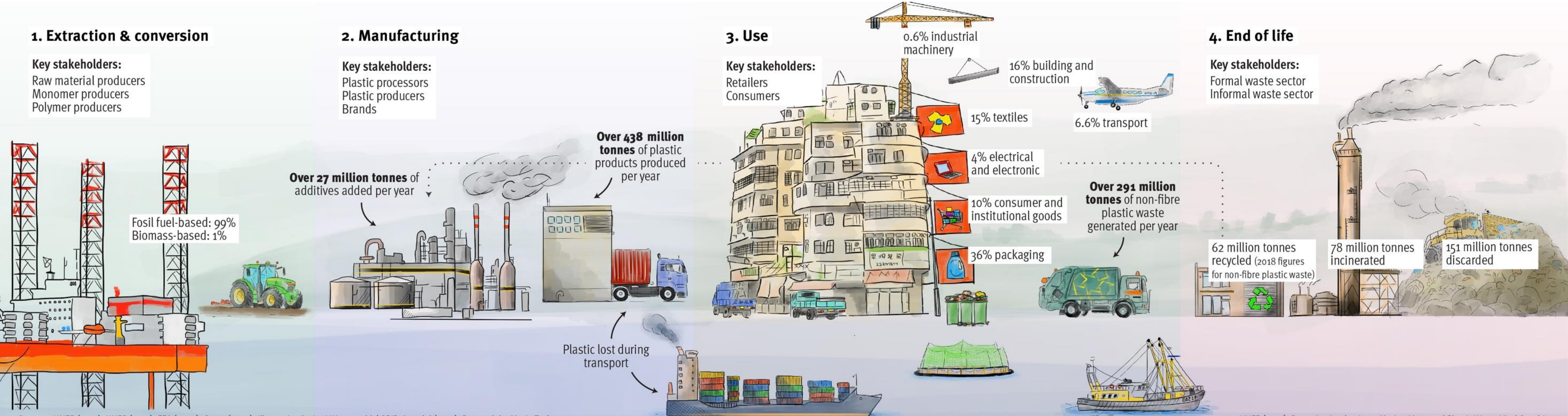
Plastic promises: How'd we do?

Data from 1950-2015:

- 8300 Mt of plastics
- 6300 Mt of plastic waste
- 12000 Mt in landfill/nature projected by 2050
- Conventional plastics do not biodegrade
- Increased demand for plastics
- Permanent elimination only by incineration

Geyer R. et al., Science Advances 2017, 3(7), 1-5.

