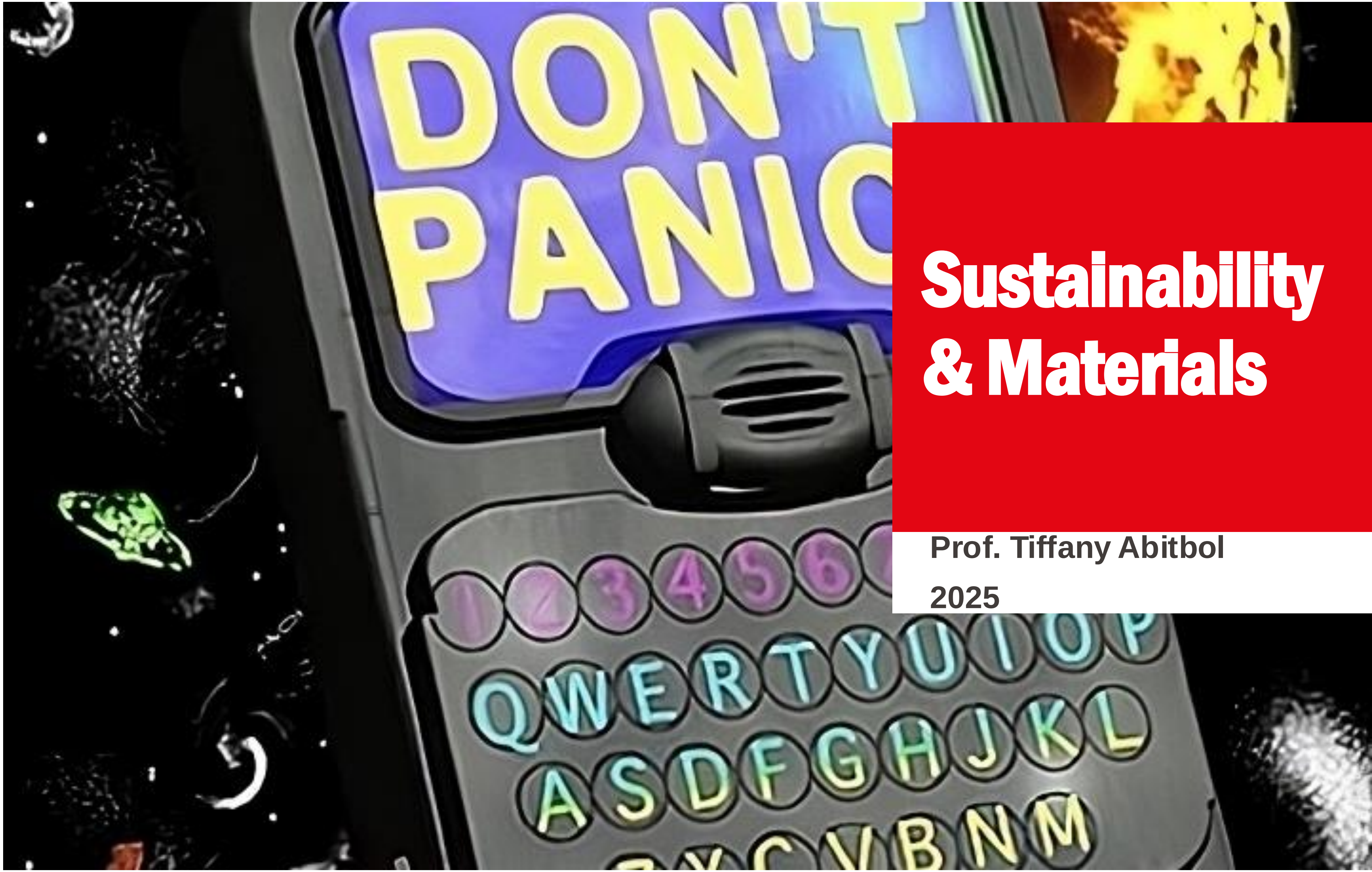
EPFL



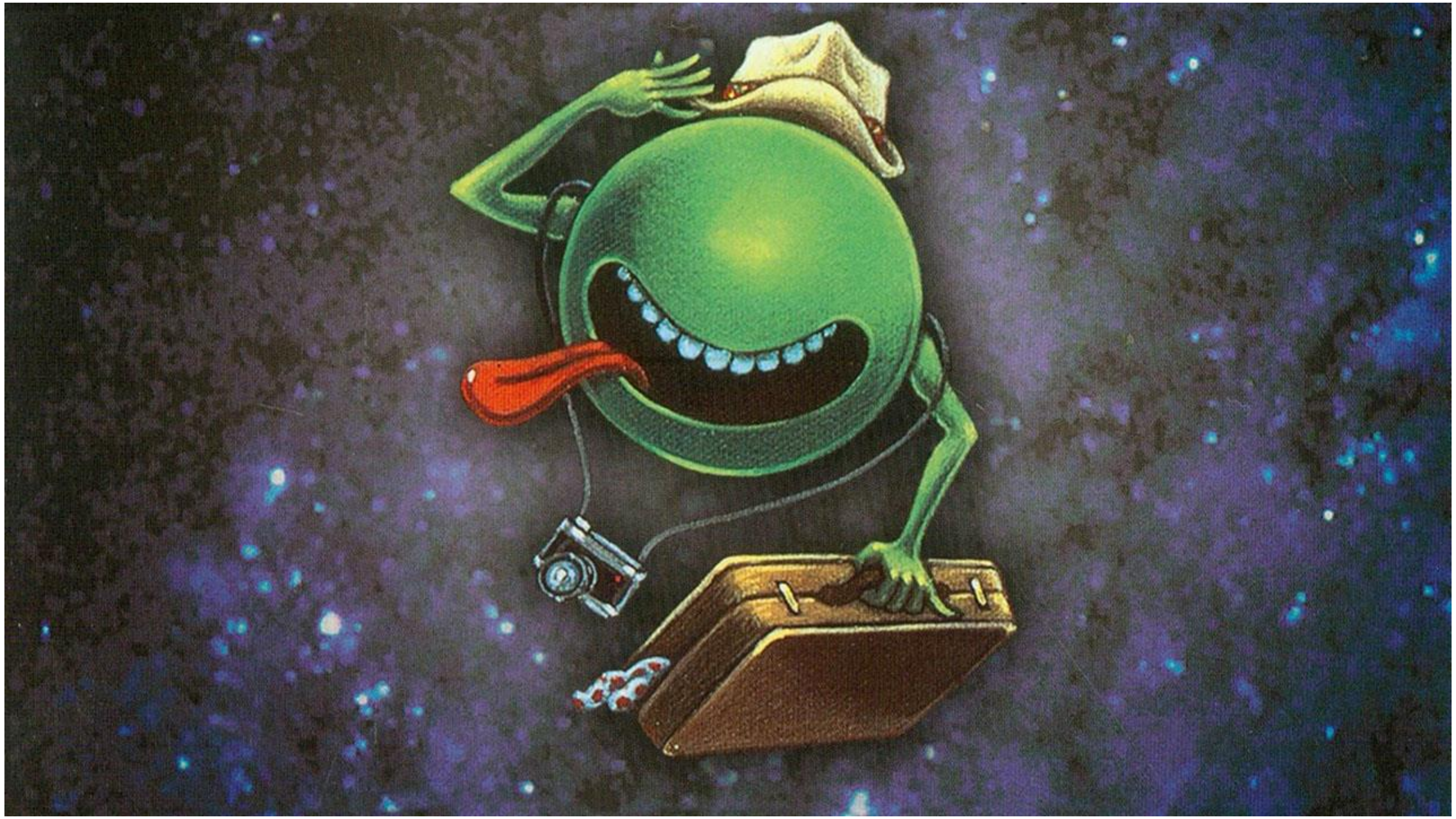
Sustainability & Materials

Prof. Tiffany Abitbol

2025

Welcome!

- Exploring the rich intersection of sustainability & materials science



[Hitchhiker's Guide to the Galaxy]

Who are we?

- Tiffany Abitbol (Professor in IMX)

MXD 230 (office)

tiffany.abitbol@epfl.ch

- Anya Koptelova (TA)

anna.koptelova@epfl.ch

- Inyoung Lee (TA)

Inyoung.lee@epfl.ch

Anya K

Inyoung L

Your prof

- **2004** McGill Chemistry
  BSc
  Prof. Derek Gray
- **2011** McGill Chemistry
  PhD
  Prof. Derek Gray
- **2012** McMaster Chem Eng
  Post Doc
  Prof. Emily Cranston
- **2014** HUJI Biotech
  Post Doc
  Prof. Oded Shoseyov
- **2017** RISE BioSci & Health
  Senior
  Scientist
- **2022** EPFL STI IMX
  Tenure track
  Industry Chair

Sustainable Materials Laboratory

BASF We create chemistry

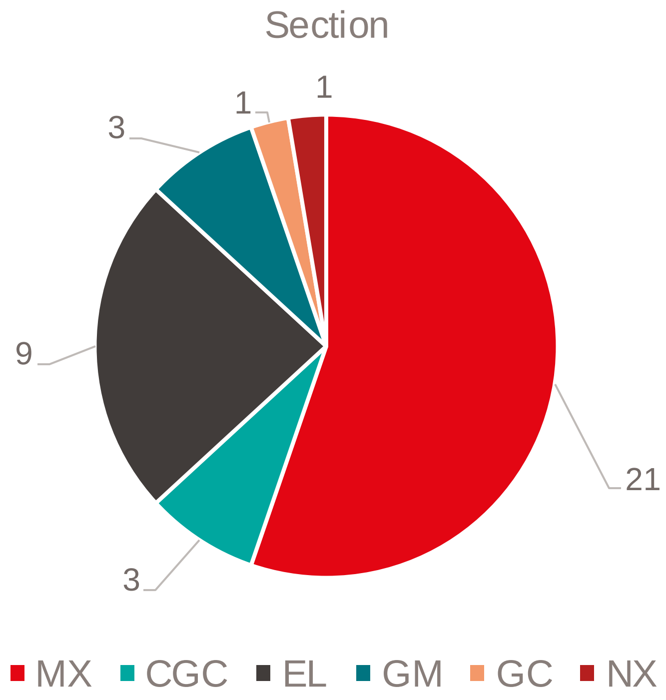
logitech

Nestlé

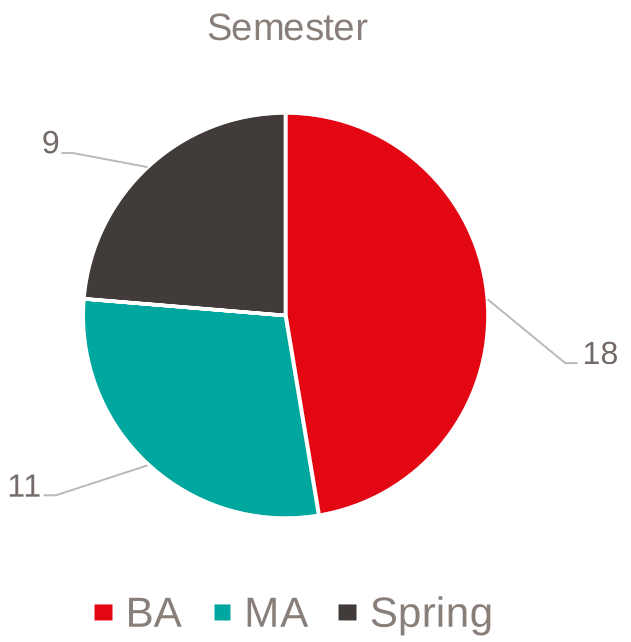
SIG

SML SUSTAINABLE MATERIALS LAB

Who are you? (38 students as of Feb 16, 2025)



