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Is a sliding layer formed when gliding on ice or snow? A chronological overview - as time-specific knowledge.

Part II

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«God made the bulk; the surface was invented by the devil.»
 Wolfgang Ernst Pauli (1900-1958), Austrian-Swiss physicist [1]

Abstract

The fact that ice is slippery will have been experienced by the first people who stood and moved on it. Thousands of years ago, the Sami exploited this special property to be able to move with less energy. To understand the basic processes of friction, people like da Vinci, Euler, Amontons and Coulomb made important scientific contributions. These determined further advances in the surface structure of ice, snow, and water. The cause of icy slipperiness, entirely without pressure or friction, was first mentioned by Faraday in 1850 and explained in 1857 and as liquid water on the surface of ice. And Reynolds confirmed this slipperiness without pressure or friction in 1899. A surface layer on ice was described by Röntgen as a combination of two different molecular structures. With the technical development, a wide variety of new measuring methods were used to characterize the thickness, range, and properties of this special layer on the surface of ice - and referred to with a wide variety of terms. For every chemist it is trivial that the molecular structure of the surface of ice must be physically and chemically different from its interior: The molecules on the surfaces, faces, edges, corners, are bound only in three, two, or one spatial direction, as opposed to the interior with four bonds. A theoretical prerequisite was Pauling's finding that the molecule water, which is stable in itself, can combine with hydrogen bonds to form larger structures. All over the world, people have gone astray scientifically with various structures of water with the polywater, which in retrospect turned out to be an impurity. Thickness and properties of the slippery surface layer were determined with increasingly specific measuring methods, but also with most different measured values and their interpretations. Thus, many hypotheses have been published today. The most important findings to date concern the temperature limits, viscosity, density, and hydrophilicity of the water clusters on the surface. The sliding layer on ice or snow is a sliding on «water polymers» down to very low temperatures. The influence of a gliding surface with the surface of ice, snow or water is not the subject of this work.

Introduction

Water cannot be used as a good lubricant because it has a low coefficient of viscosity. But in combination with lipid layers, water has a small coefficient of friction in biology for joint lubrication [2,3]. In nano dimensions water also acts with its three-dimensional hydrogen-bond network as a lubricant for molecular machines [4]. Therefore, it is surprising that surfaces of ice with pure water have very small coefficients of friction [5]. Ice has properties to form macromolecular structures with self-assembly and self-healing [6]. If you use E-Indigo [7,8], a chemically completely new, very good glide-layer for skis or sleds, you also must deal with ice and snow on which this winter sports equipment glides. Used waxes made of paraffines, greases, resins, graphite (graphene), PFC, siloxanes, gallium, molybdenum, and other disulfides, as well as nanoparticles are adapted as sliding layers for different snow conditions as mixtures. The experience with such waxes is very large, but less so the optimal surface roughness. For our innovation E-Indigo (Isantin™) as a glide coating, only years of experience are available to optimally adapt the interaction of the surfaces of ice and snow. It therefore makes sense to chronologically retrace and process the experiments accessible today and their interpretations for friction-layer on ice, snow, and water, to make improvements based on chemical findings. Whenever appropriate and possible, the verbatim statements of the researchers are used in the individual sections.

Chronological overview

Years 1902 AC until today.

in liquid lubricated contacts the coefficient of friction is affected by, for example, friction velocity.

1902 AC

Richard Stribeck (1861-1950) [52] studied different frictions in lubricated sliding contacts, leading to the development and modelling of the «Stribeck Curve». It is a fundamental tribological concept that shows how

The extraordinarily important finding is that there is a minimum in the coefficient of friction.

The question is, what types of surface are responsible for friction on ice, snow and water?

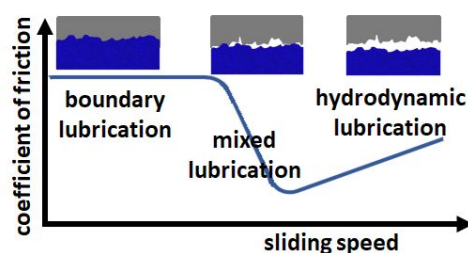


Figure 1: Stribeck-curve for different types of lubrications.

1903

Georg Thomas Beilby (1850-1924) [53] found a thin, amorphous layer on the surface of a polished material, typically about 15 nanometers thick. It is caused by a displacement of atoms (dislocation) during polishing, be it mechanical, chemical or ion

bombardment. In essence, this layer loses its normal atomic structure.

If polishing is replaced by friction on ice or snow, then that would be an explanation of how a thin, amorphous layer can form.



Figure 2: Beilby-layer of amorphous material on the surface.

1912

William Bate Hardy (1864-1933) [54] recognized the difference in the properties of individual molecules and molecules collectively as polymers (polymer ancient Greek: poly, many; meros, part): «Molecules diffusing out of the interfacial zone are changing to normal molecules, those diffusing in are becoming abnormal, just as at an interface between water and water vapour, vapour molecules entering the zone on the

average become polymerised to water molecules, while molecules leaving it to enter the vapour must on the average be in process of depolymerisation.» Thus, sliding on water is not comparable to sliding on fine grains (particles) but sliding on fine chains (polymers).

Thus it was anticipated with observations, without knowing the specific bonds, that water molecules can bond with each other.

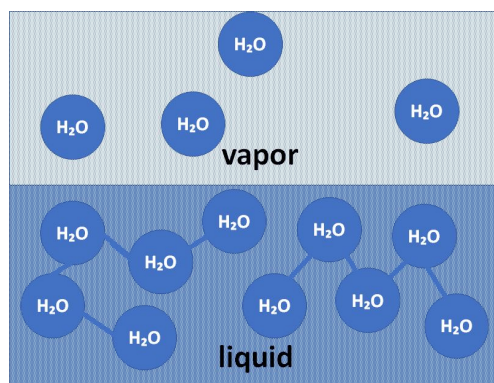


Figure 3: Water as individual molecules as vapor and collective polymer molecules as liquid or solid.

1918

John William Strutt 3rd Baron Rayleigh (1842-1919) [55]: «A cup of tea, standing in a dry saucer, is apt to slip about in an awkward manner, for which a remedy is found in the introduction of a few drops of water,

or tea, wetting the parts in contact. The explanation is not obvious, and I remember discussing the question with Kelvin many years ago, with but little progress.» This is a practical hint to water as a lubricant.



Figure 4: A cup of coffee standing on a dry saucer.

1928-1929

crystals and dry friction.

Ludwig Prandtl (1875-1953) [56,57] suggested in 1928 this model to describe the plastic deformations in

George Arthur Tomlinson (1886-1936) [58] generally agreed that friction is, in some way, a consequence

of the forces which molecules exert on one another when sufficiently close together. It is known that two molecules can exert a strong attraction on each other, and there is evidence of various kinds that the field of attraction probably extends to the distance of several times the molecular diameter, the force being a rapidly diminishing inverse function of the distance between the molecules.

In essence, the Prandtl-Tomlinson model is a further simplification of Coulomb's view of the «interlocking» of surfaces as the origin of friction. It describes many basic properties of dry friction as static and sliding friction. It is an important theory for tribology, but it made no statements specifically for ice and snow.

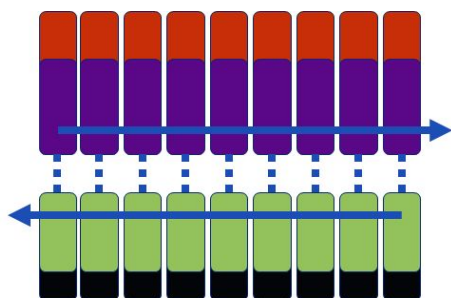


Figure 5: Friction is the consequence of the attraction of molecules lying on opposite surfaces.

1928-1960

Linus Pauling (1901-1994) [59,60,61] introduced the most important property of water molecules into the theory of chemical bonding, that they can bond with each other, with hydrogen bonding. Often hydrogen bonds are described as dipole-dipole attraction. However, the current model assumes some degree of electron sharing (between the outer, non-bonding electrons and the hydrogen; a three-center, two-electron bond). Hydrogen bonds some covalent character, they are about 20% longer than ordinary covalent bonds, and they are also about 20 times weaker. The importance affects almost all areas of our environment [62]: «It has been recognized that hydrogen bonds restrain protein molecules to their native configurations, and I believe that as the methods of structural chemistry are further applied to physiological problems it will be found that the significance of the hydrogen bond for physiology is greater than that of any other single structural feature.»

He formulated statements that are still valid today, for water:

1. In ice each oxygen atom has two hydrogen atoms attached to it at distances of about 0.95 Å., forming a water molecule, the H-O-H angle being about 105° as in the gas molecule.

2. Each water molecule is oriented so that its two hydrogen atoms are directed approximately toward two of the four oxygen atoms which surround it tetrahedrally, forming hydrogen bonds.

3. The orientations of adjacent water molecules are such that only one hydrogen atom lies approximately along each oxygen-oxygen axis.

4. Under ordinary conditions the interaction of non-adjacent molecules is not such as to appreciably stabilize any one of the many configurations satisfying the preceding conditions with reference to the others.

