MSE-238
Structure of Materials

Week 9 – amorphous structures I: glasses

Spring 2025

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General Outline

- introduction and reminder of atomic bonds, crystals – week 1

Part I: crystallography - weeks 2-6

- packing of spheres, constructing crystal structure week 2
- crystal lattice and symmetry operations week 3
- mathematical description of the lattice, Miller indices week 4
- reciprocal space (&diffraction) week 6
- characterization I: diffraction week 7
- diffraction & recap of crystallography week 8

BREAK 18.4. & 25.4.

Part III: amorphous & hierarchical structures – week 9-12

- **glasses**
- polymers
- Characterization II: scattering
- biological and hybrid materials

Recap – week 13

Overview

- amorphous vs. crystalline materials
- order and disorder
- structural parameters for amorphous materials
- Pair distribution function and how it is measured
- glass transition temperature
- atomic scale structure
- continous random-network model
- properties of crystal and amorphous structure
- application of amorphous structures

Amorphous vs crystalline materials

- Amorphous

Silica and other oxides
short-range order

- Cristalline

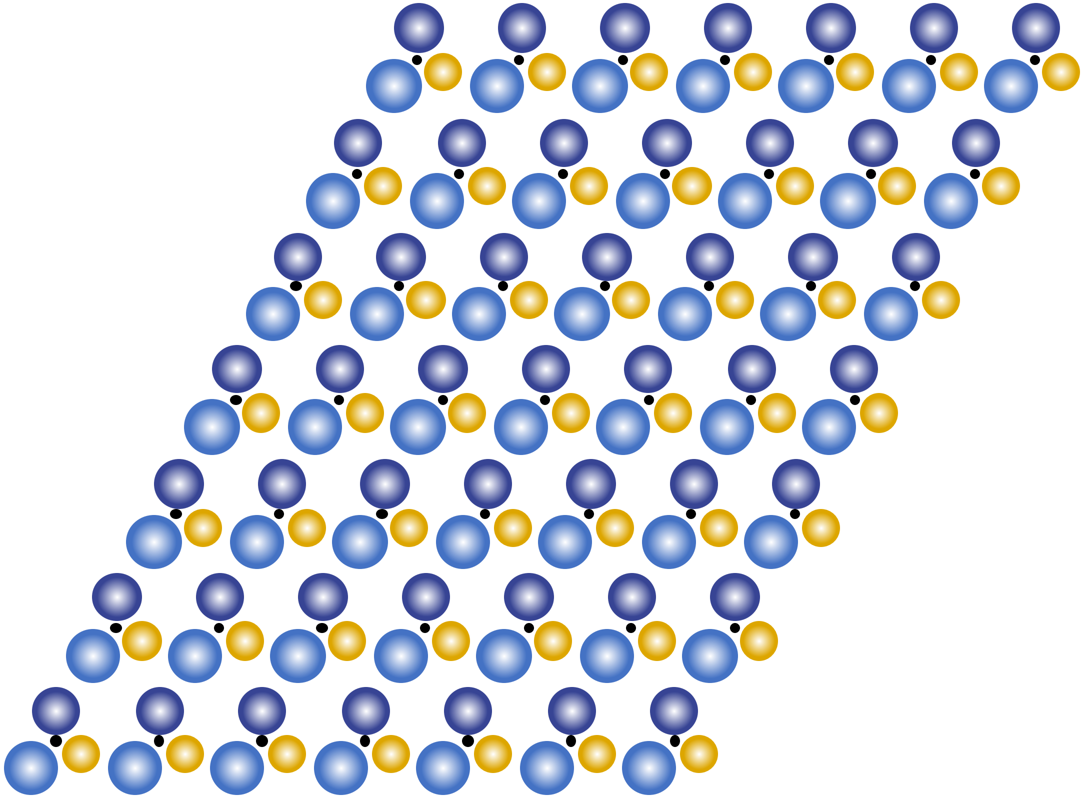
Quartz resonator, quartz and spoon in stainless steel
long range order

How to describe the structure?

Bravais lattice

⊗ Basis

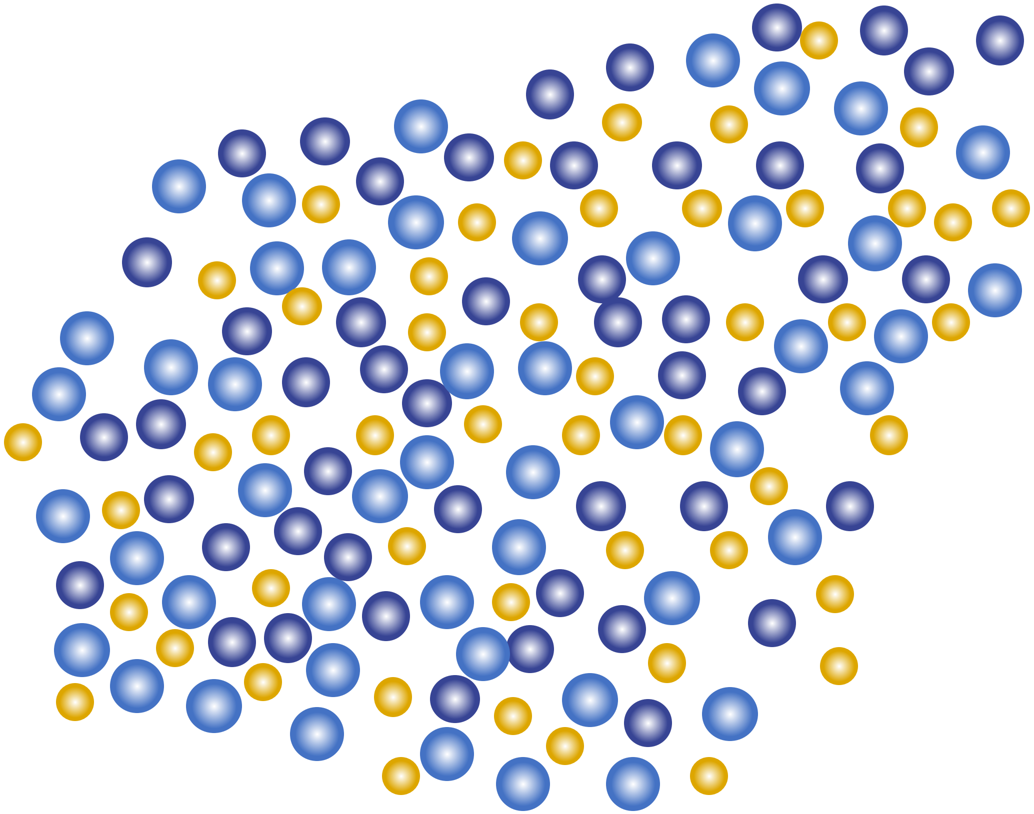
= Crystal



crystal: describe atomic structure with just one unit cell!

animation: Phil Willmott

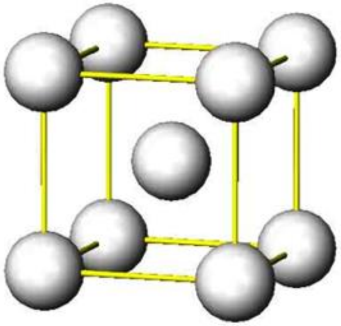
How to describe the structure?



amorphous material: the atomic arrangement of two amorphous samples are never identical

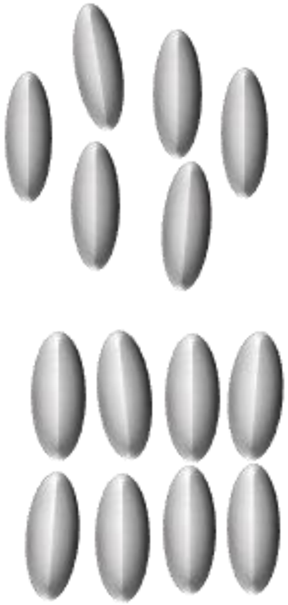
we have to look at **average** structural features

Order and disorder

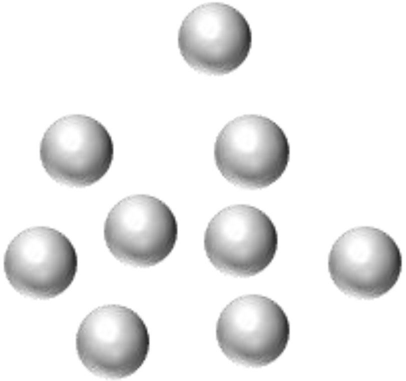


long-range order
translational symmetry

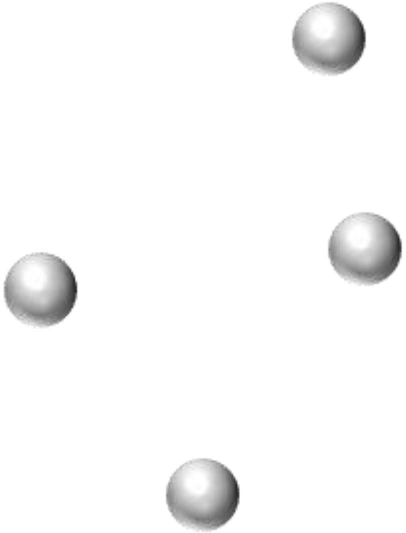
solid
densly packed
crystalline



long-range order
orientational symmetry (nematic)
orient. & transl. sym. (smectic)
liquid (2D or 3D)
densly packed
liquid-crystalline

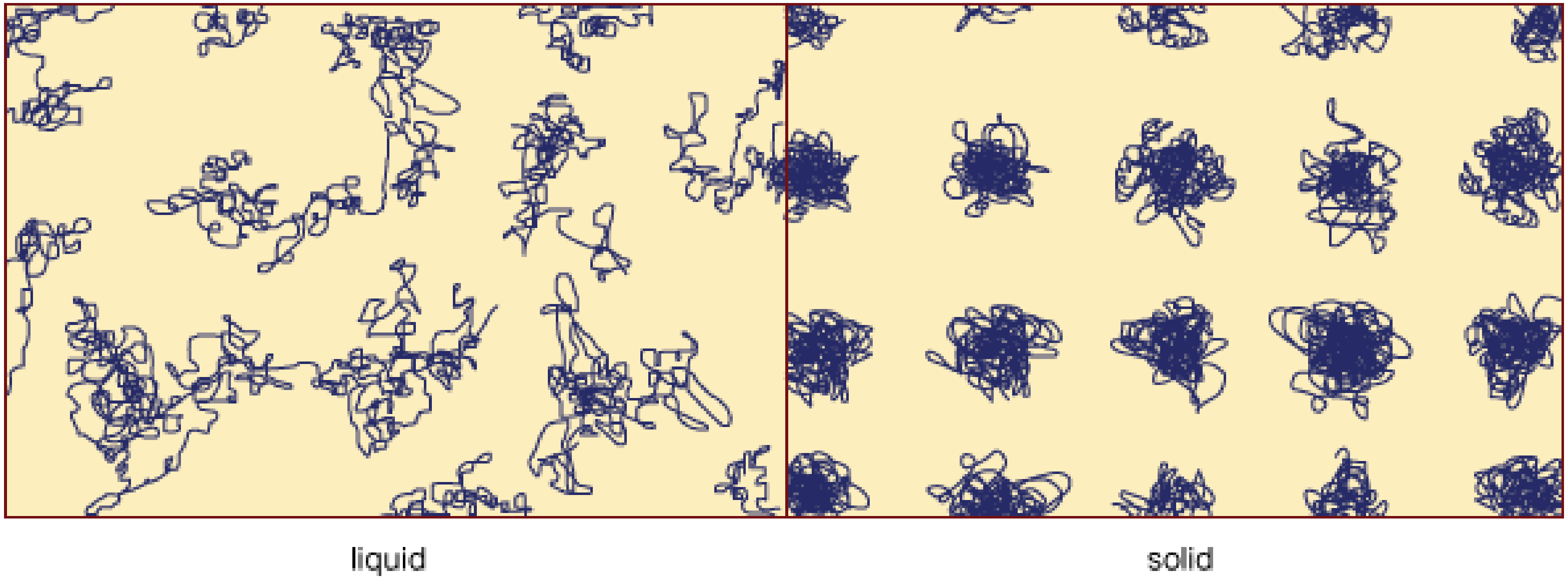


short-range order
some correlation
no symmetry
liquid or solid
densly packed
amorphous solid/glass, liquid



disordered
no correlation
no symmetry
gas
compressable
gas

solid vs. liquid



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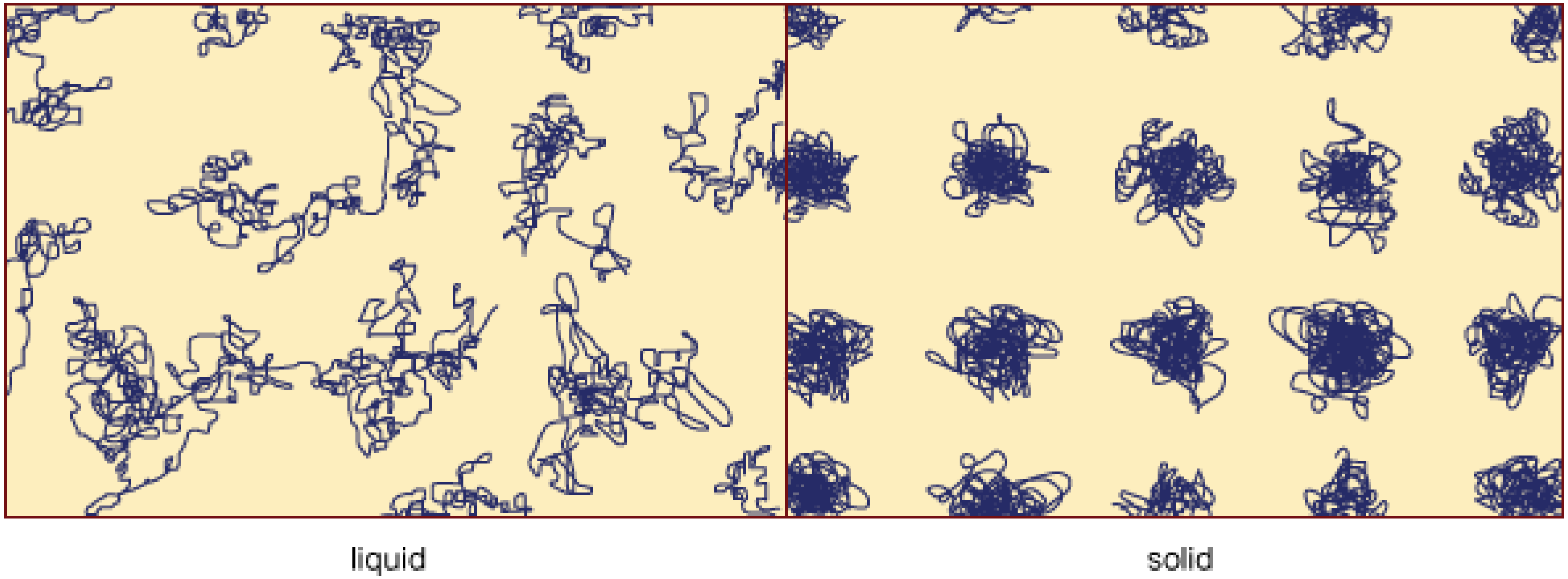
well defined volume
flows under action of external folds

well defined volume and shape
elastic stiffness

solid vs. liquid

on atomic scale:



