Environmental chemistry and biology
HSLU, Semester 1

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Preamble (Week 0)

1 Learning objectives

We should be able to:

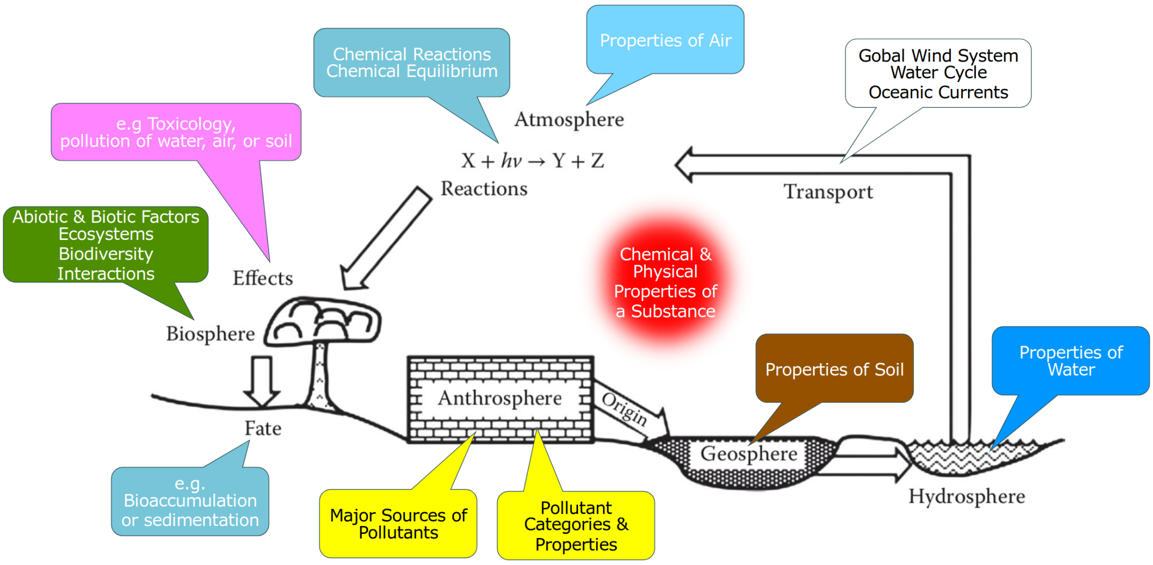
- define the term “Environment”;
- define the term “Environmental chemistry”;
- define the term “Environmental biology”;
- know the physical and chemical properties, defining the environemntal behavior of a substance;
- apply the concept of partitioning to analyze and understan the behavior of an organic substance in the environment, with the provided values.

2 Introduction SW 0

2.1 Definitions

2.1.1 Environmental Chemistry

Environmental chemistry is the discipline that describes the **origin, transport, reactions, effects and fate** of chemical species in the hydro-, atmo-, geo-, bio- and anthrosphere.



2.1.2 Enviromental Biology

Environmental biology is the study of **the relationships between living organisms and their environment**, including the impacts of human activities.

In an ecosystem, biotic factors include all living organisms and microorganisms. These organisms interact through predation, competition, and sysmbiosis, forming a complex web of life.
Abiotic factors, lie water, sunlight, temperature, pH levels, and minerals, influence the biotic components.

Human activities, such as the introduction of radioactive wastes, can disrupt the balance by altering the chemistry of the environment and harming living organisms.

2.2 Chemical structure and Environmental behavior

We consider two groups of properties of chemicals:

2.2.1 Physical properties

- Vapor pressure (mp, bp);
- Solubility (H_2O, ...);
- Acid / Base strength (pK_a, pK_b);
- Partition coefficients (e.g. K_{OW}).

These properties describe **Dispersion** in different compartments $\Rightarrow$ Mobility and Toxicity.

2.2.2 Chemical properties $\rightarrow$ Reactivity

- Functional groups (-OH, $-NH_2$, ...);
- Electronic substituent effects (push/pull of electrons);

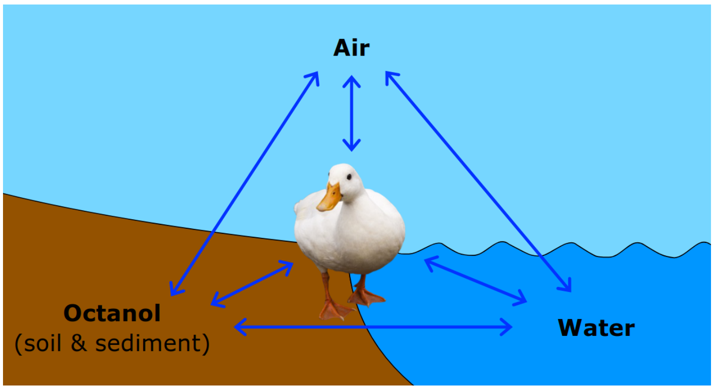
- Reaction mechanisms.

These properties describe **Transformation** of products ⇒ Degradation

2.3 Partitioning of organic substances in the environment

The partitioning is the passage of an organic substance from one environmental compartment to another. It's a physical process and does not involve a chemical reaction:

1. air ⟷ water:
   - volatility / vapor pressure;
   - water solubility;
2. water ⟷ soil:
   - adsorption (sticking to particles);
   - water solubility;
3. soil ⟷ air:
   - adsorption;
   - volatility / vapor pressure;
4. all phases ⟷ biota:
   - lipophilicity (fat solubility).



