# Simulations of water near hydrophilic and hydrophobic surfaces

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# Term paper on the theory of soft matter

#### Abstract

There is growing interest in understanding water for it represents an ubiquitous substance on Earth with profound implications in biological systems, technology, industry and transportation. Historically, its macroscopic properties were studied. However, many of inherent water properties and especially interfacial effects of vast importance are actually consequences of orientation and behaviour of water molecules at such interfaces rather than the properties of bulk water or of surfaces themselves.

Exponentially increasing computer power has allowed us to investigate those effects on a molecular scale. Various approaches, their advantages and limitations were reviewed. Specifically, solvation phenomena, surface properties and water behaviour at various interfaces were investigated. Combining theoretical studies with recent experimental techniques, molecular behaviour at interfaces was elucidated. Propensity for some solvated ions to adhere to the surface rather than to sink into bulk was compared. Formation of depletion layer and preferential orientation of water molecules near different hydrophilic and hydrophobic surfaces was investigated. Acidity of the surface water layer and basicity of the subsurface layer were discussed.

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# 1 Introduction

Water is one of the most abundant compounds in the part of Earth that is accessible to humans. It has played a key role in the genesis and development of life. Water is necessary in sustaining all known life forms in the universe. Moreover, water covers more than three quarters of the Earth's surface and is in varying quantities and forms ubiquitously present in all environments on Earth. It is heavily used in industry for a variety of technological processes as a solvent, coolant, medium of transport, or reagent, in agriculture and transportation.

This ubiquity of water and its important role in all aspects of life call for a solid understanding of its properties and behaviour. Modelling and simulating water has proven to be an elusive goal that has yet to be fully achieved. There are many properties of water that despite being adequately understood and described on an empirical scale still elude rigorous explanation. Bulk properties, such as density maximum at 4 °C, lower density of the solid phase compared to the liquid phase, nearly constant heat capacity in the liquid phase, negative expansion coefficient below the temperature of density maximum, and interface phenomena, such as surface tension, capillary effect, hidrophobicity, are largely governed by the bent geometry and polarity of water molecule and the hydrogen bonding.<sup>1,2</sup> There is no single water model or simulation that would in detail explain or reproduce all the aforementioned characteristics of water.

Nevertheless, improved understanding of quantum phenomena, atomic behaviour and molecular bonding on one hand and increase in available computing power on the other hand have helped advance the knowledge of water properties through analytical theories as well as computer simulations. Many intriguing problems about water, such as the orientation of water molecules at interfaces, around charged particles or hydrophobic macromolecules, however, can only be addressed through computer simulations.

# 2 Theoretical background

# 2.1 Water molecule

Water molecule consists of two hydrogen atoms and one oxygen atom, as shown by its molecular formula H<sub>2</sub>O. On a subatomic scale the atoms in the molecule wiggle, but its geometry in vacuum can be approximated as having fixed angle  $\angle$  HOH of 104.52° and the bond length OH of 0.09572 nm. In liquid or solid phase, in solutions and even gas phase the bond length and angle change because of local environment effects. This is further complicated by the propensity of water to form large clusters  $(H_2O)_n$ . Existence of such clusters was proven even in gas phase, where the numerical density of molecules is approximately a thousand-fold smaller than in condensed phase.

### 2.2 Description levels

### 2.2.1 Schrödinger equation

According to the present understanding of physics, Schrödinger equation is the most exact way of describing submicroscopic particles and their behaviour. Derived from quantum mechanics principles by Erwin Schrödinger in 1926, it describes the change of the quantum state of a physical system in time.

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi \tag{1}$$

 $\hat{H}$  stands for the Hamiltonian operator,  $\hbar$  is the reduced Planck constant and  $\Psi$  is the wavefunction of the system.

Should the system be in a stationary state, the equation reduces to the time-independent Schrödinger equation:

$$E\Psi = \hat{H}\Psi,\tag{2}$$

where E represents the energy of the system. The Hamiltonian operator consists of the kinetic and potential energy contributions.

$$\hat{H} = -\frac{\hbar^2}{2m}\nabla^2 + V \tag{3}$$

Schrödinger equation can only be solved analytically for trivial systems (e.g., free particle, particle in a box, hydrogen atom, linear rigid rotor, harmonic oscillator). For more complex systems, one has to resort to numerical solutions that can in principle be found for arbitrarily large systems. In doing so, trade-offs have to be made between the method and basis sets used on one side and the available computer power on the other side.

For a single water molecule in vacuum without any external potential, the Hamiltonian operator in the time-independent Schrödinger equation is written as:

$$\hat{H} = -\sum_{a=1}^{2} \frac{\hbar^2}{2M_{H^a}} \nabla_{H^a}^2 - \frac{\hbar^2}{2M_O} \nabla_O^2 - \sum_{i=1}^{10} \frac{\hbar^2}{2m_i} \nabla_i^2 + \frac{\hbar^2}{2$$

$$+\sum_{a=1}^{2} \frac{8e_{0}^{2}}{4\pi\epsilon_{0}r_{H^{a}O}} + \frac{e_{0}^{2}}{4\pi\epsilon_{0}r_{H^{1}H^{2}}} - \sum_{a=1}^{2}\sum_{i=1}^{10} \frac{e^{2}}{4\pi\epsilon_{0}r_{H^{a}i}} - \qquad (4)$$
$$-\sum_{i=1}^{10} \frac{8e_{0}^{2}}{4\pi\epsilon_{0}r_{Oi}} + \sum_{i=2}^{10}\sum_{j=1}^{i-1} \frac{e_{0}^{2}}{4\pi\epsilon_{0}r_{ij}},$$

with M being an atom mass, m an electron mass and r inter-particle distance. Indices i and j run through all electrons, while the index a describes both hydrogen nuclei.

With current computer power, this equation can be solved numerically to an arbitrary degree of precision.

#### 2.2.2 Born-Oppenheimer approximation

Solving the Schrödinger equation for a single water molecule translates to solving a partial differential eigenvalue equation in 39 variables (three spatial coordinates of ten electrons and three nuclei). Max Born and Julius Robert Oppenheimer proposed in 1927 an approximation that reduced the complexity of the problem. Instead of solving Schrödinger equation in whole, one can decompose the wavefunction into a product of uncorrelated electronic and nuclear wavefunctions. This assumption is justified by very slow movement of nuclei when compared to electrons. Born-Oppenheimer approximation is used routinely in all quantum-mechanical calculations.

$$\Psi = \psi_{electronic} \ \psi_{nuclear} \tag{5}$$

Calculations relying only on basic and well-established natural laws without any additional assumptions, models or experimental data are called *ab initio* methods. In chemistry, they denote models using quantum chemistry. They can be reliably used for no more than roughly 10 water molecules.<sup>3</sup> Their inherent problem is that they represent calculations at 0 K, but are nevertheless vastly informative. This limitation can be overcome by including the temperature effect through employing simple harmonic oscillator models. *Ab initio* methods are used for devising force fields and performing calculations of hydration of single ions (with six to twelve water molecules).

