COSMO-RS Theory

The Basics

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From μ to properties

| Property		μ_1	μ_2
activity coefficient	$\gamma_S^X = \exp\{(\mu_S^X - \mu_X^X)/RT\}$	Infinite dilution	Pure compound
vapor pressure	$p_X^X = \exp\{-(\mu_{gas}^X - \mu_X^X)/RT\}$	Gas phase	Pure bulk compound
Partition coefficient	$\log P_{OW} = \log_{10}\left[\exp\{(\mu_W^X - \mu_O^X)/RT\}\frac{c_O}{c_W}\right]$	Phase 1	Phase 2
Liquid-liquid phase equilibrium	$\mu_S^{X_i^1} + RT\ln x_{X_i}^1 = \mu_S^{X_i^2} + RT\ln x_{X_i}^2$	Phase 1	Phase 2

➢ By calculating the chemical potentials in various phases, the required properties can be derived.

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Describing a Molecule: COSMO

The screening charge density surface (σ-surface) contains all relevant information for COSMO-RS to calculate the chemical potential. Each molecule is represented by its σ-surface. The σ-surfaces are calculated only once and stored for later use.

Fenoterol
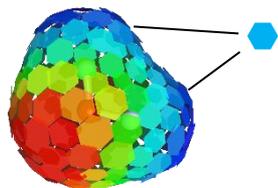
Acceptor   Donor

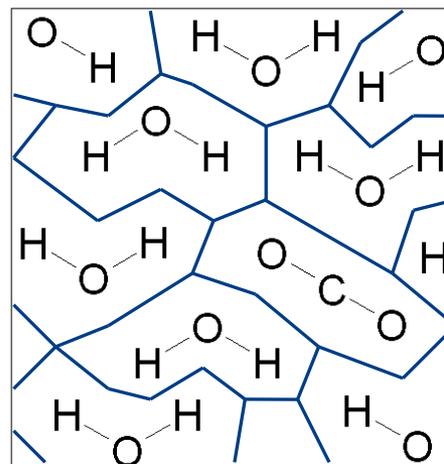2-Chlorophenol

Cl is not an acceptor
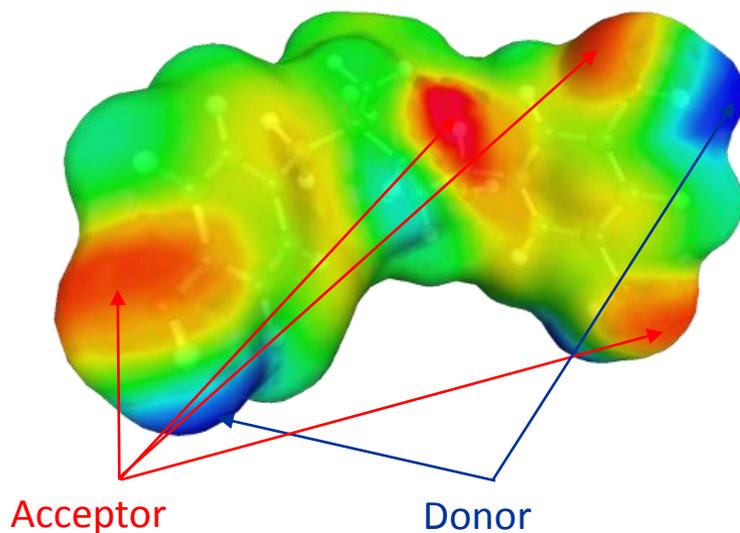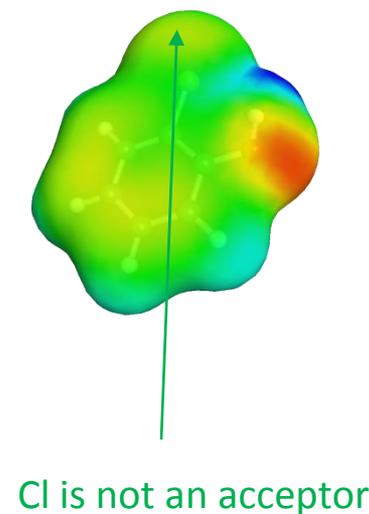
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Assumptions