2.4 Chemical transformations under environmental conditions

There are two fundamental pathways:

2.4.1 Abiotic

In compartments Air, Water, Soil → **Energy source: temperature, light**

1. Hydrolysis: water breaks down a compound;
2. Oxidation: process where a substance loses electrons, often involving oxygen;
3. Reduction: process where a substance gains electrons, often involving the breakdown of pollutant in low-oxygen conditions;
4. Photochemical reactions: reaction driven by sunlight, where light energy breaks down chemicals.

2.4.2 Biotic

In organisms → **Catalyst: enzymes**

1. Oxidation: enzymes help break down organic molecules within organisms;
2. Reduction: in organisms, reduction reactions often involve energy production, such as anaerobic environments;
3. Hydrolysis: enzymes within organisms facilitate hydrolysis to break down larger molecules, like proteins or carbohydrates;
4. Secundary reactions: additional reactions that happen following primary processes.

2.5 Biological transformations

2.5.1 Abiotic transformations

- These occur in the non-living components of the environment.
  Energy for these transformations often comes from higher temperatures or sunlight;
- Photochemical reactions are particularly important in atmosphere, driven by sunlight. They can lead to the breakdown of pollutant, through some compounds like PCBs (polychlorinated biphenyls) are resistant to degradation, causing persistance in the environment.

2.5.2 Biotic transformations

- These occur within living organisms and are often enzyme-driven;
- Persistent pollutants like PCBs, biotic transformations tend to be slow, leading to accumulation in organisms. This results in **bioaccumulation** up the foodchain.

Part I

Week 1

3 Learning objectives

We should be able to:

- provide for at least 5 of the 8 primary sources of pollutants;
- apply the 5-key aspects of a pollutant to predict its behaviour in the environemnt;
- discuss how pollutants move through different environmental compartments;
- briefly describe with one example the pollutant categories;
- recognize the pollutant classes by their Lewis structure;
- compare and contrast the similarities and differences among various pollutant categories, including their sources, chemical properties, environmental impact, and persistence.

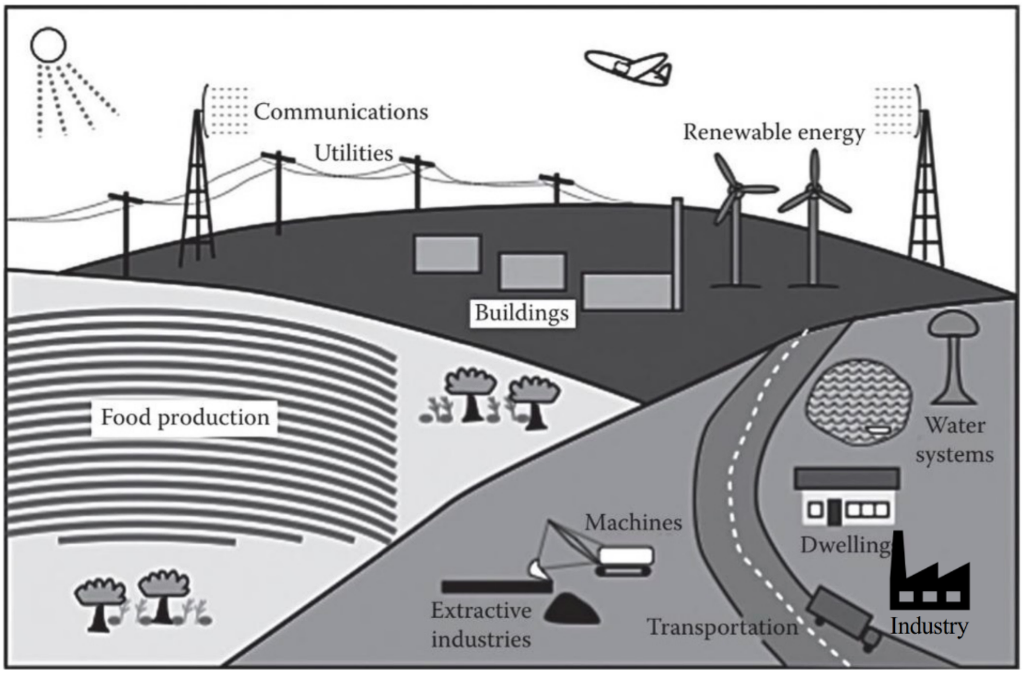
4 Anthrosphere and Environmental impact

Definition:
The anthrosphere is the part of the environment that's **made or operated by humans**. The anthrosphere is where **pollutants are made** and from which they are released with profound effect on all other environmental spheres.

It also strongly affected by pollutants, e.g. acid rains, which cause deterioration of stone structures and corrosion of metal components.

Impact:
It is essential to view the anthrosphere as a distinct environmental sphere, when considering environmental chemistry and sustainability. Just a look around us shows the dwellings, buildings, roads, factories, power lines, and numerous other things constructed and operated by human as a visible evidence of the existence of the anthrosphere of Earth.