«In ice, for example, the distance between two hydrogen-bonded oxygen atoms is 2.78 Å, and the proton has been shown by neutron diffraction to be 1.00 Å from one oxygen atom and 1.76 Å from the other,» a well-established asymmetry. «The 20 water molecules can be placed at the corners of a pentagonal dodecahedron.»

Pauling has shown, that with the self-ionization of a small part of pure water H_2O dissociates very fast in an equilibrium reaction in H^+ and OH^- . The hydrogen nucleus, H^+ , immediately protonates another water

molecule to form hydronium, H_3O^+ . (half-life about 5.3 picoseconds). The reverse reaction is among the fastest chemical reactions known, with a reaction rate constant of $1.3 \times 10^{11} \text{ M}^{-1} \text{ s}^{-1}$ at room temperature

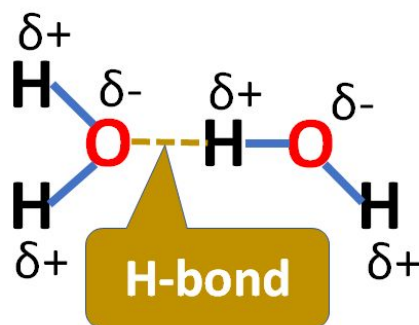


Figure 6: Two water molecules connected by a hydrogen bond - this bond is responsible for the special features of the substance water.

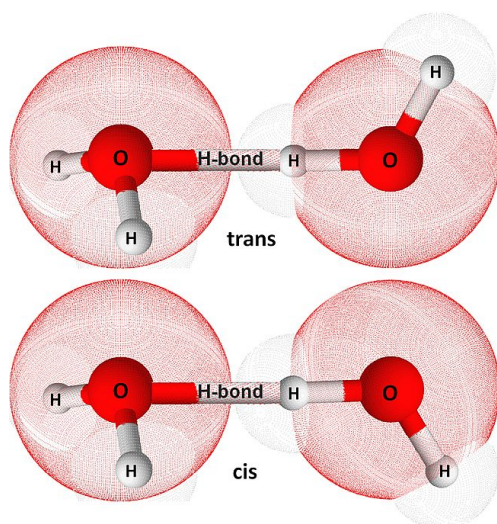


Figure 7: Trans configuration is 0.12 % stronger, than cis (left).

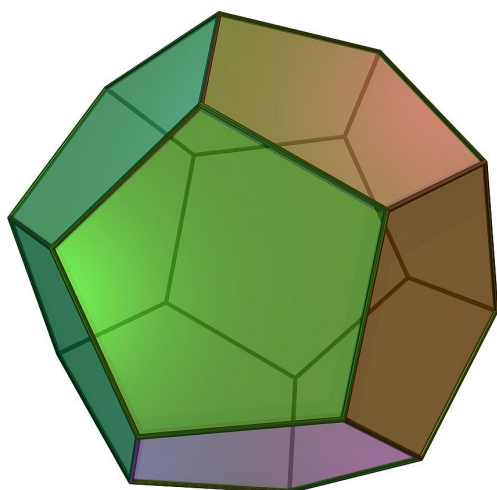


Figure 8: Proposed arrangement of water molecules in the corners of a pentagon dodecahedron to form a cluster with the edges as hydrogen bonds. (Figure: Wikipedia free)

1940

Dorsey Noah Ernest (1873-1959) explained regelation [63]: «The completeness with which two blocks of ice will freeze together increases with the pressure and its duration and de-

pends upon the relative orientations of the crystals of the two blocks. If the orientations are exactly the same in the two blocks, then they freeze together completely, the plane of union differing in no respect from any other parallel plane in either block. If the

principal axes are parallel, but the subordinate axes of the crystals in one block are not parallel to those of the crystals in the other, the blocks freeze together so completely that the plane of separation cannot be detected by polariscopic observations but can be by the production of Tyndall's flowers of ice, which show the difference in the orientations of the crystals in the two blocks. When tested by compression, the block yields first in that plane if the temperature of the room is over 0 °C, but the initial yield bears no relation to that plane if the temperature is below 0 °C. If the principal axes of the crys-

tals of one block are perpendicular to those of the other, the union may again be invisible, but its strength is less than in the preceding case.»

These statements were confirmed [64] : «The results indicate that a waterlike layer is present below the bulk freezing point. The layer thickness depends upon crystal orientation and decreases rapidly as the temperature is lowered; at -20 °C it is about 100 Å thick for the prism face, and no longer measurable for the basal face.»

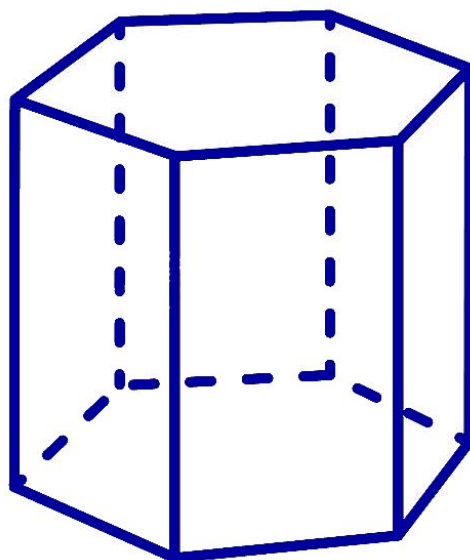


Figure 9: Ice forms hexagonal prisms, but under most condition snowflake crystals are flattened into fractal-like hexagonal structures, so for binding mutual orientation in all directions is important.

1935 - 1953

Frank Philip Bowden (1903-1968) [65] made important statements about liquid films on the surface, which significantly influence the friction of solids. «The older view that friction is caused by the mechanical interlocking of the irregularities on the surface has, to a large extent, been superseded by the view that the resistance to motion is due to inter-molecular forces at the points of contact.» With lubricated surfaces a transition from «fluid lubrication» to «boundary lubrication» is shown and in the latter state the kinetic friction (μ_k) is independent of the velocity and of the area of contact.

In 1939 he wrote [66]: «The results suggest, that, although pressure melting plays some part, the low

friction observed for rapidly moving solids on ice and snow is due in a large measure to the melting of a water layer by frictional heating. The experiments were carried out in an ice cave dug out of the ice above the Research Station at the Jungfrauoch, 3346 m. in Switzerland.» He formulated his observations for ice on ice as follows: «The addition of a small quantity of water to ice at 0 °C, for example, raised the friction from μ_k 0.024 to μ_k = 0.075. If, however, the water is melted by frictional heating we should expect the static friction to be very much higher than the kinetic friction. The results support the frictional heating mechanism. The results show that the friction of a hickory surface is reduced to about half its value by a layer of wax.» In 1953 he made the statement experiments with real ski [67]: «When the slid-

ing speed is appreciable the friction falls to a low value, and experiments support the view, put forward earlier, that this low friction is due to a lo-

calized surface melting produced by frictional heating.»

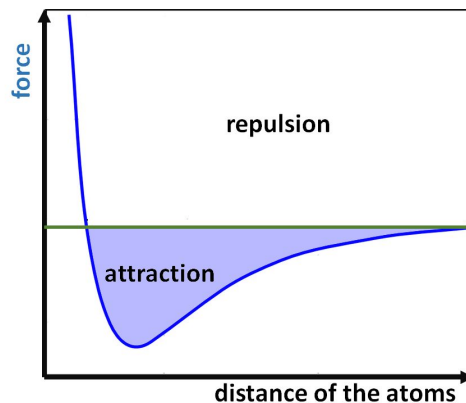


Figure 10: Graph of Lennard-Jones potential: interaction energy as a function of the atoms distance of the water molecules.



Figure 11: Postcard Jungfraujoch 3457 m where the experiments took place (11.10.1933). (Figure: from ETHHeritage, licence free)

1949-1951

Woldemar Anatol Weyl (1901-1975) [68] accepted Faraday's concept of a liquid film on the surface of ice and developed a model based on the differences between the molecular arrangement of water molecules in the bulk and on the surface. On the surface are hydrogens without hydrogen bonds and oxygens with one or two free lone pairs of electrons - both areas that can still form bonds. Inside ice, all the hydrogens are in hydrogen bonds and all the electron pairs of the oxygens are engaged in bonds. This enables to investigate how much pressure, frictional heating and the liquid-like film on the surface contribute to ice melting respectively under different temperatures.

1949 Chris Gurney [69], suggested that an intrinsic liquid film plays a role in the slipperiness of ice.

McConica [70] proposed 1948/50 an interesting theory of lubrication by an adsorbed transient layer of water «vapor», rather than a liquid film caused by friction or pressure.

It was found that the structures of the ice surface exhibit disorder at temperatures of about 30 °C below the melting point. This disorder extends into depth and increases rapidly with temperature. However, a residual disorder is maintained at least down to -1.8 °C. The magnitude of the disordered layer near 0 °C agrees with results of Weyl (see also review 1951 [71]).