The life cycle of plastic

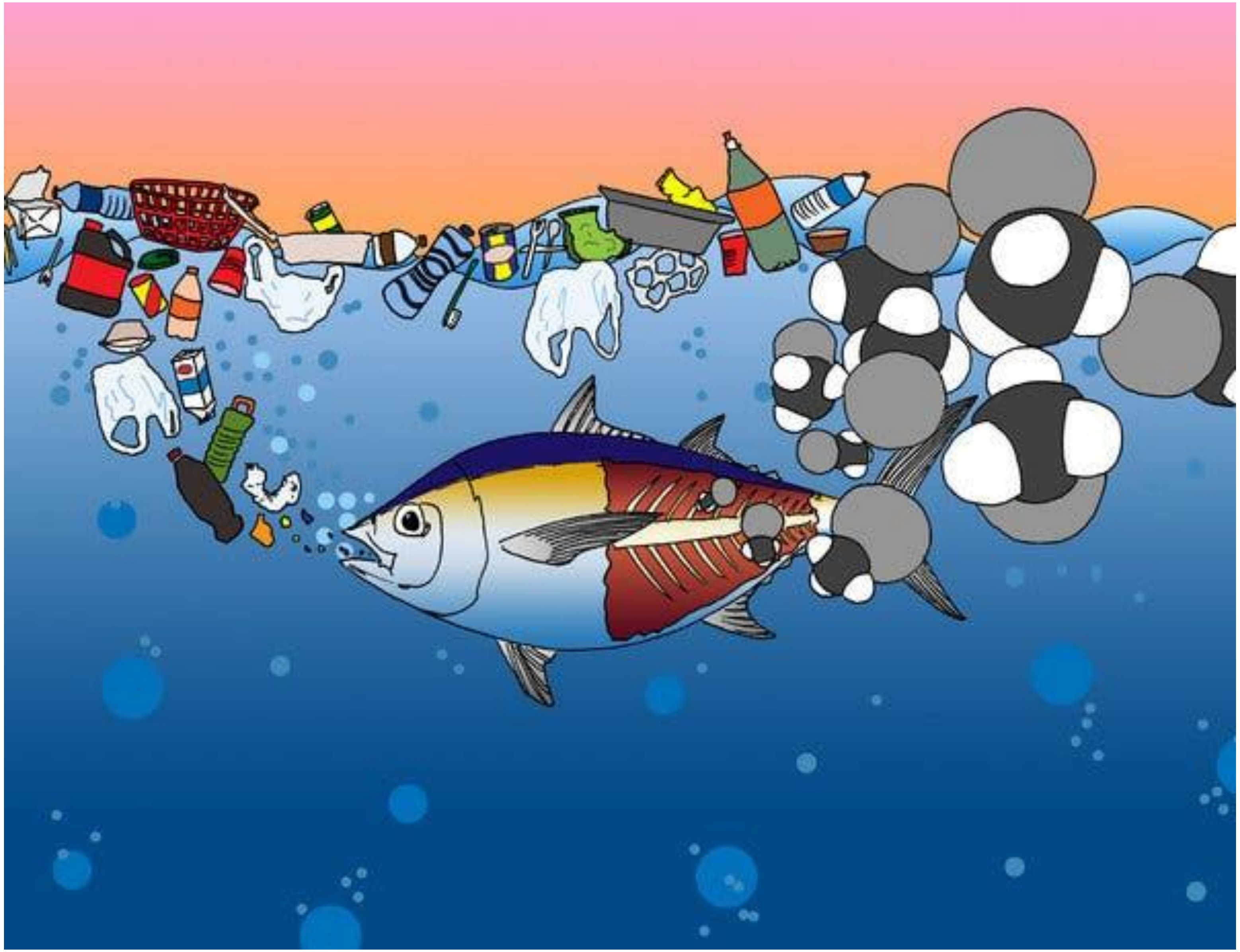


UNEP (2021). Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics.

- Of the 438 million tons of plastic produced every year, only about 14% is recycled
- A total of 99% of feedstock for plastic production is fossil fuel-based, accounting for around 8-9% of global oil and gas consumption

EPFL

Persistent and ubiquitous

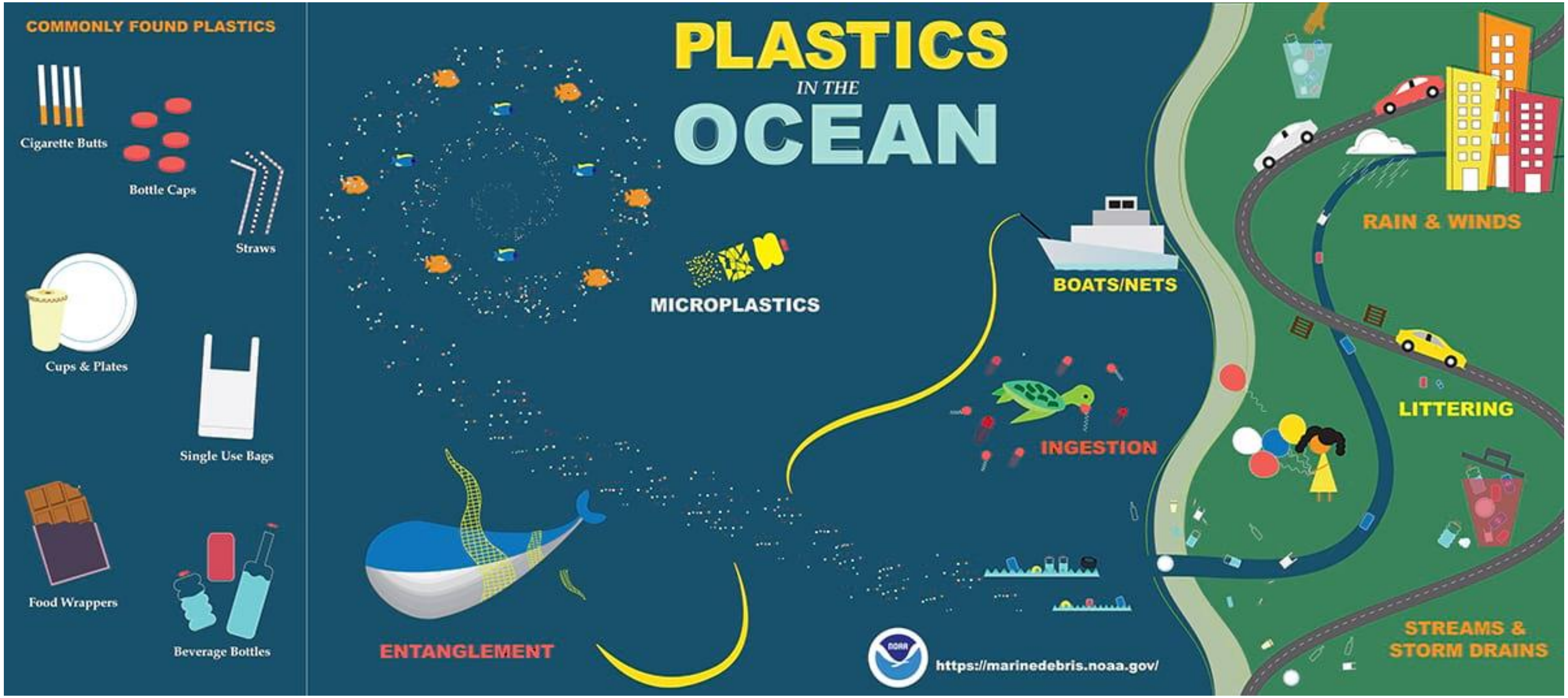


The New York Times

STEM WRITING CONTEST WINNER

An Unexpected Dinner Guest: Marine Plastic Pollution Hides a Neurological Toxin in Our Food

We are honoring each of the top eight winners of our Student STEM Writing Contest by publishing their essays. This one is by Vivian Li.