4.1 Human primary sources



1. Industrial activities: factories, mining and processing plants release air, water, and soil pollutants (SO_2, NO_x, PM, VOCs), including chemicals and heavy metals (Hg);
2. Transportation: vehicles and ships emit harmful gases (CO_2, CO, NO_x), and particulate matter, contibuting to air pollution and climate change;
3. Agriculture: farming activities generate pollutants such as pesticides (Glyphosate, Atrazin), fertilizers (NH_3), and methane (CH_3), leading to water contamination and greenhouse gas emissions;
4. Energy production: burning fossil fuels for energy emits CO_2, SO_2, and other pollutants, driving air pollution and global warming;
5. Urban development: construction and waste management in cities produce dust, noise, and runoff pollution, impacting air and water quality;
6. Deforestation and Land Use changes: clearing forests releases CO_2 and causes soil erosion, contributing to climate change, habitat and biodiversity loss;
7. Household activities: residential heating, cooking, and consumer products emit indoor and outdoor air pollutants like VOCs and particulate matter;
8. Waterwaste and Sewage: inadequate treatment of sewage and industrial wastewater pollutes water bodies with pathogens, nutrients (PO_4^{3-}), chemicals and heavy metals.

5 Pollutants and hazardous

5.1 Pollutants

A pollutant is a substance or energy introduced into the environment that has undesired effects, or adversely affects the usefulness of a resource.

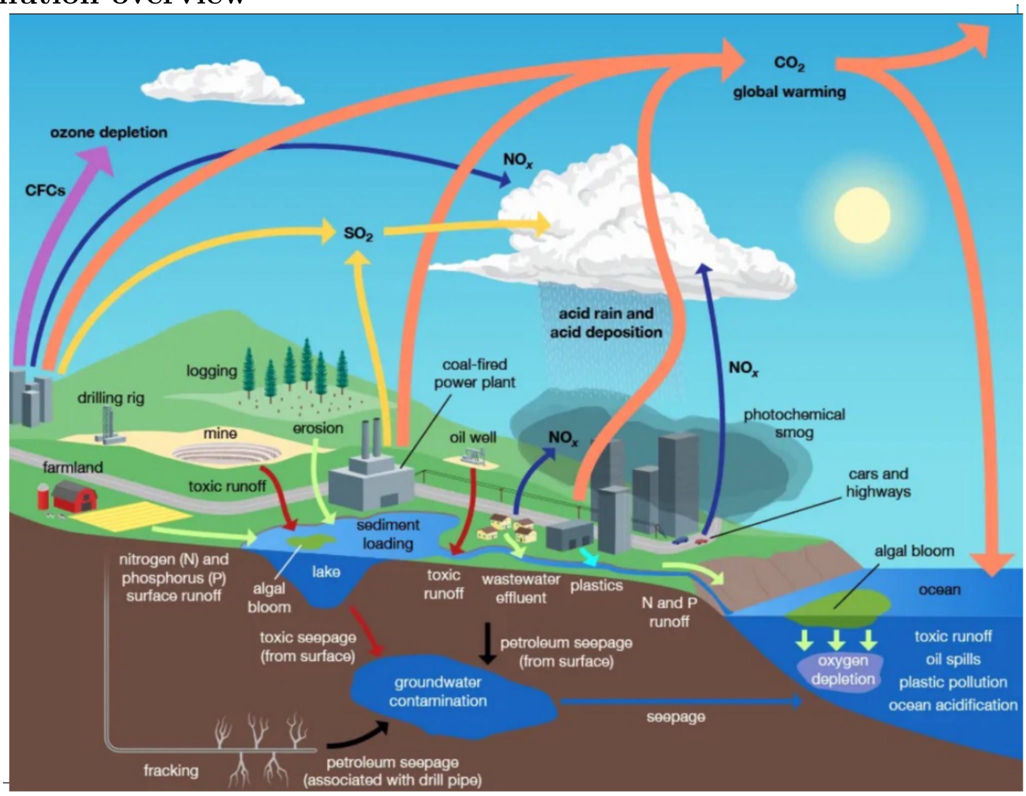
A pollutant may cause long- or short-therm damage by changing the growth rate or plants or animal species, or by interfering with human amenities, comfort, health, or property values.

5.2 Hazardous waste

Hazardous waste is a waste that is dangerous or potentially harmful to our health or the environment. Hazardous wastes can be liquids, solids, gases, or sludges.

They can be discarded commercial products, like cleaning fluids or pesticides, ore the by-products of manufacturing processes.

5.3 Pollution overview



Air pollution and climate changes:

1. Coal-fired power plants emit pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x) into the atmosphere, contributing to acid rain and acid deposition;
2. Cars and highways emit NO_x leading to photochemical smog and further contributing to air pollution;
3. Emission of carbon dioxide (CO_2) from these sources contribute to global warming;
4. Chlorofluorocarbons (CFCs) lead to ozone depletion.

Water pollution and Ecosystem impact:

1. Toxic runoff from mines and farmland introduces harmful substances into lakes, rivers, and oceans, causing algal blooms and leading to oxygen depletion in aquatic ecosystems;
2. Nitrogen (N) and phosphorus (P) from fertilizers in agricultural runoff also contribute to eutrophication in water bodies, exacerbating algal blooms;
3. Wastewater effluent, plastics, and petroleum seepage from oil swlls pollute lakes, oceans, and groundwater, leading to groundwater contamination and ocean acidification;
4. Oil spills, toxic runoff, and plastic pollution are shown to be harming ocean life.