55% MX
45% other



47% BA
53% other

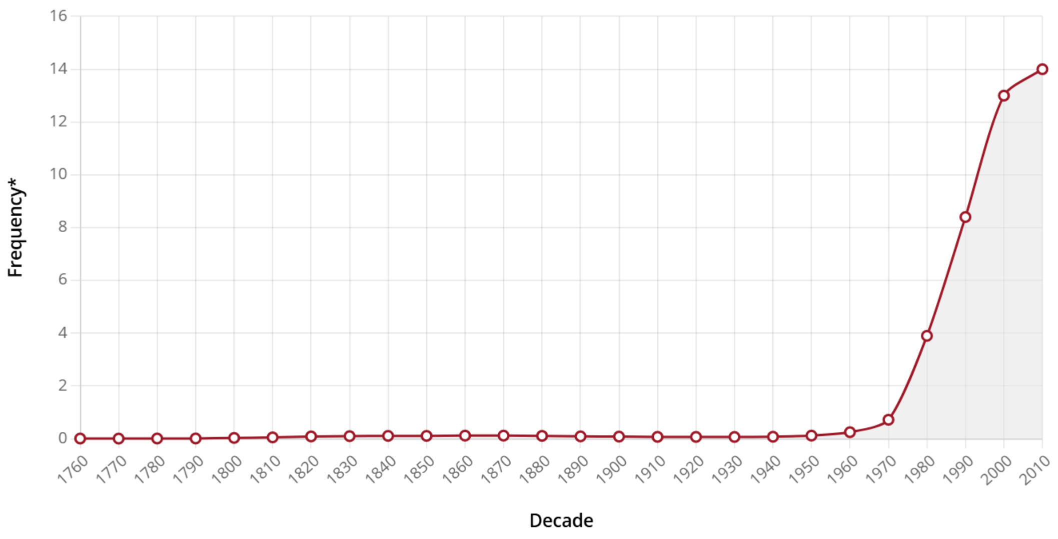
What does sustainability mean?

2.b. *spec.* The property of being environmentally sustainable; the degree to which a process or enterprise is able to be maintained or continued while avoiding the long-term depletion of natural resources. **1980–**

Show quotations

Cite | Historical thesaurus ▾

Frequency of *sustainable*, adj., 1760-2010



- About 8 times per million words

[Sustainable from OED]

What is meant by materials?

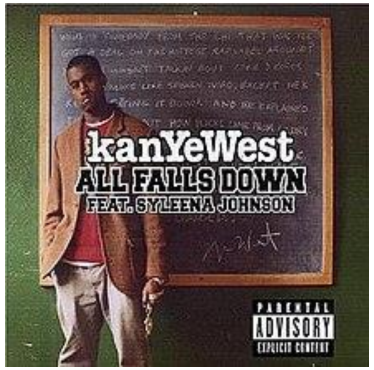
A **material** is a substance or mixture of substances that constitutes an object. Materials can be pure or impure, living or non-living matter. Materials can be classified on the basis of their physical and chemical properties, or on their geological origin or biological function.

Materials Wiki

Materialism in pop culture

George Harrison 1973

Madonna 1985



Kayne 2004

What’s this class about?

- A survey of evolving topics at the intersection of sustainability & materials science, starting with the basics
- Resources are at the heart of all materials
- How can *we* manage *our* resource use in a sustainable way?
- What are emerging technologies that can help *us* to do so?
- Who is “we”? Who is ”us”?
- Complex geopolitics

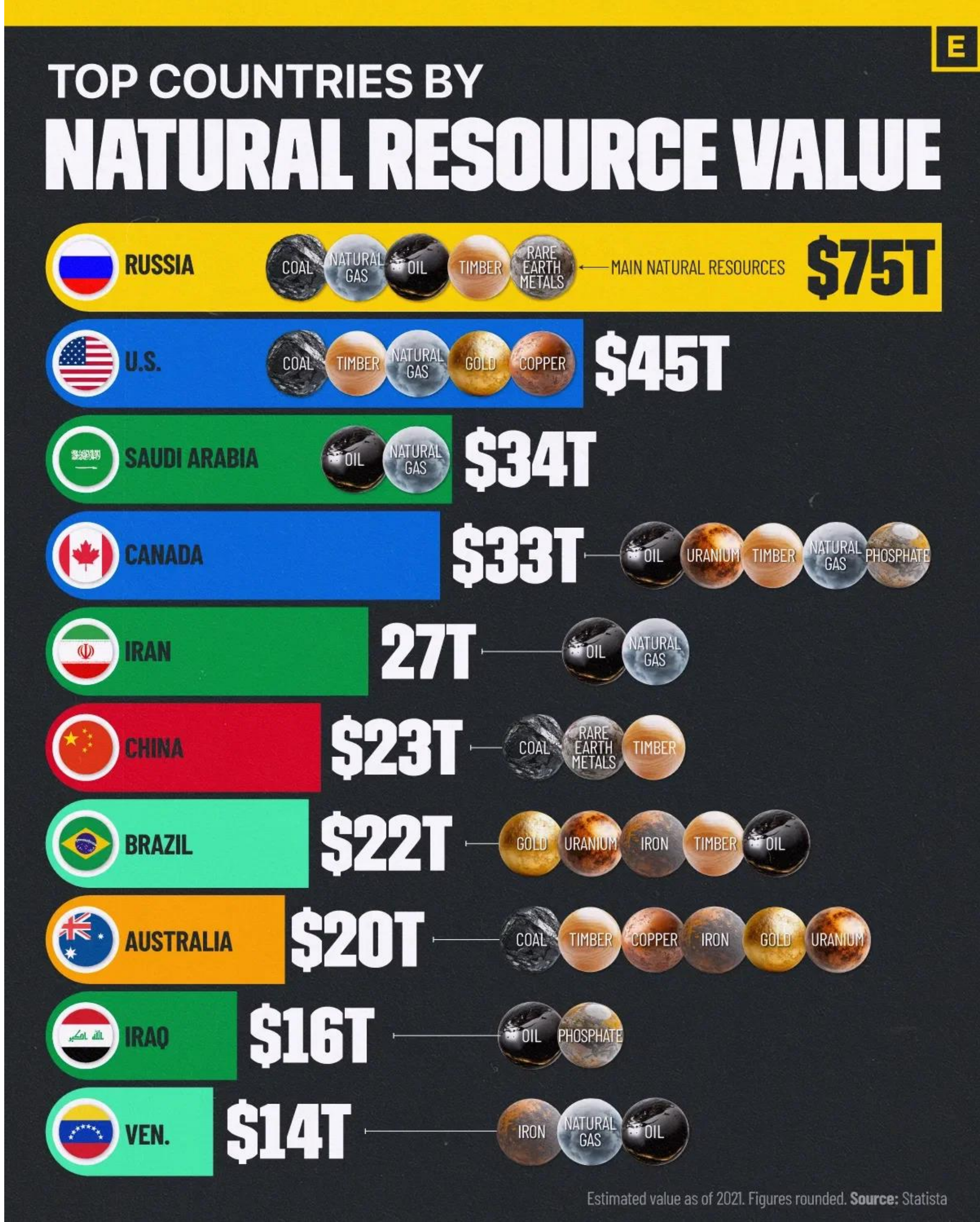
Where the resources at?

- Mineral resource – is an estimate of the minerals in a specific locations based on geological projections

- Mineral reserve – the % of the mineral resources that economically viable to extract

- Even if a country has a given resource, they may not have the infrastructure to mine, refine or process the resource, leading to material dependencies on foreign countries

- Can occur for resources that are deemed ”critical”



Critical raw materials (CRM) sneak peak

- Critical raw materials are defined in terms of their economic importance and supply risk
- These materials often have no/few substitutes available

• Material	• World producers (2022)	• Important use
• Metallurgical coal	• China, Australia, Russia, India, United States	• Steelmaking
• Lithium	• Australia, Chile, China, Argentina, Brazil	• Various batteries, lubricants
• Phosphate rock	• China, Morocco, Uzbekistan, Russia, Jordan	• Fertilizer from phosphate rock

- Steel is strategic to many key industries, with Europe relying on imports to meet demands
- Europe, lacks mining and refining infrastructure (but developing)
- Only very small amounts of phosphate rock are available in Europe

CRM's EU

Natural Resources Canada

CRM Alliance

General logistics

- **Where?** MXF 1
- **When?** Wednesdays 9-12
- **Office hours in MXD 230:** 12-13 on Wednesdays (unless otherwise indicated)
- **Communication channels**: Moodle (primary)
- **Format:** Lectures, guest lectures and activities, exercises, midterm, and group project
- **Resources:** optional readings on most weeks, lecture slides will be posted in advance when possible – *see Moodle*
- **Grading:** 2/6 exercises; 2/6 midterm; 2/6 group project

Midterm

- April 9 from 9-11 am, in class
- Evaluation of material covered in class
- Required reading for midterm: Chapters 1-3 from Materials and the Environment: Eco-informed Material Choice by Michael F. Ashby; available online at EPFL library
- Link to Book

Exercise

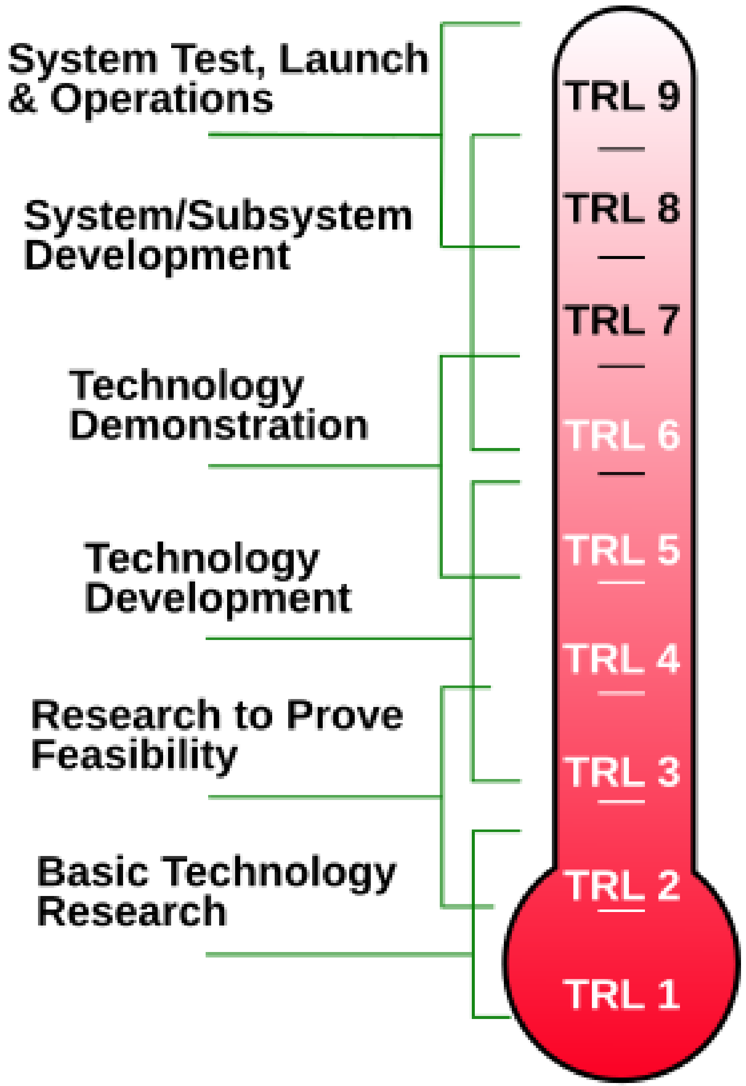
- This year less is more
- One assignment ONLY, where you will get the opportunity to take a deep dive on *current event* topic of your choice that relates to the course material
- Individual work – your chance to shine!
- More details will be provided in the coming weeks