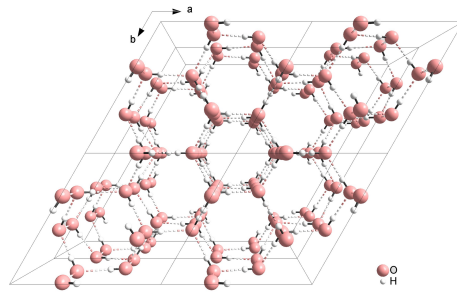


Figure 12: Crystal structure of ice Ih. (oxygen: red; hydrogen: white; dashed lines represent hydrogen bonds.) (Figure: Wikipedia CC BY-SA 3.0)

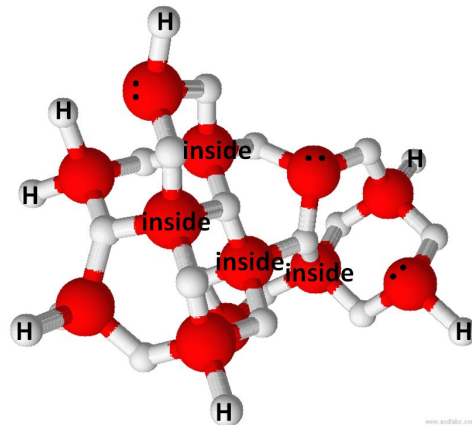


Figure 13: water molecules inside (bulk) and outside surface with free H and free electron pairs (:) Hydrogen-bonds.

1957

Hosler C.L. *et al.* [72] measured the force required to pull apart a pair of ice spheres in equilibrium and touching each other. The force increased as the temperature increased, an indication that warmer - though still subzero - temperatures form increasingly thick quasi liquid-like layers (QLL) on each sphere's surface.

At ice saturation, no aggregation

of ice crystals occurs at temperatures below -25°C and aggregation increases and becomes a maximum as 0°C is approached. At vapor pressures below ice saturation, no adhesion occurred below -4°C . The researchers inferred that the expected roughness of the surfaces was removed by the presence of a liquid film whose thickness was sufficient to provide a smooth surface of contact.

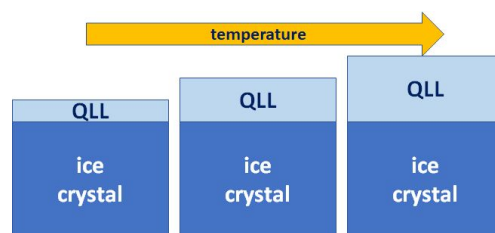


Figure 14: Increasing quasi liquid layer on the surface of ice with increasing temperature.

1961-1964

Jellinek H.H.G. [73,74] estimates of the thickness and viscosity of the water layers deduced from ice experiments at -4.5°C ranged from about 10^{-5} to 10^{-4} cm (10-100 nm) and viscosities from 70 to 700 poise

for ice/stainless steel and 15 to 150 poises for ice/quartz (compared with water: 0.0089 poise at 25°C ; stand oil (linseed): 50 poise, ketchup: 500-1000 poise) (viscosity: see Reynolds 1886).

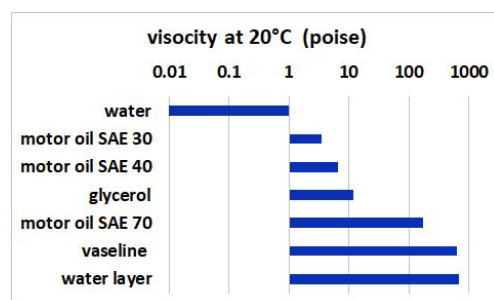


Figure 15: Viscosities for comparison with the outermost layer of ice.

1961

Henry A. Bent (1926-2015) formulated Bent's rule [75,76], which predicts the orbital hybridization of a central atom as a function of the electronegativity of the substituents bound to it. In a water molecule, smaller bond angles are formed between electronegative ligands (unusual: water 104.5° instead of the 109.5° tetrahedral angle) because the central atom to which the ligands are bound tends to direct hybrid bonding orbitals with larger p character toward its more electronegative

substituents. The hydrogens in water attract the bonding electron pairs, increasing the p character of these orbitals and thus reducing the angle in water from 109.5° to 104.5° (H-O-H). On the surface, water molecules are connected with only two bonds instead of four, which changes their physical-chemical properties. Bent's rule enables the dynamic, energetic, and structural changes of molecules to be assessed when they interact. (e.g., ice on the surface with air or with the surface molecules of a glider).

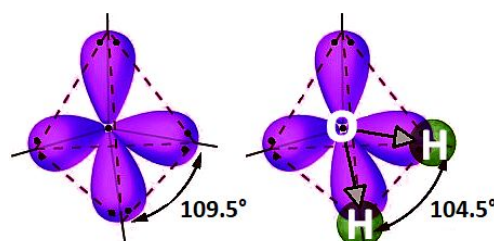


Figure 16: Water molecules do not form exactly tetrahedral structures. These deviations are especially important at surfaces.

1962

George Nemethy (1959-2018) and Harold Abraham Scheraga (1921-2020) [77] postulated an average cluster size of water molecules ranging from 91 to 25 H₂O molecules over

the positive temperature range from 0° to 70 °C, with the mole fraction of non-hydrogen-bonded molecules increasing from 0.24 to 0.39 over the same range of temperature.

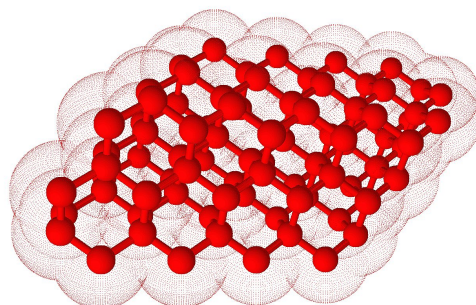


Figure 17: A cluster of 88 water molecules.

Henri Bader (1907-1998) [78] has shown, that the frozen fine structures (diameter approx. 30 μm) picked up by the falling snow crystal disappear very quickly. They do this partly by evaporation, because they have

a higher vapor pressure corresponding to their small radius of curvature, and partly by flowing into the quasi-fluid surface layer. The sharp tips of the branches become blunt. Material generally evaporates or creeps

at points with small radii of curvature: Therefore, where the branches are thin, they separate from the main body of the crystal and then become rounded. The larger spheres then grow exclusively by vapor transfer at the expense of the smaller ones, since no contact occurs. The internal structure of ice and snow is the same,

but different types of snow differ not only in structures but also in surface-to-volume ratio.

Many small contact areas of snow to a glider become larger and connected areas as the snow transforms.

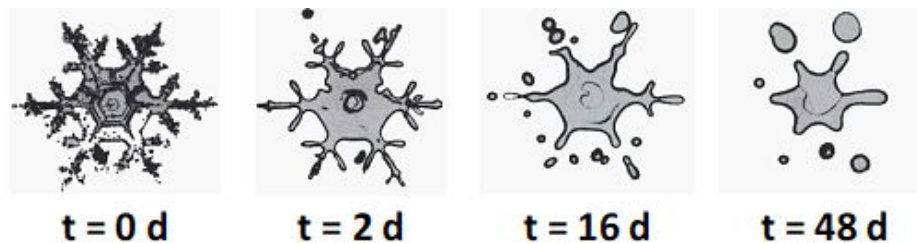


Figure 18: An extract from a series of photographs of a snow crystal over several days at a constant temperature of -2.5°C . It was placed on a microscope slide, surrounded by a vaseline ring, and covered with a thin cover glass that does not touch the crystal. (Figure: transformed and transferred from Bader.)

1962-1969

Fedyakin N.N. [79], Derjagin B.V. [80] and Donahue F.J. [81] observed a gel-like form of water in small capillary tubes. With the title: «Effects of Lyophile Surfaces on the Properties of Boundary Liquid Films» the direct experimental proofs of the ability of glass and quartz surfaces to change the physical properties of many polar liquids to a great depth are discussed. The term polywater (also called anomalous water or dense water) refers to the hypothesis that surface effects can form a polymer structure of water that has special physical properties. For example: The viscosity was comparable to syrup and higher by a factor of 15 than normal water (see Reynolds 1886). The thermal expansion was one and a half times that of normal water, it only solidified below -30°C , and the solidification did not occur at a freezing point but over a freezing interval down to -60°C . The modified water had a boiling range at a temperature of 150°C to 250°C and had a density of 1100 to 1400 kg/m^3 (ordinary

water has a density of 1000 kg/m^3). «Only the existence of natural (ambient) mechanisms which depolymerize the material would prove its safety. Until such mechanisms are known to exist, I regard the polymer as the most dangerous material on earth.» Lippincott *et al.* [82]: «Further, the mechanism of polymerization, still unknown, appears to be affected by the conditions of the «catalyst» surface.» And at the end followed a popular appraisal by Franks F. with the conclusion [83]: Polywater was just «dirty» water that had consumed millions of dollars for research [84]. But science made important progress with negative results here as well [85]. And previous work in capillaries has already shown some particular effects [86]: «The results of these experiments indicate that the freezing point of water in capillaries is independent of the volume or of the interface area, and that the radius of the capillary tubing is the only physical dimension that affects the freezing point of water contained in it.»