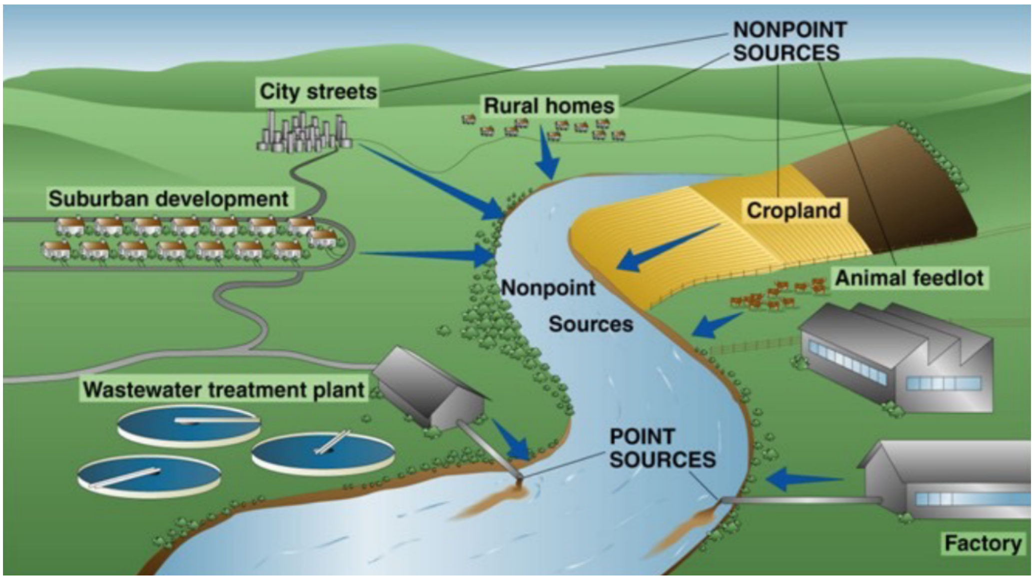
Land degradation:

1. Logging and mining activities result in erosion, causing sediment loading in nearby water bodies;
2. Fracking (hydraulic fracturing) is depicted as a source of petroleum seepage into groundwater.

Forests and Farmland:

1. The farmland in the diagram shows surface runoff of nitrogen and phosphorus into surrounding water systems, further contibuting to water pollution and ecological damate.

6 Point sources vs. Nonpoint sources



6.1 Point source

Point sources refer to specific, identifiable sources of pollution that can be traced back to a single location or outlet, such as a factory's discharge pipe or a smokestack.

These are easier to monitor and regulate because the pollution comes from a single point.

6.2 Nonpoint source

Nonpoint sources are diffuse sources of pollution that cannot be traced to a single location. They include things like agricultural runoff, urban stirnwater, and emissions from vehicles spread across a large area.

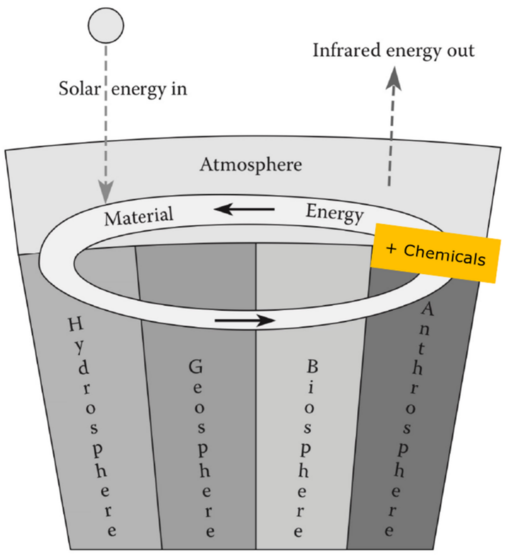
Because of their dispersed nature, nonpoint sources are harder to control and measure.