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in liquids atoms are **mobile** and continually wander throughout the material

in solid atoms are not mobile, they oscillate rapidly about **fixed points** in space

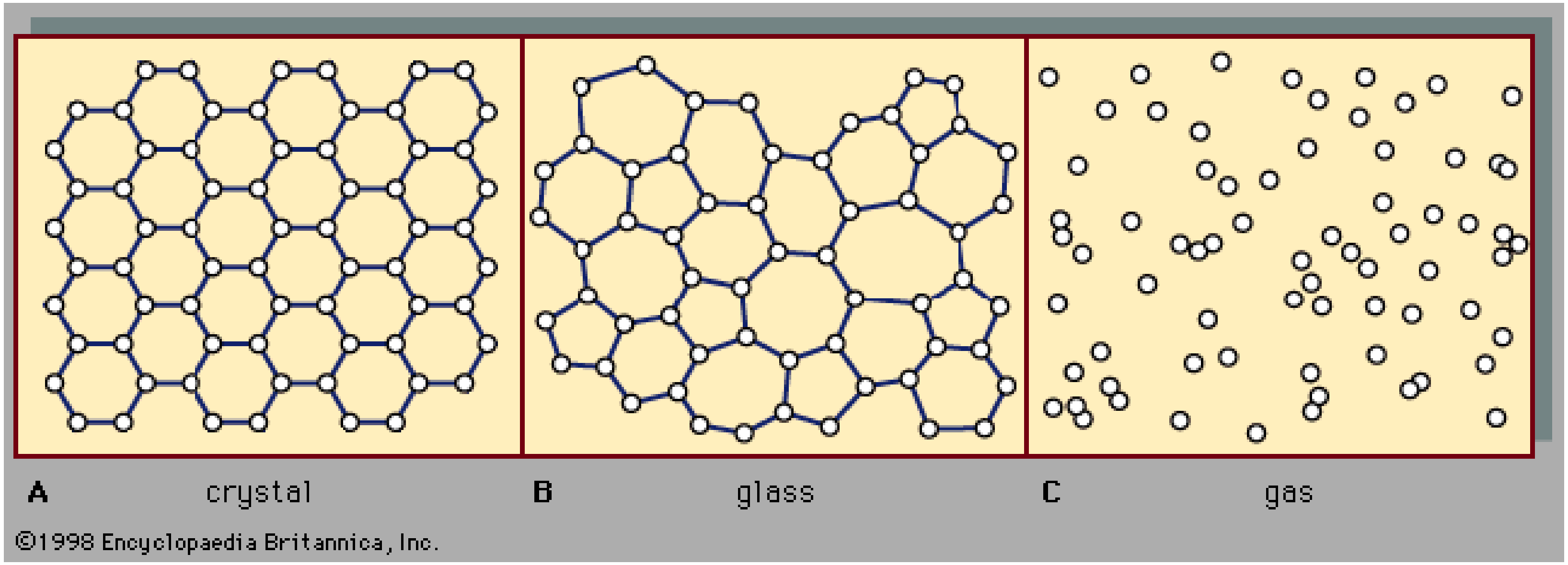
→ arrangement with long-range order: crystal

→ arrangment without long-range order: solid amorphous structure

solid: crystal and amorphous solids

solid dots: only one snap shot of one configuration of atomic positions

solid dots: fixed position



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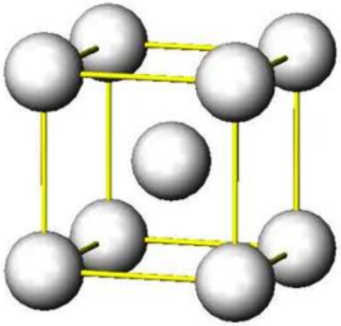
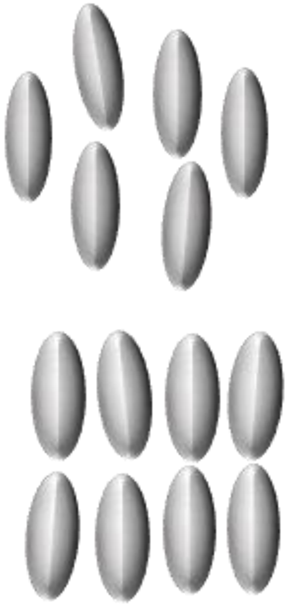
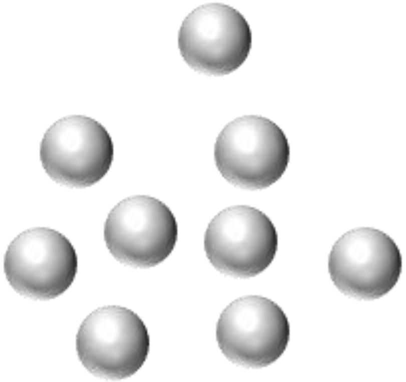
each atom has three nearest neighbours at the same distance
→ short-range order (atomic scale)
translational periodicity
→ long-range order

each atom has three nearest neighbours at the same distance
→ short-range order (atomic scale)

Order and disorder







→ how to describe structure of amorphous materials?

long-range order: periodic distribtuion of atoms ordered over large distances

exact location from an atom can be inferred relative to a chosen atom at the origin
→ **atomistic**

short-range order: over short distances (some atomic diameters) a certain periodicity in the distribution of atoms still exists.

some randomness in the position of the atoms: structural order can only be described **statistical**

Structural parameters

- density/packing efficiency: overall mass per unit volume
- free volume: the unoccupied space within the structure
- coordination number
- bond length (distribution)
- bond angle distribution: variability in bond angles
- pair distribution function, or radial distribution functions: how atomic density varies as a function of distance from a reference atom

Structural parameters in crystals

- density/packing efficiency: overall mass per unit volume
  → packing factor in one unit cell
- free volume: the unoccupied space within the structure
  → interstitial cites in one unit cell
- coordination number
  → fixed
- bond length (distribution)
  → fixed
- bond angle distribution: variability in bond angles
  →bond angles are fixed
- pair distribution function, or radial distribution functions: how atomic density varies as a function of distance from a reference atom
  → interesting for local variations due to defects, distortions etc. more sensitive to local environment

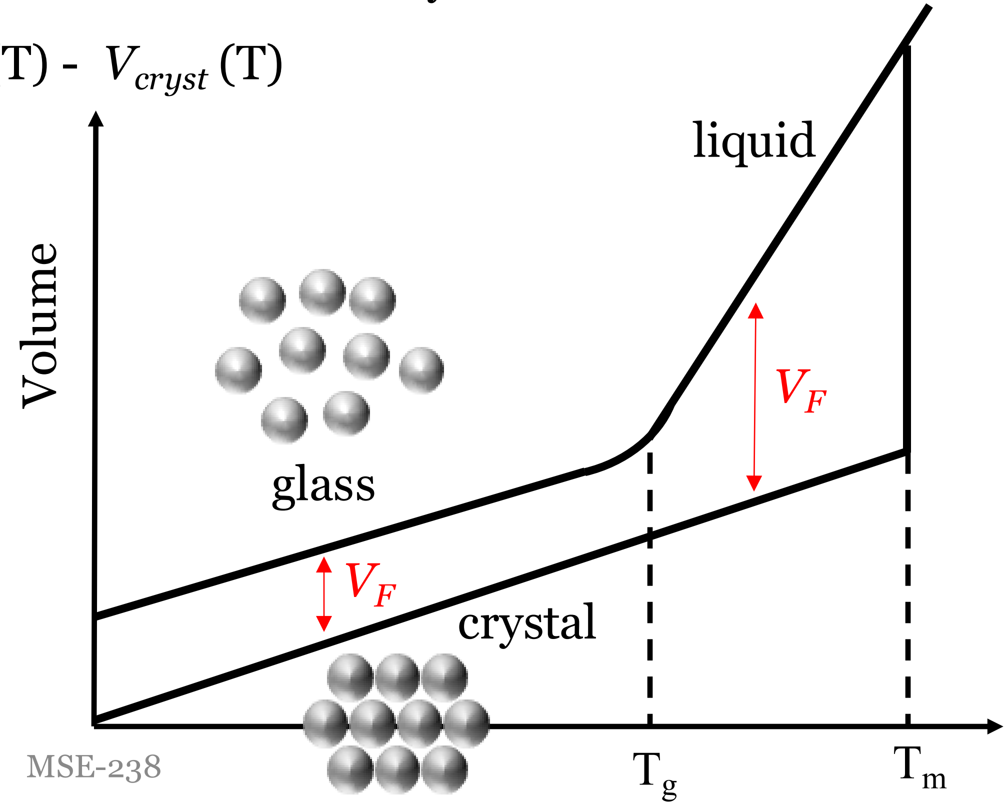
Free volume

- space in the material not occupied by atoms/molecules
- a temperature dependent property!
- the free volume V_F is the difference between the total sample specific volume (volume per unit mass) and the occupied specific volume V_o
- V_o can be approximated as the specific volume in the crystalline state

$$V_F\,(\mathrm{T}) = \mathrm{V(T)} - V_o\,(\mathrm{T}) \simeq \mathrm{V(T)} - V_{cryst}\,(\mathrm{T})$$

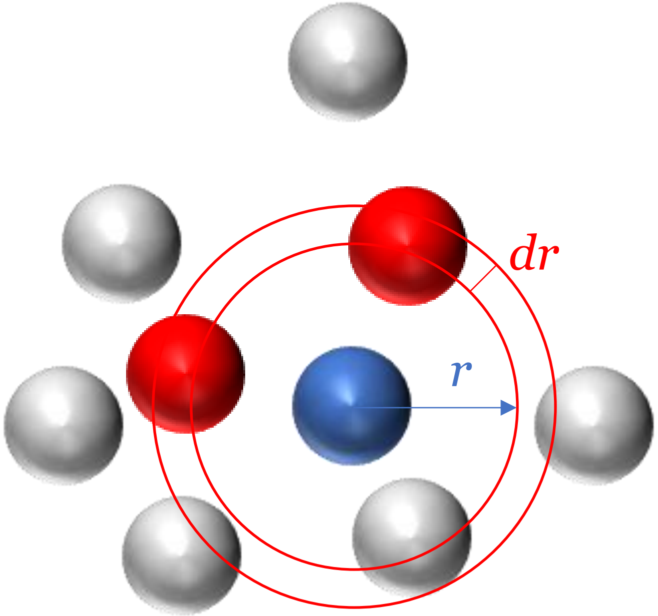
melting temperature T_m with an abrupt change in the specific volume

glass transition T_g thermal expansion coefficient changes (different slope) but no abrupt change in specific volume



Pair distribution function (PDF)

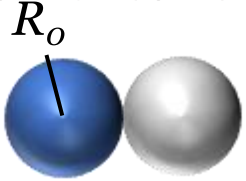
- probability of finding an atom/molecule at a certain distance normalized over the overall density → local density in the structure surrounding a typical atom



$$\boxed{g(r) = \frac{dn(r,r+dr)}{dv(r,r+dr)}\frac{1}{\rho_0} = \frac{\rho(r)}{\rho_0}}$$

