Vorlesung zum Haupt/Masterstudiengang Physik

Methoden Moderner Röntgenphysik II: Struktur und Dynamik Kondensierter Materie

Surfaces	(OHS)
Applications in Soft Matter	(MMAK / SVR)

Mottakin M. Abul Kashem / Stephan V. Roth (SVR)

Applications in Soft Matter

20.04.2010	An Introduction to Polymer Physics
22.04.2010	Small-Angle X-ray Scattering and its Applications
27.04.2010	Polymer, Colloidal and Nanocomposite Surfaces I
29.04.2010	Polymer, Colloidal and Nanocomposite Surfaces II

Aim:
Overview over using X-ray scattering to
understand soft matter

Why Polymers???

Automotive industry

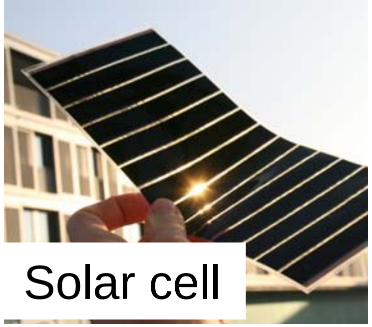
Electronics

Soaps/detergent

Medicine

Packaging industry

Textile industry



Solar cell

1. Commodity polymers: plastic shapes, packaging, bottles for beverages…

PMMA, PS, PE, PP, PET,...

2. High-performance polymers: outstanding chemical resistance and/or mechanical properties, heat resistance

PTFE, PVDF, PEEK, polyimides,…

3. Functional polymers: tailor-made molecular architecture results in specific optoelectronic properties and “smart” behavior

Materials for nanotechnology

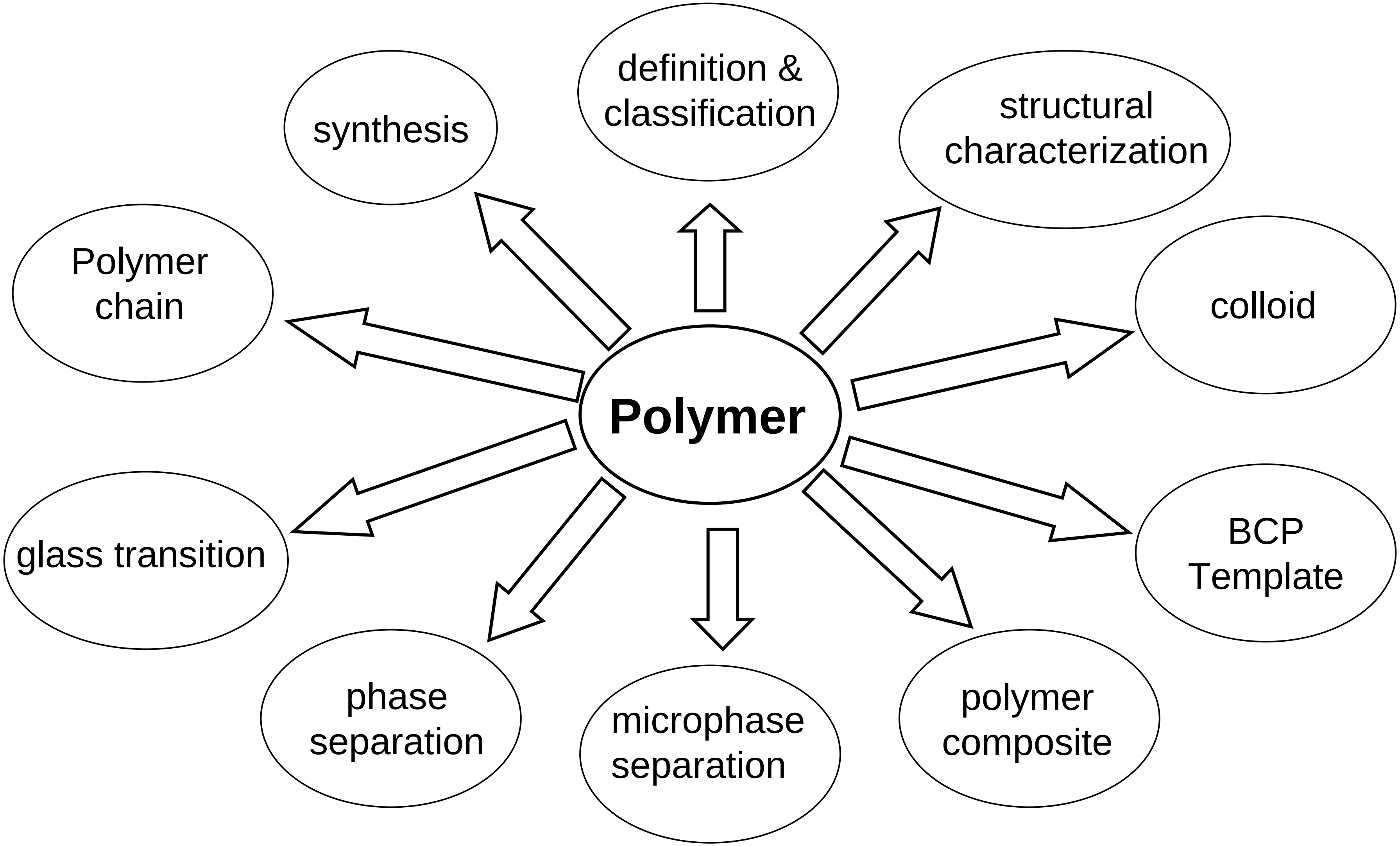
4. Biopolymer: found in nature, replacing the commodity and functional polymers

starch, protein, DNA, RNA

Flexible properties and diverse application!!!

Why?

An Introduction to Polymer Physics



Polymer

synthesis

definition & classification

structural characterization

Polymer chain

colloid

glass transition

BCP Template

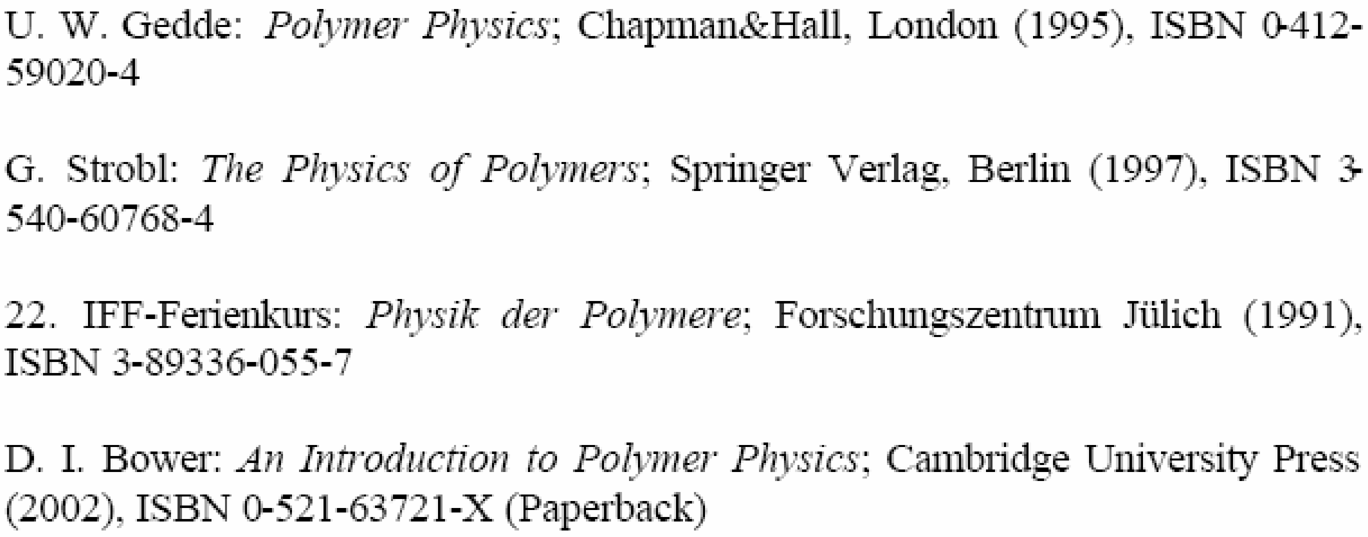
phase separation

microphase separation

polymer composite

Literature

Physics



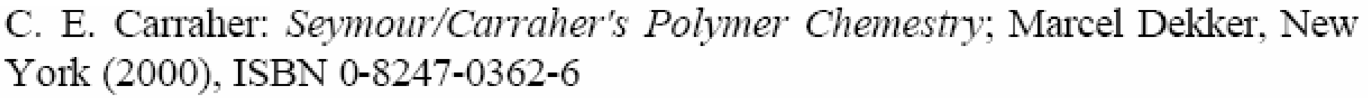
U. W. Gedde: *Polymer Physics*; Chapman&Hall, London (1995), ISBN 0-412-59020-4

G. Strobl: *The Physics of Polymers*; Springer Verlag, Berlin (1997), ISBN 3-540-60768-4

22. IFF-Ferienkurs: *Physik der Polymere*; Forschungszentrum Jülich (1991), ISBN 3-89336-055-7

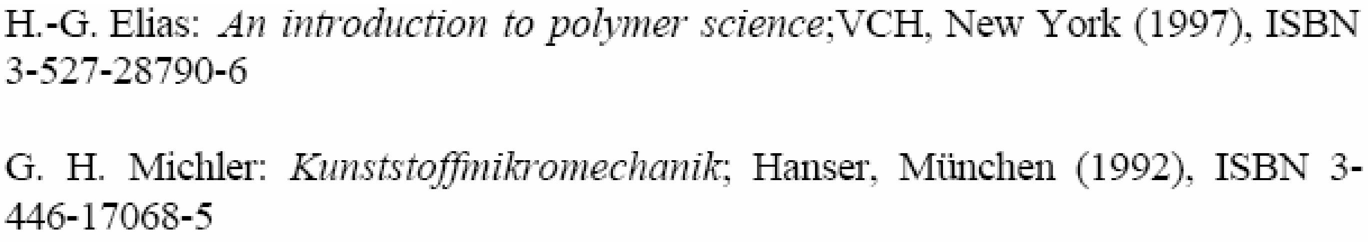
D. I. Bower: *An Introduction to Polymer Physics*; Cambridge University Press (2002), ISBN 0-521-63721-X (Paperback)

Chemistry



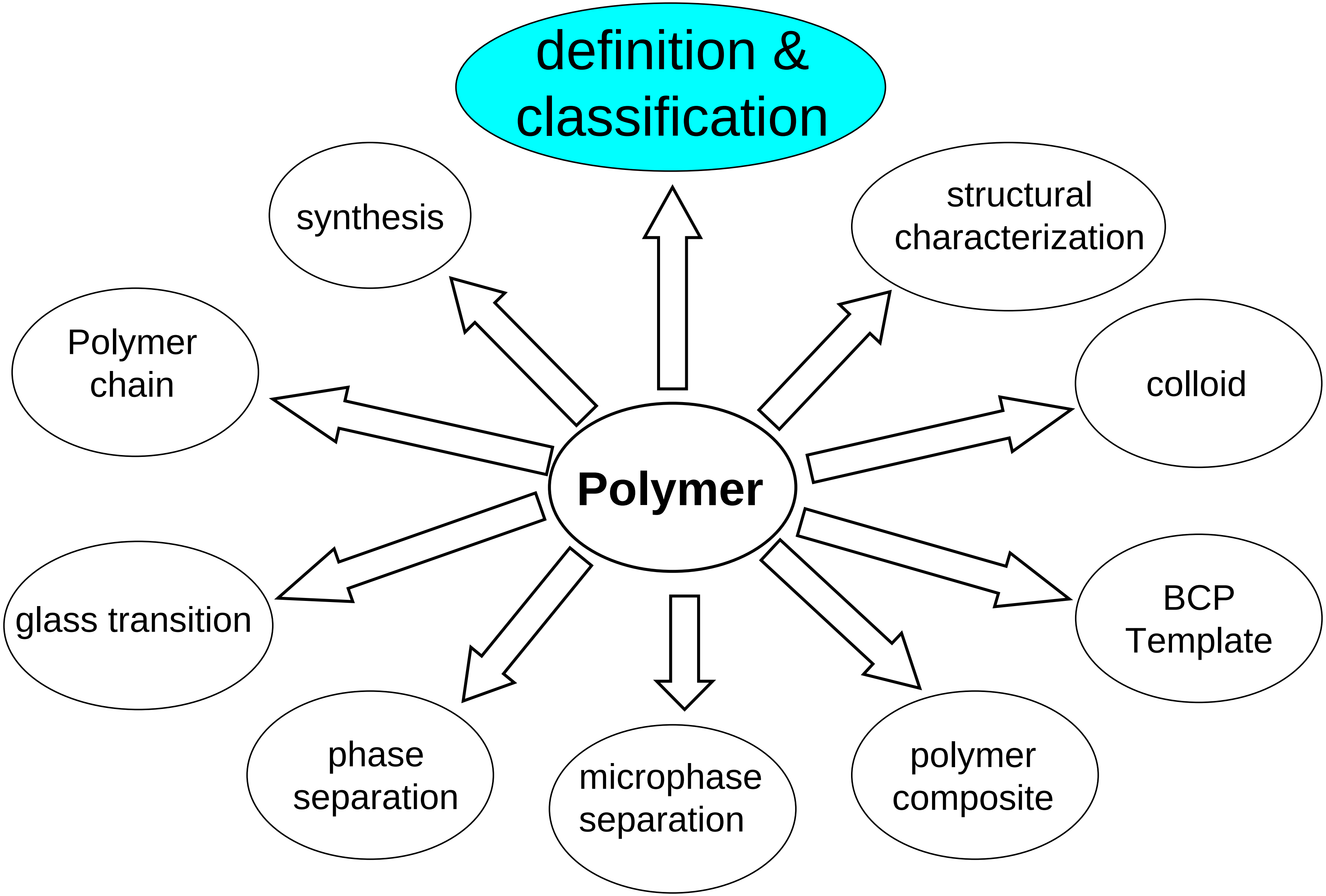
C. E. Carraher: *Seymour/Carraher's Polymer Chemestry*; Marcel Dekker, New York (2000), ISBN 0-8247-0362-6

Material Sciences



H.-G. Elias: *An introduction to polymer science*;VCH, New York (1997), ISBN 3-527-28790-6

G. H. Michler: *Kunststoffmikromechanik*; Hanser, München (1992), ISBN 3-446-17068-5



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polymer composite

basic definitions

Polymer: *polys* --- many, *meros*---parts : Macromolecules built up of a large number of molecular units that are linked together by covalent bonds. Usually they represent organic compounds, containing carbon atoms together with hydrogen, nitrogen, and halogens, etc.

