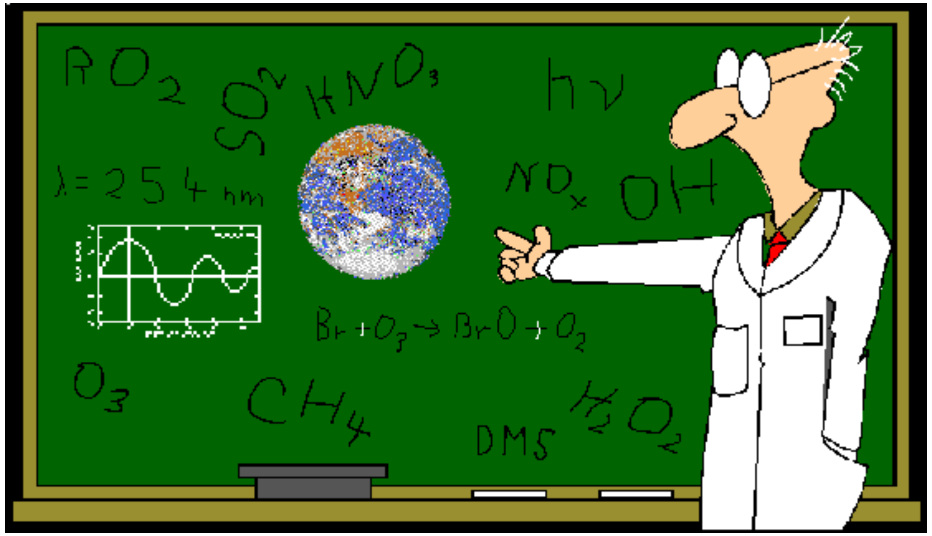
Environmental risk of chemicals



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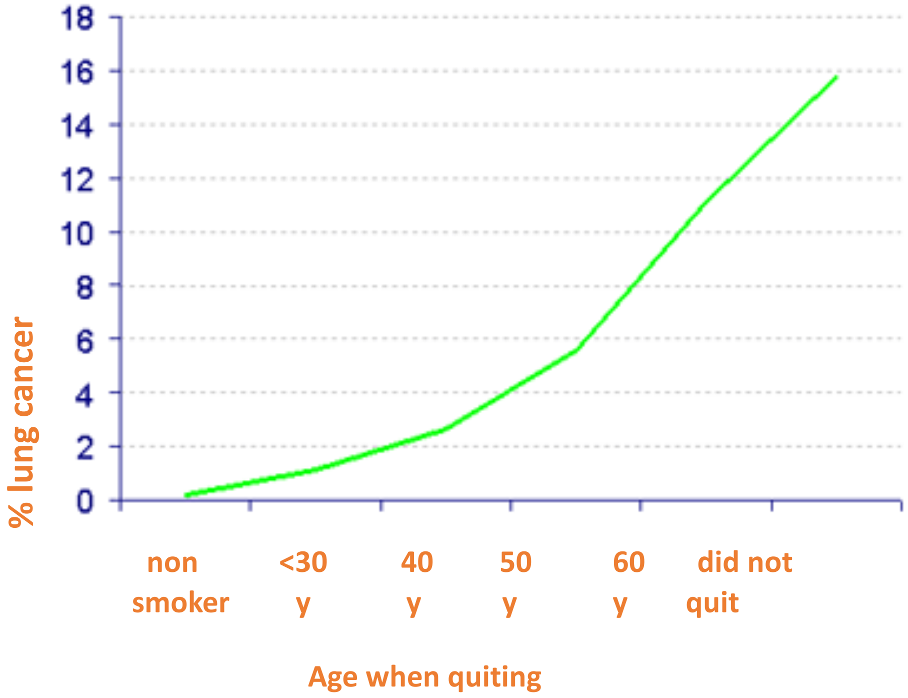
Risk

- **Risk** = the mathematical probability that some harmful outcome will result from a given action, event, or substance

- *Probability* = a quantitative description of the likelihood of a certain outcome
- *Harmful outcome* could be defined as injury, death, environmental damage, economic loss, etc.

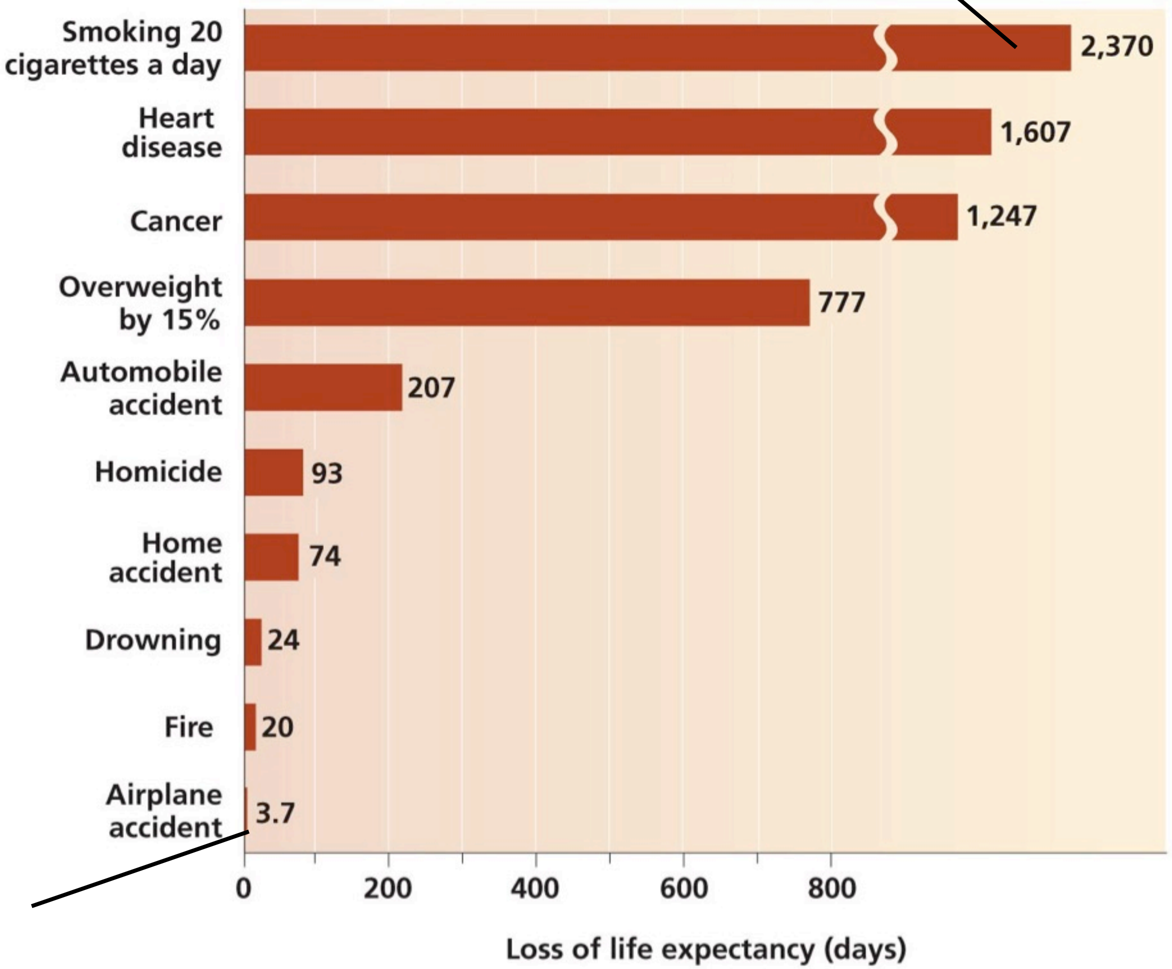
Chemical risk

- Probability of adverse effects towards human health or the environment due to a exposure to the chemical substance or mixture of substances



Our perception of risks tends not to match statistical reality

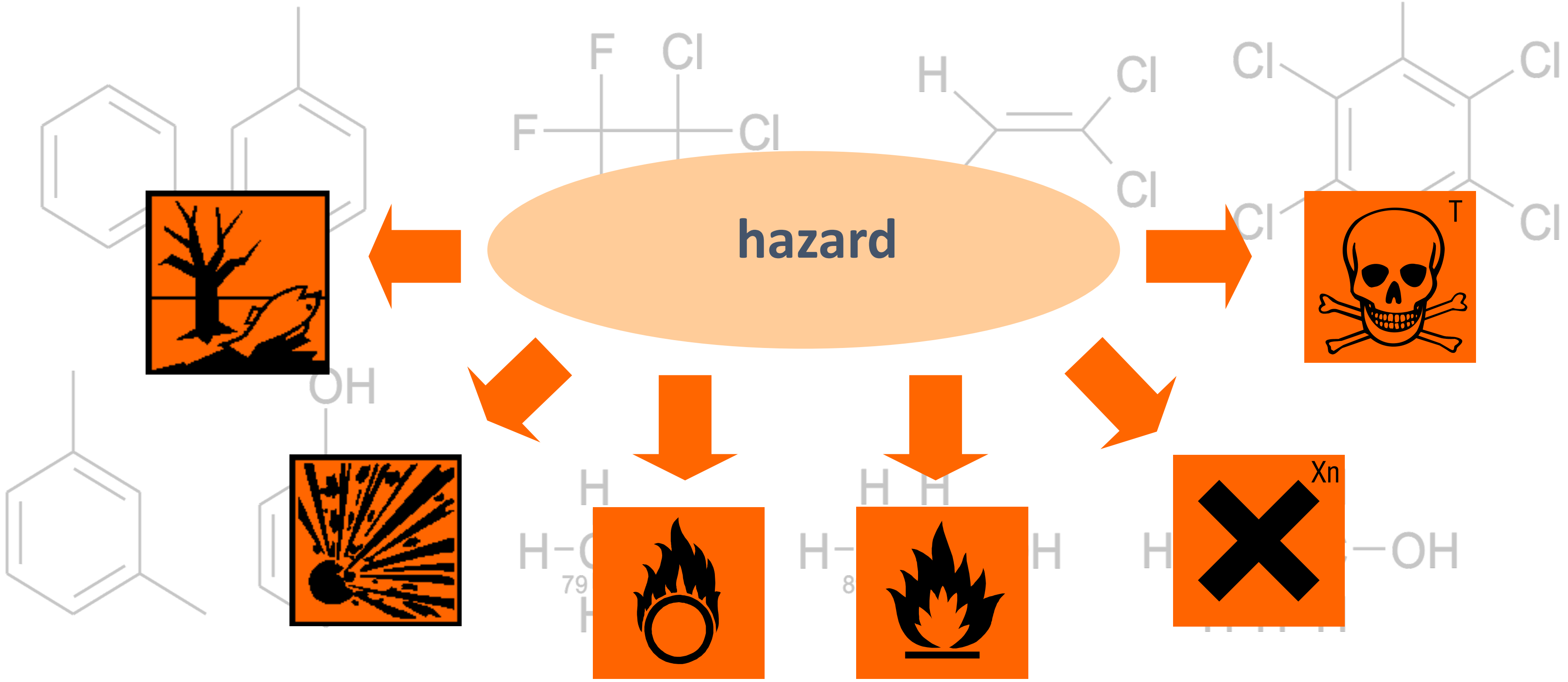
smoking



plane crash

Chemical hazard

- **Inherent capacity** of a chemical or mixture to cause adverse effects on man or the environment under the conditions of exposure



hazard

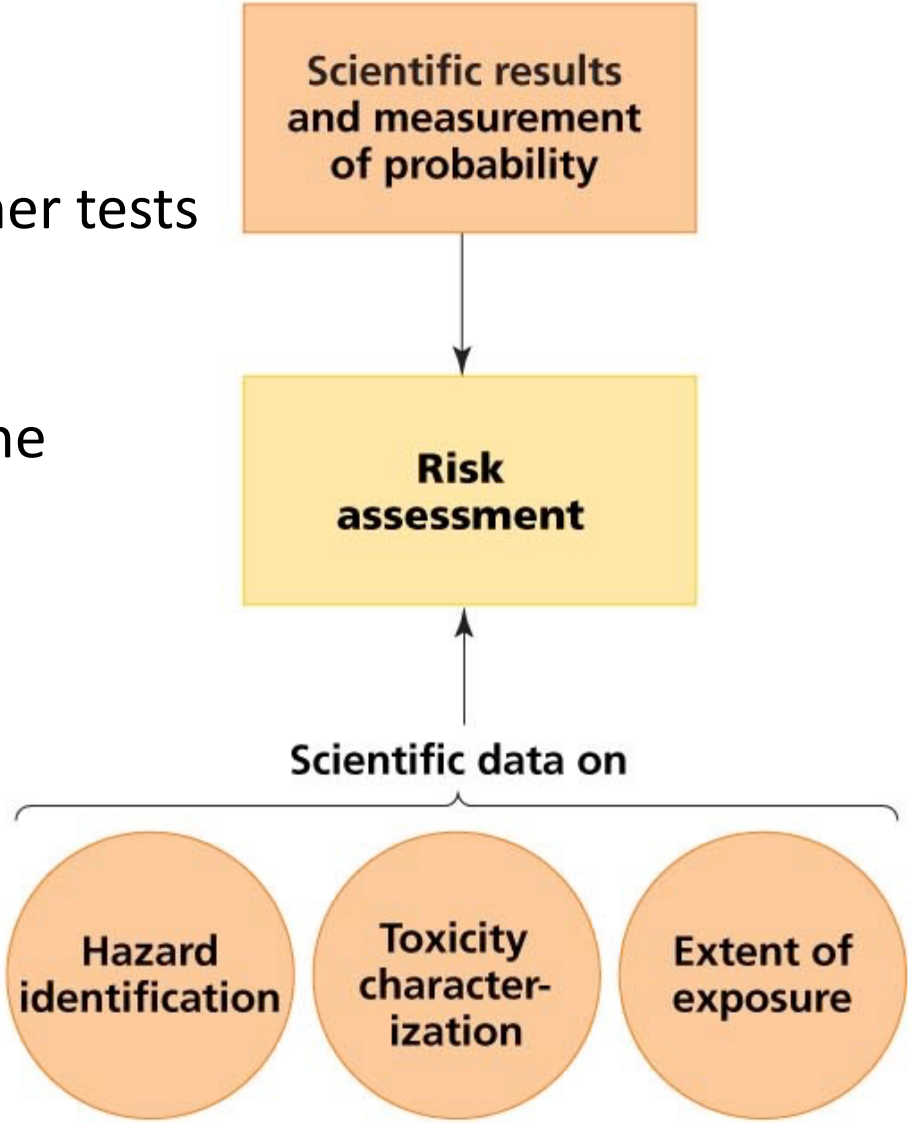
Risk assessment

- Analyzes risks quantitatively
- Measures and compares risks involved in different activities or substances
- Helps identify and prioritize serious risks
- Helps determine threats posed to humans, wildlife, ecosystems
- Includes: hazard identification, effects assessment, exposure assessment, and risk characterization

Risk assessment

Involves:

- Dose-response analysis or other tests of toxicity
- Assessing likely exposure to the hazard *(concentration, time, frequency)*



Scientific results and measurement of probability

Risk assessment

Scientific data on

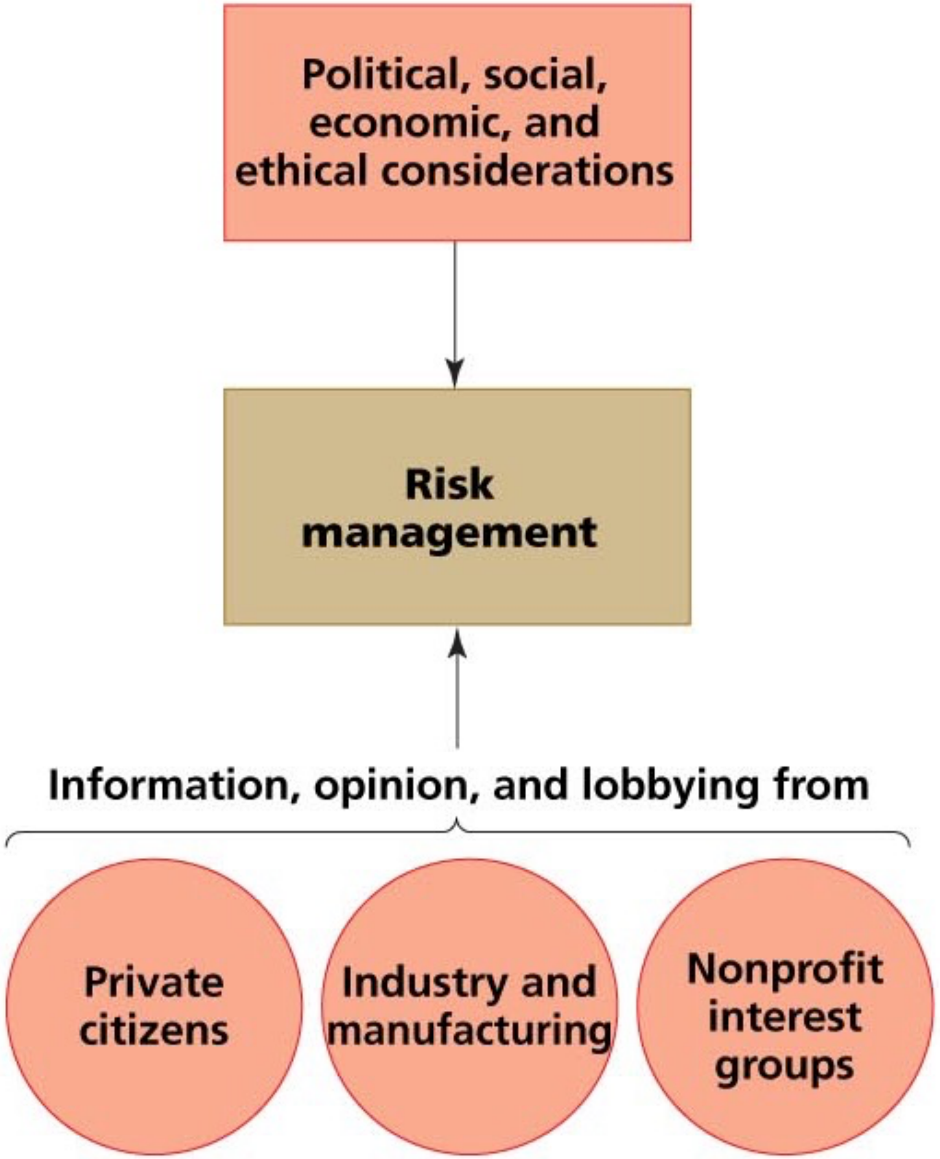
Hazard identification

Toxicity characterization

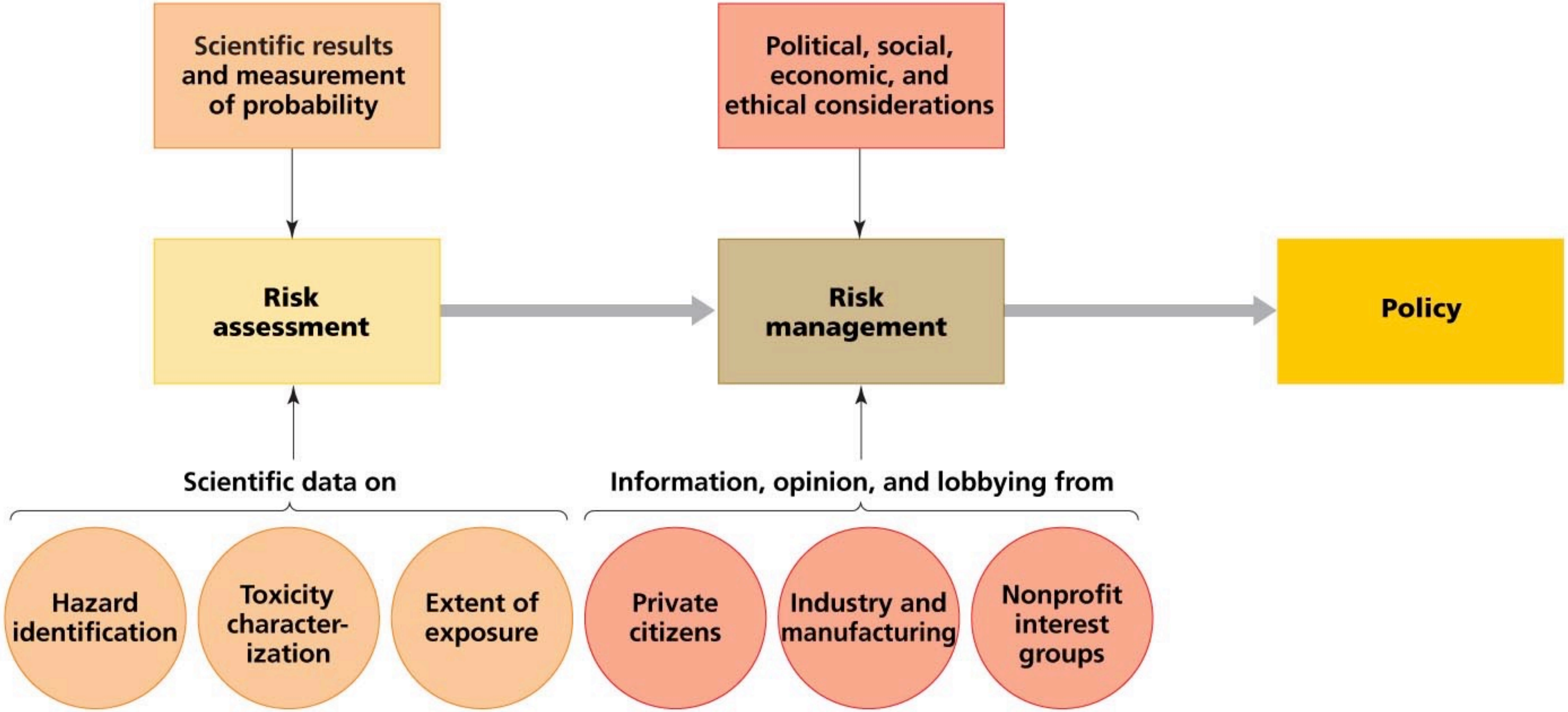
Extent of exposure

Risk management

- Consider risk assessments in light of social, economic, and political needs and values.
- Weigh costs and benefits, given both scientific and nonscientific concerns.
- Decide whether or not to reduce or eliminate risk.



Risk assessment and risk management inform policy



Scientific results and measurement of probability

Political, social, economic, and ethical considerations

Risk assessment

Risk management

Policy

Scientific data on

Information, opinion, and lobbying from

Hazard identification

Toxicity characterization

Extent of exposure

Private citizens

Industry and manufacturing

Nonprofit interest groups

Risk and hazard as functions

- Hazard is a function of toxicity and exposure and related to potential harm

Hazard = *fn{Toxicity x Exposure}*

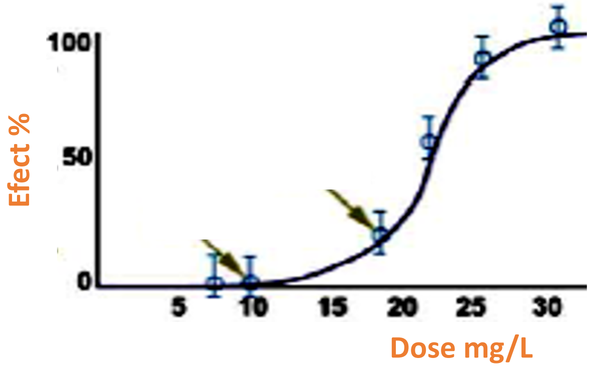
- Toxicity relates to the inherent sensitivity of the organism to a chemical and the mechanism of biological effect

- Risk relates magnitude of hazard and probability of its occurrence

Risk = fn{hazard x probability of occurrence}

How risks are expressed?

- Risk has 3 characteristic variables: (i) the type, (ii) magnitude and (iii) probability
- In quantitative terms risk is expressed in values ranging from **0** (harm will not occur) to **1** (absolute certainty that harm will occur)
- In a statistical sense it is ALWAYS possible that the effect will occur
- In the case of carcinogenic compounds the risk number represents the **probability** of e.g. additional cancer cases occuring.
- For chemicals **with threshold levels** non-linear S-shaped relationship is assumed between dose and effect. There is a threshold below which there is no effect.



How risks are expressed?

- For a chemical **X** risk might be expressed as 1 x 10^{-6} or 0,000001 or 1 in a million
- It means that one additional case of cancer is projected in a population of one million people exposed to a certain level of chemical **X** over their lifetimes
- Smoking 1 packet a cigarette a day produce a potential risk of lung cancer of 5 x 10^{-3} year or 1 in 200 per year

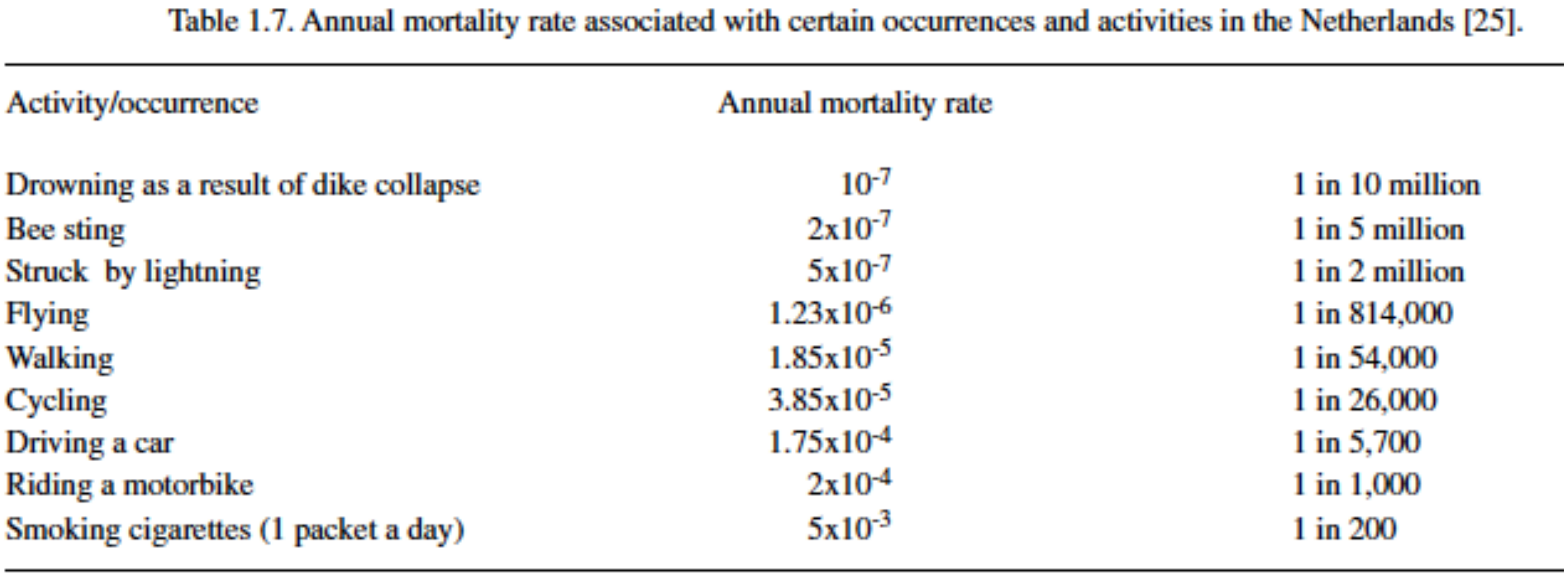


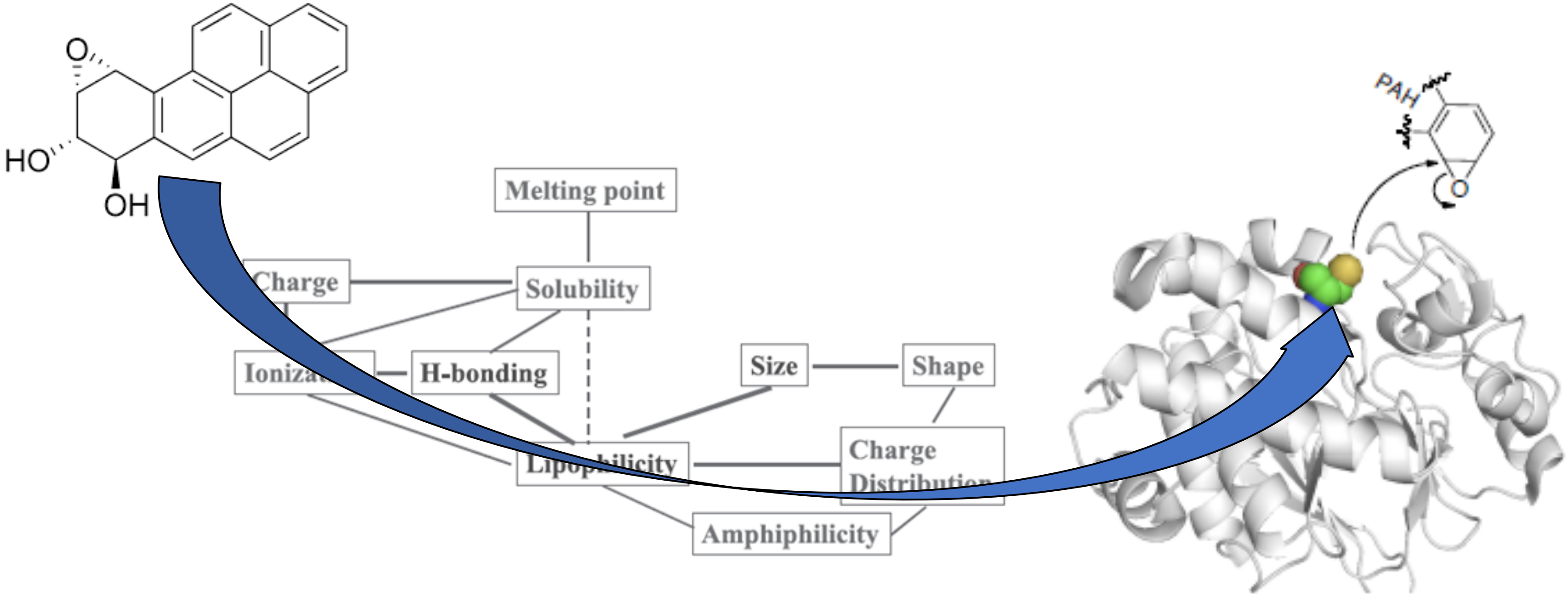
Table 1.7. Annual mortality rate associated with certain occurrences and activities in the Netherlands [25].