Project

- Group presentation
- Assigned groups (after add/drop deadline) on Moodle
- Research and pitch an emerging and potentially ***disruptive*** technology that is making or has the potential to make an impact in the big world of “Sustainability & Materials”
- The technology can be at any ***technology readiness level*** (TRL)
- It can be from academia, start-up, industry, your idea

TRL

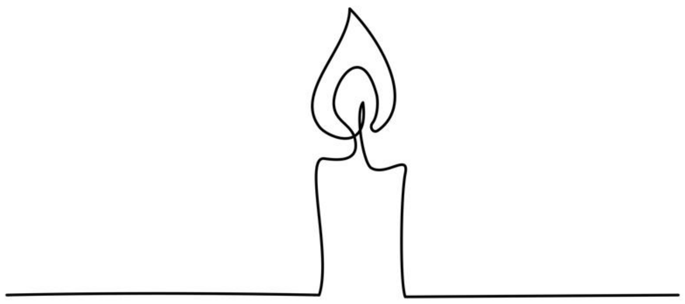
- Scale to assess the maturity of a technology
- Developed at NASA in the 1970s
- 1 is the least mature: basic principles observed and reported
- 9 is the most mature: demonstrated in an operational environment
- Commonly used term



TRL

What is a disruptive technology?

- A technology that abruptly changes the way we operate



Life changing innovations

“If I had asked people what they wanted, they would have said faster horses.”

-supposedly a quote by Henry Ford, of automobile fame

Ford Model T
1st mass-affordable automobile

- The wheel
- Assembly lines
- Automation
- Airplanes
- Light bulbs
- Cars
- Plastics
- TV
- VCR
- Polaroid cameras
- Personal computers
- The internet
- Smartphones
- Electric vehicles
- Generative AI
- Blockchain currency
- Menstrual cups, other period products

Life changing innovations

Assembly lines	The wheel	Radio	Polaroid cameras	Menstrual cups
Automation	Cars, airplanes	TV/VCR	Personal computers	Crypto
Roller blades	Plastics	Light bulbs	Smartphone, portable devices	AI

- My list ☺
- Miss anything?
- Any ideas on what’s coming?

Spaceship Earth

R. Buckminster Fuller

"He felt that all human beings were passengers on **Spaceship Earth**, and, like the crew of a large ship, people had to work together in order to keep the planet functioning properly…

Bucky tried to convince people to take the initiative to develop comprehensive design science thinking to begin to address global problems such as poverty, inadequate housing, and unequal distribution of resources."

Montreal Biosphere; designed in 1964 by American architect R. Buckminster Fuller for the US Pavilion at the World Expo 67

The Earth System (and Subsystems)

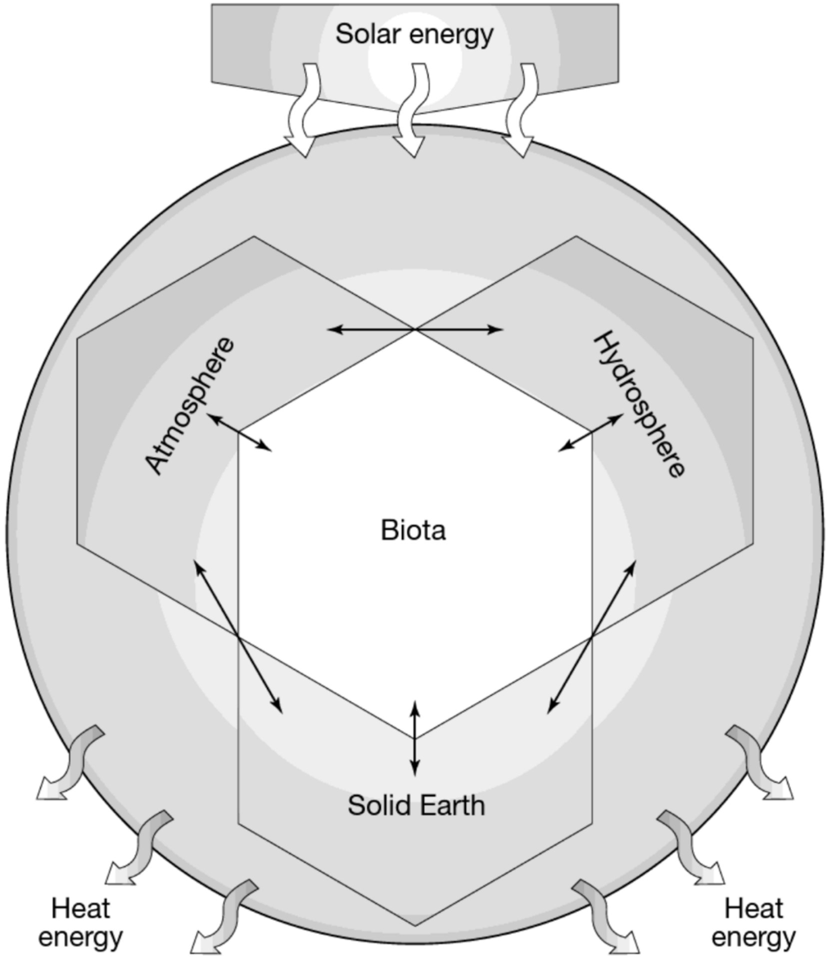


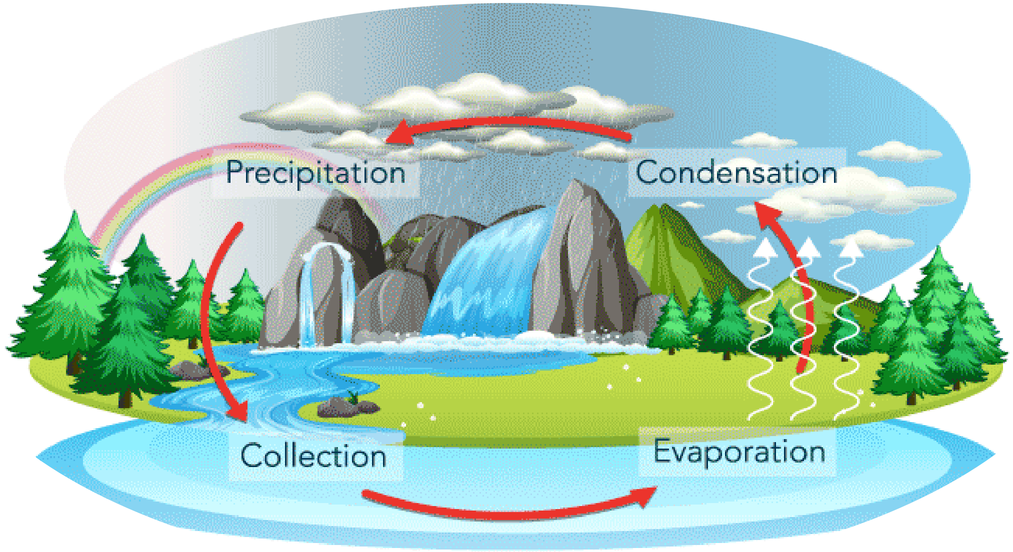
FIGURE 1 Schematic diagram of the Earth system, showing interactions among its four components. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

- The earth as a *closed* system, where materials cycle between subsystems: the lithosphere (solid Earth), atmosphere, hydrosphere, and biosphere (living part of Earth)
- Why system? Processes on Earth interact with one another, subsystems are interconnected
- Why closed system? Energy can enter/exit, not matter (except meteorites)
- Why is the Earth habitable?
  - Right distance from the Sun
  - Magnetosphere (protects from solar particle radiation)
  - Atmosphere keeps us warm
  - Right chemical ingredients (water, carbon)
  - Cyclic processes/subsystem interactions that build up mineral and energy resources

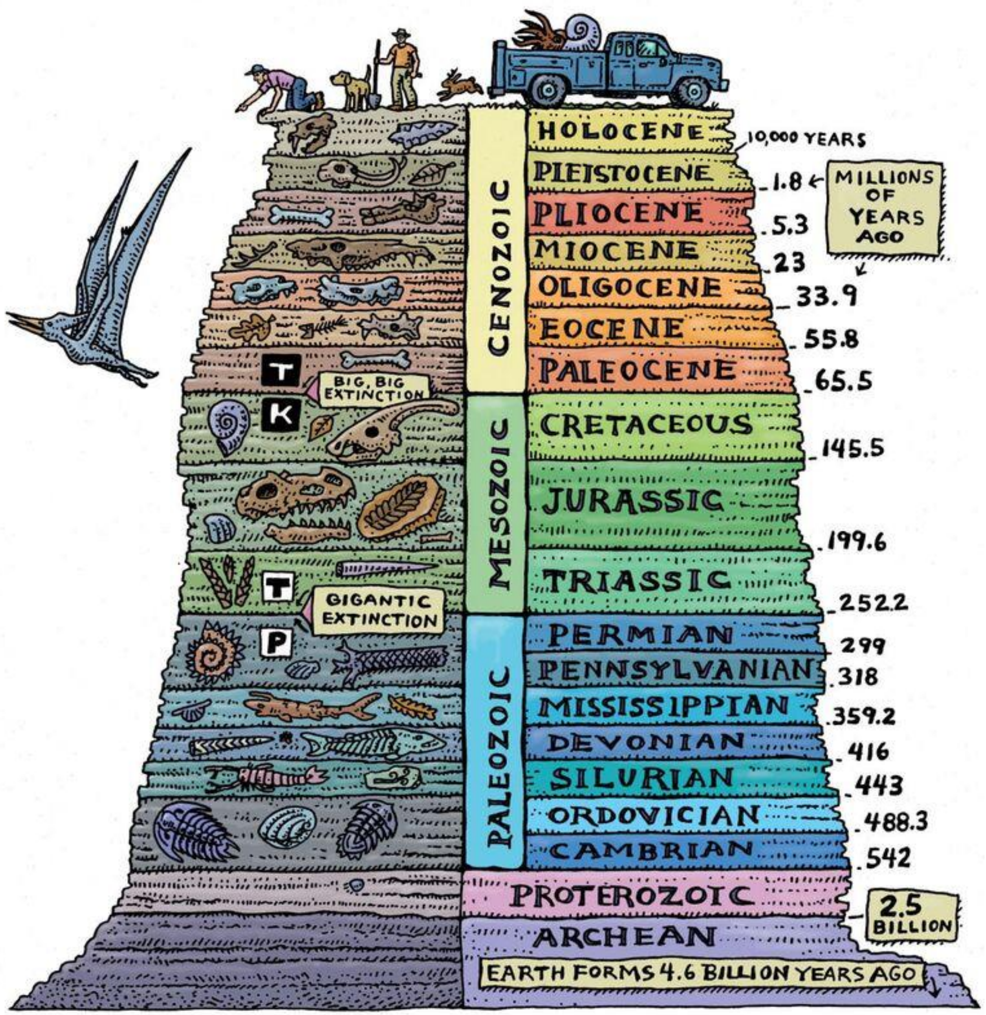
Earth cycles – how subsystems communicate