$4\pi r[\rho(r) - \rho_0]$: excess particle number density in a spherical shell at radius r

h(r) = g(r)-1 total correlation function, deviation from uncorrelated behavior

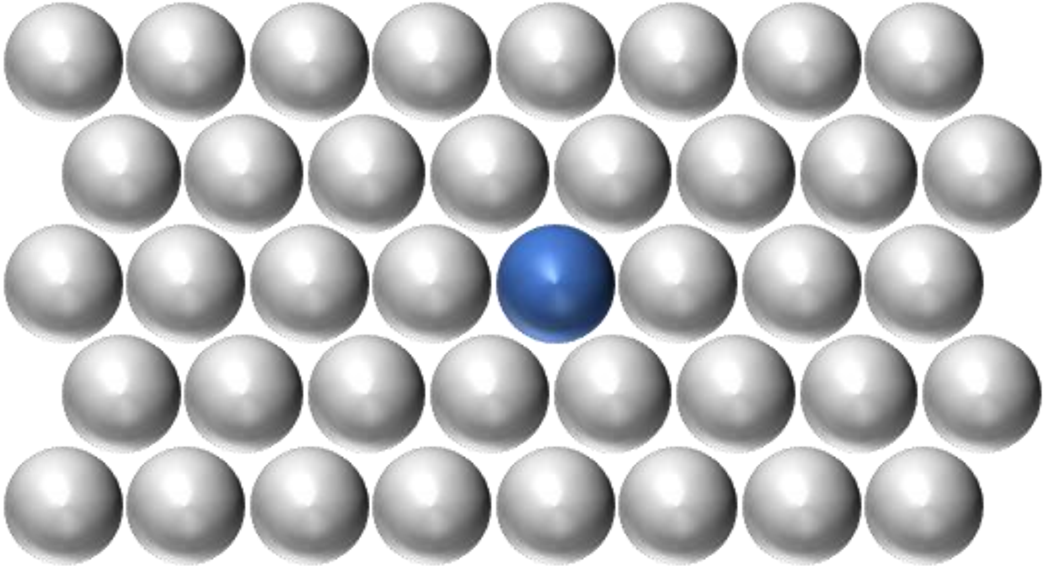


$g(r < 2R_o) = 0$

dn : number of atoms in a spherical shell
dv : spherical shell volume = $4\pi r^2 dr$
r : distance of the shell from an arbitary atom selected as the origin
ρ_0: average particle density
$\rho(r)$: atomic pair density
R_o = radius of atom (solid sphere model)

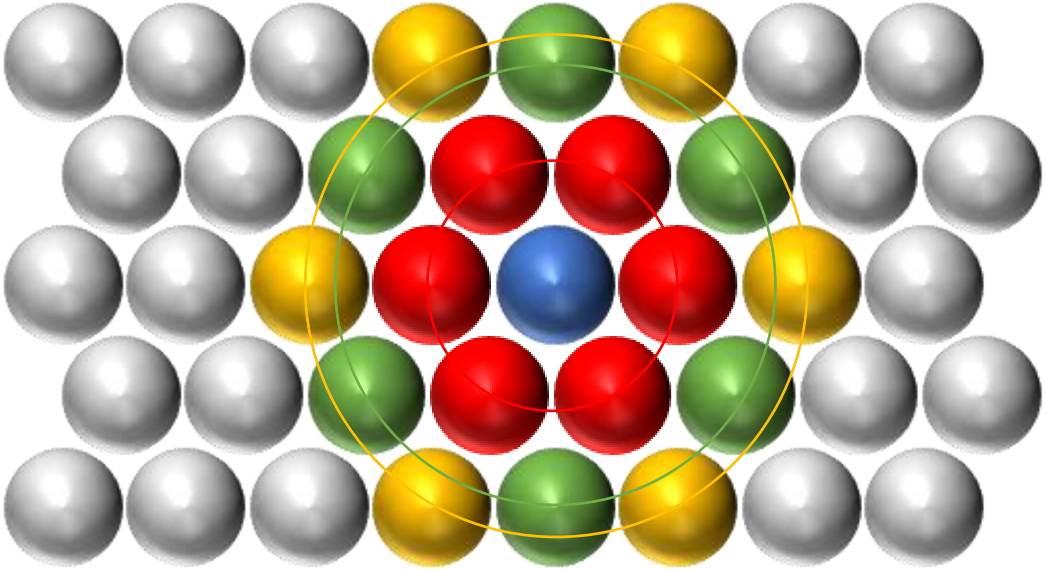
Pair distribution function for crystals

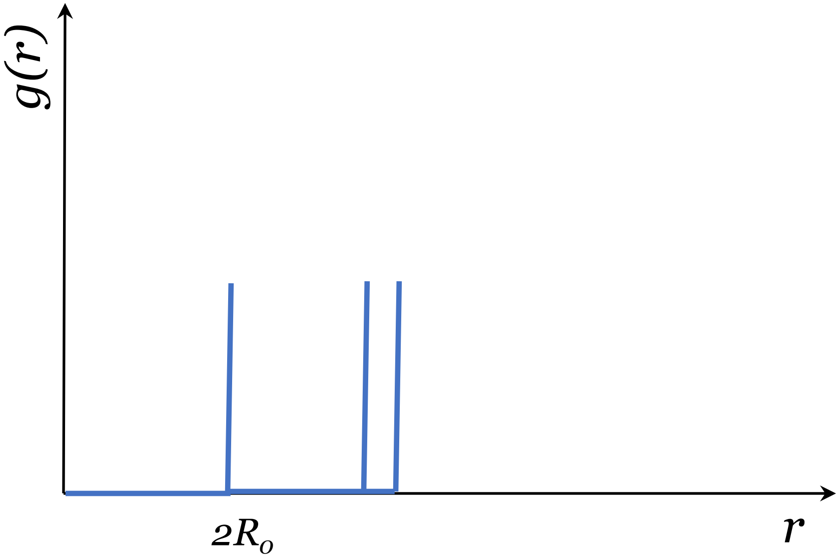
- long-range order



Pair distribution function for crystals

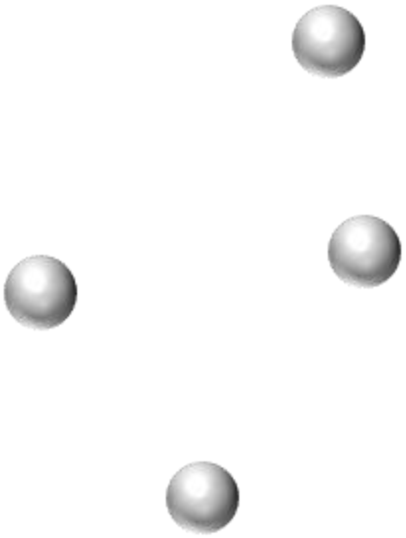
- long-range order
- *g(r)* infinite series of discrete peaks (delta functions) at the values of interatomic separation
- depends on particular crystal structure

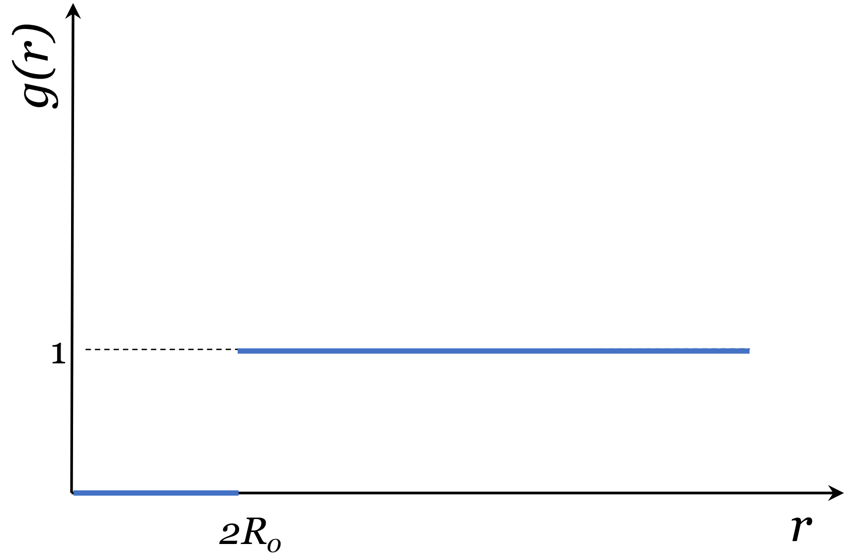


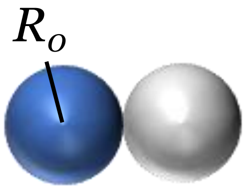


Pair distribution function for a gas

- atoms (or molecules) are uncorrelated, no short-range order
- Below the hard-sphere diameter $2R_o$ the probability finding another atom is zero (as for all materials)
- Beyond the hard sphere diameter, the probability of finding another atom is equal to the average gas density, $g(r) = 1$



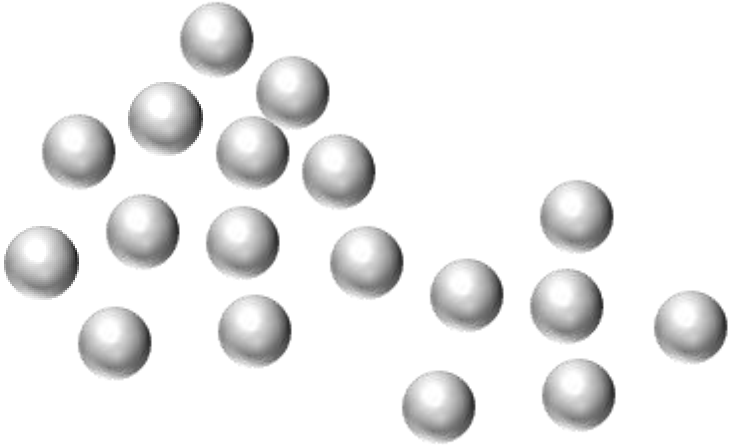


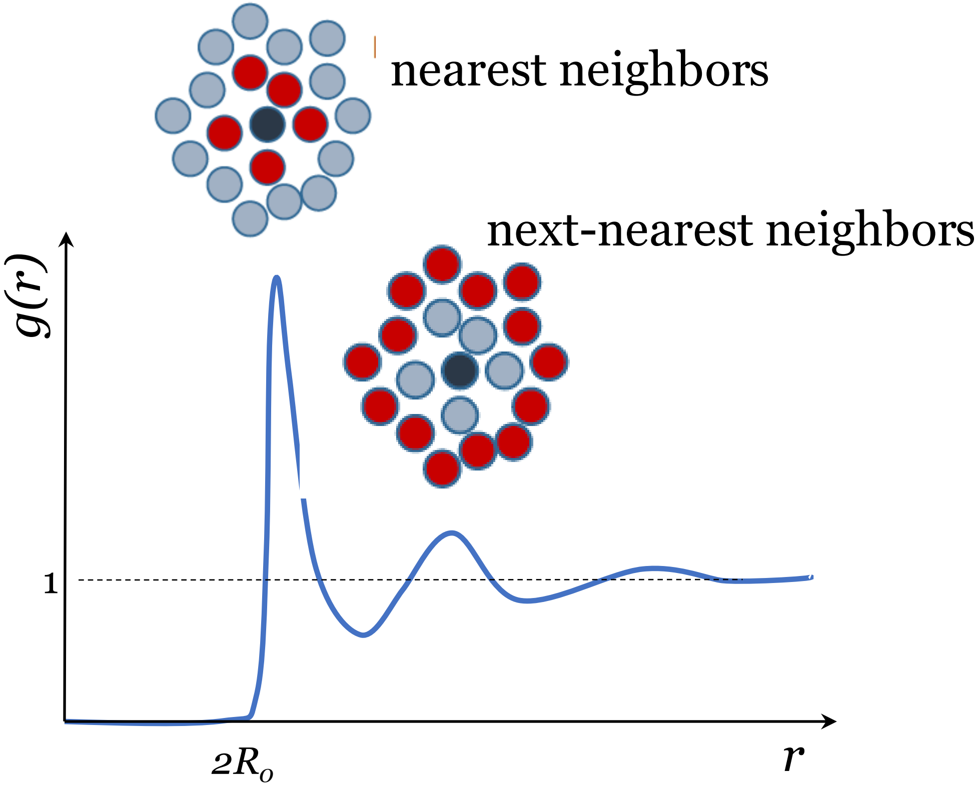


$g(r < 2R_o) = 0$

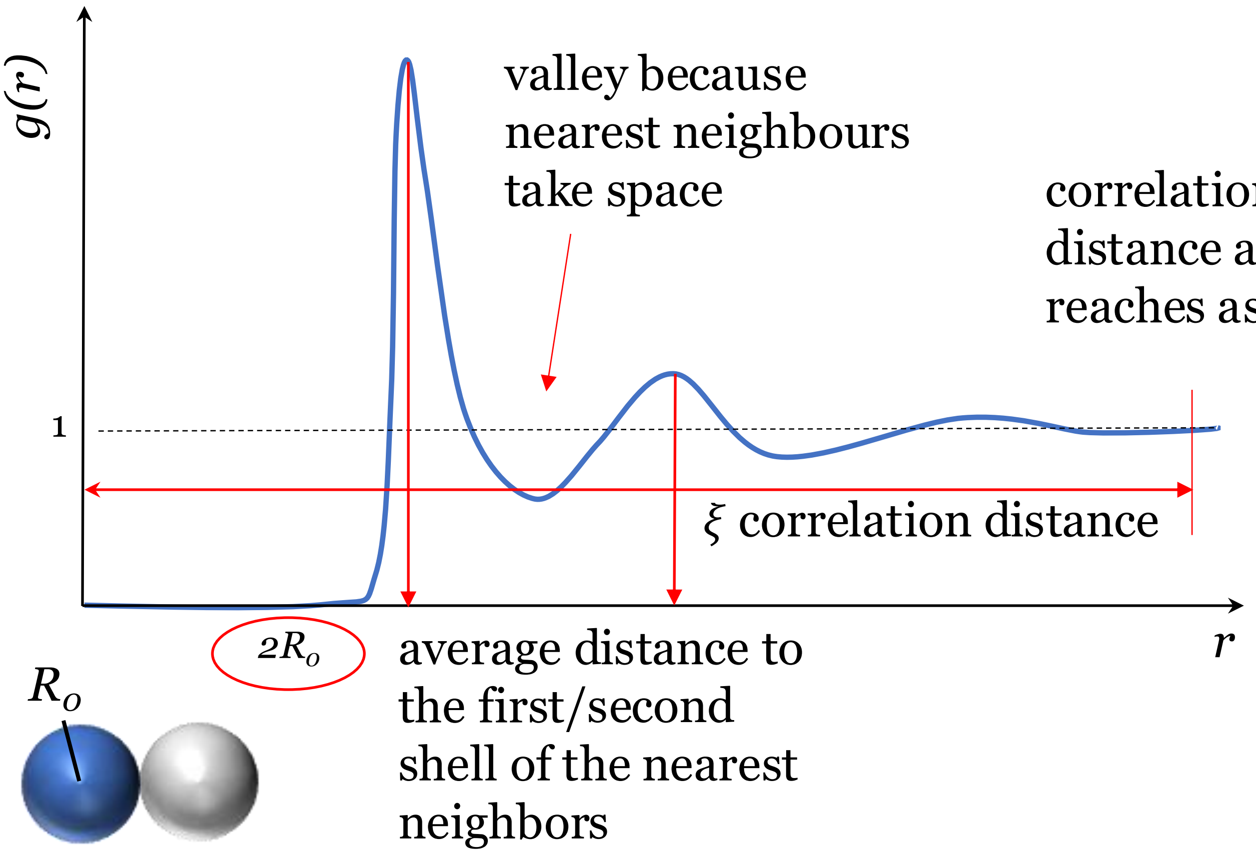
Pair distribution function for liquid/glass