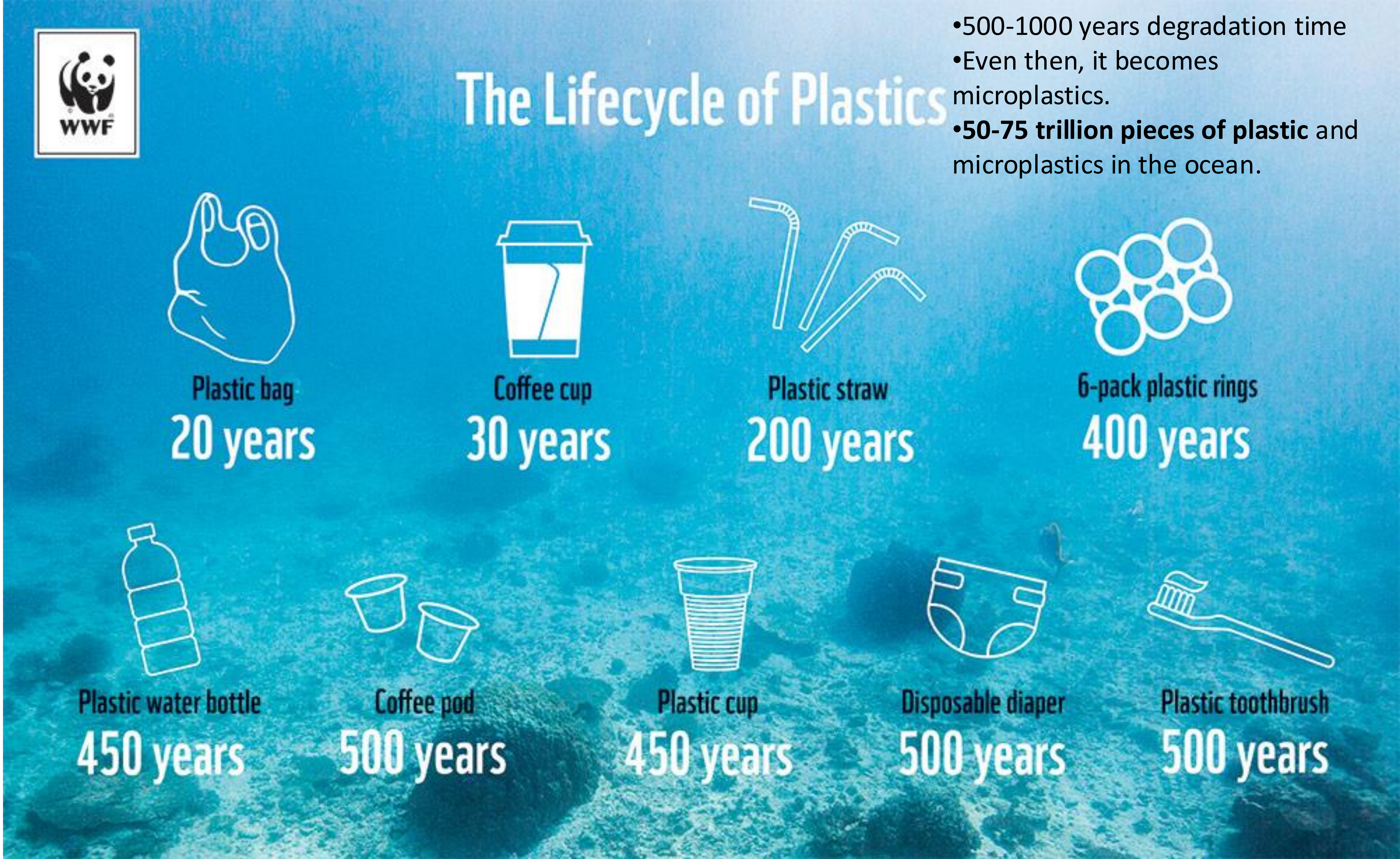


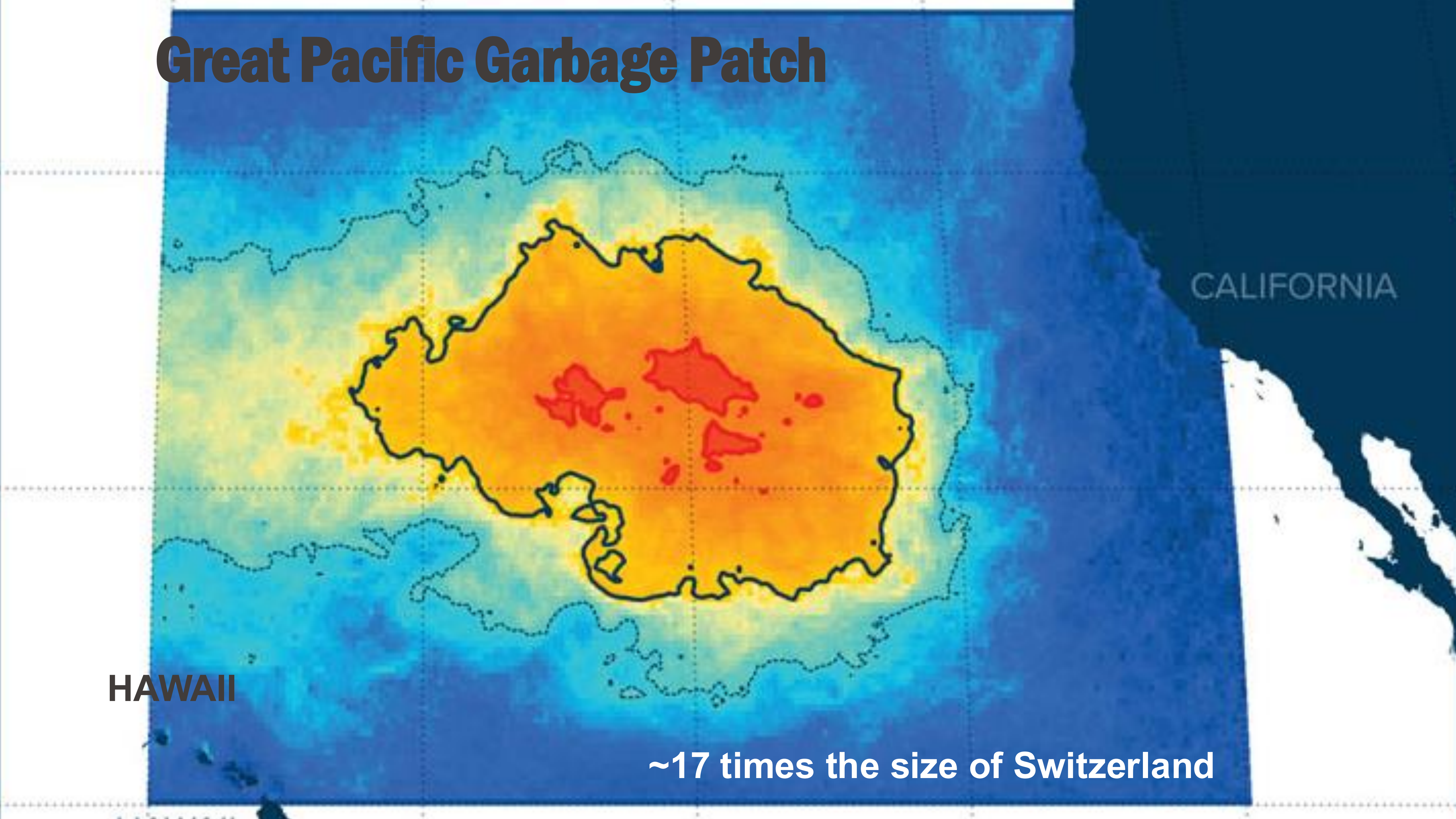
- 80% of marine pollution is plastic, 8-10 Mt of plastic/year
- Essentially all manmade plastics are still in existence (except what has been incinerated, approx. 9%)
- Plastics either break down into microplastics or form garbage patches