### 2.2.3 Explicit water

To model a typical solution of a moderately diluted concentration (1–100 mM), one has to simulate one particle of a solute and 500 to 50,000 water molecules. This cannot be done with the Schrödinger equation and Born-Oppenheimer

approximation because of a great computational cost. This problem is alleviated by using simplified water models. These represent water molecules explicitly, but treat them as non-quantum entities with macroscopic qualities, such as well-defined fixed or elastic bond lengths, localised or polarisable charges, finite sphere size *etc*. Using these water models vastly increases the simulation speed and renders simulations of systems with a couple hundreds water molecules feasible. This approach is employed in simulating water molecules orientation at interfaces, what this paper primarily deals with.

#### 2.2.4 McMillan-Mayer approximation

When simulating properties of aqueous solutions that do not depend on particular water molecules orientation and interactions, a simplification that greatly decreases the computational complexity can be used. William G. McMillan and Joseph E. Mayer postulated in 1945 that there is a one-to-one correspondence between non-ideal gas equations and simple dilute solutions.

Their approach treated water in a solution as a continuum that merely changes the relative permittivity of the space between solute particles that are modelled explicitly. Strictly speaking, for relative permittivity is a macroscopic quantity, this approach suffers from a fundamental flaw of introducing macroscopic quantities to microscopic particles where they have no physical meaning. Therefore, using this approach is a highly questionable concept.<sup>4</sup> Applying this method to calculation of interface or particular solvation effects yields wrong conclusions.

However, many bulk solution properties can be adequately reproduced using this approximation. Remarkably, even hydration enthalpies of ions can be calculated quite well if we introduce a fictitious charge  $q' = q(\epsilon - 1) / (\epsilon + 1)$ symmetrically placed on the opposite side of the medium boundary. In crudest Born model,<sup>5</sup> free energy for moving the ions from vacuum to water is equal to  $\Delta G = -(1 - 1/\epsilon) q^2/4\pi\epsilon_0 R$ .<sup>6</sup> Specific ionic interactions cannot be reproduced because this approach does not distinguish between cation and anion solvation (due to uniform water continuum).

### 2.2.5 Classical approach

In classical physics, water is viewed as a Newtonian fluid with characteristic properties of liquids. It flows, has a defined volume but takes the shape of a container. Fluids at rest cannot withstand shear stress but instead start to move. As a response to applied shear stress, velocity gradient in a moving fluid is established, as described by the viscosity equation:

$$\tau = \mu \frac{\partial v}{\partial y}.$$
(6)

Another phenomenon that arises from the fact that bulk properties differ from boundary properties is surface tension. On a molecular level, surface tension is the consequence of different local environment close to the surface as compared to the bulk. Molecules near the surface have fewer neighbouring molecules exerting attractive influence on them than the molecules in bulk. Macroscopically, this is encountered as a propensity of the liquid to minimize its surface area in the absence of outside fields or forces. Surface tension can be defined as the force parallel to the surface along a line of unit length

$$F = 2\gamma L. \tag{7}$$

The same phenomena occur near every interface, such as hydrophilic or hydrophobic macromolecules, liquid surface *etc.* Although classical approach does not seem to be particularly useful in understanding water orientation and density near interfaces, measurements of macroscopic quantities are related to microscopic orientation. There is a quantitative relationship between the concentration of solute and the surface tension, called the Gibbs adsorption equation<sup>7</sup>

$$-d\gamma = -\Gamma_1 d\mu_1 + \Gamma_2 d\mu_2. \tag{8}$$

The dividing surface can be located at the point that makes  $n_1^s = 0$  and  $\Gamma_1 = 0$ . This equation then simplifies to

$$- d\gamma = \Gamma_2^1 d\mu_2. \tag{9}$$

Relative surface excess is the excess amount of component 2 adsorbed at the particular surface where the excess of component 1 is zero. It can be shown to be equal to

$$-\Gamma_2^1 = \frac{-1}{RT} \left( \frac{\partial \gamma}{\partial \ln a_2} \right)_T.$$
(10)

It can be shown that the surfactants (amphiphilic molecules) reduce the surface tension while the inorganic electrolytes general increase the surface tension. Negative adsorption and the corresponding drop in the surface tension are explained in terms of repulsion of ions from the surface by electrostatic forces.<sup>8</sup>

Classical approach does not provide us with means to analyse water molecule orientation in those anisotropic environments. Instead, molecular simulations with explicit water must be run.

# 3 Water models

Schrödinger equation can only be solved analytically for trivial systems (*e.g.*, free particle, particle in a box, hydrogen atom, linear rigid rotor, harmonic oscillator). However, numerical solutions can *in principle* be found for systems of arbitrary complexity. Viability of this method is bounded by the available computer power and presently does not allow calculations of adequately large systems to study water systems with a few hundred molecules. Born-Oppenheimer approximation also proves to insufficiently reduce computing complexity. Thus, further approximations and models are needed to perform such calculations.

McMillan-Mayer approximation is useful only when studying the behaviour and thermodynamic properties of ions in aqueous solutions. For it represents water as a continuum that merely changes the relative permittivity of the solution, specific information about water molecules orientation is inherently inaccessible.

To address this issues, various explicit water models of varying complexity have been developed. They can be divided into four groups:

- rigid electrostatic models,
- flexible electrostatic models,
- polarisable models,
- Mercedes-Benz models.

In MC and MD simulations, electrostatic models (rigid or flexible) are predominantly used. Force field used is either empirical (water model) or the Car-Parrinello approach, which evaluates forces by performing quantum chemical calculations.<sup>9</sup>

### 3.1 Rigid electrostatic models

Rigid electrostatic models depict water as a rigid combination of positively charged or non-charged spheres and negative point charges in a fixed orientation. Negative charges represent lone electron pairs, positively charged sphere represent hydrogen atoms and the non-charged sphere usually corresponds to the oxygen atom. These models can be further divided into four groups:

- three-point models,
- four-point models,
- five-point models,
- a single six-point model.

Pair potential between two water molecules is calculated as a sum of Coulomb and Lennard-Jones interactions. Coulomb potential describes the interaction between charged entities, while Lennard-Jones potential describes the interaction between oxygen atoms. We can postulate that Coulomb interaction predominantly deals with hydrogen bonding and Lennard-Jones interaction with van der Waals interaction.

$$U_{ww}(r) = \sum_{i < j} \frac{q_i q_j}{r_{ij}} + 4\epsilon_{ww} \left( \left(\frac{\sigma_{ww}}{r}\right)^{12} - \left(\frac{\sigma_{ww}}{r}\right)^6 \right)$$
(11)

#### 3.1.1 Three-point models

Three-point models are the simplest water models developed. Each molecule is represented as a constellation of two positive charges and one negative charge in a given geometry. They are furthermore enclosed in a Lennard-Jones sphere with a centre on the negative charge. Parameters needed to describe these models are the Lennard-Jones well depth and sphere radius, charge magnitudes and their geometry (distances and angles). The most popular three-point models are SPC,<sup>10</sup> SPC/E,<sup>11</sup> TIPS<sup>12</sup> and TIP3P.<sup>13</sup> Due to their simplicity their use is still wide-spread.

