ESS 431 PRINCIPLES OF GLACIOLOGY
ESS 505 THE CRYOSPHERE

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THE PHYSICAL PROPERTIES OF ICE

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Check class web site:

http://courses.washington.edu/ess431/

For:

- Class-prep assignments
- Homework assignments
- Supplementary reading
- Lecture slides
- Exam information

Sources

Martin Chaplin
http://www.lsbu.ac.uk/water/

SnowCrystals.com, Kenneth G. Libbrecht, Caltech
http://www.its.caltech.edu/~atomic/snowcrystals/photos/photos.htm

Lecture notes from C.F. Raymond and S.G. Warren

Bulk Behavior from Micro-physics

(or Macroscopic Behavior from Microscopic Beahvior)

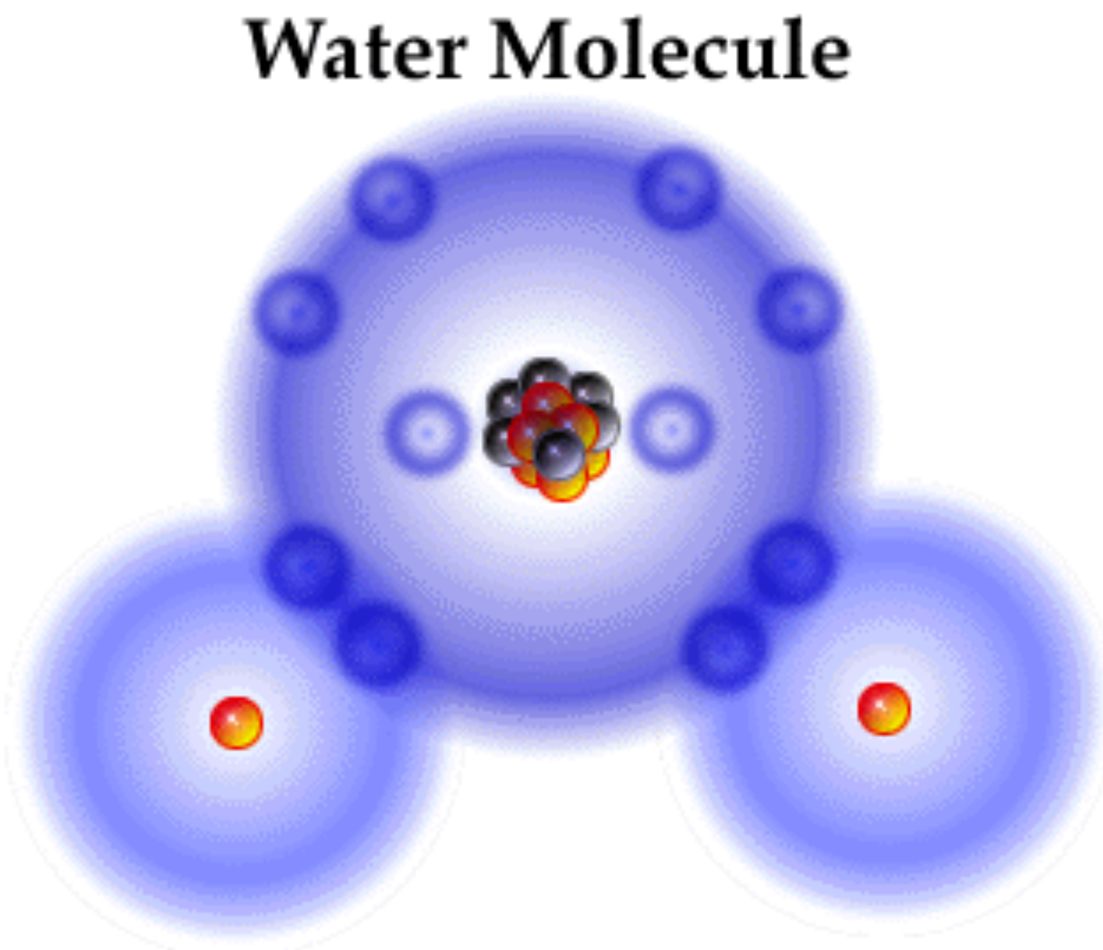
Theme for the Day (or the Quarter)

- We can understand how ice and water behave in the environment by understanding how H_2O behaves at the molecular level.
- It’s all about bonding

Questions for Today:

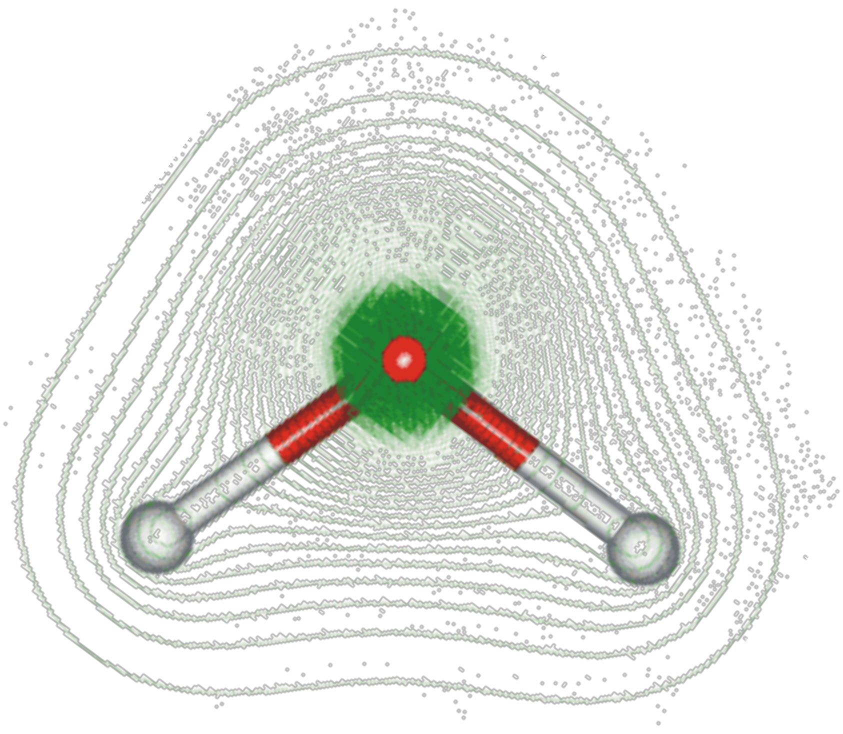
- What are the arrangements of atoms and molecules in water (Ih and Ic, liquid, vapor)?
- What physical processes are involved in the phase changes of water?
- What are the thermal properties (heat capacity, thermal conductivity, thermal volumetric properties) of water?
- What is equilibrium vapor pressure? What is its role in snow metamorphism?
- How are microscopic and macroscopic properties of ice related?