Plastics in the ocean

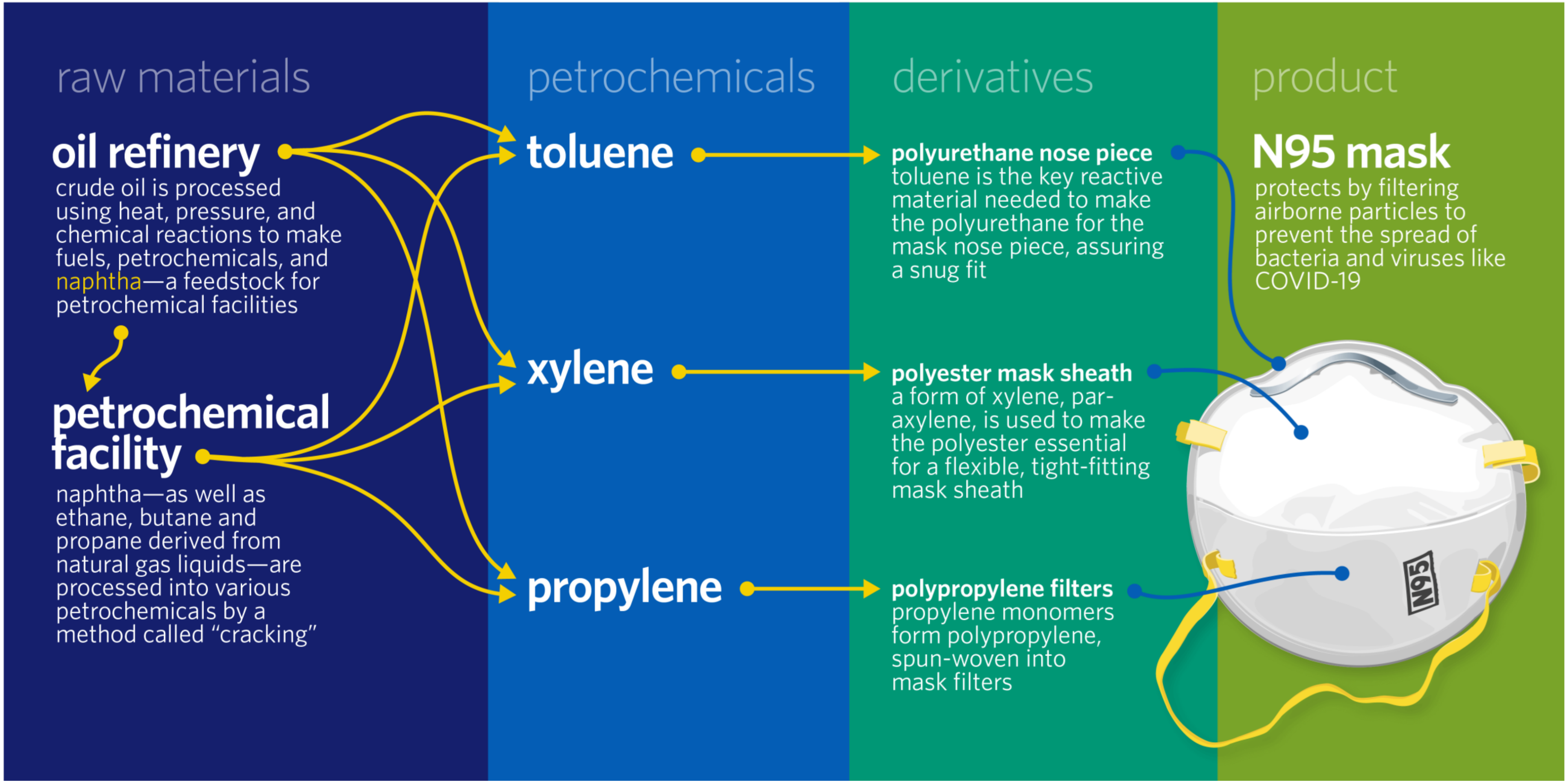
EPFL

- 500-1000 years degradation time
- Even then, it becomes microplastics.
- **50-75 trillion pieces of plastic** and microplastics in the ocean.