#### 3.1.2 Four-point models

Four-point models consist of four particles. Positive charges represent hydrogen atoms, while the negative charge represents the lone electron pairs and is not in the centre of Lennard-Jone sphere anymore. To describe these models, we need more geometric data (two distances, two angles). The most well-known four-point models are BF,<sup>14</sup> TIP4P<sup>15,16</sup> and derivations thereof (TIP4P-Ew,<sup>17</sup> TIP4P-Ice,<sup>18</sup> TIP4P-2005<sup>19</sup>).

#### 3.1.3 Five-point models

Five-point models use two positive charges in place of hydrogen atoms, two negative charges in place of two electronic lone pairs. The centre of Lennard-Jones sphere is placed in the non-charged centre of the molecule. Some early five-point models, such as BNS<sup>20</sup> and ST2,<sup>21</sup> use scaled Coulomb interactions, while newer do not scale them (TIP5P,<sup>22</sup> TIP5P-E<sup>23</sup>).

#### 3.1.4 Six-point model

A single six-point water model has been proposed.<sup>24</sup> It employs two positive charges and three negative charges. This model is not of particular impor-

tance because it is computationally very expensive and does not provide better results that simpler models.

For details on the parametrisation of a particular model, various reviews have been written.  $^{25}$ 

# 3.2 Flexible electrostatic models

Flexible models are re-parametrisations of rigid models that additionally take into account the flexibility of water molecule. In the example of SPC flexible model, <sup>26</sup> anharmonic O-H stretching is taken into account. Other models, such as  $CF^{27}$  and  $MCY^{28}$  can reproduce vibration spectra quite well. Others have been tailor-made for niche applications, such as  $F3C^{29}$  for MD simulations of biological macromolecules. Such models generally provide very good calculation results, only surpassed by much more complicated polarisable models.

# 3.3 Polarisable models

Polarisable models include an explicit polarisation term, aiming to improve their ability to reproduce water behaviour across different phases and the interaction between them. The first polarisable model PE was developed by Barnes in 1979, and his work was quickly followed by others. Nowadays, many polarisable models are known: *e.g.*, SPC/FQ,<sup>30</sup> TIP4P/FQ,<sup>30</sup> SCPDP,<sup>31</sup> Chialvo-Cummings,<sup>32</sup> GCPM.<sup>33</sup> Their use is still impeded by large computational cost that often outweighs the benefits of more accurate results.

# **3.4** Mercedes-Benz models

Mercedes-Benz water models try to emulate water in a different fashion. Water is viewed as comprised of identical perfect spheres (or circles in previously developed 2D variation) that interact according to Lennard-Jones potential. Additionally, electrostatic effects and hydrogen bonding are implicitly factored in. Each particle has four (or three in 2D) hands that allow for angle-specific interactions. The strength of this interaction depends upon the separation and angle according to Gaussian functions  $(G(x) = e^{\frac{-x^2}{2\sigma^2}})$ . Total interaction is written as the sum of those two:

$$U_{LJ}(r_{ij}) = 4\epsilon_{LJ} \left[ \left( \frac{\sigma_{LJ}}{r_{ij}} \right)^{12} - \left( \frac{\sigma_{LJ}}{r_{ij}} \right)^6 \right]$$
(12)

$$U_{HB} = \epsilon_{HB} G \left( r_{ij} - r_{HB} \right) \sum_{k,l=1}^{4} G \left( \mathbf{i}_k \cdot \mathbf{u}_{ij} - 1 \right) G \left( \mathbf{j}_l \cdot \mathbf{u}_{ij} + 1 \right).$$
(13)

Two variations of the model have been proposed.  $^{34,35}$ 

Models from this group are only useful for computing thermodynamic properties of water solutions. Since they use abstract representation of water molecules, they cannot be used to determine the structure of water in bulk or at the interfaces.



Figure 1: A typical three-point water model.  $^{25}$ 



Figure 3: A typical five-point water model.  $^{25}$ 

Figure 2: A typical three-point water model.  $^{25}$ 



Figure 4: A typical six-point water model.  $^{25}$ 

# 4 Computer simulations

There are two fundamentally different approaches to computer simulations:<sup>36</sup> Monte Carlo method (MC) and molecular dynamics (MD). They were both devised in the 1950s with the aim of simulating real substances and materials, but proceed from entirely different premises and subsequently allow for the calculation of different properties.





Figure 5: A typical polarisable model.<sup>25</sup>

Figure 6: A 3D Mercedes-Benz water model.  $^{25}$ 

MC is a numerical method that has been invented for the numerical evaluation of integrals by random number generators. When running simulations, one starts with a pre-set arrangement of particles and step after step randomly chooses a particle and randomly changes its position. Upon every iteration, the energy of the system is calculated. If the new position of a particle yields lower total energy, the move is accepted, otherwise it *can* be rejected and the old one re-accepted. Eventually, the system reaches an equilibrium.

MD follows a fundamentally different principle. In contrast to MC, it is deterministic and dynamic. After particles have been arranged in a particular order with their respective velocities, we solve the Newton's equations of motion. These yield the acceleration and their new velocities that are used to calculate their new positions after time  $\Delta t$ . The procedure is then iteratively repeated. After a certain amount of iterations, the system has attained an equilibrium.

Before running any type of molecular simulation, the inter-particle potential function must be envisaged. This function allows us to compute the energy of the system through addition of inter-particle interactions and is, in general, an infinite sum:

$$U = \sum_{i} u_{1}(\mathbf{r}_{i}) + \frac{1}{2!} \sum_{i < j} u_{2}(\mathbf{r}_{i}, \mathbf{r}_{j}) + \frac{1}{3!} \sum_{i < j < k} u_{3}(\mathbf{r}_{i}, \mathbf{r}_{j}, \mathbf{r}_{k}) + \dots$$
(14)

The first term represents eigenenergies of particles (due to hybridisation, ion compressibility, *etc.*) and the second term describes the pair potential (Pauli repulsion, Coulomb potential, van der Waals forces, *etc.*). Usually, the sum is truncated after the second term, but in principle, higher terms could be used as well. Rather, one introduces a so-called effective pair potential that views the potential energy of the system composed only of pair interactions between any two particles that are dependent only on their separation. Higher terms are included implicitly.

$$U = \sum_{i}^{N-1} \sum_{j=i+1}^{N} u_{ij}(r_{ij})$$
(15)

A prudent choice of the potential function is a prerequisite for a useful simulation.

# 4.1 Monte Carlo method

Monte Carlo method was originally devised for a numerical computation of multi-dimensional integrals. Since molecular simulations generally seek to evaluate the configurational part of the partition function

$$Z = \int e^{-\beta U(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n)} \, \mathrm{d}\mathbf{r}_1 \mathrm{d}\mathbf{r}_2 \dots \mathrm{d}\mathbf{r}_n \tag{16}$$

in order to compute the average value of some quantity A

$$\langle A \rangle = \frac{\int A \ e^{-\beta U(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n)} \ \mathrm{d}\mathbf{r}_1 \mathrm{d}\mathbf{r}_2 \dots \mathrm{d}\mathbf{r}_n}{\int e^{-\beta U(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n)} \ \mathrm{d}\mathbf{r}_1 \mathrm{d}\mathbf{r}_2 \dots \mathrm{d}\mathbf{r}_n},\tag{17}$$

MC is a suitable method for these aims.