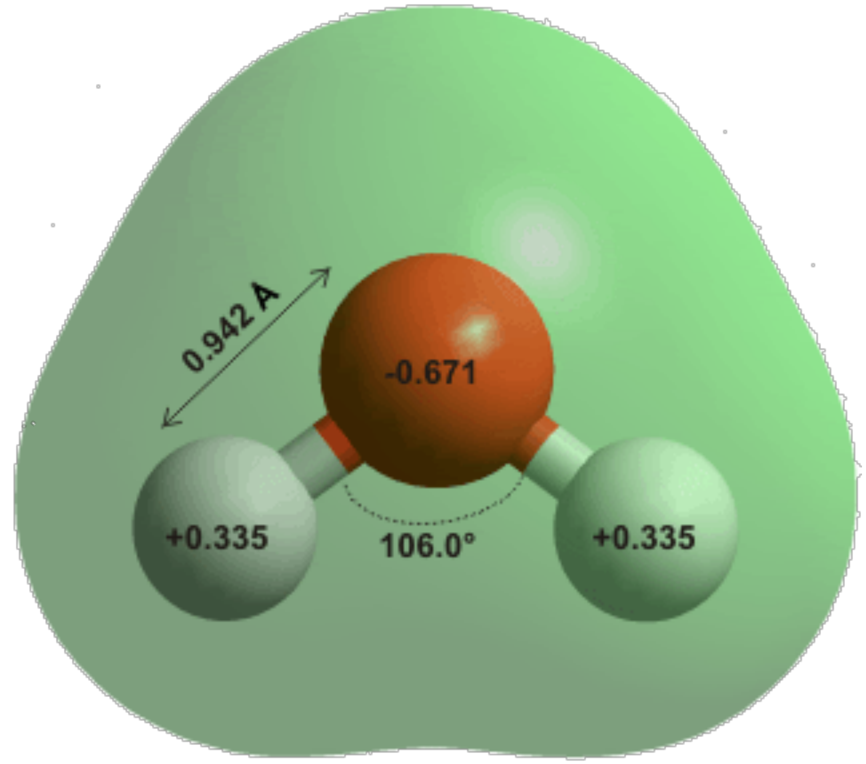
Tetrahedral Structure of H_2O Molecule



www.brooklyn.cuny.edu/bc/ahp/SDgraphics/PSgraphics/SD.PS.LG.Water.html

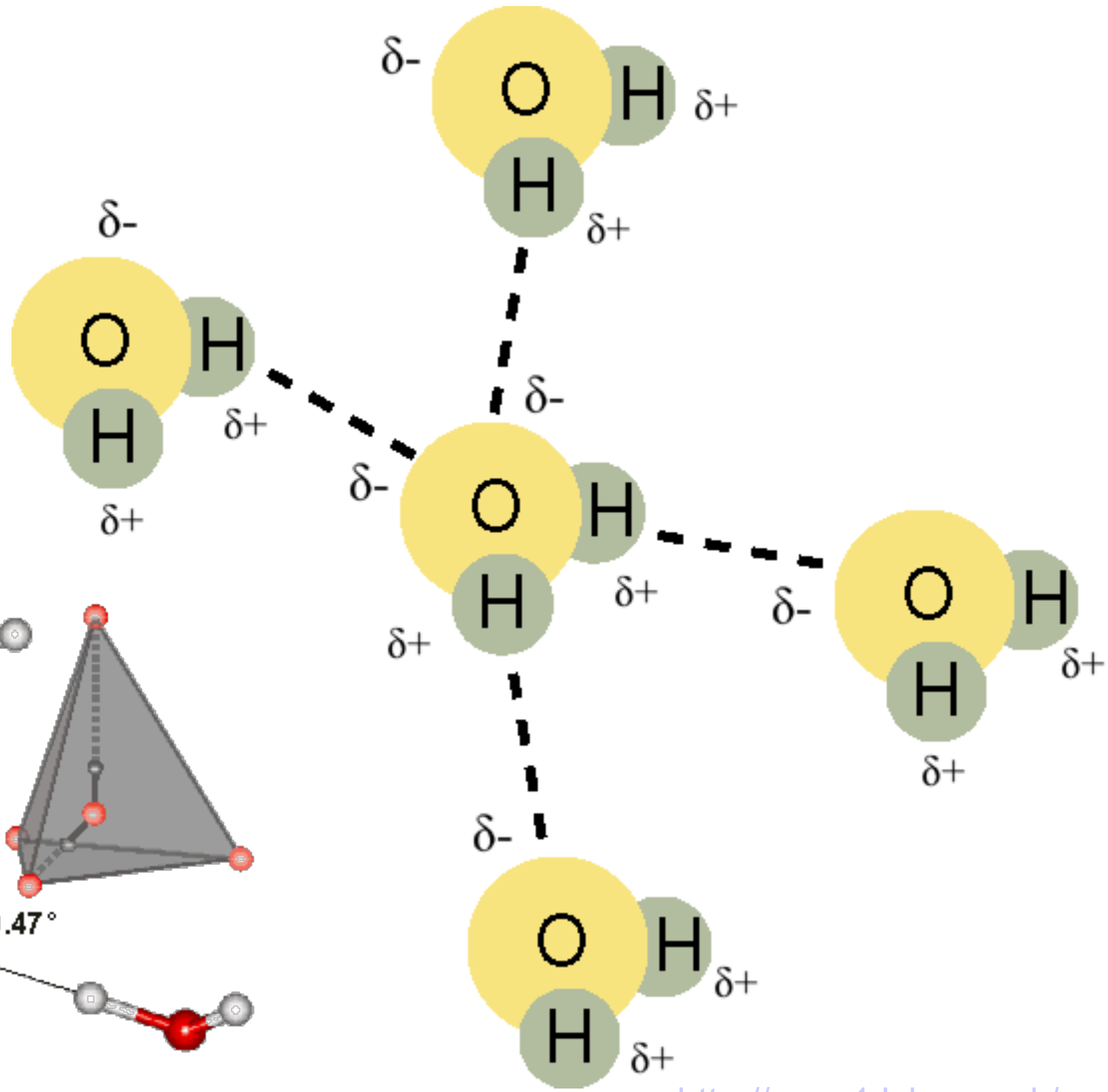
Tetrahedral Structure of H_2O Molecule

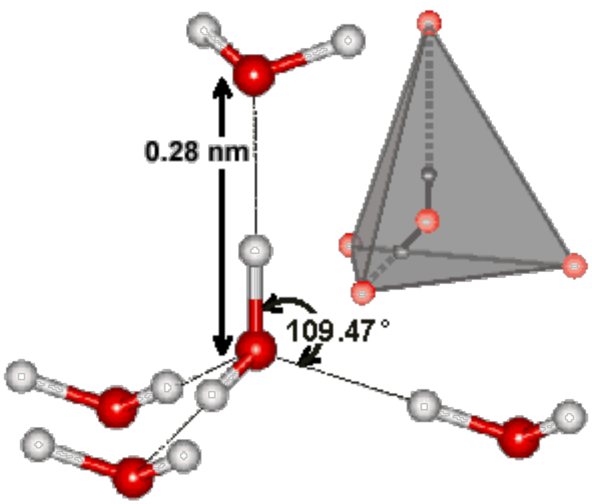




http://www1.lsbu.ac.uk/water/water_molecule.html

The Hydrogen Bond

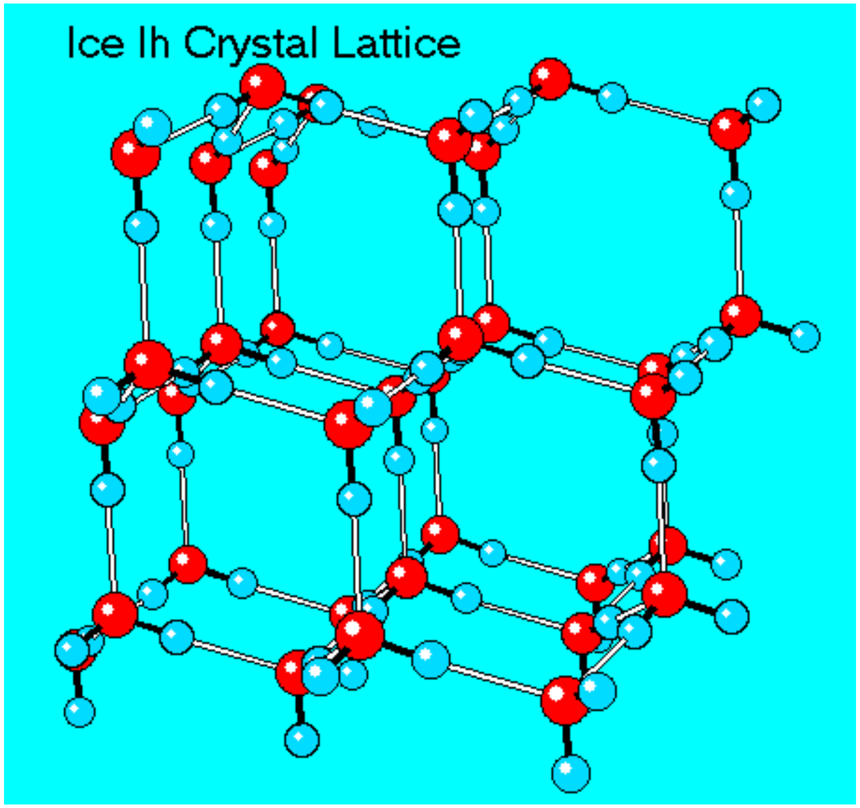


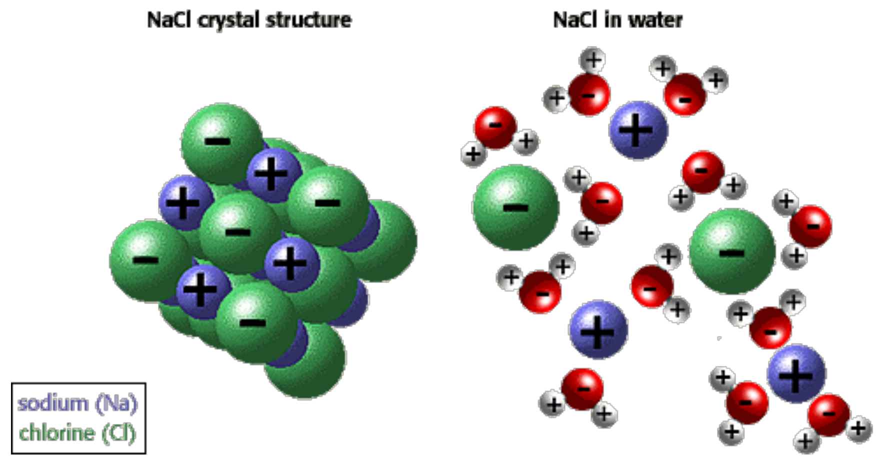


http://www1.lsbu.ac.uk/water/water_molecule.html

ed101.bu.edu/StudentDoc/Archives/spring04/srb2007/Site

Ice Lattice





There is lots of empty space in the ice lattice.

http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm

Where's the Hydrogen in Ice?

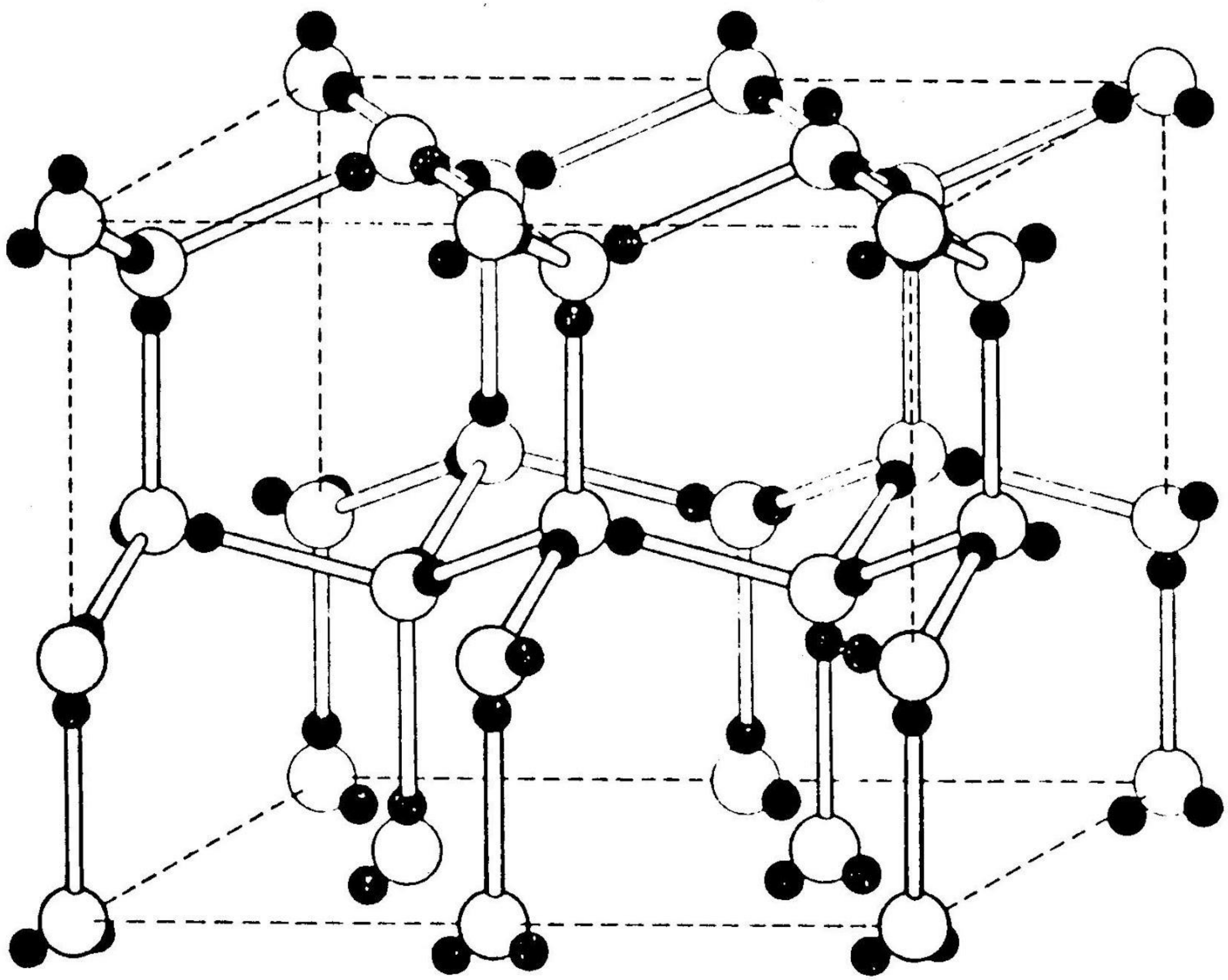


Fig. 2.3. A typical disordered arrangement of protons in the ice structure. Each oxygen has two close protons, forming an H_2O molecule, and there is one proton on each bond.