Activity/occurrence	Annual mortality rate	
Drowning as a result of dike collapse	10^{-7}	1 in 10 million
Bee sting	$2x10^{-7}$	1 in 5 million
Struck by lightning	$5x10^{-7}$	1 in 2 million
Flying	$1.23x10^{-6}$	1 in 814,000
Walking	$1.85x10^{-5}$	1 in 54,000
Cycling	$3.85x10^{-5}$	1 in 26,000
Driving a car	$1.75x10^{-4}$	1 in 5,700
Riding a motorbike	$2x10^{-4}$	1 in 1,000
Smoking cigarettes (1 packet a day)	$5x10^{-3}$	1 in 200

Structure – Activity Relationship

- Exposure is related to the following scheme:

Structure of chemical → Physical and Chemical Properties → Chemical Reactivity in Environment (distribution and degradation) → Transport to Biological Receptor



Role for Environmental / Green Chemistry

- Chemical inventories (US, EU) contains 100,000 substances that have not been fully evaluated; list is growing rapidly
- How do you ensure risk minimization with such a large inventory of chemicals?
- Many chemical properties are not available through empirical measurements
- Chemical design: how can we better design chemicals to be environmentally friendly and non-toxic? ***Green Chemistry***

Leading Environmental Pollutants

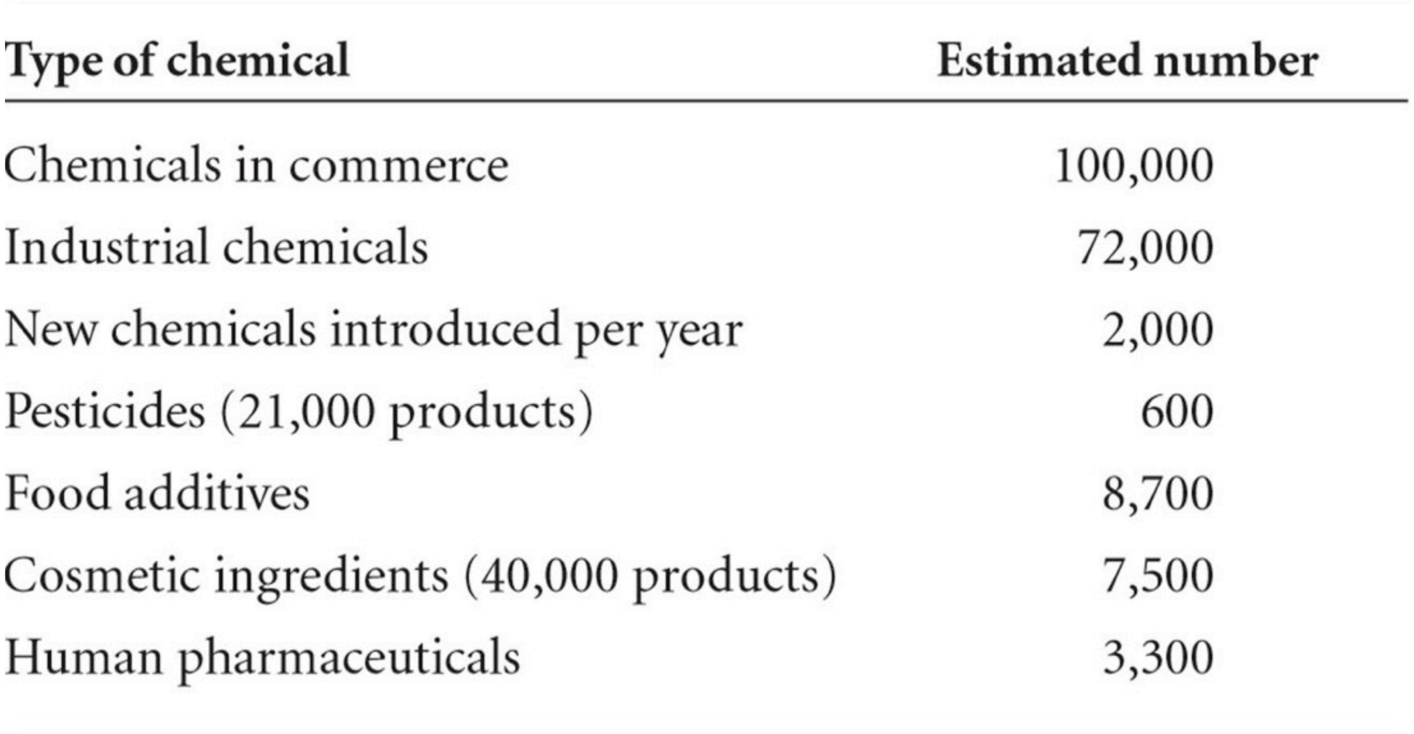
- Silt (erosion from farmlands and urban/suburban regions)
- Nutrients (agricultural/urban runoff)
- Metals (urban runoff, industrial discharge, energy production, transportation)
- **Toxic Organics (agricultural/urban runoff, energy production, transportation; industry)**
- Pathogens (feed lots, wastewater)
- Organic matter: (wastewater, runoff)

Rise of synthetic chemicals

- Widespread synthetic chemical production after WWII
- People were largely unaware of the health risks of many toxicants.

The potent insecticide DDT was sprayed widely in public areas, even on people.

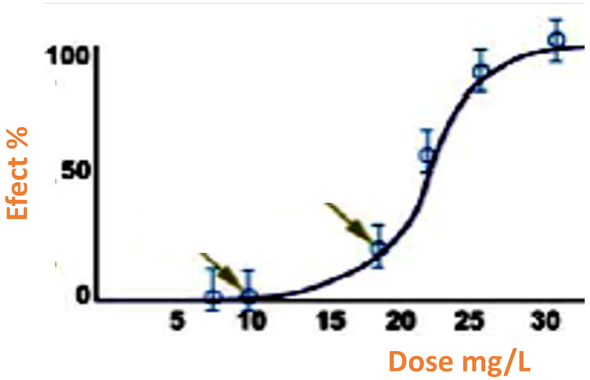
Synthetic chemicals are numerous



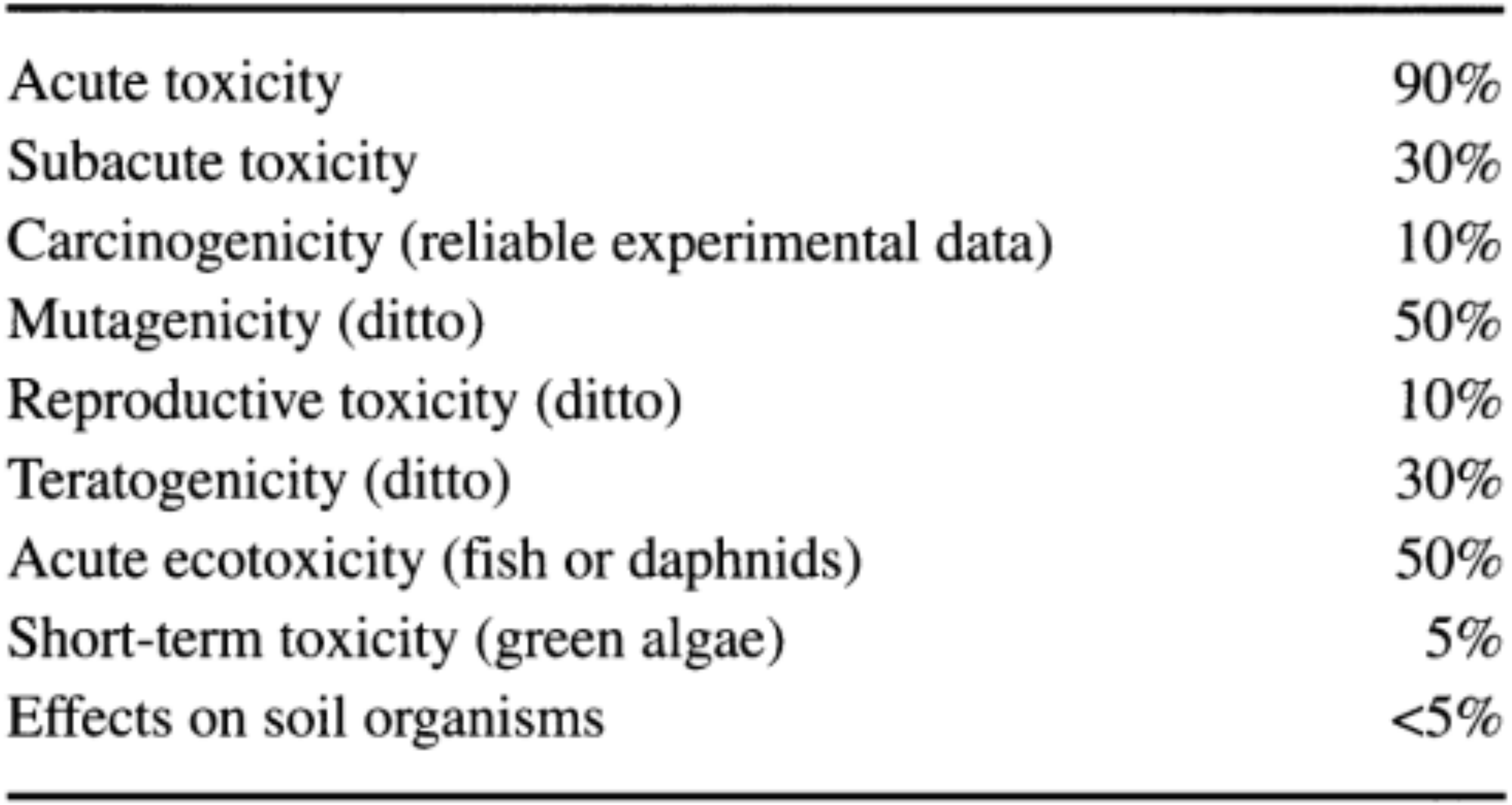
Type of chemical	Estimated number
Chemicals in commerce	100,000
Industrial chemicals	72,000
New chemicals introduced per year	2,000
Pesticides (21,000 products)	600
Food additives	8,700
Cosmetic ingredients (40,000 products)	7,500
Human pharmaceuticals	3,300

Synthetic chemicals

- Of the 100,000 synthetic chemicals on the market today, very few have been thoroughly tested for harmful effects.



Estimation of available toxicological data % for High Production volume chemicals



Acute toxicity	90%
Subacute toxicity	30%
Carcinogenicity (reliable experimental data)	10%
Mutagenicity (ditto)	50%
Reproductive toxicity (ditto)	10%
Teratogenicity (ditto)	30%
Acute ecotoxicity (fish or daphnids)	50%
Short-term toxicity (green algae)	5%
Effects on soil organisms	<5%

REACH

- **Registration, Evaluation, Authorisation and Restriction of Chemicals (2006)**
- REACH is a regulation of the EU, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals.
- It also promotes alternative methods for the hazard assessment in order to reduce the number of tests on animals.
- It established **European Chemical Agency** which manages the technical, scientific and administrative aspects of REACH.

How does REACH work?

- Companies need to register their substances (100 t/a) and to do this they need to work together with other companies who are registering the same substance.
- **European Chemical Agency** receives and evaluates individual registrations for their compliance, and the EU Member States evaluate selected substances to clarify initial concerns for human health or for the environment. Authorities and ECHA's scientific committees assess whether the risks of substances can be managed.
- Authorities can ban hazardous substances if their risks are unmanageable. They can also decide to restrict a use or make it subject to a prior authorisation.

Chemicals - what should be assessed ?

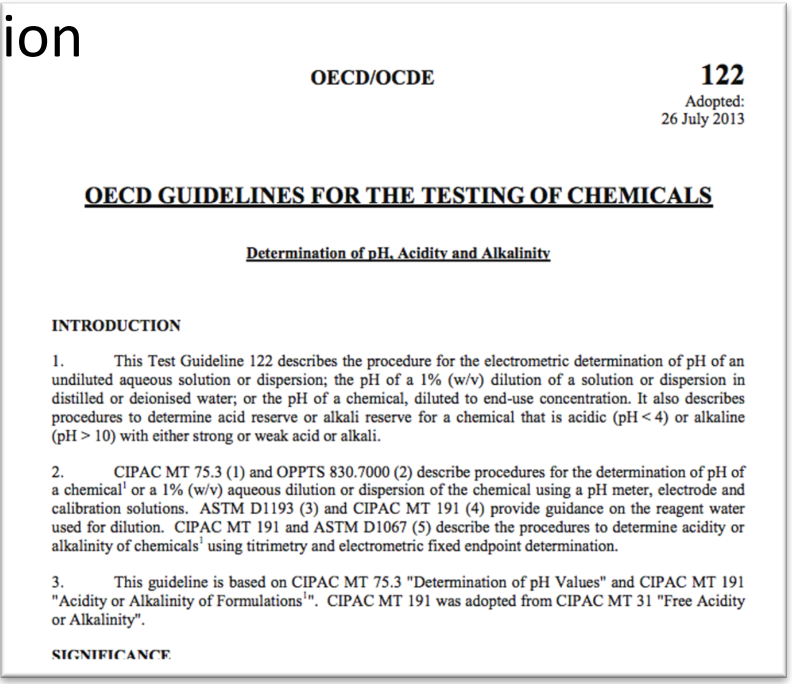
OECD Guidelines for the Testing of Chemicals

Section 1: Physical Chemical Properties

Section 2: Effects on Biotic Systems

Section 3: Degradation and Accumulation

Section 4: Health Effects



OECD/OCDE

122

Adopted:
26 July 2013

OECD GUIDELINES FOR THE TESTING OF CHEMICALS

Determination of pH, Acidity and Alkalinity

INTRODUCTION

1. This Test Guideline 122 describes the procedure for the electrometric determination of pH of an undiluted aqueous solution or dispersion; the pH of a 1% (w/v) dilution of a solution or dispersion in distilled or deionised water; or the pH of a chemical, diluted to end-use concentration. It also describes procedures to determine acid reserve or alkali reserve for a chemical that is acidic (pH < 4) or alkaline (pH > 10) with either strong or weak acid or alkali.

2. CIPAC MT 75.3 (1) and OPPTS 830.7000 (2) describe procedures for the determination of pH of a chemical[1] or a 1% (w/v) aqueous dilution or dispersion of the chemical using a pH meter, electrode and calibration solutions. ASTM D1193 (3) and CIPAC MT 191 (4) provide guidance on the reagent water used for dilution. CIPAC MT 191 and ASTM D1067 (5) describe the procedures to determine acidity or alkalinity of chemicals[1] using titrimetry and electrometric fixed endpoint determination.

3. This guideline is based on CIPAC MT 75.3 "Determination of pH Values" and CIPAC MT 191 "Acidity or Alkalinity of Formulations[1]". CIPAC MT 191 was adopted from CIPAC MT 31 "Free Acidity or Alkalinity".

SIGNIFICANCE

Physical Chemical Properties

- melting point, boiling point, vapour pressure
- Water solubility, Partition coefficient (n-octanol water coef.)
- Adsorption / desorption (soil)
- Density
- Hydroysis as function of pH
- Viscosity
- Surface tension
- Solution / extraction of polymers in water

Effects on Biotic Systems

- Reproduction Test and Development Assay (Daphnia magna, Fish, Avian)
- Acute and prolonged Toxicity Test (Daphnia magna, fish algae, Lemna minor, Earthworms, avians, honeybees)
- Fish Embryo Acute Toxicity / Sexual Development Test
- Activated Sludge, Respiration Inhibition Test
- Amphibian Metamorphosis Assay
- Inhibition of the Activity of Anaerobic Bacteria
- Terrestrial Plant Test: Vegetative Vigour Test
- Sediment-Water Chironomid Toxicity Sediment / water
- Soil Microorganisms: N / C Transformation Test
- Dietary Toxicity Test

Degradation and Accumulation

- Ready Biodegradability – CO_2 / Inherent Biodegradability / Biodegradability in Wastewater or digested sludge
- Bioaccumulation in Fish, Terrestrial Oligochaetes
- Bioaccumulation in Sediment-dwelling Benthic Oligochaetes
- Phototransformation of Chemicals in Water
- Aerobic Mineralisation in Surface Water
- Leaching in Soil Columns
- Aerobic and Anaerobic Transformation in Soil / Aquatic Sediment
- Aerobic Sewage Treatment
- Bioconcentration: Flow-through Fish Test
- Inherent Biodegradability in Soil

Health effects

- Reproduction, Developmental Toxicity, Carcinogenicity, Gene Mutation, Chromosomal Abberation, Cell Micronucleus tests
- Estrogen Receptor Agonists and Antagonists
- Rodent Dominant Lethal Test
- In Chemico, in Vitro, in Vivo Skin Corrosion / Sensitisation / Irritation
- Classification for Eye Irritation or Serious Eye Damage
- Estrogen Receptor Agonists
- Toxicokinetics, Phototoxicity and Chronic Toxicity Studies
- Acute, Subacute, Subchronic Inhalation Toxicity
- Repeated Dose 28-day Oral Toxicity Study in Rodents
- Acute Oral Toxicity: Up-and-Down Procedure
- Developmental Neurotoxicity Study
- Acute Oral Toxicity - Fixed Dose Procedure
- Prenatal Development Toxicity Study
- Neurotoxicity Study in Rodents

Some Critical Observations on Organics

- Egg shell thinning in Pelicans by DDT (1960’s) - led to Rachel Carson’s book “Silent Spring”
- Ozone depletion by CFCs (1970’s – Nobel prize by Howard, Rowland and Molina)
- Food chain biomagnification of synthetic chemicals (1970’s)
- Global dispersal of organochlorines (1980’s)
- Health problems in polar populations (1990’s)
- Public health issues (present): causes of cancer, hormonal regulation and other diseases

Chemicals of concern

Persistent, bioaccumulative, and toxic (PBTs) or very Persistent and very Bioaccumulative (vPvB)

- PAHs (polycyclic aromatic hydrocarbons)
- PCBs (polychlorinated biphenyls)
- Dioxins and Furans
- Pesticides
- PBDEs (Polybrominated diphenyl ethers)
- Phthalate Esters

Emerging Contaminants

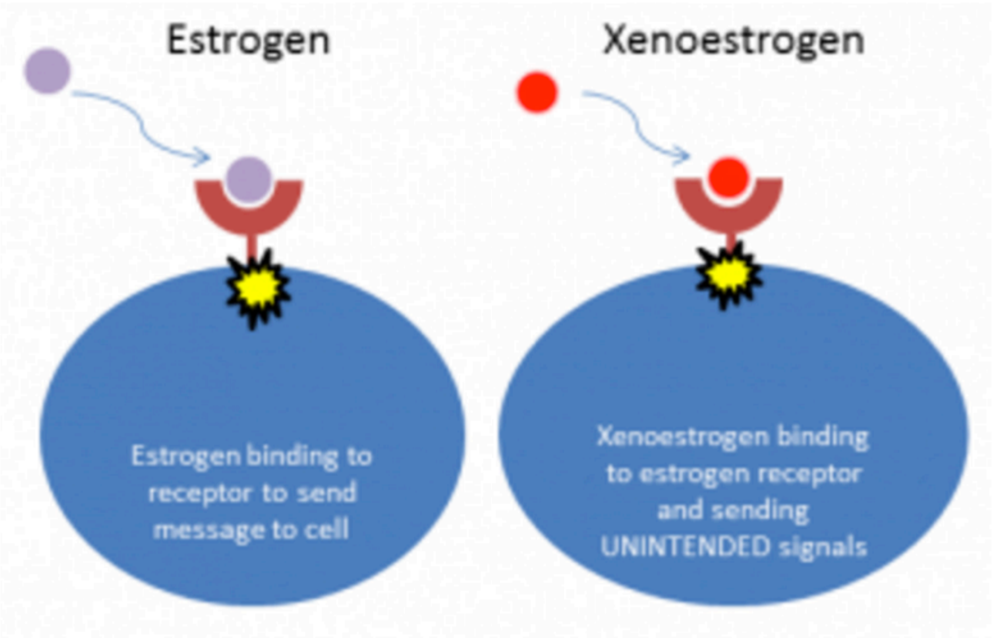
- Pharmaceuticals (human and vet) & Personal Care Products
- Perfluorinated acids (derived from Teflon)
- Fragrances and Detergents

Biogenic Substances

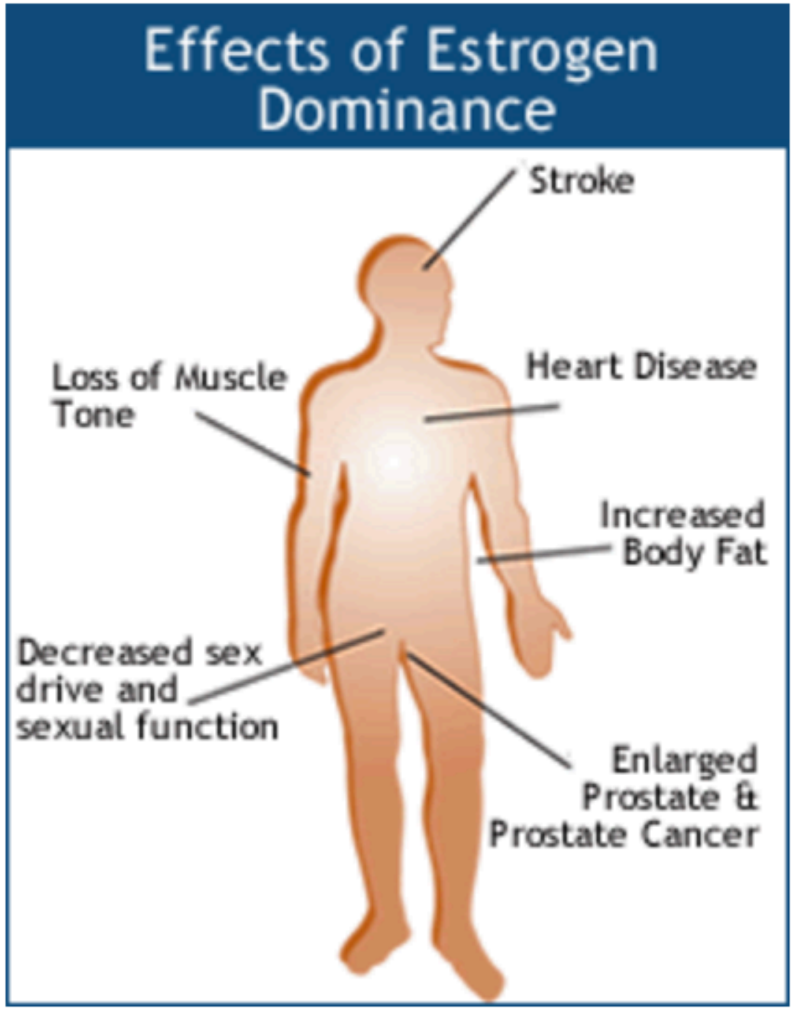
- Steroids
- Aromatic hydrocarbons

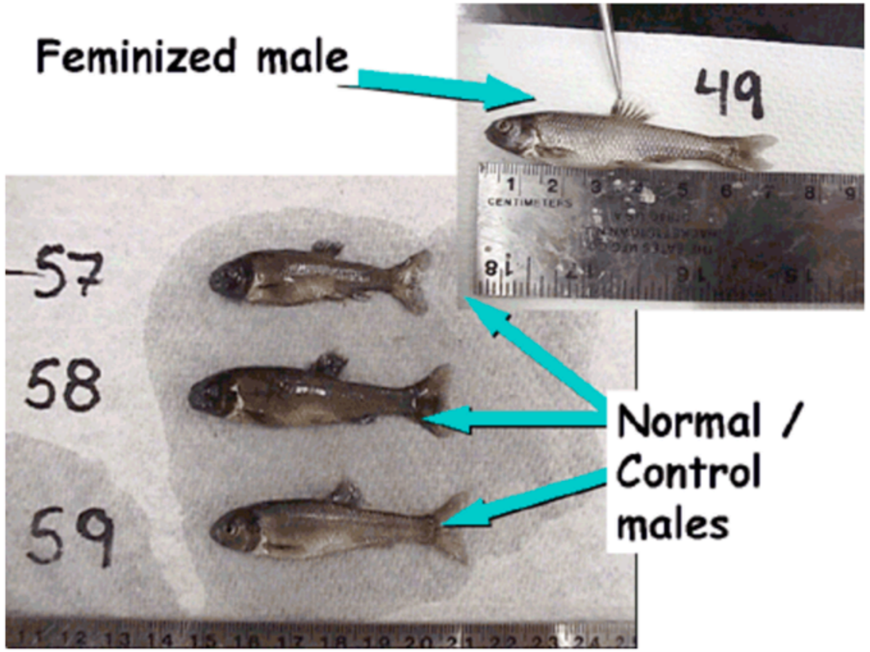
Xenoestrogens

- Some contaminants interfere with the normal hormonal regulation of estrogen
- Evidence becoming more widespread of “feminization” effect in males of aquatic species
- Examples of important environmental estrogens
  - Organohalogen compounds (esp. those that bind strongly to the AH receptor)
  - Pesticides
  - n-Nonyl phenol (detergents)
  - Pharmaceuticals (esp. some steroids)

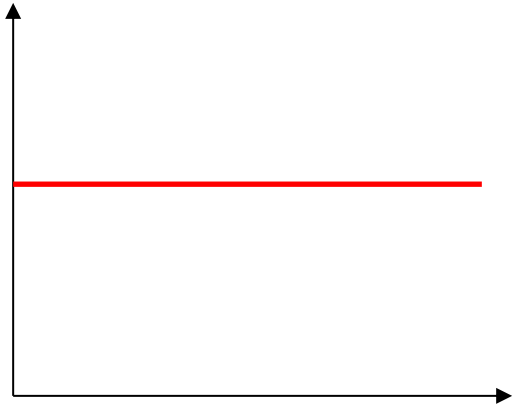


The effect ?