A few assumptions are necessary to make the COSMO-RS equations solvable:

- Interactions are based on surface segments
- With screening charge σ

- The surfaces are in close contact
- Only pair wise surface interactions
- The 3D geometry is neglected

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Interaction Terms

COSMO-RS features explicit interaction terms for the relevant interactions in liquids
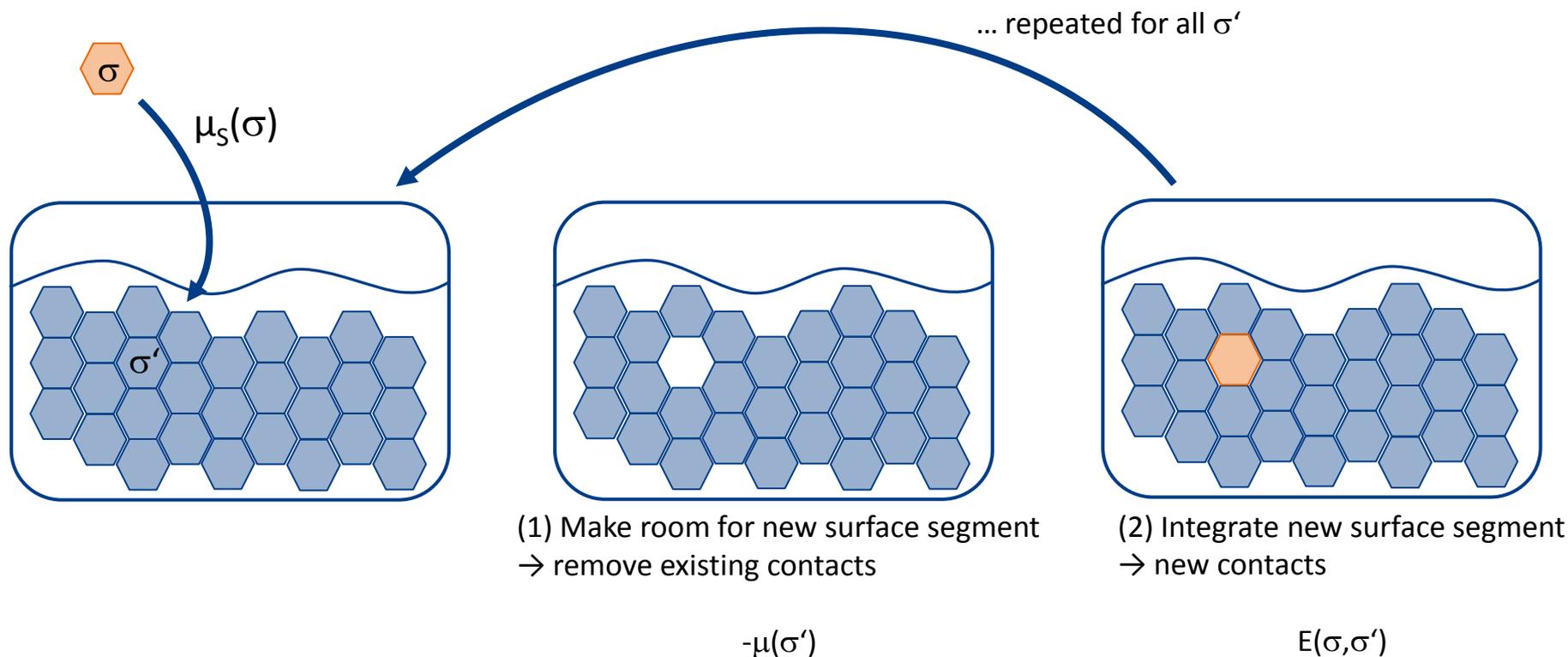
- Coulomb interaction (misfit term) $E \sim (\sigma + \sigma')^2$

- Hydrogen bond interaction $E \sim (\sigma \times \sigma')$

- Van der Waals interaction $E \sim$ area

- Combinatorial term E (Shape)

The exact equations for the interactions are complex and represent the essence of each COSMO-RS implementation.