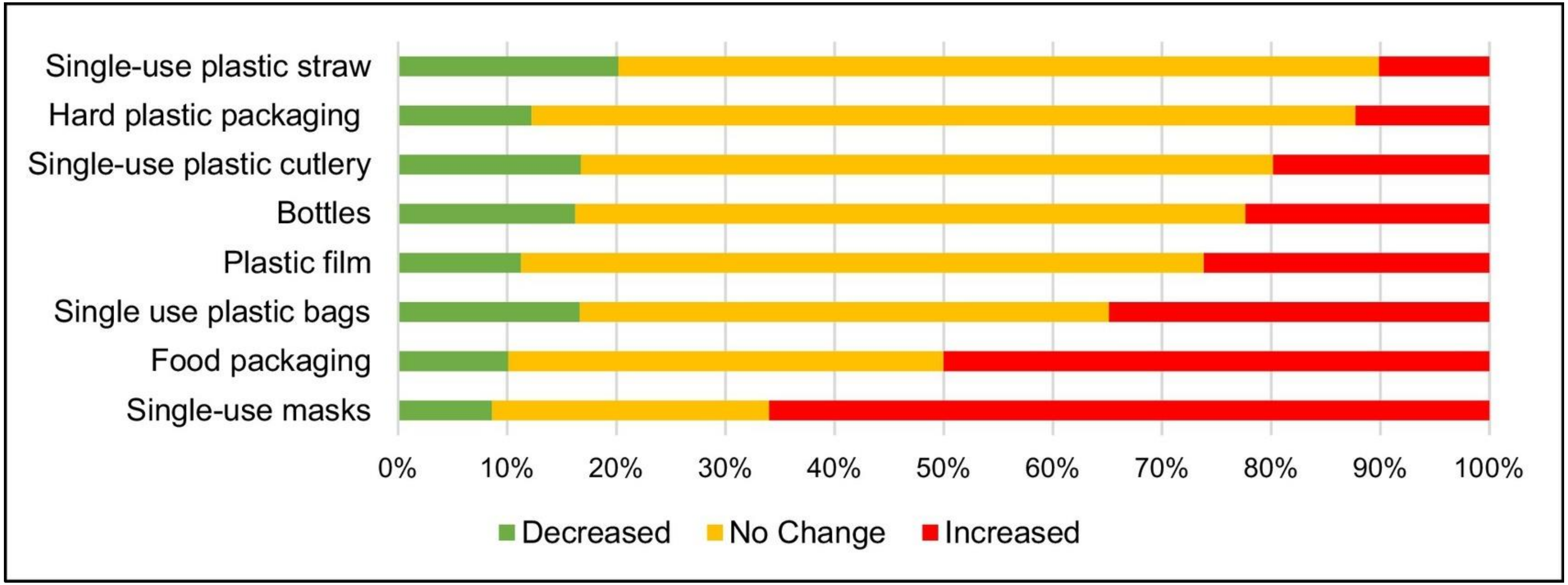



Great Pacific Garbage Patch
CALIFORNIA
HAWAII
~17 times the size of Switzerland

Pandemic plastics



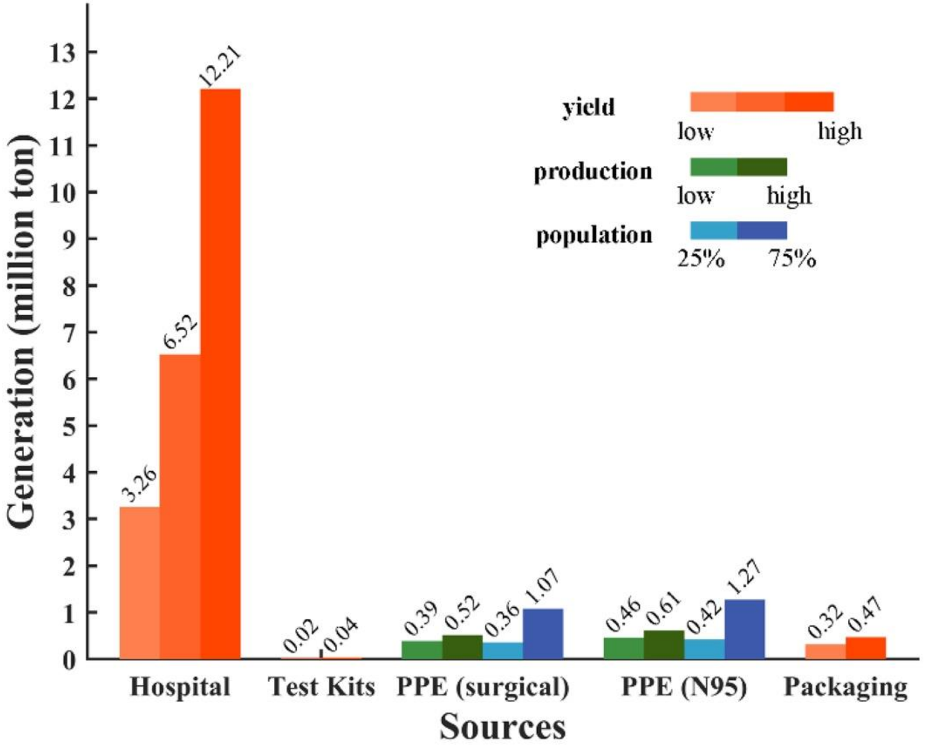
Pandemic plastics

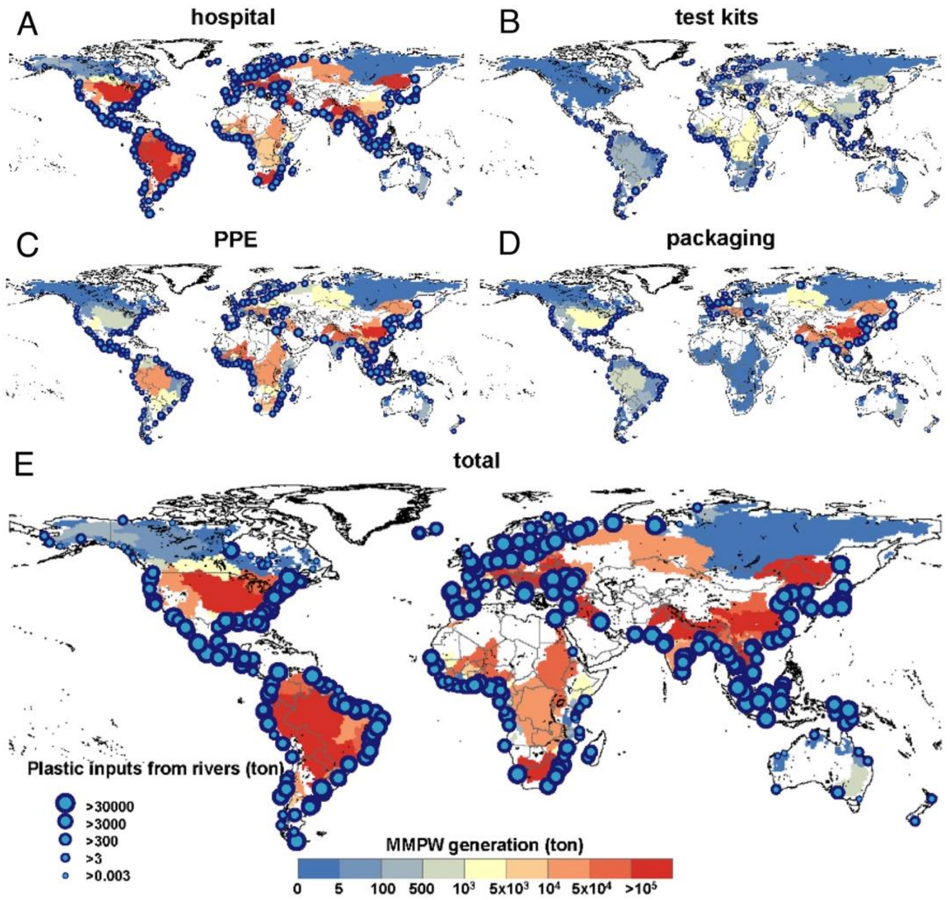


SUPs in the Pandemic

*Based on 202 respondents from 41 countries

Pandemic plastics in marine environment