Effects of Estrogen Dominance
Stroke
Loss of Muscle Tone
Heart Disease
Increased Body Fat
Decreased sex drive and sexual function
Enlarged Prostate & Prostate Cancer

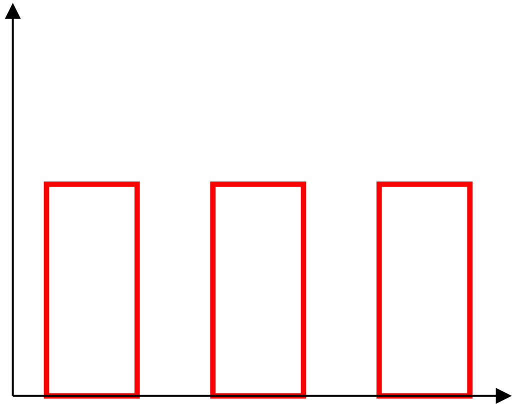

Feminized male
49
57
58
59
Normal / Control males

Emissions



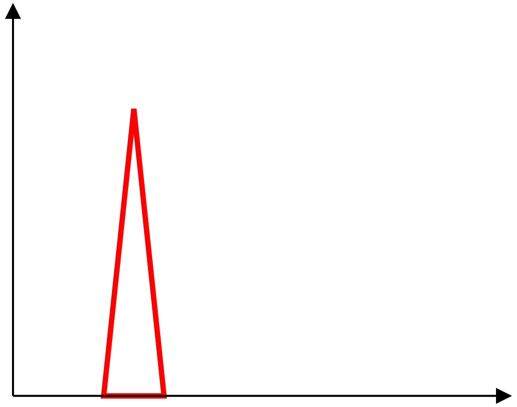
continuous

Typical for industrial emissions



Block

Typical for traffic emissions



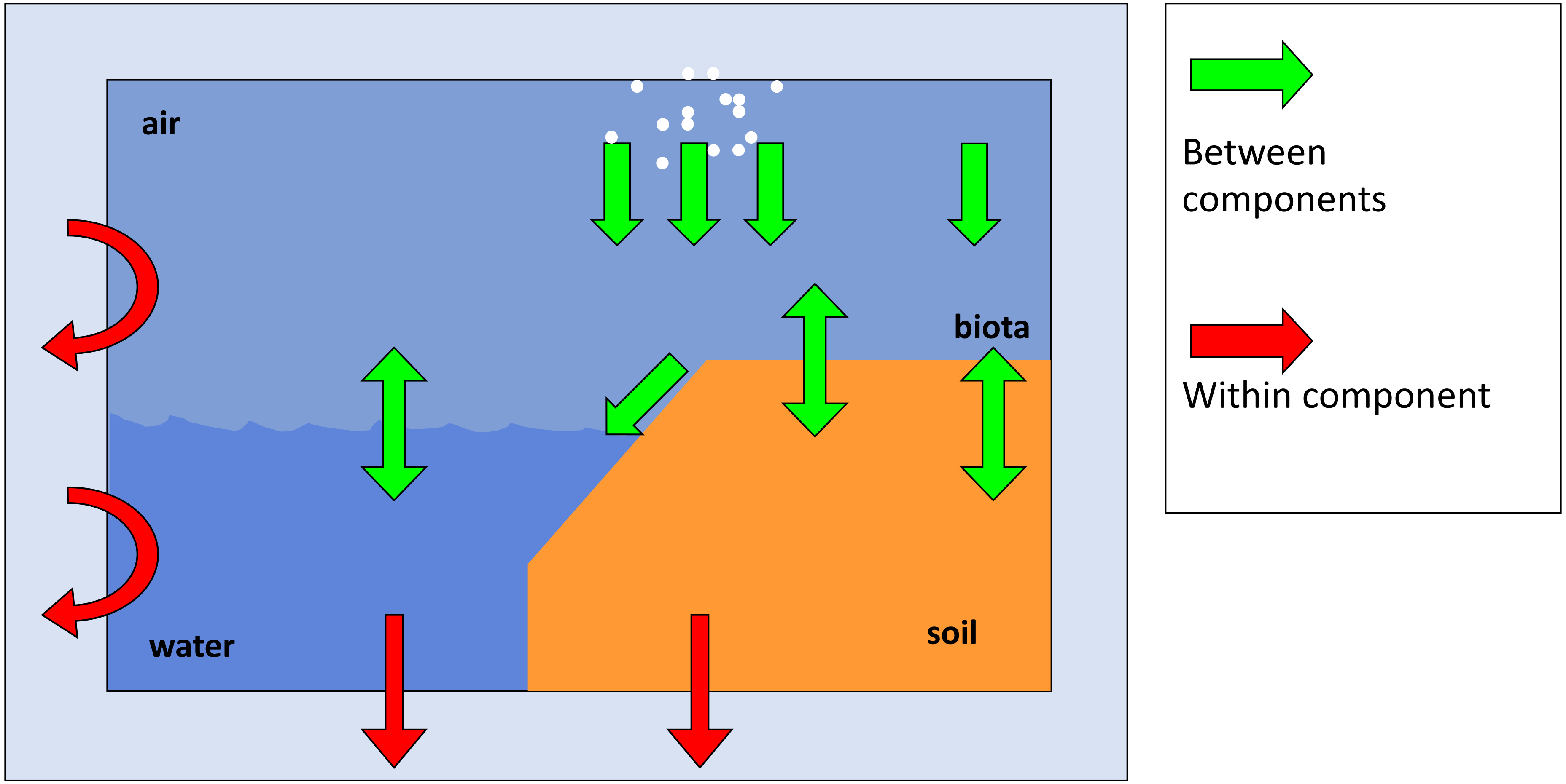
Peak

Typical for accidents

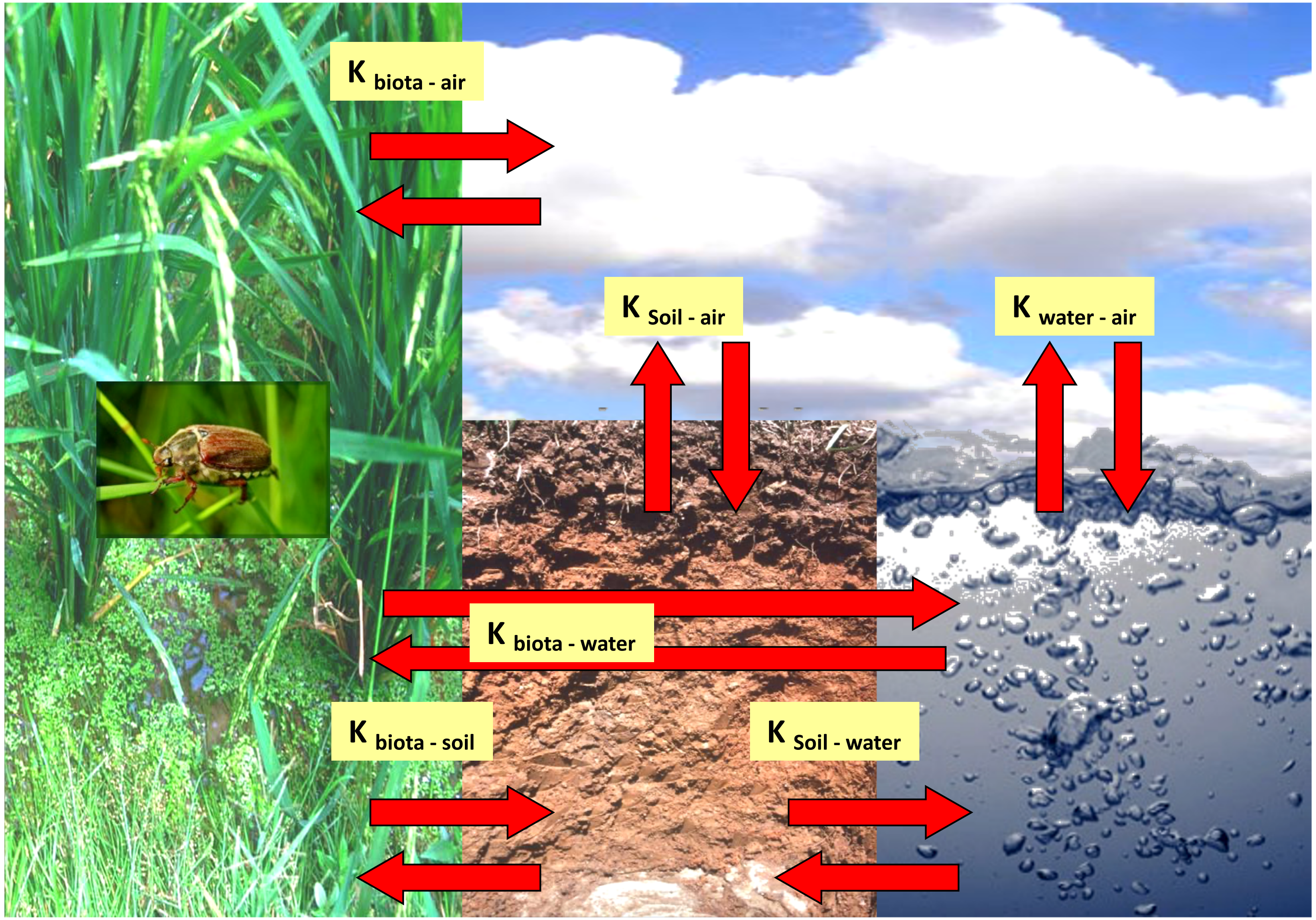
Sources

- Point sources
  - Defined by location
- Diffuse sources
  - A large number of little point sources of a similar character, distant from each other
- Surficial sources
  - A large number of little point sources of a similar character close to each other
- Linear sources
  - A large number of little point sources of a similar character along the certain path

Transport



Partition coefficients

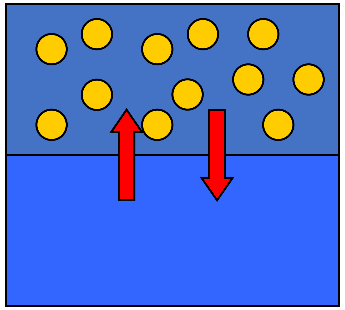


Equilibrium partitioning between phases

$$\mu_i = \mu^\theta + RT \ln a_i$$

$$\mu_w = \mu^\theta + RT \ln a_w$$

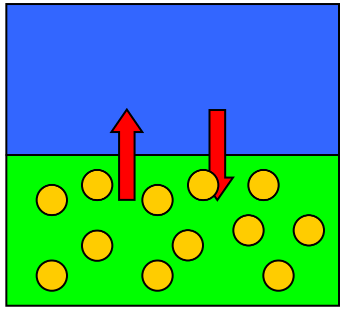
$$\Delta G_{sol} = \mu_w - \mu_i$$



Gas

Pure Liquid or solid

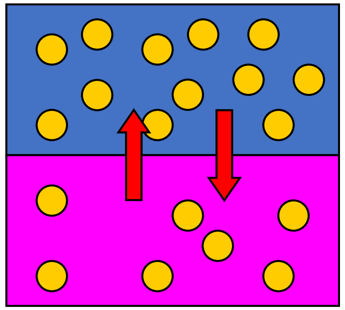
Vapour pressure



Pure Liquid or solid
(sat. with water)

Saturated aqueous
solution

Aqueous solubility



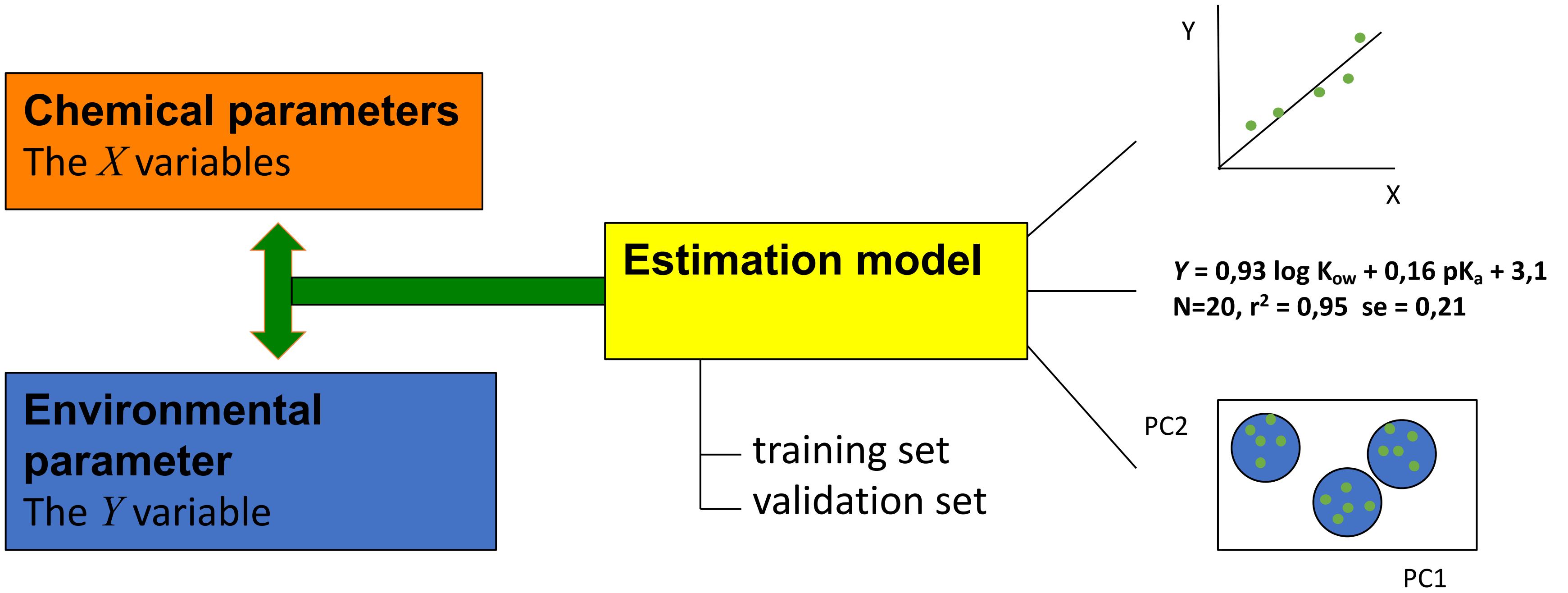
Gas (air)

(Dilute) aqueous solution

Air – water partition
Constant (Henry's constant)

Estimation methodologies

- Procedures by which certain parameters (Y variable) for a chemical is calculated on the basis of other parameters, which is easier to obtain experimentally or can be derived directly from a structure (the X variable or variables)
- QSPR „property” – physciochemical feature, fate
- QSAR „activity” – biological or toxicologica feature
- SAR - qualitative relation



Chemical parameters
The X variables

Environmental parameter
The Y variable

Estimation model

training set
validation set

$Y = 0{,}93 \log K_{ow} + 0{,}16\ pK_a + 3{,}1$
$N=20,\ r^2 = 0{,}95\ \ se = 0{,}21$

Chemical descriptors

- Y variable :
  - Sorption to soils or sediments, chemical degradation, biodegradation, bioconcentration, ecotoxicity
- X variables – structural:
  - Molecular connectivity index (MC), **Fragment constants**, Substituent constant – Hammett sigma constant (σ) or Taft constant (E_s), Van der Waals volume, Total surface area (TSA), Total molecular volume (TMV), atomic charges (q), energy of molecular orbitals (lumo, homo), delocalizability (D), hardess (η),
- X variables - physicochemical:
  - Aqueous solubility (S_w), Octanol water partition coefficient (K_{ow}), Acid dissociation constant (pK_a), Density, Melting point,(T_m), Boiling point (T_b), Chromatographic indices, Reduction potential.

Empirical models

- Simple graphical presentations
- Linear or non linear equations between Y and X
- Linear or non linear equations based on different properties (Y versus $X1$, $X2$, etc.)
- Mulitvariate techniques suchas prinicipal component analysisi PCA, partial least square (PLS, discriminant analysis (DA) etc.

$$\boxed{Y(\mathrm{i}) = a1X1(i) + a2X2(i) + a3X3(i) + \ldots..+ b}$$

$Y(i)$ – value of the depenent parameter of the chemical i

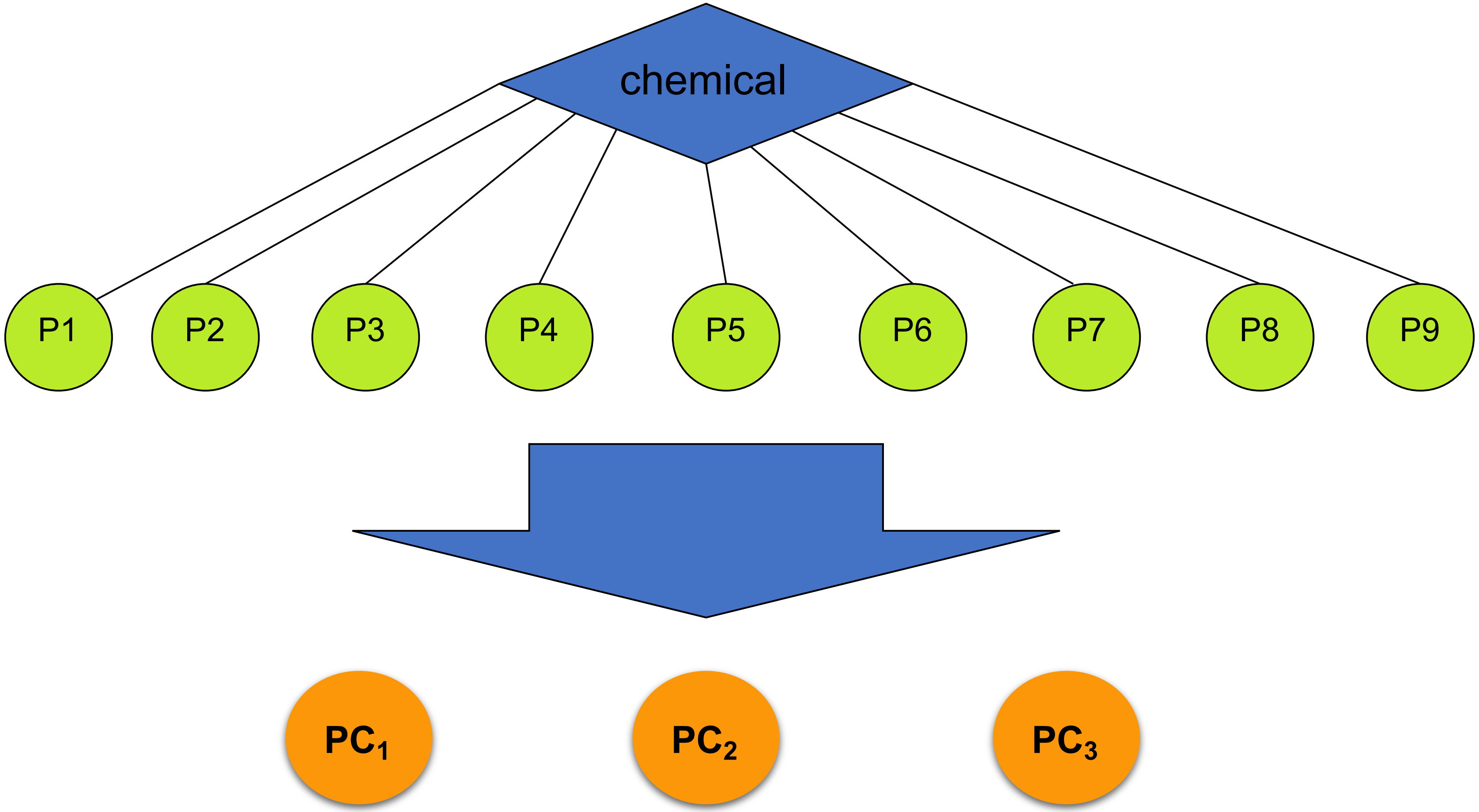
$X1\text{-}X3(i)$ – values of the independent parameters of chemical i

$A1\text{-}a3$ – regretion coefficients (95% confidence)

b - The intecept of the linear equation

The quality is described by correlation coefficient r or r^2 and standard error estimate

Principle of PCA



68%

12%

4%

Basic properties (X)

- Octanol water partition coefficients
- Water solubility
- Vaopur pressure
- Henry’s law constant
- Acid dissociation constant

Octanol water partition coefficient (K_{ow})

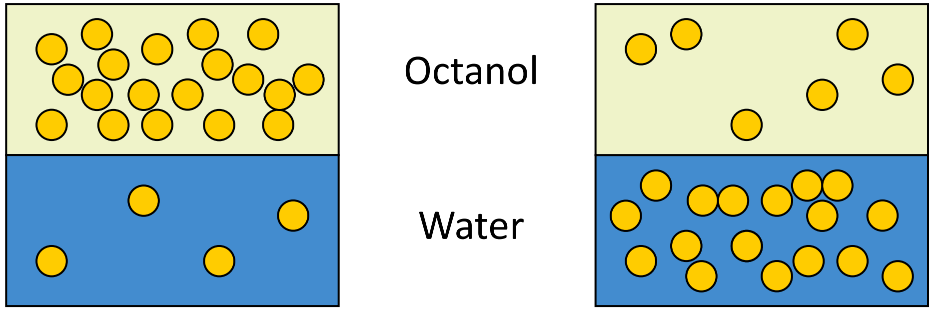
- One of the key properties in estiamtion models for toxicity, bioaccumultation and sorption to oils and sediment.
- Octanol resemble lipids in organisms or organic carbon in soil

$$K_{ow} = [i]_{\text{octanol}} / [i]_{\text{aqueous}}$$

$$log\ K_{ow} = log\ [i]_{\text{octanol}} - log\ [i]_{\text{aqueous}}$$

$log\ K_{ow} = 5{,}73$

$log\ K_{ow} = \text{-}0{,}24$



hexachlorobenzene

acetone

Ionizable compounds (acids and bases)

- The proportions of the species of compound (neutral, anionic, cationic) depend on the pH value of the surrounding phase
- Dissociation detemines further properties of the substance – partition and distribution coefficients, solubility, adsorption/desorption, accumulation and degradation.

$$f_{\mathrm{u}}^{\mathrm{acid}} = f_{\mathrm{i}}^{\mathrm{base}} = \frac{1}{1 + 10^{\mathrm{pH}\text{-}\mathrm{p}K_{\mathrm{a}}}}$$

$$f_{\mathrm{i}}^{\mathrm{acid}} = f_{\mathrm{u}}^{\mathrm{base}} = \frac{1}{1 + 10^{\mathrm{p}K_{\mathrm{a}}\text{-}\mathrm{pH}}}$$

f_u	undissociated fraction
f_i	ionized fraction

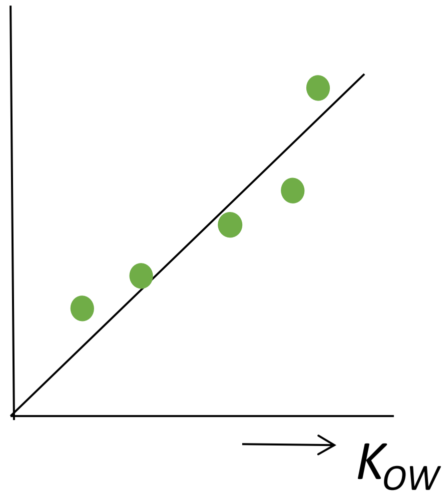
$$D_{\mathrm{ow}} = f_{\mathrm{u}} \cdot K_{\mathrm{ow}} + f_{\mathrm{i}} \cdot \left(K_{\mathrm{i}} + \sum_{k} K_{\mathrm{ip}}(k) \right)$$

K_i	partition of ionized form
$K_{ip}(k)$	partition of ion pairs

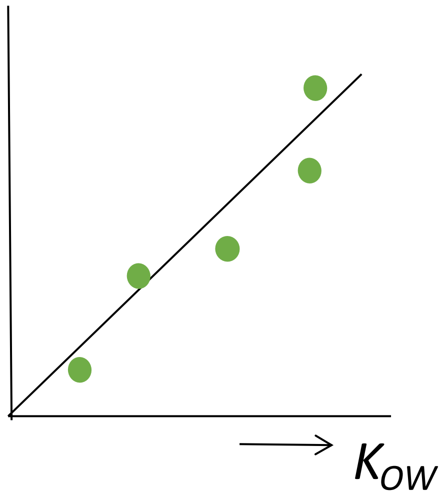
$$\boxed{D_{\mathrm{ow}}^{\mathrm{u}} = f_{\mathrm{u}} \cdot K_{\mathrm{ow}}}$$

Octanol water partition coefficient (K_{ow})

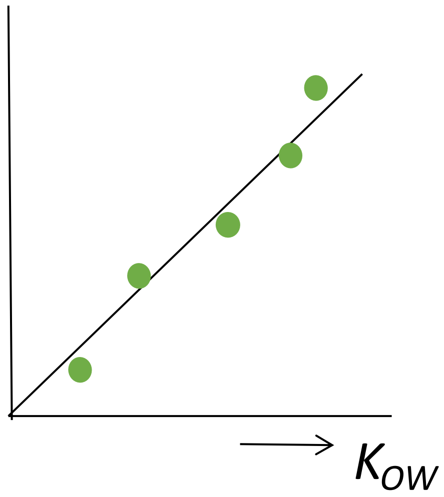
BIOCONENTRATION FACTOR



SOIL SORPTION



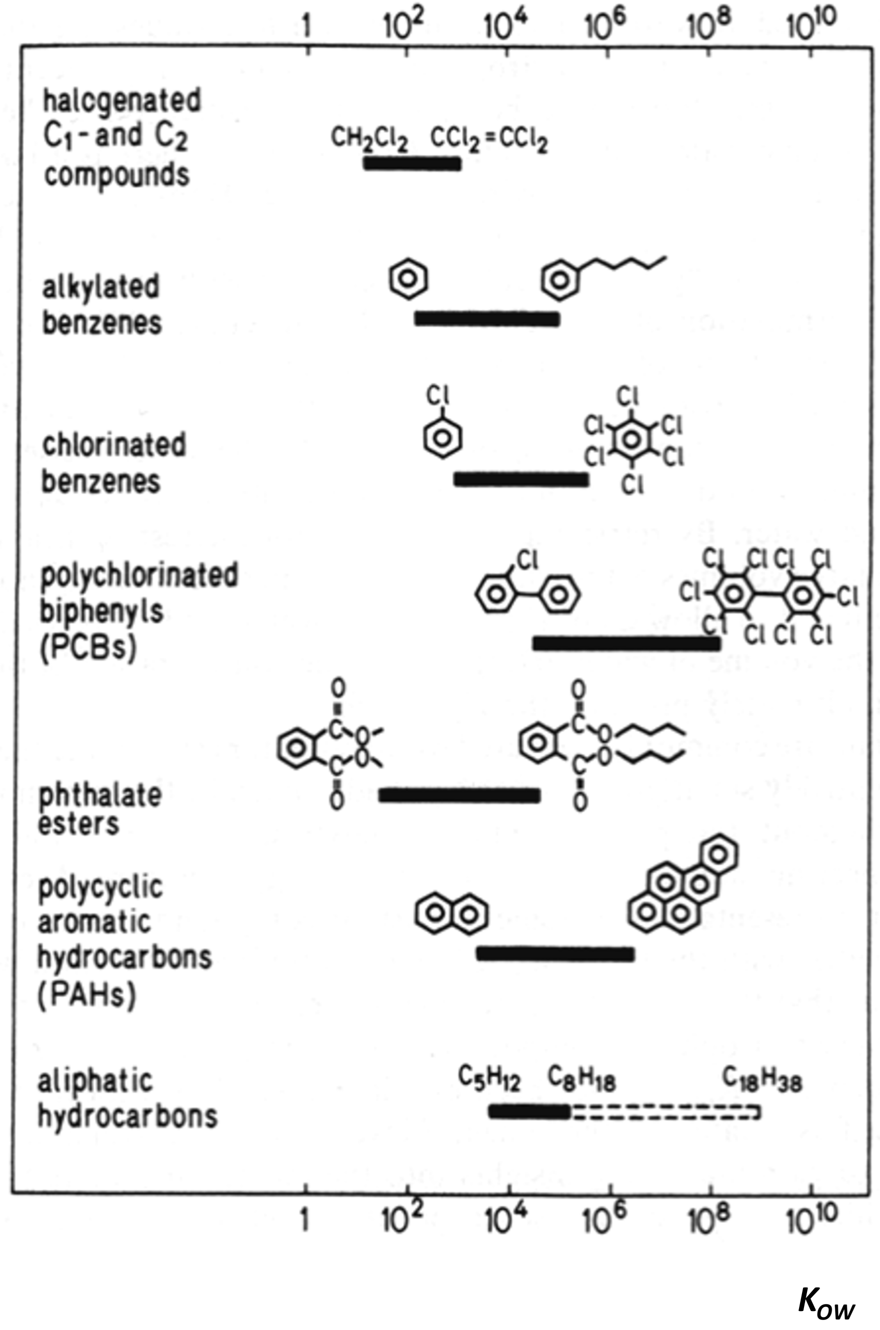
LC_{50}

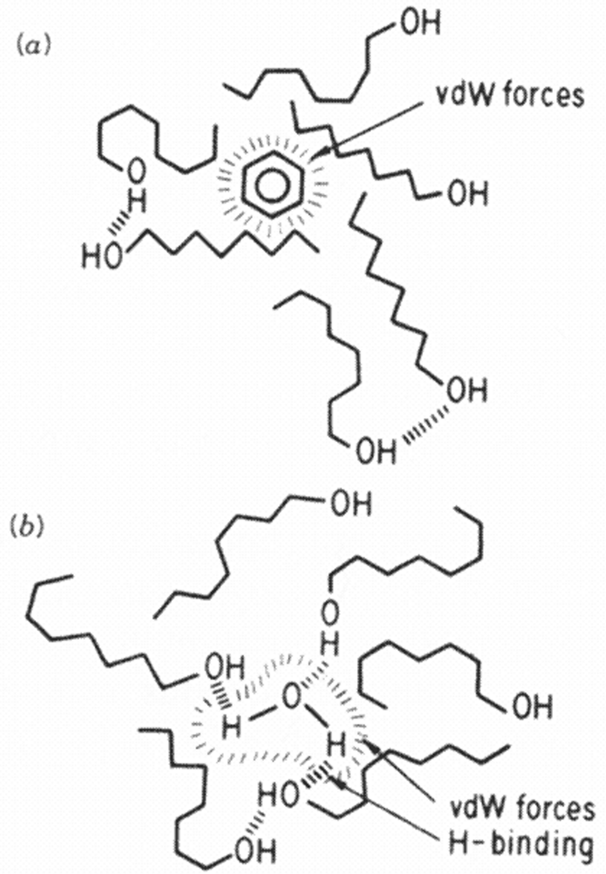


Octanol water partition coefficient (K_{ow})

chemical	*Log* K_{OW}
Methanol	-0,77
Acetone	-0,24
Benzene	2,19
1,2-dichlorobenzene	3,34
Pentachlorobenzene	5,18
DDT	6,99
Decachlorobiphenyl	8,27