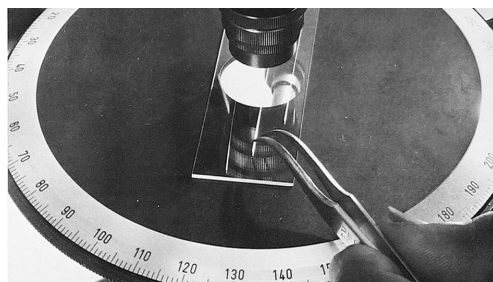


Figure 19: A sample of polywater being examined under a microscope at the National Bureau of Standards, 1969. (Figure: NIST Archives)

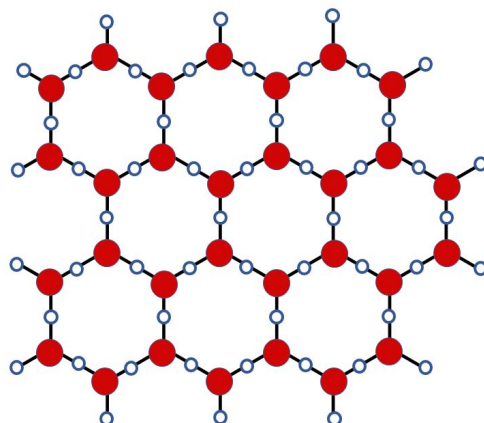


Figure 20: Model of polywater, a structure with a negative charge.

1962-1968

Fletcher N.H. [87,88] deduced from his experiments, that the preferred molecular orientation of water molecules on the surface of water is that with protons directed outwards from the liquid and the dipole layer so formed, modified by the presence of an equilibrium ionic atmosphere, leads to a calculated surface potential jump of about 0.1 V, the surface being positive with respect to the bulk liquid. This is contrary to the observation [89]: «Films of water on surfaces usually make the surface negative when rubbed.» Recent semi-quantitative arguments suggest [90]: «that the surface zone of ice

may have a disordered, quasi-liquid structure and a thickness of perhaps ten molecular layers at temperatures down to -10°C or so.» It is concluded that, at temperatures above about $-5 \pm 3^{\circ}\text{C}$ the surface of ice is covered by a quasi-liquid layer whose thickness is of order 1 to 4 nm, increasing as the temperature approaches 0°C . The experiment suggests that the proposed liquid layer persists to at least -11°C , which is below an estimate but within the range of uncertainty.

These experimental results are best explained by assuming a viscous Newtonian boundary layer on the ice [91].

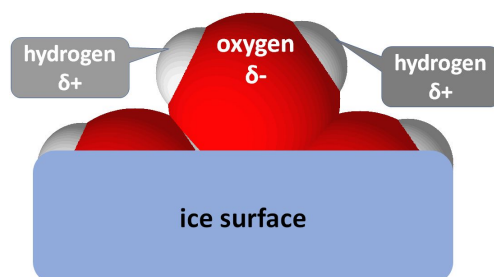


Figure 21: A water molecule on the surface has the hydrogens directed outwards and the oxygens directed inwards. Such a layer of water is about 0.2 nm thick.

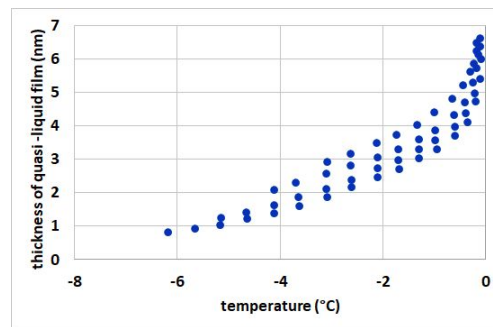


Figure 22: Number of «atomic layers» of water depending on temperature. (Data from Fletscher)

1963

«Using any reasonable definition of a scientist, we can say that 80 to 90 percent of all the scientists that have ever lived are alive now. Alternatively, any young scientist, starting now and looking back at the end of his career upon a normal life span, will find that 80 to 90 percent of all scientific work achieved by the end of the period will have taken place before his very eyes, and that only 10 to 20 percent will antedate his experience. [92] »

Derek John de Solla Price (1922-1983), British physicist, historian of science, and information scientist

1969

Orem M.W. and Adamson A.W. [93] found surprising evidence for a liquid-like layer (LLL) on the ice surface when they compared the physical adsorption of simple hydrocarbon vapors on ice to their adsorption on a water surface. Above -35 °C, the adsorption isotherm of n-hexane va-

por on the surface of ice follows that on the surface of liquid water, but not at temperatures below -35 °C. The entropy and adsorption enthalpy also follow the course of liquid water above -35 °C, but not below. They interpreted their results to mean that the beginning of the pre-melting of the ice surface is only above -35 °C.

The surface electrical conductivity of freshly cut ice surfaces was determined to be on the order of $10^{-10} \text{ Ohm}^{-1}$, which was interpreted as equivalent to a surface layer 1 to 4 nm in thickness [94].

In the first phase of condensation, a positive potential was observed. This was achieved by the H_2O molecules arranging themselves so that the protons are directed outward from the liquid surface during condensation [95]. In the later condensation phase, a negative potential was observed, generated by negatively electrified dislocations on the ice crystal surface. (see also Fletcher 1968) (see also a review 1974 [96]).



Figure 23: A thin liquid-like water layer on ice.

1976

Evans D.C.B. *et al.* [97] mentioned: «Low kinetic friction near the melting point in fact seems to be a general property of materials, as would be expected on the frictional melting theory.» Measurements show that kinetic friction on an ice surface has a coefficient of friction (μ) 10 to 100 times lower than most other ice-skating conditions (temperatures from -15 °C

to -1 °C and speeds from 0.2 ms^{-1} to 10 ms^{-1}) with conventional materials. μ is proportional to the temperature below the melting point and to $v^{-\frac{1}{2}}$.

They found strong evidence that water forms in the contact area. It was clear to them that there was mixed lubrication: the lubricant absorbs a large part of the load between the surfaces. But at elevated points, the surfaces touch or are only sep-

arated in a few places by a film a few molecules thick. These spots are the source of most frictional forces. When considering the friction of ice, the physical picture is further com-

plicated by the fact that ice makes its own lubricant. The coexistence of ice and water at the interface implies that it is at the melting point.

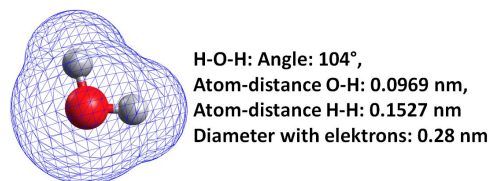


Figure 24: Dimensions of a water molecule in nanometers (oxygen: red; hydrogen: white; electron hull: blue).

1981

Ambach W. and Mayr B., [98] described a dielectric probe, in the form of a comb-shaped capacitor, that was built into the sliding surface of a ski. It was used to measure the thickness of the water film in the contact zone between the sliding surface of a ski

and the snow surface. This under the usual gliding conditions when skiing at temperatures from -6 °C to -11 °C. The water film determined in this way is several micrometers thick. It was also found that the gliding quality improves with increasing thickness of the water film.

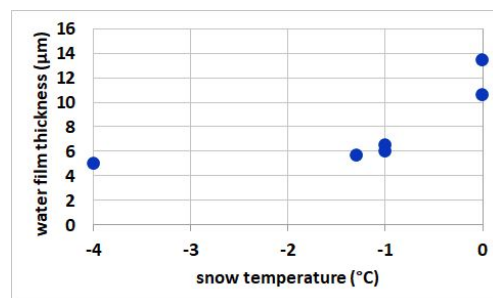


Figure 25: Water film thickness dependent on snow temperature obtained in several test runs at velocities up to 20 km/h. (Data from Ambach et al.)

1987

Akkök M. et al., [99] added to the suggestion with their experimental laboratory results and their regression analyzes that a thermal control mechanism could explain friction on ice under certain conditions. Initially, the temperature at the immediate surface of the contact reaches a characteristic friction temperature that cannot be exceeded as friction increases. The characteristic friction temperature assumed for ice is -1 °C, which is both an upper limit and a lower limit. Thus, the frictional contact can be modeled as a constant energy source, which determines the coefficient of friction over temperature. The thermal control model is related to adhesive friction and does not consider plow friction or surface roughness. Deviations from ideal conditions can be explained with surface contamination. The basis for the friction hypothesis is that simple calculations can be used to disprove the hypothesis that a water

film can be formed by the pressure of a skater at temperatures below -1 °C. The melting point of ice decreases by 1 °C (0.0075 °C/atm) at a pressure of 133 bar. A skater weighing about 70 kg sliding on skates with a blade length of 30 cm and a blade width of 0.5 mm exerts a pressure of approximately 23 atmospheres on the ice. The conclusion is that a pressure-related freezing point depression cannot be responsible for gliding over the ice on a thin layer of liquid water.

The depth and temperature of the liquid-like layer on pressure-melting solids could be estimated as a function of the total pressure [100].

The critical temperatures at which the quasi-liquid layer (QLL) was detected on the surface were -2 °C for the 0001 surface and -2 to -4 °C for the 1010 surface [101]. The structure of the interface changed from smooth to rough between the QLL and the ice crystal on the 1010 sur-

face at a temperature of $-2\text{ }^{\circ}\text{C}$. X-ray diffraction gives first clear evidence that the so-called «quasi-liquid layer» (QLL) is a liquid layer [102].