- short-range order
- *g(r)* several broad peaks and valleys until reaching a constant value at large distance r





Pair distribution function for liquid/glass



valley because
nearest neighbours
take space

correlation distance ξ
distance at which $g(r)$
reaches asymptotic 1

ξ correlation distance

average distance to
the first/second
shell of the nearest
neighbors

$g(r < 2R_o) = 0$

PDF of crystalline materials

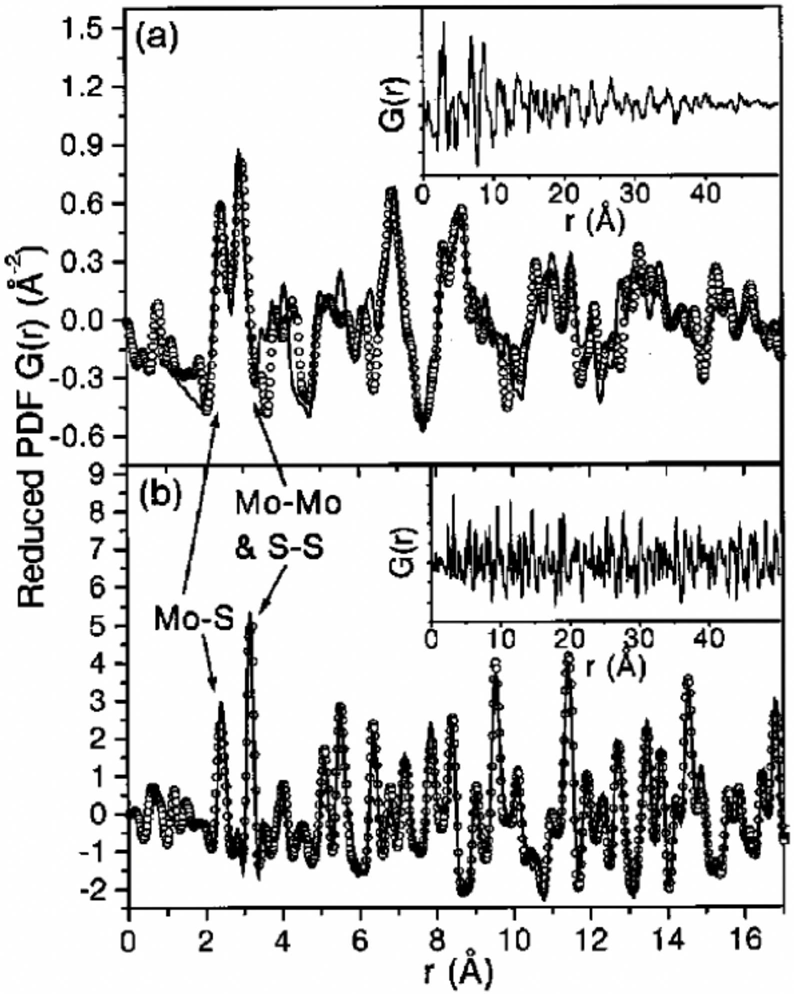


Fig. 6 PDFs from (a) $LiMoS_2$ and (b) MoS_2 from the data in Fig. 5 (dots). The experimental data are shown on an extended scale in the insets. Solid lines in the main panel are PDFs calculated from structural models.

$LiMoS_2$

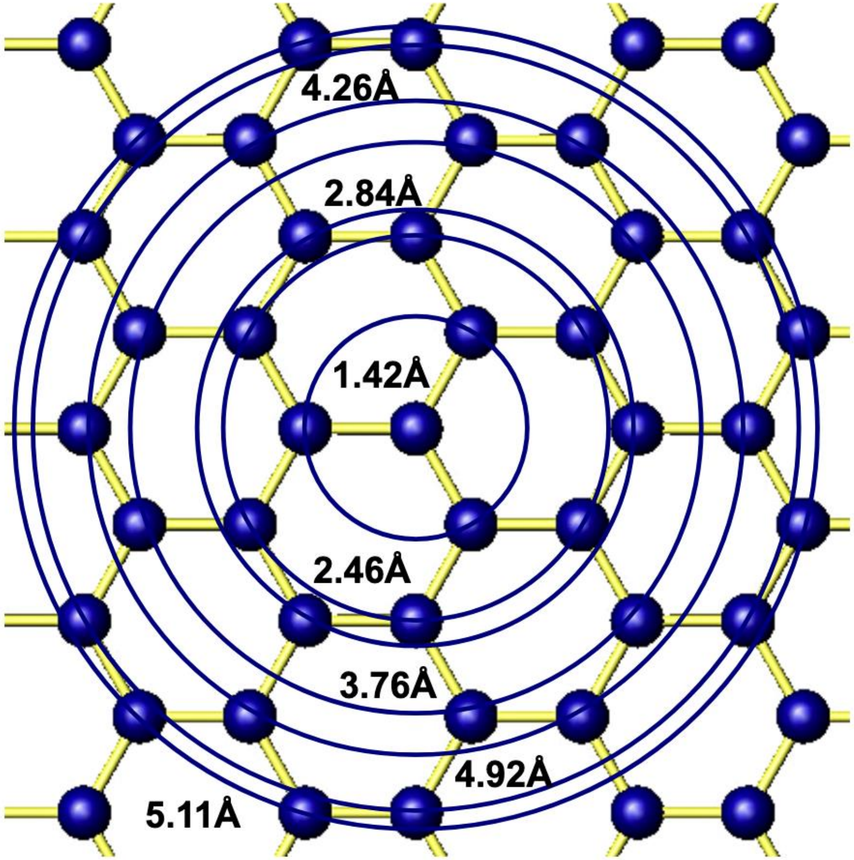
Li intercalate in MoS_2 structure creating a lot of distortion
The peaks are dying out over about 4nm “nanocrystalline”

MoS_2

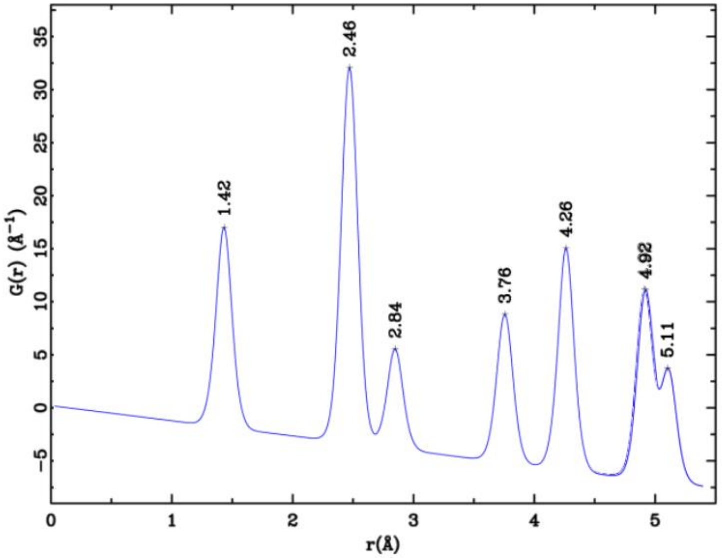
crystalline material, G(r) shows sharp peak with same intensity through the whole PDF

Billinge and Kanatzidis. *Chem . Commun.*, 2004, 749 – 760
Beyond crystallography: the study of disorder, nanocrystallinity and crystallographically challenged materials with pair distribution functions

Coordination number



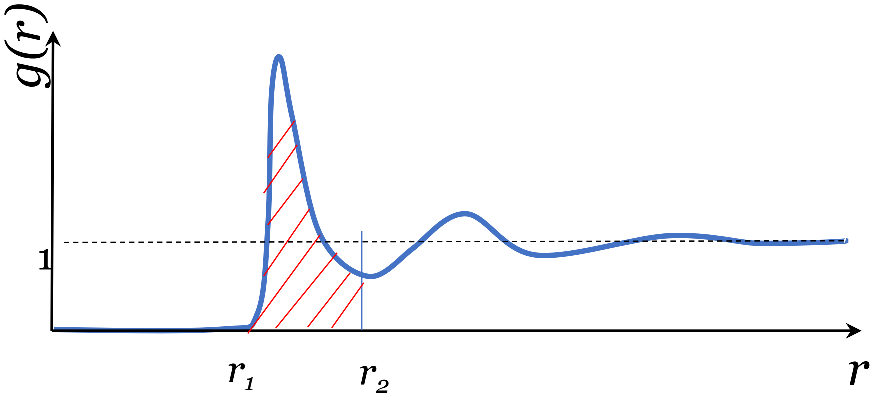
Peak area: proportional with the number of the neighbours in each shell



Coordination number

$$N_c = 4\pi\rho \int_{r_1}^{r_2} r^2 g(r)\, dr$$

N_c: Coordination number (average number of neighbors around a central atom)
ρ = Atomic number density
r1,r2 = limits of the first coordination shell



Measure PDF experimentally → scattering

- the pair distribution function g(r) is related to the measured X-ray or neutron powder diffraction pattern through a Fourier transform

$$g(r) = (2/\pi)\int_{Q=o}^{Q_{\max}} Q[S(Q)-1]\sin(Qr)\,dQ$$

- where S(Q) is the “liquid (or glass) structure factor”

measured and corrected Intensity from powder diffraction

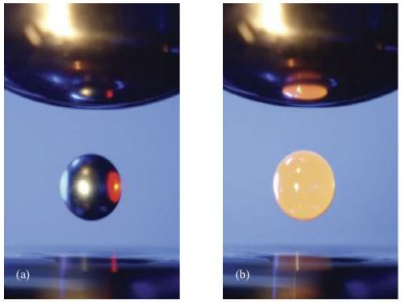
$$S(Q) = \frac{I^{coh}(Q) - \sum c_i \left|f_i(Q)\right|^2}{\left|\sum c_i f_i(Q)\right|^2} + 1$$

the atomic form factor

→ the interaction term of the scattering
i.e. structure factor, see analogy with diffraction of crystal unit cell and later SAXS!)

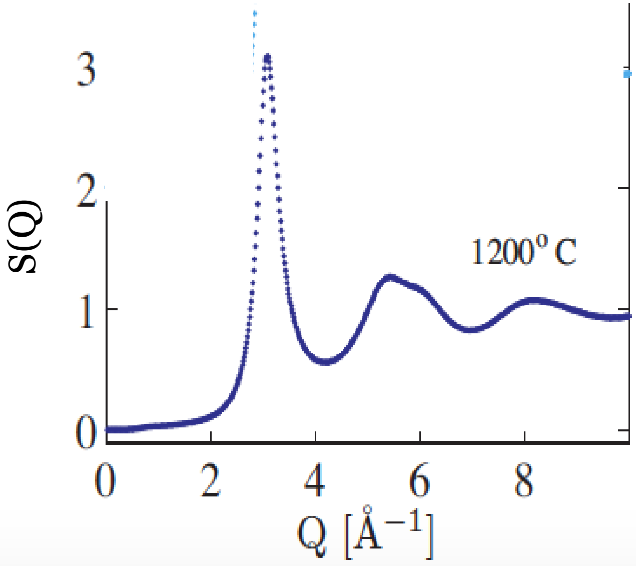
Measure PDF experimentally → scattering

example of PDF of liquid metal

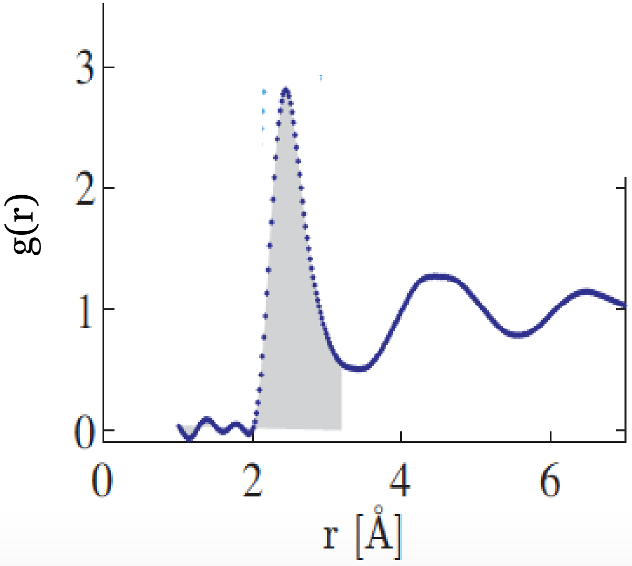


leviating liquid metal droplet
heated with a laser

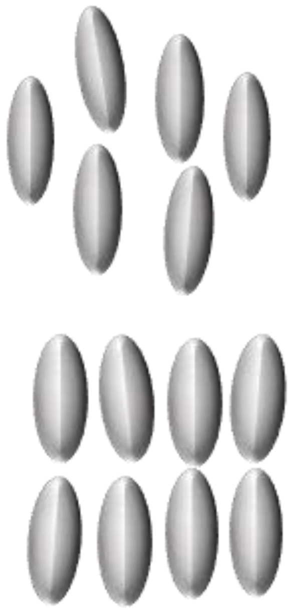
structure factor:
in reciprocal space



PDF
in real space



PDF of liquid-crystals



long-range order
orientational symmetry (nematic)
orient. & transl. sym. (smectic)
liquid (2D or 3D)
densly packed
liquid-crystalline

orientational symmetry is important:
PDF in 2D in order to capture orientation order