Log K_{OC} <1 hydrofilic, do not bioaccumulate.
1 < *log* K_{OC} < 3, medium hydrophobic, may undergo partial bioaccumulation
Log K_{OC} > 3, highly hydrophobic, bioaacumulate intesively


1
10^2
10^4
10^6
10^8
10^10
halogenated C1- and C2 compounds
CH2Cl2
CCl2=CCl2
alkylated benzenes
chlorinated benzenes
Cl
polychlorinated biphenyls (PCBs)
phthalate esters
O
C
polycyclic aromatic hydrocarbons (PAHs)
aliphatic hydrocarbons
C5H12
C8H18
C18H38
Kow


(a)
OH
O
H
HO
vdW forces
(b)
vdW forces
H-binding

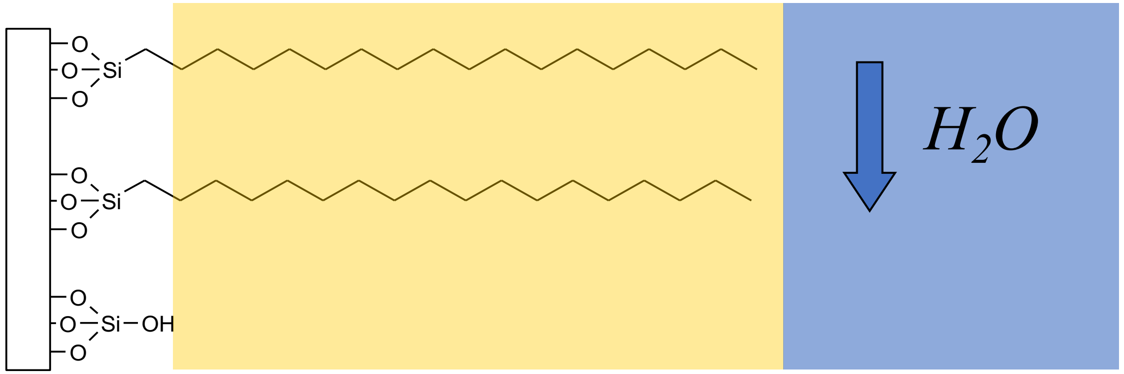
Shake flask method

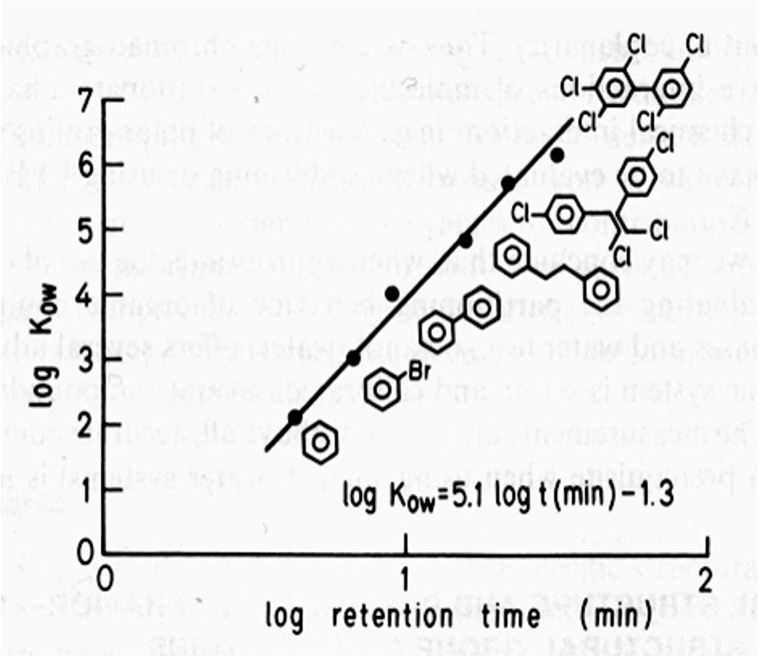
- Saturated phases
  - 2,3 mole of water/L
  - 4,5 x10^{-3} mole of octanol/L.
- Analyte concentration <0.01 mole/L
- Accurate for Log K_{ow} below 4-5
- Emulsification – leads to overestimation

Prediction with RP HPLC

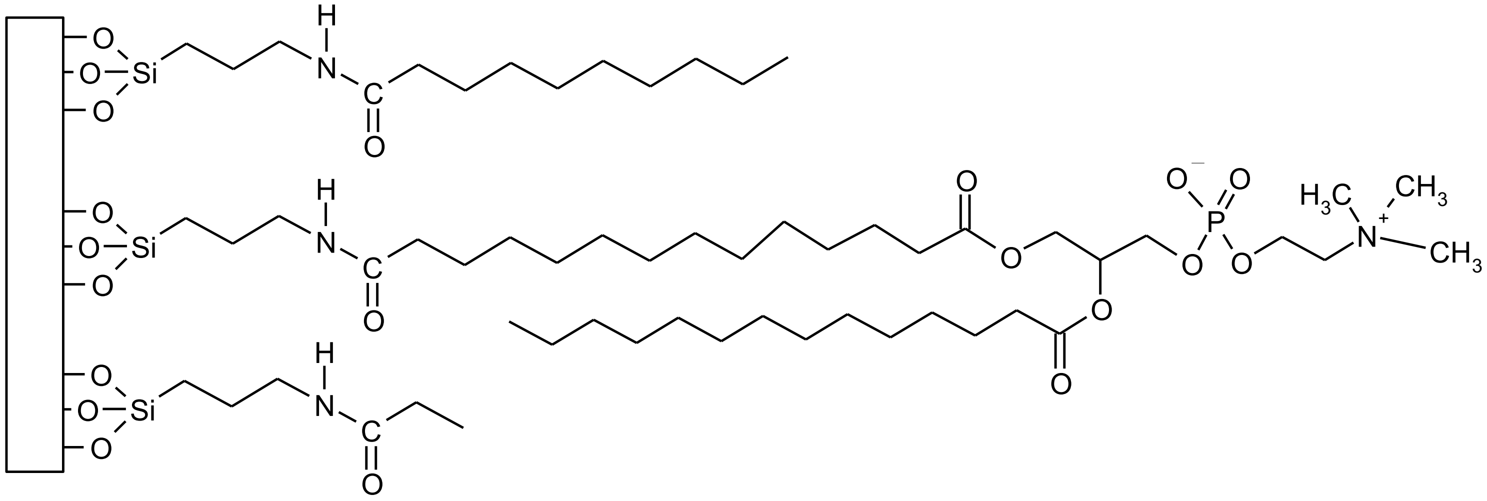
- *K_{OW} is related to capacity factors in RP-HPLC ($\log k$)*
- $\log k_w$ – value extrapolated to 0% of methanol

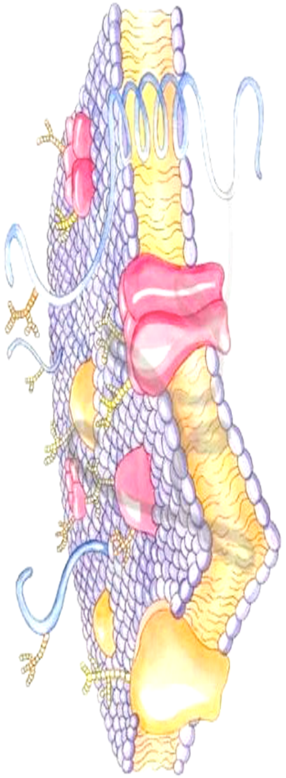
$$\log K_{OW} = a \log k' + b$$





Immobilized artificial membrane

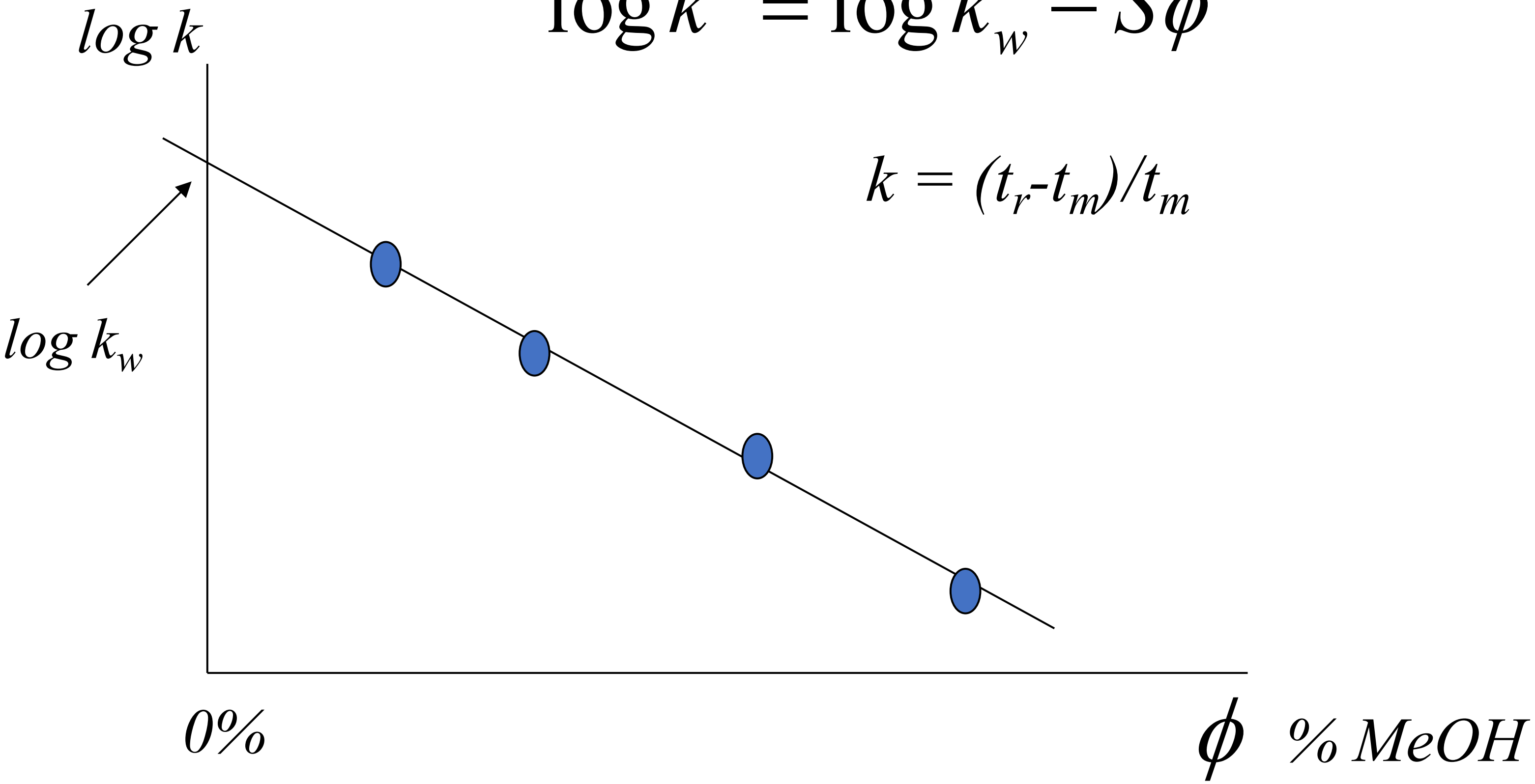




Snyder – Soczewiński equation

$$\log k = \log k_w - S\phi$$

$k = (t_r\text{-}t_m)/t_m$

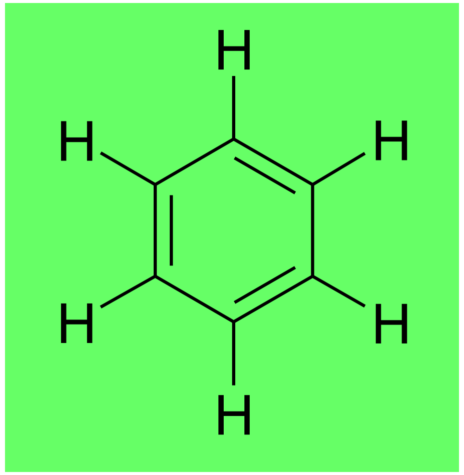


QSAR methods

- One of the most representative example of QSAR (Leo et al., 1981; Nys and Rekker, 1973; Rekker 1977; Hansh and Leo, 1979; Lyman 1982)
- The structure of a molecule is reduced to fragments (atoms or molecular fragments) and $log\ K_{OW}$ can be calculated by summing the values of these fragments
- Energy needed to transfer the chemical compound between octanol and water equals sum of free energies of particular fragments contributing in this process

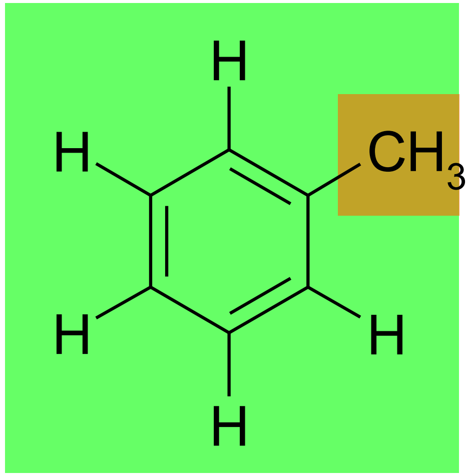
$$\log K_{OW} = \sum a_i \cdot f_i + \sum b_j \cdot F_j$$

f_i fragment constant of i
a_i number of fragments
Fj structural / geometrical feature constant j
b_j number of these features



Benzene

Log K



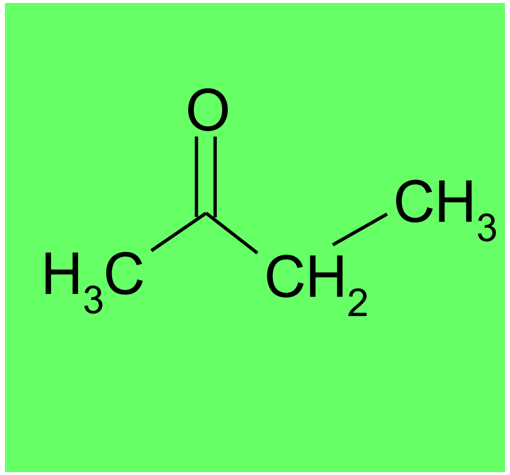
toluene

$Log\ K_{OW} = 2{,}69$

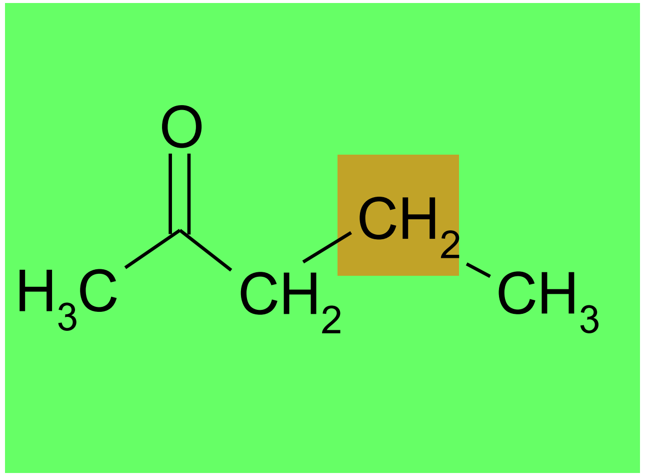
Δ = 0,56

Methyl fragment constant

$$f_i = 0{,}56$$



Methyl ethyl ketone
Log K_{OW} = 0,29

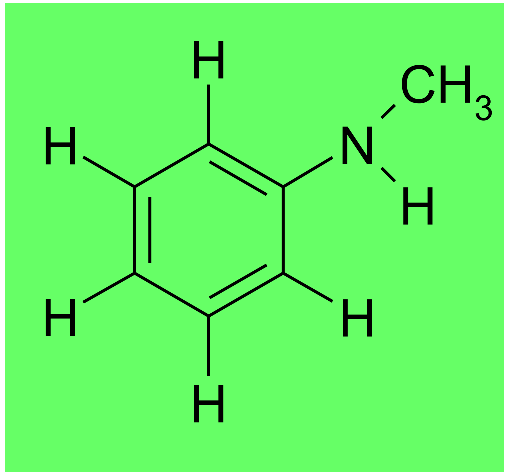


Methyl pentyl ketone
Log K_{OW} = 0,79

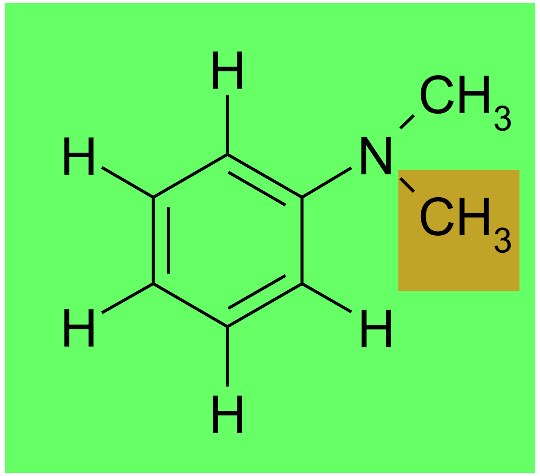
Δ = 0,50

Methylene fragment constant

$f_i = 0{,}50$



***N*-methylaniline**
$Log\ K_{OW} = 1,66$



***N,N*-dimethyloaniline**
$Log\ K_{OW} = 2,31$

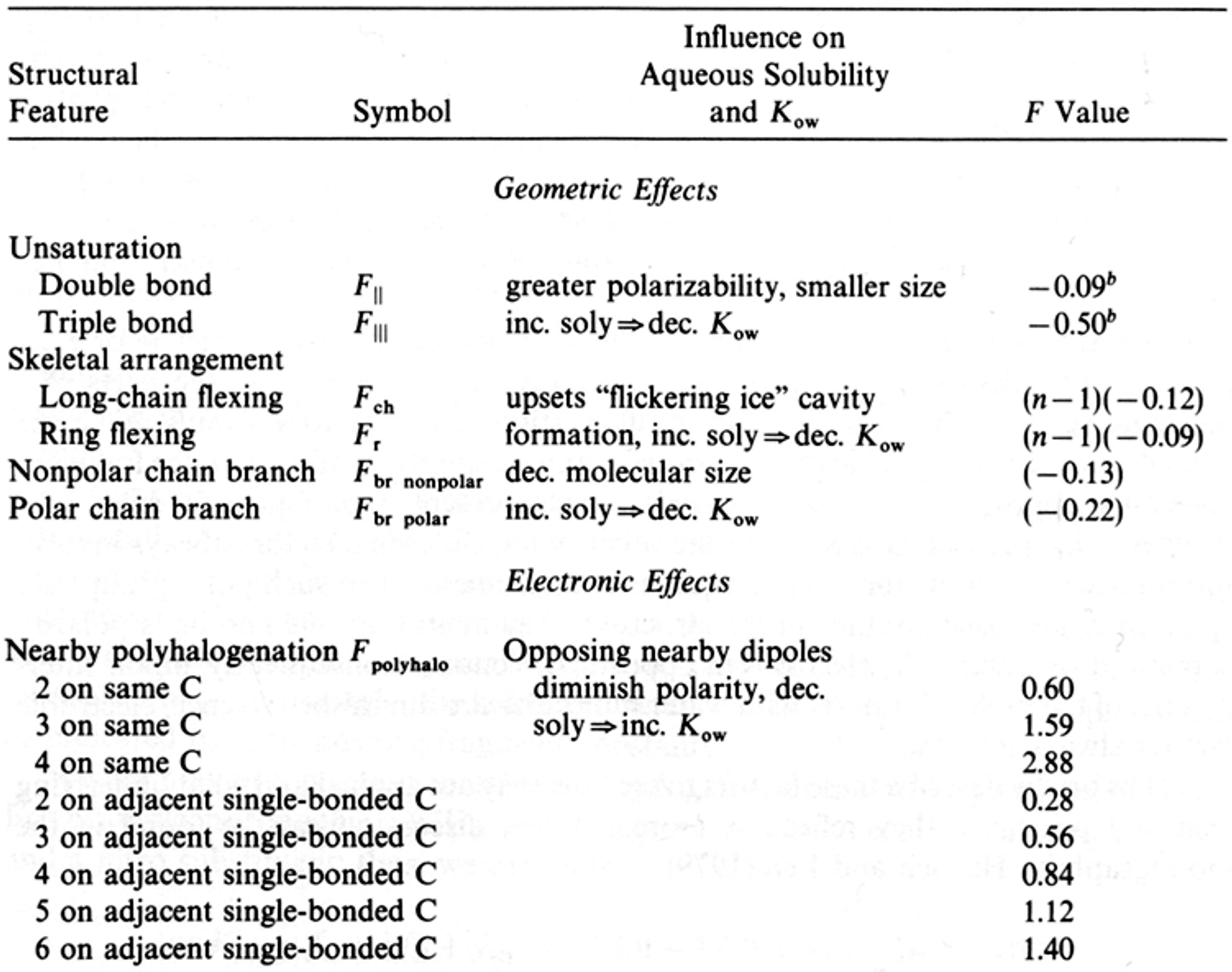
Δ = 0,55

N-methyl fragment constant

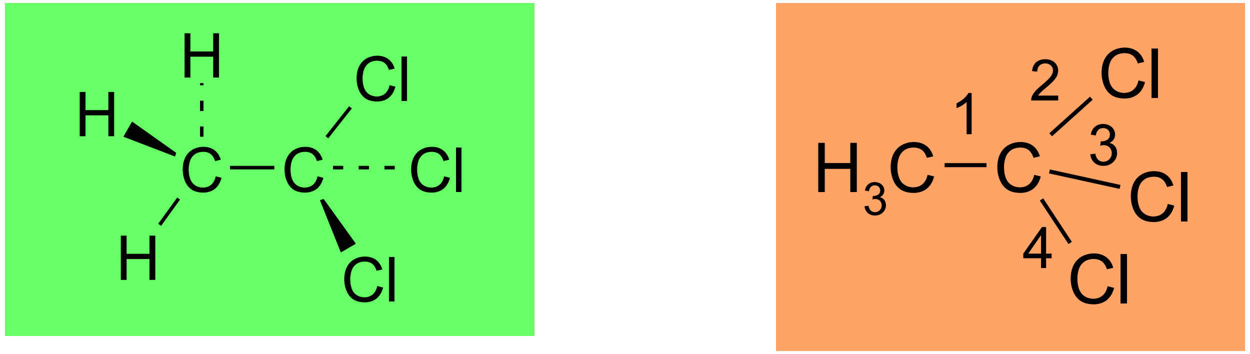
$f_i = 0,55$

Fragment	f
—H	0.23
—C—	0.20
C aromatic	0.13
C aromatic between rings	0.23
—F	−0.38
—Cl	0.06
—Br	0.20
—I	0.59
—O—	−1.82
—OH	−1.64
$—N<$	−2.18
—NH—	−2.15
$—NH_2$	−1.54
$—NO_2$	−1.16
Ketone —C(=O)—	−1.90
Carboxylate	
$—COO^-$	−5.19
Carboxylic acid	
—COOH	−1.11
Ester—COO—	−1.49

Structural features



Structural Feature	Symbol	Influence on Aqueous Solubility and K_{ow}	F Value
		Geometric Effects	
Unsaturation			
Double bond	$F_{\vert\vert}$	greater polarizability, smaller size	-0.09[b]
Triple bond	$F_{\vert\vert\vert}$	inc. soly ⇒ dec. K_{ow}	-0.50[b]
Skeletal arrangement			
Long-chain flexing	F_{ch}	upsets “flickering ice” cavity	$(n-1)(-0.12)$
Ring flexing	F_r	formation, inc. soly ⇒ dec. K_{ow}	$(n-1)(-0.09)$
Nonpolar chain branch	$F_{br\ nonpolar}$	dec. molecular size	(-0.13)
Polar chain branch	$F_{br\ polar}$	inc. soly ⇒ dec. K_{ow}	(-0.22)
		Electronic Effects	
Nearby polyhalogenation	$F_{polyhalo}$	Opposing nearby dipoles	
2 on same C		diminish polarity, dec.	0.60
3 on same C		soly ⇒ inc. K_{ow}	1.59
4 on same C			2.88
2 on adjacent single-bonded C			0.28
3 on adjacent single-bonded C			0.56
4 on adjacent single-bonded C			0.84
5 on adjacent single-bonded C			1.12
6 on adjacent single-bonded C			1.40



- 1,1,1 – Trichloroethane
- Sum of constants: $2f_c + 3f_H + 3f_{Cl}$
- Intramolecular interaction:
- 4 flexible single bonds $[(4\text{-}1) \times F_{ch}]$ = 3(-0.12)
- Electronic effects – polihalogenation $F_{polyhalo}$: 3 on the same C = +1.59

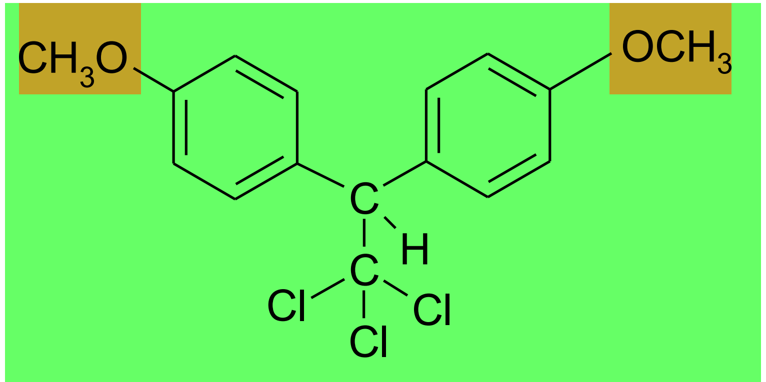
$$\log K_{OW} = 2f_c + 3f_H + 3f_{Cl} + (4-1)F_{Ch} + F_{polyhalo}$$

$$= 2(0.20) + 3(0.23) + 3(0.06) + 3(-0.12) + (1.59)$$

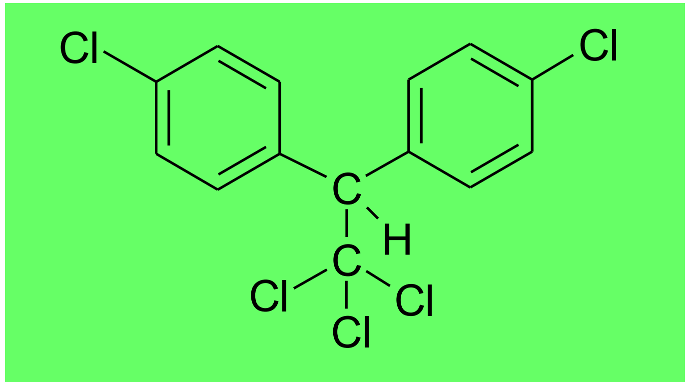
$$= 2.50$$

Simplified methods

$$\log K_{OW} = \log K_{OW}(new) - \log K_{OW}(old) - \sum_{remove} f + \sum_{add} f - \sum_{remove} F + \sum_{add} F$$



metoksychlor



DDT

$$\log K_{OW}(metoxyychlor) = \log K_{OW}(DDT) - 2f_{Cl}^{\varphi} + 2f_{O}^{\varphi} + 2f_{C} + 6f_{H} + 2(2-1)F_{Ch}$$

$$= 6.36 - 2(094) + 2(-0.61) + 2(0.2) + 6(0.23) + 2) - 0.12)$$

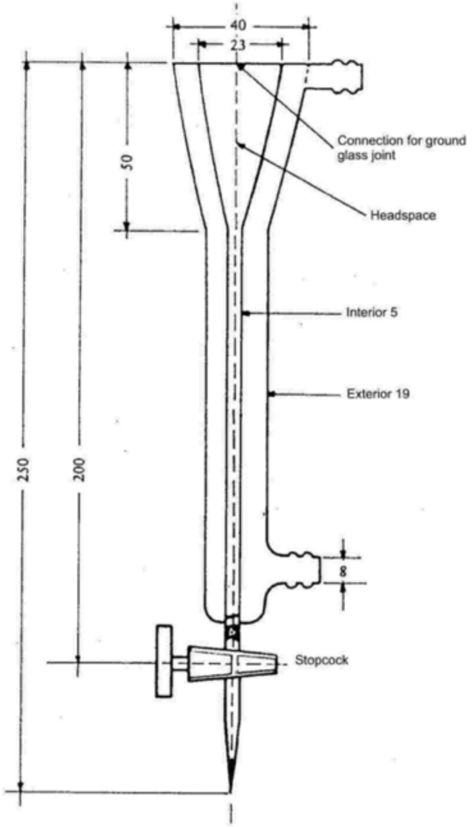
$$= 4.80$$

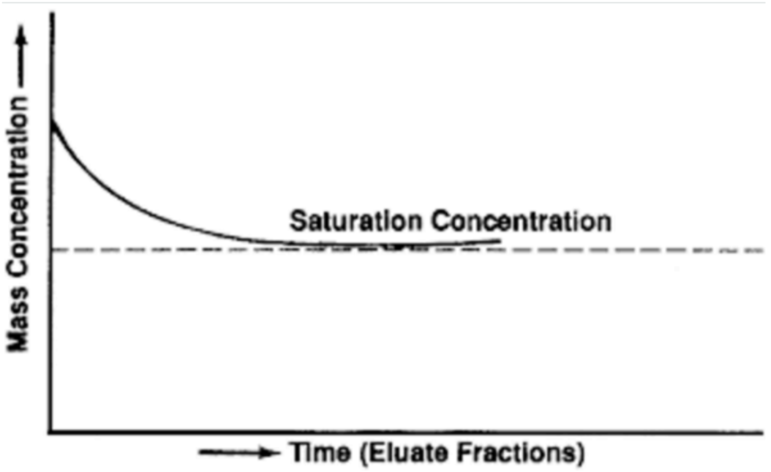
Water solubility S_w

- The maximum amount of the compound that dissolves in pure water at equlibirum (at const. *T* and *P*)
- Assessment of the fate and exposure of chemicals in the environment
- Distribution by hydrologic cycle, mobility, contaminant concetrations in vasrious media
- Water soluble compounds - low $log\ K_{OW}$, low adsorption to soil, low bioconcentration, bioavailable
- Large range, e.g.
  - 1,2,3,4,6,7,8-Heptachlorodibenzo-p-dioxine: 5,64 x 10^{-9} mole/ m^3
  - Ethanol: infinitely miscible with water
  - Most compounds between 1 mg/L – 100 g/L
- Experimental method – column elution method