Figure 26: The pressure from ice skates is too low to melt ice below a temperature of $-0.2\text{ }^{\circ}\text{C}$. (Figure: Stephen Weiss, Wikipedia Public Domain)

1988-1992

Samuel C. Colbeck [103] made calculations that he used to explain the formation of a film of water on snow. At temperatures below freezing, a small area in the front part of the glider is dry and the friction is high. Once a water film is formed, its thickness increases up to an equilibrium value that is very sensitive to slider properties, speed, and temperature. Since the friction increases with the thickness of the water film below $0.4\text{ }\mu\text{m}$, the friction on the rear part of a glider is strongly temperature dependent. It has been proven that there are differences between the friction of the slider at temperatures from $0\text{ }^{\circ}\text{C}$ to $-40\text{ }^{\circ}\text{C}$, namely that the total friction at $-10\text{ }^{\circ}\text{C}$ is around 30 % greater and at $-40\text{ }^{\circ}\text{C}$ by 150 % (minimum at $-7\text{ }^{\circ}\text{C}$ [104]). The calculations suggest that the frictional force on the slider, front to back, varies little over an intermediate range of water film thicknesses of about 0.2 to $1.2\text{ }\mu\text{m}$. The obvious explanation for the increase in friction with large layer thicknesses

is the capillary effect between the ice grains and the glider. It is therefore particularly important to understand the nature of the capillary attraction between gliders and non-load-bearing snow grains since this friction component can only occur in snow. In addition, observations show that friction mechanisms for hydrophobic and hydrophilic gliders can be very different. In 1992 he showed [105] with experiments that “polished” snow grains appear to be melt-water caps formed on snow surfaces. They can be generated by rubbing a flat surface over them and indicate melting and refreezing (with exclusion of dissolved substances and dirt; see Faraday).

Water does not completely wet ice because its contact angle on ice near the triple point does not appear to be zero. Also, the highly faceted growth forms of ice from the vapor near the melting point indicate the absence of a thick, liquid surface transition region [106].

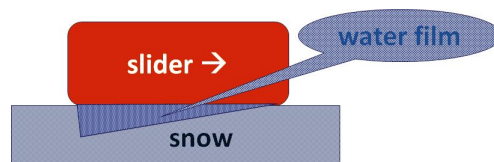


Figure 27: Under a glider, friction creates from front to back an increasingly thick film of water.

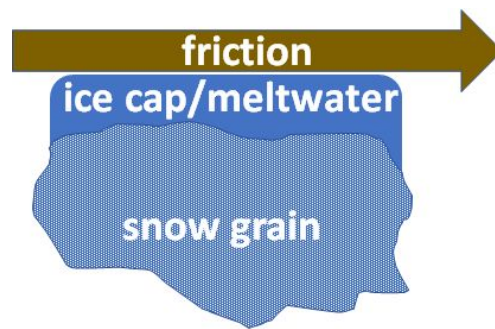


Figure 28: “Polished” snow grains show an ice cap of meltwater.

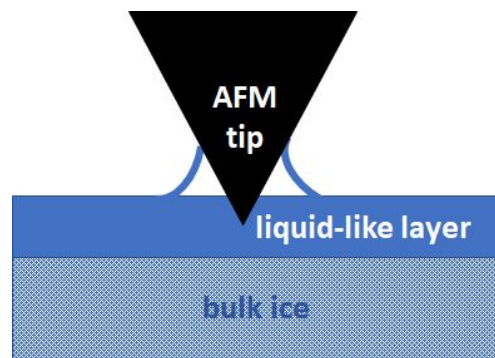


Figure 29: An AFM-tip in the liquid-like-layer (LLL) on ice.

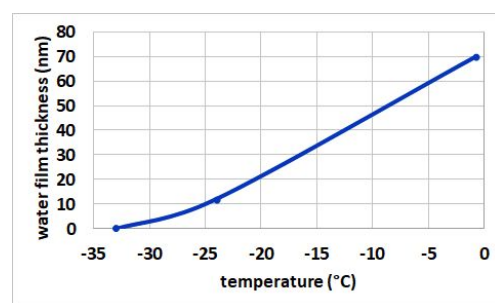


Figure 30: Thickness of the liquid-like layer on ice increasing with temperature. (Data from Döppenschmidt)

1998-2018

Döppenschmidt A. *et al.* [107] interpreted capillary forces on the liquid surface that prompted the atomic force microscopes (AFM) cantilever tip to jump into contact with the solid ice once it reached the much softer layer's level (silicon nitride cantilevers). The ice surface was examined in a temperature range from -24 °C to -0.7 °C. The tip penetrated the ice. The upper limit of the thickness of the liquid-like layer (LLL) on the ice varies between about 12 nm at -24 °C and 70 nm at -0.7 °C (confirmed by Strausky *et al.* [108], 2.7-5.5 nm at -0.036 °C resp. -0.022 °C [109]). In the force-distance measurements, the tip penetrated the ice, with the force decreasing approximately linearly with increasing temperature. Two interpretations are possible: either there is a «soft layer of ice» between the liquid-like layer

and the solid ice, or the pressing in of the solid tip causes the ice surface to change its mechanical properties. It could contribute as frictional heating to the lubricating fluid layer that reduces friction. In addition, the friction was measured on individual micro-contacts with a contact area of a few 100 nm² at -23 °C. Friction increased with decreasing velocity, likely due to the tip penetrating deeper into the ice at low velocity (see also [110]). Further results show that the surface begins to melt at around -33 °C (see also premelting [111]) (see also review 1999 [112]).

Other results also show that the disordered (quasi-liquid) layer on ice is structurally different from normal liquid water, beginning at -73 °C [113].

In a model [114], unique properties of ice near the surface result from

a reduction of an order parameter due to a certain boundary condition on the ice surface. Here, the layer thickness at -10 and -1 °C is equal to 0.8 and 3 nm, respectively. Observations near the critical temperature show that deviations from the ideal ice structure occur not only on the surface, but also in the whole mass of the ice crystal.

2002

«It is a myth that the success of science in our time is mainly due to the huge amounts of money that have been spent on big machines. What really makes science grow is new ideas, including false ideas [115]».

Karl Raimund Popper (1902-1994), Austrian-British philosopher

2003 - 2021

Pollack G.H. *et al.* [116,117,118] claims to have discovered a new phase of water on hydrophilic surfaces and/or narrow passages (see

also Henniker [119]: «The surface zone of a liquid is not merely a monomolecular layer with unaltered liquid immediately underneath it, but it is a region in which orientation extends effectively to many molecular lengths.»). Normal water is H_2O , but this new phase of water, the restricted-zone water, is H_3O_2^- , an ion with a negative charge and an unbound proton H^+ . This structured water should have a hexagonal crystalline structure between liquid water and crystal. Such a phase is called the exclusion zone or EZ because it excludes even small molecules (see Faraday 1850 exclusion). The hypothesis is that structured water is also found inside most of our cells and in extracellular tissues. It is also assumed that ice turns into structured water (EZ water) when it melts. This proposed new phase, structured water, is classified between liquid and solid (see also review [120]). It is important to note that EZ structures form only on hydrophilic surfaces.

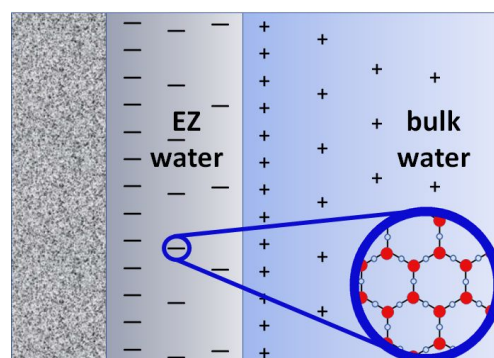


Figure 31: Hexagonal, EZ-water at the surface, structures analogous to those proposed for polywater.

2005-2008

Becker T. and Mugele F. [121] correlated that the viscosity of a lipophilic lubricant increases by a factor of 10 as the layer thickness decreases from 6 to 2 layers (with Octamethylcyclotetrasiloxane). Friction is broken down into two components, one the sliding of layers of liquid on the substrates and the other the sliding of liquid on liquid. Liquid on liquid is based on the known bulk viscosity while liquid on substrate is about 35 times higher for the present system (see Reynolds 1886). Conde M.M. *et al.* [122] calculated with simulations the thickness of the liquid layer with

0.8 nm for -3 °C and 0.65 nm for -7 °C and 0.55 nm for -33 °C.

In a survey 2007 it is concluded [123] that surface premelting of ice is responsible for the unique surface properties of the important substance (see also review 2005 [124], 2007 [125] and 2008 [126]).

A review 2007 concluded [127]: «The glancing X-ray scattering experiments revealed an onset temperature for premelting of -13.5 °C for the basal and -12.5 °C for the non-basal surfaces, with LLL thicknesses of 30 and 10 nm at -1 °C for the basal

and nonbasal surfaces, respectively.» And as a quintessence: «However, the nature of the LLL is far from being understood - there is not even agreement on its two most fundamental characteristics, namely the onset temperature for surface melting and the thickness of the LLL as a function of temperature.»