According to the IUPAC (*International Union of Pure and Applied Chemistry*)
Polymer is a substance composed of macromolecules. A macromolecule is a molecule having high relative molar mass, the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molecular mass.

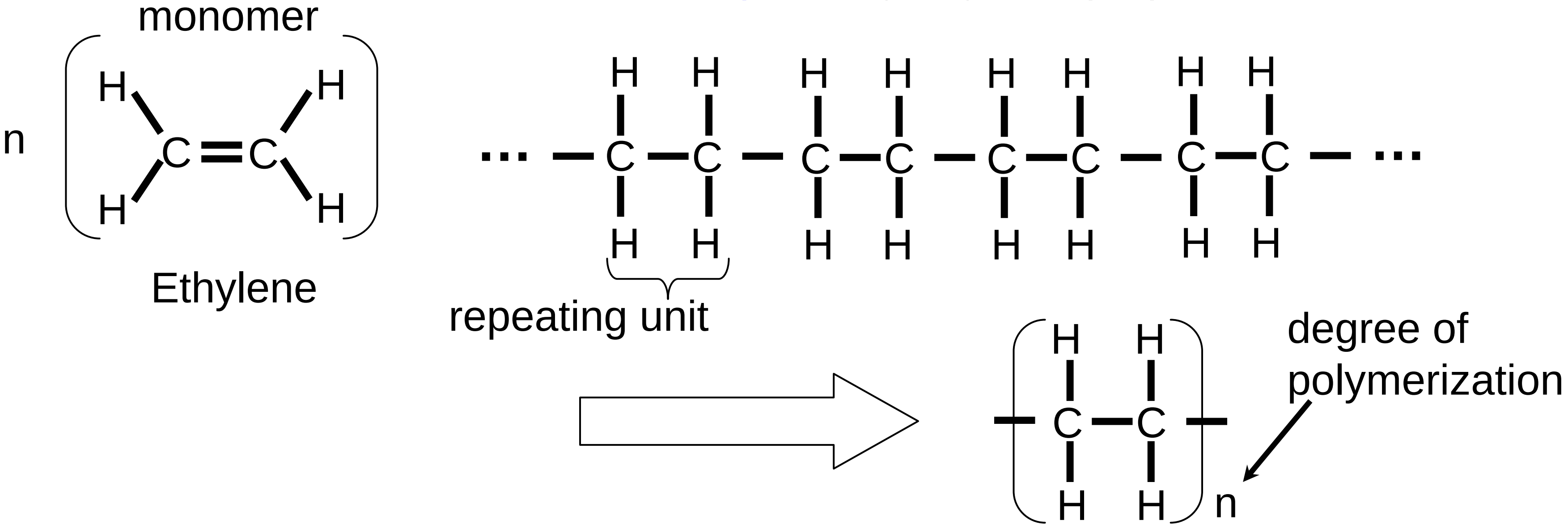
To distinguish polymers from other chain molecules scientists use quite often one general classification of molecules based on their molecular weight, M_W. This classification is following:

- Micromolecule with $M_W < 1{,}000$ g/mol
- Oligomer with $M_W \approx 1{,}000$ - $10{,}000$ g/mol
- Polymer with $M_W > 10{,}000$ g/mol

basic definitions

Monomer: Chemically identical small molecules having the potential of chemically binding to other monomers of the same species to form a Polymer.

Standard example: Polyethylene (PE)



Polyethylene (PE)

Polymerization: polymerization is a process of reacting monomers together to form a higher molar mass polymer chains.

Degree of polymerization: The number of monomer units present in one single polymer chain is called degree of polymerization and denoted often as N.

basic definitions

Molecular weight

- Polymerization reaction yields macromolecules of different chain length!!!
- The molar mass of polymer is characterized by the molar mass distribution function.

M -----------Molar mass

$\rho(M)$ --------Number density distribution function

Normalizing $\int\limits_0^\infty \rho(M) dM = 1$

- Number average molecular weight:

$$\boxed{\overline{M_N} = \int\limits_0^\infty \rho(M) M dM}$$

- Weight average molecular weight:

$$\boxed{\overline{M_W} = \frac{\int\limits_0^\infty \rho(M) M \cdot M dM}{\int\limits_0^\infty \rho(M) M dM}}$$

- Weight fraction $\rho' = \dfrac{\int\limits_0^\infty \rho M}{\int\limits_0^\infty \rho(M) M dM}$

basic definitions

Note: $\overline{M}_W > \overline{M}_n$

- Polydispersity: $\boxed{P = \frac{\overline{M_W}}{\overline{M_N}}}$
- Polydispersity coefficient /index $\boxed{U = \frac{\overline{M}_W}{\overline{M}_n} - 1}$

- Centrifugal average or Z-average $\overline{M}_z$
- Viscosity average $\overline{M}_\eta$

Molar mass distribution function

- Schulz-Zimm => step polymerisation (polycondensation)

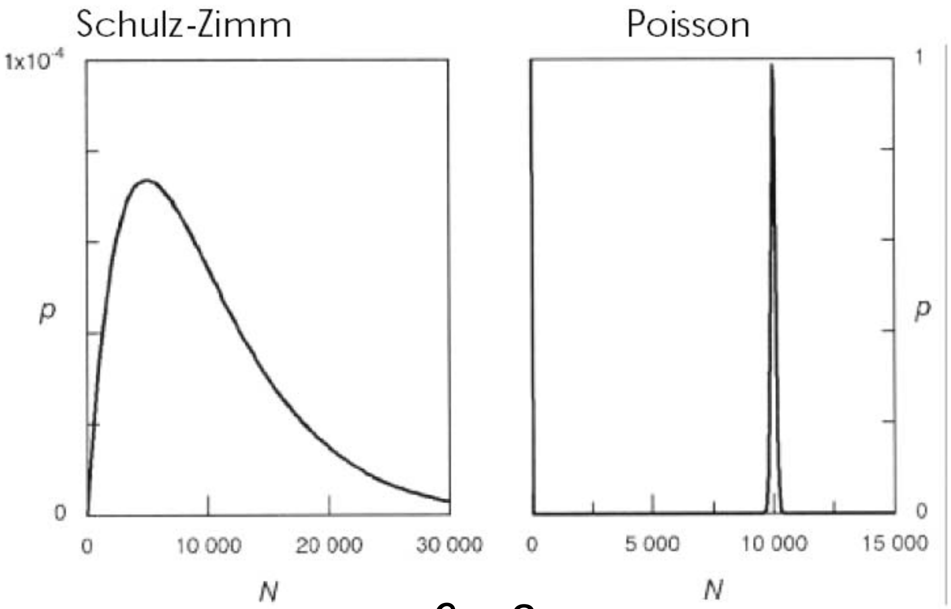
$$p(N) = \frac{1}{\Gamma(\beta)}\left(\frac{\beta}{\overline{N}_n}\right)^{\beta} \cdot N^{\beta-1} \exp - \frac{\beta N}{\overline{N}_n} \quad \Rightarrow \quad U = \frac{1}{\beta}$$

- Poisson => chain polymerisation (anion)

$$p(N) = \exp - \overline{N}_n \cdot \frac{\left(\overline{N}_n\right)^{N}}{\Gamma(N+1)} \approx \exp - \overline{N}_n \left(\frac{\overline{N}_n e}{N}\right)^{N} \quad \Rightarrow \quad U = \frac{1}{\overline{N}_n}$$

β determines the shape

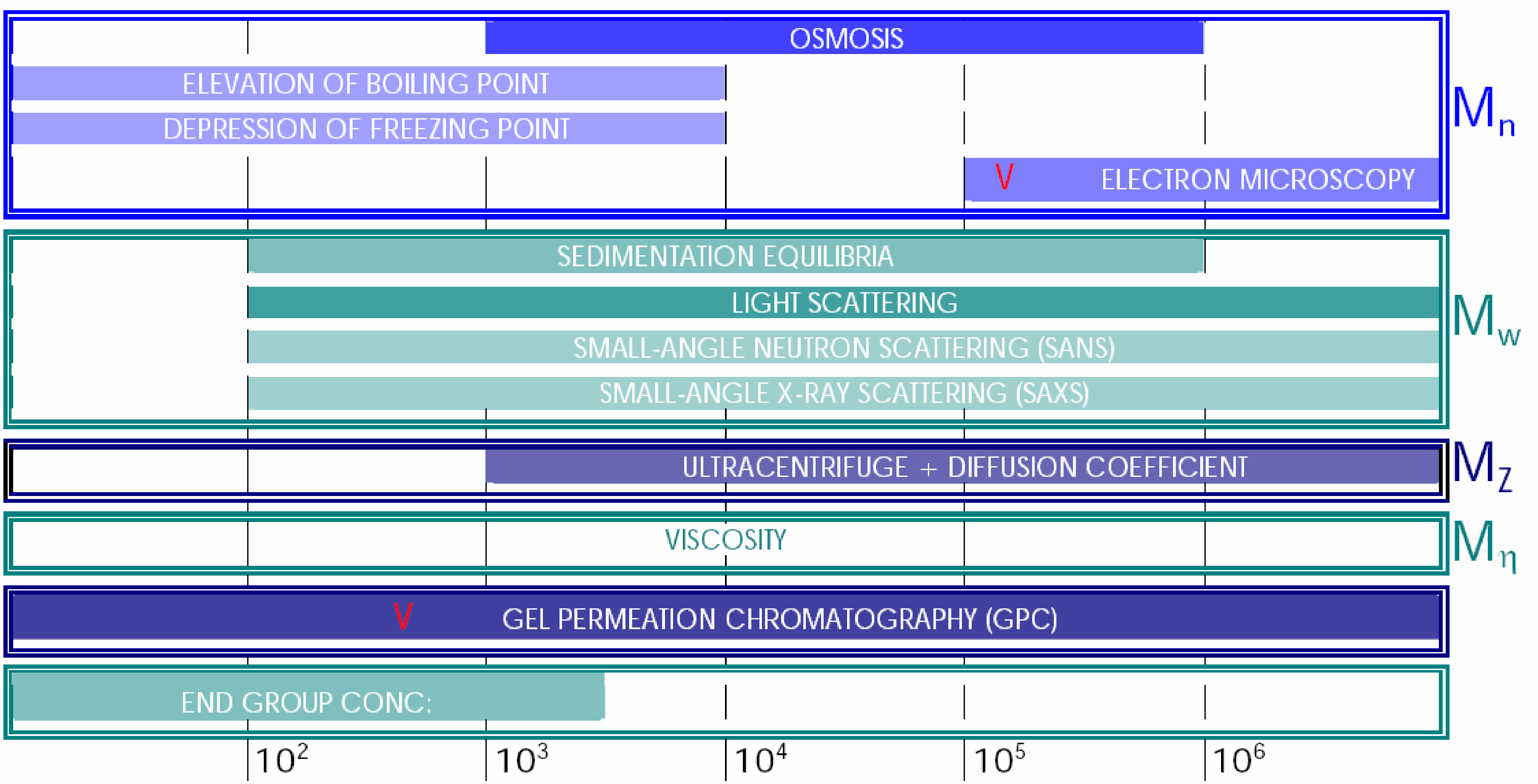
$\overline{N}_n$ Number average degree of polymerization



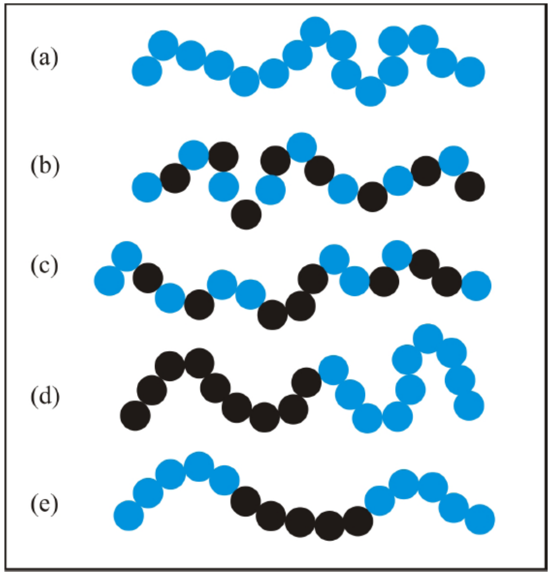
$\beta = 2$

$\overline{N}_n = 10{,}000$

Molecular weight determination



Nomenclature



- According to the basic repeating unit, e.g.