- Cycling of matter and energy between the different global reservoirs – biosphere, atmosphere, hydrosphere, solid earth
- The rock cycle; how rocks are formed
- The water cycle; how water cycles between the atmosphere, hydrosphere and biosphere
- The nutrient cycle; e.g., carbon, nitrogen, oxygen
- We will discuss aspects of some key cycles later…

4 main steps of water cycle



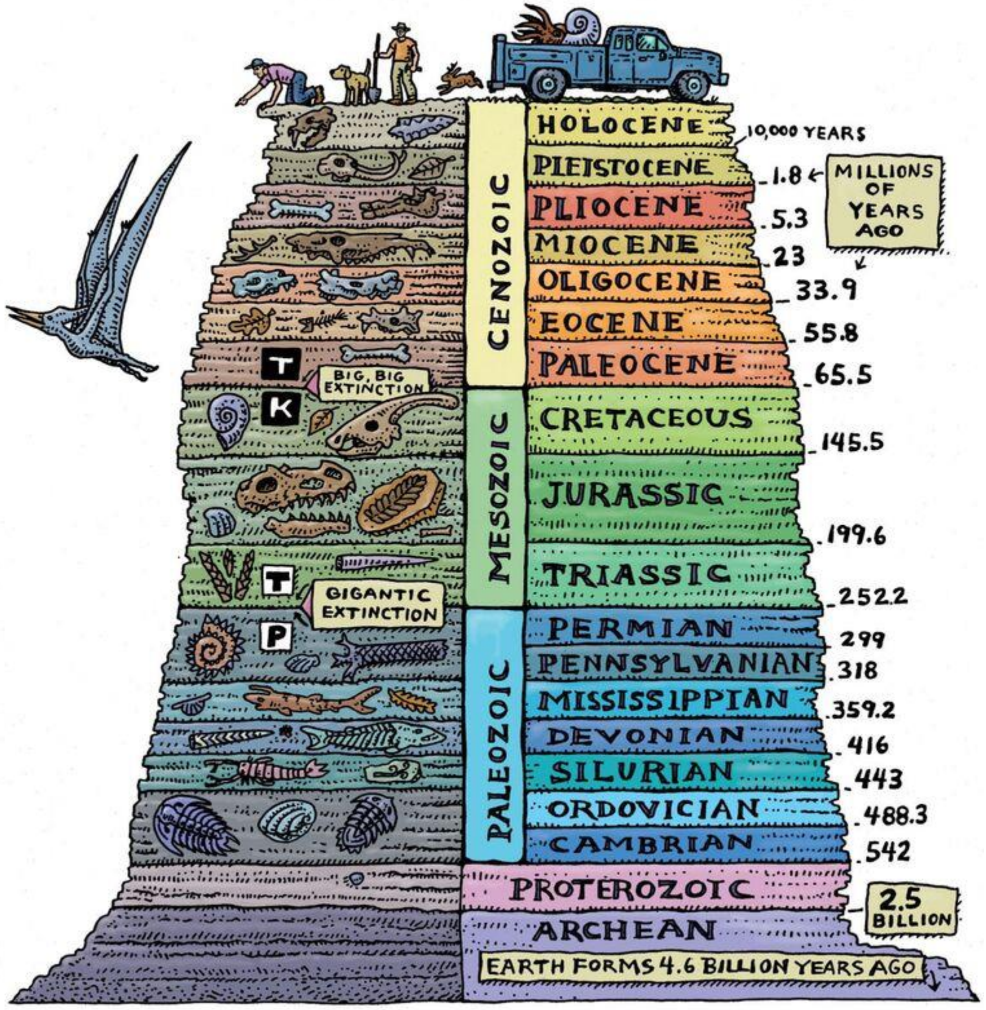
The geologic time scale



Geologic time scale

- Earth history organized by the order and positions of strata
- Eras, subdivided by periods
- Oldest at bottom and youngest at top
- Relates changes in the Earth's geology and biota to time

Where are we now?

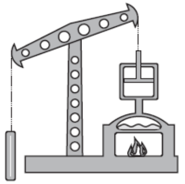
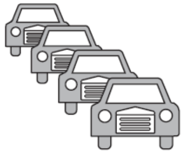
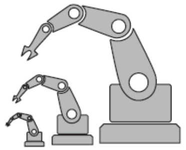


Geologic time scale

- We are in the ***Holocene*** - past 10,000 years, period of environmental stability
- ***Anthropocene*** – *unofficial epoch*, most recent period in the Earth's history, where human activity started to significantly disrupt the climate and ecosystems
- Anthropocene began in 18th century at start of Britain's industrial revolution with burning of fossil fuels, other causes: agriculture, urbanization, deforestation, pollution
- ***Plasticene*** – "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)."

Anthropocene
Plasticene

The materials time scale

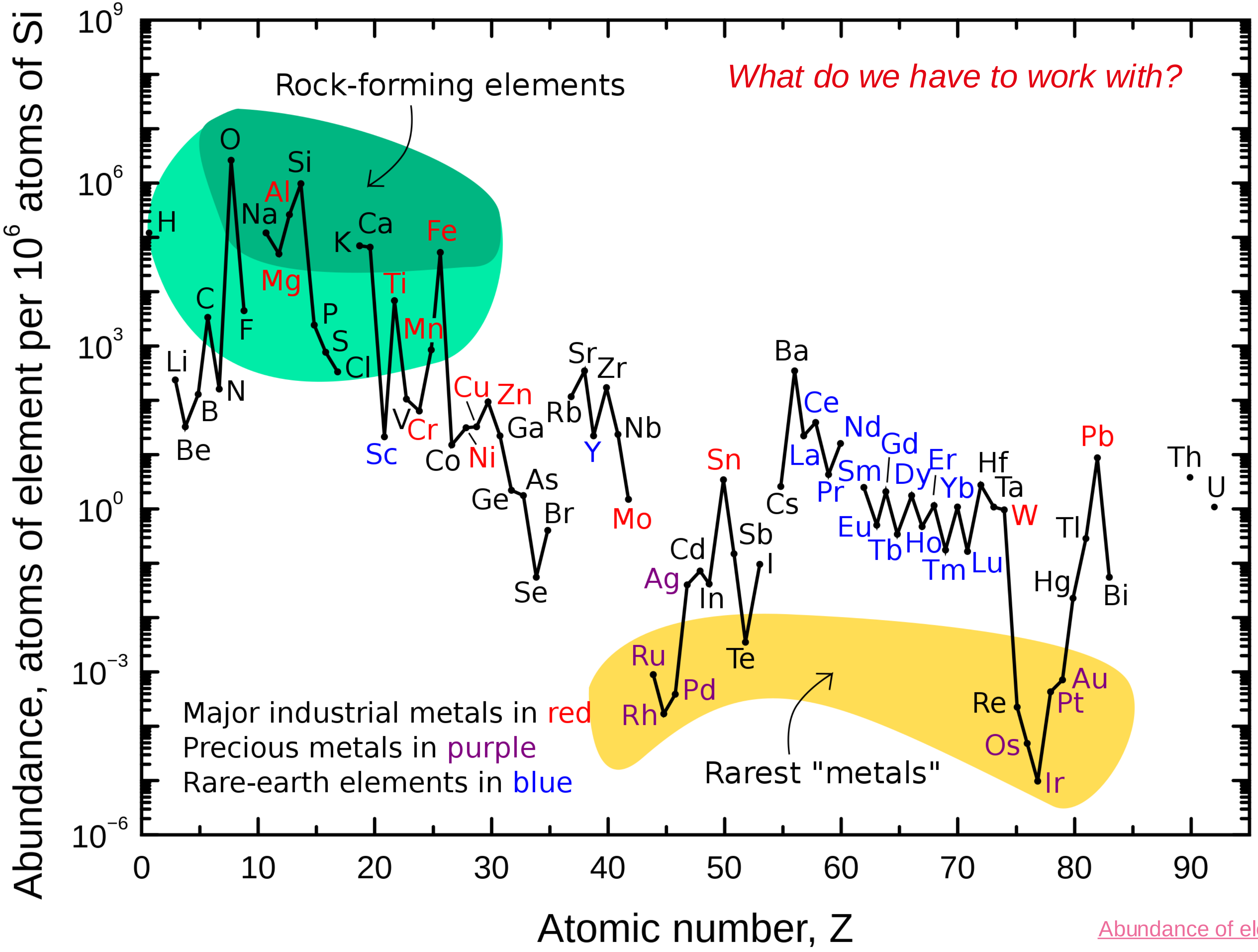
Industrial revolution	Characteristics	Enabling materials
0 	**2.5 million years BCE** • Tools • Changed subsistence patterns	• Wood • Stone, particularly flint • Bone, Shell, • Leather
1 	**1760 onward** • Water and steam power • Mechanization • Industrial growth	• Coal, water • Cast iron • Brass, Bronze
2 	**1810 onward** • Mass production • Electric power • Urbanization	• Oil • Steel • Rubber, Glass • Magnetic materials
3 	**1960 onward** • Digital control • Automation • Globalization	Polymers, • Silicon • Aluminum • Advanced alloys
4 	**Today: Industry 4.0** • Connectivity, IoT • Autonomy • Big data • Artificial intelligence	**Materials 4.0** • Electrical material • Optical materials • Magnetic material • Sensing materials • Actuating materials

- Materials have been at the forefront of human development, enabling the technologies required for development