PDF of liquid-crystals

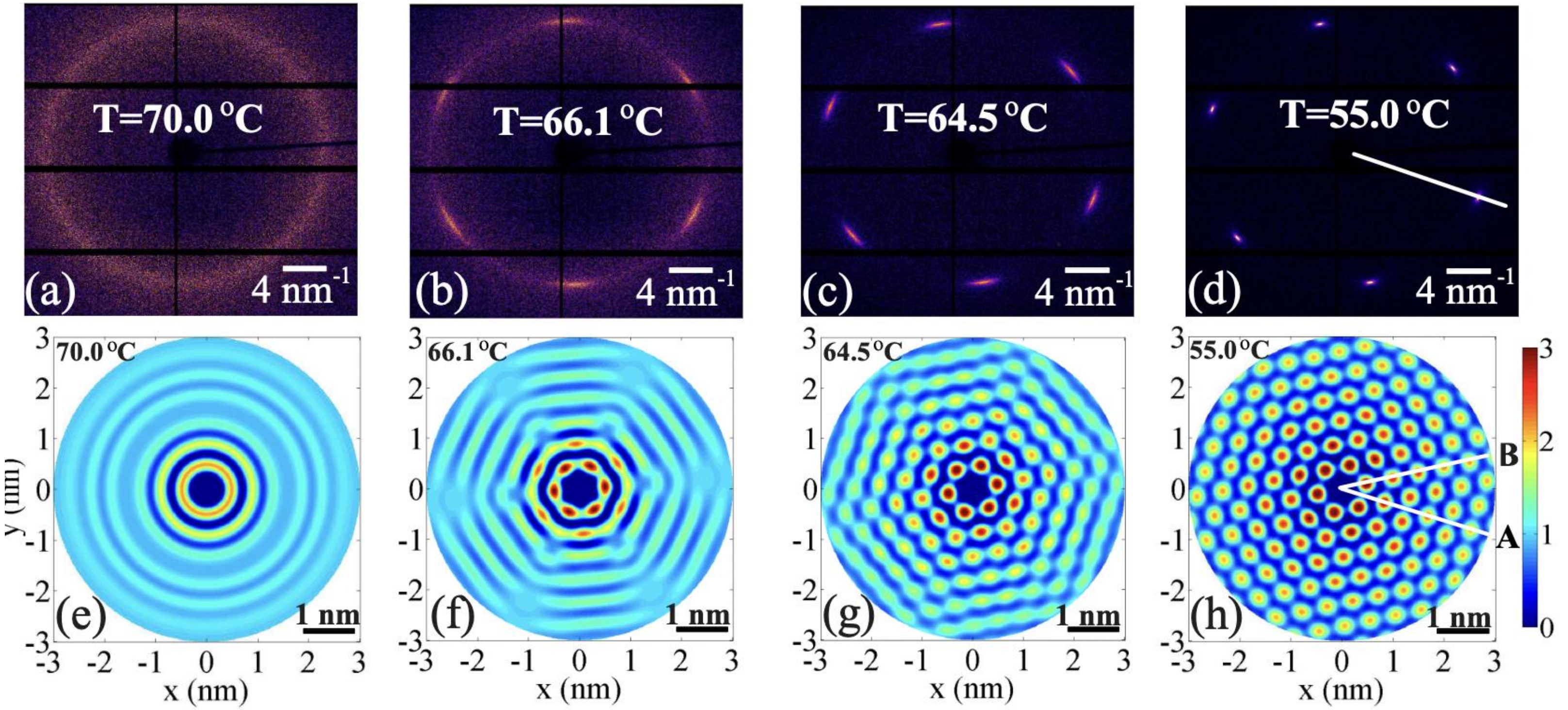


FIG. 1. (a)–(d) Diffraction patterns measured at different temperatures from the LC film undergoing the smectic-*A*-hexatic-*B* phase ansition. (e)–(h) The PDFs $g(\mathbf{r})$ determined from the diffraction patterns (a)–(d).

PDF of liquid-crystals

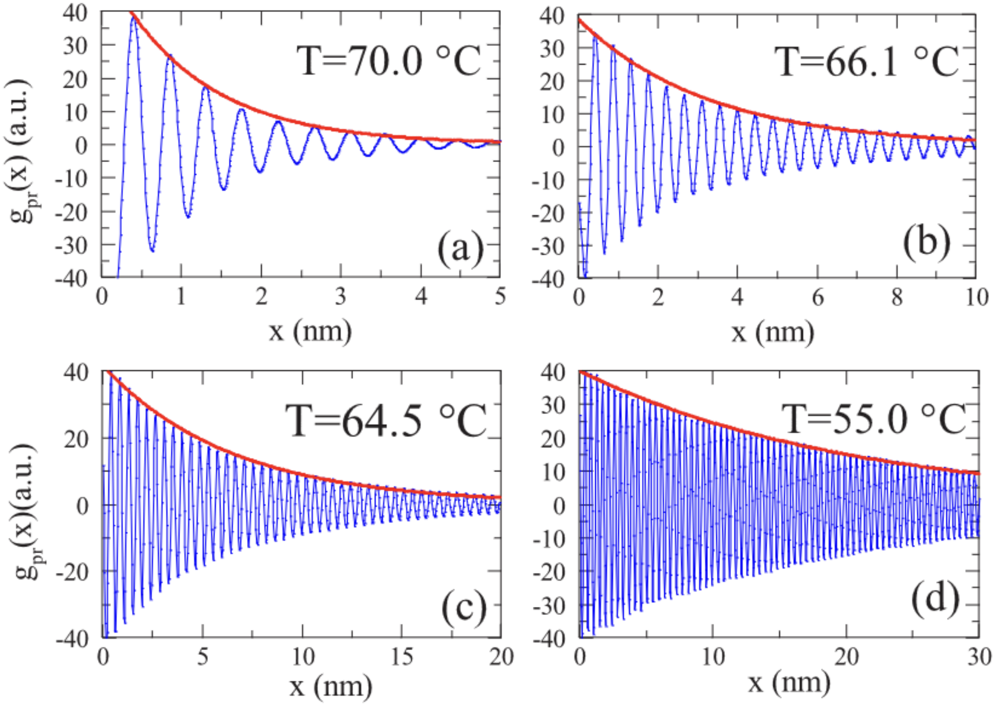
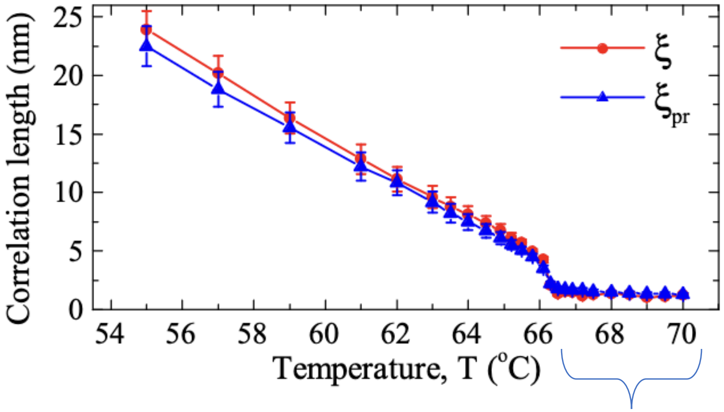


FIG. 3. Projection of the PDF $g_{pr}(x)$ on the direction of the diffraction peak A [see Fig. 1(h)] at different temperatures. The projection $g_{pr}(x)$ is shown with the blue line and the envelope function in the form of an exponent $A\exp(-\gamma x)$ is shown with the red line.

note that in this paper a different definition of gr was used, so negativ values and no correlation at 0 not at 1



increasing long range order

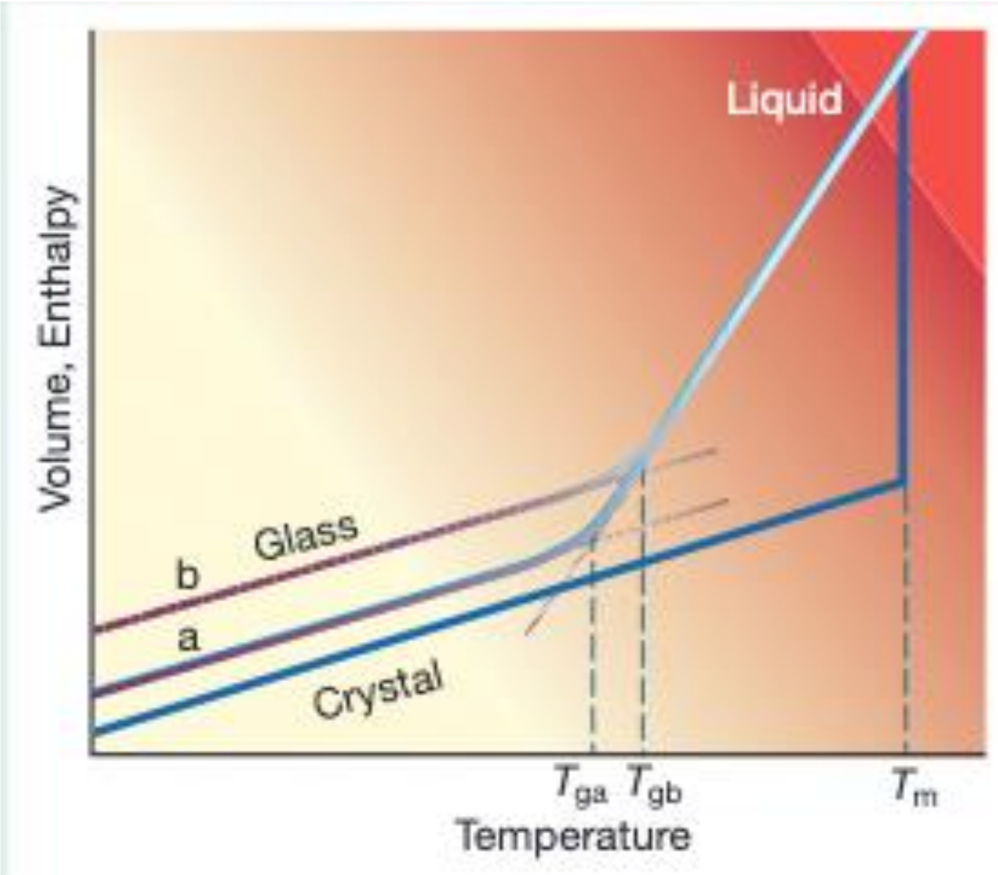
amorphous structure

Amorphous solids: glasses

- metals usually form crystalline solids, but can form glasses → metal glasses
- ceramic materials can be either crystalline or amorphous → mineral glasses
- polymers can be semi-crystalline or completely amorphous → organic glasses

- the amorphous solid state is not thermodynamically stable, crystal structure is preferred
- but depending on the cooling rate most liquids can form amorphous solids, for metal glasses extremly high cooling rates needed, realistic for alloys, not pure metals
- some material can only solidify in glass form, for example branched polymers, too much disorder to crystallize

Glass transition temperature



Crystallization happens at a well defined melting temperature T_m with an abrupt change in the specific volume

Glass transition: The temperature where the glass transition happens depends on the cooling rate
→ glass a) with a slower cooling rate than glass b)

thermal expansion coefficient changes (different slope) but no abrupt change in specific volume

Debenedetti, P. G., & Stillinger, F. H. (2001). Review article Supercooled liquids and the glass transition. *Nature*, *410*(March), 259.

Glass formation

Glass formation is a matter of bypassing crystallization → cooling "quick enough" from above the melting point (T_m) to below the glass transition temperature (T_g) for silicate that can be very slow, for metals it must be very fast.