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Statistical Thermodynamics

The chemical potential of adding a surface piece with polarity σ is calculated from the probability $p_S(\sigma')$ to find a certain polarity inside the solvent and the interaction terms:

$$\mu_S(\sigma) = -kT \ln \int p_S(\sigma') \exp\left\{-\frac{E_{int}(\sigma, \sigma') - \mu_S(\sigma')}{kT}\right\} d\sigma'$$

... repeated for all σ'

(1) Make room for new surface segment
→ remove existing contacts

$-\mu(\sigma')$

(2) Integrate new surface segment
→ new contacts

$E(\sigma, \sigma')$

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Statistical Thermodynamics

The equation has to be solved iteratively
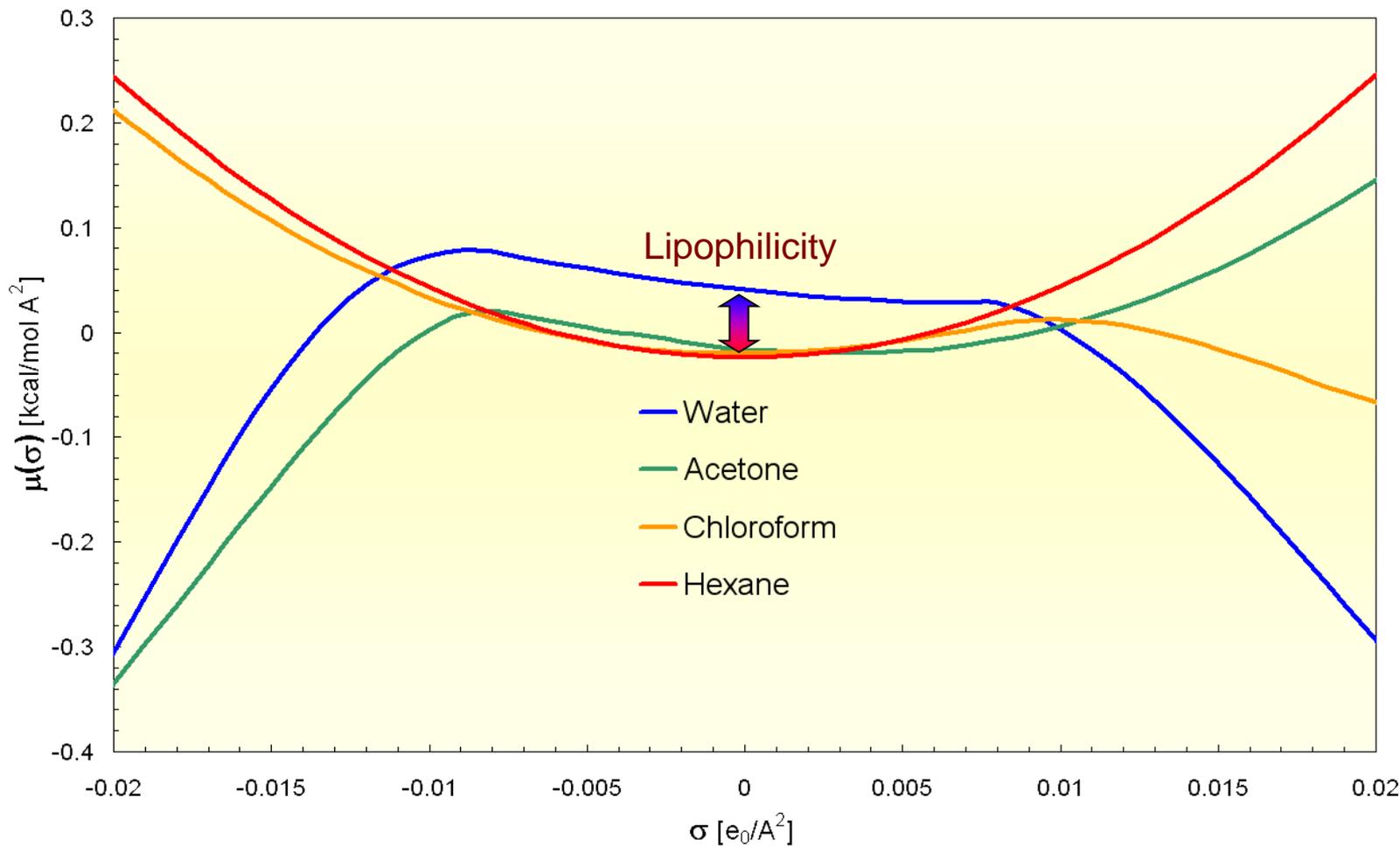
Iterative Solution

$$\mu_S(\sigma) = -kT \ln \int p_S(\sigma') \exp\left\{ -\frac{E_{int}(\sigma,\sigma') - \mu_S(\sigma')}{kT} \right\} d\sigma'$$