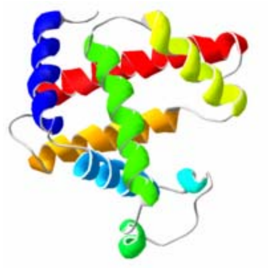
Polypropylene - PP, Poly(mehtylmethacrylate) – PMMA, Polystyrene - PS, Poly(ethyelene terephtalate) – PET, Poly(p-phenyleneterephtahalamide) – PPTA

- trade names: Kevlar, Nylon, Aramid, Plexiglas etc.
- IUPAC: Poly (1-phenyl ethylene) -- PS

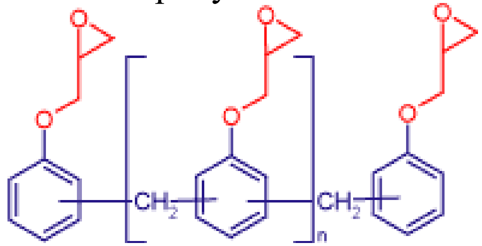
Type		**Example**
Homopolymer (a)		PolyA
Not specific	-co-	Poly(A-co-B)
Statistical	-stat-	Poly(A-stat-B)
Random (c)	-ran-	Poly(A-ran-B)
Periodic	-per-	Poly(A-per-B)
Alternating (b)	-alt-	Poly(A-alt-B)
Network	net-	Net-Poly A
Diblock (d)	-*b*-	Poly (A-*b*-B)
Triblock (e)	-*b*-	Poly (*A*-*b*-B-*b*-A)

Classification

myoglobin



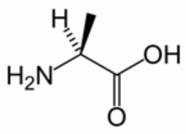
epoxy novolacs



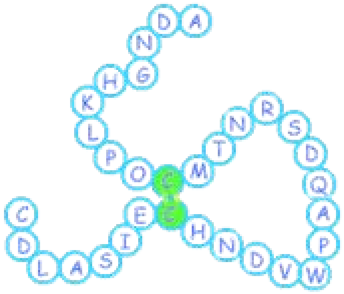
polymer

- natural
  - protein, DNA, RNA
  - polysaccharide
- elastomer
- synthetic
  - thermoplastic
  - thermosetting

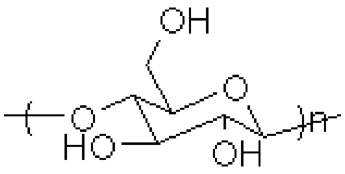
(amino acid sequence)



L-alanine



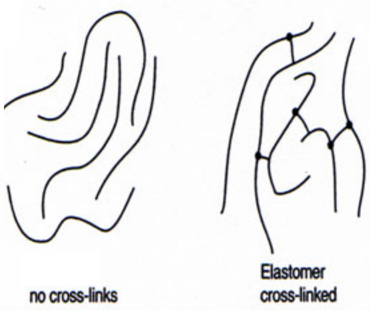
(sugar unit)



cellulose

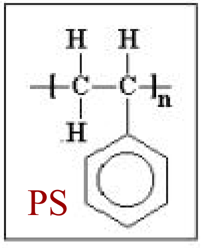
starch, glycogen, chitin, gums, resin

natural rubber, butyl rubber, nitrile rubber, SBR, Silicone, EPM, resilin



plastic $\underset{+H}{\overset{-H}{\rightleftarrows}}$ brittle glassy

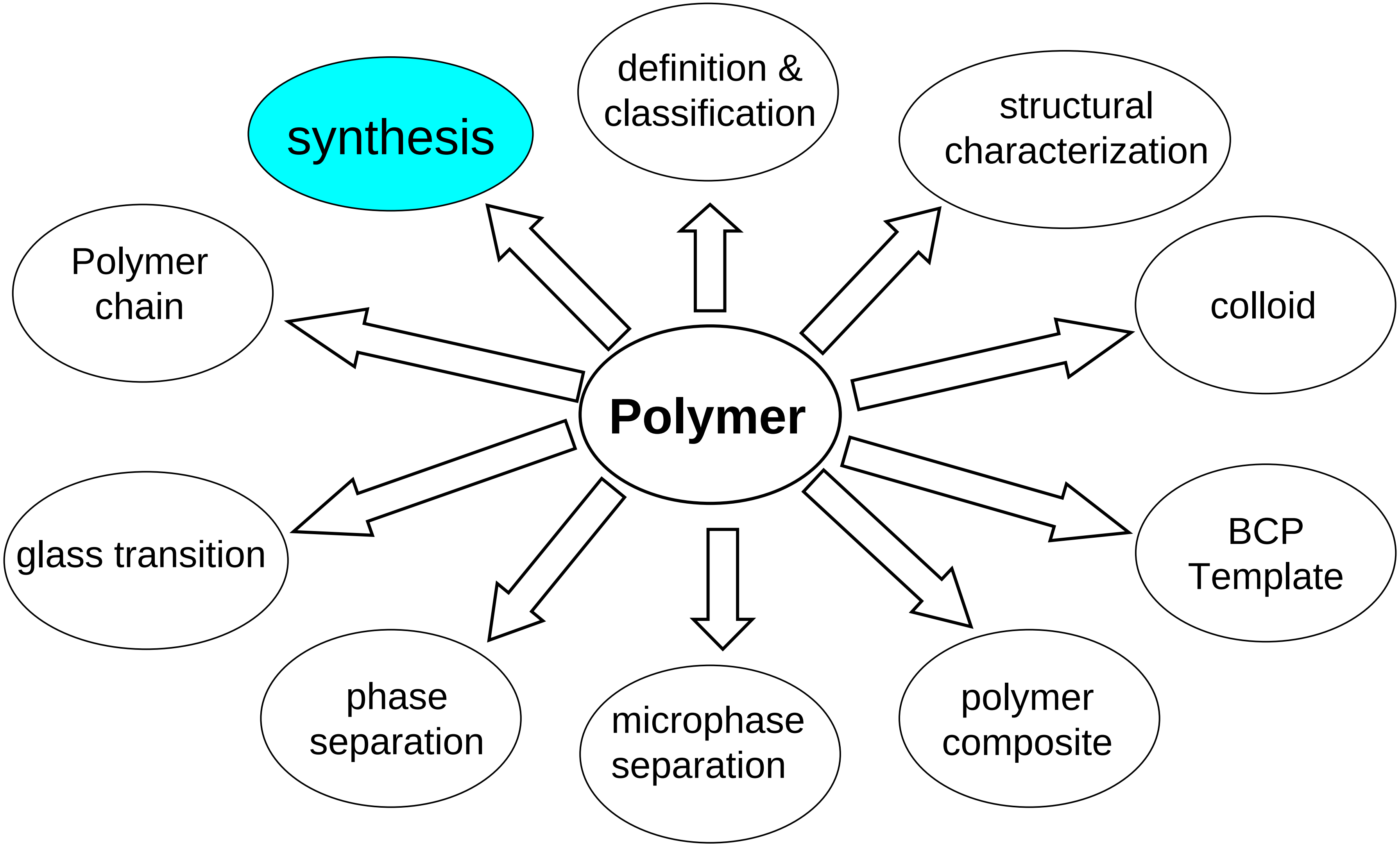
PE, PP, PC, PB, polyester, PS, PVC, PTFE, celluloid, cellulose acetate



PS

plastic $\begin{array}{c} \xrightarrow{+H} \\ \cancel{\xleftarrow[-H]{}} \end{array}$ cured

vulcanized rubber duroplast, bakelite, melamine, epoxy resin, urea-formaldehyde



Polymer

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structural characterization

colloid

BCP Template

polymer composite

microphase separation

phase separation

glass transition

Polymer chain

Polymer synthesis

Chain-growth Polymerization:

1. Initiation: Initiator initiates the chemical reaction by breaking the unsaturated bonds. Peroxides (-O-O-), disulfides (-S-S-) and Azo (-N=N-) compounds are typical initiators

$\boxed{M+I \rightarrow --MI}$

2. Propagation: increase of chain length

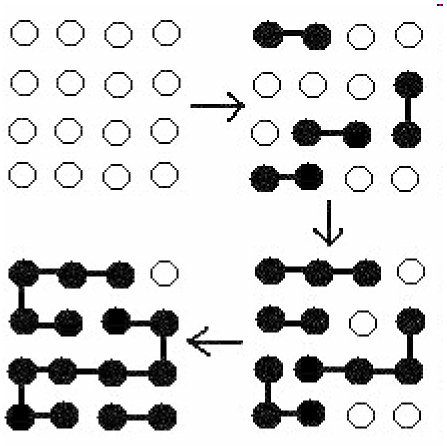
$\boxed{(n+1)M+MI \rightarrow (M)_nI}$

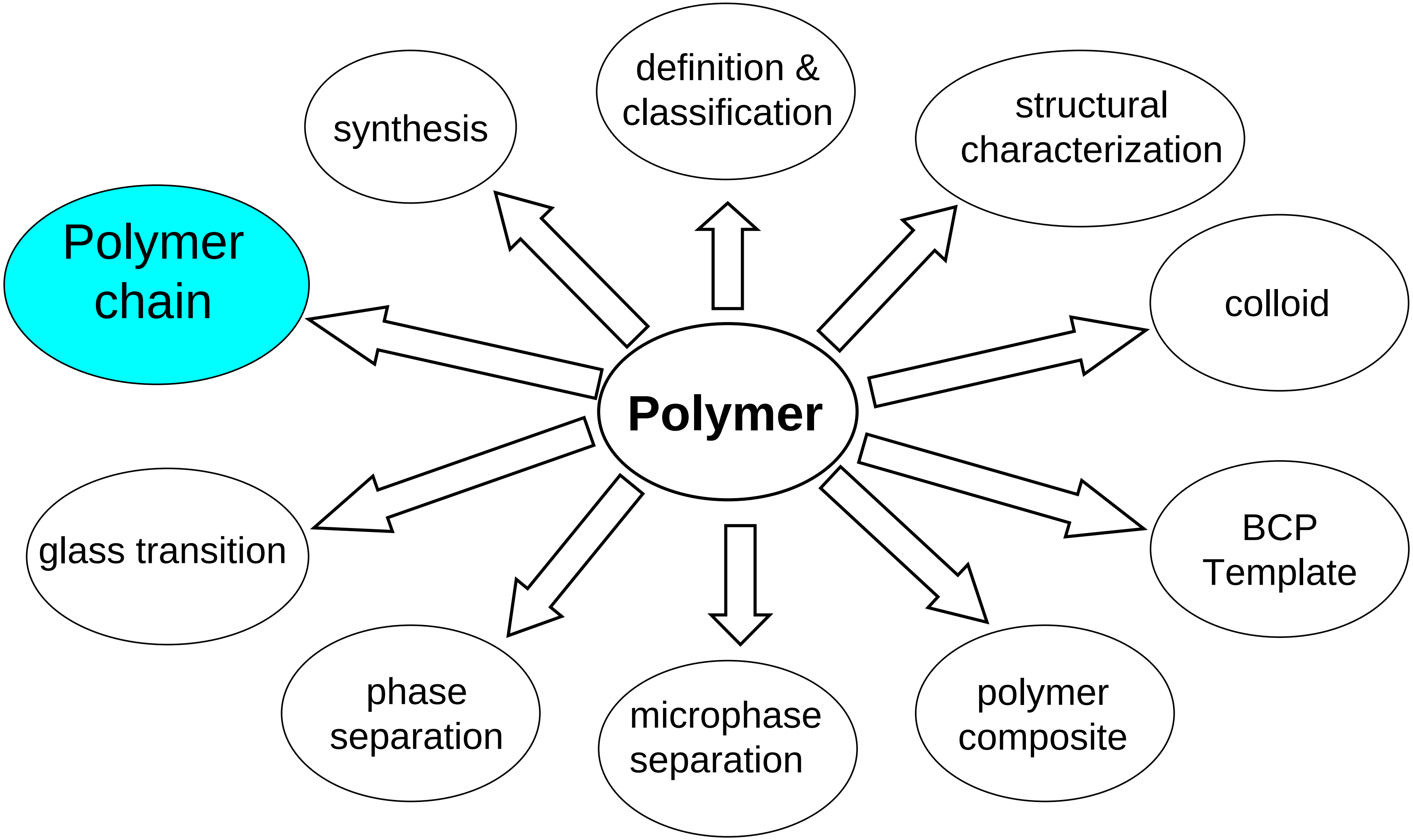
3. Termination: combination or disproportionation of free radicals

$\boxed{(M)_nI \rightarrow M_n}$

Step-growth Polymerization:

- bifunctional or multifunctional monomers react to form dimers, trimers, longer oligomers and long chain polymers, e.g; esters (Polyesters), amines & esters (Polyamide).





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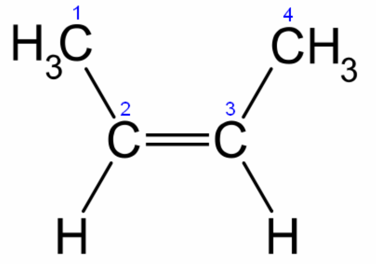
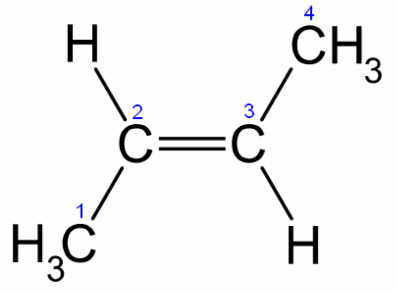
The polymer chain

Configuration and conformation

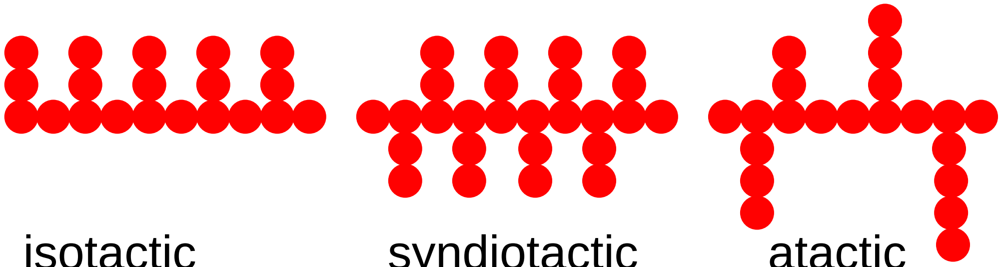
Configuration refers to the order that is determined by chemical bonds. The configuration of a polymer cannot be altered unless chemical bonds are broken and reformed. The two types of polymer configurations are *cis* and *trans*. The *cis* configuration arises when substituent groups are on the same side of a carbon-carbon double bond. *Trans* refers to the substituents on opposite sides of the double bond. Arrangement of the side chains (steric order) present in the main chain of a polymer is called tacticity. Polymers with a unique way of coupling of the monomeric units are called isotactic and with an irregular steric structure, called as atactic. If the coupling varies, in a regular way, polymer chains are called syndiotactic. Tacticity is very important in polymer thermodynamics.



cis-2 butene



trans-2 butene

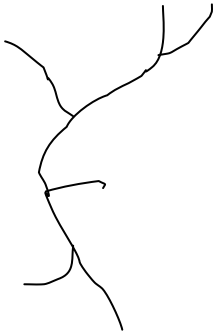


The polymer chain

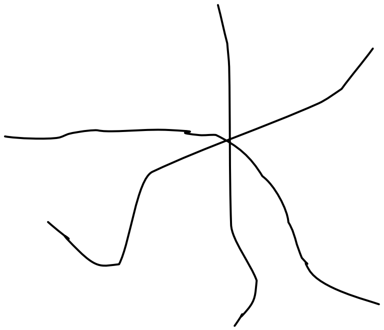
Configuration and conformation

Configurations that arise due to the rotation of two atoms, bonded by a single bond, relative to each other are called conformations. Three generalized types of conformations based on the potential energy as a function of torsional angle are anti (trans), eclipsed (cis) and gauche (+ or -).