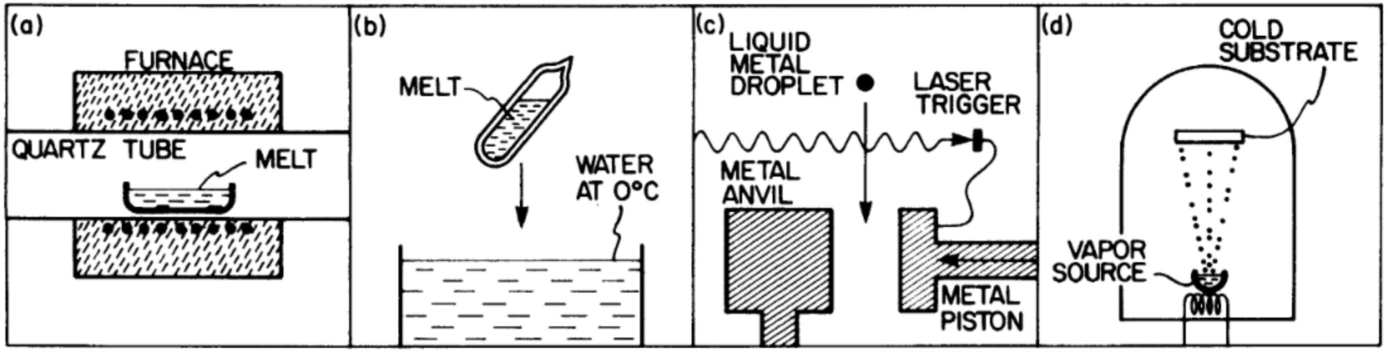


Figure 1.4 Four methods of forming amorphous solids: (*a*) slow cooling, (*b*) moderate quenching, (*c*) rapid "splat-quenching", and (*d*) condensation from the gas phase.

slow → fast

$10^{-4} – 10^{-1}$ K/s

$10^{1} – 10^{2}$ K/s

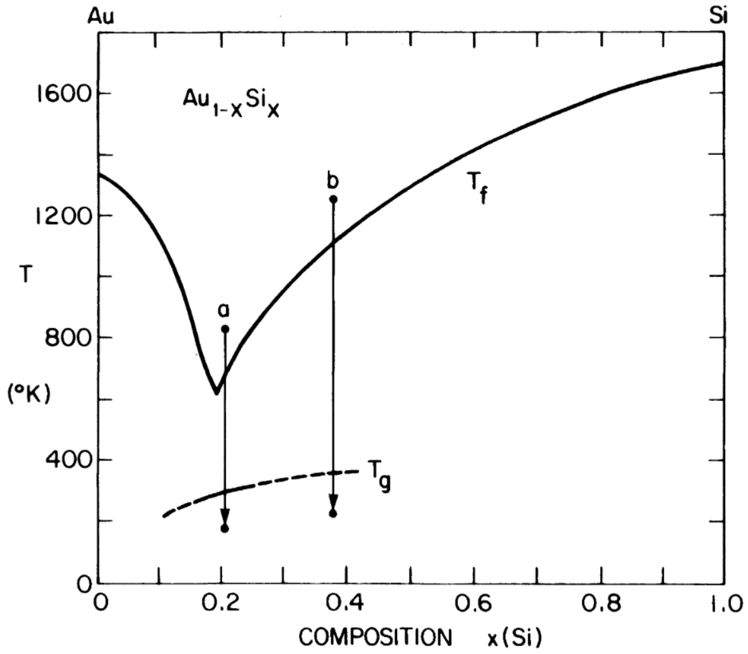
$10^{5} – 10^{8}$ K/s

bypass liquid phase
atom-by-atom
(thin films)

Glass formation

glass-forming tendency is greater for mixtures than for elemental one

example binary mixture of Silicon and Gold



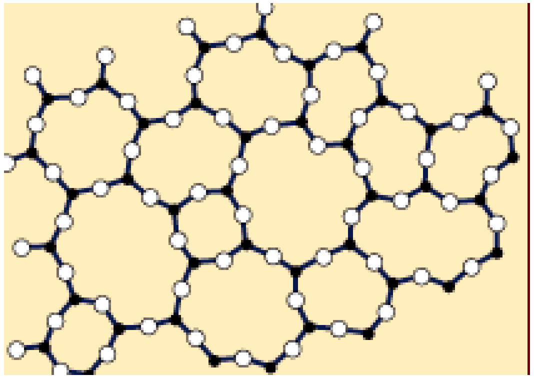
eutectic composition has the highest glass-forming tendency

Figure 1.5 Glass formation in the gold–silicon system. Two quenches from the liquid state, at two compositions, are indicated. Glasses can be prepared much more readily in quench *a* than in quench *b*, since the latter must cross a greater temperature range between T_f and T_g in which it is "at risk" vis-à-vis crystallization. (The T_f curve is from the work of Predel and Bankstahl, 1975; the T_g curve is from the work of Chen and Turnbull, 1968.)

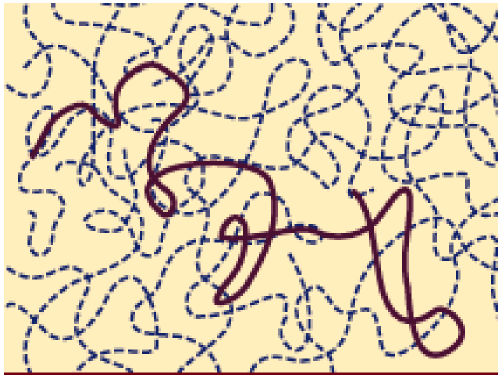
Richard Zallen, "The physics of amorphous solids" Wiley 1998

Atomic scale structure: models

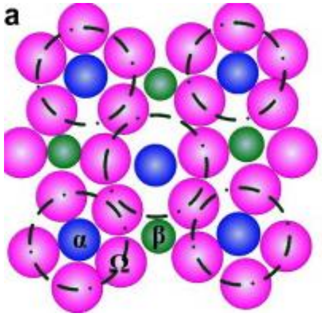
random-network model → covalently bonded glasses (amorphous silicon, oxide glasses)
random-coil model → polymer-chain organic glasses
random close-packing model → metallic glasses



continous random-network model for network glasses



random-coil model for polymeric glasses

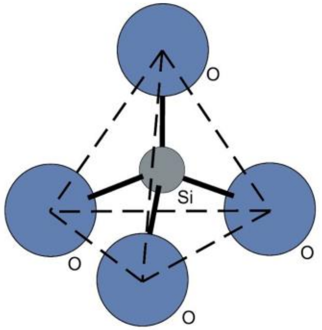


random close-packing model “efficient cluster packing” for metallic glasses

Enyclopaedia Britannica

see polymer lecture week 11 polymers

Silica glass

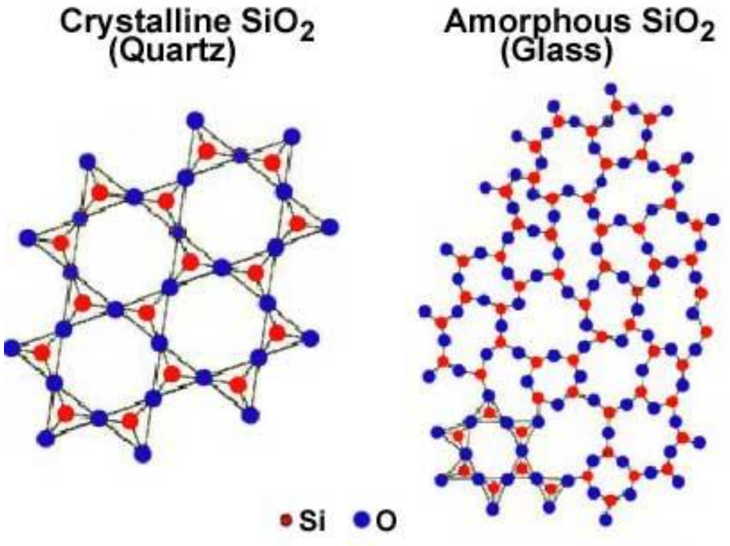


Silica: SiO_2

Si_{14}: $1s^2\ 2s^2\ sp^6\ 3s^2\ 3p_x^1\ 3p_y^1$
O_8: $1s^2\ 2s^2\ 2p_z^2\ 2p_x^1\ 2p_y^1$

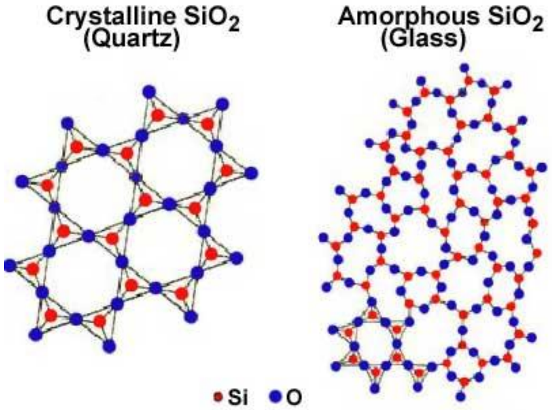
$\Big\}$ sp^3 bonds

Tetrahedra can order in crystalline order or amorphous

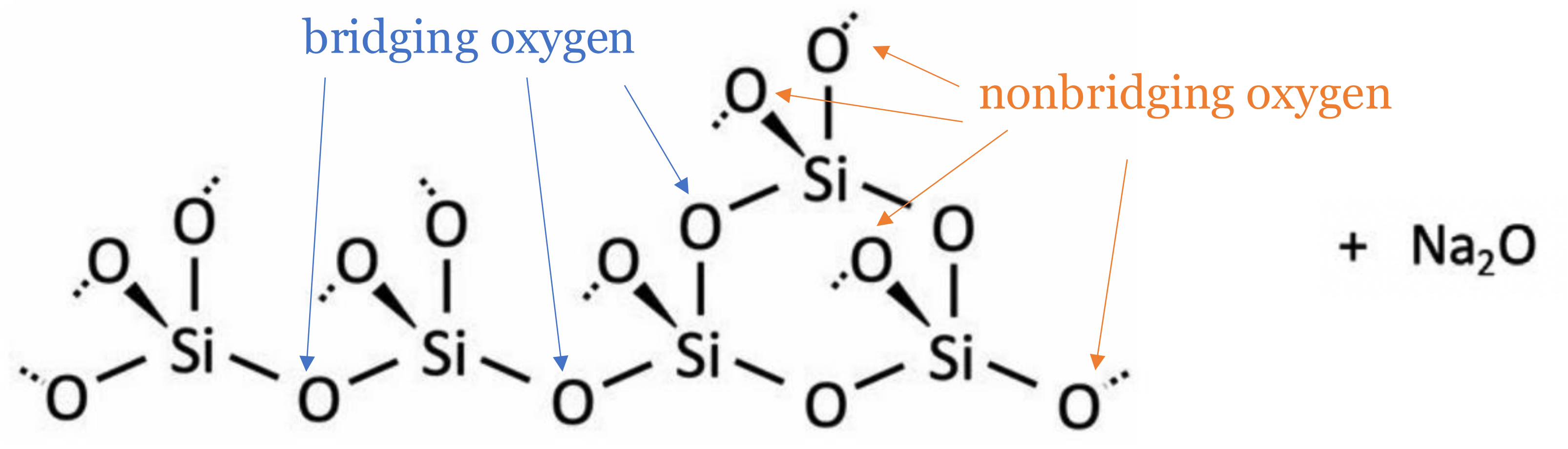


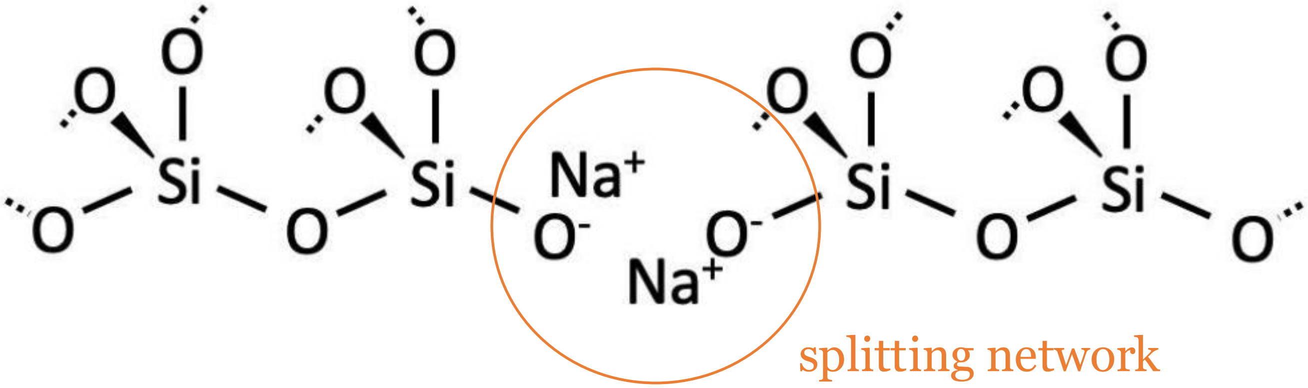
Continous random network model

- Based on the observation that oxid glasses have similar mechanical properties (elastic modulus etc) as crystals: properties are driven by the local bonding
- → continous random network model: three-dimensional network of bonded units that lack translational symmetry, but respects bond functionality and can be extended indefinitely (W.H. Zachariasen 1932)
- chemical species which enter into the structure of the network forming strong chemical bonds with oxygen are called network formers. Chemical species such as Na or Ca, which do not bond directly with the network but sit (in ionic form) within its interstitial holes are called network modifiers → they modify interaction



Network modifiers for Silica





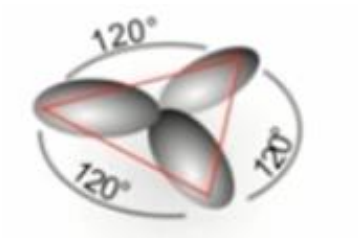
decreases connectivity number of bridging oxygen is reduced

→ change mid-range order

→ change properties and T_g

SiO2 has a very high viscosity, does need very high temperature to get into working range to be formable: network modifiers added to reduce the temperature needed