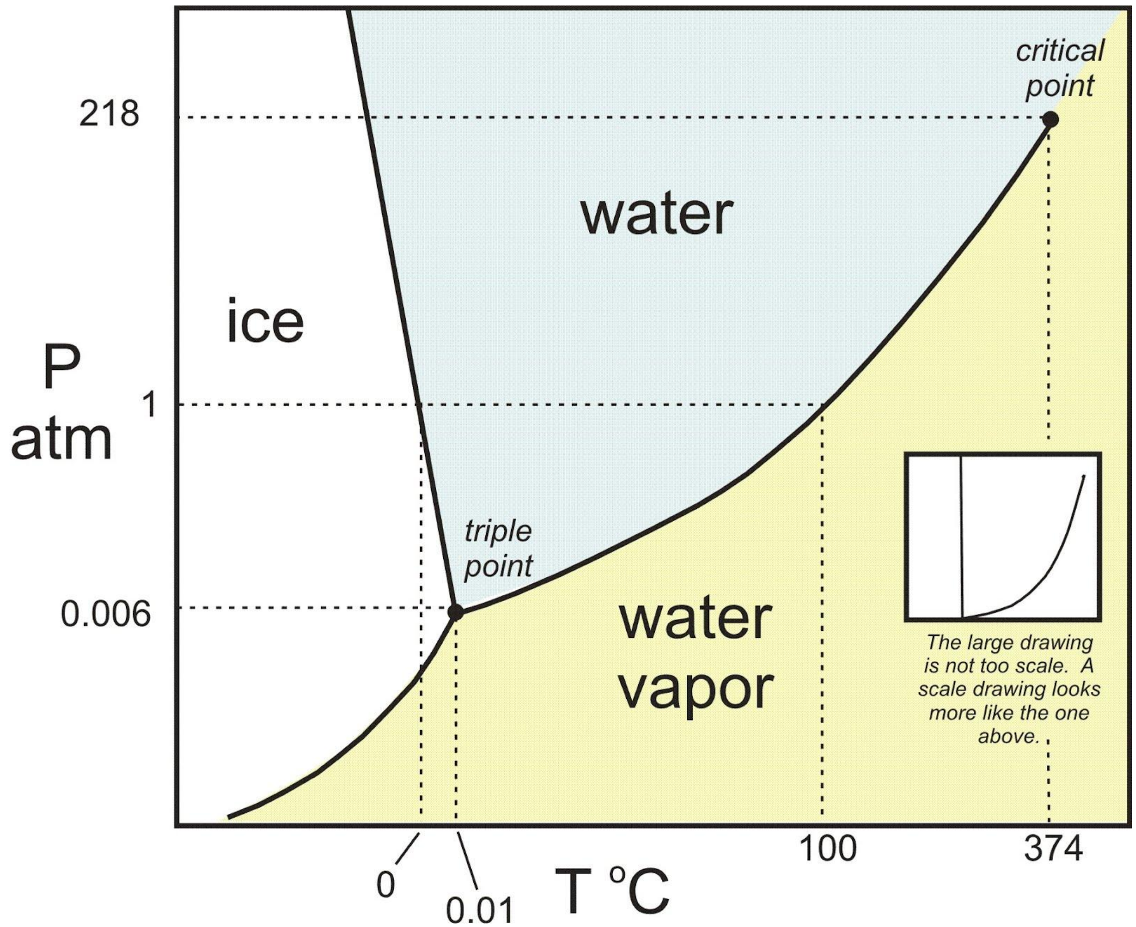
Impact of Proton Disorder

- Defects (2 or 0 protons on an H-bond) can move through the lattice.

- If there is an applied voltage, the motion is not random, i.e. becomes an electric current of positive charges

- Even at absolute zero, ice still has some entropy

The Phase Diagram of H_2O



At the triple point: P = 0.006 atm, T = 0.01 °C

The ice/water coexistence curve slopes backward -- why?

Why does H_2O change phase?

Types of natural interfaces:

- liquid-vapor
- solid-liquid
- solid-vapor

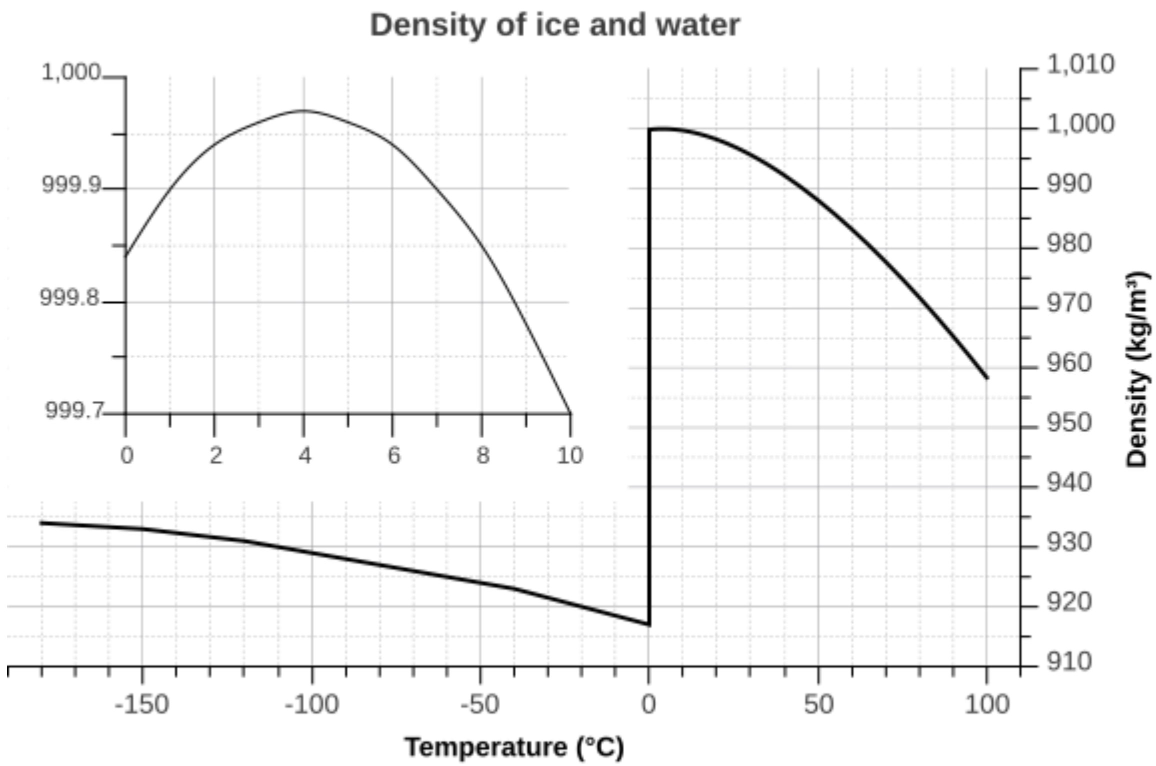
- Due to statistical fluctuations in energy among molecules, there are always some molecules crossing a natural interface.
- Under equilibrium conditions on boundaries of phase diagram, equal numbers go both ways. Two phases can coexist indefinitely (equilibrium).
- In interiors of phase-diagram regions, conditions favor more molecules going one way than the other. One phase will disappear over time (disequilibrium).

Hydrogen Bonds and Phase Changes

- It takes energy to break bonds (like springs)
- To convert ice into liquid, we need to break ~15% of the hydrogen bonds
- To convert liquid water to vapor, we need to break the remaining 85% of the H-bonds

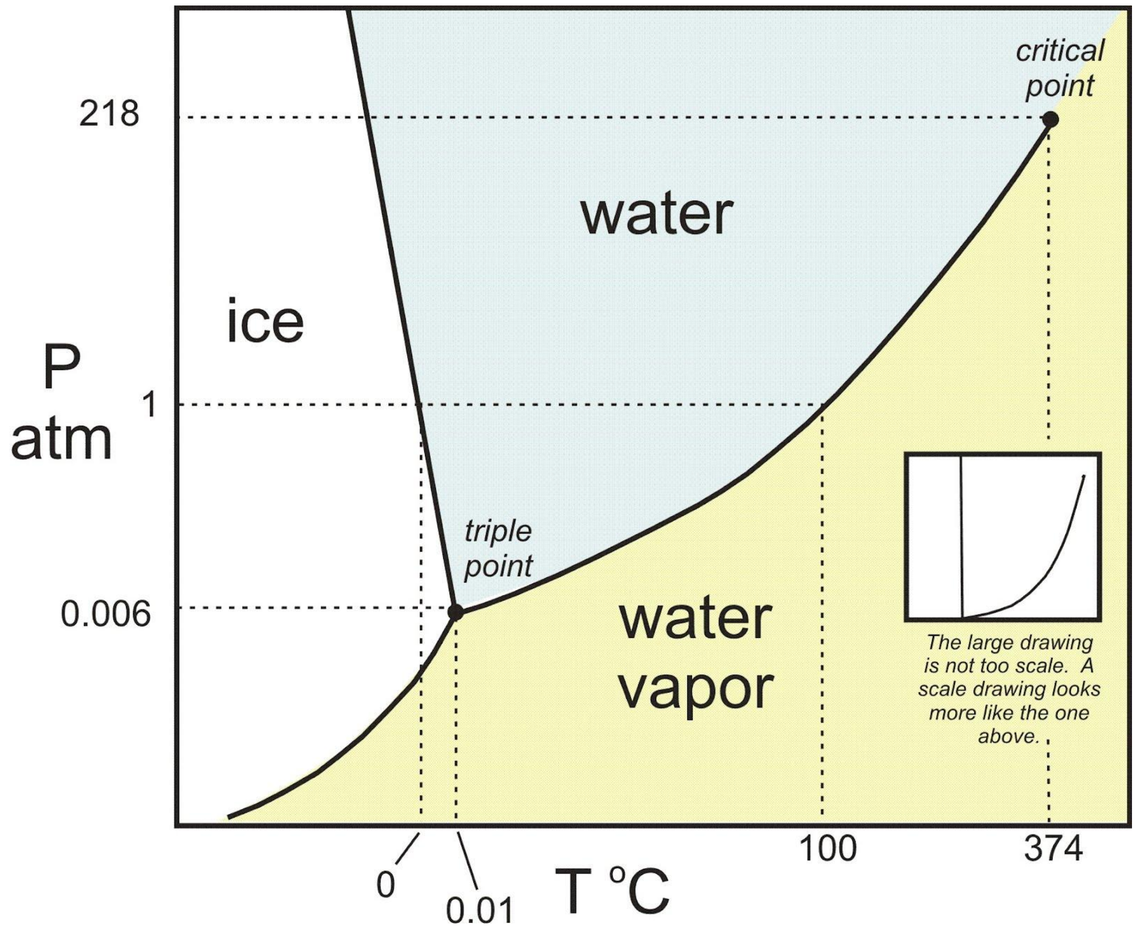
- Heat of fusion (melting) 334 kJ kg^{-1}
- Heat of vaporization (boiling) 2255 kJ kg^{-1}

Density of Water



- Why is water more dense than ice?
- Why is the maximum density at 4°C?