Computer simulations of the ice crystal surface show a free energy preference for a striped phase with alternating rows of free H and free O

atoms [128] (see also Fletcher 1992).

Libbrecht Kenneth [129]: «The surface is a very dynamical place, where molecules in the solid phase are being very rapidly exchanged with those from the surrounding vapour,» and since the typical tips of the dendrites of ice crystals have radii on the order of 1 μm , the «liquid» surface layer must be at least a factor of 10 thinner ($d < 100 \text{ nm}$). (see also Nakaya *et al.* 1938)

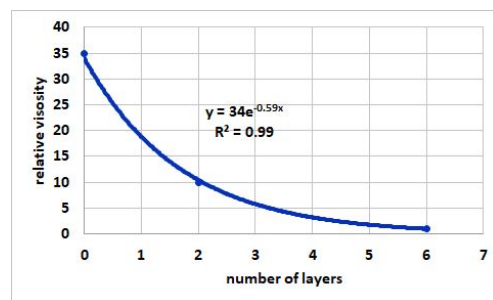


Figure 32: Decreasing viscosity with increasing number of molecularly thin lubricant layers. (Data from Becker)

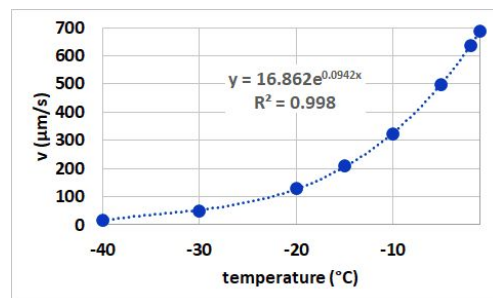


Figure 33: Ice-diffusion-limited growth (v : growth velocity normal to the surface). (Data from Libbrecht)

2010-2019

Sazaki G. *et al.* [130,131,132,133] have studied ice crystal surfaces and melting at temperatures below 0 °C and the formation of two quasi-liquid layers (QLLs). They directly visualized the appearance of round liquid-like droplets (α -QLLs) and thin liquid-like layers (β -QLLs) on ice surfaces by optical microscopy. Round, α -QLLs and β -QLLs on the ice surfaces could be visually distinguished depending on defective parts. This result indicates that QLLs occur at lower temperatures on lower quality ice crystals. In addition, a different formation mechanism of β -QLLs was found. The α -QLLs form in association with crystal dislocations, and β -QLLs form on crystal surfaces with many distributed microdefects. As a result, β -QLLs were observed to form spontaneously at interfaces on the sur-

face from multiple α -QLLs when their diameter becomes larger than tens of micrometers. A disordered layer on ice is visible in the temperature range from -90 °C. At a temperature of -16 °C a second layer starts to become disordered, and from -2 °C more complicated structures, LQ-drops and LQ-film, are formed on the ice surface [134]. It is shown that quasi-liquid layers (QLLs), when fully wetting ice, have a thickness of $9 \pm 3 \text{ nm}$ and characteristic wetting dynamics about 200 times lower than inside water, while QLLs, when partially wetting ice, have dynamics 20 times lower than inside [135]. Quasi-liquid layers (QLLs) are metastable transition states determined by vapor growth and sublimation of ice. They have more than two wetting states and there is a first order wetting transition between melting at undersaturation

and surface condensation at supersaturation at $T = -0.6\text{ }^{\circ}\text{C}$ [136]. (see also [137]).

Tusima Katsutoshi concludes from experiments [138]: The friction co-

efficient of ice is low even in low-speed range. The friction shows remarkable anisotropy on ice crystallographic plane and sliding orientation (see also review 2010 [139]).

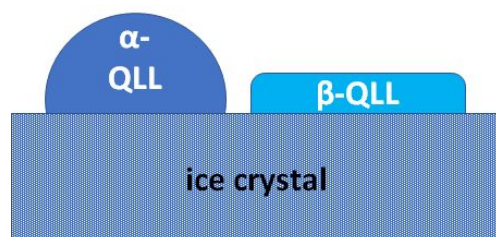


Figure 34: Two types of quasi-liquid layers (QLL) phases appear that exhibit different morphologies (droplets and thin layers).

2012 - 2020

Sun Ch. *et al.* [140,141,142,143,144], are basing on the fact the water molecules on the surface differ with their bonds from those inside water or ice. For both hydrogen bonding (O: H-O) is fundamental (see Pauling 1960). The oxygen (O:) binds with its two free pair of electrons (:) the hydrogen (H-) from the neighboring water (H-O-H). The (O: H) bond (hydrogen bond) is longer and weaker than the (H-O) bond (covalent bond) under normal conditions. With pressure the (O: H) distance shortens while the (O-H) and (O:) distances lengthen. The melting point decreases as the (H-O)-bond loses energy. When the pressure is released, the bonds return to their original states. The process is an example of hydrogen bond memory. This essentially takes place at the phase boundary between the liquid and the solid phase of the water. In fact, ice remains slippery even when standing still on it, with no frictional heating involved. And it remains slippery even at temperatures well below $-22\text{ }^{\circ}\text{C}$. These interpretations exclude the possibilities of skin pre-melting, pressure melting, liquid skin presenting, or even the friction heating for the slipperiness of ice. This is confirmed for ice at temperatures not far below $0\text{ }^{\circ}\text{C}$ by the low coefficient of about 0.05 for static friction, as well as the small difference to 0.04-0.02 for dynamic friction [145].

According to Bent's-rule [146] the reduced number of bonds of the water molecules on the surface causes the (H-O) bond to shorten from ≈ 1.0 to 0.84 \AA and the (O: H) bond to lengthen from ≈ 1.75 to 2.11 \AA , thereby decreasing the skin's bulk density from $0.92/1.0\text{ gcm}^{-3}$ to 0.75 gcm^{-3} (value 0.92 for ice; 1.0 for water). The change in polarization caused by the lone pairs of electrons leads to the formation of a common supersolid layer with greater elasticity and viscosity. This layer is characterized by the wave number of 3450 cm^{-1} , which can be measured with an infrared spectrometer, both on water and on ice. This change in polarization at the surface is not only responsible for the high elasticity, hydrophobicity, thermal stability and viscosity of the ice skin and water skin, but also as a super solid layer for the lubricity of ice.

Common for crystalline materials is premelting, a quasi-liquid film that can appear on the surface below the melting point. The above statements contradict the measurements on this premelting [147]: «The mean values are 1.20 g/cm^{-3} for the rough substrate and 1.19 g/cm^{-3} for the smooth substrate. The density of the quasi liquid is thus about 20% higher than in bulk water.»

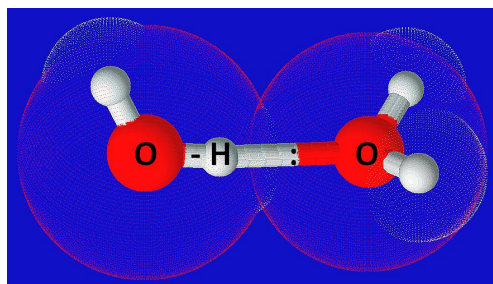


Figure 35: Two water molecules connected by a hydrogen bond (O-H : O). Length: O-H: 99 pm, bond strength of 492 kJ/mol; H : O: 117 pm, bond strength of 23 kJ/mol.

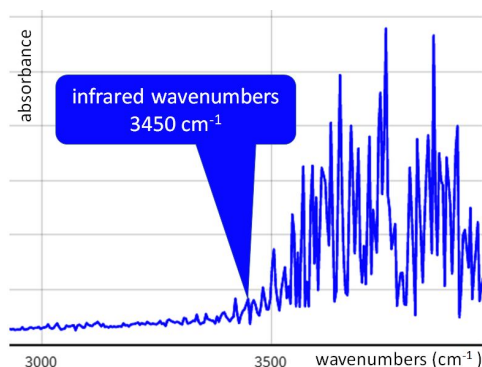


Figure 36: Infrared spectrum of water with the O:H vibration for the «supersolid» property. (Figure: Partial spectrum from NIST Chemistry Webbook)

2014

Bartels-Rausch, T. *et al.*; conclude [148]: Disordered interface (DI), a general interfacial phenomenon of crystals, is most controversially discussed in the context of ice and snow. A convincing correlation of DI thickness and temperature is even not possible for clean ice yet. This because the disordered interface perpendicular to the surface is not homogeneous, and furthermore, some studies suggest that its structure does not continue to form continuously into the liquid with increasing temperature.

While the disordered interface (DI) increases steadily with temperature, it remains confined to the outermost molecular layer of the ice down to about -10 °C. Only at higher temperatures does disorder spread into the ice layers, and in this process the

thickness of the disordered interface (DI) increases to about 0.5 nm. However, above -10 °C, simulations show larger fluctuations in the thickness of the of about 2 nm for periods of about 50 ns (see also self-dissociation Pauling 1960).

Experiments [149] in 2002 with high-pressure x-ray photoelectron spectroscopy give hints to the existence of a liquid-like layer at the ice surface at temperatures as low as -20 °C. Near 0 °C this film is about 2 nm thick, corresponding six bilayers.

A preliminary conclusion [150] in 2008 was that only down to about 10-20 °C below the melting point of ice could the film be interpreted as «liquid», with the thickness of this film being about one is nanometers (see also review 2014 [151]).