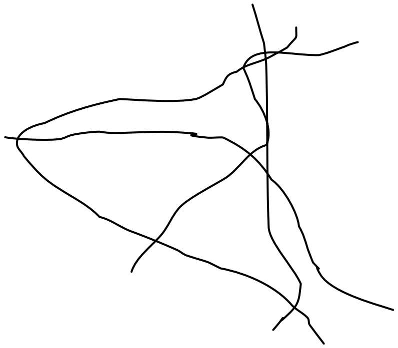
Chain architecture



Short chain and
Long chain branches

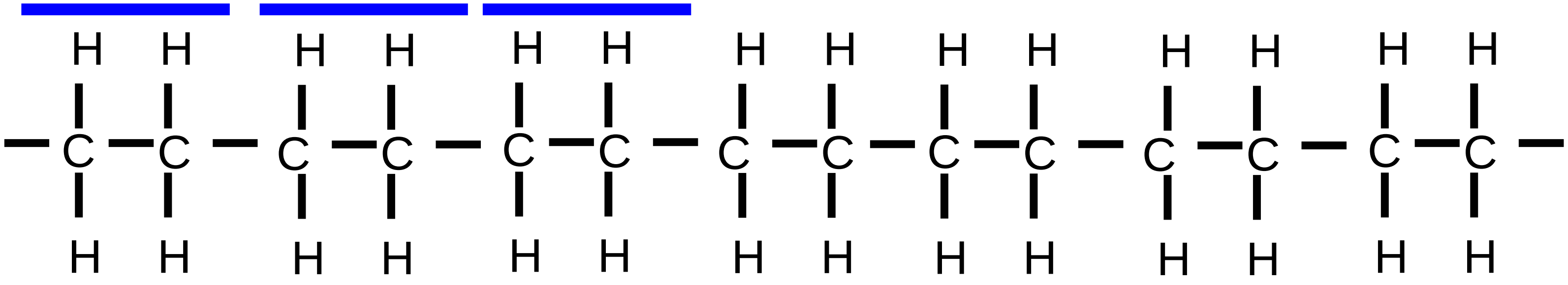


Star polymers

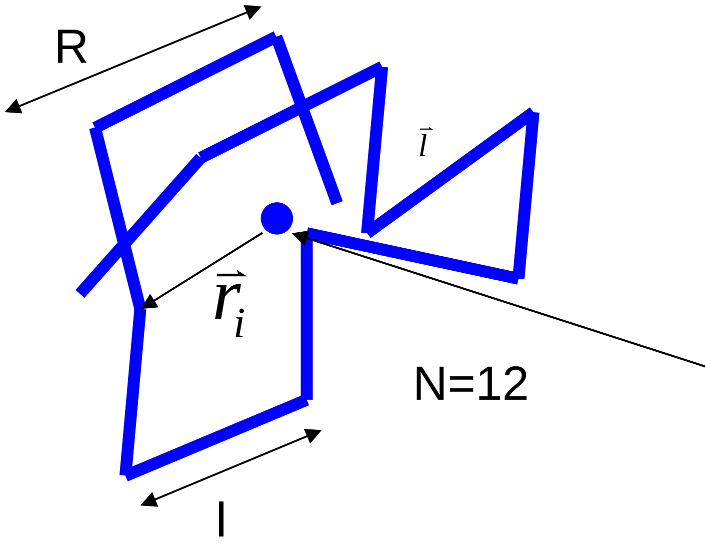


Network of cross-linked chains

The polymer chain



Linear chains exist, but more realistically:
Rotational degree of freedom



Mean segment length l=

Contour length path length $L = 12 \cdot \left|\vec{l}\right|$

End-to-end distance R

Center of gravity

The polymer chain

End-to-end distance: $R = \sqrt{N} \cdot \sqrt{\langle |\vec{l}|^2 \rangle} = \sqrt{N} \cdot l$

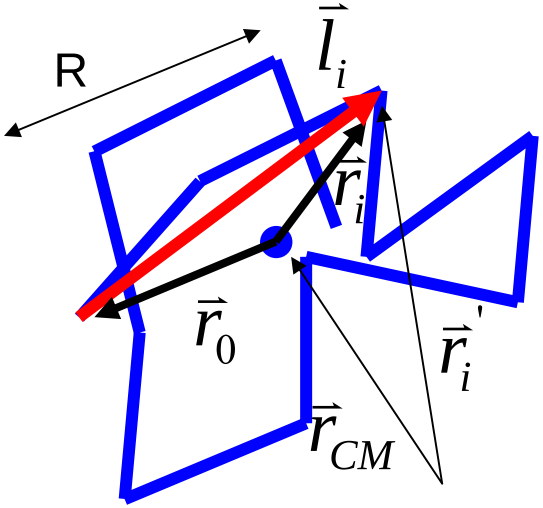
$$R_G = \sqrt{\frac{1}{M} \sum_1^N \langle m_i \vec{r}_i^{\,2} \rangle}$$

M mass of macromolecule

m_i mass of segment

Mean over all configurations

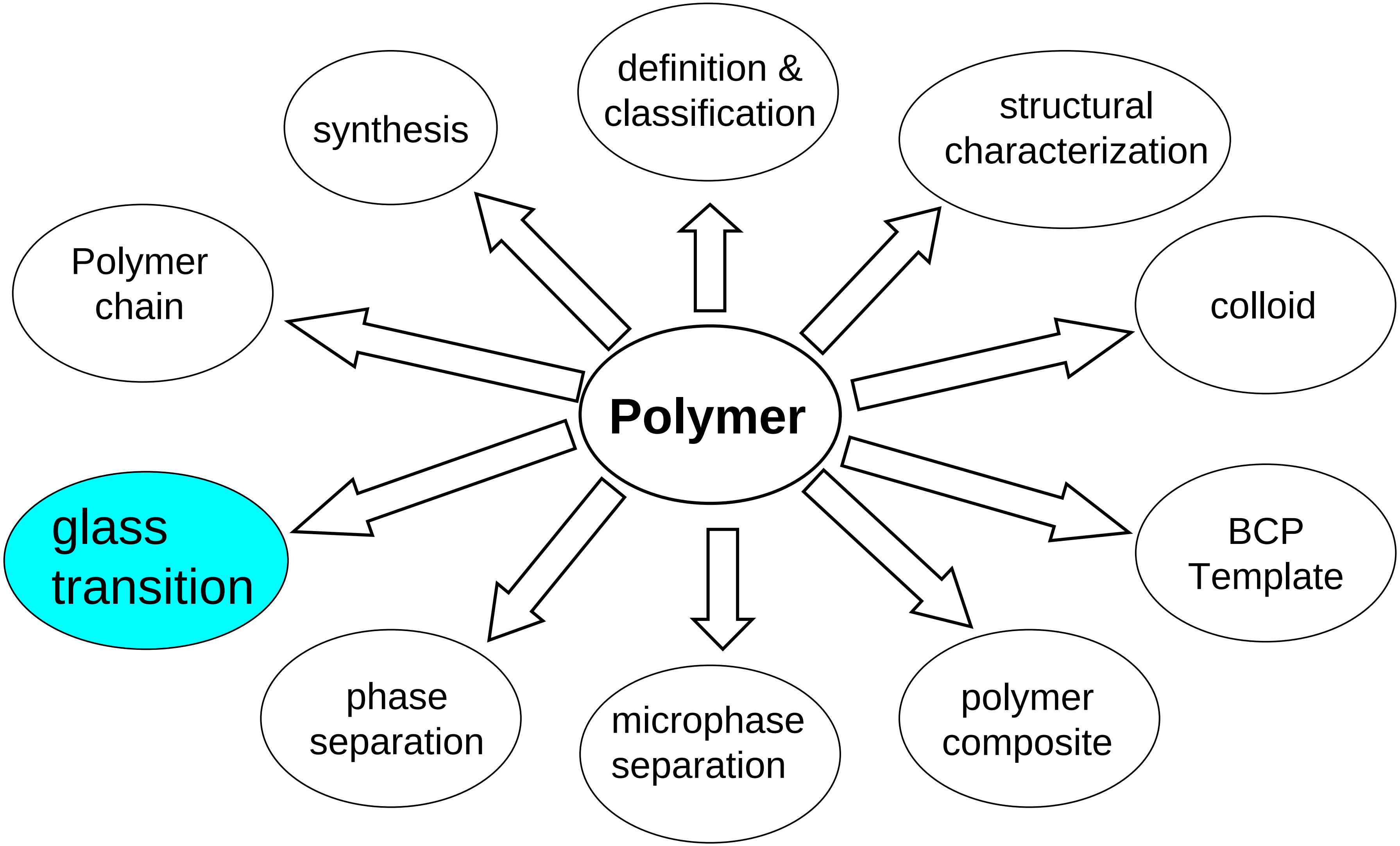
Radius of gyration (for a gaussian, uncorrelated chain) → Measure for extension of macromolecule



Relation between R_G and R $\quad R_G^{\,2} = R^2 / 6$

Using $\quad \vec{r}_i = \vec{r}_0 + \vec{l}_i = \vec{r}_i^{\,'} - \vec{r}_{CM}$

We will need this for small angle x-ray scattering!



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Glass transition

… more during part II, summer semester lectures (Hermann Franz)

Brief introduction – important to understand structure of thin films!

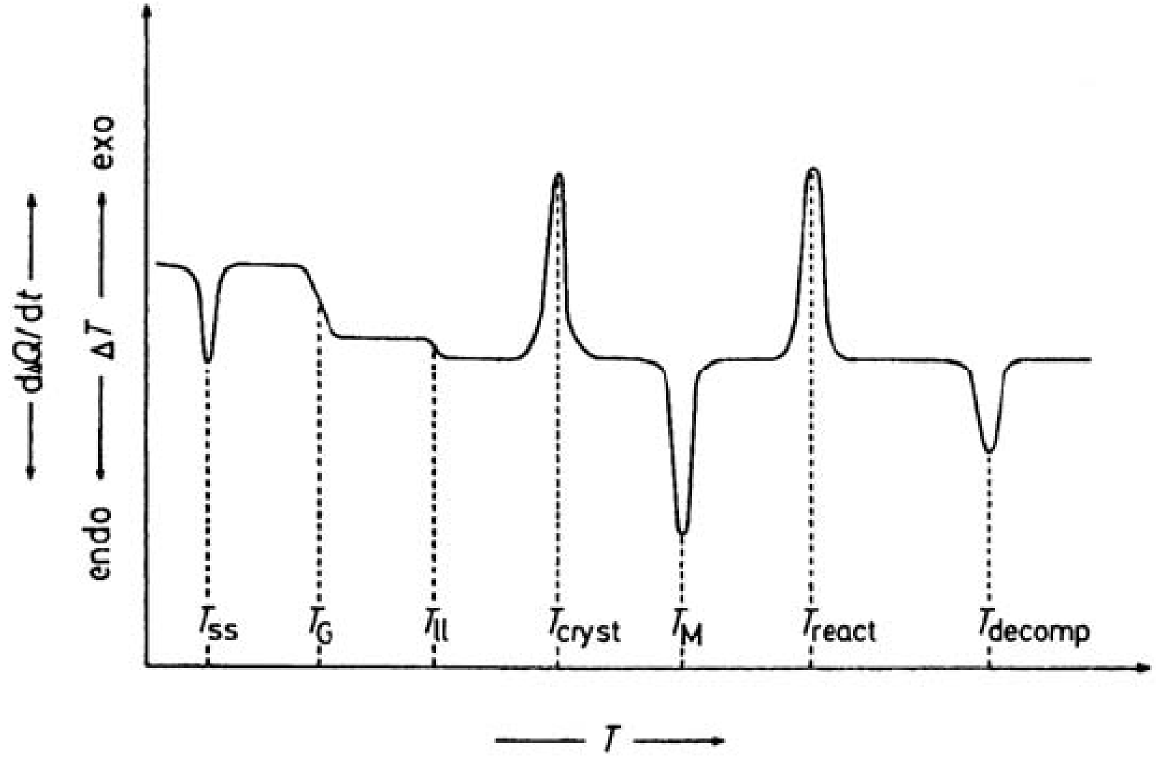
The glass transition is a very important physical property of amorphous polymers. It is characterized by the temperature above which the polymer starts flowing like rubber and below this temperature the polymer behaves like a supercooled liquid (for example glass). Since it is the transition of polymer between rubbery state and glassy state, it is called the glass transition temperature. It is denoted by Tg. This temperature is determined usually by differential scanning calorimetry (DSC).