A typical algorithm for MC is, as follows:

- 1. Energy of the system U is calculated.
- 2. A random particle is selected and given a random displacement  $r' = r + \Delta r$ .
- 3. A new energy of the system U' is calculated.
- 4. If U' < U, the move is accepted. If U' > U, the move is accepted with probability min  $(1, e^{-\beta(U'-U)})$ . This is called Metropolis sampling and is the most commonly used sampling method.

This algorithm holds true as written when the simulation is run in a canonical ensemble (NVT). When run in other ensembles, other quantities must be allowed to fluctuate as well, necessitating the use of modified probabilities for accepted moves.

In isothermal-isobaric ensemble (NPT), particles are moved while the volume is allowed to fluctuate. In addition to calculating energy, we must

also calculate enthalpy. The criterion for accepting a move of a particle or a fluctuation in volume is modified as min  $(1, e^{-\beta(H'-H)})$ , where

$$H' - H = U' - U + P(V' - V) - Nk_b T \ln(V'/V)$$
(18)

In other ensembles (grand canonical, Gibbs ...), number of particles also fluctuates. The equations for determining the probability of a fluctuation are accordingly modified.

#### 4.1.1 Scope of use and limitations

Due to its nature, MC can only be used for simulating equilibrium properties (*e.g.*, internal energy, osmotic coefficient, activity coefficient, microscopical structure, heat capacity, compressibility).

Upon running a simulation, one must wait for the system to attain an equilibrium. In equivalent conditions, the system must attain the same equilibrium regardless of the starting particle configuration. Simulation results while the system is equilibrating can be monitored to check the correctness of the algorithm and simulation but do not have any physical meaning. Consequently, dynamic properties such as diffusion coefficient, process kinetics, protein folding or molecular docking cannot be simulated.

# 4.2 Molecular dynamics

In MD, we observe the behaviour of the system through time. First, we must set the parameters of the simulation. These include the number of particles, box size, time step, initial temperature, effective potential model, *etc.* Secondly, the system must be initialised by placing the particles in their positions and assigning each one its velocity. Chosen positions must be in agreement with the simulated system and their velocities must correspond to the desired temperature. Usually, the particles are placed in a crystallinic lattice and the "melting" of the crystal is observed. This is done to ensure the same starting conditions and to eschew the overlap of their nuclei.

The following two steps constitute the core of MD algorithm:

- 1. Forces on all particles are computed.
- 2. Newton's equations of motion are integrated, moving the particles accordingly.

These steps are repeated to obtain the behaviour of the system on a  $\Delta t$  time scale.

Forces on any particle in x direction are computed, as follows:

$$F_x(r) = \frac{\partial u(r)}{\partial x} = -\left(\frac{x}{r}\right) \left(\frac{\partial u(r)}{\partial r}\right).$$
(19)

This calculation must be repeated for every particle in three directions. The force field used can be empirical (see water models section) or calculated via quantum chemistry (Car-Parrinello approach<sup>9</sup>). The latter method is much more computationally complex, for it solves a simplified pseudo-Schrödinger equation. However, it includes the motion of electrons and their contribution to forces.

After the force acting upon each particle has been determined, one has to integrate the Newton's equations of motion. Usually, this is done with Verlet algorithm, which is one of the best algorithms available despite its simplicity. The coordinate of a particle is expanded into a Taylor series around time t

$$r(t + \Delta t) = r(t) + v(t)\Delta t + \frac{f(t)}{2m}\Delta t^2 + \frac{\Delta t^3}{3!}\frac{\mathrm{d}^3 r}{\mathrm{d}t^3} + \mathcal{O}\left(r^4\right)$$
(20)

$$r(t - \Delta t) = r(t) - v(t)\Delta t + \frac{f(t)}{2m}\Delta t^{2} - \frac{\Delta t^{3}}{3!}\frac{\mathrm{d}^{3}r}{\mathrm{d}t^{3}} + \mathcal{O}\left(r^{4}\right).$$
(21)

Upon summation we arrive at

$$r(t + \Delta t) = 2r(t) - r(t - \Delta t) + \frac{f(t)}{2m}\Delta t^2 + \mathcal{O}\left(r^4\right).$$
(22)

The trajectory is calculated with the knowledge of two previous positions of a particle and the force that is exerted upon it. Verlet algorithm does not use velocity explicitly, but it can (and must) nevertheless be calculated as

$$v(t) = \frac{r(t + \Delta t) - r(t - \Delta t)}{2\Delta t} + \mathcal{O}\left(r^2\right).$$
(23)

The algorithm for integration Newton's equations of motions can be a source of considerable error. Thus, choice of a good algorithm is crucial. Verlet algorithm is the most popular one, but there exist many higher-order algorithms. Computational complexity of these algorithms is not a particularly limiting factor because the computer spends the most time calculating the potential energy of the system and just a fraction on integrating the motion equations.

Because of the accumulation of numerical errors, the temperature of system is slowly departing from the desired value. This is solved by introducing an external thermostat. Periodically, the temperature of the system is evaluated according to the thermodynamic definition of the temperature for each degree of freedom:

$$\left\langle \frac{1}{2}mv^2 \right\rangle = \frac{1}{2}k_bT.$$
(24)

Velocities of all particles are then scaled to align the instantaneous temperature with thermostat temperature. Also, linear momentum of the system must periodically be checked. If it is non-zero in any direction, this would imply a net outside force moving the system. Therefore it must be compensated by scaling all the velocities in a given direction.

One should note that the results of MD simulations are not true trajectories of the particles because of the Lyapunov instability. Rather, it is a statistical average that still enables us to calculate many equilibrium and dynamic properties of the system. In contrast to MC, MD allows us to calculate diffusion coefficient, protein folding, molecular docking, *etc*.

# 4.3 Boundary conditions

Nowadays, a typical computer system can simulate systems of no more than a few thousand particles. In a system with free boundaries, the fraction of particles at the surface is roughly proportional to  $N^{-1/3}$ . For a system with 1000 water molecules, approximately half of them are at the surface. Properties of such system are inherently different from bulk properties. This issue can be addressed in a multiple ways.

One can introduce periodic boundaries. We treat the volume of N simulated particles as a primitive cell in an infinite lattice of identical cells. We then take into account not only the interaction between particles in a primitive cell but between particles across the n cells.

$$U = \sum_{i}^{N-1} \sum_{j=i+1}^{N} \sum_{n} u_{ij} \left( \mathbf{r}_{ij} + n \mathbf{L} \right)$$
(25)

The problem of having to deal with an infinite number of cells is solved by truncating all inter-molecular interactions past a cut-off distance. The truncation must be done carefully as to avoid the irregularities that could arise from non-continuity and non-differentiability of the potential at the cut-off distance. Usually, simple truncation is avoided in lieu of shifted smoothing.

Alternatively, it is possible to use minimum image convention. Interaction between the particle in the box and nearest image of every other particle is calculated. This means that the potential is not a constant on the surface of a box around a particular particle.