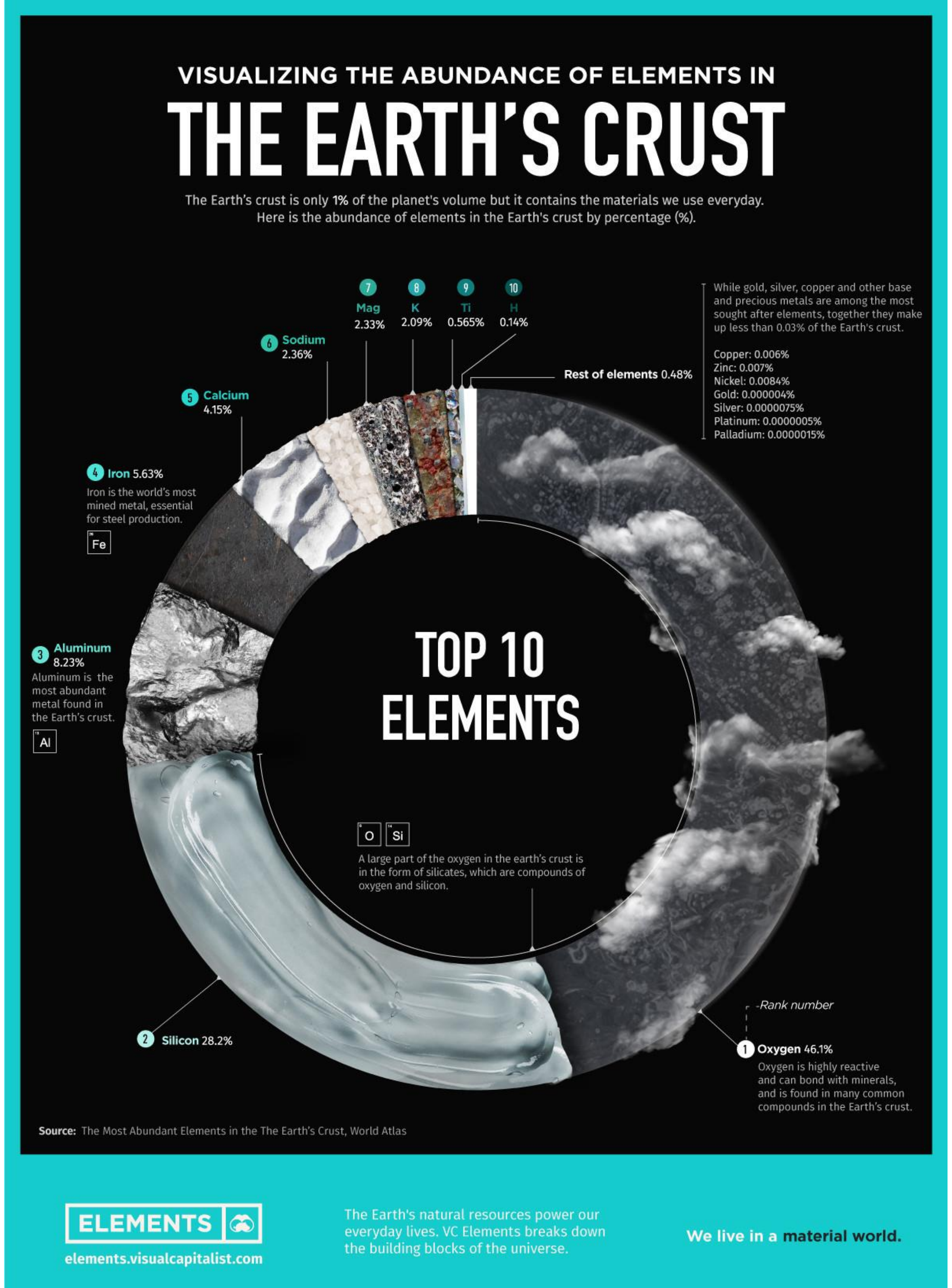
- Humankind is dependent on materials resources, increasingly non-renewable resources

- Non-renewable materials are *just that* non-renewable and finite

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 1.



Abundance of elements in crust

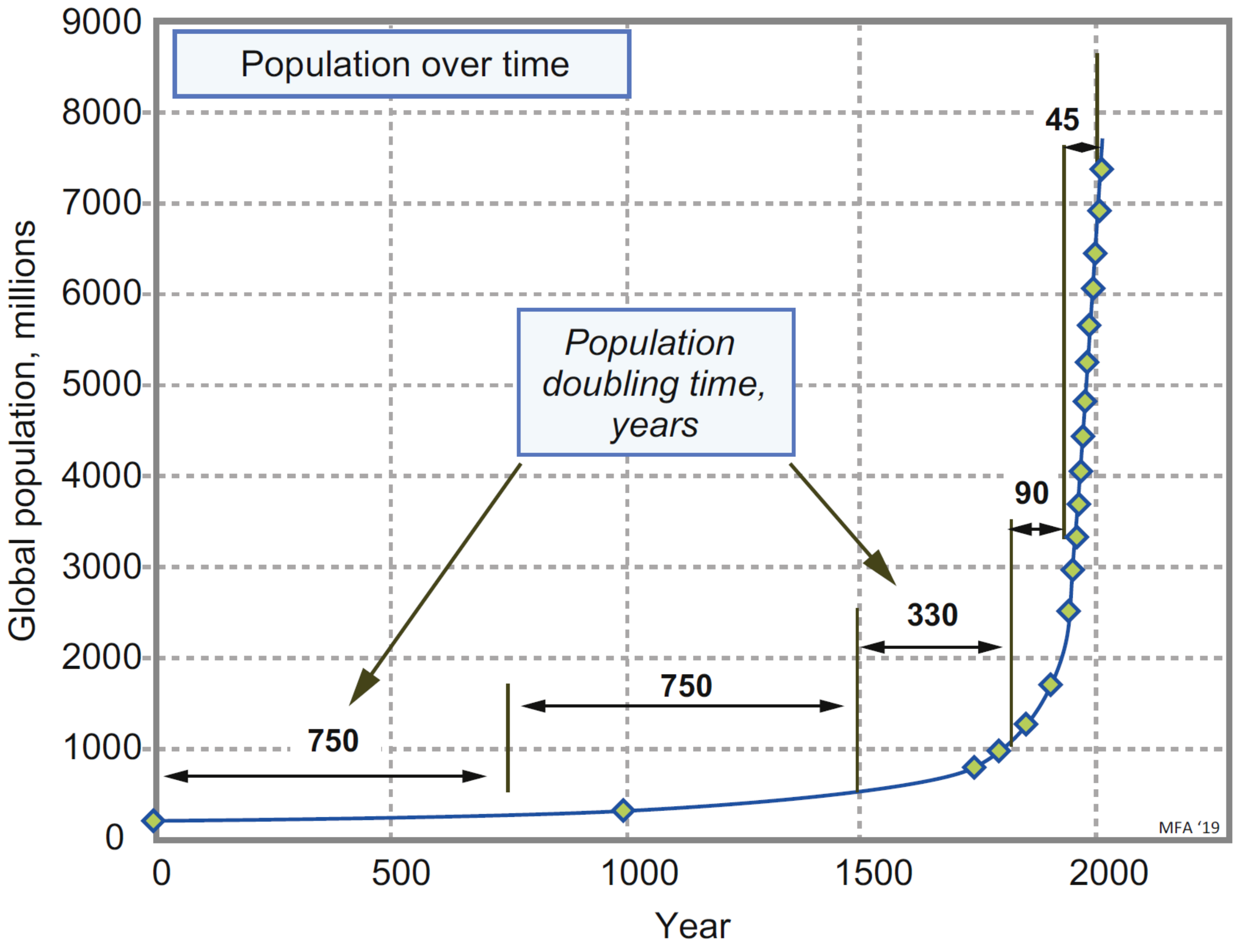


- 92 usable elements
- Mostly metals
- Mostly found as oxides, sulfides, carbonates
- Mixed with other stuff
- Need to be *mined*, *refined, processed*
- Highly energy intensive
- The more dilute the ore, the more intensive the entire process (*environmental and social implications!*)

Crust visualization

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2

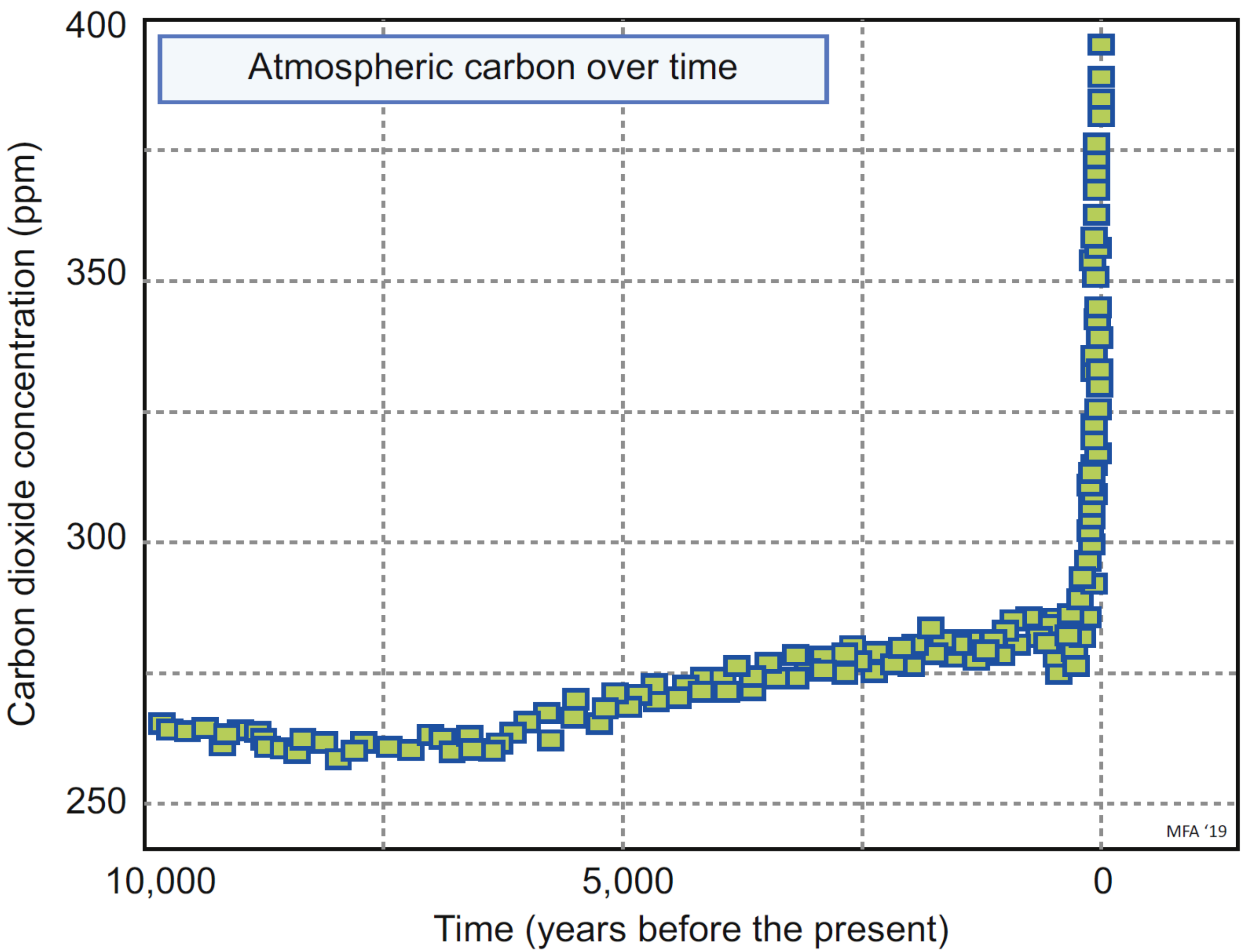
Since the industrial revolution…



- Exponential growth has a constant doubling time
- After 1500, the doubling time halves, then halves again, and again
- This is referred to as *explosive population growth*
- Population projected 9.8B by 2050

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 1.

Since the industrial revolution…



- Accelerated increase in atmospheric CO_2
- Increasingly strong evidence that rise in temperatures is linked to anthropogenic green house gas emissions

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 1.

Renewable vs. non-renewable

- Renewable: a resource that can be replenished at a rate that is faster than its rate of consumption (e.g., biomass, water) – a question of time scale and consumption rate

- Non-renewable: a resource that is consumed at a faster rate than the rate it can be regenerated (e.g., coal, uranium)

EPFL

Since the industrial revolution…

- As little as 300 y/ago, mankind depended almost exclusively on renewable materials (wood, leather, bone, natural fibers) and stone, until the 20th century

- Implications of dependence
  - Where are these resources located?
  - What happens when resources become limited?
  - What if demands exceed supply or supply is capped by producers?