The Phase Diagram of H_2O



At the triple point: P = 0.006 atm, T = 0.01 ^{o}C

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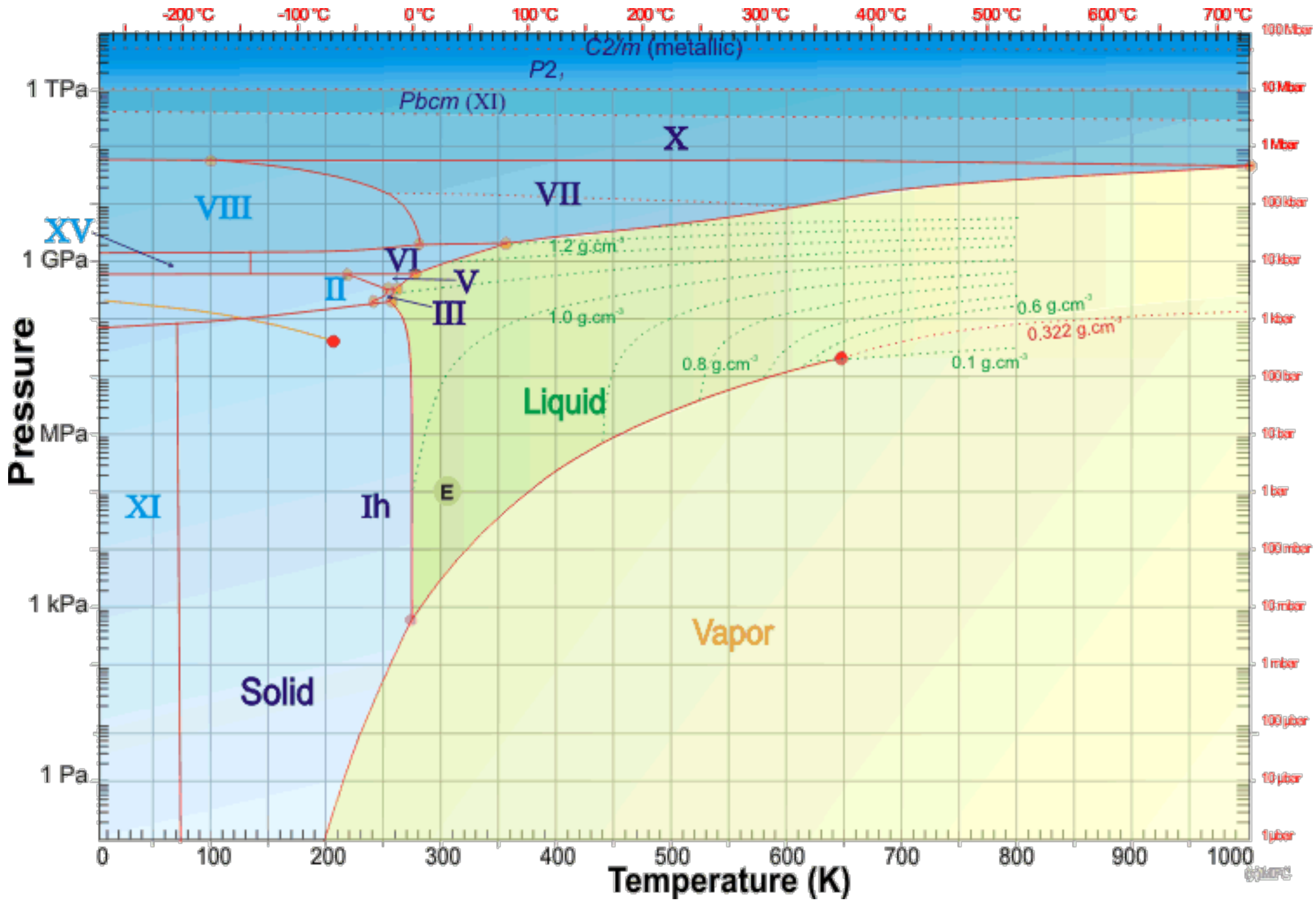
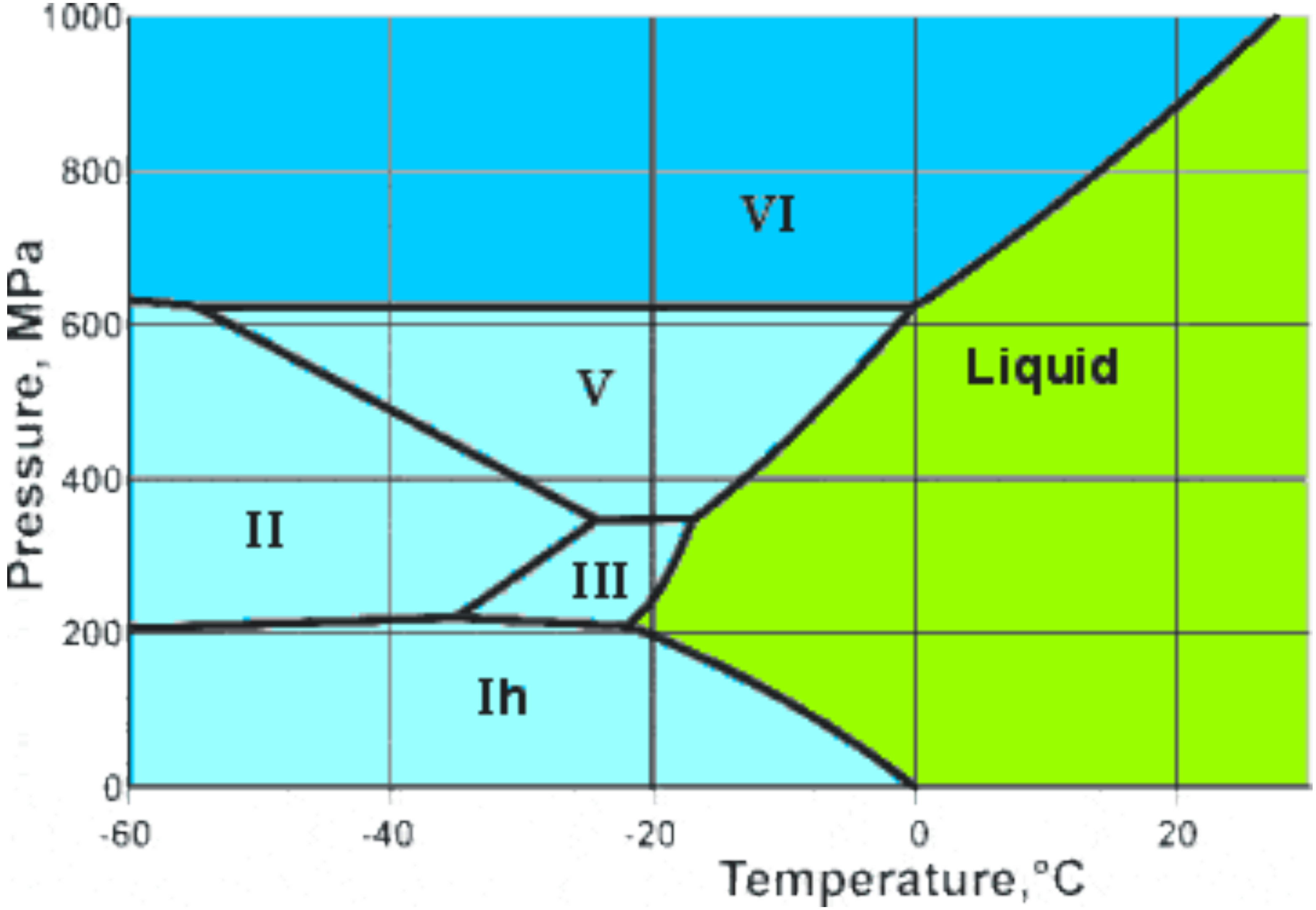
Phase Diagram for H_2O



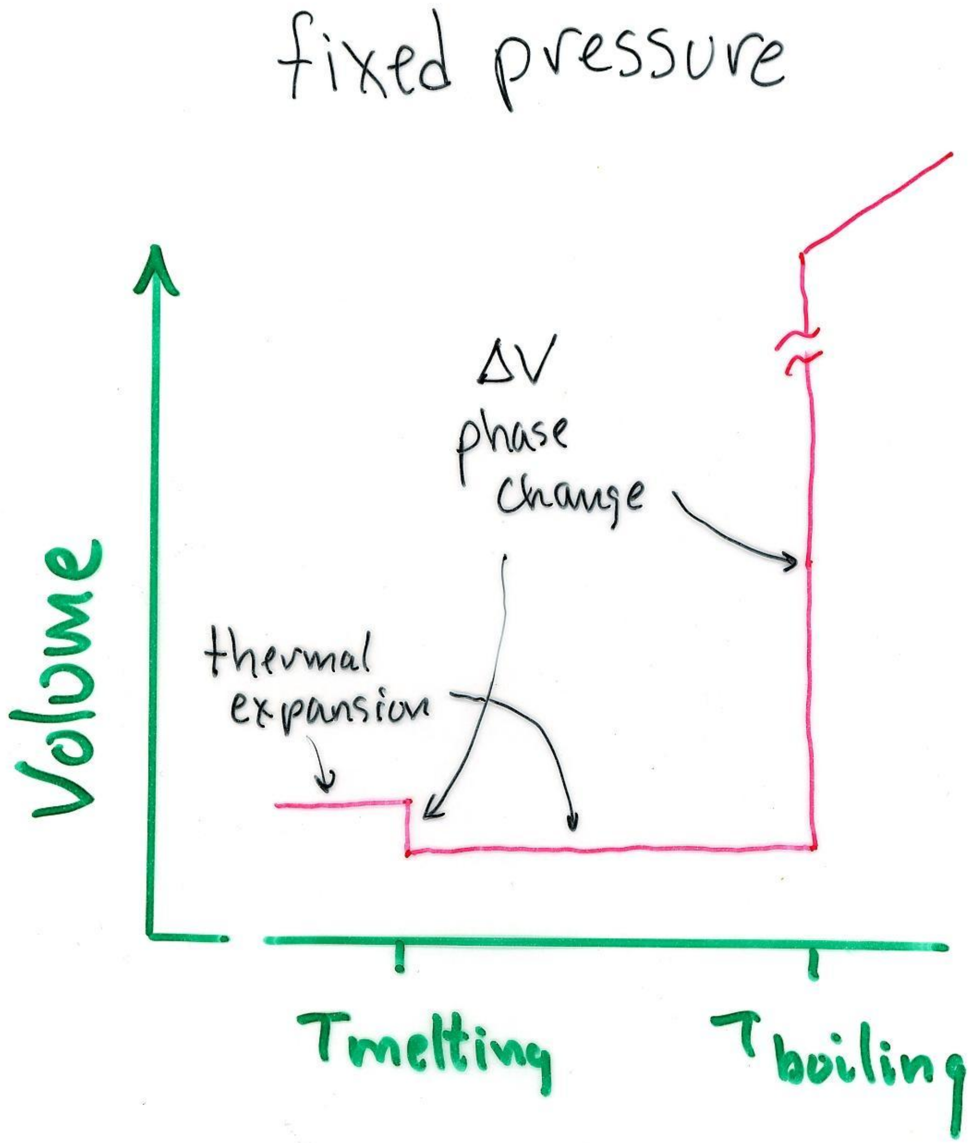
http://www.lsbu.ac.uk/water/

Detail near 10^8 Pa



http://www.lsbu.ac.uk/water/phase.html

Volume Changes in H_2O



What is Temperature?

Energy is stored in various ways at molecular level:
- Kinetic energy (fast-moving molecules)
- Molecular rotations
- Bond oscillations (vibrating springs)
- Lattice vibrations (more springs)

Each different way is called a "degree of freedom".

Temperature measures amount of energy stored on average in ***each*** degree of freedom.