Column elution method

- the elution of a test substance with water from a micro-column which is charged with an inert support material (such glass beads or sand), coated with an excess of test substance.
- The water solubility is determined when the mass concentration of the eluate is constant.
- This is shown by a concentration plateau as a function of time





Estimation methods

- *Lyman et al. 1982*

  $\log S$ (mg/l) = $-0.922 \log K_{ow} + 4.184$ (n=90, r^2=0.740)

  $\log S$ (µmol/l) = $-1.49 \log K_{ow} + 7.46$ (n=34, r^2=0.970)

- *Isnard and Lambert 1989*

  $\log S$ (mg/l) = $6.05 - 1.29 \log K_{ow}$ (n=300, r=0.964, sd=0.631)

  $\log S$ (mg/l) = $5.90 - 1.18 \log K_{ow} - 0.0048(MP-25)$ (n=300, sd=0.560)

- *OECD (1993)*

  $\log S$ (mol/l) = $1.17 - 1.38 \log K_{ow}$

- *Meylan and Howard 1994*

  $\log S$ (mol/l) = $0.796 - 0.854 \log K_{ow} - 0.00728MW + cf$ (n=85, r^2=0.865, sd=0.961)

322 Pesticides

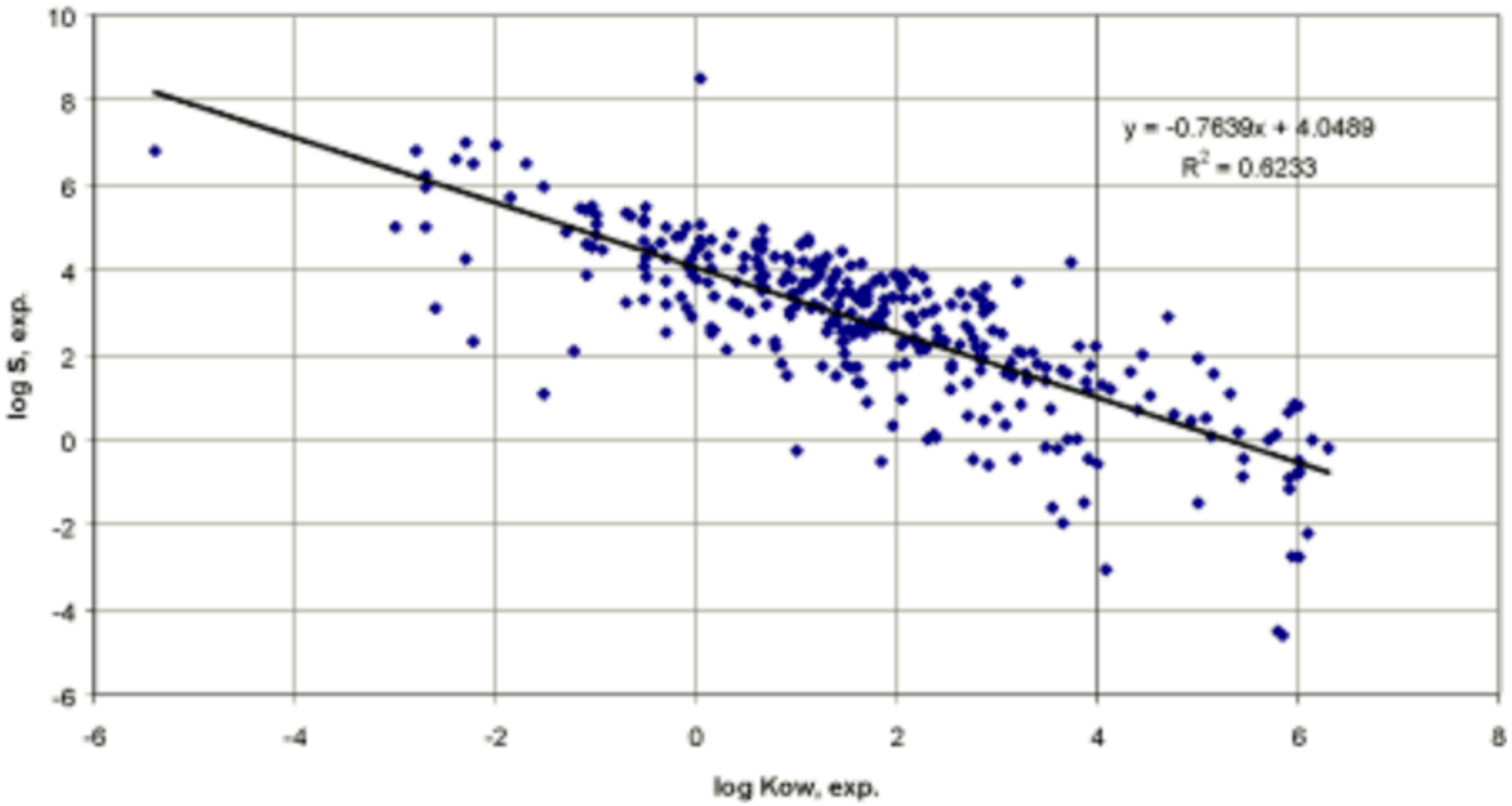


Figure 3
Correlation between the logarithm to the measured water solubility and log Kow.

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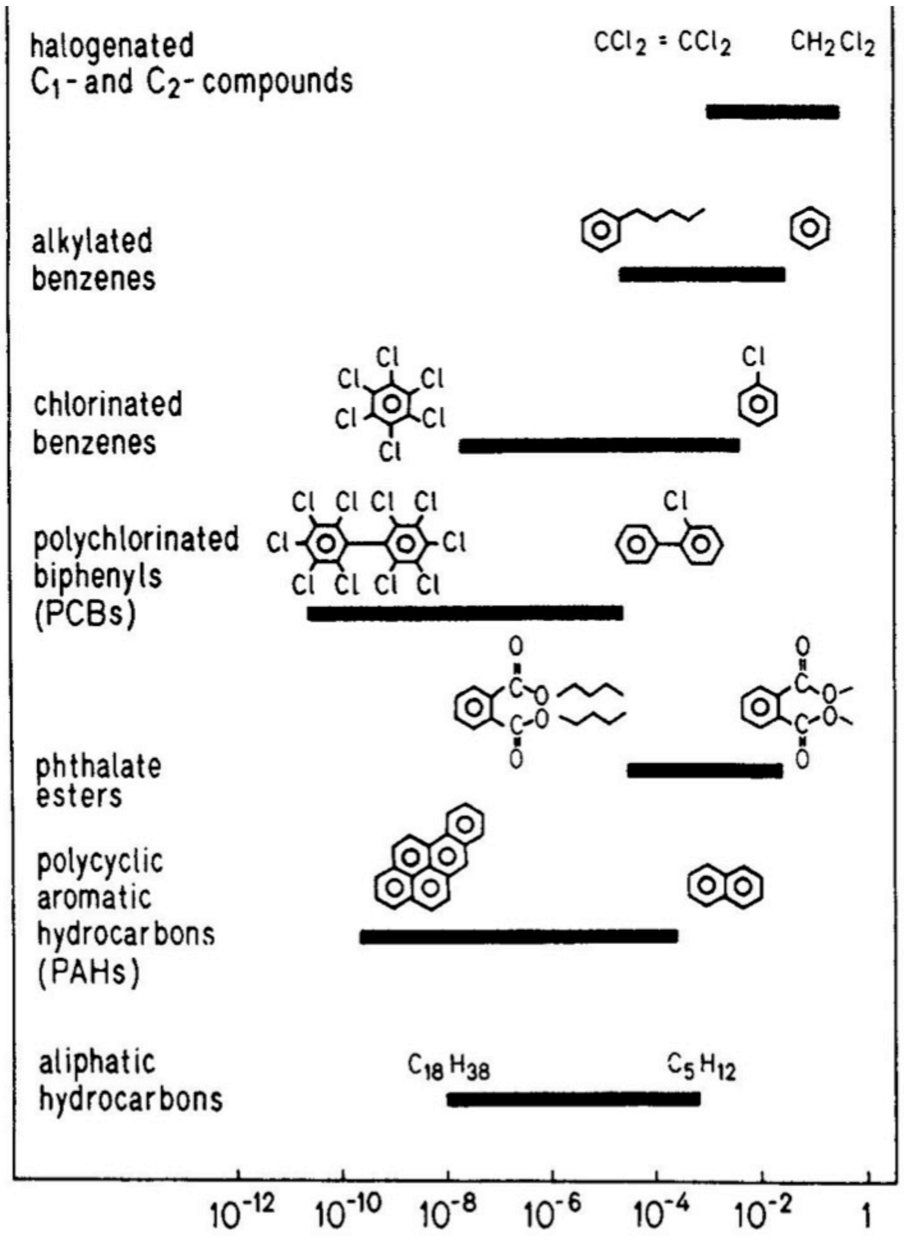
Solubility in wa



Solubility (sat.) mol/L w 25ºC

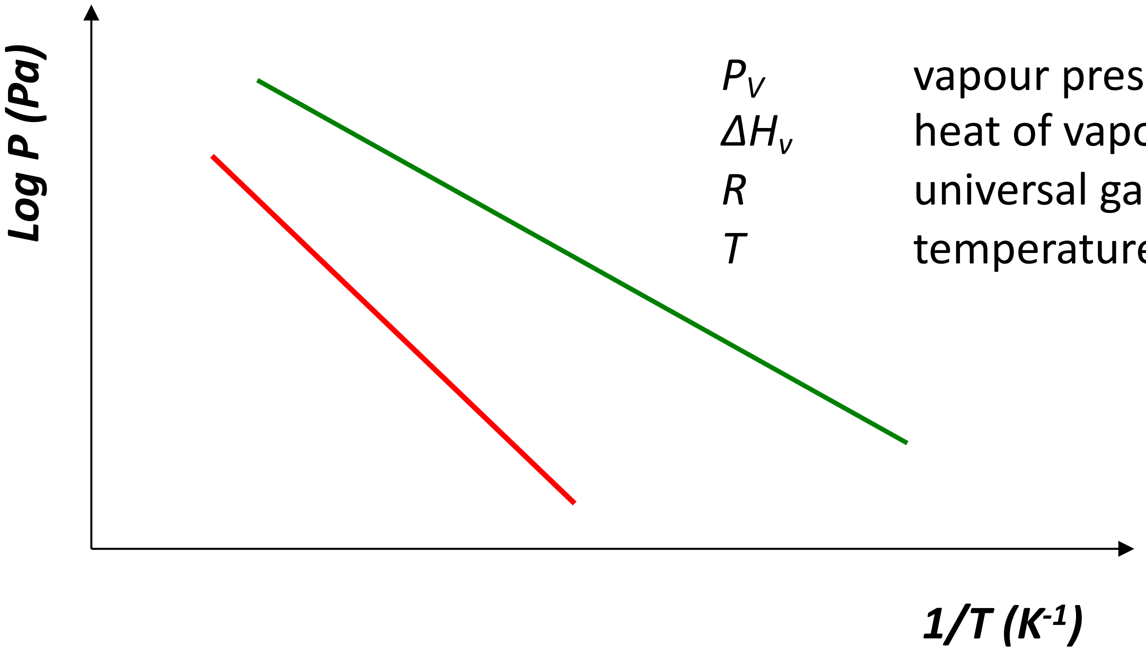
Vapour pressure P_V

- Factor determining the residence time of a chemical in soil or water – may be defined as “solubility in air”
- the pressure at which a liquid and its vapour are in equilibrium at a given temperature.
- The vapour is said to be "pushing" against the atmosphere - the higher the vapour pressure the faster a liquid evaporates.
- When the vapour pressure reaches the atmospheric pressure, the liquid is at its boiling point.
- Vapour pressure is measured in units of atmospheres (atm), millimeters of mercury (mmHg) or kilopascals (kPa).
- normal atmospheric pressure is 1 atm (760 mmHg or 101.325 kPa).

Pressure – Temperature

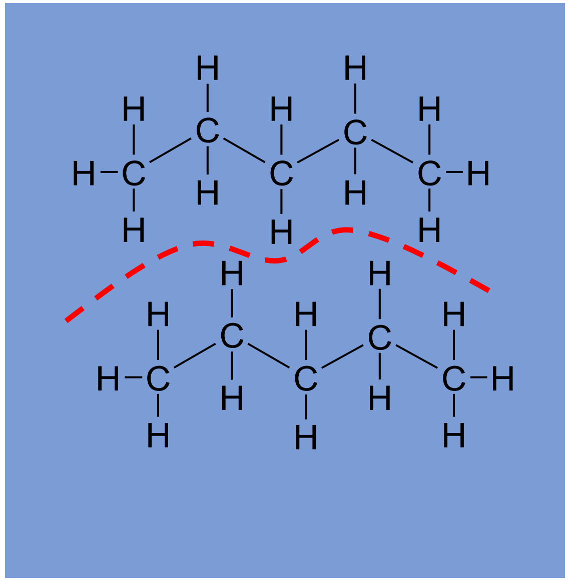
Clausius - Clapeyron equation

$$\log P_v = \frac{\Delta H_v}{2{,}3RT} + const$$

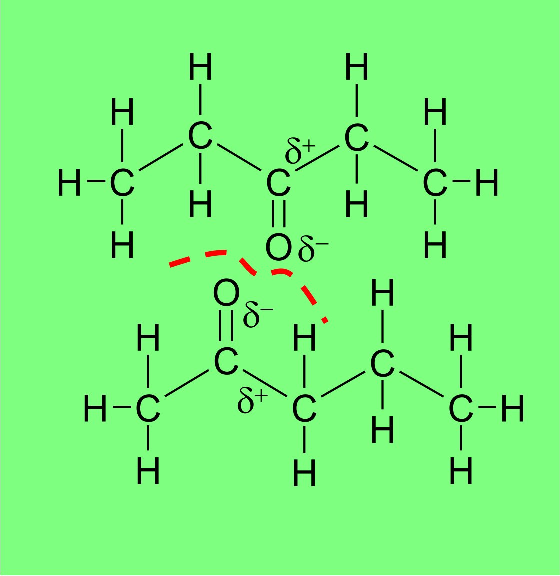


P_V	vapour pressure (*Pa*)
ΔH_v	heat of vaporization (*J mol^{-1}*)
R	universal gas const.: 8,3145 *J mol^{-1} K^{-1}*
T	temperature (*K*)

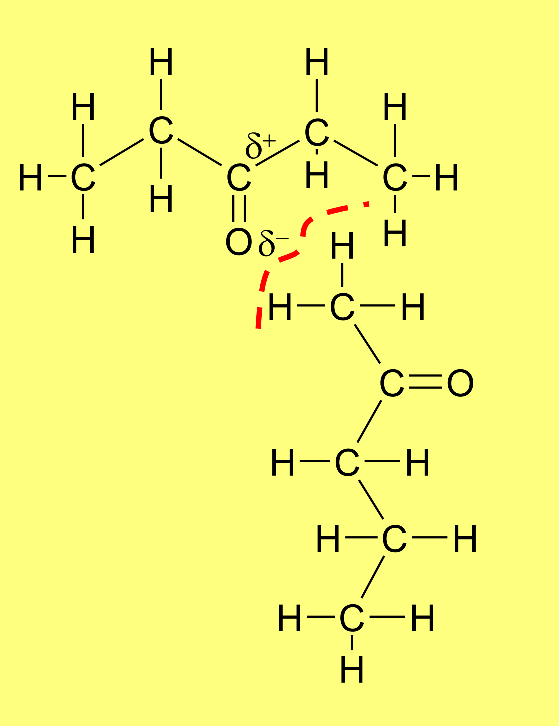
Intermolecular interactions



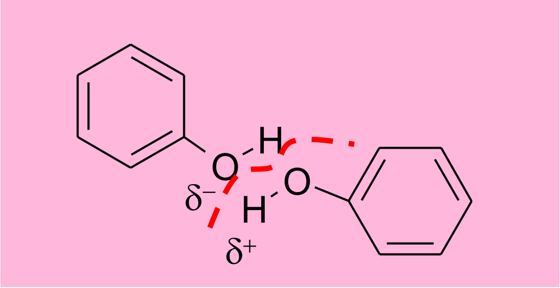
-4 kJ/mol



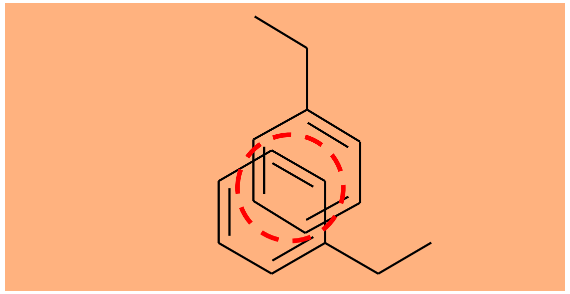
-(4 – 20) kJ/mol



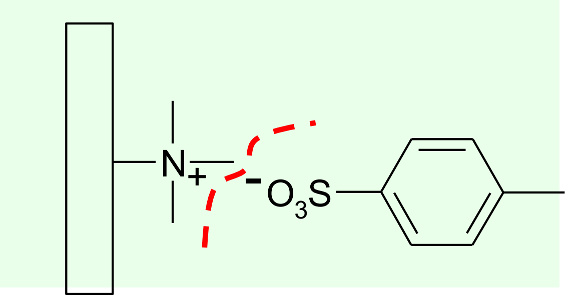
-(4 – 20) kJ/mol



-(4 – 20) kJ/mol

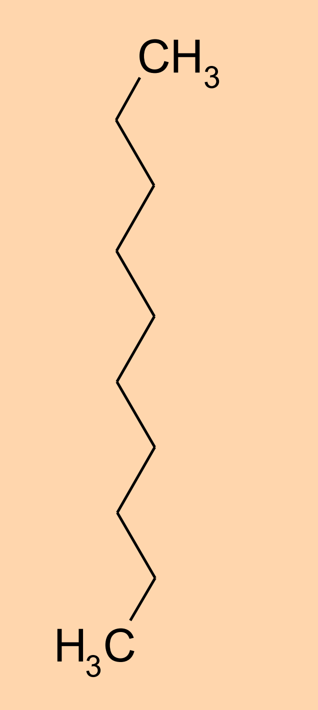


-(4 – 40) kJ/mol



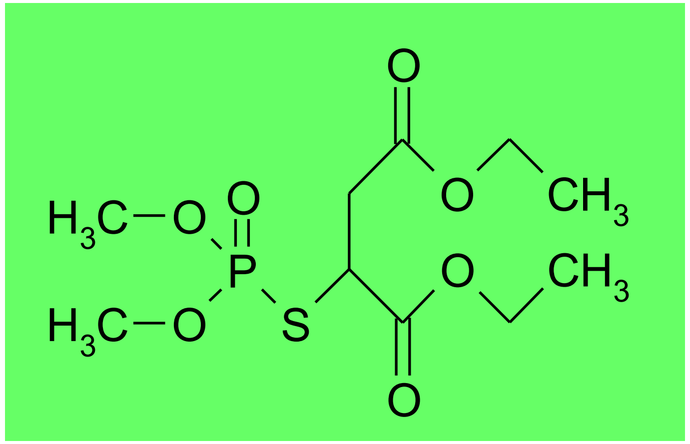
-(20 - 40) kJ/mol

decane



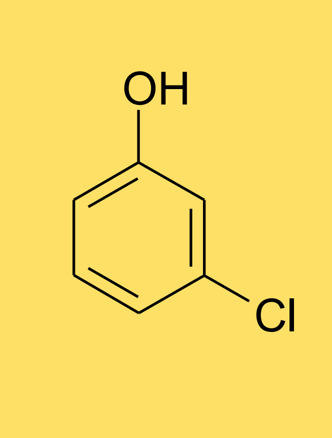
2,0 x 10^{-2} Pa

malathion



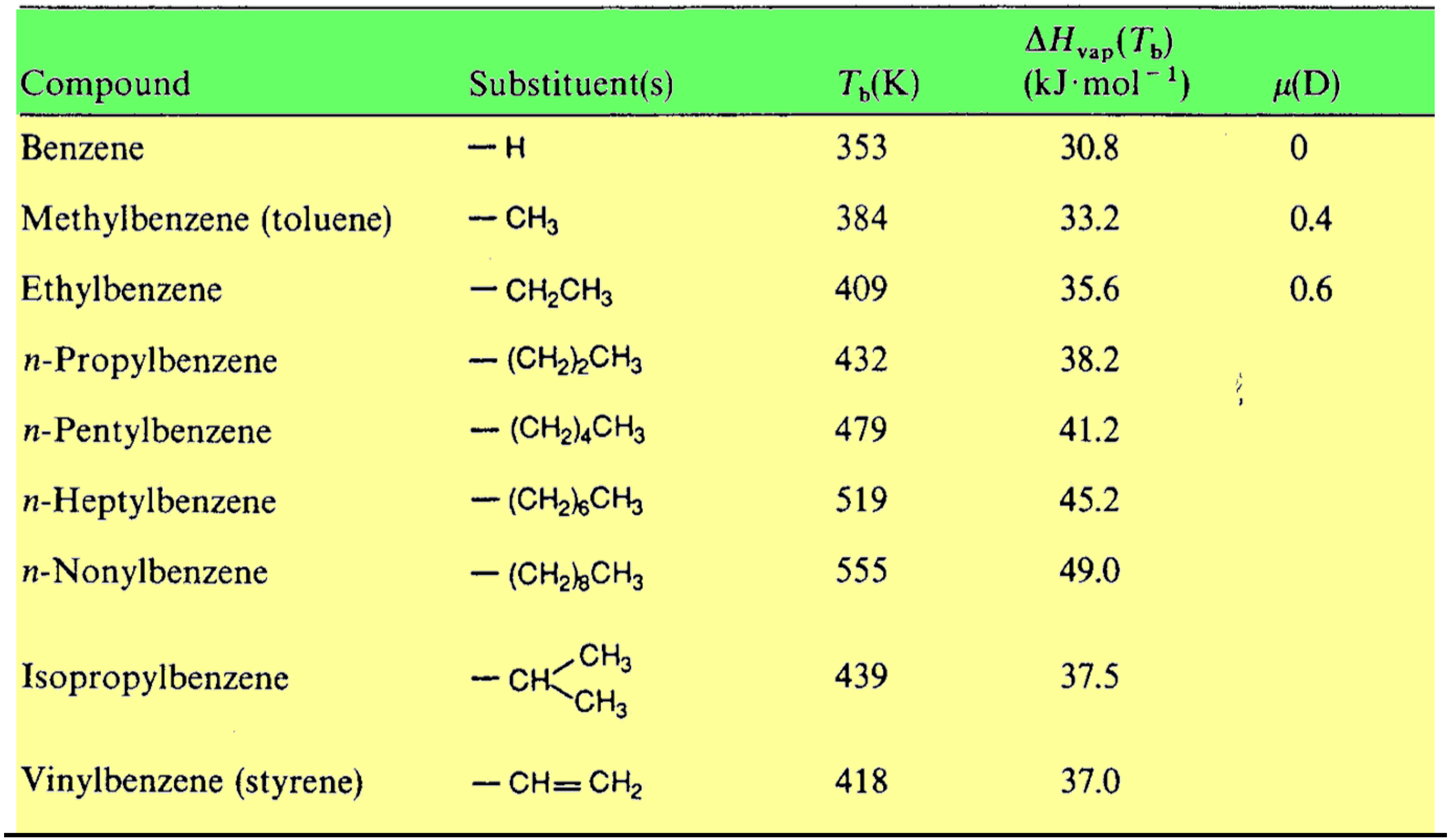
7,4 x 10^{-8} Pa

chlorophenol



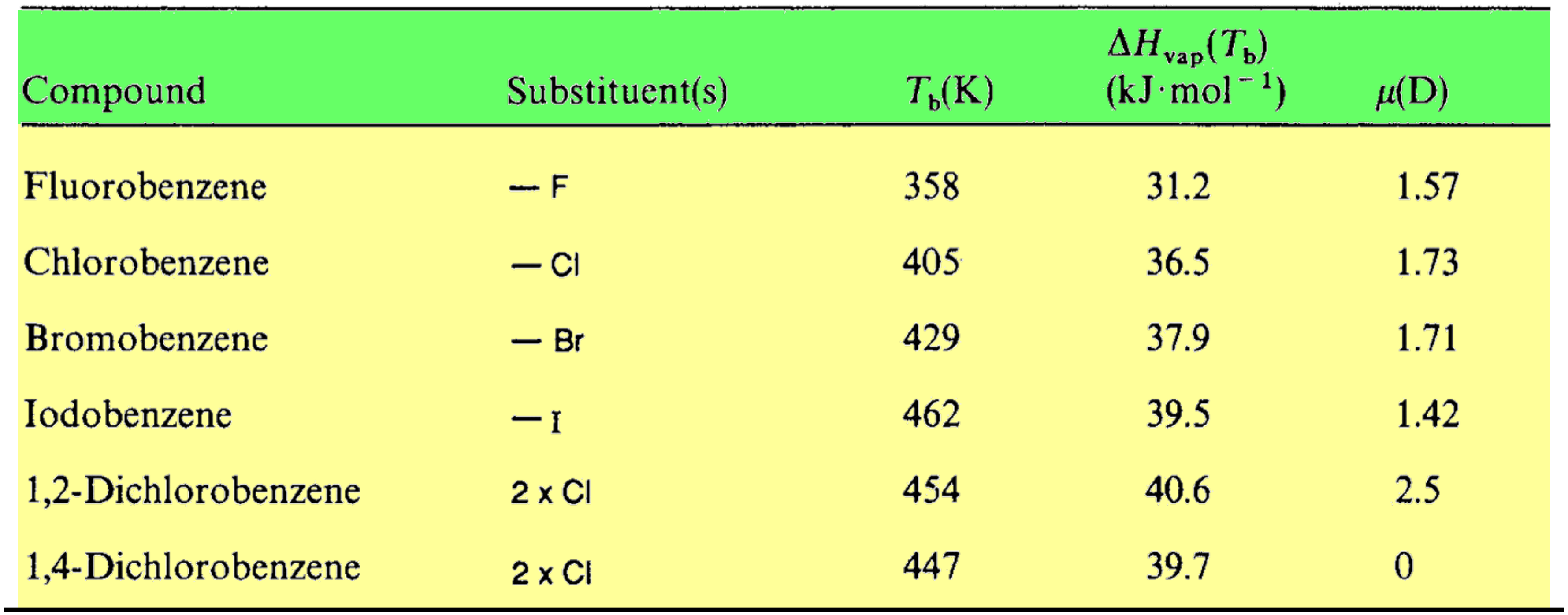
6,9 x 10^{-3} Pa

Heat of vaporisation and melting point



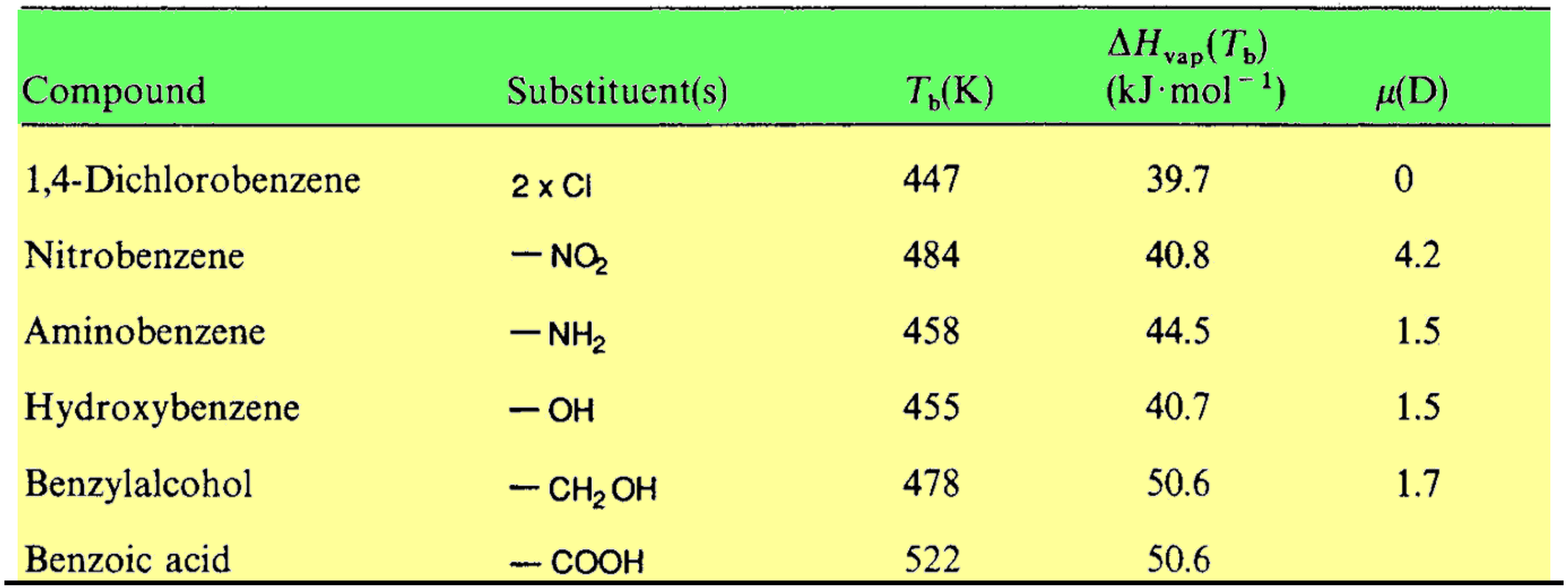
Compound	Substituent(s)	$T_{\mathrm{b}}(\mathrm{K})$	$\Delta H_{\mathrm{vap}}(T_{\mathrm{b}})$ $(\mathrm{kJ \cdot mol^{-1}})$	$\mu(\mathrm{D})$
Benzene	$—\mathrm{H}$	353	30.8	0
Methylbenzene (toluene)	$—\mathrm{CH_3}$	384	33.2	0.4
Ethylbenzene	$—\mathrm{CH_2CH_3}$	409	35.6	0.6
n-Propylbenzene	$—\mathrm{(CH_2)_2CH_3}$	432	38.2	
n-Pentylbenzene	$—\mathrm{(CH_2)_4CH_3}$	479	41.2	
n-Heptylbenzene	$—\mathrm{(CH_2)_6CH_3}$	519	45.2	
n-Nonylbenzene	$—\mathrm{(CH_2)_8CH_3}$	555	49.0	
Isopropylbenzene	$—\mathrm{CH}\begin{smallmatrix}\mathrm{CH_3}\\\mathrm{CH_3}\end{smallmatrix}$	439	37.5	
Vinylbenzene (styrene)	$—\mathrm{CH{=}CH_2}$	418	37.0	