7 Earth system and Pollution dynamics

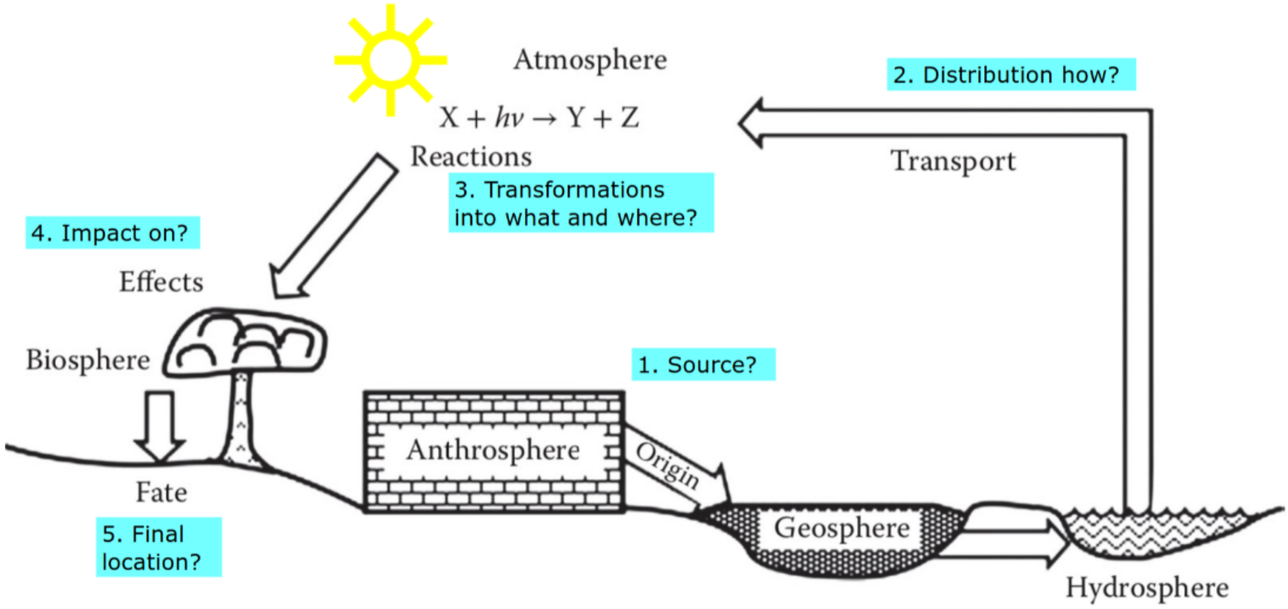
7.1 Earth system and chemicals

The Earth system is essentially a closed system with respect to matter, which circulates within the five spheres of the environment. Energy enters the Earth system in the form of sunlight and leaves primarily as infrared radiaton. The balance between these two flows largely determines Earth's climate and conditions leading to the Antrhopocene.

<u>Definition</u>: The Antrhopocene epoch is an unofficial unit of geologic time, used to describe the most recent period in Earth's history when human activity started to have a significant impact on the planet's climate and ecosystems.



7.2 5-key aspects of pollutants



Hazardous materials amost always originate in the anthrosphere, are often discarded into the geosphere, and are frequently transported through the hydrosphere or the atmosphere. The great concern for their effects is usually on the biosphere, particularly humans beings.

To understand the effect of a chemical in its entirety, it is important to look at the following 5 steps:

1. Origin: source of the chemical or pollutant;
2. Transport: distribution of the pollutant;
3. Reactions: trasformation of the pollutant;
4. Effects: impact of the pollutant;
5. Fate: whereabouts of the pollutant.

Warning: as long as the pollutant is not completely degraded or remover, the whole cycle can/will start again

8 Important pollutant categories

8.1 Heavy metals

Heavy metals are material with very high densities.

8.1.1 Sources

- Pb: lead-acid batteries, lead-bases paints, leaded gasoline;
- Hg: coal burning, mining, industrial processes.

8.1.2 Reactions

- Pb, Hg: strong affinity to sulfur (S) $\rightarrow$ bind to enzymes (proteins), controlling metabolic reactions;
- Hg: bacteria (in water and soil) transform it into $CH_3Hg^+ \rightarrow H_3C - Hg^+\ X^-$.

8.1.3 Effect

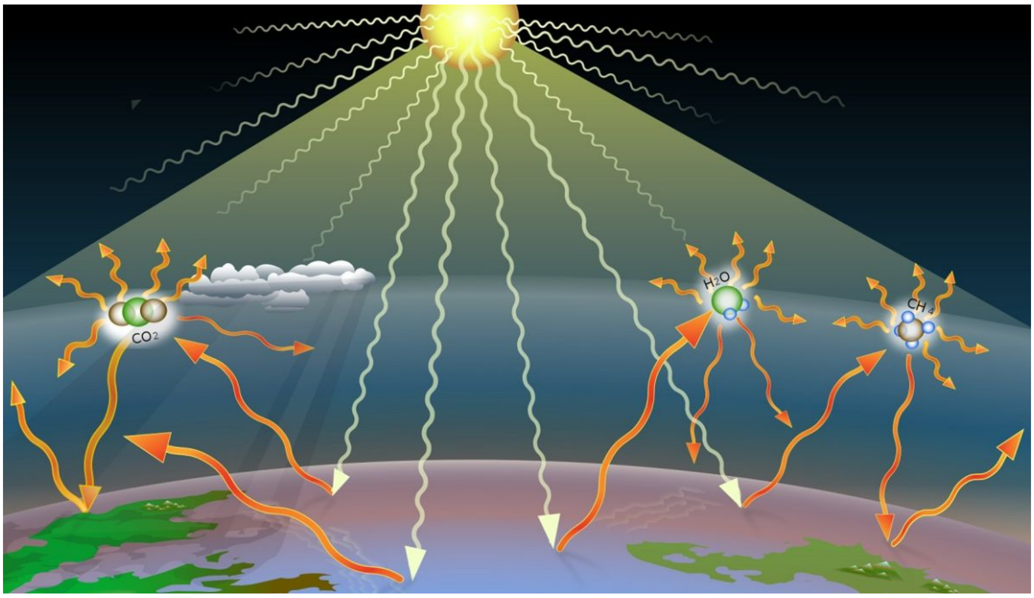
- Hg and Pb damage several organs, mainly the central nervous system;
- developmental disorders.

8.1.4 Fate

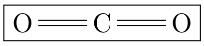
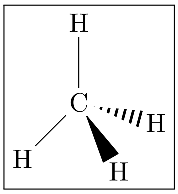
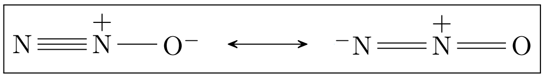
- persistent in the environment $\rightarrow$ bioaccumulation / biomagnification.

8.2 Greenhouse gases (GHGs)

GHGs are gases which reflects UVs, impeding them to exit from the ozone and therefore dissipate their heat in it.