Borate glass

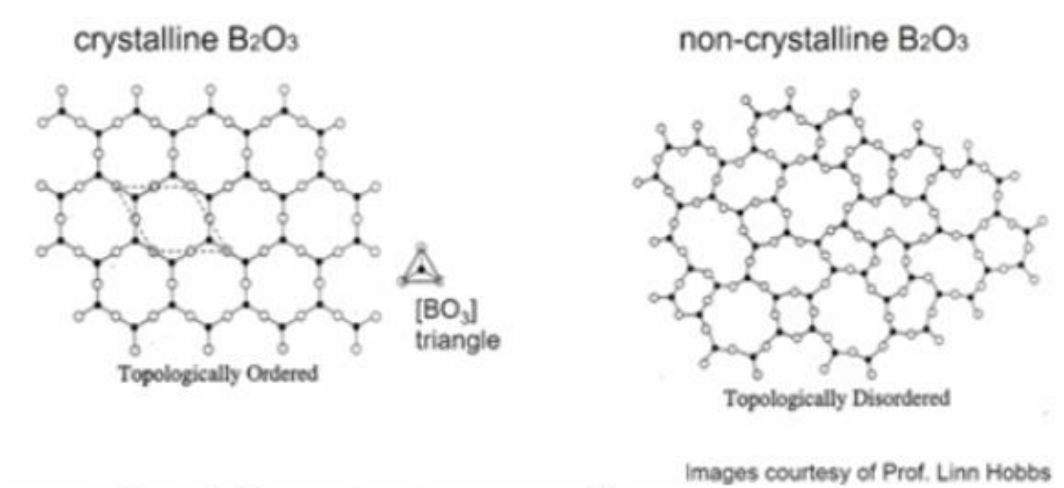


Borate: B_2O_3

B_5: $1s^2\ 2s^2\ 2p_x^1$
O_8: $1s^2\ 2s^2\ 2p_z^2\ 2p_x^1\ 2p_y^1$

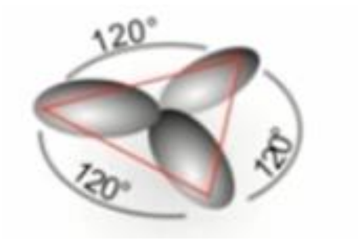
sp^2 bonds

planar can order in crystalline order or amorphous



Images courtesy of Prof. Linn Hobbs

Borate glass and network modifier



Borate: B_2O_3

B_5: $1s^2\ 2s^2\ 2p_x^1$
O_8: $1s^2\ 2s^2\ 2p_z^2\ 2p_x^1\ 2p_y^1$
} sp^2 bonds

<u>connected in plane</u>

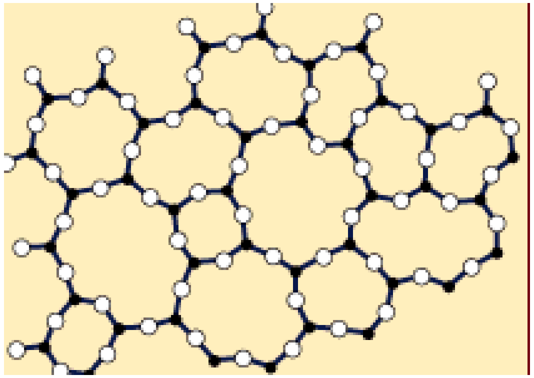
+Na_2O

sp^2 bonds → sp^3 bonds

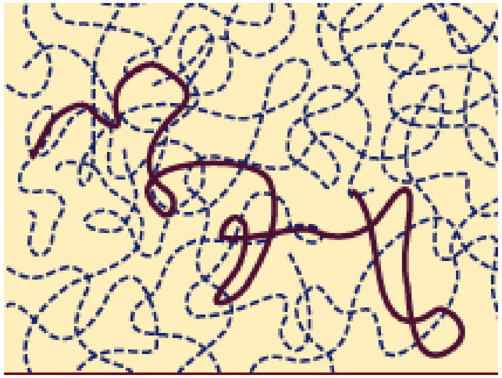
connection will increase as additional connections in three dimensions are possible
stiffer material due to stronger bonding
→ the Boron anomaly

Atomic scale structure: models

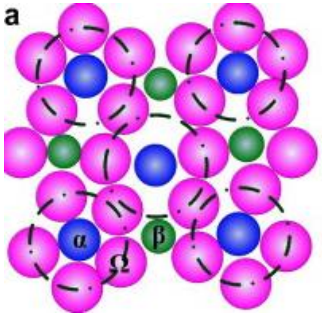
random-network model → covalently bonded glasses (amorphous silicon, oxide glasses)
random-coil model → polymer-chain organic glasses
random close-packing model → metallic glasses



continous random-network
model for network glasses



random-coil model
for polymeric glasses



random close-packing model
“efficient cluster packing”
for metallic glasses

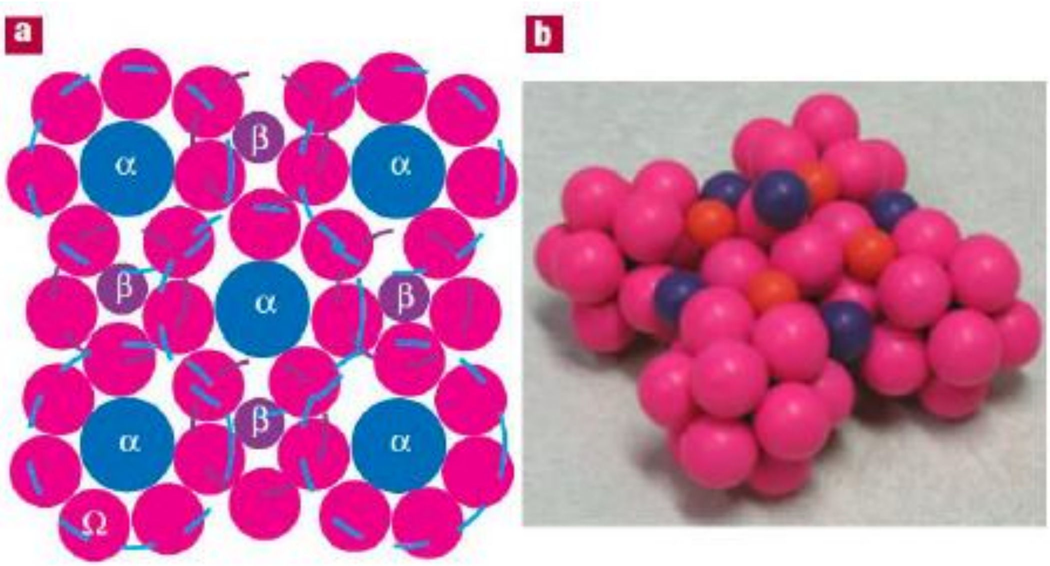
Enyclopaedia Britannica

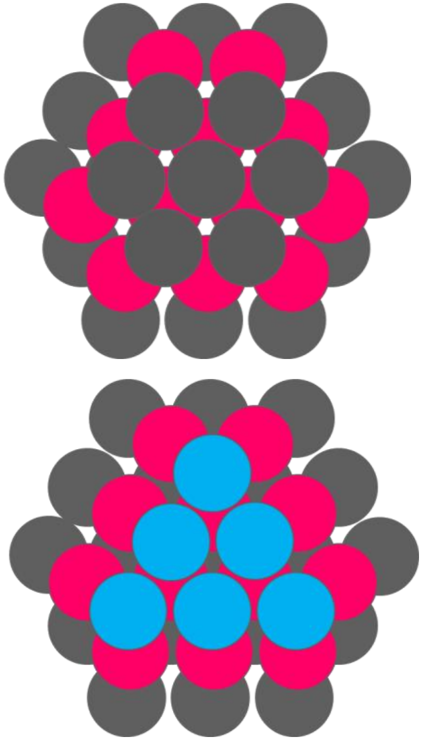
see polymer lecture week 11 polymers

Metallic glasses

- Packing density:
- Face-centered cubic: 74%
- dense random packing of hard spheres: 64% → too low for metallic glasses
- How to pack atoms efficiently without introducing long-range translational order? → certain degree of short- and medium-range order (beyond next neighbor) is required!

Efficient cluster packing



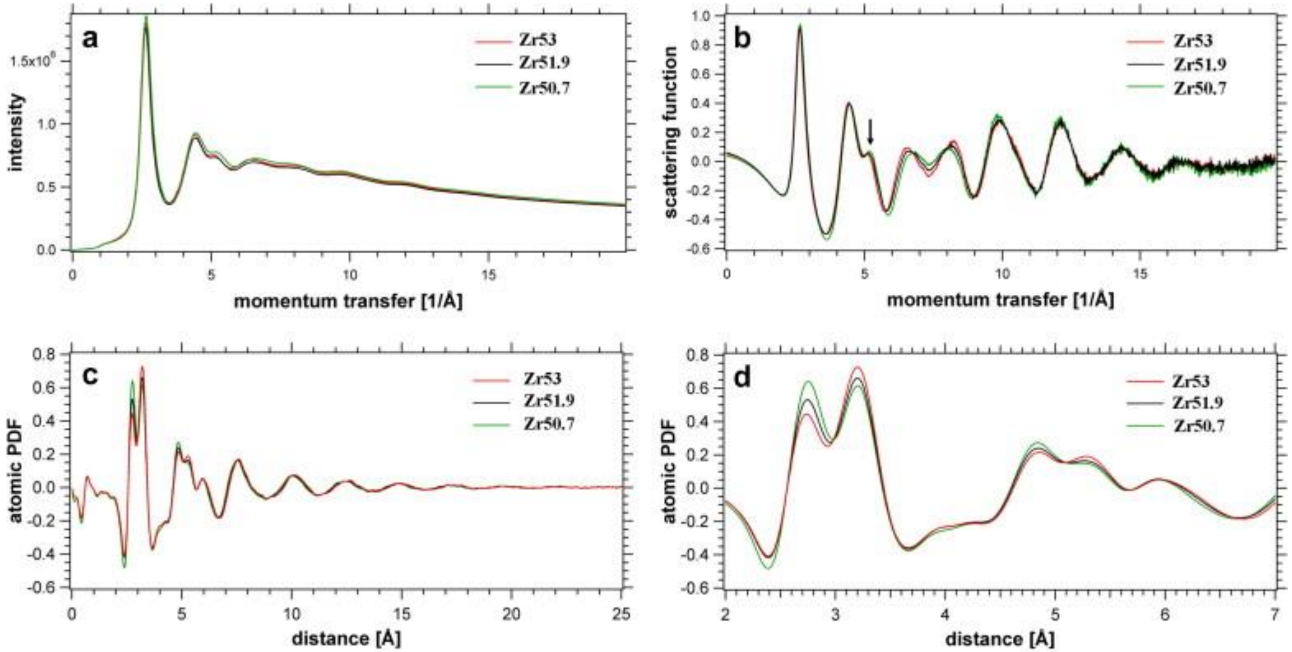


solute-centered clusters in a way similar to face-centered cubic (fcc) or hexagonal close packing
cluster overlap in first coordination shell
no orientational order amongst the cluster (atoms occupy random positions)

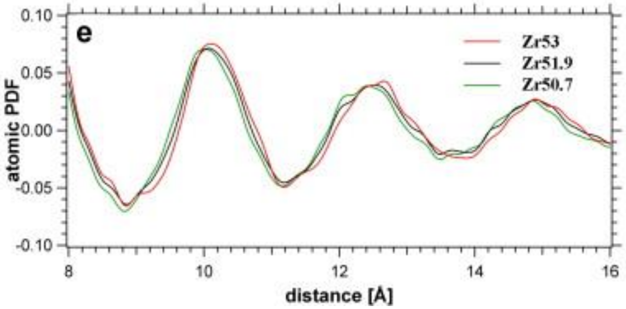
→ efficient cluster packing, also known as Miracle model

D.B. Miracle, *Nature Materials* 3 (2004) 697-702

Metallic glass: PDF analysis



→ mid-range order extending further than the nearest neighbor



Synchrotron radiation high-energy X-ray diffraction results for the as-cast Zr53, Zr51.9 and Zr50.7 bulk amorphous alloys: (a) intensity-quantum transfer ($I(Q)$–Q) curves; (b) scattering function-quantum transfer ($S(Q)$–Q) curves; (c) atomic pair distribution functions, and the zoomed view of the near range (d) and the far range (e) of (c).

Y.J. Sun, *et al*. Zr–Cu–Ni–Al bulk metallic glasses with superhigh glass-forming ability,
Acta Materialia, 57, 4,2009

Properties crystals vs. glasses

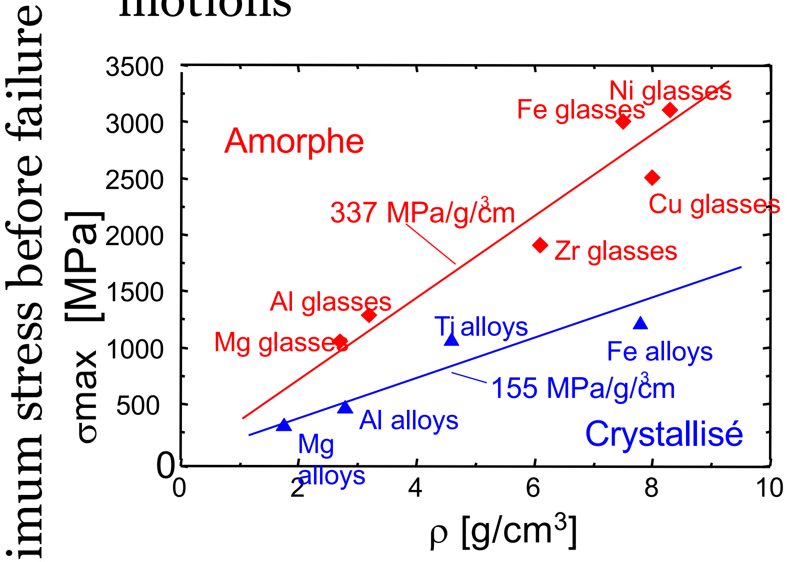
- electrical and thermal conductivity: lower conductivity due to the disorder which impedes the motion of the mobile electrons
- difference in optical spectra (crystals often exhibit sharp features)
- transparency often higher in glass state due to the absence of grain boundaries and defects (scattering light)
- viscosity: crystal have an aprubt change from liquid to solid with $T_{m,}$ glasses have a continous liquid-to-solid transition T_g

→ tuneable viscosity with temperature (glass-blowing, formable)

→ in polymers above the glass transition temperature: rubber state

Metallic glasses

- Metallic glasses have remarkable mechanical properties due to their atomic structure.
- in crystalline metal energy is absorbed and dissipated through dislocation movements, the disordered structure of amorphous material minimizes dislocation motions