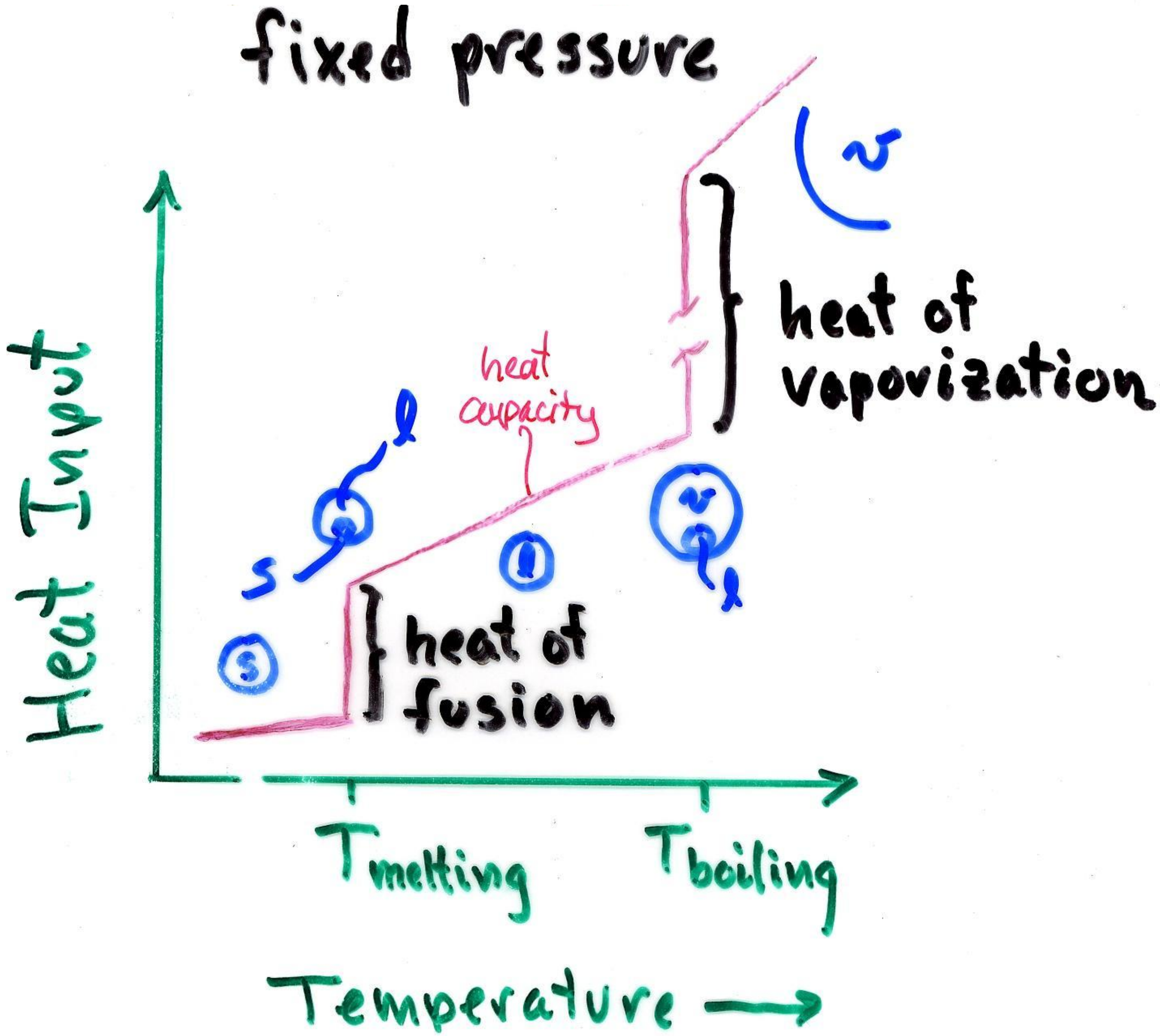
What is Heat Capacity?

Heat capacity measures amount of energy needed to raise temperature of 1 kg by 1 deg C.
We have to add energy equally to every degree of freedom.

- The more degrees of freedom in a substance, the higher its heat capacity will be.

Liquid water has a very high heat capacity.

Heating H_2O



fixed pressure
Heat Input
heat of fusion
heat capacity
heat of vaporization
s
l
v
Tmelting
Tboiling
Temperature →

What is Thermal Conductivity?

Thermal conductivity (K) measures the ease with which thermal energy can move through a substance (heat flux Q, in units of J m^{-2} s^{-1}) in response to a temperature gradient (dT/dx)

$$Q = K\, dT/dx$$

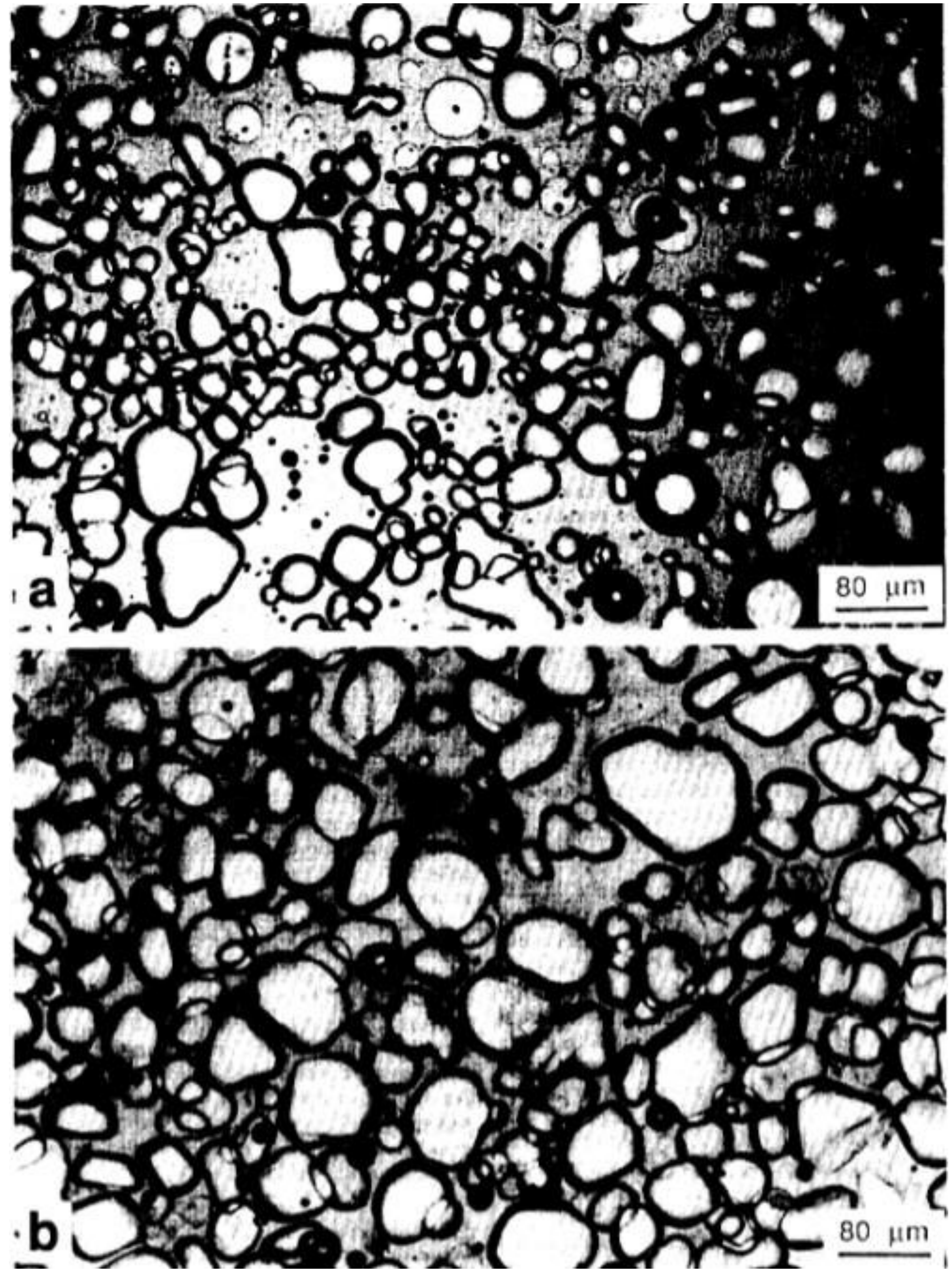
- Energy can be transmitted through a substance by molecular collisions (gas, liquid) and by vibrations (liquid(?), solid)
- Vibrations in a crystal are very effective at moving thermal energy.

Some Thermal Properties

latent heat of fusion:		334 kJ kg^{-1}
specific heat capacity:	ice	2.1 kJ kg^{-1} $^{o}C^{-1}$
	water	4.18
thermal conductivity:	ice	2.3 W m^{-1} $^{o}C^{-1}$
	water	0.6
thermal expansion coefficient:	ice	5×10^{-5} $^{o}C^{-1}$
	water	-6.6×10^{-5} $^{o}C^{-1}$ (at $0^{o}C$)
		2.1×10^{-4} (at $20^{o}C$)

Metamorphism in snow pack

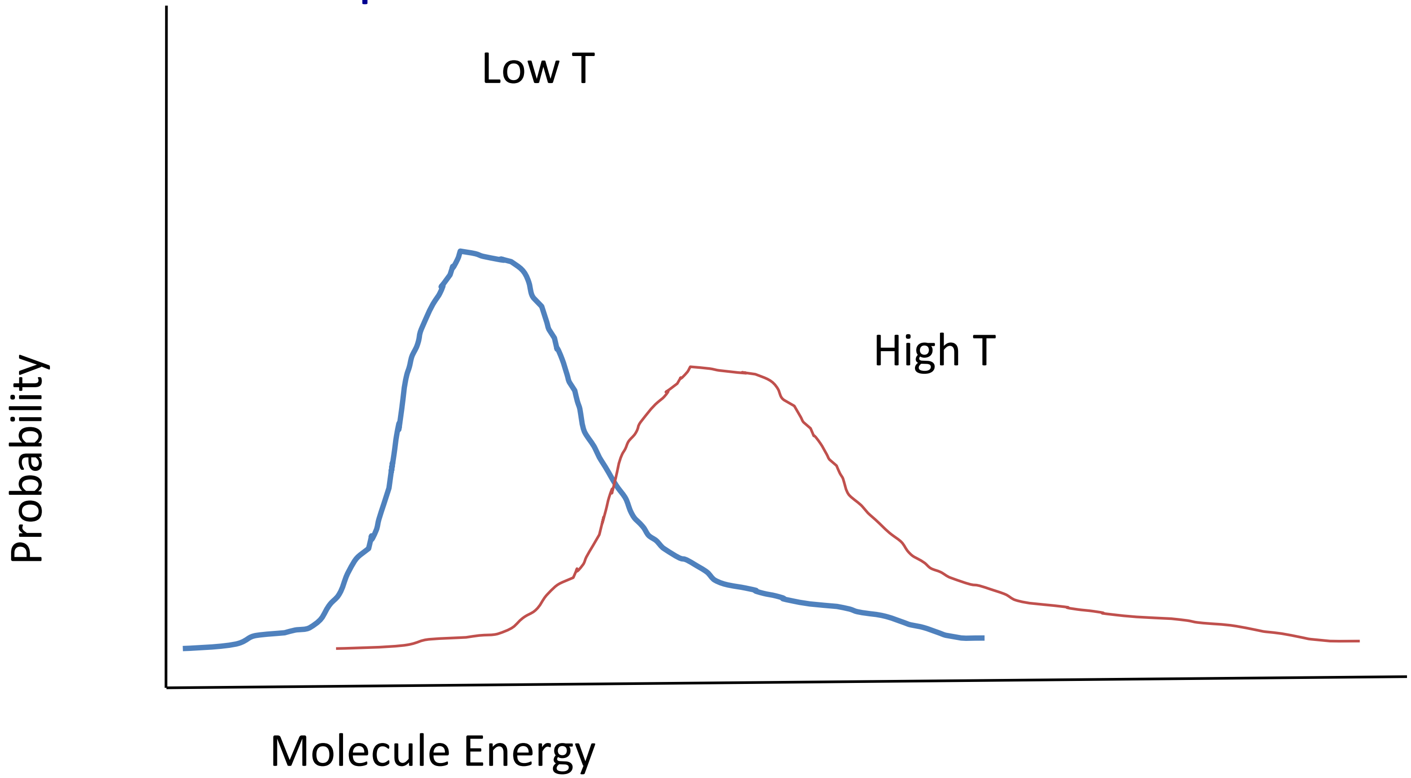
- Convex ice surfaces melt faster than flatter or more concave surfaces.
- Why do you think this is?
- What happens in snowpack at 0°C?
- Large ice crystals grow at the expense of smaller ones.