The σ-potential $\mu_S(\sigma)$ is a measure for the affinity of system S to a surface of polarity σ.

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σ-potential

The σ-potential $\mu_s(\sigma)$ is a characteristic function of a system at a given T.

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Statistical Thermodynamics

The *microscopic* interactions are transferred to *macroscopic* thermodynamics:

- All segments can interact with all other segments.

- The energy of all segment-segment interactions needs to be evaluated.

- Segments with similar σ will have similar energies.

- Only the total amount of surface with a certain σ enters the final solution, i.e. the σ distribution $p(\sigma)$ of each molecule.

- This σ distribution is called σ-profile and is a molecular property.

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σ-profiles

A σ-profile: a histogram of charged surface segments of a molecule

COSMO-RS
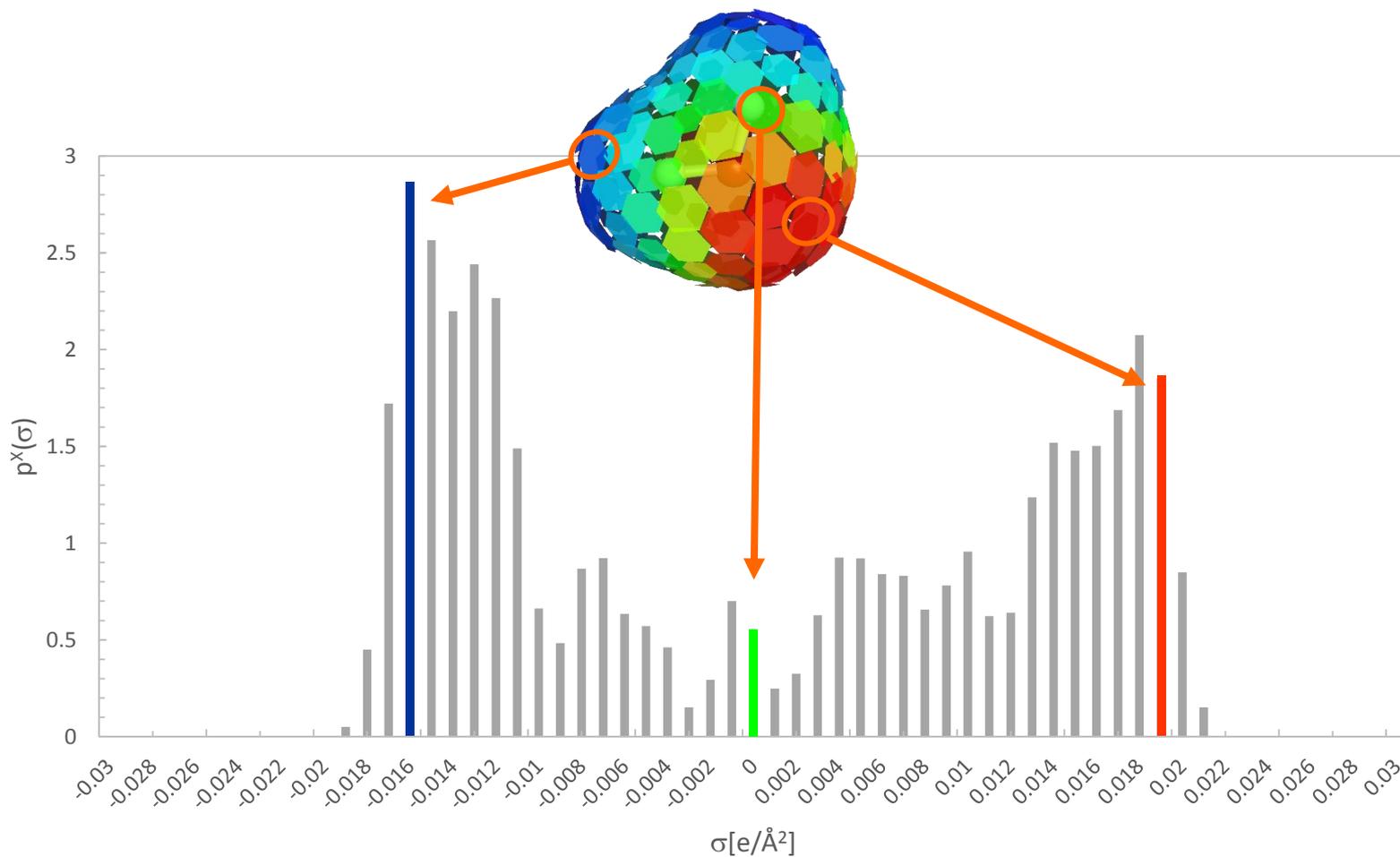
σ-profiles
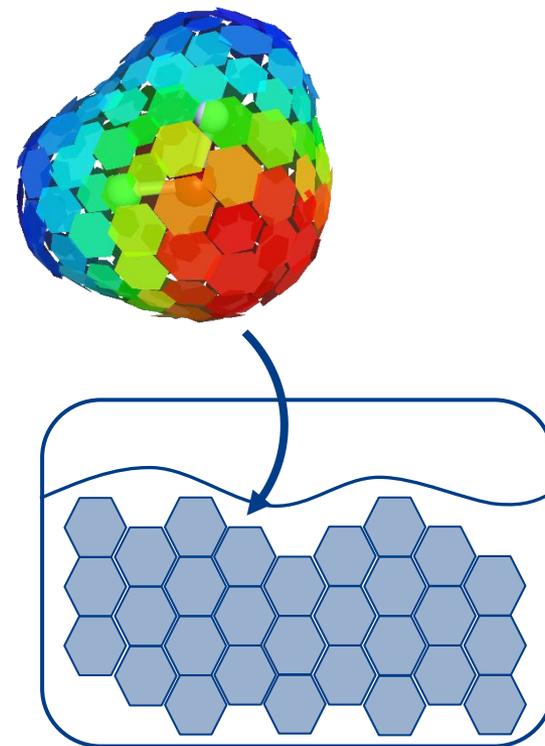
Example σ-profiles for a selection of molecules.
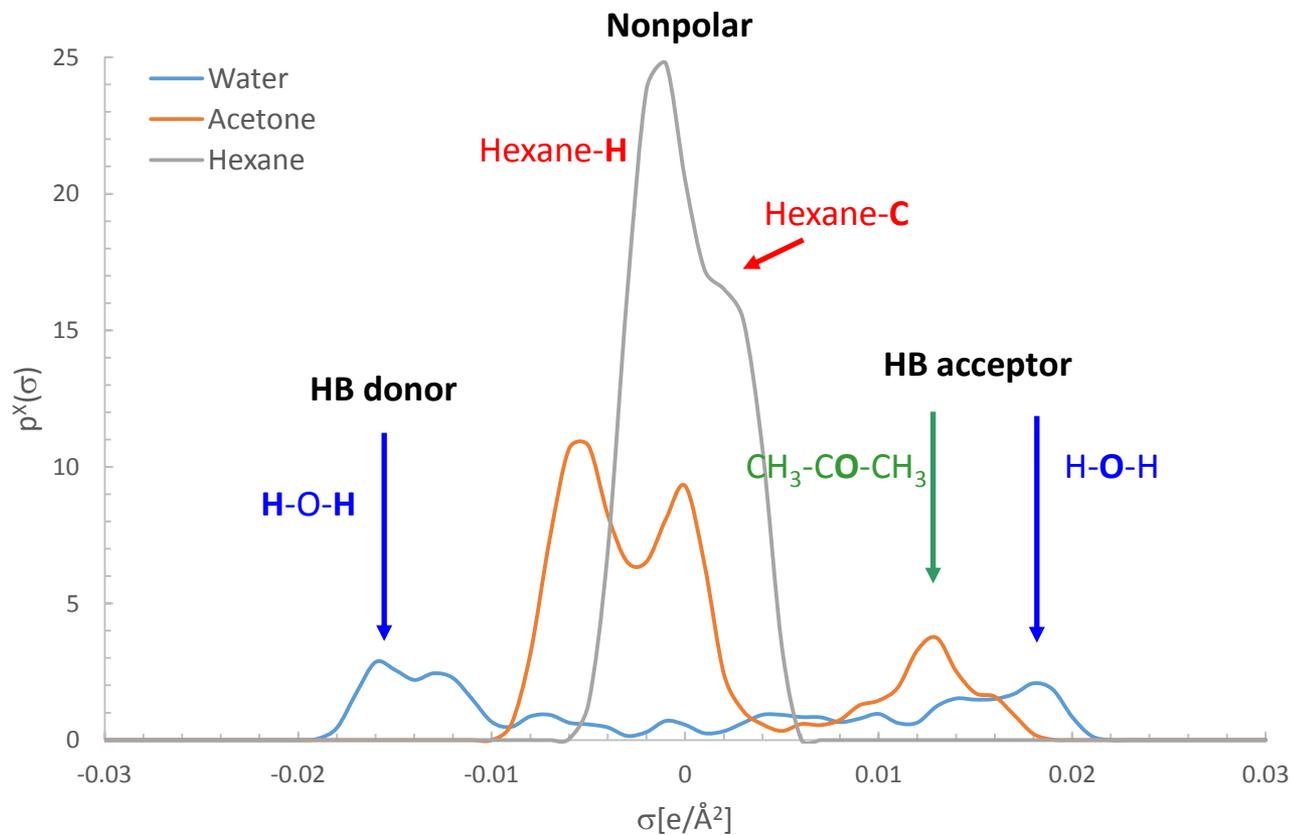
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Chemical Potential