- Excess mismanaged plastic waste (MMPW) 4.4-15.1 million tons (8.4 million tons best estimate)
- 87% from hospitals, 8% PPE by individuals, packaging 4.7%, test kits 0.3%

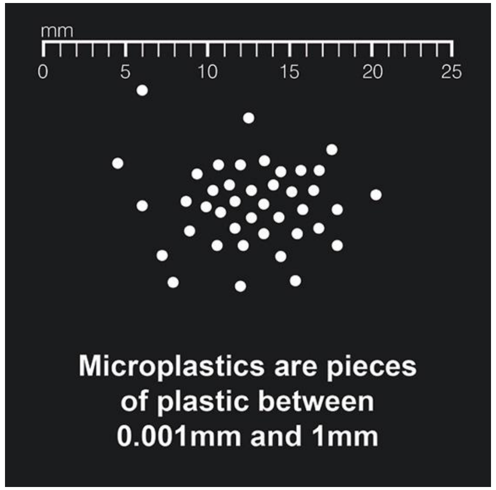
- Top river discharges from – Shatt al Arab, Indus, Yangtze River, Ganges, Danube, Amur
- 73% of discharge is from Asia, 11% from Europe

Pandemic Plastics in the Marine Environment

Persistent and ubiquitous

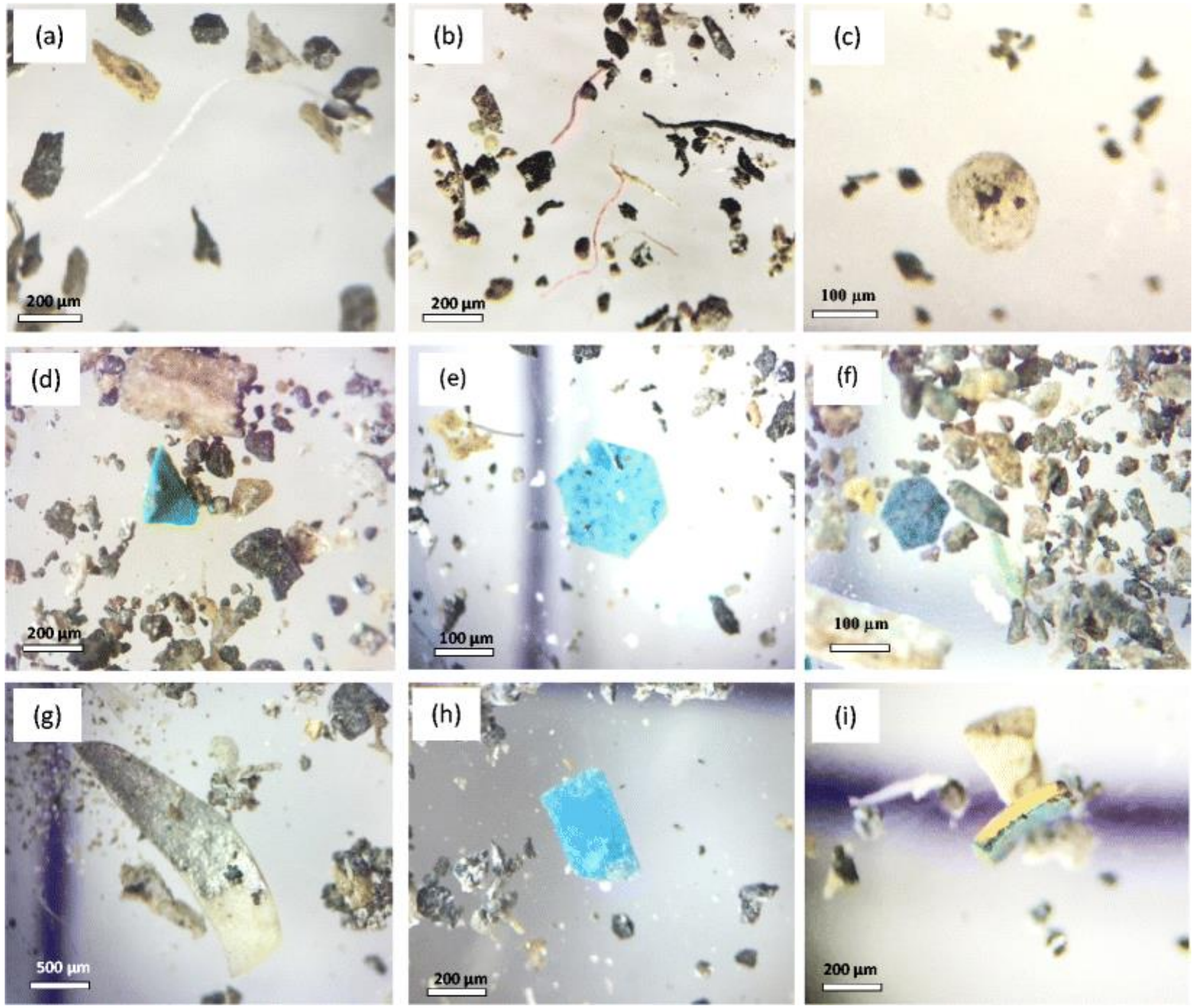
This collage of Arctic Ocean plastic, assembled by Andres Cozar, the lead author of a 2017 study "The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation," and his colleagues, shows just some of the estimated billions of pieces of plastic in ice-free Arctic waters. (Nunatsiaq News file photo)