Vapor Pressure

Temperature describes a mean energy stored in each degree of freedom

Some molecules are always in an energy state that favors a different phase



What determines equilibrium vapor pressure?

Number of molecules leaving solid or liquid must equal number of molecules leaving vapor phase.

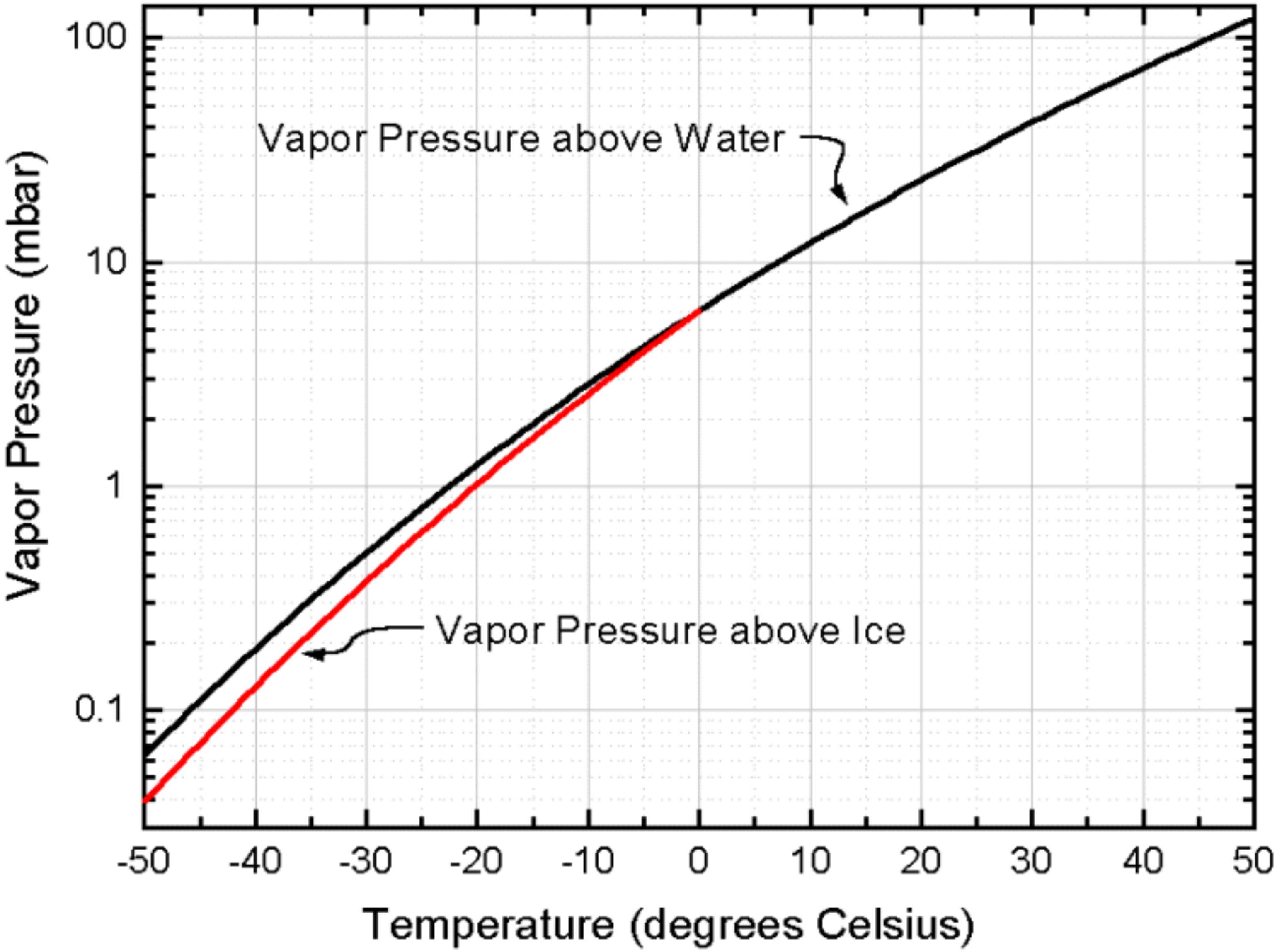
Number leaving solid or liquid:

- increases with temperature T (more energy available to break H-bonds)
- is greater with fewer H-bonds to break to liberate a molecule (water *vs* ice)

Number leaving vapor phase:

- is proportional to density of the vapor (molecules cm^{-3})
- increases as T decreases (slower-moving vapor molecules have less energy to get rid of to form H-bonds)

Vapor Pressure over water and ice



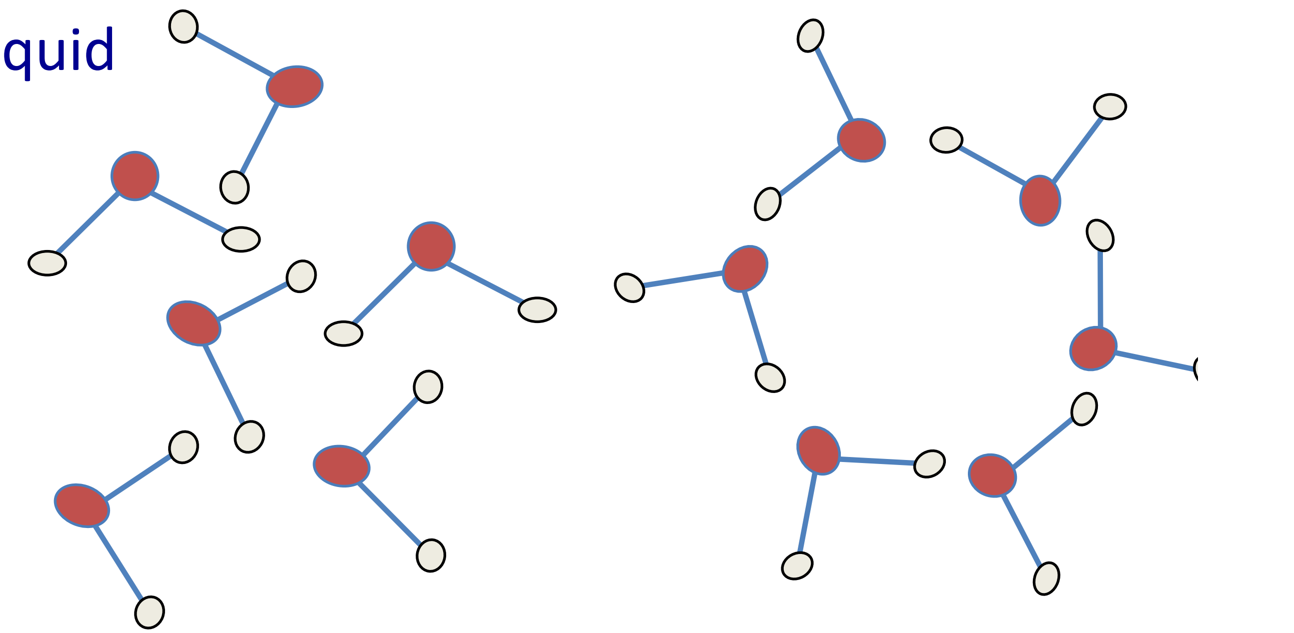
http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm

Supercooling

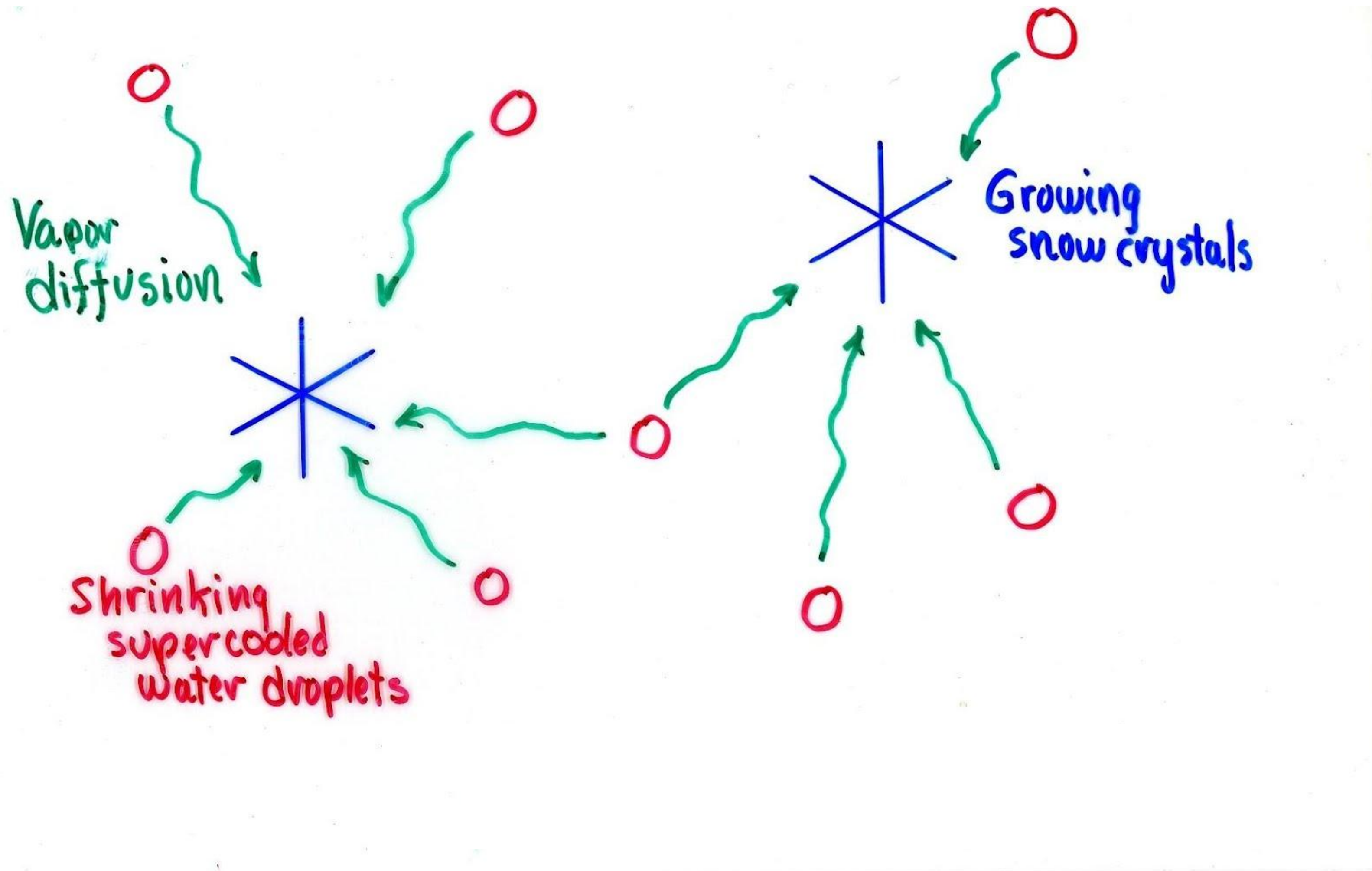
- Freezing Vs Melting point (Not always the same)
- Between -40 °C and 0 °C, ice crystals are energetically stable, but their formation needs a kick start