Both methods of periodic boundary conditions must be used with caution. While they do not pose significant problems for MC simulation if parametrised suitably, their use in MD is disadvantageous because the system would no longer conserve energy. Even with MC, truncation in anisotropic interactions must be used with caution. It must never be done at a fixed distance but at the point where the potential between two particles attains a fixed value. This is the case in simulating water molecules near interfaces, what this paper deals with.

When dealing with long-ranging interactions such as those due to Coulomb potential, a different approach must be followed. Long-ranging interactions are still considerable even outside the primitive cell and their sum is only conditionally convergent. To obtain an absolutely convergent sum over the whole range of cells, Ewald summation is used.<sup>37</sup> This method, originally developed for crystallographic purposes, is an efficient method for computing interactions in periodic systems, in particular Coulomb interaction. However, its results presuppose the relative permittivity of a vacuum. For use in solutions, this must be additionally corrected.

# 5 Results

# 5.1 Ions at water surface

The traditional view of water holds that the air-solution interface is virtually devoid of ions. Measurements of macroscopic surface properties (*e.g.*, surface tension) seemed to support that fact although there was no definite experimental verification. These conclusions were drawn primarily from the Gibbs adsorption equation, because inorganic electrolytes typically increase the surface tension of aqueous solution-air interface and surfactants typically decrease it. However, MD simulations show that particular ions actually preferably bind to the surface and do not sink to bulk.

Jungwirth *et al.* studied the ionic solvation of alkali halides and confirmed<sup>3</sup> previous studies that certain ions stay at the surface. They showed that polarisable force field must be used to get correct results on surface adsorption of halide ions. Pioneering studies<sup>38,39</sup> failed to demonstrate that because they employed only non-polarisable force fields. This implies that the ion polarisability plays the crucial role in surface solvation, what Jungwirth *et al.* confirmed.

First, they performed *ab initio* calculations using Möller-Plesset (MP2)

perturbation theory with 6-31G<sup>\*</sup> basis set augmented by standard diffuse functions on chloride. They studied the water hexamer with one sodium chloride molecule. Although this represents an oversaturated solution, some interesting conclusion were drawn. While continuum solvent model with mean force potential (McMillan-Mayer approximation) predicts at least 12 water molecules needed for a successful ion separation in aqueous NaCl, *ab initio* calculations showed that this number is actually six.



Figure 7: Chloride ions bind to surface while sodium stays in bulk.<sup>3</sup>

Figure 8: The propensity for surface adsorption increases along the halide series.<sup>3</sup>

For large clusters with 9–288 water molecules, classical MD simulations of saturated NaCl solution were run. It was shown that large polarisable chloride ions were significantly exposed to the surface, while small non-polarsiable sodium ions tended to stay in bulk. However, when using non-polarsiable force fields, the percentage of surface exposed chloride ions shrank by the factor of three.

Finally, water slabs with NaF, NaCl, NaBr and NaI solutions with concentration of 1.2 M were simulated. Simulations successfully reproduced the order of surface tension in the series: NaI < NaBr < NaCl < NaF. Analysis of the results shows that fluoride ions did not appear at the surface, while the iodide ions almost exclusively bound to the surface. The propensity to stick to the surface increased along the halide series. This explains the shortcomings of Onsager-Samaras theory<sup>8</sup> which was postulated mainly on the measurements of NaF and NaCl solutions, where the surface adsorption is not important (surface concentration of chloride ions is still slightly below bulk concentration). Sodium ions keep in bulk.

There is also indirect experimental evidence supporting these simulations.

X-ray photoelectron spectroscopy and scanning electron microscopy of bromide doped NaCl crystals under conditions of relative humidity where partial dissolution takes place showed segregation of bromide to surface compared to chloride.<sup>40,41</sup> Present understanding implies that the propensity of ions to adsorb to the water surface increases with the size and polarisability of ions.<sup>3</sup> This is in excellent agreement with HSAB theory (hard and soft acids and basis), first put forward by Ralph Pearson in early 1960s.<sup>42–44</sup> This theory distinguishes between hard acids and bases (small ionic radii, high oxidation states, low polarisability) and soft acids and bases (large ionic radii, low oxidation states, high polarisability).

Soft ions are attracted to surface while hard ions are not.

# 5.2 Value of pH at water surface

As seen in halogenide ions, it is possible for particular ions to display propensity to migrate to the water surface. Due to autoionisation of water, there is a small concentration of hydronium (H<sup>+</sup>) and hydroxide (OH<sup>-</sup>) in water. In pure water at ambient conditions, approximately one in  $6 \cdot 10^8$  water molecules is autoionised. In bulk water, the concentrations of ions are the same and yield the neutral value of pH = 7. However, should hydronium or hydroxide preferably migrate to the surface, this would change the acidity of the top layer of water. Computer simulations and experiments give various and contradicting results, as reviewed by Jungwirth *et al.*<sup>45</sup>

### 5.2.1 Acidity

Non-linear spectroscopic techniques (such as vibrational sum frequency generation (VSFG)<sup>46–48</sup> and second harmonic generation (SHG)<sup>49,50</sup>) show the occurrence of increased hydronium concentration at the water surface. This is explained as follows. Hydronium has three strongly charged hydrogens and one weakly charged oxygen, resulting in being a very good hydrogen bond donor and a very poor acceptor. Hydronium in bulk water disrupts local hydrogen bonding network. At surface, however, this can be compensated by its orientation with hydrogens pointing into bulk and oxygen protruding into the gas phase. Hydroxide on the other hand is a poor hydrogen bond donor and a very good acceptor. Consequently, it does not disrupt the hydrogen bonding network in bulk as much and does not show surface enhancement. Should an individual hydroxide ion migrate to the surface, its hydrogens would protrude to the gas phase.<sup>48,50</sup>

Classical molecular dynamic simulations use empirical force fields. These potentials do not allow for hydrogen bond breaking or making, or proton hopping. Instead, one has to use fixed Eigen cation  $(H_3O^+)$  or Zundel cation  $(H_5O_2^+)$ . This strong bonding is somewhat mitigated by using a polarisable force field. Results show that hydronium is not repelled from the surface but instead show an enhancement. The concentration of hydronium at the surface was found to be 150 times greater than in bulk (pH = 4.8).<sup>45</sup> Hydroxide is repelled from the surface to the bulk, where it contributes to the bulk pH = 7.7 - 8.4.<sup>45</sup>

Studies employing *ab initio* energy minimisations for clusters  $(H_2O)_{48}H^+$ and  $(H_2O)_{47}OH^-$ ,<sup>45</sup> and molecular dynamics (Car-Parrinello) also showed the build-up of a hydronium enhancement area at the surface. Conversely, hydroxide tends to sink to bulk.