- *the molecular theory* : The polymer chains have a great deal of freedom of mobility to take all possible conformation allowed by the rotation around the single bonds at temperature well above Tg. At temperature well below Tg all these conformations are frozen out and the polymer acts like a glassy solid.

- *the free-volume theory*: If the conformational changes of the backbone are to take place, there must be available free space for the molecular segments to move into. As the temperature is lowered from a temperature well above Tg, the molecules are able to rearrange locally to reduce the free volume. When the temperature approaches Tg the molecular motion becomes so slow that the molecules can not rearrange within the time-scale of the experiment and the volume of the material then contracts like that of a solid.

Tg determination

Differential scanning calorimetry (DSC): heat capacity as a function of temperature



Thermogravimetry (TGA)

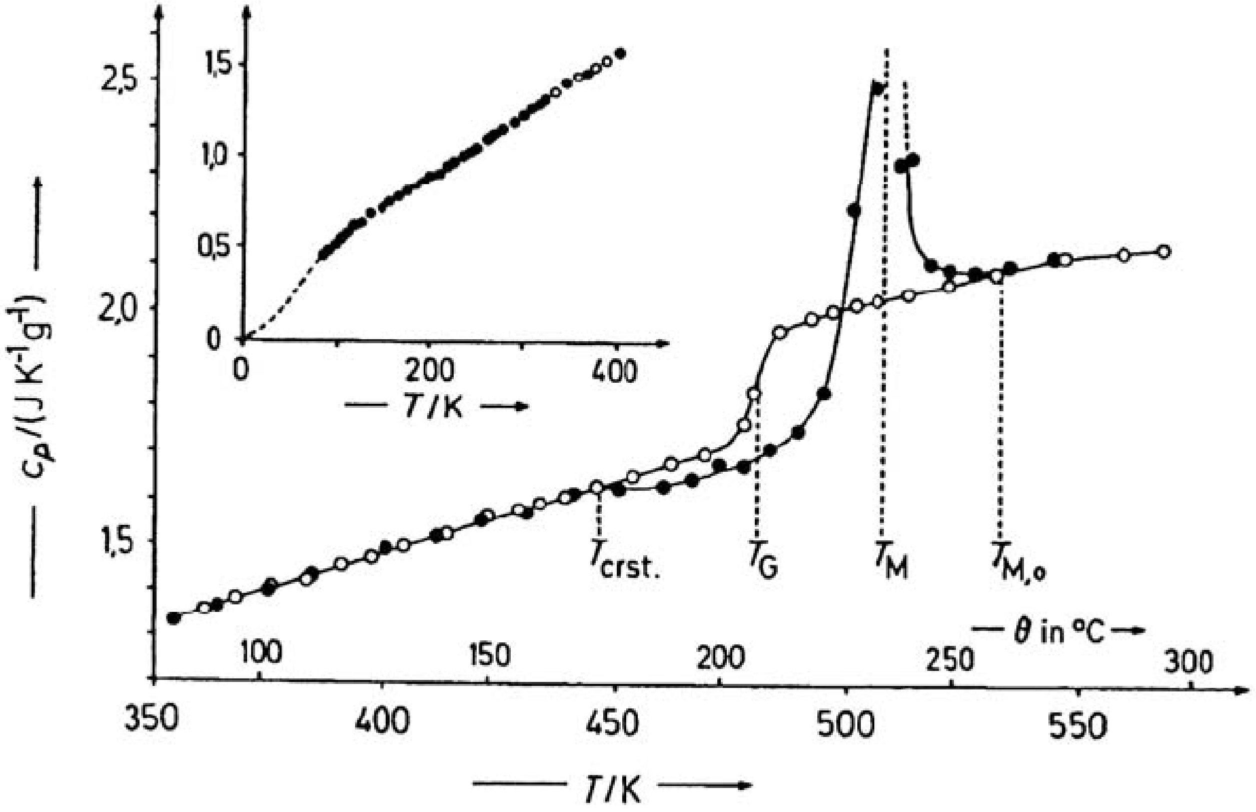
Differential thermal analysis (DTA)

Thermomechanical analysis (TMA)

Heating and cooling rate ~ 10°C/min

Tg determination

Typical DSC data for semicrystalline (filled circle) and amorphous polymer

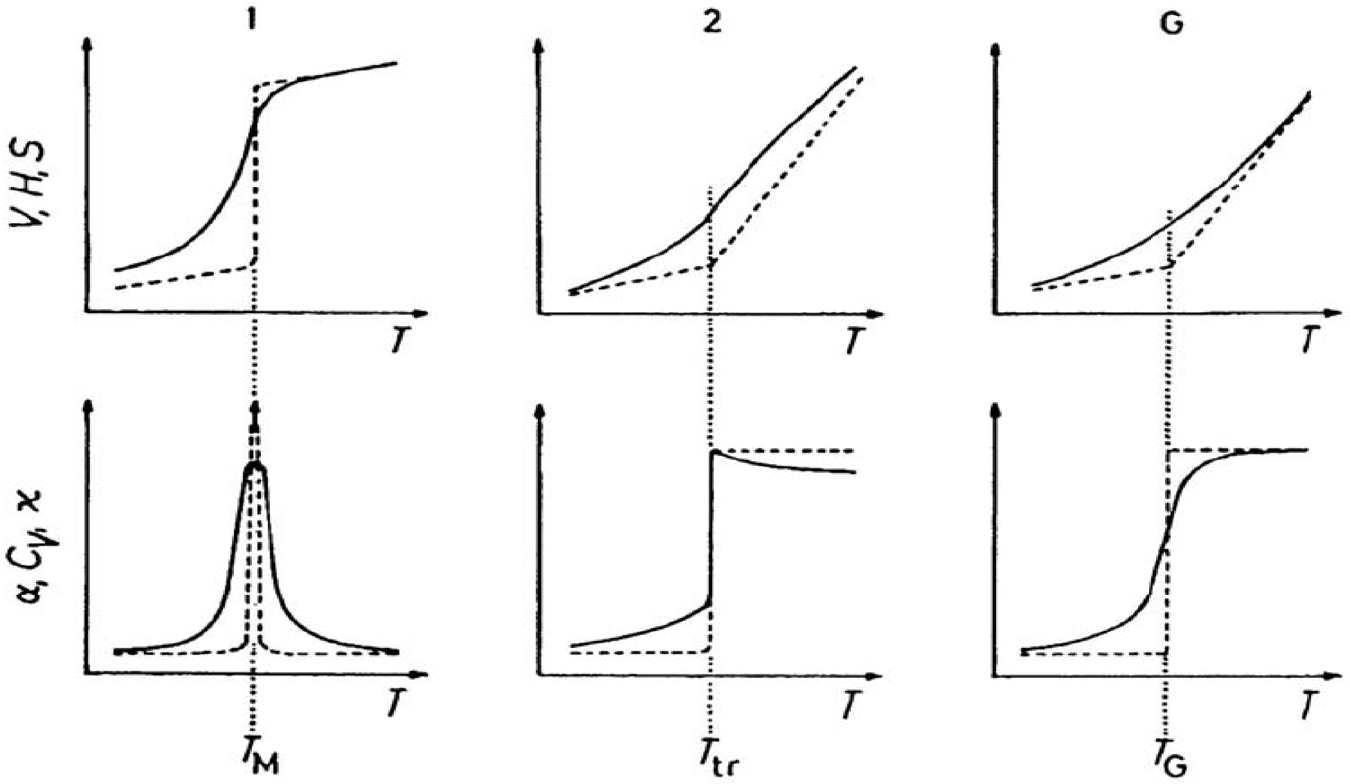


PS : 104°C

PB : -109°C

PBMA : 35°C

Phase transition vs. glass transition

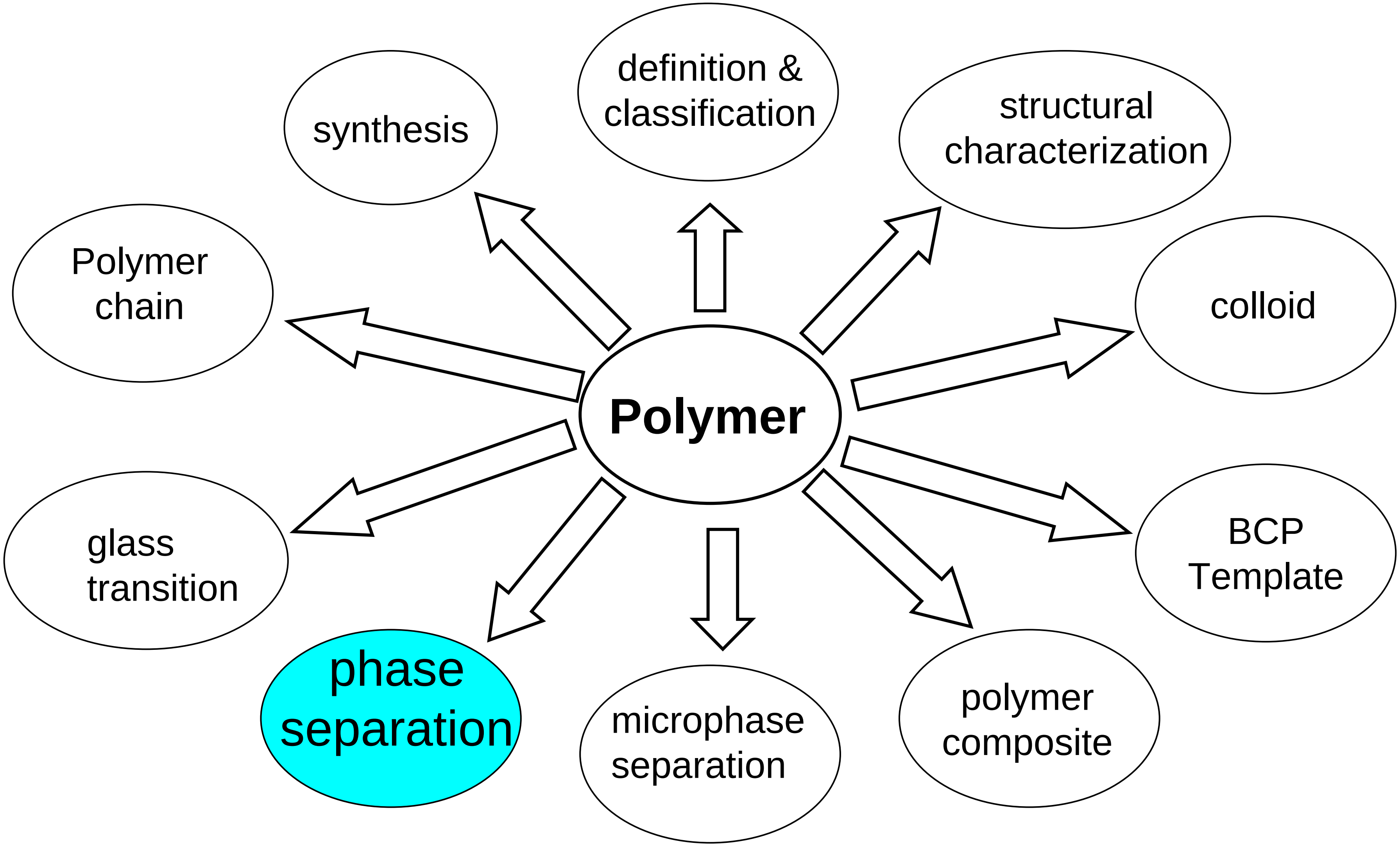


1st order phase transition: Melt of Crystal with or without deffect

2nd order phase transition: intermolecular cooperative effect

glass transition: infinite process. Normal experiment. Endless slow.

Glass transition is not a thermodynamic equilibrium state!!!



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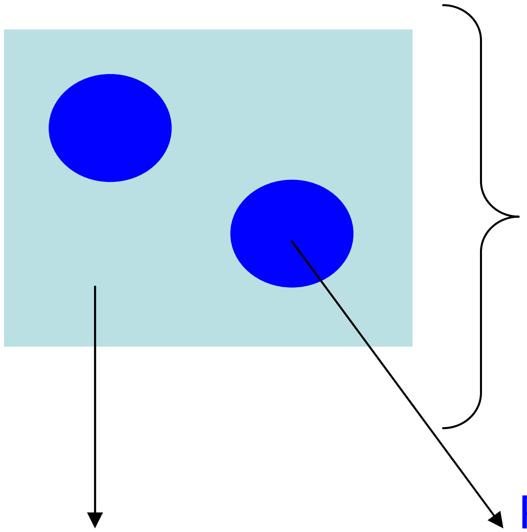
Phase separation

Polymer blends →mixing of two more homopolymers
→a route to combine different materials properties

High fracture resistance and stiff

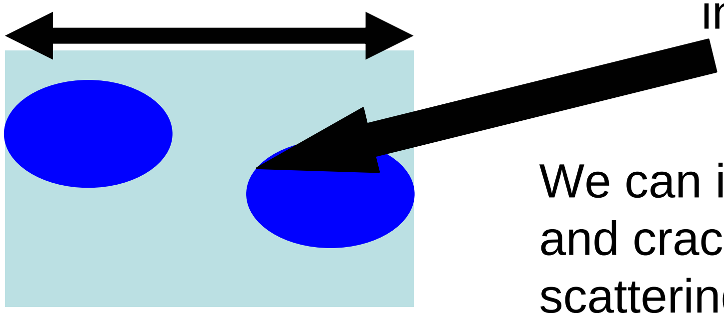
Problem: increase in elastic moduli → brittle



high fracture resistance
‚tough‘ material
Still stiff enough

Polybutadiene ~rubber

PS: stiff, but brittle



Fracture starts here and is initially localized here!

We can investigate deformation and crack propagation with X-ray scattering!