Heat of vaporisation and melting point

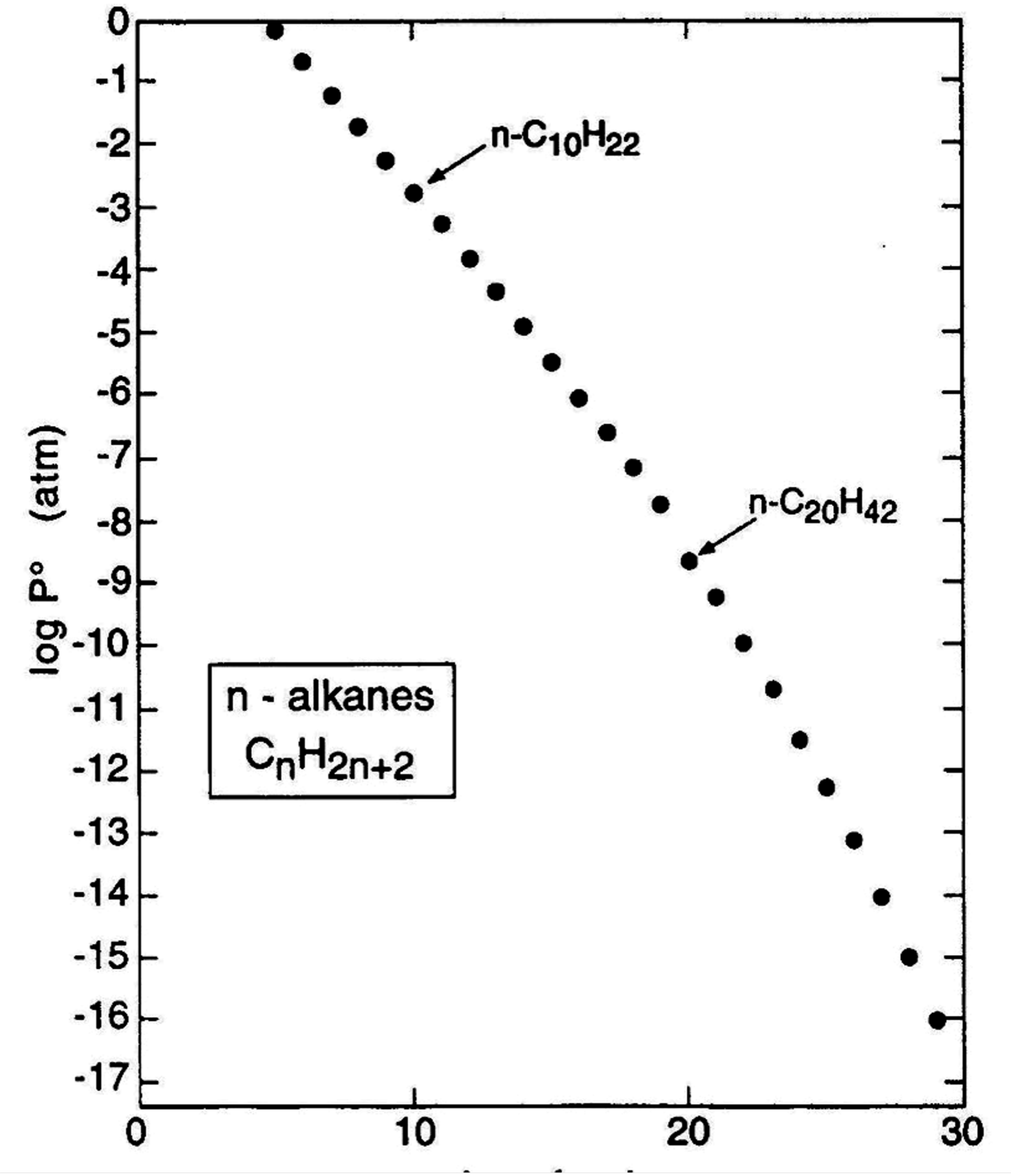


Compound	Substituent(s)	T_b(K)	$\Delta H_{vap}(T_b)$ ($kJ \cdot mol^{-1}$)	μ(D)
Fluorobenzene	— F	358	31.2	1.57
Chlorobenzene	— Cl	405	36.5	1.73
Bromobenzene	— Br	429	37.9	1.71
Iodobenzene	— I	462	39.5	1.42
1,2-Dichlorobenzene	2 x Cl	454	40.6	2.5
1,4-Dichlorobenzene	2 x Cl	447	39.7	0

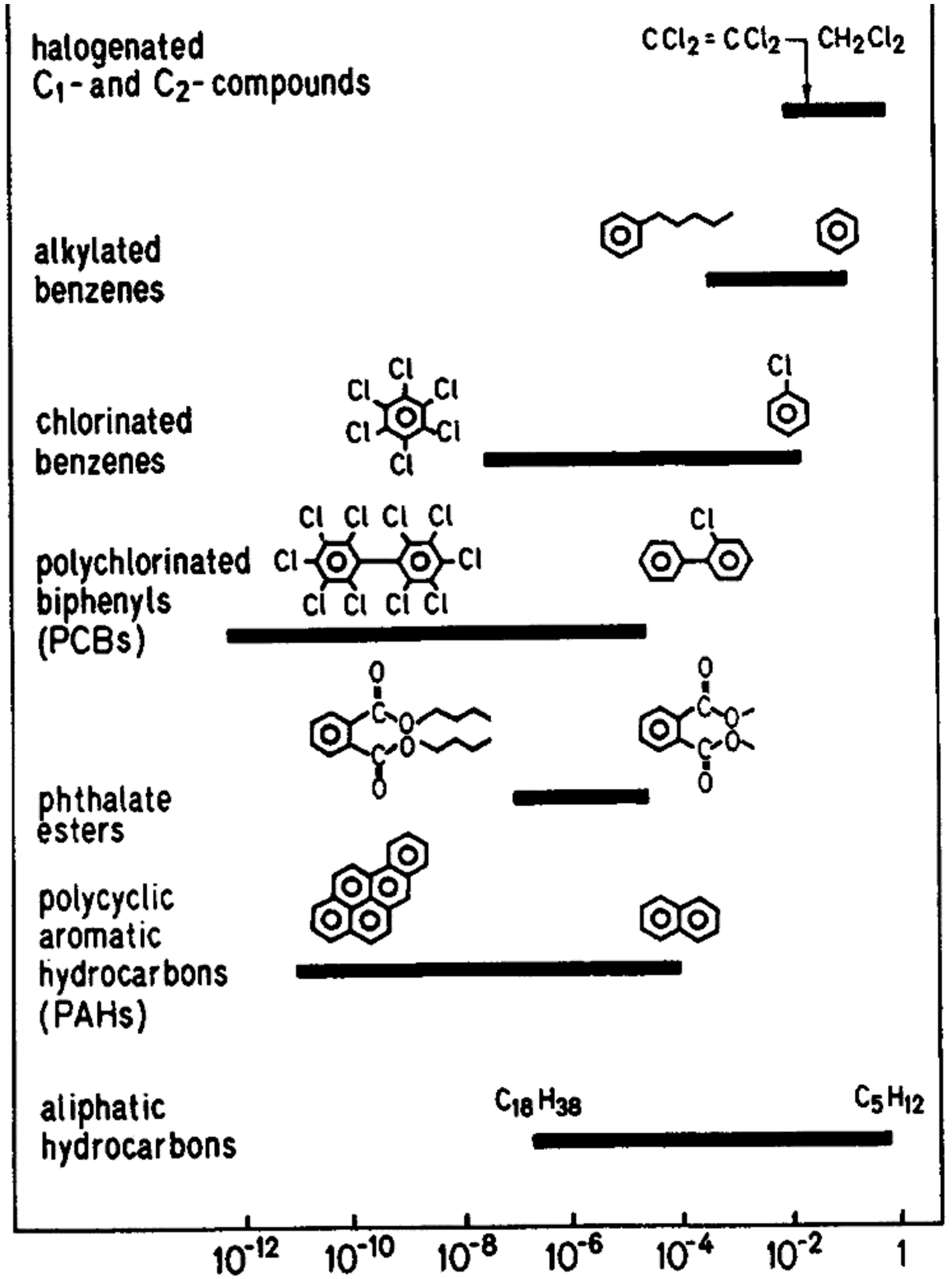
Heat of vaporisation and boiling point



Compound	Substituent(s)	T_b(K)	$\Delta H_{vap}(T_b)$ (kJ·mol^{-1})	μ(D)
1,4-Dichlorobenzene	2 x Cl	447	39.7	0
Nitrobenzene	$-NO_2$	484	40.8	4.2
Aminobenzene	$-NH_2$	458	44.5	1.5
Hydroxybenzene	$-OH$	455	40.7	1.5
Benzylalcohol	$-CH_2OH$	478	50.6	1.7
Benzoic acid	$-COOH$	522	50.6	



Number of carbon atoms in n-alkane



Vapour pressure P_o (atm) w 25^{o}C

Estimation methods

- *The Antoine method*

$$\ln P_V = [(\Delta H_v (BP-C2)^2) / (0{,}97\ R\ BP^2)] \times [1/(BP-C2) - 1/(T-C2)]$$

- *Mackay method*

$$\ln P_V = -(4.4 + \ln \mathrm{BP})[1.803(\mathrm{BP}/\mathrm{T}-1) - 0.803 \ln (\mathrm{BP}/\mathrm{T})] - 6.8 (\mathrm{MP}/\mathrm{T}-1)$$

ΔH_v *heat of vaporisation (cal/mol),*
BP boiling point in °K,
C2 constant = $-18 + 0.19BP$*,*
R gas constant = 1.987 *cal/mol × K*

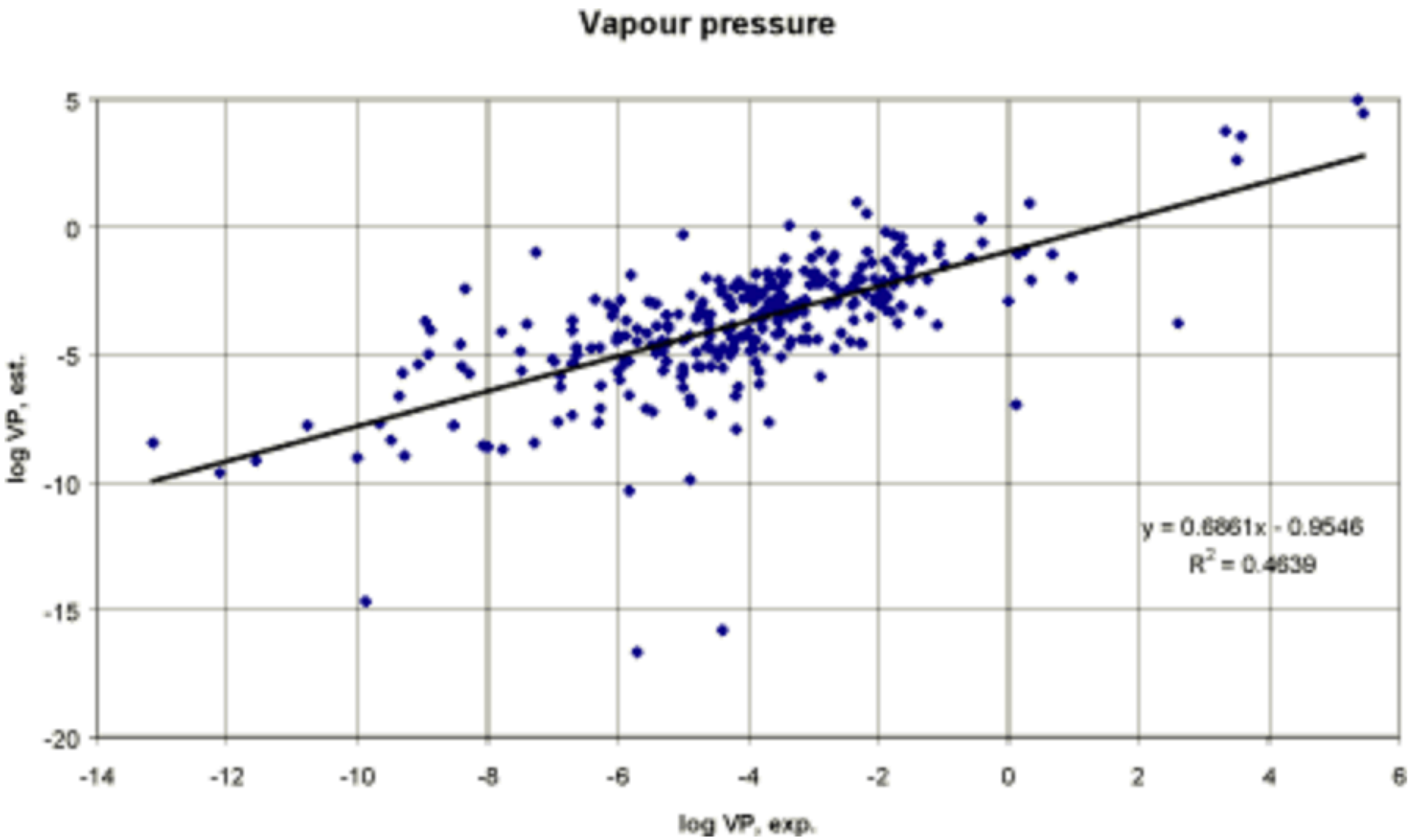


Figure 4
Correlation between the experimentally reported vapour pressure and the model-estimated vapour pressure (both logarithmic).

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Henry’s Law constant H

- The partitioning of a chemical between air and water (suface, moist soils, rain, fog etc) in the equlibrium
- The proportionality factor obtained for equlibrium conditions is represented by Hery’s Law constant H (Pa x m^3/mole)
- In air compound concentration is expressed as vapour pressure P_V (Pa)
- In water compound concentration is expressed as molar concetration C_W (mol/m^3)

$$H = \frac{P_V}{C_w}(Pa \cdot m^3 \cdot mol^{-1})$$

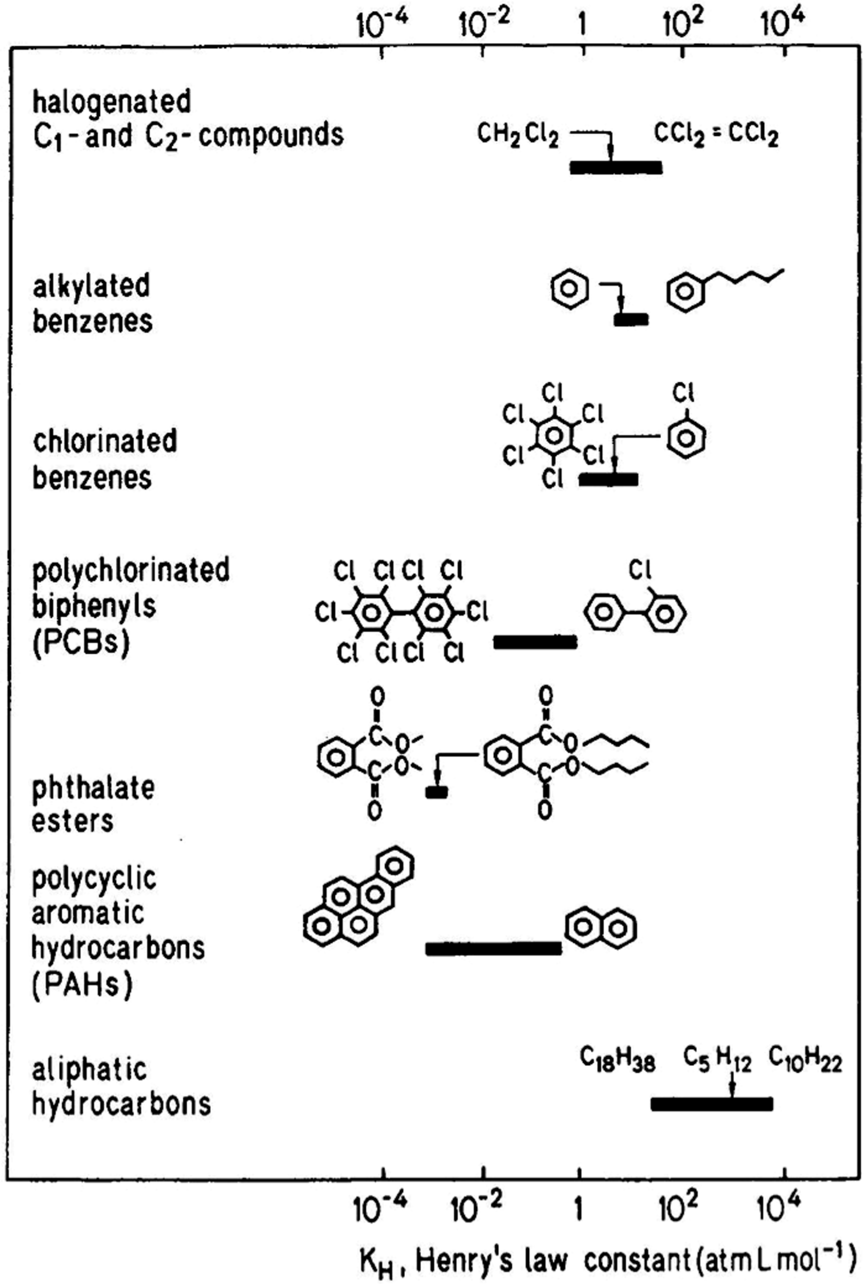
$$H' = \frac{C_a}{C_w}$$

dimentionless

$$H' = \frac{H}{RT}$$

- H' is regarded as air-water partition coefficient noted also as K_{aw} or $K_{H'}$

Henry's Law constant H



Influence of salinity

Substance	*H’* (deionized water)	*H’* (seawater)
CCl_3F	3,6	5,0
CCl_4	0,98	1,5
Hexachlorobenzene	0,054	0,07
2,4-dichlorobifenyl	0,0071	0,079
2,4,4-trichlorobifenyl	0,0059	0,0088
$(CH_3)_2S$	0,075	0,089

Estimation methods

$$H = \frac{P_V}{S_w} (Pa \cdot m^3 \cdot mol^{-1})$$

- The I it applicable if the total pressure is near 1 atm and there is no association of molecules in the vapour pressure
- not applicable to chemicals completely miscible with water or very poorly miscible with water

Estiamtion methods of H'

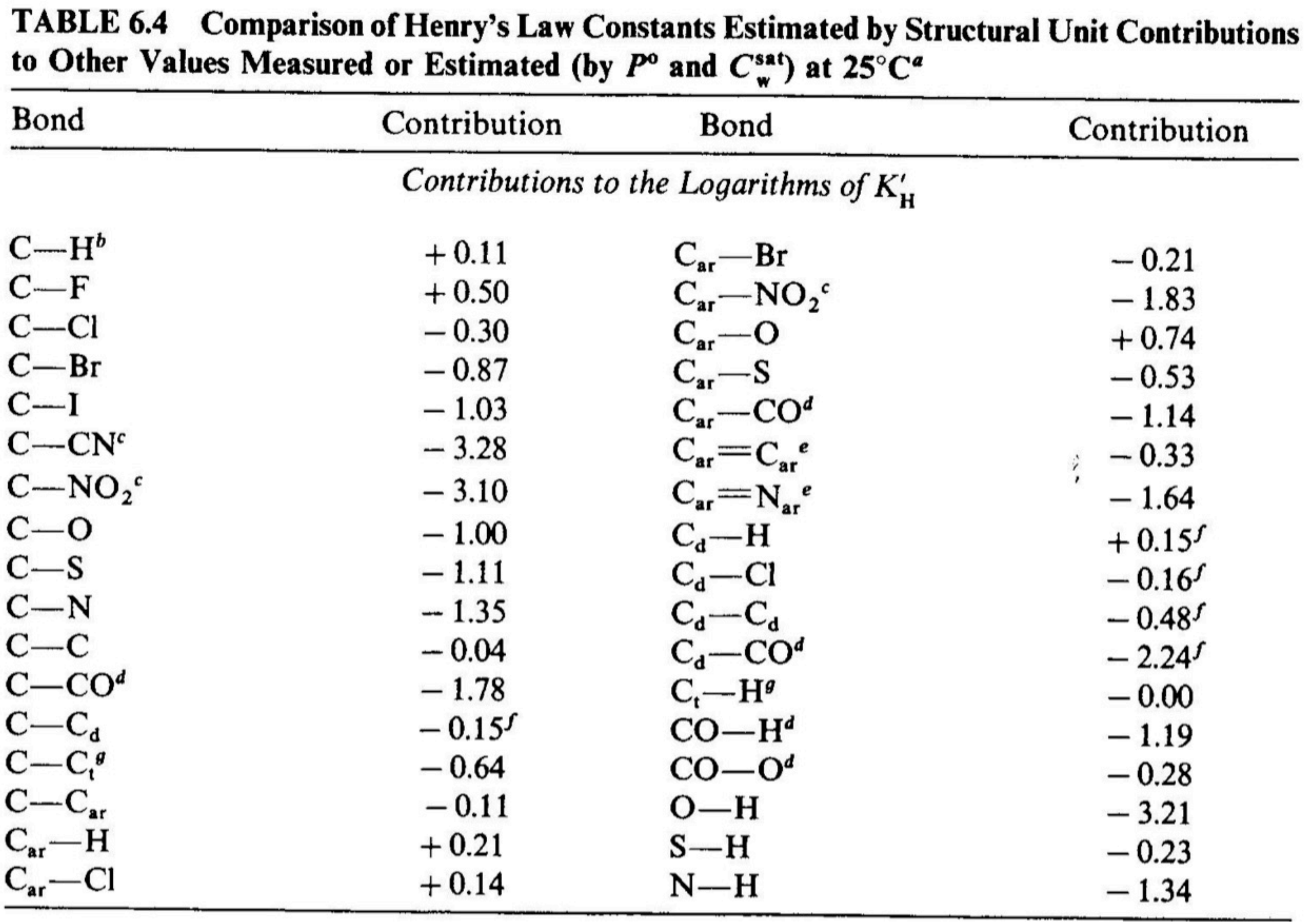


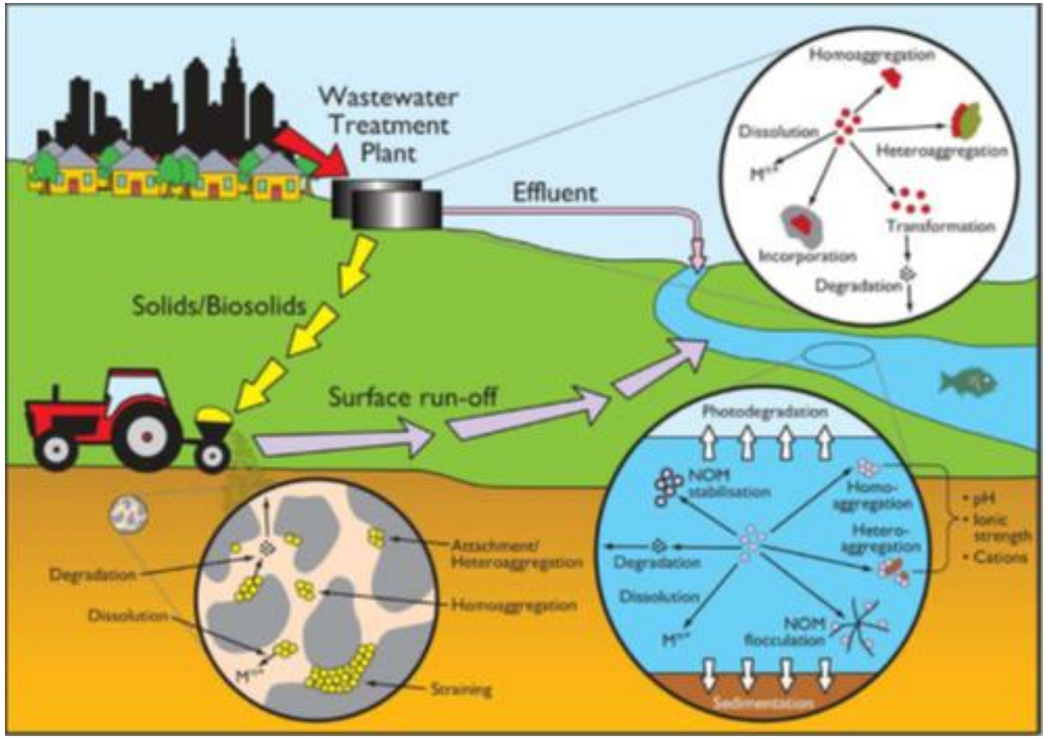
TABLE 6.4 **Comparison of Henry's Law Constants Estimated by Structural Unit Contributions to Other Values Measured or Estimated (by P^o and C_w^{sat}) at 25°C**[a]

Bond	Contribution	Bond	Contribution
Contributions to the Logarithms of K'_H			
$\mathrm{C-H}$[b]	+0.11	$\mathrm{C_{ar}-Br}$	−0.21
$\mathrm{C-F}$	+0.50	$\mathrm{C_{ar}-NO_2}$[c]	−1.83
$\mathrm{C-Cl}$	−0.30	$\mathrm{C_{ar}-O}$	+0.74
$\mathrm{C-Br}$	−0.87	$\mathrm{C_{ar}-S}$	−0.53
$\mathrm{C-I}$	−1.03	$\mathrm{C_{ar}-CO}$[d]	−1.14
$\mathrm{C-CN}$[c]	−3.28	$\mathrm{C_{ar}{=}C_{ar}}$[e]	−0.33
$\mathrm{C-NO_2}$[c]	−3.10	$\mathrm{C_{ar}{=}N_{ar}}$[e]	−1.64
$\mathrm{C-O}$	−1.00	$\mathrm{C_d-H}$	+0.15[f]
$\mathrm{C-S}$	−1.11	$\mathrm{C_d-Cl}$	−0.16[f]
$\mathrm{C-N}$	−1.35	$\mathrm{C_d-C_d}$	−0.48[f]
$\mathrm{C-C}$	−0.04	$\mathrm{C_d-CO}$[d]	−2.24[f]
$\mathrm{C-CO}$[d]	−1.78	$\mathrm{C_t-H}$[g]	−0.00
$\mathrm{C-C_d}$	−0.15[f]	$\mathrm{CO-H}$[d]	−1.19
$\mathrm{C-C_t}$[g]	−0.64	$\mathrm{CO-O}$[d]	−0.28
$\mathrm{C-C_{ar}}$	−0.11	$\mathrm{O-H}$	−3.21
$\mathrm{C_{ar}-H}$	+0.21	$\mathrm{S-H}$	−0.23
$\mathrm{C_{ar}-Cl}$	+0.14	$\mathrm{N-H}$	−1.34