Figure 9: Hydronium and hydroxide in water.<sup>3</sup>

### 5.2.2 Basicity

In colloidal chemistry, water surface has been believed to be slightly basic. Measurements of charging effects on air bubbles and oil droplet show that in most cases bubbles or droplets acquire a negative charge. Its origin remains unknown but is believed to stem from the accumulation of hydroxide ions at water surface or oil-water interface.<sup>51,52</sup> Recently, a negative value of zeta potential of air bubbles in water of -35 mV was measured.<sup>53</sup> Analogously, from zeta-potential and titration experiments on oil emulsions in water it is possible to extrapolate the water-oil interface hydroxide concentration of about 0.5 M.<sup>54</sup>

These results are in striking contradiction with computer simulations and non-linear spectroscopic techniques. Jungwirth *et al.* proposed a hybrid explanation for this phenomenon.<sup>55</sup> They postulate that the water surface is both acidic and basic. The surface is acidic, as shown by the computer simulations and non-linear spectroscopic techniques. The subsurface, situated just below the surface and only a few nanometres thick, is basic because of the electrostatic balance condition. This also explains why different experiments give varying results. If they probe the surface from the air, they would detect increased acidity, while those probing it from the bulk side would detect increased basicity. Further research is needed to give this theory additional merit.

# 5.3 Water at hydrophobic substrates

Hydrophobic surfaces generally repel water molecules. Due to unfavourable interactions between water and the hydrophobe (or *lack* of favourable interactions), one would expect a diminished concentration of water near such surfaces. Interestingly, sometimes the concentration is actually increased. In either case, many of the features believed to be the cause of properties of surfaces themselves may actually originate in the interfacial water layer instead.

Near small hydrophobic object, water molecules arrange in a clathrate-like geometry of the hydration shell surrounding the solute. Hydrogen bonding groups are oriented parallel to the solute surface. The water density close to the hydrophobic surface is increased relative to the bulk density.<sup>56,57</sup> For very large hydrophobic objects (the limit being a hydrophobic planar surface) the water density is reduced.<sup>58,59</sup>

Netz *et al.* researched the water layer depletion and water molecule orientation near the hydrophobic substrates and the effects of the curvature, temperature and pressure in detail.<sup>60</sup> In their MD simulations with 2,718 water molecules, they used SPC/E water model with typical Lennard-Jones and Coulomb interaction between water molecules in isothermal-isobaric (NPT) ensemble. Interactions between water molecules and the spherical hydrophobic objects were modelled with Buckingham potential

$$U(R) = k_b T A e^{-Br}.$$
(26)

Buckingham parameters were varied to give different radii of the hydrophobic particles (radius was defined as the value R at which  $U(R) = k_b T$ ). For the hydrophobic planar surface, a stack of 64 icosane (C<sub>20</sub>H<sub>42</sub>) molecules was used to build a hydrophobic wall. Interaction between water molecules and icosane molecules was purely Lennard-Jones. The parameters were chosen by the combination rule, giving the well depth as  $\epsilon_{sw} = (\epsilon_s \epsilon_w)^{0.5}$ . Temperature, pressure and curvature were varied.

#### 5.3.1 Spherical solutes

It was confirmed that the water density depends strongly upon the solute radius. For small spherical solutes with radius 4 Å, the density at the solute surface is increased. This is explained by the formation of a clathrate-like water molecule network. For a larger solute with radius 18 Å, there is a depletion layer near the surface. A spherical shell with thickness of approximately 2 Å is almost completely devoid of water molecules. For intermediate solute particles, the water distribution function is between both extrema. There is a thin depletion layer adjacent to the solute surface followed by a small increase in the density at the second shell.

#### 5.3.2 Planar hydrophobic wall

There was a noticeable depletion layer between the icosane slab and the water layer. At ambient temperatures, there was a depletion layer with thickness of 2–3 Å near the icosane slab. There is a slight difference between the thickness measured with respect to the reduced substrate potential and the thickness measured with respect to the substrate density profile. The former is of particular importance for it can be measured experimentally with neutron scattering or X-ray scattering experiments. They show to support the simulation results.<sup>61</sup>

#### 5.3.3 Temperature and pressure effects

Simulations were run with different temperatures (273, 300, 320, 340 and 360 K) and pressures (1, 500, 1000, 2000 bar). It was found that the temper-





Figure 10: Icosane slab and water.<sup>60</sup>

Figure 11: Depletion layer.<sup>60</sup>

ature importantly influences the depletion layer thickness. At high temperature, it increases substantially. At the temperature of 360 K, it is almost twice as large as at the temperature of 273 K. This effect might potentially be used in the experiments to distinguish the vacuum layer of depleted water from a layer of surface-adsorbed contaminants.

Surprisingly, depletion layer was found to be almost invariant to the pressure applied. Only at the pressure of 2000 bar, there was a noticeable decrease of the depletion layer. In total, the compressibility of the depletion layer was found to be only five times greater than that of the bulk water. This can be rationalised as follows. Relevant free energy scale that is causing the depletion layer is about  $k_bT$ , being spent on a single water molecule with a volume of 0.003 nm<sup>3</sup>. The water depletion is to some degree driven by the entropic effects. Water is not fully oriented in the first interfacial level, but it might be if it were located closer to the substrate. The entropic pressure following thereof is  $p = k_bT/V \approx 1.3 \cdot 10^9 \text{ J/m}^3 = 1300 \text{ bar}$ . This explains why there is no noticeable compressibility of the depletion layer below 1000 bar.

#### 5.3.4 Water orientation

In bulk, orientation of water molecules is on average random. This does not mean that the orientation of a particular water molecule is uncorrelated with its neighbours (in fact, due to hydrogen bonding it strongly correlates), but rather that on average there is the same amount of molecules in every available orientation. Water in bulk is isotropic. Near hydrophobic surfaces, however, water molecules exhibit preferential orientation. Richmond *et al.* investigated this phenomenon.<sup>62</sup>

They used two order parameters as a measure of the extent of the water molecule orientation. First parameter  $S_1 = 0.5 \langle 3 \cos^2 \theta - 1 \rangle$  describes the degree of the tilt angle  $\theta$  between the water *c*-axes and the interface normal *z*. It is bound within the range  $-0.5 < S_1 < 1$ . The second parameter  $S_2 = \langle \sin \theta \cos 2\psi \rangle / \langle \sin \theta \rangle$  measures the degree to which the molecules are twisted by  $\psi$  about their *c*-axes. It is bound within the range  $-1 < S_2 < 1$ . In isotropic environment (bulk water), both parameters are zero.



Figure 12: Order parameters useful for describing the extent to which water molecules are structured at hydrophobic-aqueous interface.<sup>62</sup>



Figure 13: Water molecules next to four hydrophobic phases: air (black), carbon tetrachloride (red), chloroform (blue), and dichloromethane (green).<sup>62</sup>

They ran the MD simulations with 2,135 POL3 water models to calculate these parameters near the air, carbon tetrachloride, chloroform and dichloromethane surfaces at the temperature of 300 K. They found that organic liquids with weaker dipole moments encourage a greater orientation of water molecules near the surface (figure 13). Also, it was found that the organic solvents with stronger dipole moments result in wider interfacial regions (depletion layer).

Viewed together, two dominant orientations of water molecules were observed. Those molecules "straddling the interface" the interface with one OH bond directed toward the bulk water phase and other toward the bulk hydrophobic phase; and those molecules with both OH bonds oriented in the plane of the interface.

### 5.4 Water at hydrophilic surface

Hydrophilic surfaces are characterised by their attraction for water molecules. Because they contain polar groups at the surface, they form strong favourable interactions with water, resulting in layer with increased water molecule concentration near such surfaces and non-uniform molecular orientation.