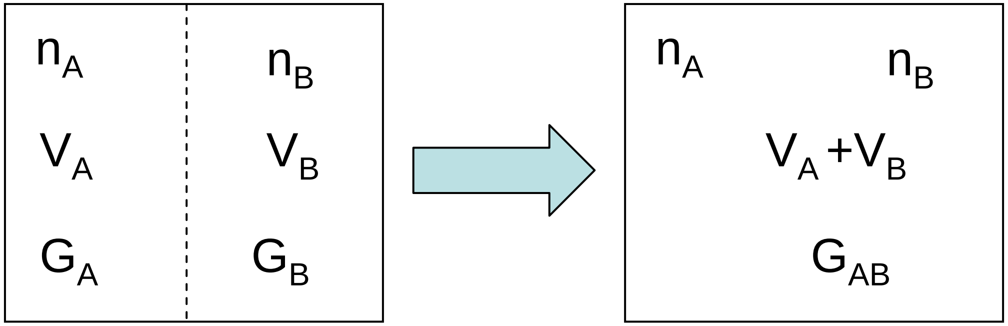
Phase separation

Flory-Huggins-Theory

Q: when do we obtain a homogenous or heterogenous morphology during blending?

A: Flory-Huggins theory – phase diagrams as function of T and M:

When can we expect single, binary… phases



Reminder: $$dG = -SdT + Vdp + \underbrace{\mu dN} + \gamma dA$$

S… entropy
µ… chemical potential (keyword: diffusion), change in phase: equilibrium µ1=µ2
γ… surface tension (2D)

For mixing: $$\Delta G_{mix} = G_{AB} - (G_A + G_B)$$

Phase separation

Flory-Huggins-Theory

It states:

$$\Delta G_{mix} = -T\Delta S_t + \Delta G_{loc}$$

Change in entropy:
Mixing → increase

Associated with motions of center of mass of all polymer molecules

+ : favours mixing

Change of local interactions and motion of monomers

General rule: Van-der-Waals interactions → attractive energies between equal monomers are stronger than between different ones

- : unfavorable for mixing

Change in V: Shrinking, expansion

Formulas?

Flory-Huggins-Theory

$$\boxed{\Delta G_{mix} = -T\Delta S_t + \Delta G_{loc}}$$

1) $$\Delta S_t = Rn_A \ln\frac{V}{V_A} + Rn_B \ln\frac{V}{V_B} \qquad \phi_{A,B} = \frac{V_{A.B}}{V}$$

$$\boxed{\Delta S_t = -Rn_A \ln\phi_A - Rn_B \ln\phi_B}$$

Assumption: Polymer chains ~ ideal gas

2) $$\boxed{\Delta G_{loc} = RT\frac{V}{v_C}\chi\phi_A\phi_B}$$

v_C Molar volume of a reference unit common to A and B

„The higher the concentration, the more likely the interaction“

χ Flory-Huggins-Parameter

Empirical parameter $\rightarrow$ χ

Nearest neighbour interactions

„contact energies“

This makes sense: $$\Delta G_{loc} \rightarrow 0$$ $$\phi_A, \phi_B \rightarrow 0$$

Flory-Huggins-Theory

$$\Delta G_{mix} = RTV\left(\frac{\phi_A}{v_A}\ln\phi_A + \frac{\phi_B}{v_B}\ln\phi_B + \frac{\chi}{v_C}\phi_A\phi_B\right)$$

v Molar volume

Low molar mass → entropy leads to mixing

Polymers: large molecular weights $v_{A,B} \to \infty$ $\Delta S_t \to 0$

Mixing takes place, when $\Delta G_{mix}<0$

$\chi < 0$ Mixing! $\chi > 0$ incompatibility

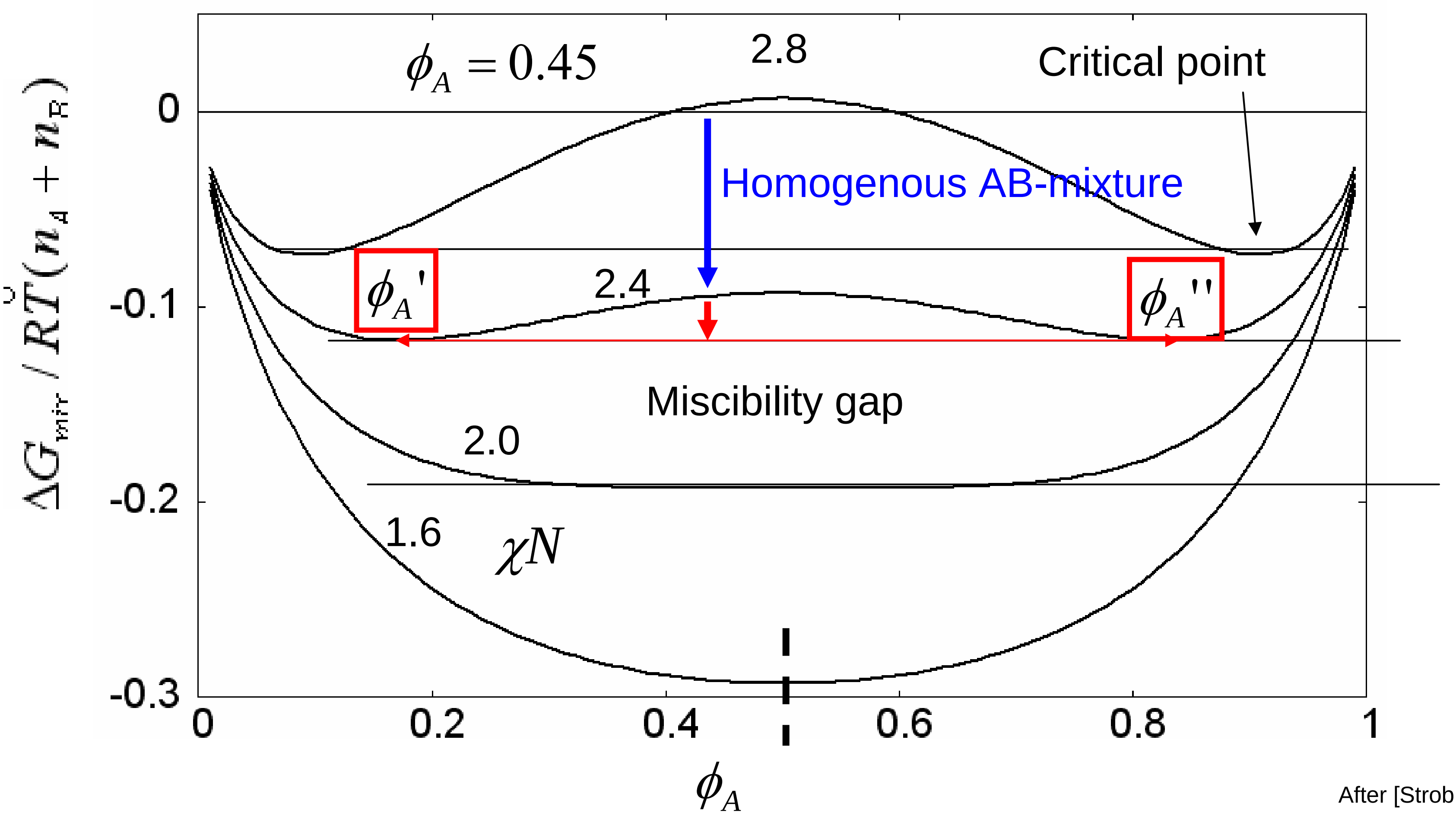
Symmetric mixture: Equal degree of polymerization

$$N_{A,B} = \frac{v_{A,B}}{v_C} \qquad N_A = N_B = N \qquad \phi_A + \phi_B = 1$$

$$\Delta G_{mix} = RT(n_A + n_B)\left(\phi_A\ln\phi_A + \phi_B\ln\phi_B + \boxed{\chi N}\phi_A\phi_B\right)$$

Phase separation

Symmetric binary polymer mixture



After [Strobl]

$\phi_A' < \phi_A < \phi_A''$ Two phases, demixing

Phase separation

Consequences
$$\left.\frac{\partial^2 \Delta G_{mix}}{\partial {\phi_A}^2}\right|_{\phi_A=0.5} = \frac{1}{\phi_A} + \frac{1}{1-\phi_A} - 2\chi N = 0$$
Vanishing curvature

$$\chi N = 2$$
Critical value: separates region with miscibility gap

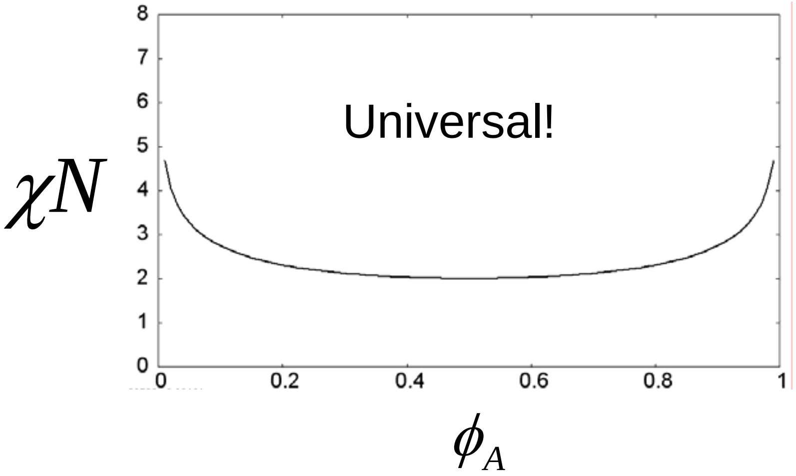
$$\chi < \chi_C = \frac{2}{N}$$
Compatibility through all concentrations, mixing

$$\chi > \chi_C$$
Miscibility gap → N>>0

$$\chi > 0$$
No mixing for high molecular weight!

Critical concentrations

$$\frac{\partial \Delta G_{mix}}{\partial \phi_A} = 0$$



Universal!

Phase separation

In general: upper and lower miscibility gap possible

Include T, one can show (thermodynamics!):

$$\Delta G_{loc} = \underset{\swarrow}{\Delta H}_{mix} - T\Delta S_{loc}$$

Endo- or exotherm : >0 or <0

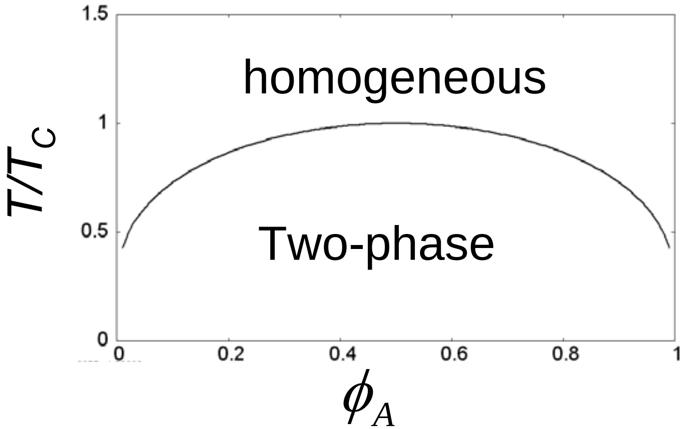
$$\chi \sim \frac{1}{T} \qquad \chi = \frac{2}{N}\frac{T_C}{T} > 0$$

Entropic contributions to ΔG_{loc} (‚mobility‘) neglected

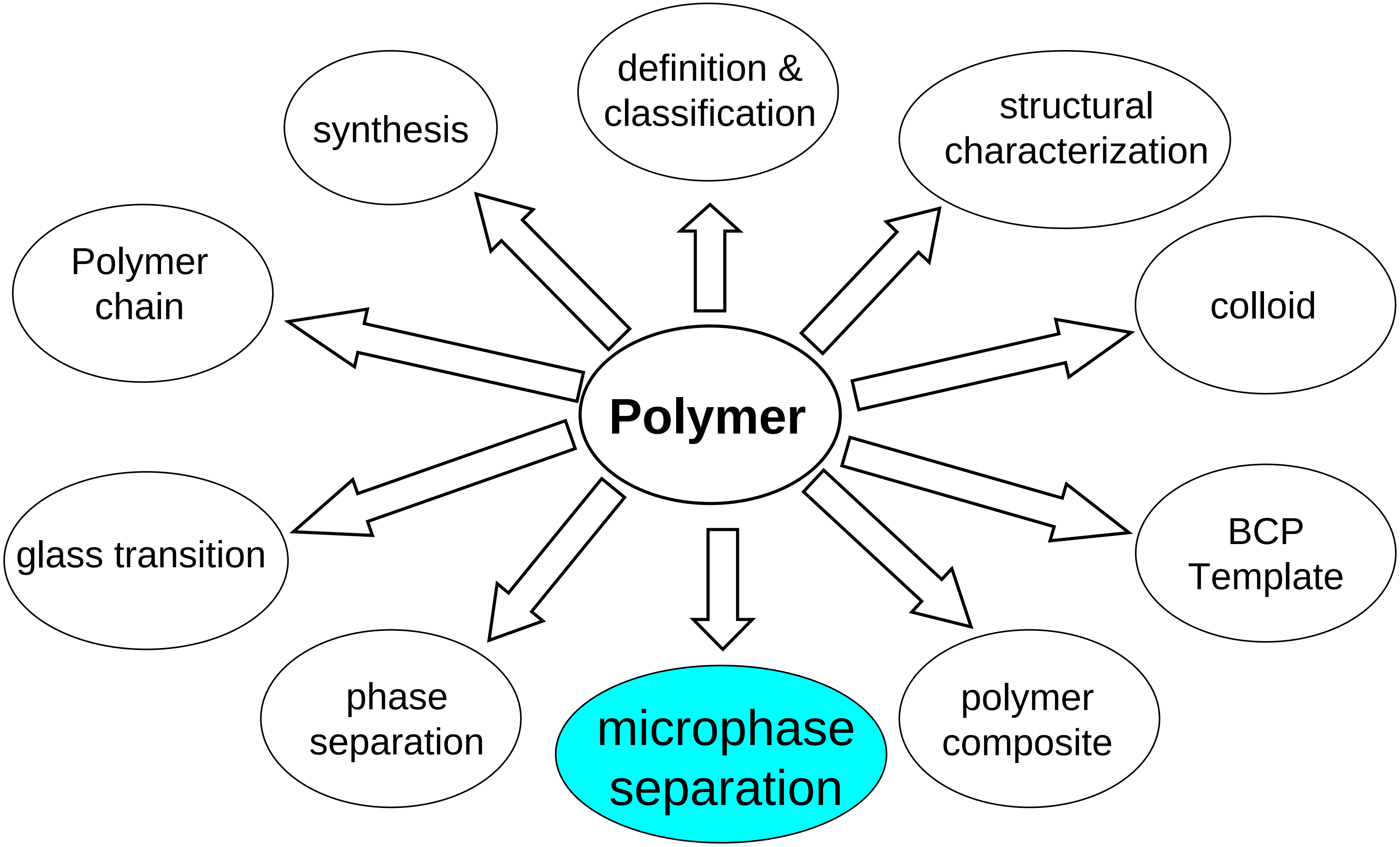
Endothermal polymer mixture

miscibility for high temperatures, if molecular weights low enough

-> mobile enough!