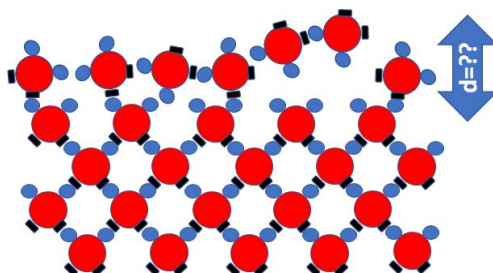


Figure 37: Disordered interface (DI) with unknown thickness and extension into the ice structure.

2015

Algara-Siller G. *et al.* [152] found mono-, di- and triple-layers of water with a square structure formed on hydrophobic surface of graphene. This is a phase with a symmetry that differs principally from the conventional tetrahedral geometry of hydrogen bonding. Square ice is allegedly formed even at room temperature. It is claimed that such structures can be expected on hydrophobic surfaces with nanoscale capillaries in contact with water. This is even though these square structures are non-planar and energetically unfavorable due to lat-

tice stresses. The surfaces would be formed by the oxygens, each with two free electron pairs, and would thus be determined by their negative dipoles. Tetragonal symmetry of ice was also found at high pressures above 5 GPa [153].

In general: All these discussions about structure of water and ice entails a subtle balance of energy expenditure: that of bond making and breaking (enthalpy) and that of disorder changes in the molecular components (entropy) (see also review 2016 [154,155]).

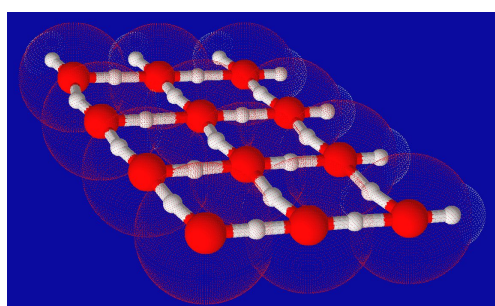


Figure 38: Square ice in graphene nanocapillaries (oxygen: red; hydrogen: white).

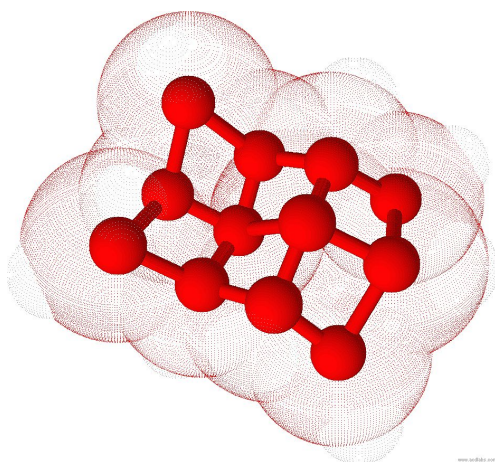


Figure 39: The molecular model shows that square ice is not planar. It binds to surfaces with lone pairs of electrons - with negative dipoles.

2017

Sánchez M.A. *et al.*, [157] studied surface melting of tetrahedral ice with hexagonal symmetry using surface-specific vibrational spectroscopy. A strong change in the vibrational response of the ice-air interface at a transition temperature 257 K (-16 °C) is interpreted as the melting of a quasi-liquid layer (QLL), here a double layer, of hexagonal ice at the surface - a sudden weakening of the hydrogen-bonded structure of the outermost water layers. Below this transition temperature, the first dou-

ble layer has already melted; the second bilayer melts at this transition temperature. The vibrations of the outermost water molecules show an increasing weakening of the hydrogen bonds between the water molecules and this with an increase in the water layer thickness. Water appears to be one of the few cases that show gradual melting at low temperature and divergent melting at higher temperature. The QLL appears to have stronger hydrogen bonds than normal liquid water. But: The molecules undergo rapid thermal motions on a time scale of picosec-

onds (10-12 seconds) [158,159,160], so the lifetime of a given cluster configuration will be exceptionally short. The surface of ice is like supercooled liquid water (higher viscosity, density approx. that of ice) [161].

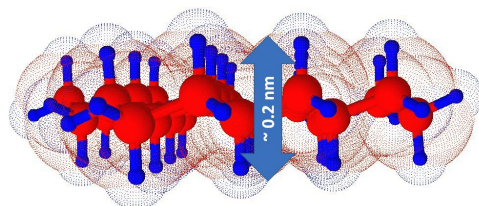


Figure 40: A layer of hexagonal water (front view).

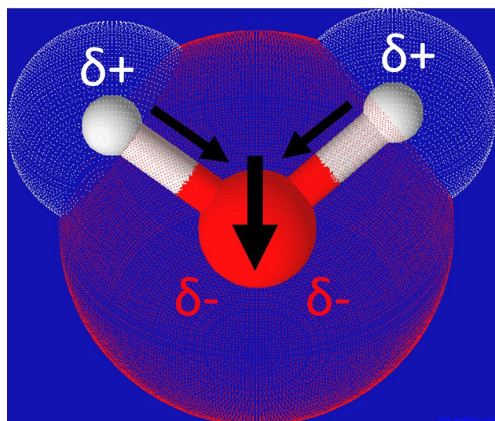


Figure 41: Water with its dipole due to differences in electronegativities with O-H group pointing towards hydrophilic surfaces (dipole moment gaseous: 1.85 Debye, liquid: 2.6 Debye [156]).

2017-2018

Constantin, J.G. *et al.* [163], reported measurements of the thickness of the ice-air QLL layer in the literature using different experimental techniques. «... we prove that the use of the Mini Environmental Chamber (mEC), which provides a better control of the temperature and humidity of gases in contact with the sample, changes qualitatively the results of the experiments.» «These results suggest a QLL thickness below 1 nm for the explored temperature range (-7 to -2 °C).» Conclusion [164]: «Skaters

slide across ice because they're riding atop a layer of rolling molecules — not because the skates melt the ice as they go, as was previously thought.»

«Dangling valences on the ideal prism faces seem to be oriented in a manner nearly perfect for small-molecule docking, a phenomenon that could have a profound effect on the environment [165] » (see also Fletcher *et al.* 1962-1968, Sánchez *et al.* 2017, Pollack *et al.* 2003 - 2021)

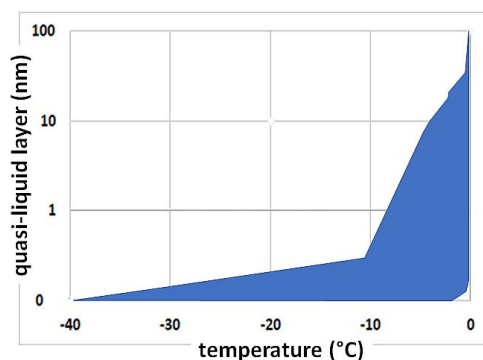


Figure 42: Range of measurements of the quasi-liquid layer with (X-Ray, ellipsometry and molecular-dynamics) [162]. (Data from Michalelides)

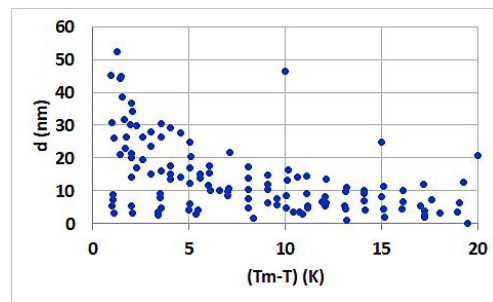


Figure 43: QLL thickness with atomic force microscope (AFM)-method with different experimental setups. (Data from Constantin)

2018 - 2021

Lever J.H. *et al.* [166,167,168], questioned that ice is an acceptable surrogate for studying the mechanics of snow friction, since snow consists of bound grains of ice. And, snow is porous and much weaker than solid ice, and other mechanisms may play a significant role. The long-accepted theory to explain snow gliding postulates self-lubrication: the frictional heat from gliding melts and thereby lubricates the snow grains in contact. Observations at microscale interfaces contradict this explanation. Rather, the touching grains showed polishing across a common plane, consistent with dry contact wear. It seems likely that good thermal contact from polishing leads to heat dissipation through a fine layer of wear bodies. With high-resolution (15 μm) infrared thermography, no melting on contact with snow grains could be observed despite low coefficients of friction ($\text{COF} = \mu$). These IR-measured contact temperatures were well below

0 °C under all test conditions for skis and sleds. In some cases, slip shear ruptured intergranular bonds and resulted in widespread snow movement with no permanent melt contacts ($\mu < 0.03$). When the snow granules were not moving and sustained contacts developed, the slider abraded the granules at low resistance ($\mu < 0.05$) rather than melting them. Optical microscopy showed that the abraded particles settled in air pockets between the grains, thereby transporting heat away from the interface - a process not included in current models. Overall, the results raise the question of whether self-lubrication is indeed the dominant mechanism underlying the low kinetic friction in snow. It is therefore possible for ice/snow debris particles to act as a dry lubricant to reduce sliding friction and prevent fully lubricating water films from forming, except for long-term, repeated sliding over the same ice substrate (see also [169]).