Microplastics



1. Plastic litter
2. From washing synthetic clothes
3. Cosmetics
4. Toothpaste
5. Abandoned and Derelict vessels
6. Car tires and rubbers
7. Scrubbing agents in toiletries

Microplastics

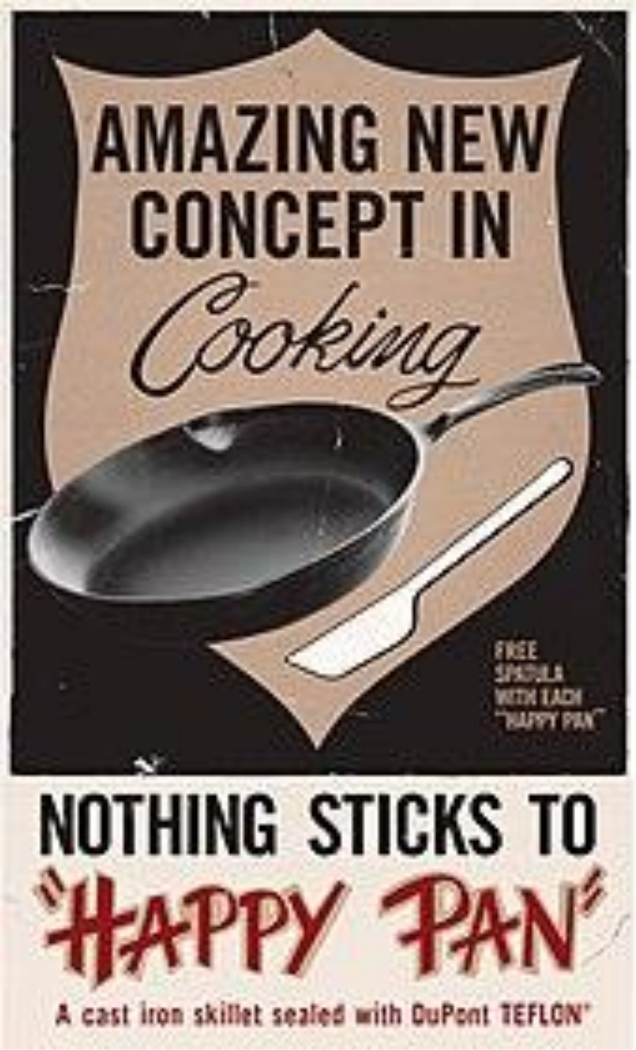


Microplastics in urban dust, Tehran

What went wrong?

- Perception of unlimited resources
- Plastics are largely stable and inert, e.g., PFAS “forever chemicals
- Complicated EoL due to versatility in chemistry and function
- Mismanaged waste
- Limited recycling infrastructure
- Limited technologies for sorting and separation
- Global movement of microplastics
- Shipping trash may not be the answer (see China’s ban on plastic import)
- Hard to compete! Plastic is cheap, highly functional, growing in demand!

Easy, drop-in solution probably not possible



Packaging…

Next week!

Problematic because of plastics & multimaterials, high volume, short life span, and recycling challenges

Key take aways

- Ceramics: main impacts related to mining, processing, and difficulties in recycling
- Plastics: it's complicated…
- Next week: Packaging and guest lecture on Sustainability at EPFL (what's the carbon footprint of a lab?)
- May 14: Glencore activity (please prioritize attendance – will not be recoded)
- May 21 and 30: Final project presentations! Summer in sight!