Of course, inverse for exothermal…



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phase separation

microphase separation

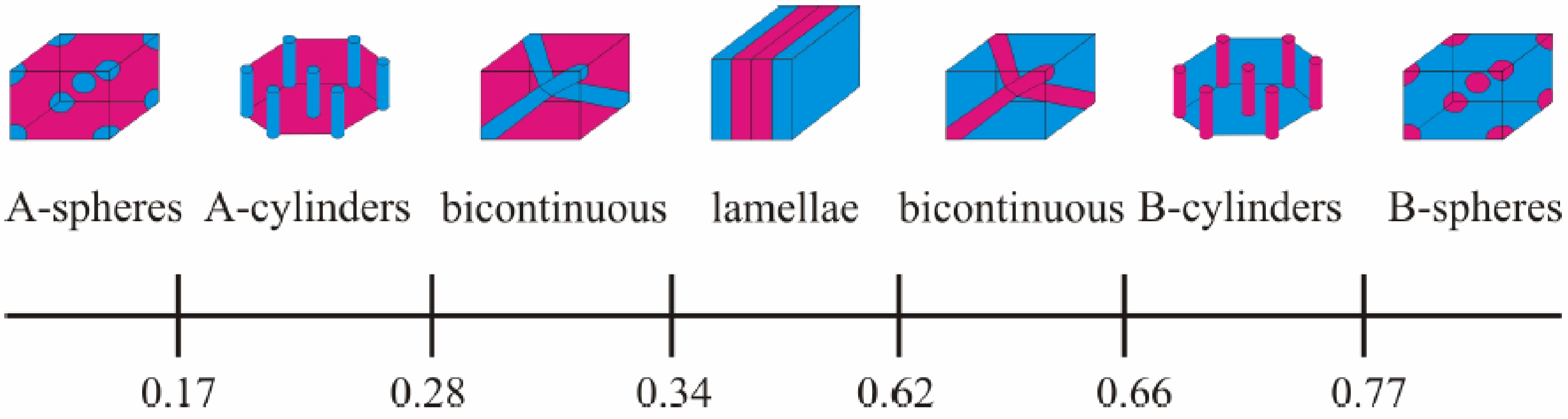
polymer composite

Microphase separation

In a diblock copolymer, where two blocks are built up from two chemically dierent monomers. Both cannot be separated macroscopically because they are linked by covalent bond, but will segregate with their phase separated domain size having a mesoscopic dimension, which corresponds to the sizes of the single blocks. Because all domains have a uniform size, they can be arranged in a regular manner producing ordered mesoscopic lattices. Such kind of phase separation in block copolymer systems is called microphase separation. A theoretical prediction and experimental investigation of microphase separation in block copolymer has been first reviewed by Bates and Fredrickson. The type of the structure depends on the volume fractions of the present blocks. The volume fraction of the block A in an A-B diblock copolymer is determined by:

Volume fraction of block A, $\phi_A = \dfrac{N_A}{N_A + N_B}$

Microphase separation



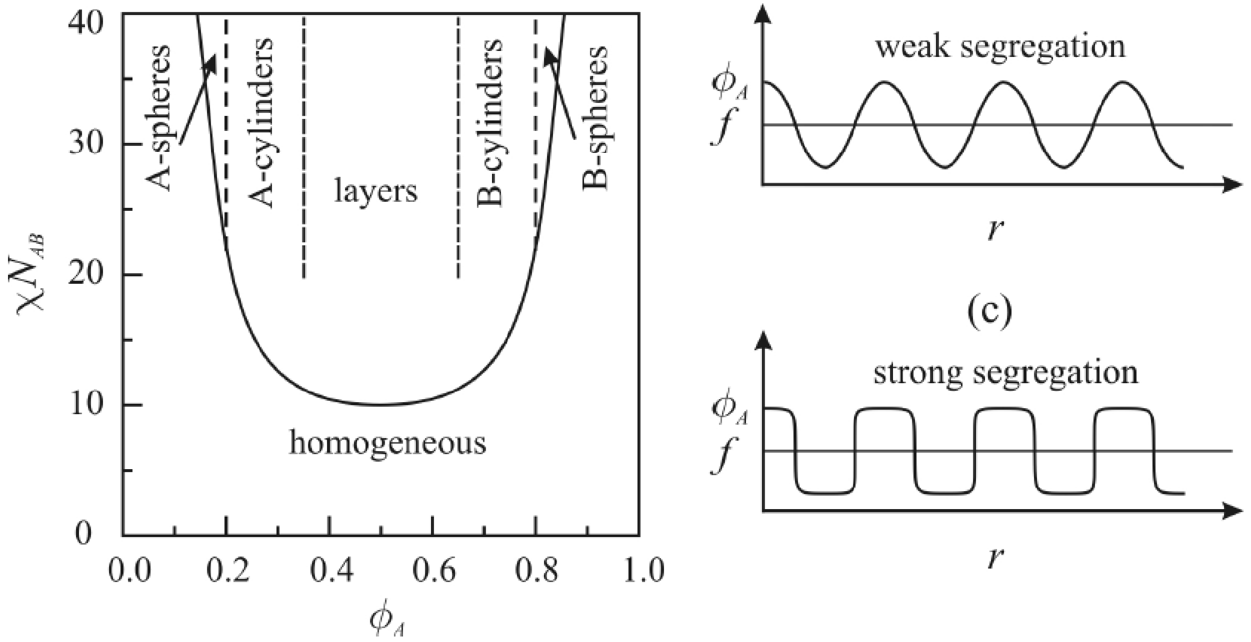
Possible mesoscopic lattice structures formed due to microphase separation in block copolymers having blocks of two different types of chemical species assumed as A and B. The numbers given under the boundary of the different structures represent the volume fractions of block A.

- $N_A << N_B$ → spherical domains of A in matrix of B will form as body-centered cubic lattice arrangement.
- $N_A < N_B$ ($\phi_A \sim 0.3$) → hexagonal array of cylindrical domains of A in matrix of B
- $N_A \approx N_B$ ($\phi_A \sim 0.5$) → lamellar arrangement

Microphase separation

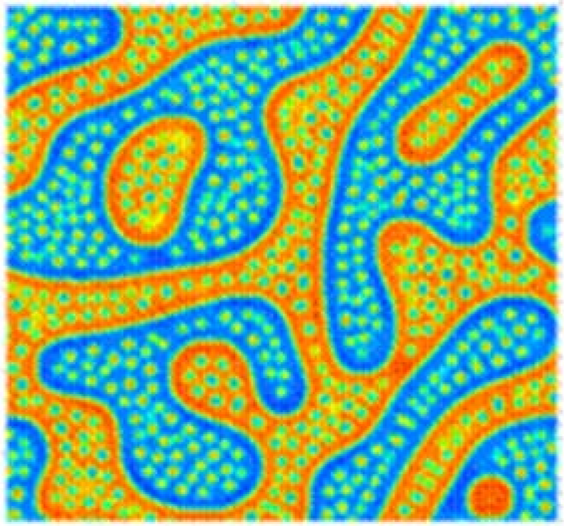
Phase diagram

symmetric block copolymer $(\chi N_A)_c \approx 10.5$ symmetric binary blend $(\chi N_A)_c = 2$

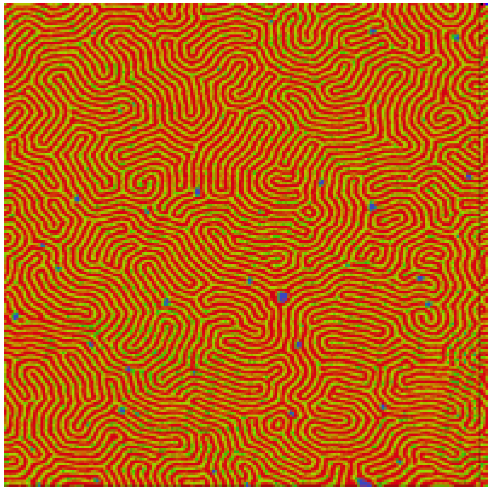


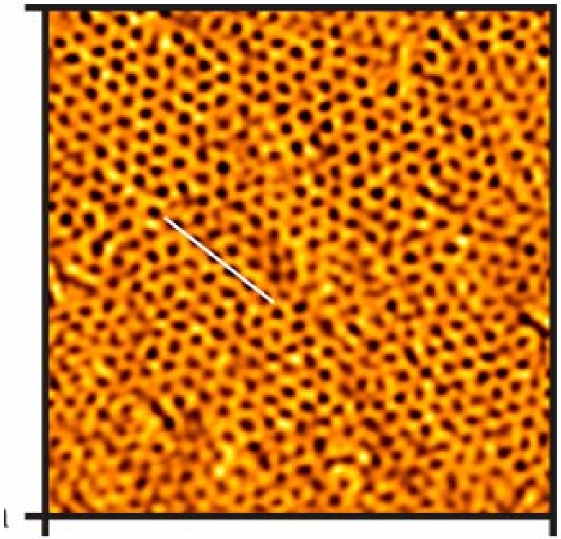
A schematic representation of phase diagram (a) of a diblock copolymer having A and B blocks above the strong segregation limit, $\chi N_{AB} >> 10$. The solid curve (ODT curve) separates the homogeneous phase and the microphase separated states, where weak segregation occurs. The *dashed boundary lines* represent the boundaries among different types of ordered mesoscopic domain structures. One-dimensional composition profiles of block A in weak (WSL) and strong segregation limits (SSL) are shown in (b) and (c) respectively. ϕ_A and f are the local and stoichiometric (macroscopic) volume fractions of block A, respectively

Micrograph of phase separated and mcirophase separated thin film

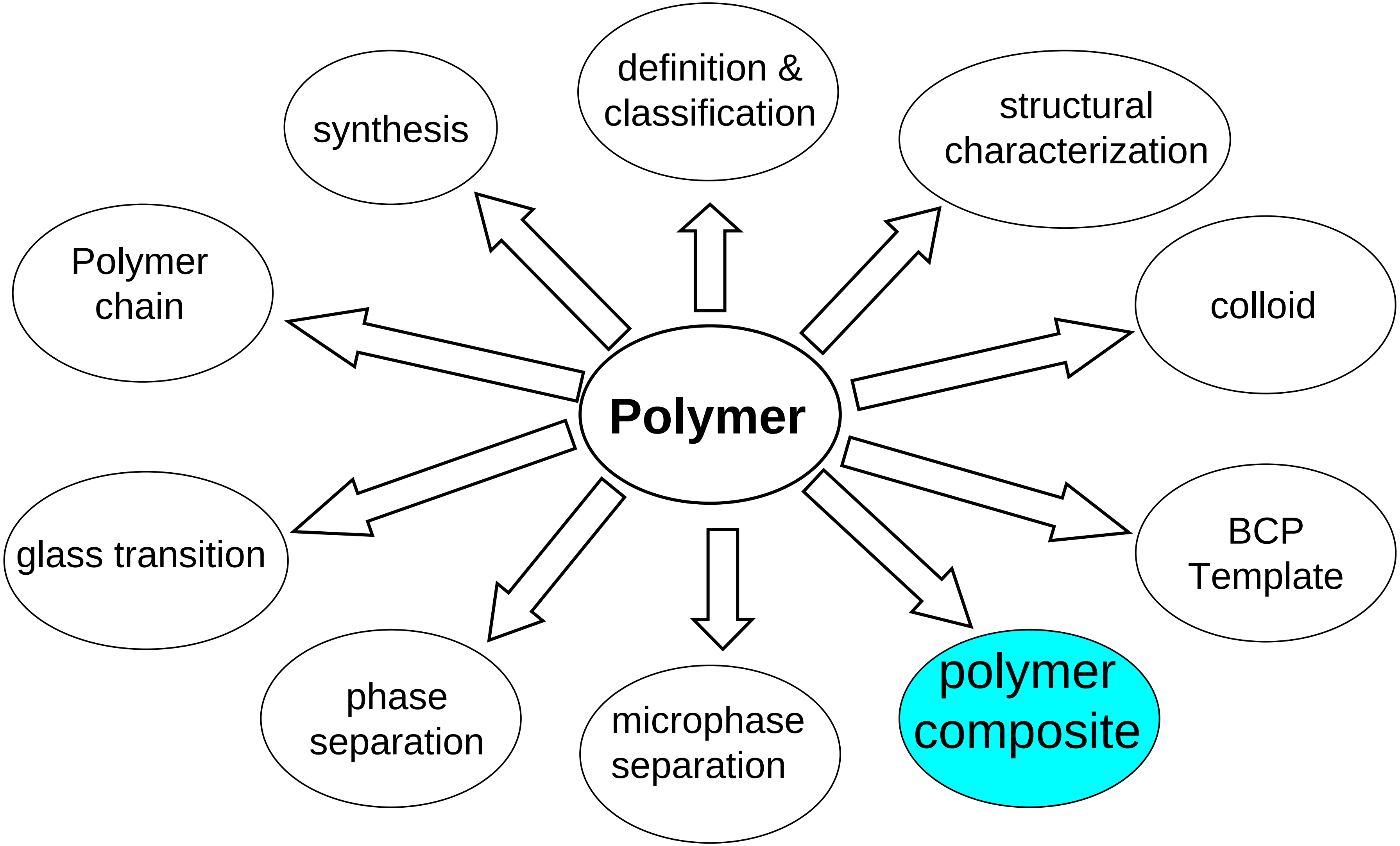


A blend of PS/PB





P(S-b-MMA)