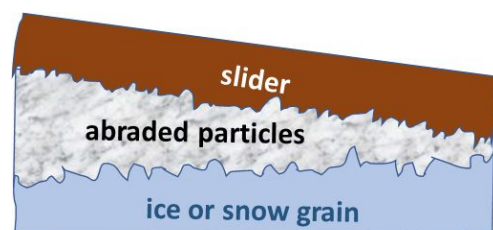


Figure 44: Hypothesis of friction due to dry abrasion. The direct contact due to the roughness of the slider causes wear particles that serve as a dry lubricant.

2019

Canale L. *et al.* [170], found in contrast with standard views, meltwater to exhibit a complex viscoelastic rheology, with a viscosity up to 2 orders of magnitude larger than pristine water (see Reynolds 1886). The unconventional rheology of meltwater provides a new, consistent, rationale for ice slipperiness. Hydrophobic coatings are furthermore shown to strongly reduce friction due to a sur-

prising change in the local viscosity, providing an unexpected explanation for waxing effects in winter sports. During sliding a very small increase in local temperature is observed. This agrees with recent measurements, reporting microscale infrared thermography and optical measurements of snow-grain contacts, which highlighted abrasion, rather than melting, of the interstitial contact region. This observation supports the hypothesis

that the liquid film is not composed of pure meltwater at 0 °C, as assumed by standard frictional-melting models. (The smallest droplet of water in which ice can form is only as big as 90 water molecules [171,172]). So, gliding on ice takes place on a

water-ice particle film. It is not an understatement that the fundamental mechanisms for the slipperiness of ice (and snow) remain a mystery (see also review [173]).

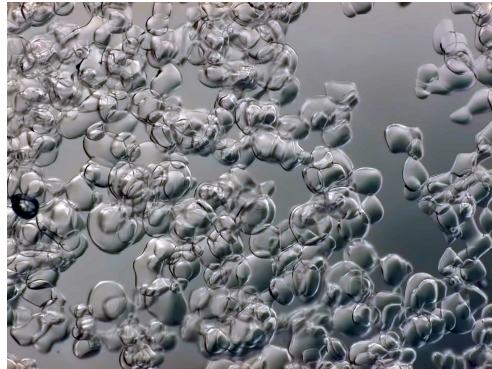


Figure 45: Microscopic picture of slurry ice with propylene glycol as depressant (average diameter 0.01mm). (Figure: Michael Froehlich, Wikipedia Public Domain)

2021

Liefferink R.W. *et al.*, [174] found, that at temperatures well below the melting point, friction is strongly temperature dependent and where an activation energy must be overcome - which we interpret as resulting from the thermally activated diffusive motion of surface ice molecules (see also [175]). Ice remains very slippery at very low velocities of only 1 $\mu\text{m/s}$ at -20 °C. The energy input into the interface is negligible at these sliding velocities, making the frictional heating insignificant. This motion is

hindered when the contact pressure is increased; in this case, the friction increases exponentially, and the slipperiness of the ice disappears. Close to the melting point, the ice surface is plastically deformed due to the pressure exerted by the slider, a process depending on the slider geometry and penetration hardness of the ice. The ice penetration hardness is shown to increase approximately linearly with decreasing temperature and sub linearly with indentation speed.

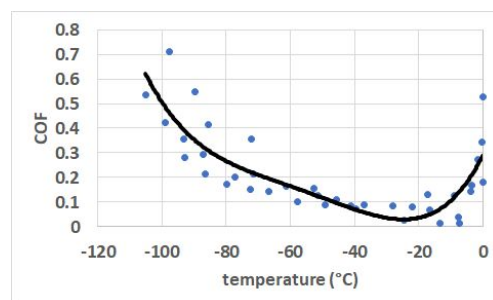


Figure 46: Coefficient of friction depending on temperature for SiC-surfaces. (Data from Liefferink)

2021

Chen L. and Qian L., [176] have suggested that, unlike the water body, the water layer on a hydrophobic surface is highly disordered and may behave as isolated clusters at high relative humidity values. Adhesion, friction, and nanoscale wear were found to be significantly correlated with the thickness and structure of the adsorbed water layer. In addition, it is assumed that capillary forces at

the nano-roughness contact make an equal contribution to the interface frictional force as the imposed normal force. The principal problem is that the very concept of «structure» (and of water «clusters») depends on both the time frame and volume under consideration.

The clusters form spontaneously and show a stable distribution, which is determined by the growth rate [177]. (see also review 2021

[178,179]).

The term hydrophobic comes from the Greek hydro meaning water and phóbos fear. So hydrophobic can be translated as «water-averse». Normally, synonyms for hydrophobic are used, such as water-repellent. By this we mean the property of a substance to have almost no affinity for water, i.e., not very soluble in it and hardly being wetted by water. But: Actually, there are no hydrophobic or water-repellent surfaces, because no

surface repels water. But the binding of water to a surface is much smaller than that of water molecules to each other. In a drop, water molecules minimize the energy and try to achieve a spherical shape. The deviation from the spherical shape, measured as the critical angle at the point of contact with the surface, is then a measure of the differences in the binding forces water-water and water-surface.

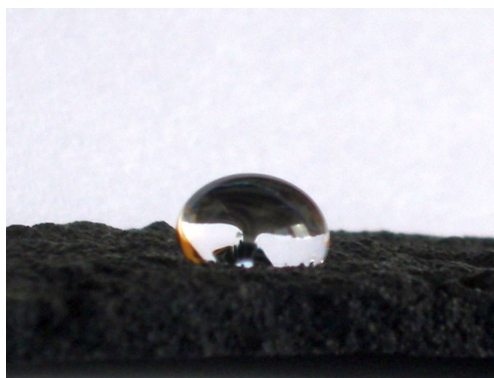


Figure 47: A drop of water on a surface of alkane bonded E-indigo.

«Those who cannot remember the past are condemned to repeat it. [180] »

Jorge (George) Santayana (1863-1952), Spanish philosopher

Conclusions

It was recognized early on that smooth, hydrophobic ski surfaces are particularly suitable for gliding on snow. Differences in gliding on dry, wet, soft, or hard snow were certainly perceived by the first skiers. Scientifically, the corresponding frictions were increasingly better studied and presented with theories. The clearly noticeable influence of roughness was also recognized early on. But it was soon discovered that ice and snow particles have special surface properties on which ice skates, sleds, and skis slide. Attempts were made to prove that a thin, slippery film can be produced by pressure or friction. Many sophisticated measurements have been used to determine the thickness such of special films as a function of temperature and friction. The specific viscosity differences of these films compared

to «normal» water were estimated to be unexpectedly large. But different measuring methods also provided different film thicknesses. These films, named as skin on ice, as liquid water, layer of vapor film, as plastic deformation of the ice crystals, as a quasi-liquid-layer (OLL), Newtonian shear layer, liquid-like-layer (LLL), double layer, supersolid skin, quasi-solid layer, water-ice particle film, highly disordered layer, nano-ice, premelting, surface disorder, disordered interface (DI) and exclusion zone (EZ), which is largely due to the different measurement methods and interpretations. Such developments are more and more often semantic peculiarities to make science unique. For every chemist, however, it is trivial as a common ground that water molecules on the surface of ice or snow have different bonding conditions than water molecules that build up the solid body with bonds in all 3 dimensions inside ice, snow or even water. The water molecules on surfaces still have electron pairs for further bonds and/or hydrogens for hydrogen bonds - therefore two ice cubes easily stick together. Similarly, the poor binding of ice to lipophilic

surfaces is chemically obvious. More recent, detailed analyzes of the binding of water molecules to surfaces are based on the hypothesis that a anisotropic thin skin is present, with higher values for viscosity, elasticity, hydrophobicity, and thermal stability - because ice is described slippery without pressure and friction since 1850. At present (2022) it is agreed that on the surface of ice, snow, and water there is a thin film, which has different properties compared to the usual liquid water. But there is no consensus about its composition, extent, and properties. A great many, very different structures are proposed for layers and clusters, including those that are only stable at very low temperatures of -120 °C to -44 °C. Structure oscillations in the nano [181] and microsecond [182] range are then measured at higher temperatures (self-dissociation of water with local charges). But these rather exotic, fast dynamics could also play a role in friction, provided they occur simultaneously in very many different places. Ice and snow have the intrinsic property to form macromolecular structures by self-organization and to close defective sliding surfaces with self-healing. Hydrophobicity would be better described as low hydrophilicity, as low binding

with water. This can be achieved in two ways, either by weak chemical bonding or physically by a small number of binding sites (see also bionics) [183,184].

Progress in sliding on ice, snow, or water is possible by chance, but systematic success can only be achieved based on the dynamics and molecular-chemical interactions of energies and structures of the two contacting surfaces. Thus, friction on the surface of ice is primarily determined by the molecular properties and structures in the micro- and nanometer range. And it is therefore inevitable that the surface that glides on it must also be adapted and optimized in this range. Secondly, the hierarchical structures of the glider must be optimized with the physicochemical properties of the surface. The now scientifically known properties, structures and dimensions allow an optimization of the sliding surface. We have accepted this challenge and are developing exclusively with experimentally and AI-estimated non-toxic and ecological substances forming macromolecular structures by self-assembly and processes in this area.

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