- Environmental, economic, and social consequences, especially considering growing populations and demands for resources that are being depleted

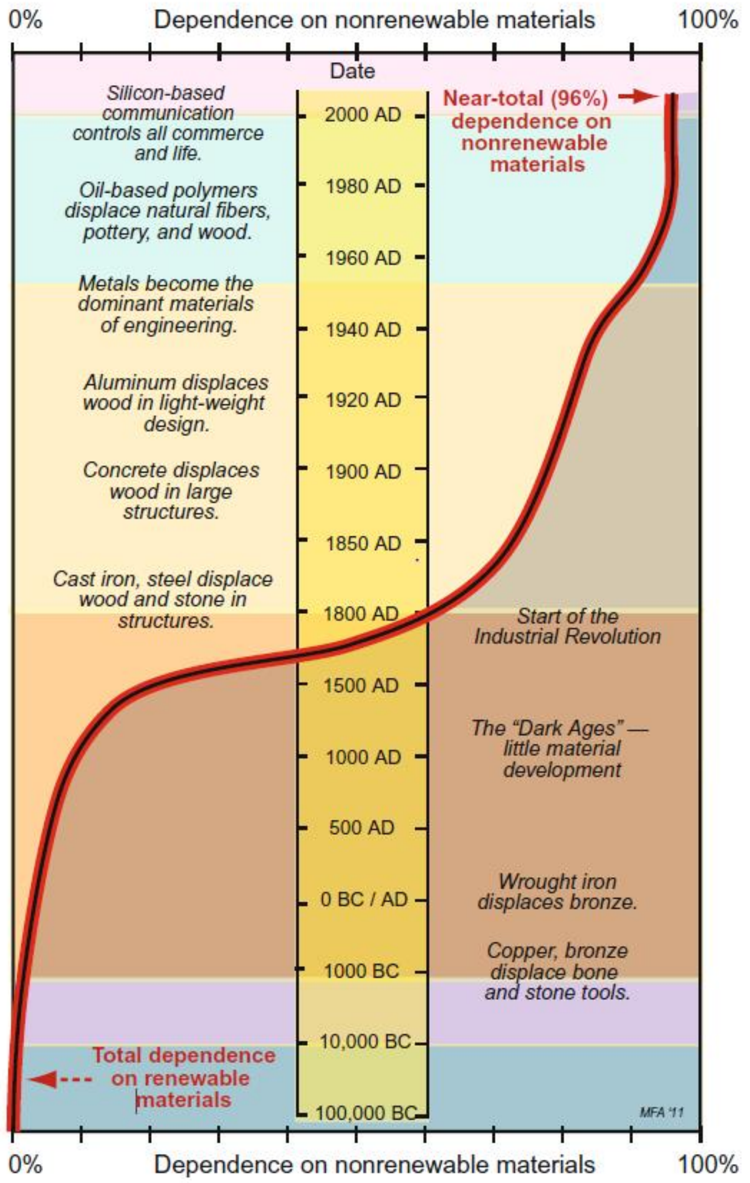
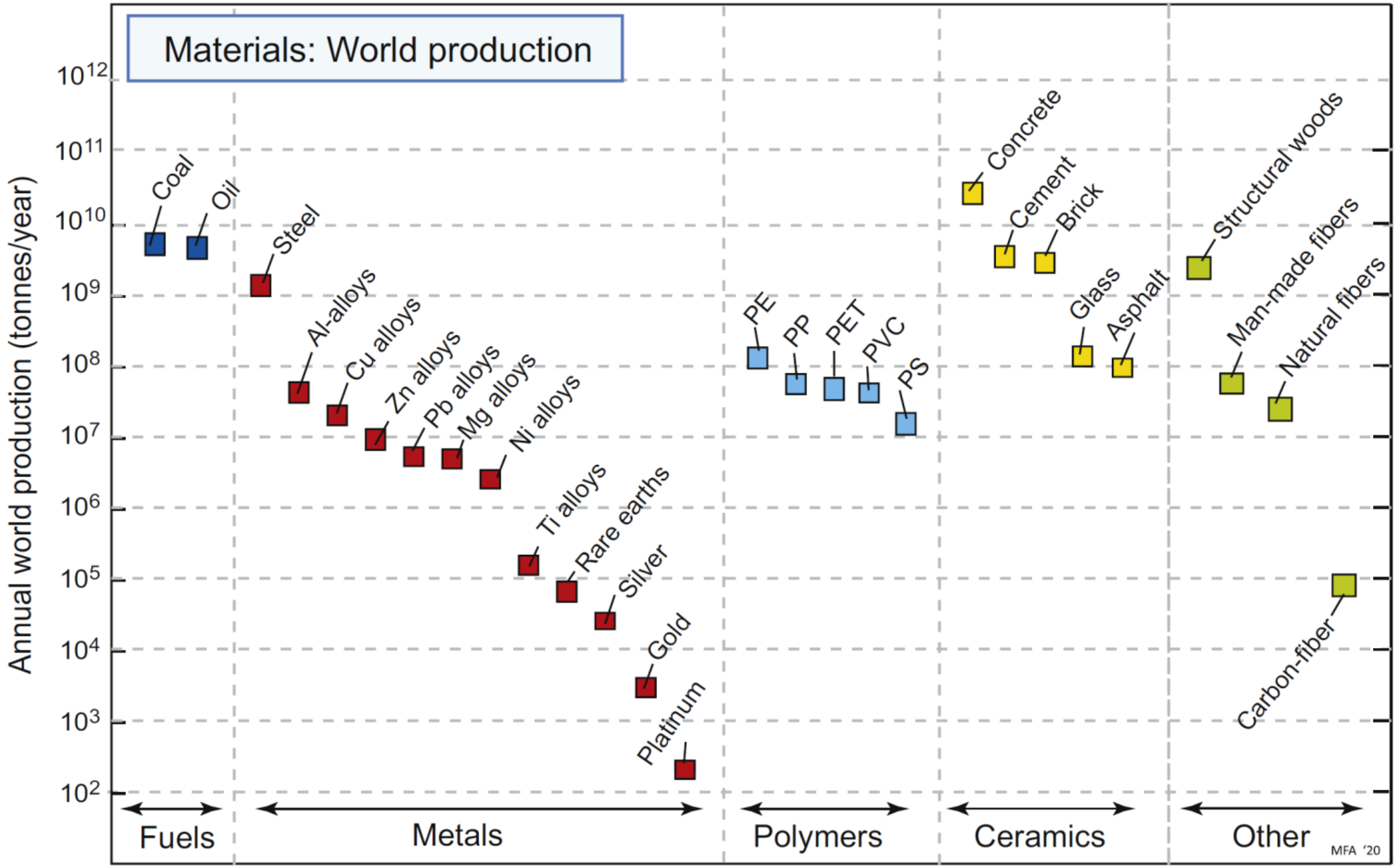


FIGURE 1.2 *The increasing dependence on nonrenewable materials over time, rising to 96% by weight today. This dependence is not of concern when resources are plentiful but is an emerging problem as they become scarce. (Data in part from USGS [2002].)*

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 1.

Since the industrial revolution…



Man-made fibers: predominantly polyester, with lesser quantities of nylon, acrylic and PP
Natural fibers: cotton and wool

- Average consumption of *2.7 tonnes* of materials per person per year
- As little as 50 years ago, few plastics were produced

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

Key ingredients for materials: #1 Resources

- Extraction of raw materials (even if we have the raw material, is extraction financially and ecologically feasible?)

- Transformation and processing into finished products

- Exact steps depends on material/product

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 1.

Mining – four main types

- **Surface mines** are typically used for more shallow and less valuable deposits, close to surface

- **Underground mines** are more expensive and are often used to reach deeper deposits – *coal, iron ore, oil, diamonds*

- **Placer mining** is used to sift out valuable metals from sediments in river channels, beach sands, or other environments.

- **In-situ mining** involves dissolving the mineral resource in place then processing it at the surface without moving rock from the ground, can be done above or below ground – *gold, silver, zinc, lead, uranium, and other metals*

Main Methods of Mining

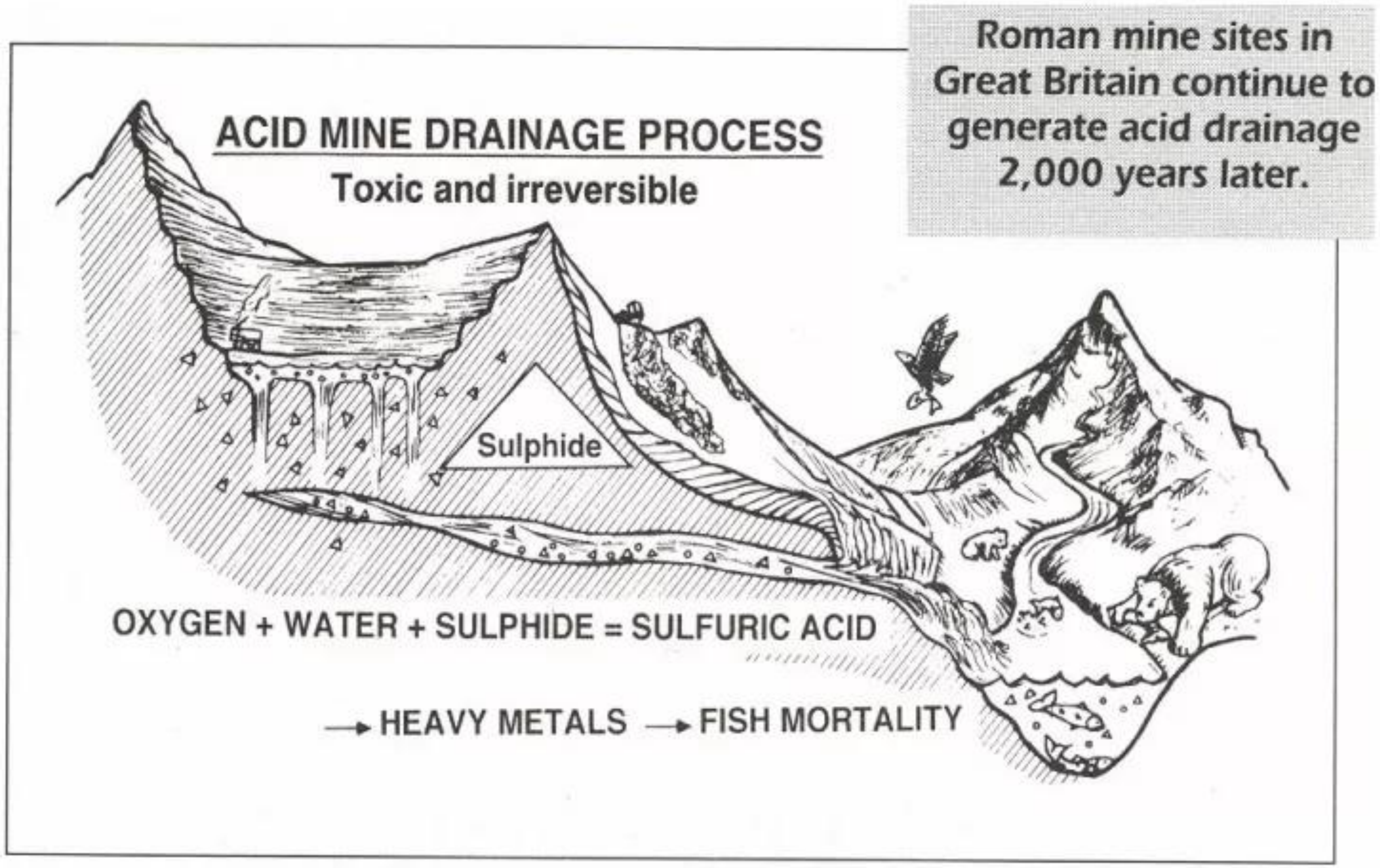
Main surface mining approaches and challenges