The chemical potential of component X in system S
is calculated by

$$\mu_S^X = \sum_\sigma p^X(\sigma)\mu_S(\sigma) + \mu_{C,S}^X$$

$\mu_{C,S}^X$ is a combinatorial term, accounting for size and
shape differences of the molecules in the system.

Parameterization

Why

Assumptions

- COSMO-radii

- Only pairwise interactions and incompressibility (no free space)

- Neglect of 3D geometry

Inaccuracies

- σ as calculated by DFT

- Quantum chemical energies as calculated by DFT

Unknown quantities

- Size of the average contact area

- Exact enthalpy terms e.g. for Misfit, Hydrogen Bonding, Dispersion

- Exact entropy terms e.g. for Misfit, Hydrogen Bonding, Dispersion

Parameterization

Data set and accuracy

Parameterization data (2014)

- 6739 data points between 144 K and 714 K

- 1300 different chemical compounds (incl. ionic liquids)

- Elements: H, He, C, N, O, F, Ne, Si, P, S, Cl, Ar, Ge, As, Se, Br, Kr, I, Xe

- Partitioning, free energy of solvation, vapor pressure, activity coefficients

➢ Accuracy: 0.45 kcal/mol

Validation

- > 20000 data points

➢ Accuracy: 0.5 kcal/mol

Limitations

COSMO*therm* is not able to (directly) deal with

- Non-equilibrium dynamic and transport properties such as viscosity or excess volume

- Systems near or beyond the critical point

- Properties of highly polar ions (F^-, OH^-, Mg^{2+}, Al^{3+}) are calculated at low accuracy

- Tertiary amines have low accuracy on SVP, TZVP and DMOL3
  (not on TZVPD-FINE level)

Combining COSMO*therm* with other methods can help

- QSPR model for pure compound viscosity available

- Combination with Equation of State methodology is possible (1)

- Individual system-dependent solutions required (EoS, Mixing Rules, …)

1) C. Panayiotou, *Ind. Eng. Chem. Res.* 42 (**2003**) 1495 ; O. Milocco, M. Fermeglia, S. Pric, *Fluid Phase Equilib.* 199 (**2002**) 15.