Seed Crystal

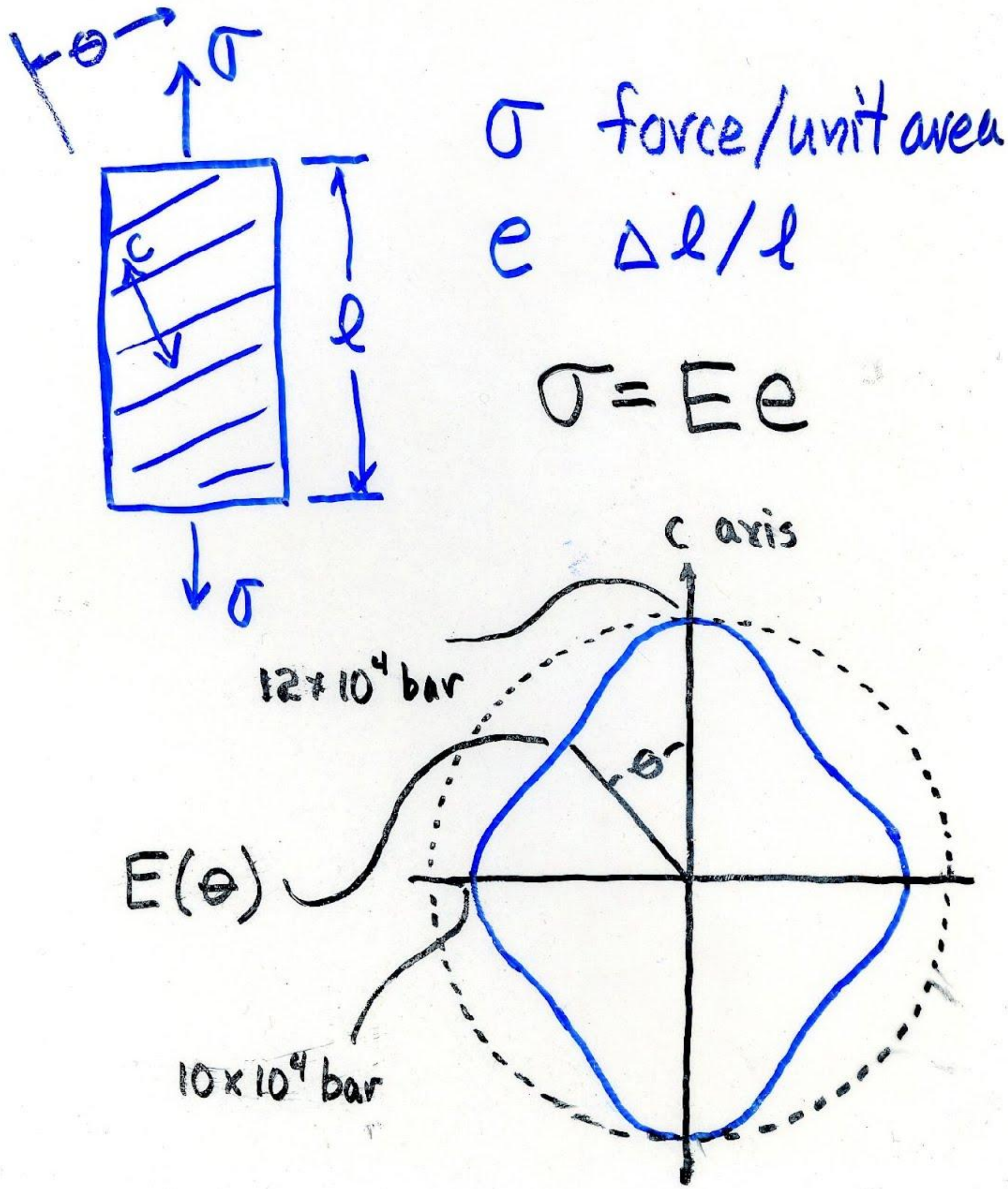
- Water in Atmosphere can be pure enough to supercool -> freezing rain
- Glass vs. Supercooled liquid



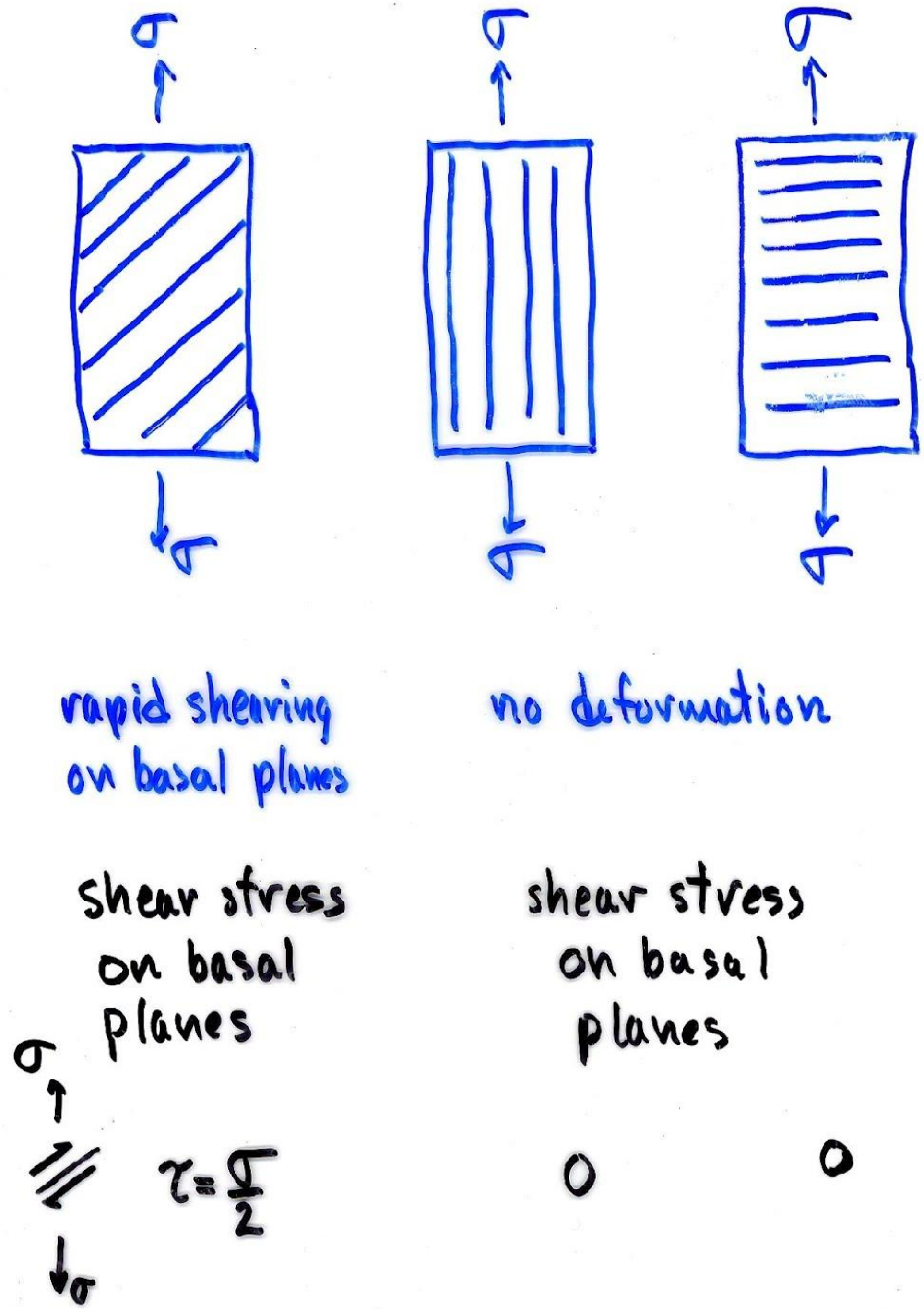
A Mode of Snow Crystal Growth in the Atmosphere



Elasticity of a Single Crystal



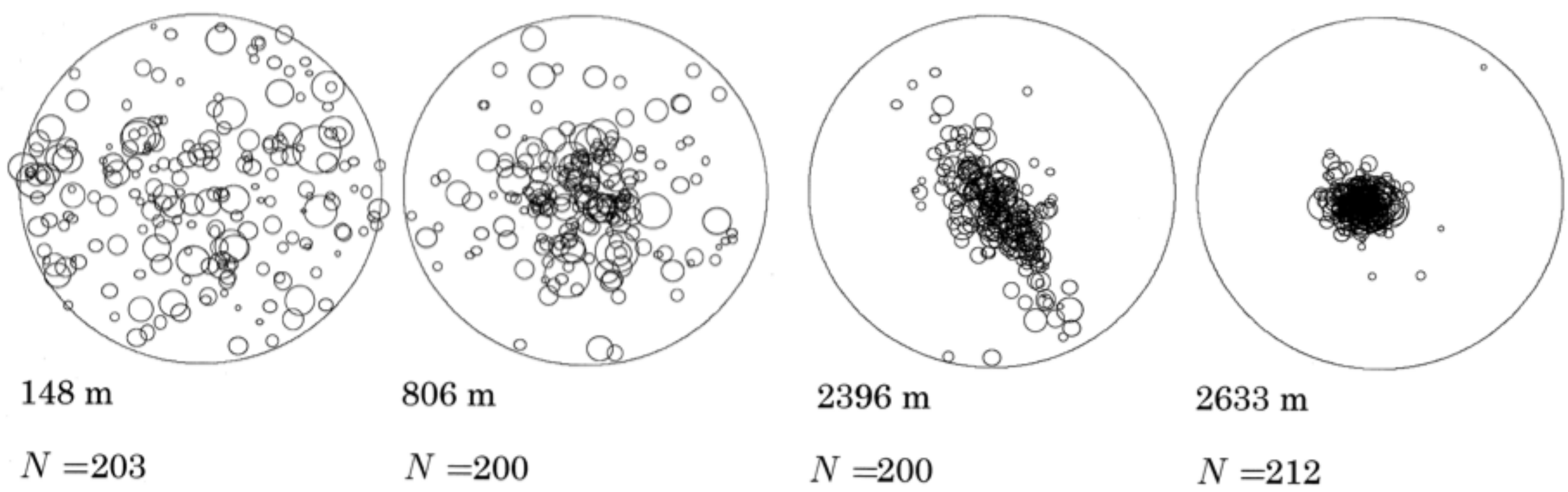
Creep of a Single Ice Crystal



Bulk Properties of Ice

- Natural ice (e.g. in glaciers or sea ice) is composed of many crystals (polycrystalline)
- Bulk properties may depend on the orientations of the crystals
- The statistics of the orientations of c-axes is called a c-axis fabric