Figure 14: Schematic picture of the definition of (a) hydroxyl angle and (b) dipolar angle for a water molecule near the interface.<sup>63</sup>



Figure 15: Wetting coefficient k and depletion thickness  $d_1$  as a function of the surface density  $\xi$  of hydroxyl groups for tetragonal (O) and hexagonal ( $\diamond$ ) arrangements of the solid surface.<sup>63</sup>



Figure 16: (a) Probability distribution of the cosine of the angle between water OH bonds and the water surface normal. (b) Probability distribution for the dipole angle. All angles are defined with respect to the surface normal. Results are shown for three distances: in bulk (squares), at maximal oxygen site density (triangles), at separation with half the bulk density (circles).<sup>63</sup>



Figure 17: Schematic representation of typical configuration of interfacial water molecules. They can (a) act as electron acceptors, (b) donors, (c) form two hydrogen bonds on a hexagonal sruface, (d) form two hydrogen bonds on a tetragonal surface.<sup>63</sup>

Netz *et al.* performed extensive Monte Carlo simulations in isothermalisobaric ensemble, investigating water at hydrophilic surfaces.<sup>63</sup> They used empirical force field potential, characterised by SPC/E water with Lennard-Jones and Coulomb interactions. For interactions between unlike sites (such as those between water and hydrophilic surface), Lorentz-Berthelot combining rules were used ( $\sigma_{ij} = (\sigma_{ii} + \sigma_{jj})/2$  and  $\epsilon_{ij} = (\epsilon_{ii}\epsilon_{jj})^{1/2}$ ). Lennard-Jones interactions were truncated at 12.5 Å, while the Coulomb interactions were summated using Ewald method. Systems included 1,420 SPC/E molecules. Hydrophilic surface was modelled as self-assembled monolayers (SAMs) of hydrocarbons in fixed (hexagonal or tetragonal) lattice. To investigate the effects of increased hydrophilicity, an increasing proportion (1/2 or 2/2, and 1/3, 2/3 or 3/3, for hexagonal and tetrahedral lattice, respectively) of terminal methylene groups was substituted with OH groups (bond lengths:  $r_{CO} = 1.43$  Å,  $r_{OH} = 0.945$  Å). The angle between OH bonds and the surface normal was varied from  $\delta = 0 - 135^{\circ}$ .

For different configurations, depletion layer thickness, electrostatic potential due to preferential orientation of water molecules at the interface, and wetting coefficient were investigated. The latter is defined as the cosine of the contact angle:

$$k = \cos \theta = -\frac{\gamma_{sl} - \gamma_{sv}}{\gamma_{lv}}.$$
(27)

They were found to correlate strongly with the hydrophilicity of the interface. Additionally, not only the proportion of OH groups at the surface but also the lattice type played an important role.

When the rotation of OH groups at the surface was frozen to the value of  $\delta = 71.5^{\circ}$  (as to ensure the maximum hydrophilicity of the surface), wetting coefficient increased from -0.59 and -0.48 for non-polar surface (OH density of 0) to 3.8 and 6.9 for polar surface (OH density of 1) in tetragonal and hexagonal lattice, respectively. Additionally, depletion layer went from 2.08 and 1.96 Å to negative values of -0.85 and -0.47 Å. (see figure 15). This implies net adsorption of water molecules to polar hydrophilic surfaces. Water molecules exhibit preferential orientation only at hexagonal lattice, as this contribution to electrostatic potential was calculated to be -0.58 V. At tetragonal lattice, the potential is negligible (0.03 V). Water gets highly ordered (see figure 16) as more OH groups are present at the surface.

Water was found to bind to surface OH groups in two ways. It can acts as an electron pair acceptor or as a donor. Due to strong electrostatic interaction, oxygen atom of a water molecule and OH group approach to 2.6 Å, while the distance between methylene group and water molecule equals Lennard-Jones parameter of approximately 3.5 Å. The apparent size of these two surfaces differs by 40 %, heavily favouring the orientation of water molecules at first density maximum with one hydrogen pointing away from the surface (see figure 17a). The fraction of water molecules binding to the surface with both hydrogens is comparatively small (see figure 17b). Orientation with water molecule forming two hydrogen bonds with the surface OH groups (see figures 17c,d) is encountered when the fraction of OH groups at the surface is high (more than 2/3 or 1/2 for tetragonal or hexagonal lattice, respectively).

# 6 Conclusions

Water modelling is a very lively topic of research that has experienced a surge of interest by the recent advances in the available computer power. Throughout the twentieth century, many water models of varying complexity and approaches have been developed. The simplest ones model water as a fixed constellation of positive and negative charges with Lennard-Jones and Coulomb interactions, while the most complex one take into account polarisability and even quantum effects. Nevertheless, as demonstrated by a plethora of studies, simplified models can be as accurate as complex ones. Moreover, no single water model is adequate for simulating all water properties under all conditions.

There are two simulation approaches: Monte Carlo and molecular dynamics. Although they are founded upon completely different principles (random sampling versus Newton equations of motion), when used correctly they provide consistent picture of water behaviour. Many variations of each method have been developed, tailored specifically to the demands of a particular problem. When combined with *ab initio* quantum calculations, they provide valuable insights into the molecular structure of non-bulk water.

Research has shown that many phenomena previously attributed to specific properties of surfaces are in fact the consequence of the water behaviour near such surfaces. Preferential orientation of water molecules and formation of (positive or negative) depletion layer near such surfaces play a crucial role in those phenomena. Simulations confirm the intuitive picture of water molecules shying away from hydrophobic surfaces through the formation of a depletion layer and net adsorption to hydrophilic surfaces. Additionally, surfaces and interfaces introduce some degree of order to water orientation in their vicinity. More surprisingly, solvated ions are not universally found in bulk, but are in many instances preferentially bound to surface. Consequently, pH of water surface is believed not to be neutral, although there exists some incongruence between simulations and experimental data as to the acidity or basicity of the top water layer. Further research of this topic is warranted by the importance of surface and interfacial phenomena in water solutions. They are crucial in biological systems, atmospheric reactions, industrial applications and many other fields.

# References

- [1] Eisenberg, D.; Kauzmann, W. *The structure and properties of water*; Oxford University Press: Oxford, United Kingdom, 1969.
- [2] Tanford, C. The Hydrophobic Effect: Formation of Micelles and Biological Membranes; John Wiley & Sons Inc: New York, NY, 1980.
- [3] Jungwirth, P.; Tobias, D. J. Journal of Physical Chemistry B 2002, 106, 6361–6373.
- [4] Netz, R. R. Colloid & Interface Science **2004**, *9*, 192–197.
- [5] Born, M. Zeitschrift für Physik **1920**, 1, 45–48.
- [6] Jungwirth, P.; Tobias, D. J. Chemical Reviews 2006, 106, 1259–1281.
- [7] Gibbs, J. W. The Collected Work of J. W. Gibbs; Longsmans: Green: New York, NY, 1931.
- [8] Onsager, L.; Samaras, N. N. T. Journal of Chemical Physics 1934, 2, 528–536.
- [9] Kaasonen, K.; Sprik, M.; Parrinello, M.; Car, R. Journal of Chemical Physics 1993, 99, 9080.
- [10] Intermolecular Forces, 1st ed.; D. Reidel: Dordrecht, The Netherlands, 1981; pp 331–342.
- [11] Berendsen, H. J. C.; Grigera, J. R.; Straatsma, T. P. Journal of Chemical Physics 1987, 91.
- [12] Jorgensen, W. L. Journal of the American Chemical Society 1981, 103.
- [13] Jorgensen, W. L.; Chandrasekhar, J.; Madura, J. D. Journal of Chemical Physics 1983, 79.
- [14] Bernal, J. D.; Fowler, R. H. Journal of Chemical Physics 1933, 1.
- [15] Jorgensen, W. L.; Chandrasekhar, J.; D., M. J. Journal of Chemical Physics 1983, 79.