Example Compound	Contributions
1. Bromodichloromethane	$1\,(\mathrm{C{-}H}) + 1\,(\mathrm{C{-}Br}) + 2\,(\mathrm{C{-}Cl})$ $1\,(+0.11) + 1\,(-0.87) + 2\,(-0.30)$ $\log(K'_{\mathrm{H}}) = -1.36$ $K'_{\mathrm{H\,estim}} = 0.044\,\frac{\mathrm{mol \cdot L_a^{-1}}}{\mathrm{mol \cdot L_w^{-1}}}$; $K'_{\mathrm{H\,obs}} = 0.085$ Nicholson et al., 1984
2. Phenol	$6(\mathrm{C_{ar}{=}C_{ar}}) + 5(\mathrm{C_{ar}{-}H}) + 1(\mathrm{C_{ar}{-}O}) + 1(\mathrm{O{-}H})$ $6(-0.33) + 5(+0.21) + 1(+0.74) + 1(-3.21)$ $\log(K'_{\mathrm{H}}) = -3.40$ $K'_{\mathrm{H\,estim}} = 0.00040\,\frac{\mathrm{mol \cdot L_a^{-1}}}{\mathrm{mol \cdot L_w^{-1}}}$; $K'_{\mathrm{H\,calc'd}} = 0.00041$ from P° and soly

Environmental fate

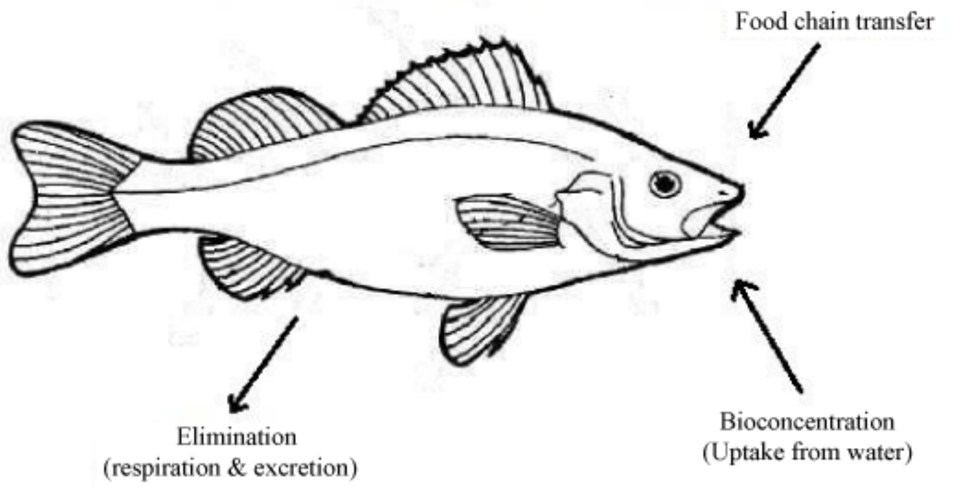
- Bioaccumulation
- Chemical degradation
- Biodegradation
- Soil sorption



Definitions

- **Bioaccumulation** – accumulation of xenobiotic in organism, which produces higher concentrations of a chemical in an organism than in its immediate environment, **including food**
- **Bioconcentration** – similar, but referring to uptake and accumulation of a substance from **water alone**
- **Biomagnification (bioamplification)** – occurs when **food** is the major source of bioaccumulation; substance concentration increases as it moves up a food chain

Bioaccumulation & Bioconcentration Process



Bioaccumulation = bioconcentration + food chain transfer - (elimination+ growth dilution)

BCF and BMF

- **Bioconcentration factor (BCF)** – the ratio of the concentration in an organism (Co; mg kg^{-1}) and that in the surrounding water (Cw; mg L^{-1}) at steady-state:

$$\boxed{\mathrm{BCF} = C_O / C_W}$$

- **Biomagnification factor (BMF)** – the ratio of the concentration in an organism (Co; mg kg^{-1}) and that in its food (Cfood; mg kg^{-1}) at steady-state:

$$\boxed{BMF = C_O / C_{food}}$$

Bioconcentration factor (BCF)

- BCF and BMF values for a certain compound depend on the species and its position in a food chain
- For one species and many classes of compounds BCF values are well correlated with log K_{OW} values of the compounds:

$$Log\ BCF = a\ logK_{OW} + b$$

where *a* and *b* are characteristic for each class of compounds

- Loss of linear correlation is often observed for the compounds with $log\ K_{OW}$ values above 6

BCF vs. Log K_{OW}

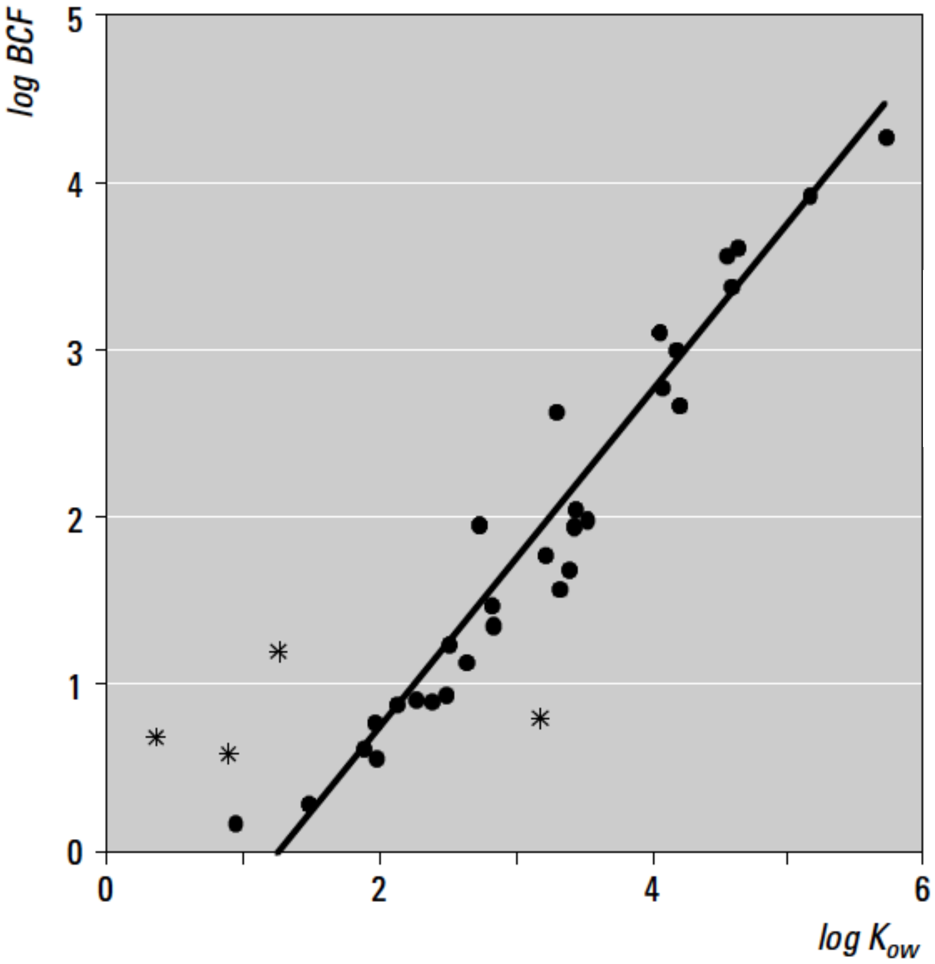
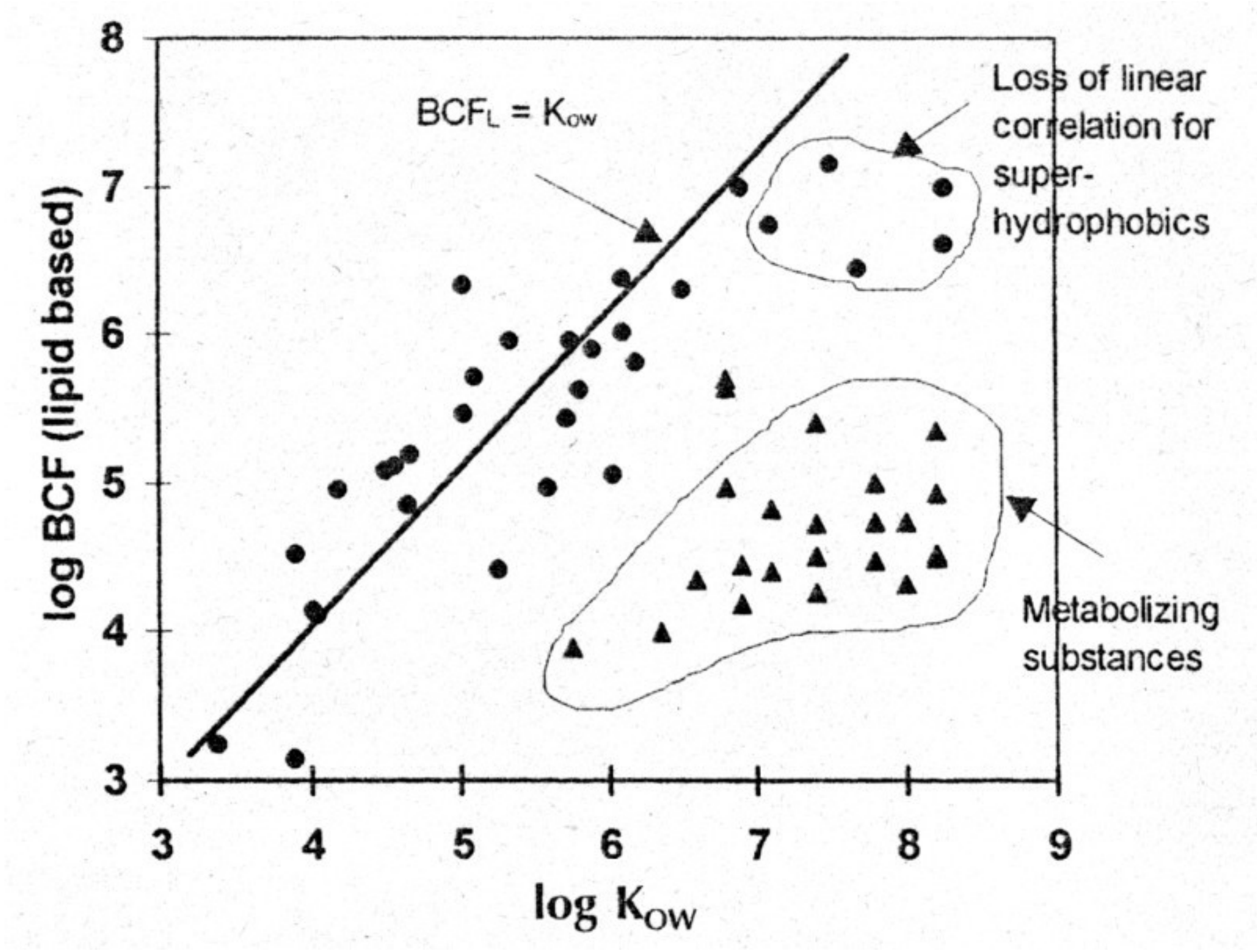


Figure 9.3. Log BCF vs. log K_{ow} for 35 nonpolar narcotic compounds. The regression line is according to Equation 9.9 ($r^2 = 0.94$, $rms = 0.29$), excluding the four compounds plotted with the star symbol.

$$\log \text{BCF} = 1.00 \log K_{\text{ow}} - 1.25$$

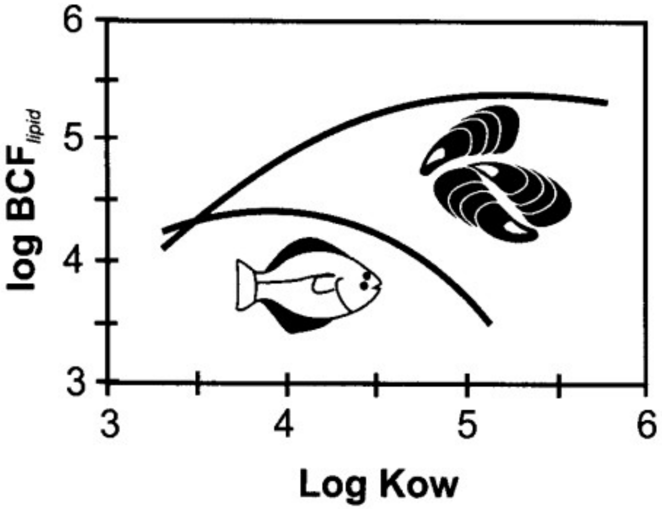
$$n = 31,\ r^2 = 0.94,\ q_{\text{cv}}^2 = 0.93,\ rms = 0.29$$

BCF vs. Log K_{OW}



Bioconcentration factor (BCF)

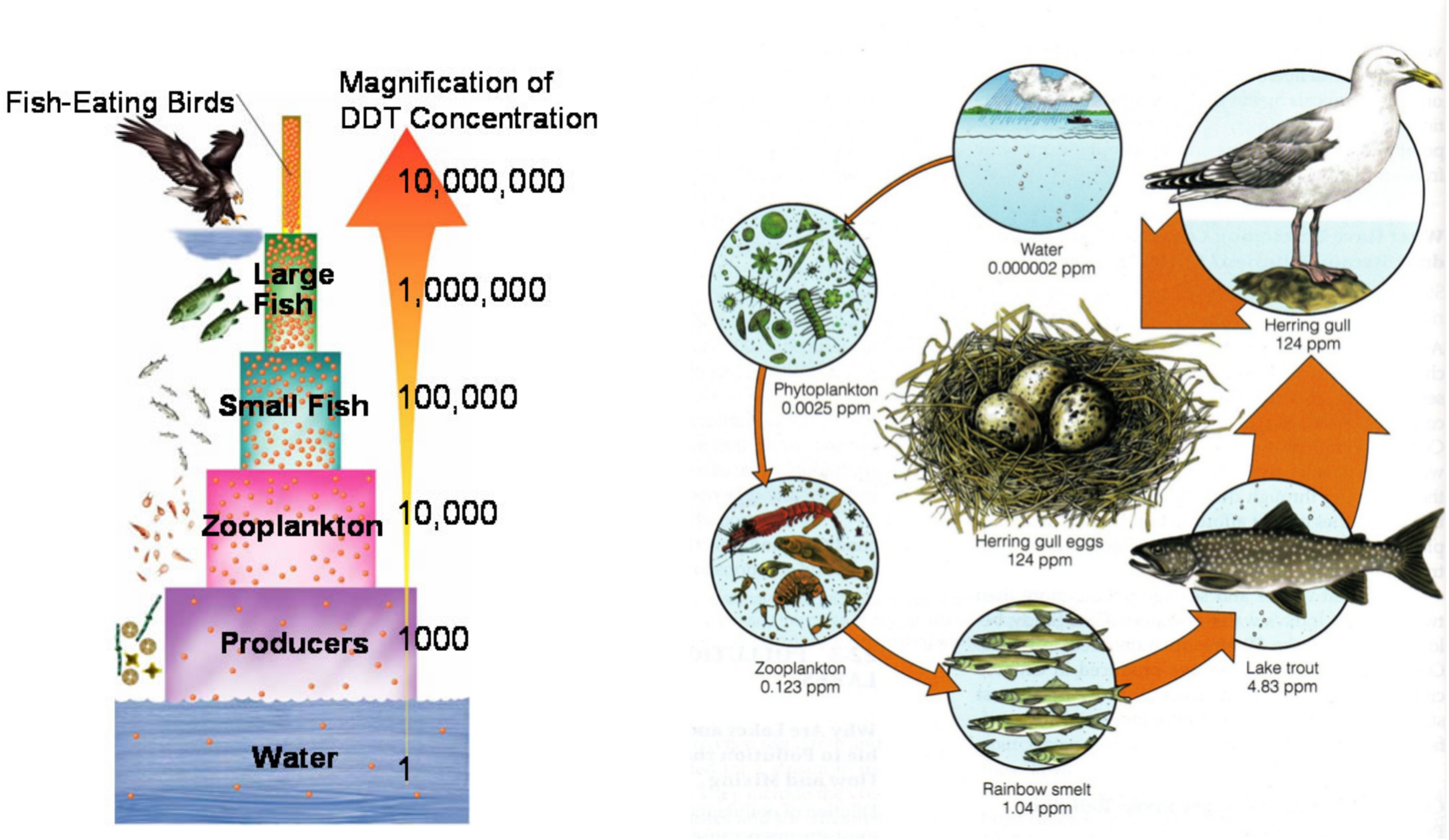
BCF values decrease for hydrophobic compounds, if:



- There is a compound accumulation in sediments **or**
- The compound is readily degradable in the environment **or**
- The compound is metabolized very fast

Neff, JM (2002), *Bioaccumulation in Marine Organisms: Effect of Contaminants from Oil Well Produced Water,* Elsevier

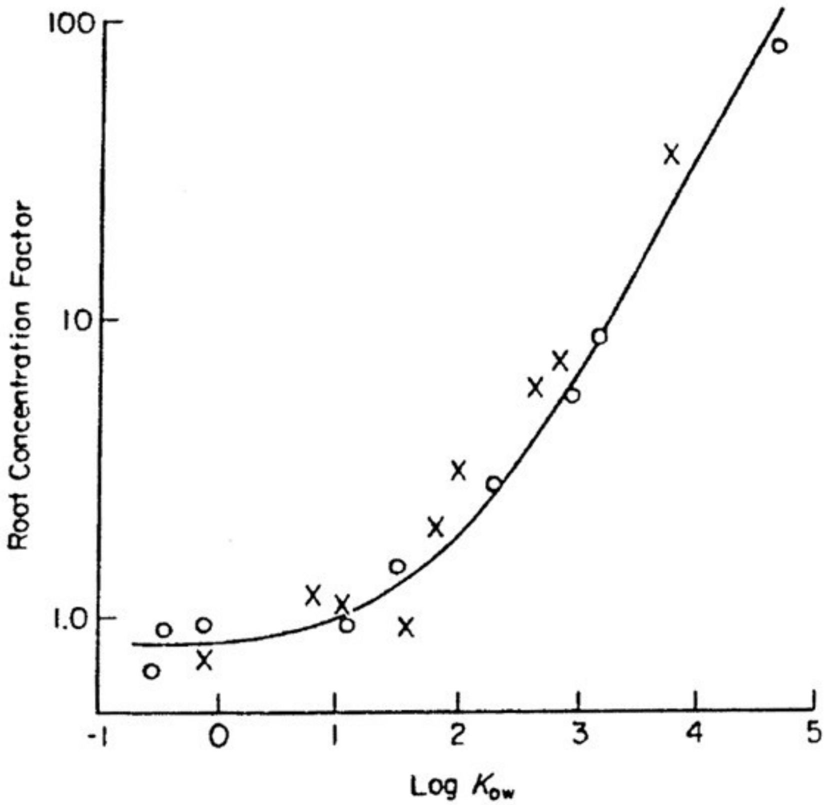
Biomagnification factor (BMF)



Biomagnification of PCBs and DDT

http://learn.anaee.com/

Plant uptake from soil



- **RCF (root accumulation factor):**

$$RCF = \frac{C_r}{C_s}$$

where:

C_r – compound concentration in roots (mg kg^{-1})

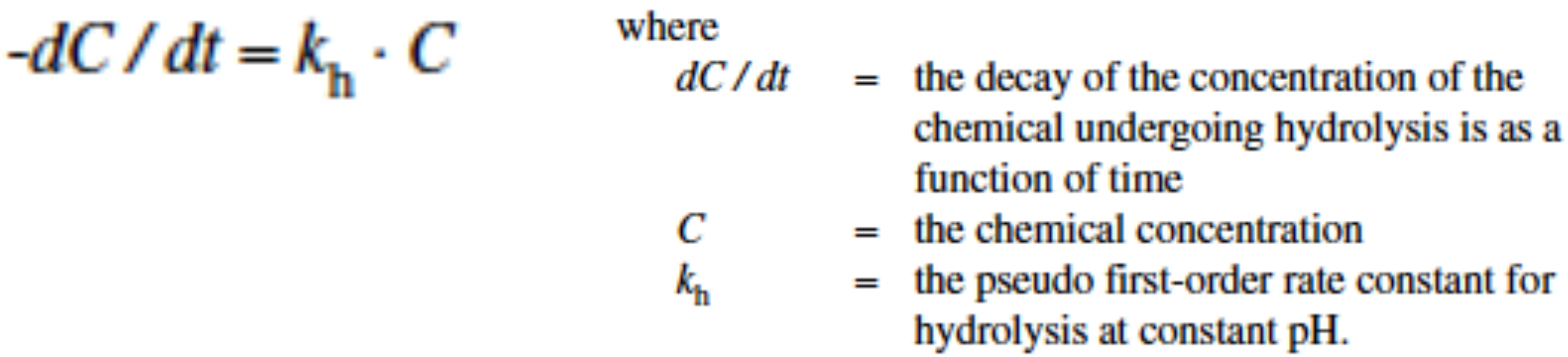
C_s – compound concentration in soil solution (mg L^{-1})

Briggs et al. (1982), *Pesticide Science*, **13**, 495-504

Abiotic (chemical) degradation

- Hydrolysis: alteration of the chemical structure by direct reaction with water.
- Oxidation: a transformation process in which electrons are transferred from the chemical to a species accepting the electrons; the oxidant.
- Reduction: the reverse of oxidation; electron transfer takes place from a reductant to the chemical to be reduced.
- Photochemical degradation: transformation due to interaction with sunlight.

Hydrolysis



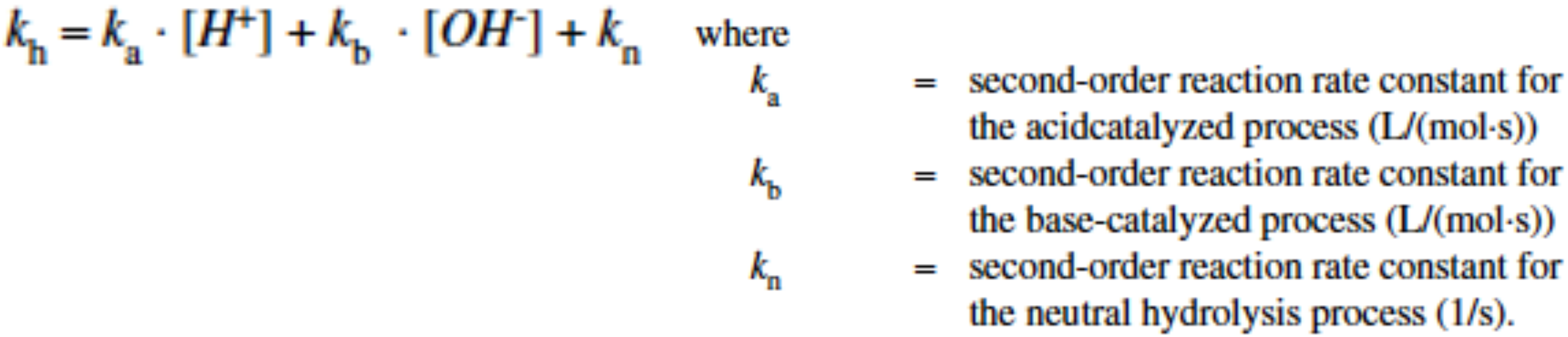
$$-dC/dt = k_h \cdot C$$

where

dC/dt = the decay of the concentration of the chemical undergoing hydrolysis is as a function of time

C = the chemical concentration

k_h = the pseudo first-order rate constant for hydrolysis at constant pH.



$$k_h = k_a \cdot [H^+] + k_b \cdot [OH^-] + k_n$$

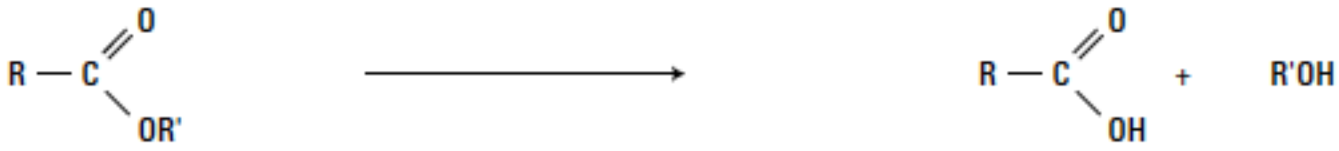
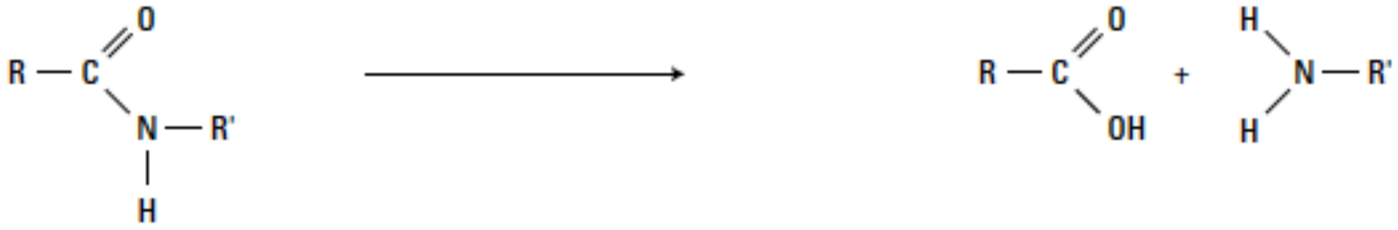
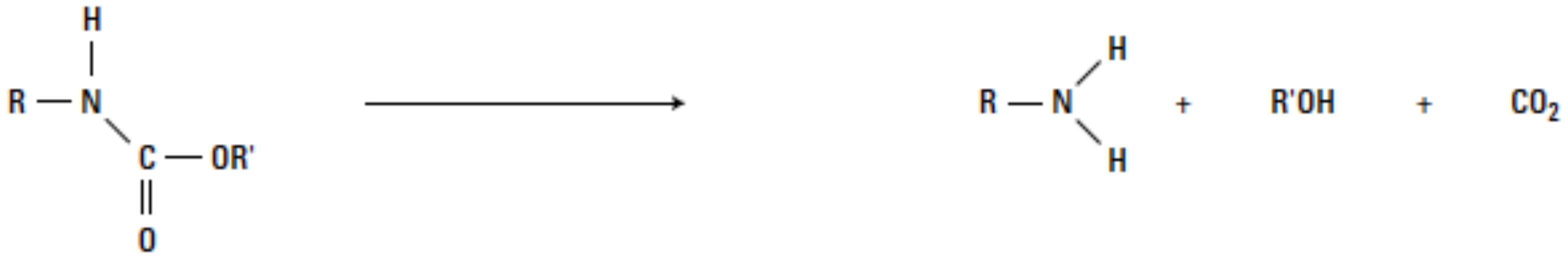
where

k_a = second-order reaction rate constant for the acidcatalyzed process (L/(mol·s))

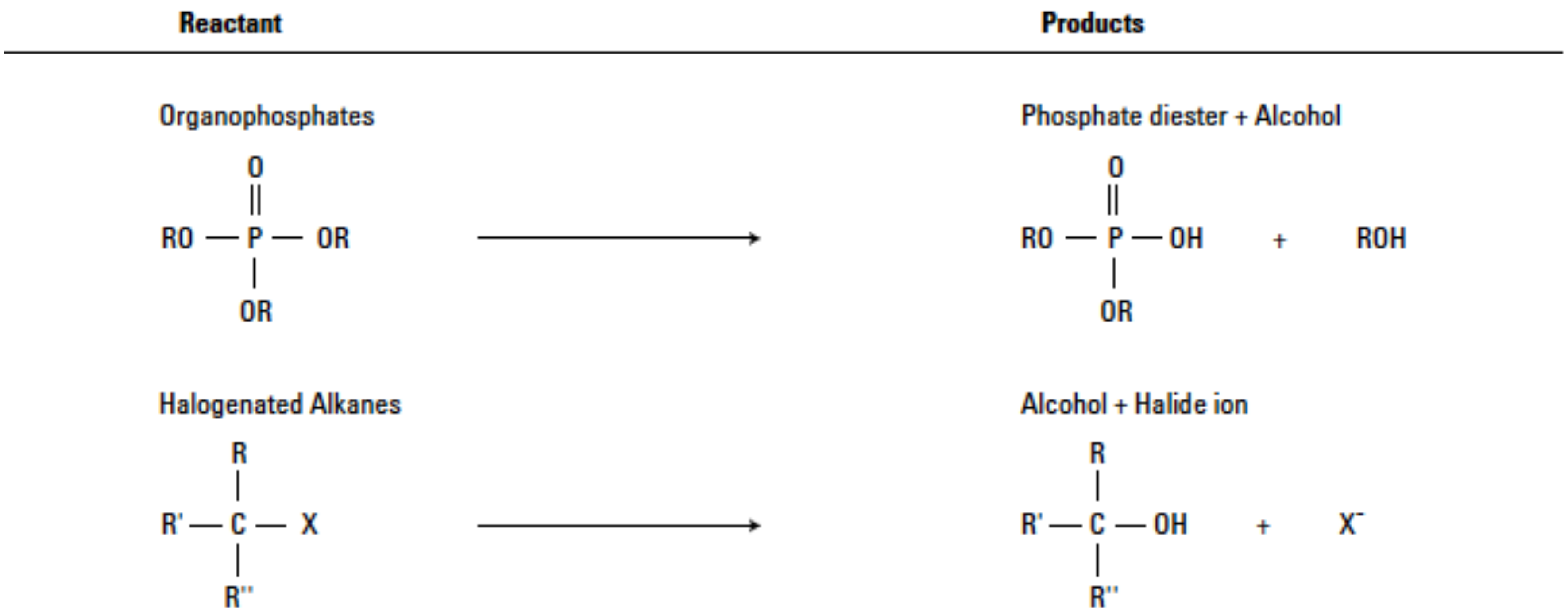
k_b = second-order reaction rate constant for the base-catalyzed process (L/(mol·s))

k_n = second-order reaction rate constant for the neutral hydrolysis process (1/s).