Some Ice Fabrics

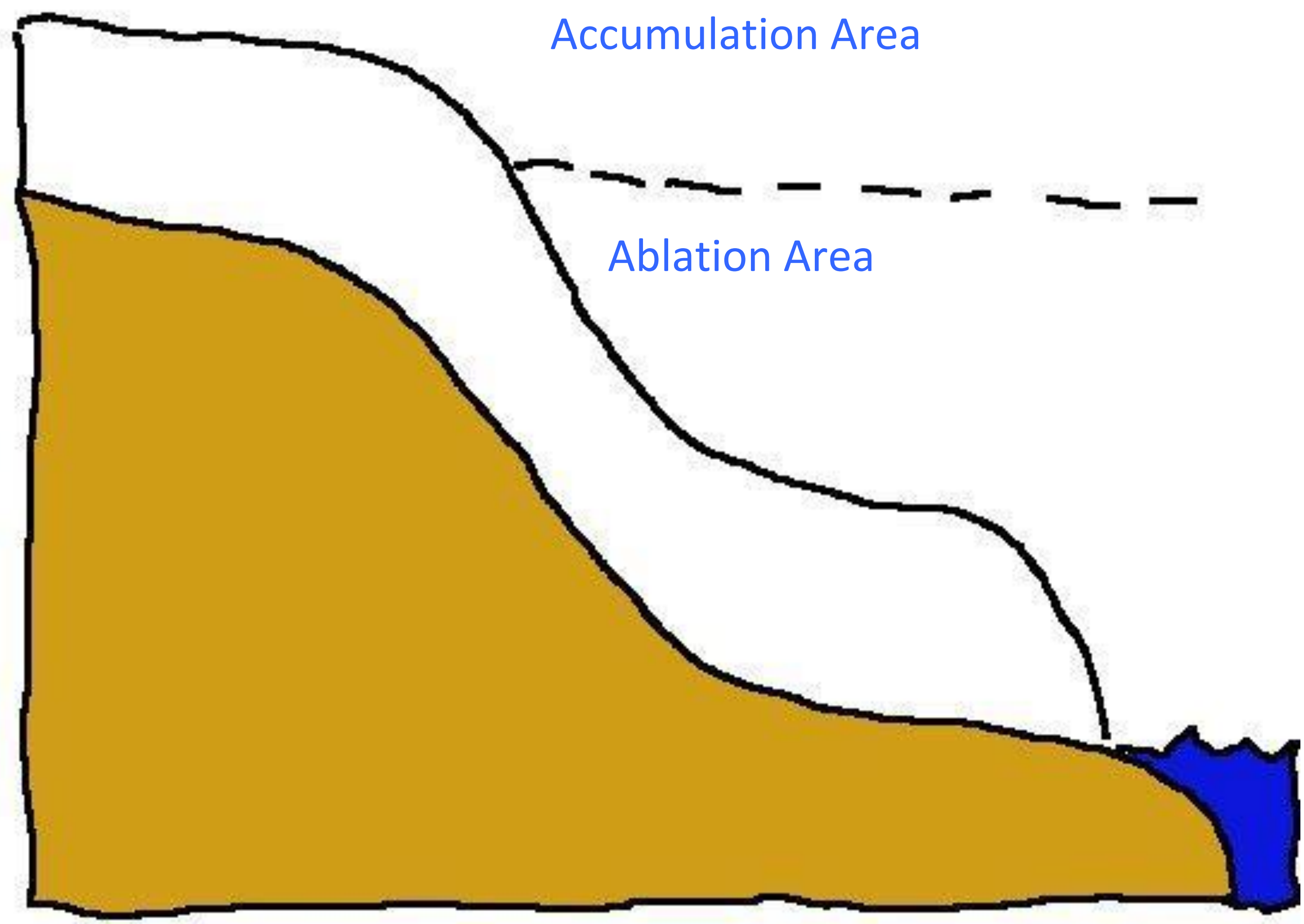


Schmidt plots

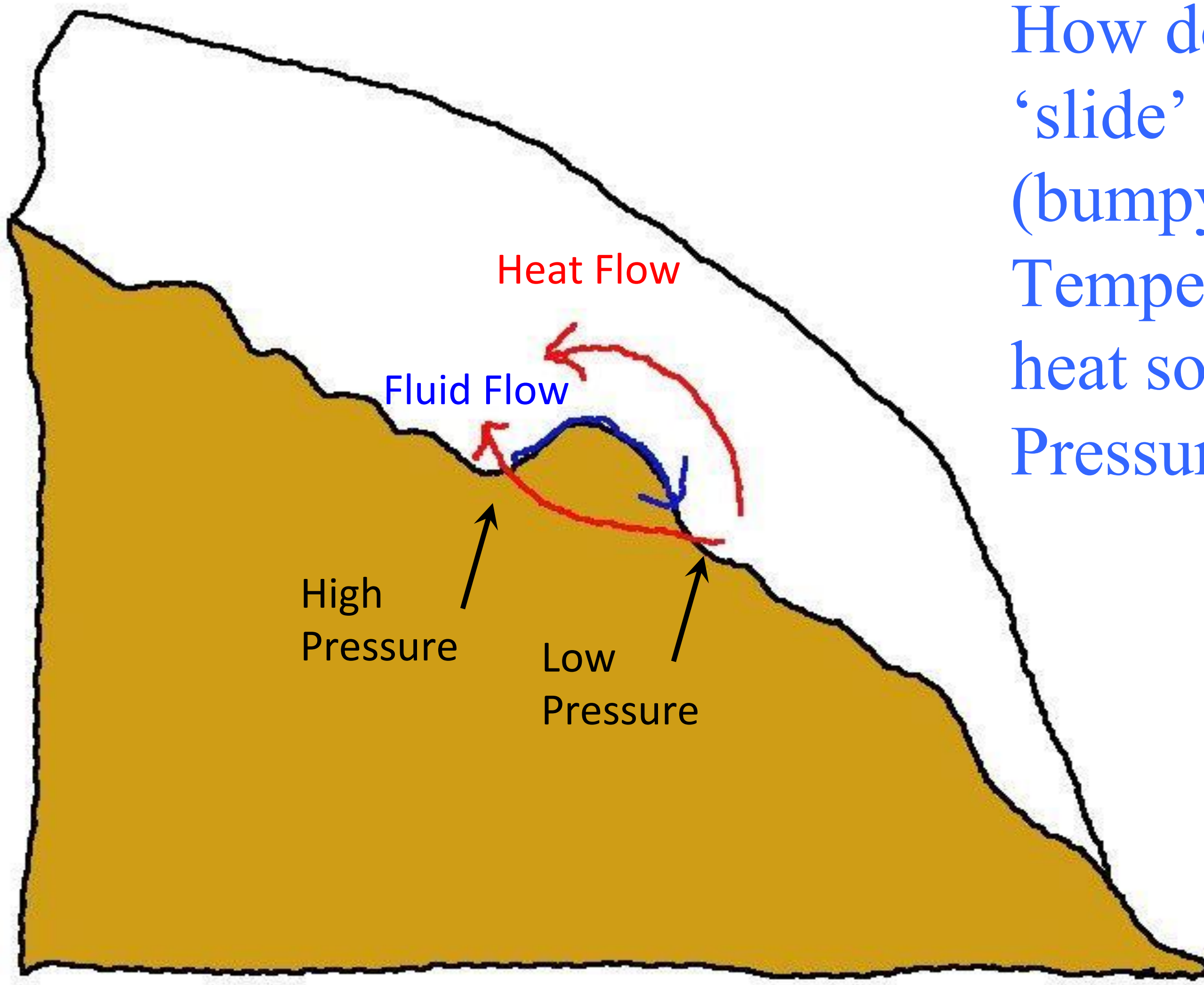
- Horizontal thin sections from NGRIP ice core, Greenland
- Circle location marks orientation of a c axis on a hemisphere
- Circle area indicates crystal size

Gagliardini et al. (2004) *J.Glaciol.*

Large-Scale Glacier Properties

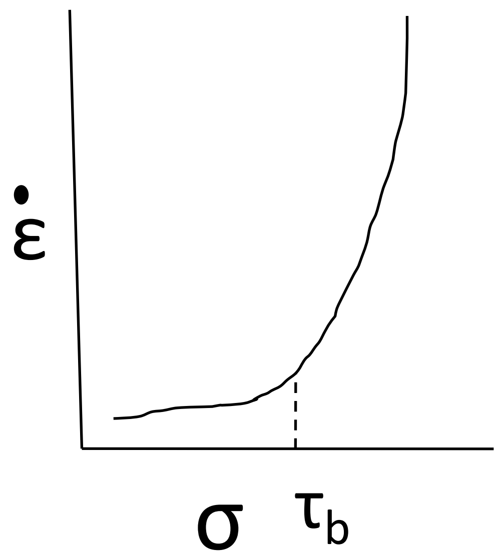


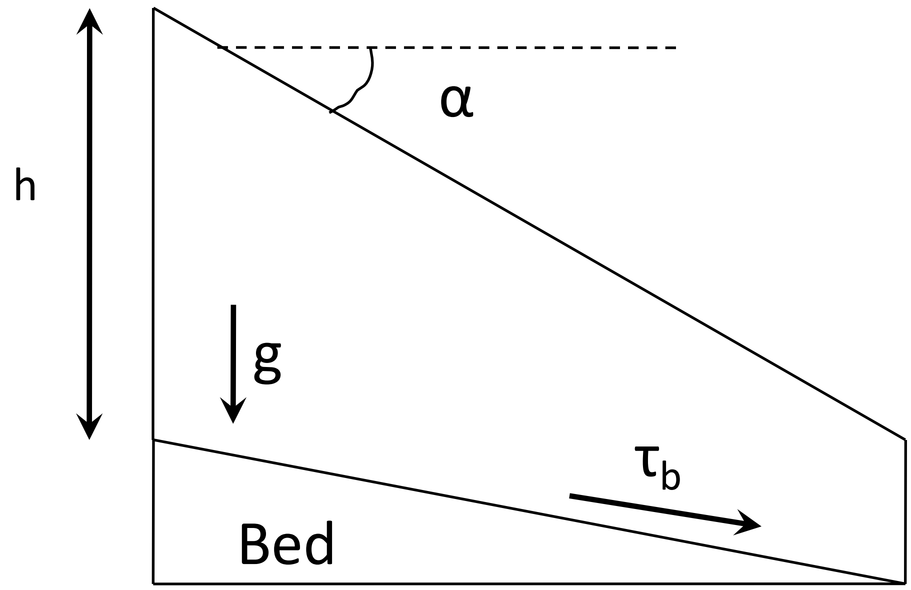
Regelation



How does a glacier 'slide' over it's (bumpy) bed?
Temperature at bed, heat source?
Pressure melting

Shape of a Glacier





Highly nonlinear ~ plastic

$\tau \sim \tau_b$ at bed

$$\tau_b = \rho g h \sin(\alpha)$$