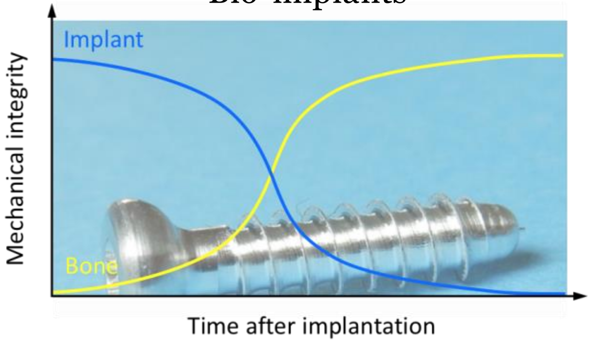


J. Loeffler, ETHZ

https://www.giantbomb.com/images/1300-370232

high elasticity
→ greater energy return

Bio-implants



Prof. Löffler group at ETH Zurich

amorphous Mg-alloys
high wear resistance
mechanical strength similar than bone
biocompatible
biodegradable

Application of glasses

type of amorphous solid	**representative material**	**application**	**special properties**
oxide glass	$(SiO_2)_{0.8}(Na_2O)_{0.2}$ $(SiO_2)_{0.9}(GeO_2)_{0.1}$	window glass fibre-optic	transparency formable purity, ultratransparency, formable
organic polymer	polystyrene, PMMA	structural materials, plastics shatter proof glass	light weight, ease of processing shock resistance
chalcogenide glass	Se, As_2Se_3 Ge-Sb-Te	copiers and laser printers memories	photoconductivity phase change
amorphous semiconductor	$Si_{0.9}H_{0.1}$	solar cells, copiers, flat-panel displays	photovoltaic optical properties, large-area thin films, semiconducting properties
metallic glass	$Fe_{0.8}B_{0.2}$ $Mg_{60}Zn_{35}Ca_5$ $Zr_{58}Cu_{15.6}Ni_{12.8}Al_{10.3}Nb_{2.8}$	transformer cores Bone implants Sports, anti-wear	ferromagnetism, low power loss dissolves in body elasticity, resistance, corrosion
ionic glasses (salts)	Esomeprazole	Pharmaceuticals	Bioavailability (soluble)

from Britannica Academic

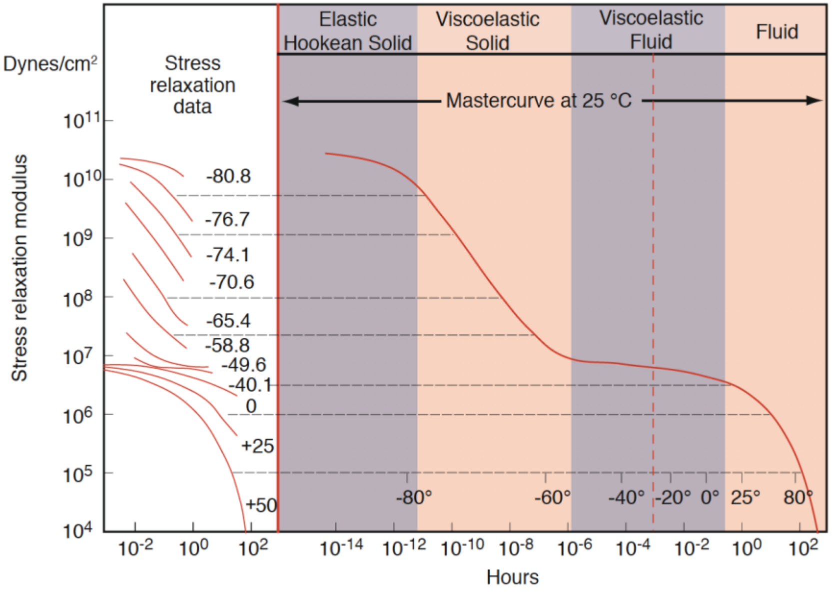
Glasses in pharameceutics: Bioavailability

- drug in glass state have in general a better solubility and therewith a better biological availability than their crystal state
- in mixtures glasses are formed much easier, since crystallization is hindered
  →drug formulations with polymer mixture to stabilize the amorphous form

→example: HIV antiretroviral therapy Kaletra®
the anti-viral drug Lopinavir is in its crystalline form very poorly solutble in water
if hot-melt extruded together with Ritonavir they form an amorphous solid dispersion → massively improves oral bioavailability

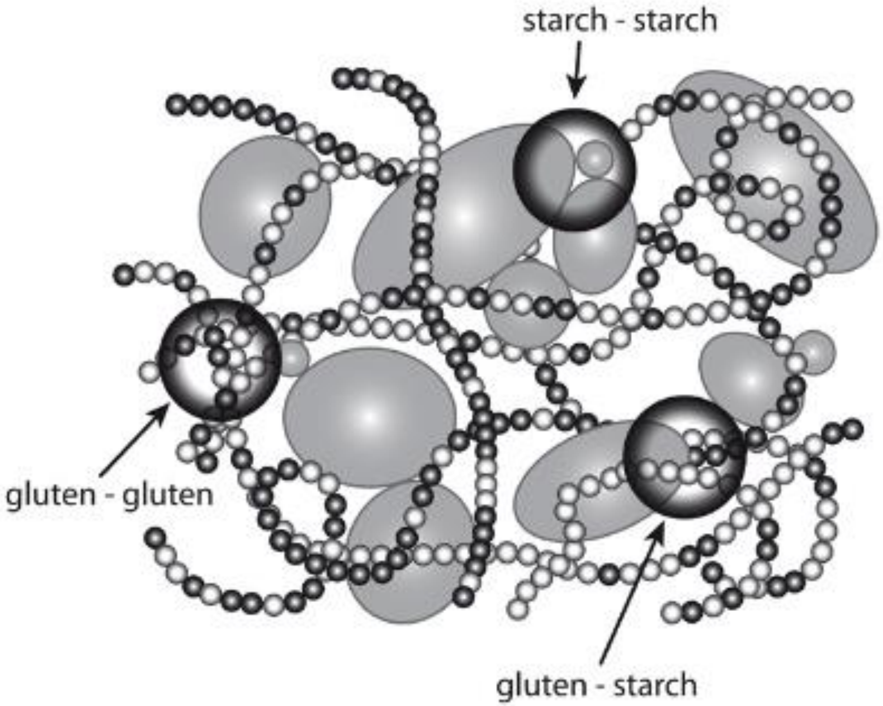
Glasses in Food: Texture

- amorphous structure such as rubber and glass have very different texture compared to crystalline structures
- Bread becoming hard/stale: recrystallization of previously amorphous starch
- Polyisobutylene: chewing gum, glass transition at around -70°C, but influenced by water content (plastizier)



Glasses in Food: Pasta

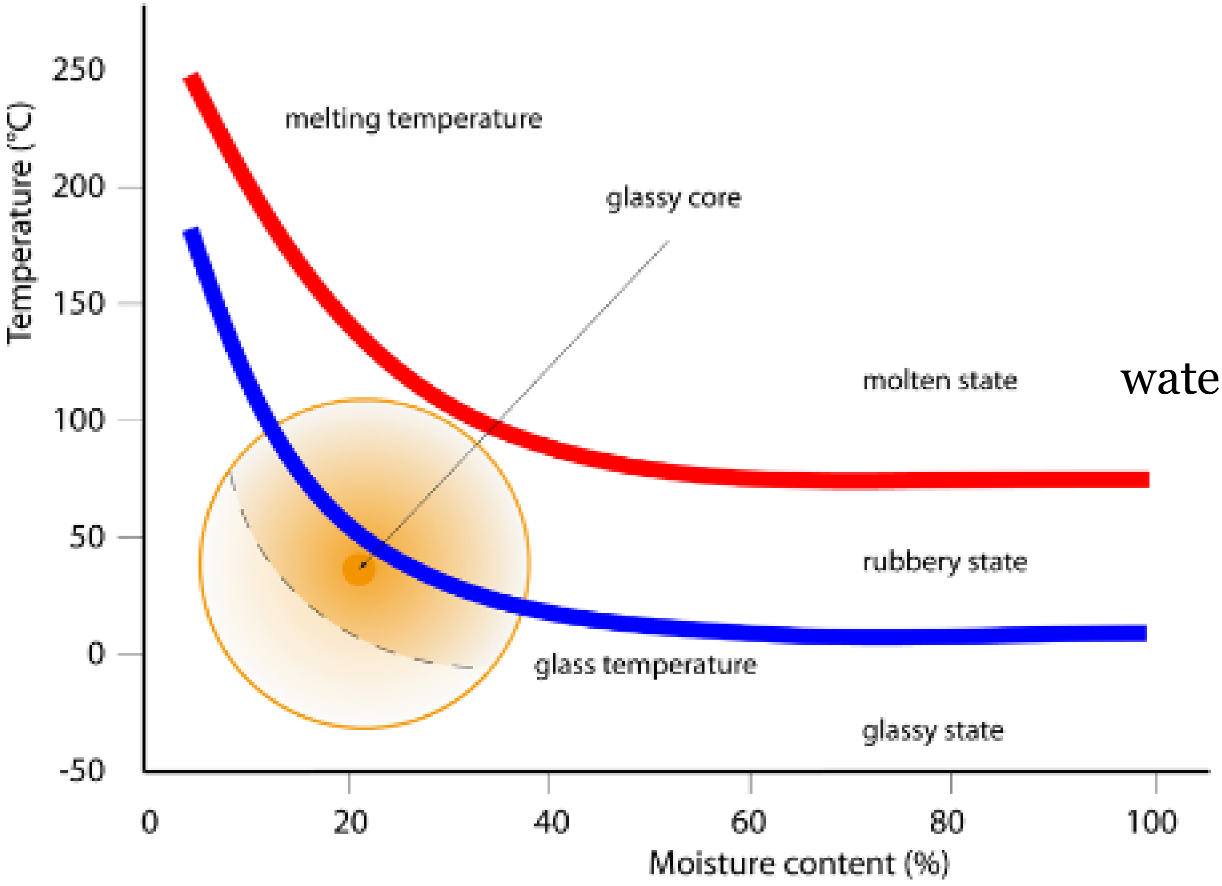
- dough: starch, gluten and water (and air bubbles)



starch in native state is crystalline, in mixture higher glass forming tendency

“Soft matter food physics – the physics of food and cooking”
T.A. Vilgis, Rep. Prog. Phys. 78, 124602, (2015)

Pasta – al dente

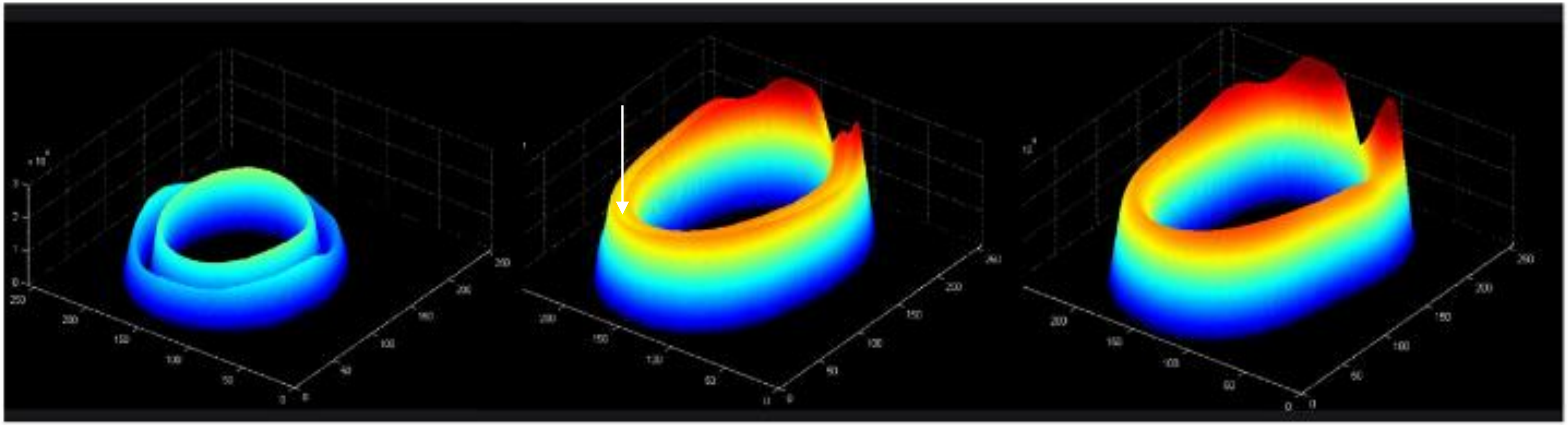


water acts as plasticizer!

T.A. Vilgis, Rep. Prog. Phys. 78, 124602, (2015)

Pasta – al dente

NMR imaging: qualitative visulization of water uptake in penne



after short cooking time

right cooking time

overcooking

T.A. Vilgis, Rep. Prog. Phys. 78, 124602, (2015)

Glasses in Food: Texture

- amorphous structure such as rubber and glass have very different texture compared to crystalline structures
- Polyisobutylene: chewing gum, glass transition at around -70°C, but influenced by water content
- al dente pasta: core is still in glassy state
- Bread becoming hard/stale: recrystallization of previously amorphous starch
- Potato chips: glassy state: if left open and humidity is taken up → transition to rubber state

Summary

- structure characterization of amorphous structure → average parameters, statistical description instead of one fixed parameter (for coordination number, bond length, bond angle distribution etc.), density, free volume
- long-range, mid-range and short-range order
- pair-distribution function: local density in the structure of a reference atom/molecule: typical curves for crystalline, gas, liquid/glass
- liquid crystals: orientational long-range order
- types of glasses: metal, mineral and organic glasses
- glass formation and glass transition temperature: bypass crystallization
- atomic scale structure models
  - continous random-network model (silica and borate glass), network modifieres
  - random coil model (polymeric glasses) → next week
  - efficient cluster packing (metallic glasses)
- examples of application and properties of glasses