Hydrolysis - examples

Reactant	**Products**
Esters	Carboxylic Acid + Alcohol
	
Amides	Carboxylic Acid + Amine
	
Carbamates	Amine + Alcohol + Carbon dioxide
	

Hydrolysis - examples

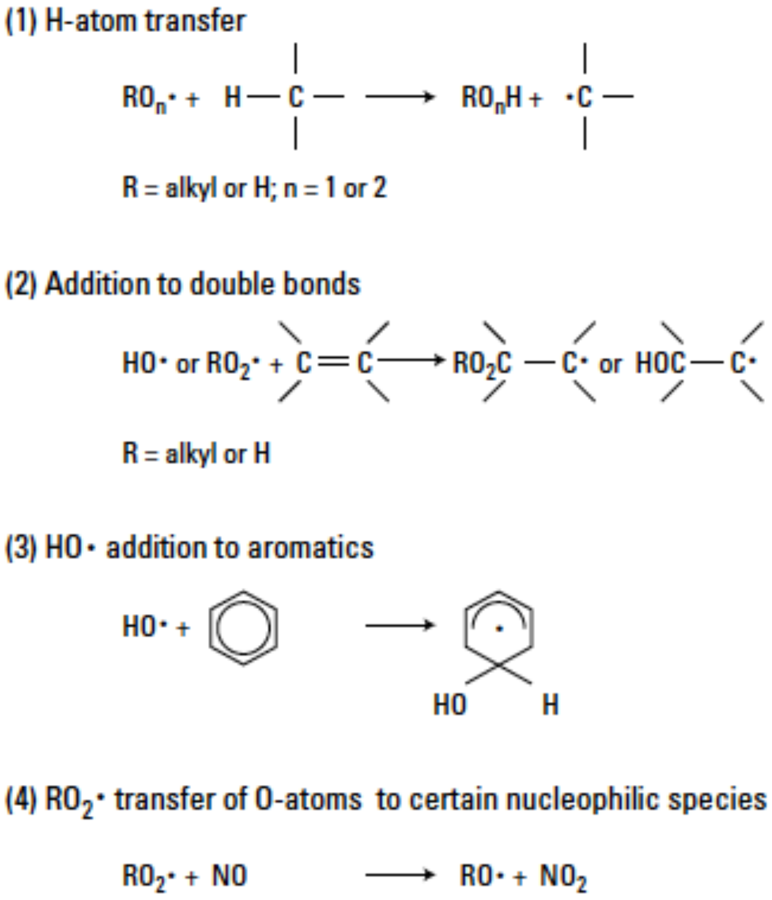


$$(RO)_3P{=}O \longrightarrow (RO)_2P(=O)OH + ROH$$

$$RR'R''C{-}X \longrightarrow RR'R''C{-}OH + X^-$$

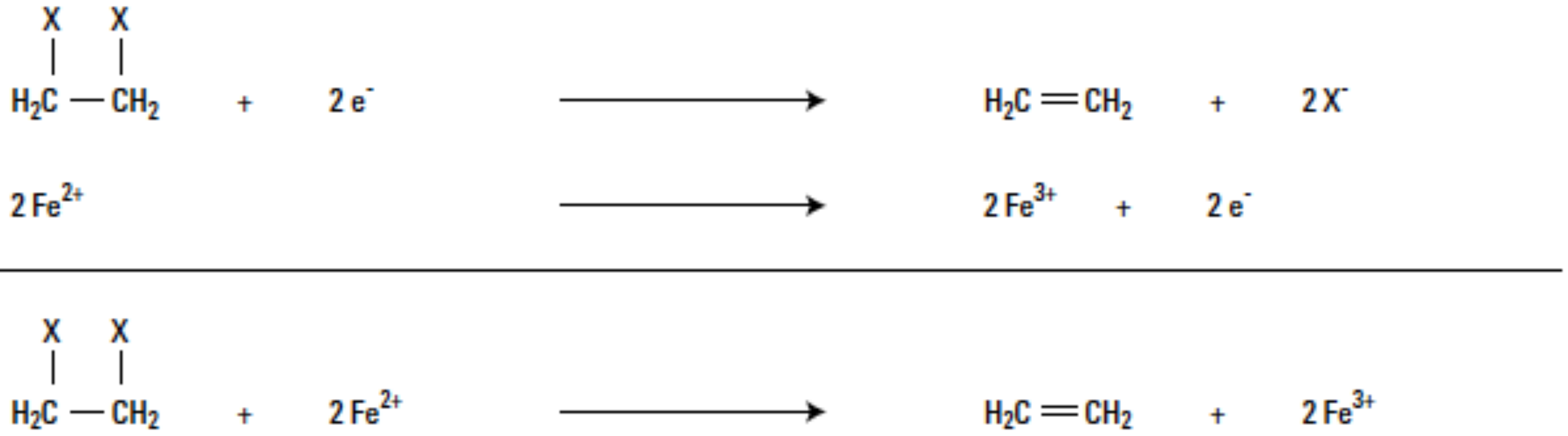
Oxidation

- chemical process in which an electron-deficient particle (the oxidant) accepts electrons from the compound to be oxidized:
  - Alkoxy radicals (RO·)
  - Peroxy radicals (RO_2·)
  - Hydroxyl radicals (HO·)
  - Singlet oxygen ($^1O_2$)
  - Ozone (O_3)



Reduction

- Reduction is the chemical process by which electrons are transferred from an electron donor (reductant) to the compound to be reduced



$$\overset{X}{H_2C} - \overset{X}{CH_2} + 2e^- \longrightarrow H_2C{=}CH_2 + 2X^-$$

$$2Fe^{2+} \longrightarrow 2Fe^{3+} + 2e^-$$

$$\overset{X}{H_2C} - \overset{X}{CH_2} + 2Fe^{2+} \longrightarrow H_2C{=}CH_2 + 2Fe^{3+}$$

Figure 3.31. Example of a reductive transformation: electron transfer from Fe^{2+} to 1,2-dihalogen substituted ethane (X denotes a halogen atom).

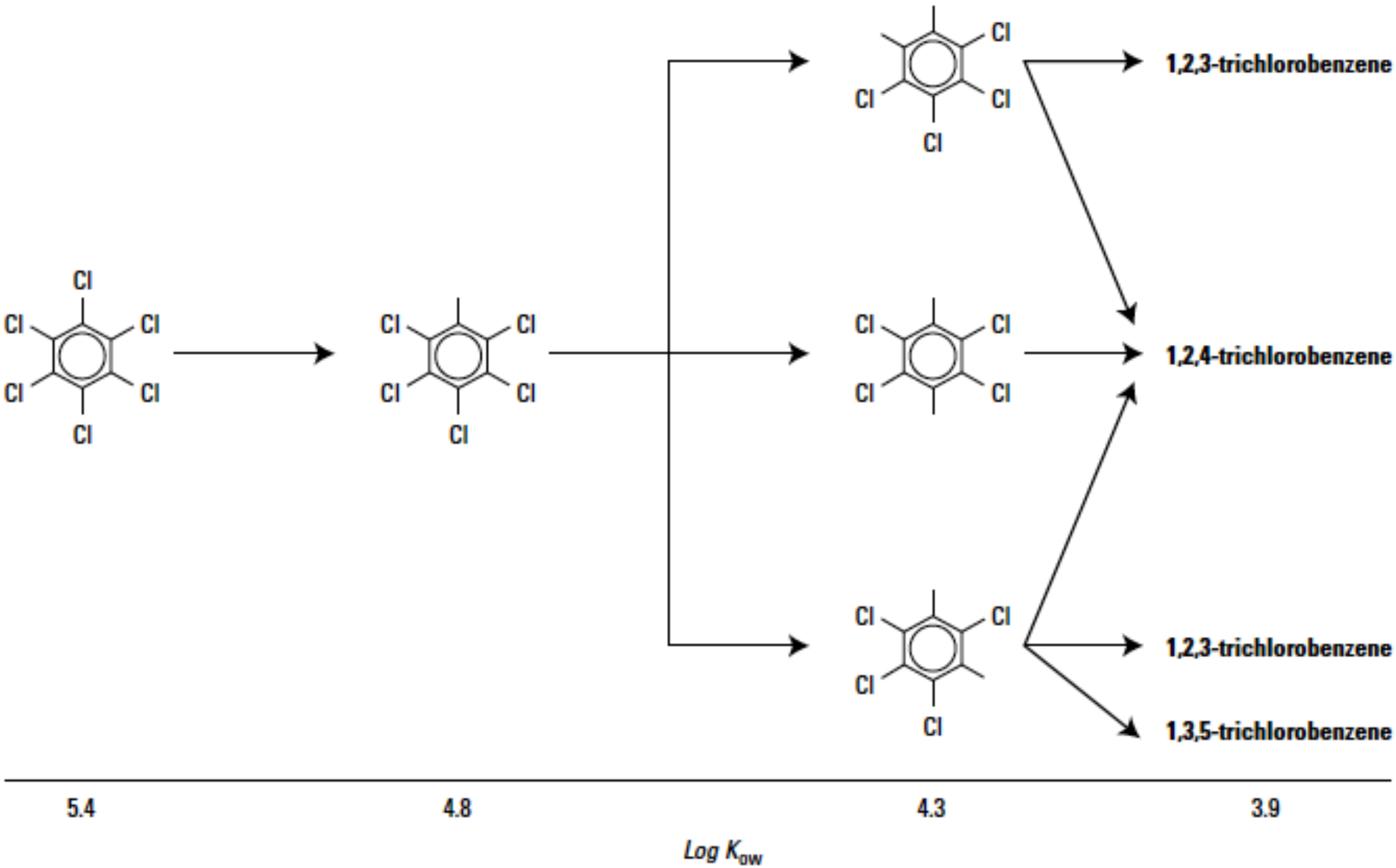


Figure 3.32. Products formed by reductive dehalogenation of hexachlorobenzene and the corresponding values of log K_{ow}.

Photodegradation

- Following absorption of a photon by a compound, the photon energy either needs to be transferred to the reactive site within the molecule or transferred to another molecule, which may subsequently undergo a photo-chemical transformation
- Two types of photochemical conversions are generally distinguished:
  - Direct photoreactions, in which the reacting molecule itself directly absorbs light.
  - Indirect or sensitized photolysis, in which a light absorbing molecule transfers its excess energy to an acceptor molecule causing the acceptor to react

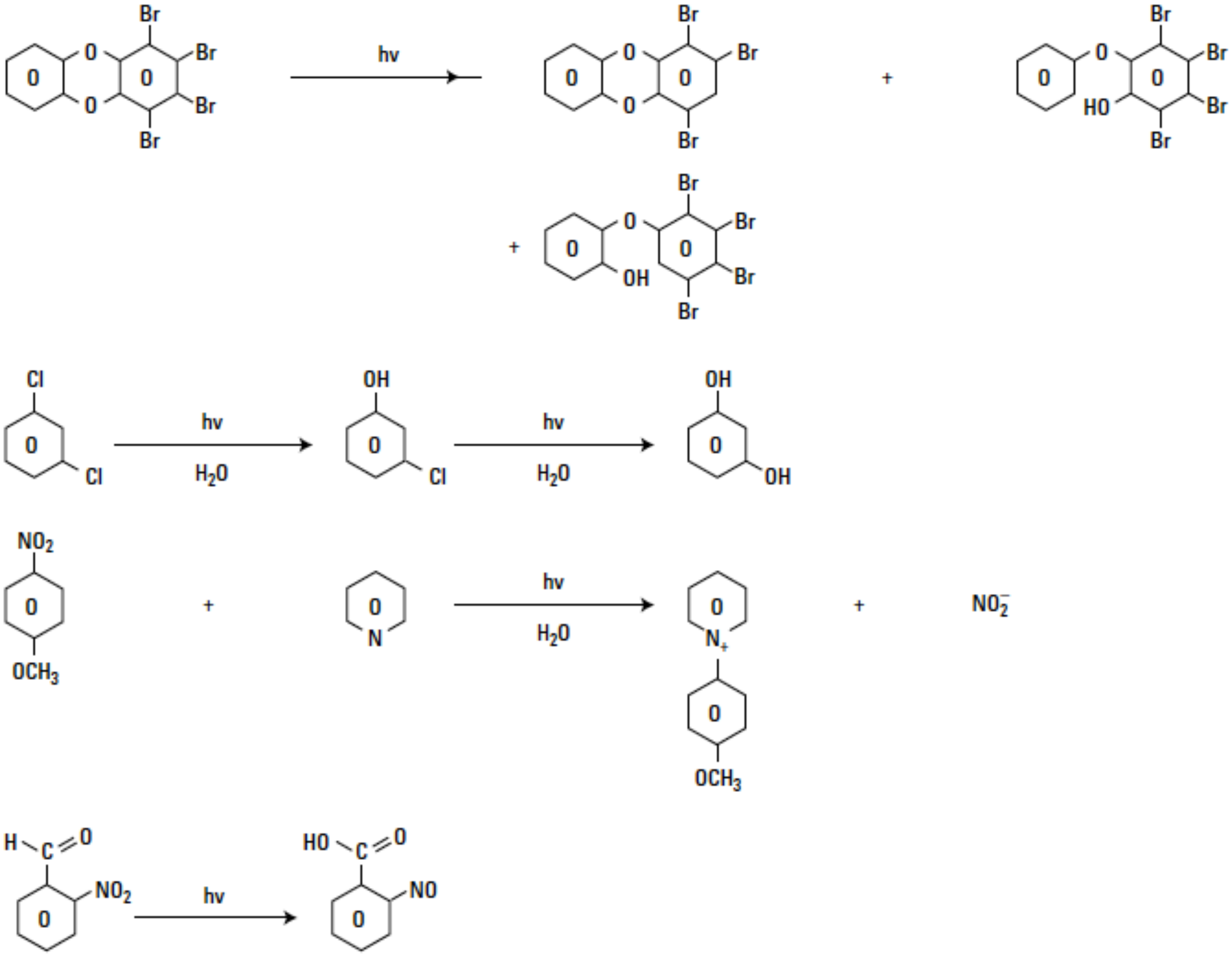


Figure 3.33. Some typical examples of photochemical transformation processes.

Biodegradation

- Micro-organisms - environmental catalysts (bacteria, fungi, protozoans, yeasts, and algae)
- complex multi-step process (uptake, intracellular transport and enzymatic reactions)
- In different environmental conditions, a given chemical may be biodegraded by different pathways, resulting in different degrees of persistence.
- Bacteria have a variety of enzyme systems, but specific enzymes for transforming xenobiotics are generally absent
- Primary metabolic reactions are mediated mostly by non-specific enzyme systems, which catalyze oxidation, reduction and hydrolysis

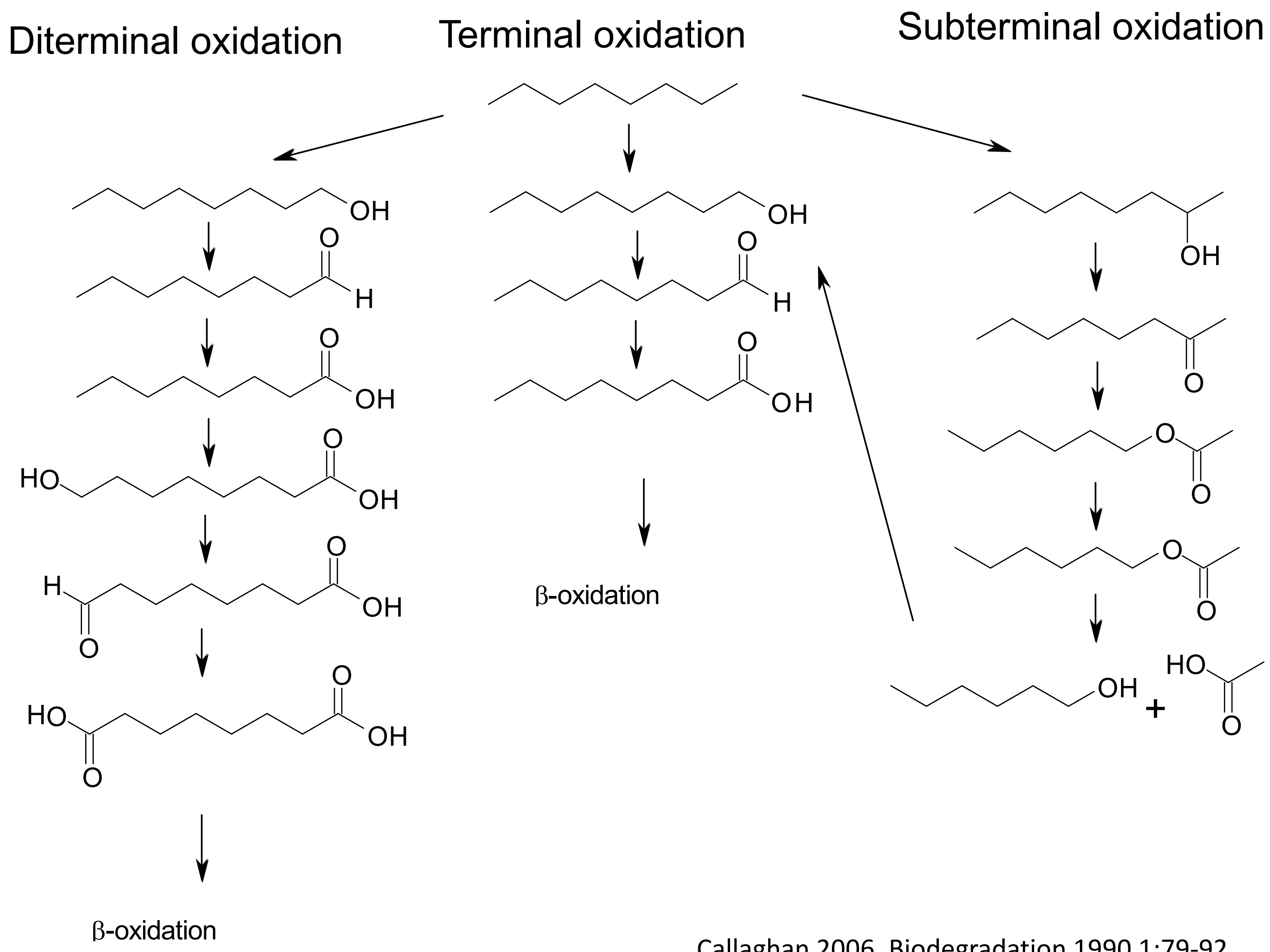
Biodegradation

- Three categories
  - Rapid breakdown- days to weeks
  - Slow breakdown- months to years
  - Almost no breakdown- many years
- Chemical structure important
- Biodegradation requires the presence of the appropriate organism, the chemical in an available form, and the right environmental conditions for organisms to function

Biodegradation

- Aerobic
  - Rapid degradation by aerobes
- Anaerobic
  - Hydrolysis, Acidogenesis, Acetogenesis, Methanogenesis

n-alkane aerobic degradation pathways


Diterminal oxidation

Terminal oxidation

Subterminal oxidation

β-oxidation

β-oxidation

Callaghan 2006, Biodegradation 1990 1:79-92

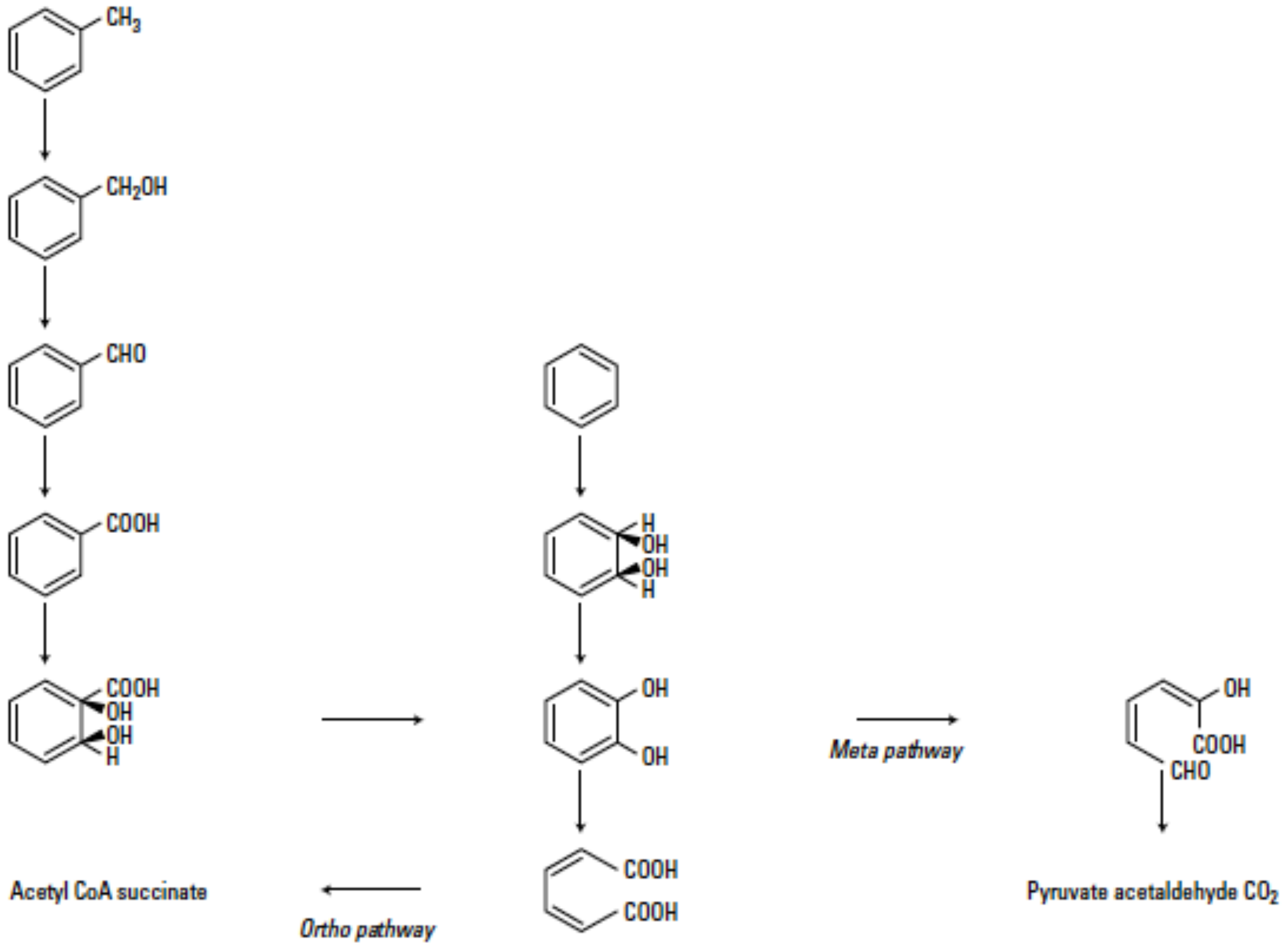


Figure 3.35. Aromatic oxidation by bacteria after catechol formation. Left *ortho* and right, *meta* fission.

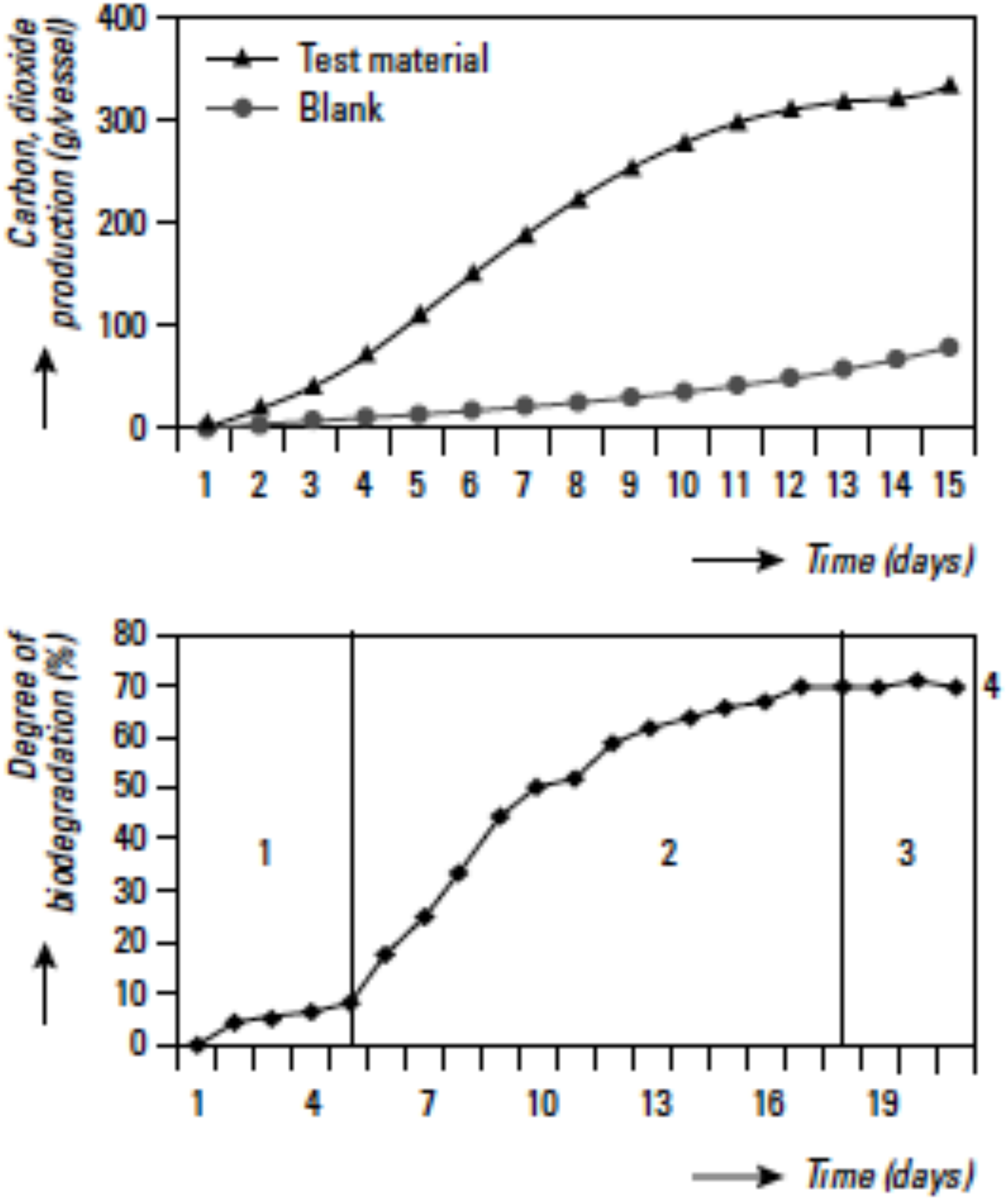


Figure 3.37. Above: CO_2 production curve in a OECD 301B Modified Sturm test. By subtracting the CO_2 blank production from the test material production and dividing by the Theoretical CO_2 Production ($ThCO_2$) the corresponding biodegradation curve is calculated (below), showing lag phase (1), exponential growth or log phase (2), plateau phase (3) and mean degree of biodegradation (4) of a readily biodegradable substance.

Table 3.11. Influence of molecular structure on the biodegradability of chemicals in the aerobic environment.

Type of compounds or substituents	More biodegradable	Less biodegradable
Hydrocarbons	linear alkanes > C_{12}	linear alkanes < C_{12}
	alkanes with not too high molecular weight	high molecular weight alkanes
	linear chain	branched chain
	-C-C-C-	-C-O-C-
	aliphatic	aromatic
	mono- and bicyclic aromatic	polycyclic aromatic
Aliphatic chlorine	Cl more than 6 carbons from terminal carbon	Cl at 6 or less carbon atoms from terminal C
Substituents to an aromatic ring	-OH	-F
	$-CO_2H$	-Cl
	$-NH_2$	$-NO_2$
	$-OCH_3$	$-CF_3$