8.2.1 Sources

- CO_2: fossil fuels, deforestation 
- CH_4: production of fossil fuels, livestock 
- N_2O: agricultural and industrial activities 

8.2.2 Reactions

- N_2O and CO_2 are not reactive;
- CH_4 can oxide to CO_2 and H_2O over time.

8.2.3 Effect

- absorb an re-emit infrared radiation $\rightarrow$ global warming / climate change;
- Global Warmint Potential (GWP) $\rightarrow$ $N_2O > CH_4 > CO_2$.

8.2.4 Fate

- atmospgeric persistence:
  - CO_2 centuries;
  - N_2O: 120 years;
  - CH_4: 12 years.

8.3 Particulate matter (PM)

PM is made by microscopic particles which can depositate inside the respiratory system of animals and create health problems, such as asthma or cardiovascular issues.

8.3.1 Sources

- $PM_{2.5}$ (fines particles): combustion primary, reaction of gases in the atmosphere secondary;
- PM_{10}: construction sites, road dust, agricolture.

8.3.2 Reactions

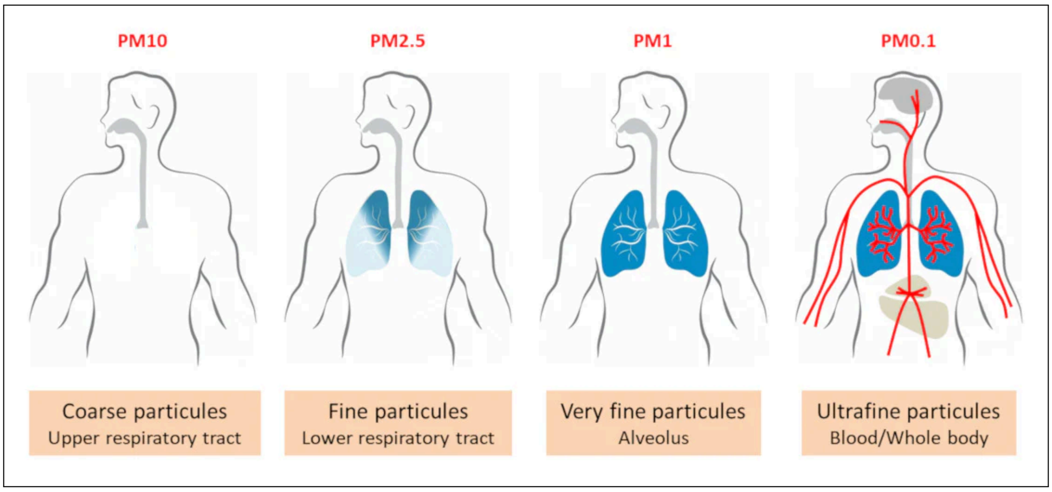
- SO_2 or NO_2 can retract to particulate ammonium sulfate $(NH_4)_2SO_4$ / -nitrate NH_4NO_3;
- the surface of PM facilitates chemical reactions (e.g.: $SO_2 \rightarrow H_2SO_4$ in water droplets).

8.3.3 Effect

- $\geq PM_{2.5}$: respiratory disease (asthma, COPD);
- $\leq PM_{2.5}$: cardiovascular issues (heart attacks, strokes);
- chronic exposure: lunge cancer, premature death.

8.3.4 Fate

- atmospheric dispersion (long distances);
- deposition (soil, water, vegetation);
- bioaccumulation ($\geq PM_{2.5}$).



8.4 Persistent organic pollutants (POPs)

POPs are chemicals which have a very long degradation time. They are called “forever chemicals”.

8.4.1 Halogenated organic compounds (HOCs)

Example:
Polychlorinated biphenyls (PCBs);

Source:
Insulation material (transformers, capacitors), and plastic (until 1979).

8.4.2 Per- and Polyfluoroalkyl substances (PFASs)

Example:
Perfluorooctanoic acid (PFOA);

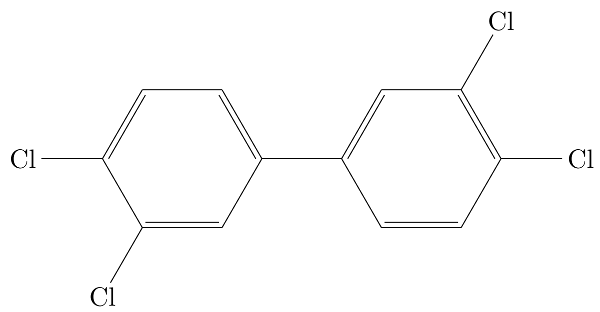
Source:
Production of non-stick cookware (Teflon), water-resistant textiles (Gore-Tex) until 2013/14.

8.4.3 Both categories

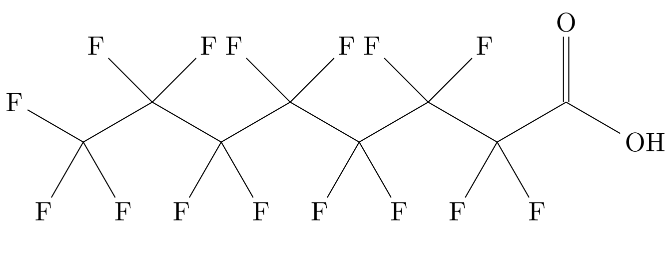
- Reactions: chemically highly stable;
- Effect: toxicity (liver, endocrine disruptor), carcinogenity, developmental issues;
- Fate: bioaccumulation / biomagnification, can travel long distancies via air and water.