Surface mining	How?	Environmental impact
Strip Mining	Land is cleared or stripped, mainly used for coal	All vegetation removed in process; tailings added to pit with soil can be a source of toxic leaching
Mountain top removal	Mountains are removed and exposed area is mined	Permanently alters landscape and ecosystem; landslides
Open-pit mining	Large areas of land are excavated to form a pit that is mined	Permanently alters landscape and ecosystem; sinkholes, flooding, toxic leaching

Surface mining

Mining and water pollution

- Mining can pollute water
- Metal mines, often rich in sulfides
- Exposure of sulfides to water and air produces sulfuric acid
- Acid can dissolve harmful metals (As) from surrounding rock
- Acidify waterways
- Different approaches can be applied to remediate, e.g., increase pH



Acid mine drainage

Acid mine drainage: Challenges and opportunities

Estimated cost of metal extraction

$C_m \approx 10/G$

Where:

- C_m is the cost of extraction ($/kg)
- G is the ore grade (%); tonnes of metal per tonnes of ore mined

Example:
If copper is extracted from an ore with a grade equal to its average concentration (50 ppm)

$C_m \approx 10/0.005 \approx 2000$ $/kg

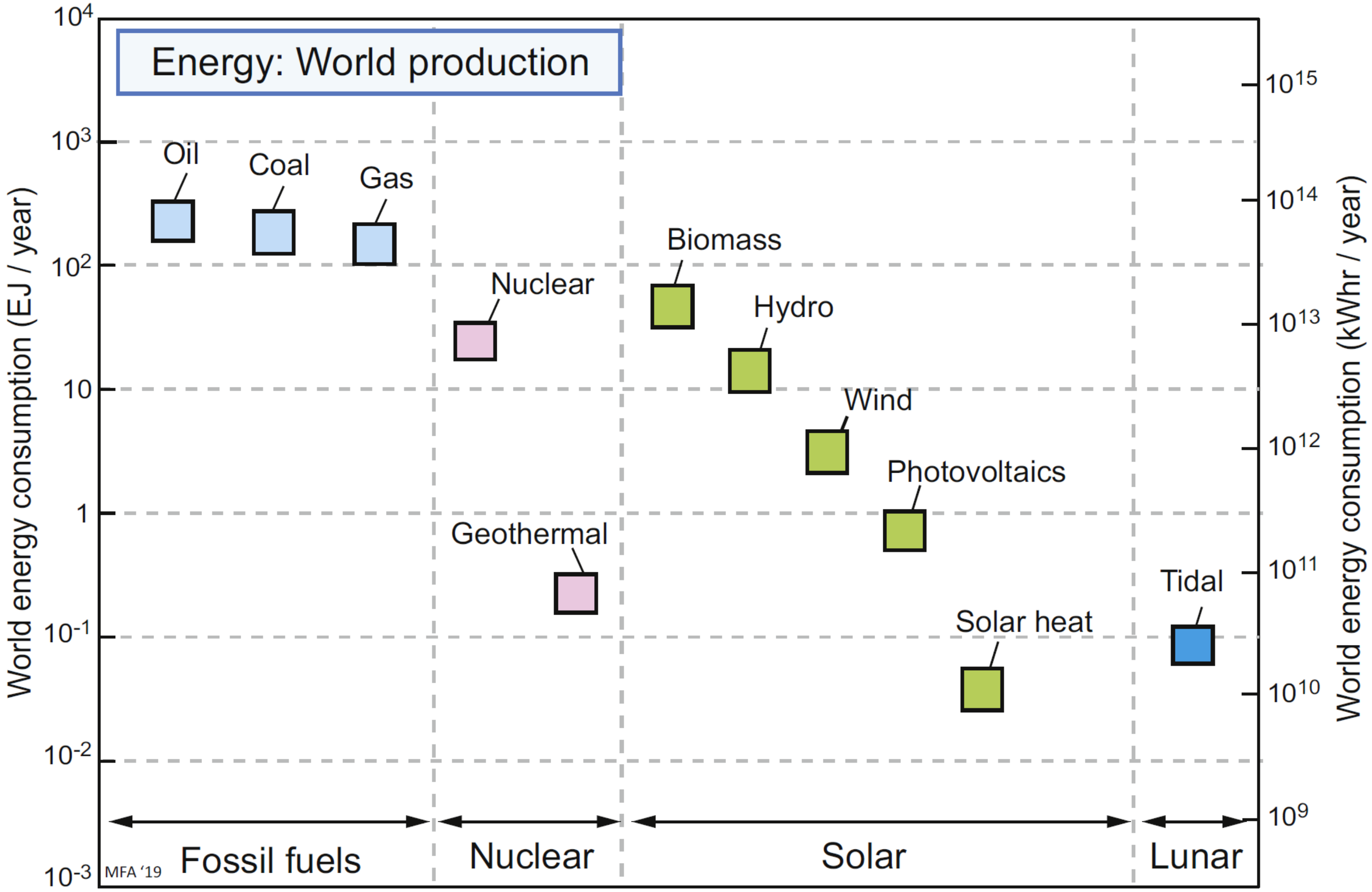
Actual cost is about 10 $/kg

Why the discrepancy?

- We don't mine the average crust, we mine mineral-rich, localized deposits

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.
time evolution of copper prices

Key ingredients for materials - #2 Energy



Making materials consumes approx. 15% of global energy and contributes approx. 15% of carbon emissions

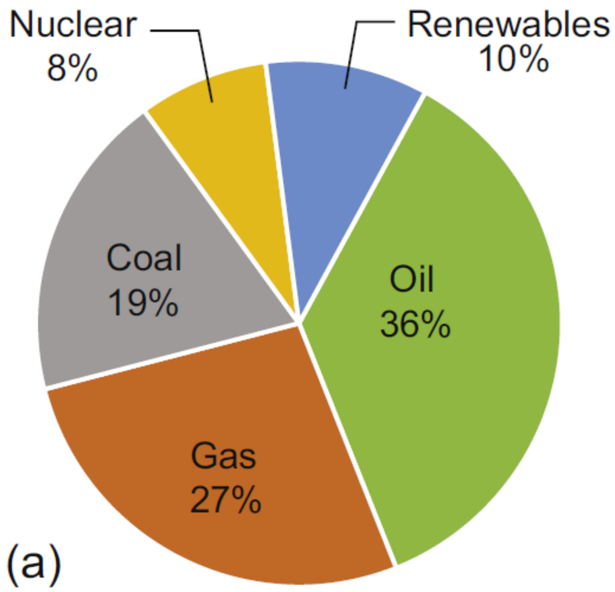
Four sources of energy:

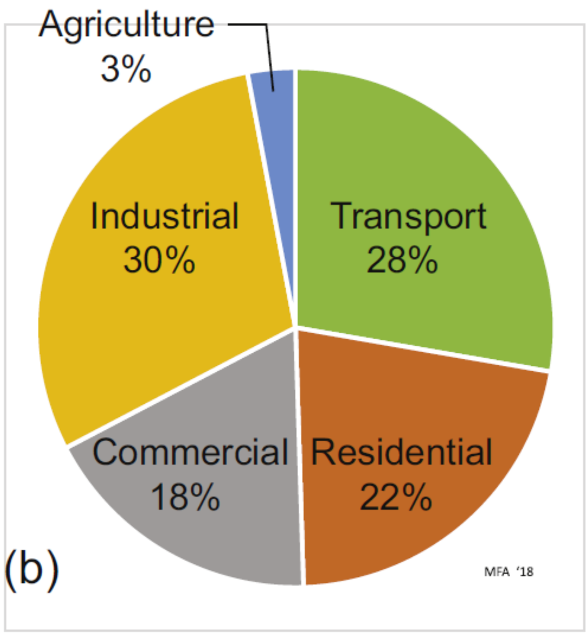
- The sun
- The moon
- Nuclear
- Hydrocarbon fuels

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

Key ingredients for materials - #2 Energy

World energy consumption by source (a) and by use (b):



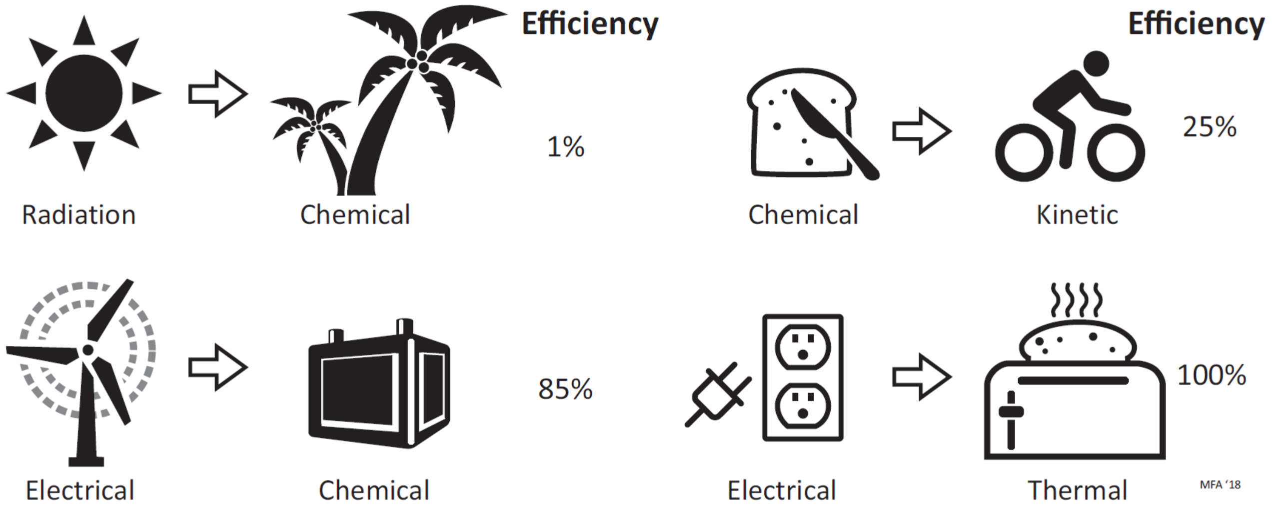


- Oil, gas, coal
- Transport, buildings, industry

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2, page 28.