- [16] Jorgensen, W. L.; Madura, J. D. Molecular Physics 1985, 56.
- [17] Horn, H. W.; Swope, W. C.; Pitera, J. W.; Madura, J. D.; Dick, T. J.; Hura, G. L.; Head-Gordon, T. Journal of Chemical Physics 2004, 120.
- [18] Abascal, J. L. F.; Sanz, E.; Fernández, R. G.; Vega, C. Journal of Chemical Physics 2005, 122.
- [19] Abascal, J. L. F.; Vega, C. Journal of Chemical Physics 2005, 123.
- [20] Structure and Transport of Processes in Water and Aqueous Solutions, 1st ed.; Wiley-Interscience: New York, NY, 1972; pp 295–330.
- [21] Stillinger, F. H.; Rahman, A. Journal of Chemical Physics 1974, 60.
- [22] Mahoney, M. W.; Jorgensen, W. L. Journal of Chemical Physics 2000, 112.
- [23] Rick, S. W. Journal of Chemical Physics 2004, 120.
- [24] Nada, H.; van der Eerden, J. P. J. M. Journal of Chemical Physics 2006, 118.
- [25] Huš, M. Odvisnost potenciala med molekulama vode od lokalnega okolja. M.Sc. thesis, Univerza v Ljubljani, Fakulteta za kemijo in kemijsko tehnologijo, Slovenia, 2011.
- [26] Toukan, K.; Rahman, A. *Physical Review B* **1985**, *31*.
- [27] Lemberg, H. L.; Stillinger, F. H. Journal of Chemical Physics 1975, 62.
- [28] Matsuoka, O.; Clementi, E.; Yoshimine, M. Journal of Chemical Physics 1976, 64.
- [29] Levitt, M.; Hirshberg, M.; Sharon, R.; Laidig, K. E.; V., D. Journal of Physical Chemistry B 1997, 101.
- [30] Rick, S. W.; Stuart, S. J.; Berne, B. J. Journal of Chemical Physics 1994, 101.
- [31] Chialvo, A. A.; Cummings, P. T. Journal of Chemical Physics 1996, 105.
- [32] Chialvo, A. A.; Cummings, P. T. Fluid Phase Equilibria 1998, 150–151.
- [33] Paricaud, P.; Předota, M.; Chialvo, A. A. Journal of Chemical Physics 2005, 122.

- [34] Ben-Naïm, A. Water and Aqueous Solutions, Introduction to a Molecular Theory; Plenum Press: New York, NY, 1974.
- [35] Dias, C. L.; Ala-Nissila, T.; Grant, M.; Karttunen, M. Journal of Chemical Physics 2009, 131.
- [36] Frenkel, D.; Smit, B. Understanding Molecular Simulation: From Algorithms to Applications; Academic Press: Waltham, MA, 2001.
- [37] Ewald, P. Annalen der Physik **1921**, 369, 253–287.
- [38] Benjamin, I. Journal of Chemical Physics 1991, 95, 3698.
- [39] Wilson, M. A.; Pohorille, A. Journal of Chemical Physics 1991, 95, 6005.
- [40] Ghosal, S.; Shbeeb, A.; Hemminger, J. C. Geophysical Research Letters 2000, 27, 1879.
- [41] Finlayson-Pitts, B. J.; Hemminger, J. C. Journal of Physical Chemistry A 2000, 104, 11463.
- [42] Pearson, R. G. Journal of the American Chemical Society 1963, 85, 3533-3539.
- [43] Pearson, R. G. Journal of Chemical Education **1968**, 45, 581–586.
- [44] Pearson, R. G. Journal of Chemical Education **1968**, 45, 643–648.
- [45] Vácha, R.; Buch, V.; Milet, A.; Devlin, J.; Jungwirth, P. Physical Chemistry Chemical Physics 2007, 9, 4736–4747.
- [46] Gopalakrishnan, S.; Liu, D.; Allen, H. C.; Kuo, M.; Shultz, M. J. Chemical Reviews 2006, 106, 1155.
- [47] Tarbuck, T. L.; Ota, S. T.; Richmond, G. L. Journal of the American Chemical Society 2006, 128, 14519.
- [48] Mucha, M.; Frigato, T.; Levering, L. M.; Allen, H. C.; Tobias, D. J.; Dang, L. X.; Jungwirth, P. Journal of Physical Chemistry B 2005, 109, 7617.
- [49] Petersen, P. B.; Saykally, R. J. Annual Review of Physical Chemistry 2006, 57, 333.

- [50] Petersen, P. B.; Saykally, R. J. Journal of Physical Chemistry B 2005, 109, 7976.
- [51] Graciaa, A.; Creux, P.; Lachaise, J. *Electrokinetics of bubbles*; Dekker: New York, NY, 2002.
- [52] Graciaa, A.; Creux, P.; Lachaise, J. Surface Science Series 2002, 106, 825.
- [53] Takahashi, M. Journal of Physical Chemistry B 2005, 109, 21858.
- [54] von Klitzing, R.; Stubenrauch, C. Journal of Physics: Condensed Matter 2003, 15, R1197.
- [55] Vácha, R.; Buch, V.; Milet, A.; Devlin, J.; Jungwirth, P. Physical Chemistry Chemical Physics 2008, 10, 332–333.
- [56] Pratt, L. R.; Chandler, D. Journal of Chemical Physics 1977, 67, 3683.
- [57] Rapaport, D. C.; Scheraga, H. A. Journal of Physical Chemistry 1982, 86, 873.
- [58] Stilinger, F. H. Journal of Solution Chemistry 1973, 2, 141.
- [59] Lee, C. Y.; McCammon, J. A.; Rossky, P. J. Journal of Chemical Physics 1984, 80, 4448.
- [60] Mamatkulov, S. I.; Khabibullaev, P. K.; Netz, R. R. Langmuir 2004, 20, 4756–4763.
- [61] Schwendel, D.; Hayashi, T.; Dahint, R.; Pertsin, A. J.; Grunze, M.; Steitz, R.; Schreiber, F. Langmuir 2003, 19, 2284.
- [62] Hore, D. K.; Walker, D. S.; Richmond, G. L. Journal of the American Chemical Society 2008, 130, 1800–1801.
- [63] Janeček, J.; Netz, R. R. Langmuir **2007**, 23, 8417–8429.