8.4.4 POPs examples

PCB No. 77



PFOA



8.5 Chlorofluorocarbons (CFCs)

CFCs are man-made chemical compounds consisting of chlorine, fluorine, and carbon.

8.5.1 Sources

- refrigerants (air conditioners and refrigerators);
- aerosol propellants (historically);
- foam-blowing agents;
- industrial solvents.

8.5.2 Reactions

- highly stable in troposphere;
- breakdown by UV light in stratosphere;
- release of Cl-atoms, leading to ozone depletion.

8.5.3 Effect

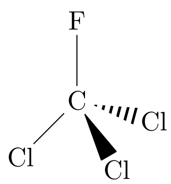
- non-toxic;
- ozone depletion, Cl-atoms catalyze;
- increased UV radiation of Earth's surface.

8.5.4 Fate

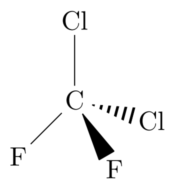
- very persistent;
- global transport in the atmosphere;
- long atmospheric lifetime, between 50 and 100 years.

8.5.5 CFCs examples

CFC-11 (Freon-11)



CFC-12 (Freon-12)



8.6 Polycyclic aromatic hydrocarbons (PAHs)

PAHs are gases created by incompleted combustions, such as tobacco smoke or grilled food.

8.6.1 Sources

- incomplete combustion;
- tobacco smoke;
- grilled/smoked food.

8.6.2 Reactions

- chemically relatively stable;
- can partially be degraded by sunlight / microbial activity.

8.6.3 Effect

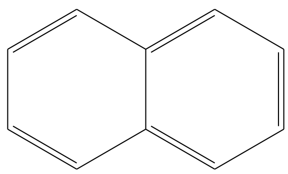
- toxicity: skin, respiration, immune system;
- carcinogens: lung, skin cancer;
- developmental issues.

8.6.4 Fate

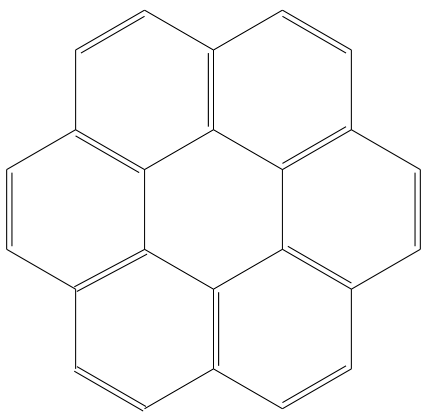
- persistence (depending on the size);
- bioaccumulation / biomagnification;
- transport over long distances via air and water.

8.6.5 PAHs examples

Naphtalene (Naphta)



Coronene



8.7 Volatile organic compounds (VOCs)

VOCs are gases with a low molecular weight which can evaporate at room temperature.

8.7.1 Sources

- fossil fuel, fuel storage;
- tobacco smoke;
- solvent use consumer products (paints, cleaning agents).

8.7.2 Reactions

- VOCs react with NO_x + sunlight to ground-level ozone (O_3);
- oxidation: reaction with OH, NO_3 or O_3.

8.7.3 Effect

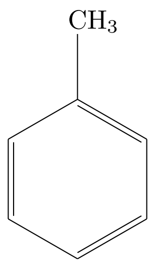
- toxicity (acute): respiration, headache, dizziness;
- toxicity (chronic): liver, kidney, central nervous system;
- carcinogens;
- developmental issues (certain VOCs).

8.7.4 Fate

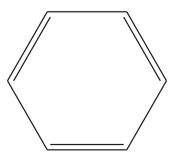
- volatility, easily evaporate into the atmosphere;
- degradation (photochemical / oxidation processes);
- transport over long distances via air.

8.7.5 VOCs examples

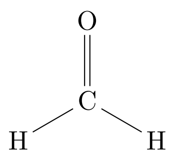
Toluene



Benzene



Formaldehyde



8.8 Environmentally persistent pharmaceutical pollutants (EPPPs)

EPPPs are pharmaceutical chemicals with a complex structure, which gives to molecules a big stability and a slow biodegradability.

8.8.1 Sources

- human and veterinary use;
- pharmaceutical waste water.

8.8.2 Reactions

- designed to be chemically stable and bioactive.

8.8.3 Effect

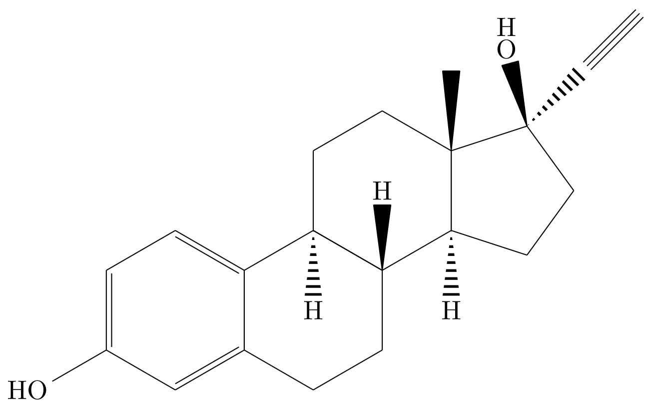
- toxicity (chronic): reproductive, developmental and behavioral effects in acquatic and terrestrial organisms;
- antimicrobial resistance;
- endocrine disruption.