Key ingredients for materials - #2 Energy

- Conversion accompanied by losses, usually as heat
- Low-grade heat (low T) is usually lost; high-grade heat (high T) can be used to do work
- Conversion efficiency in material production is usually low, around 30%

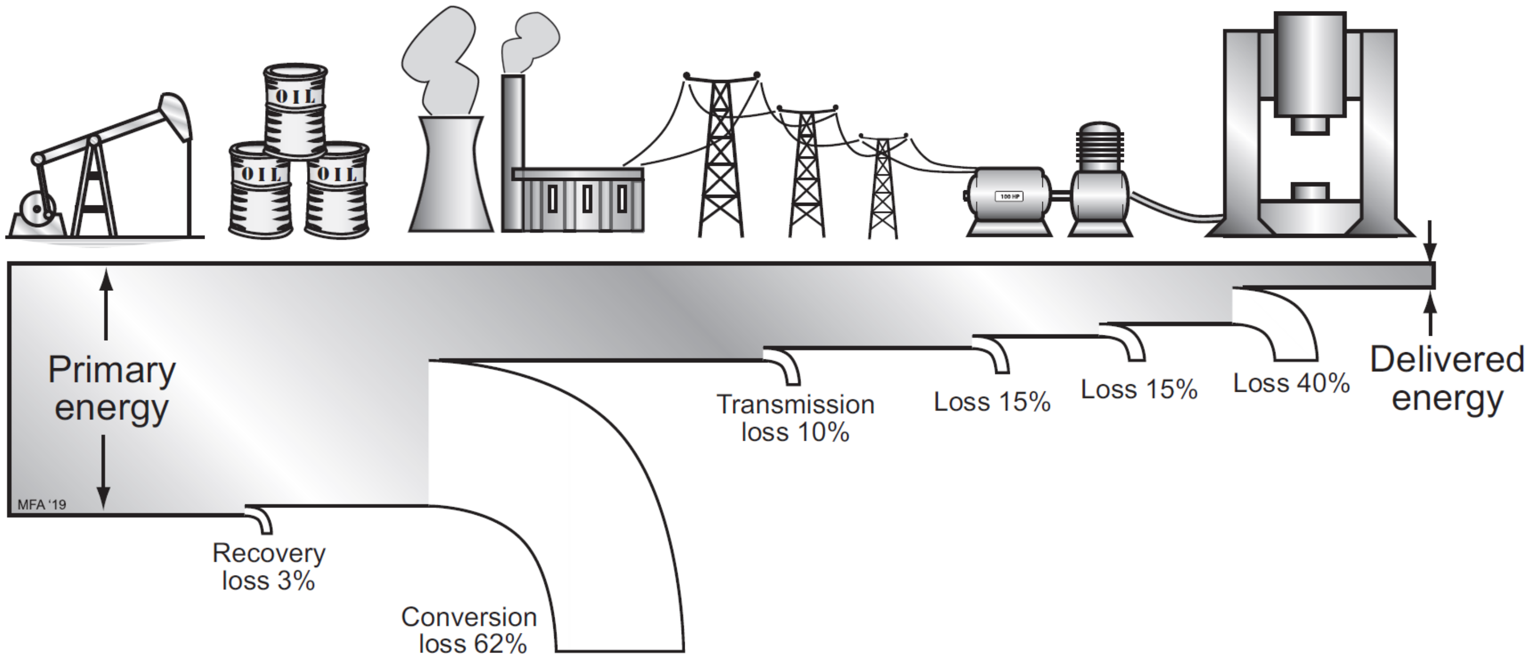


From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2, page 29.

EPFL

Key ingredients for materials - #2 Energy

- Chain of energy conversion steps in powering a hydraulic press



What is the overall conversion efficiency?

ηtot
=0.97*0.38*0.85*0.9*0.85*.09*0.35
= 0.1

90% of primary energy is lost as heat, with no useful work done

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2, page 30.

Embodied energy

- The *embodied energy* usually considers the energy used in *the production* of a material: **extract, refine, process, transport, & fabricate**

- Analogous metric exists for *embodied carbon*

- Different databases can be accessed; e.g., ICE database with emphasis on building materials

- Data can change

Estimate of cement's contribution to global energy consumption

- In 2023, 4.1 billion tonnes produced
- Embodied energy of cement ≈ 4.5 MJ/kg (mega Joule; 1×10^6 J)
- Annual global energy consumption ≈ 580 EJ (exa Joule; 1×10^{18} J)

What is the fraction of the world's annual energy is required to provide the cement we use?

- Annual energy embodied in concrete:

$= 4.1\times10^9 \times 1000 \times 4.5\times10^6$

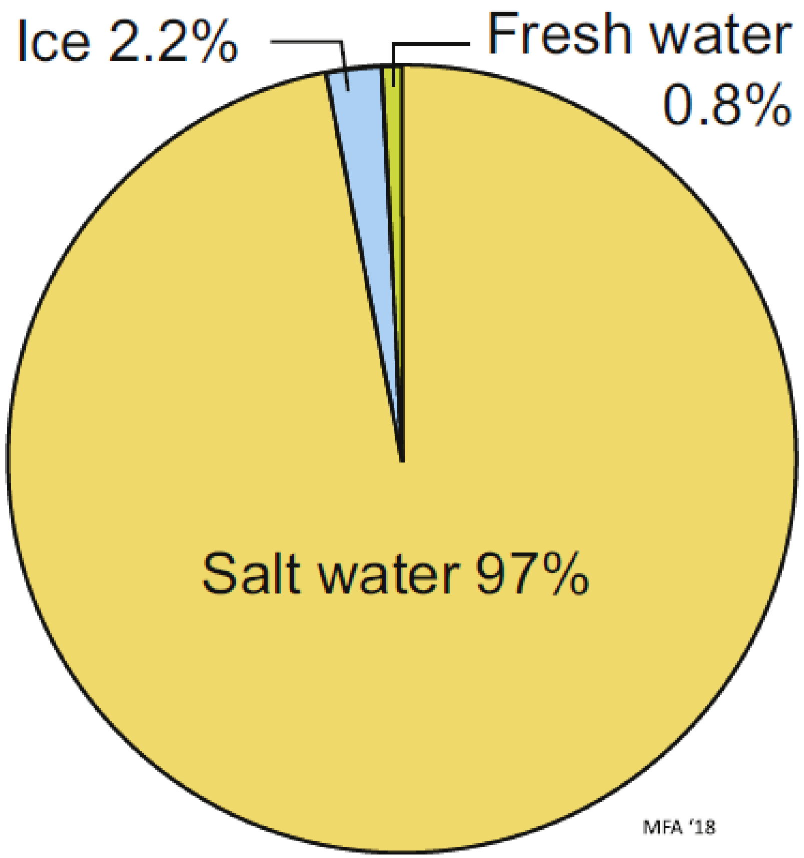
$= 1.8\times10^{19}$ J = 18 EJ

- Percent of total global energy consumption

$\approx 18/580 * 100 = 3\%$

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

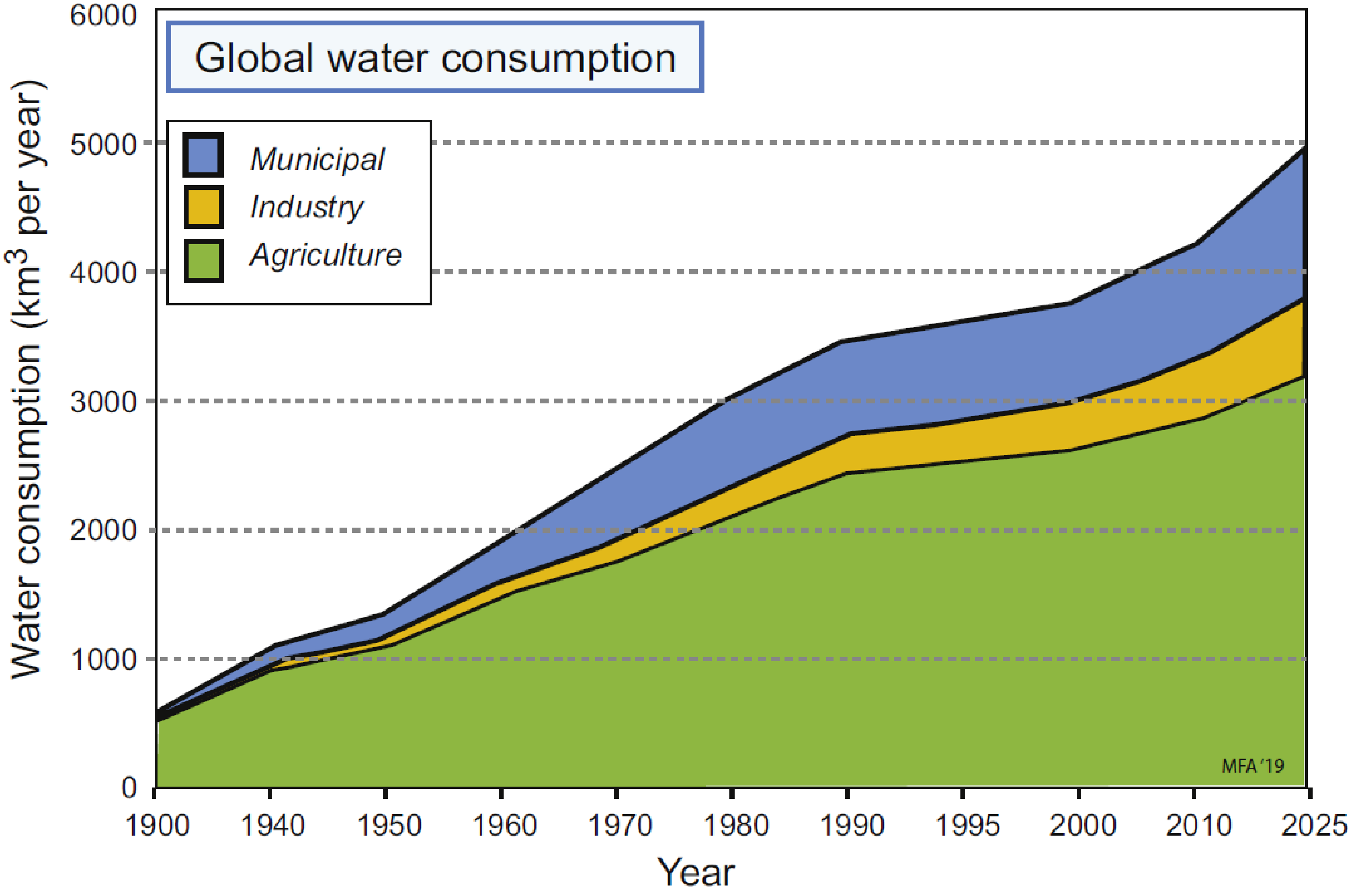
Key ingredients for materials - #3 Water



- Water is a renewable but *finite* resource
- We mainly rely on freshwater
- Freshwater is unevenly distributed on the planet
- It takes time for freshwater to be replenished in the water cycle
- This can lead to scarcity, especially if demands are high due to human activities like farming and materials production
- Worldwide water demands have tripled since 1970
- By 2050, half the population is forecast to be short on water

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

Key ingredients for materials - #3 Water



Energy accounts for half the industry band

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

Key ingredients for materials - #3 Water

Table 2.1 Approximate water demands of energy and energy demands of water[4]

Energy source	Water demand (m^3/GJ)	Water source	Energy demand (MJ/m^3)
Grid electricity	24	Groundwater abstraction	1
Industrial electricity	11	Surface-water abstraction	0.2
Energy direct from coal	0.35	Groundwater treatment	0.01
Energy direct from oil	0.3	Surface-water treatment	0.1
Solar	0.3	Distribution	0.8
Wind	0.001	Desalination, reverse osmosis	15

- Interconnected with energy - Energy supply depends on water, water supply on energy
- Water consumption for engineering materials is 10 to >1000L/kg

From: Materials and the Environment by Michael F. Ashby, 2020, Chapter 2.

Take aways

- Earth can be viewed as a closed system or a spaceship
- Subsystems interact with one another through Earth cycles; cycling matter
- Materials are finite; mostly limited to the upper continental crust
- Resources vs. reserves
- Renewable vs. non-renewable
- Humankind has shifted toward non-renewable materials dependence
- The population has grown explosively
- Carbon emissions have also grown
- Making engineered materials requires raw materials, energy, and water
- All of this comes with a cost, e.g., carbon emission, pollution, water shortage, ecosystem destruction, land loss, biodiversity loss