8.8.4 Fate

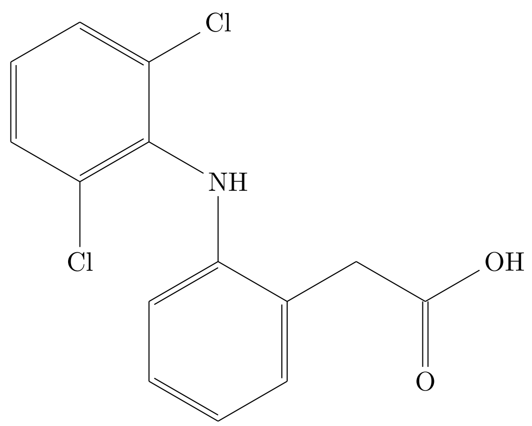
- persistence;
- bioaccumulation / biomagnification;
- can travel through water systems far from the source;
- removal inefficiency (waste water treatment plants).

8.8.5 EPPPs examples

Ethinylsetradiol



Diclofenac (Voltaren)



8.9 Plastics

Plastic are synthetics materials made from polymers, long chains of molecules typically derived from petroleum or natural gas.

8.9.1 Sources

- production and manufacturing;
- consumer use and disposal;
- industrial waste;
- agricoltural use.

8.9.2 Reactions

- chemically highly stable;
- photodegradation limited: breakdown by sunlight → microplastics.

8.9.3 Effect

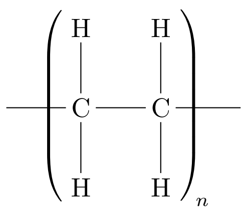
- physical harm: ingestion, entanglement → starvation;
- chemical exposure: release of toxic additives (phthalates, bisphenol A) → endocrine disruptors;
- habitat disruption.

8.9.4 Fate

- microplastic formation (< 5mm) → found everywhere;
- bioaccumulation / biomagnification;
- transport by wind, water and ocean currents → widespread.

8.9.5 Plastics examples

Polyethylene (PE)



Polymer chains

Part II

Week 2

9 Learning objectives

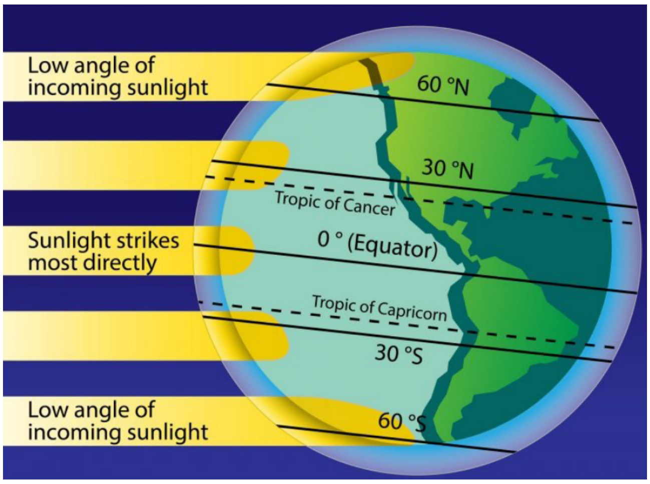
1. You can apply your knowledge of solar radiation, convection, and gravitational force to assess their combined effects on energy distribution and matter transport across different Earth spheres.
2. You can apply the 1st and 2nd law of thermodynamics to understand flows of matter/energy in environmental systems, particularly within the context of photosynthesis, respiration, and the decomposition of organic matter.
3. You know the 6 elements of life and can give for each an example of a biomolecule.
4. You can compare and contrast the redox states of CNPS compounds in different environmental contexts, and predict the impact of redox changes on energy flow, chemical reactivity, and environmental stability in both natural and engineered systems.
5. You can apply your knowledge of photosynthesis and respiration reactions to analyze environmental contexts, such as energy flow, oxygen- and carbon cycling.
6. You can differentiate between aerobic and anaerobic metabolic pathways, and evaluate their environmental impacts, particularly in oxygen-deprived habitats.
7. You know the water cycle by heart and can apply it to address environmental issues, such as pollutant transport.
8. You can compare and contrast the similarities and differences between (provided) biogeochemical cycles through pair-wise analysis.

10 Foundations of Environmental chemistry and biology

10.1 The five spheres

10.2 Solar radiation and transportation of energy and matter

10.2.1 Solar radiation



10.3 Energy and thermodynamics

10.4 Flow of matter and energy in ecosystem

11 Chemical processes in elemental cycles

11.1 The six essential elements of life (CHNOPS)

11.2 Oxidation and reduction, O- and H-transfer

11.3 RedOx and energy states of CNPS elements

12 Photosynthesis and respiration

12.1 Overview

12.2 Photosynthesis

12.3 Cellular respiration, “reversed photosynthesis”

12.4 Aerobic and Anaerobic metabolism

12.5 Fermentation

12.6 Anaerobic conditions in the Environment

13 Microbial activity and elemental cycles

13.1 Bacteria as key players in Element recycling

13.2 Overview of bacterial metabolism

13.3 Microbial role in CNPS cycles

14 Biogeochemical cycles