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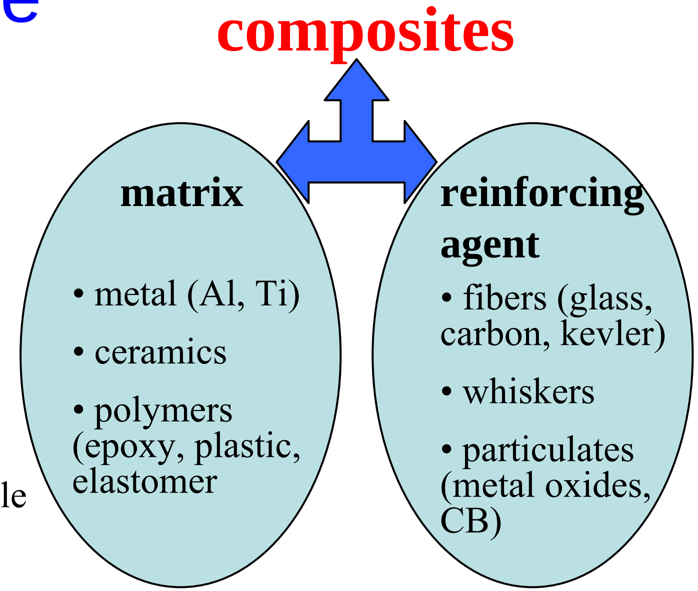
Polymer composite

- Throughout history -- ancient building materials, straw/mud huts
- In nature ---------------- bones in human body are composed of hard brittle hydroxyapatite and soft protein collagen

  wood is composed of strong and flexible cellulose fibers surrounded by stiff lignin
- Modern world ------- aerospace, underwater, transportation, sports, commodity life



composites

matrix

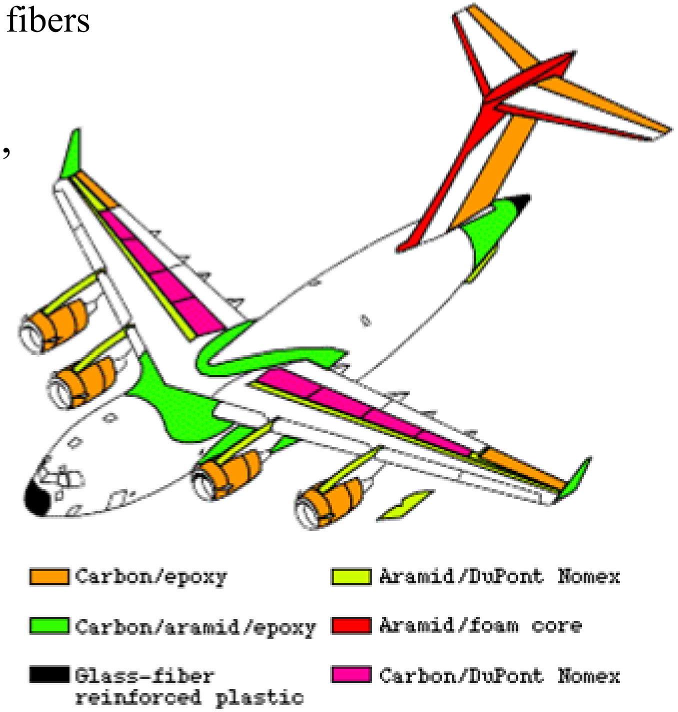
- metal (Al, Ti)
- ceramics
- polymers (epoxy, plastic, elastomer

reinforcing agent

- fibers (glass, carbon, kevler)
- whiskers
- particulates (metal oxides, CB)

Why composites?

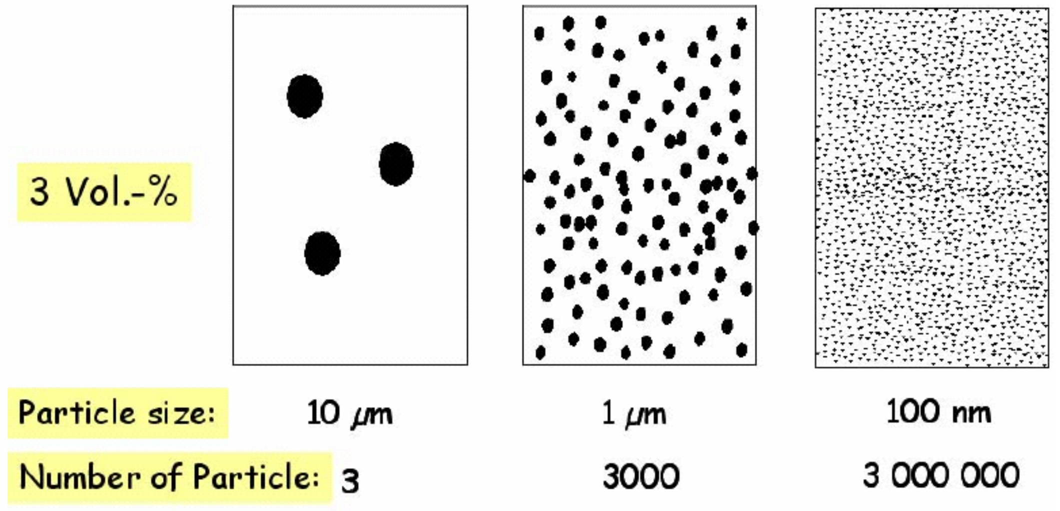
- Controlled and desired thermal, mechanical, electrical, chemical, optical properties
- low density
- high stiffness
- abrasion and impact resistant
- not easily corroded



Polymer nanocomposites

(at least one dimension of the reinforcing agent is ~100 nm or less)

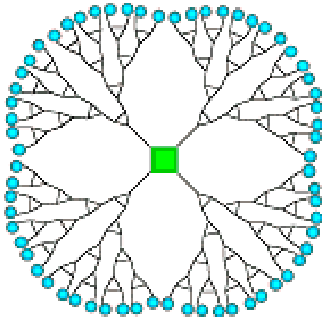
- surface to volume ratio is very high
- property modification at nano-scale
- toughness without sacrificing stiffness
- lighter than metal and other filled composites



Nanoparticles

(at least one dimension of the particle is ~100 nm or less)

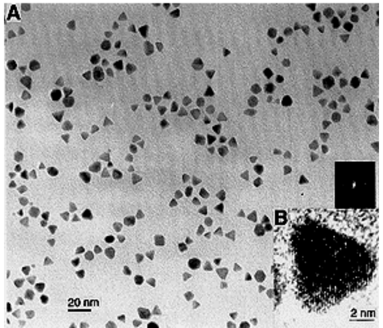
from metal, metal oxide, polymer,hybrid metal oxide and polymer, carbon etc…



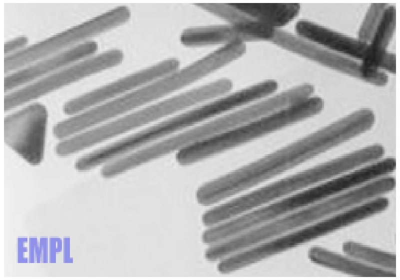
dendrimeric

Application:

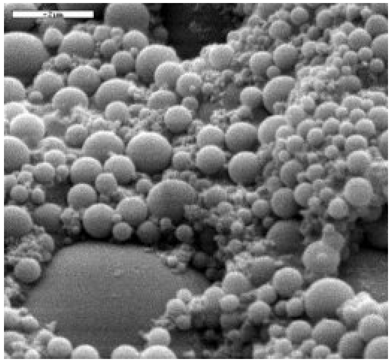
- optical: light based sensor, anti-reflection coating
- magnetic: increased storage density media, MRI
- mechanical: composites----wear resistance, anti-corrosion, stronger and lighter
- electronic: capacitor in mobile phone,displays, high conductivity materials
- biomedical: antibacterial coating on wounds dressings, sensor for diseases, drug delivery, "interactive" food and beverages
- environmental: clean up of soil contamination and pollution, e.g. oil, biodegradable polymers, aids for germination. treatment of industrial emissions.



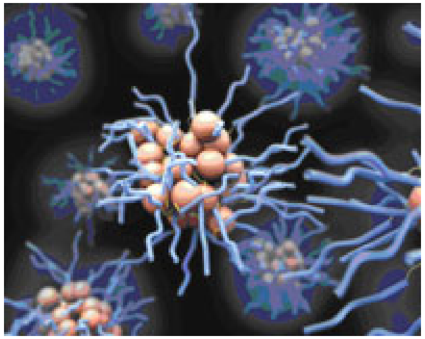
tetrahedral



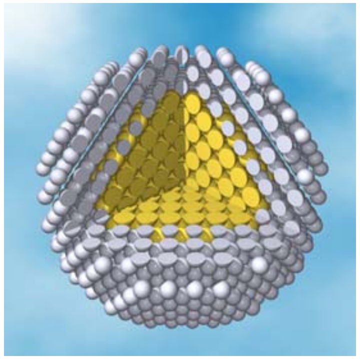
gold nanorod



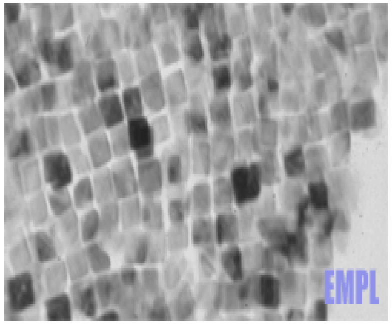
Sio$_2$



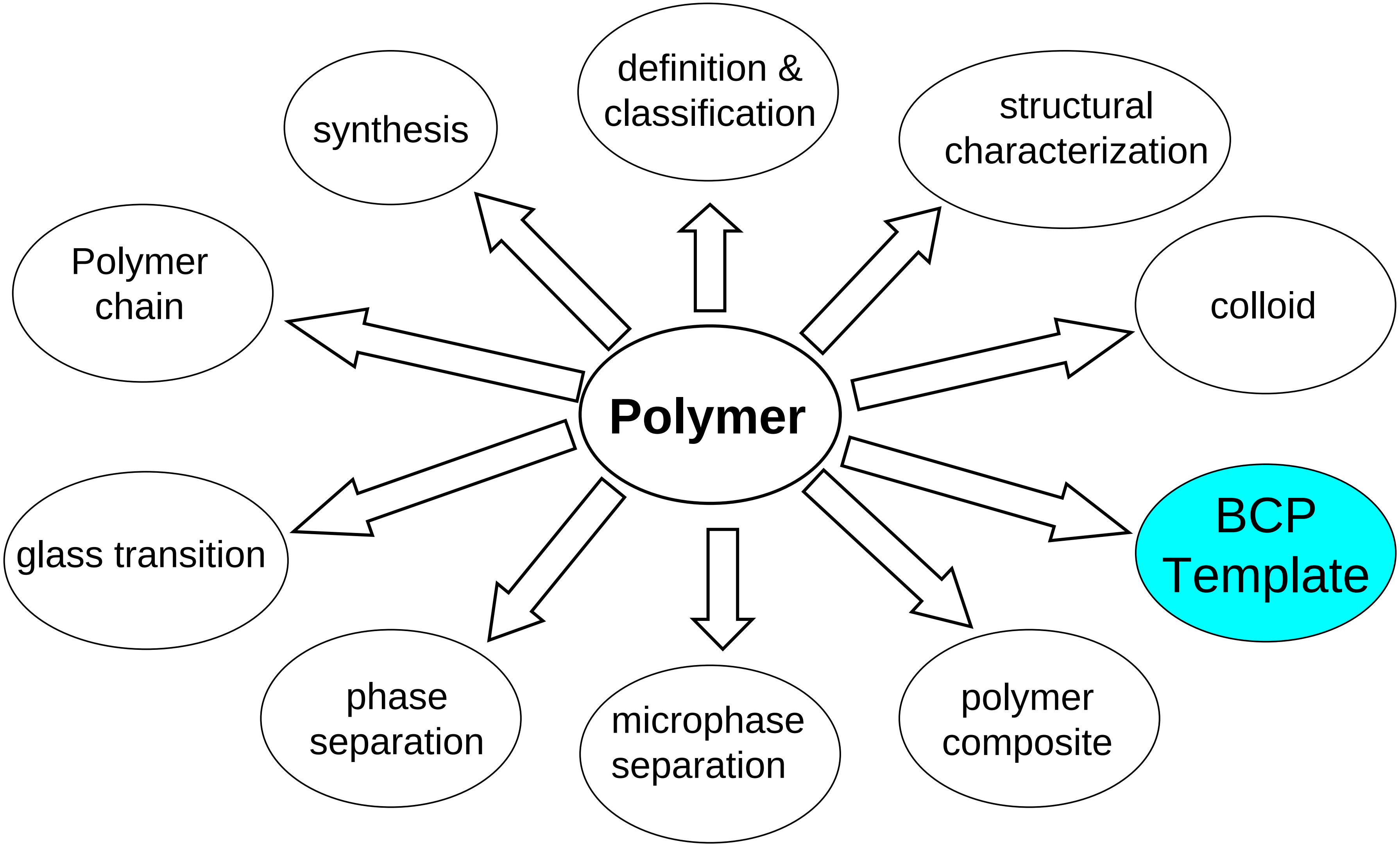
polypetide



core-shell



cubic titania



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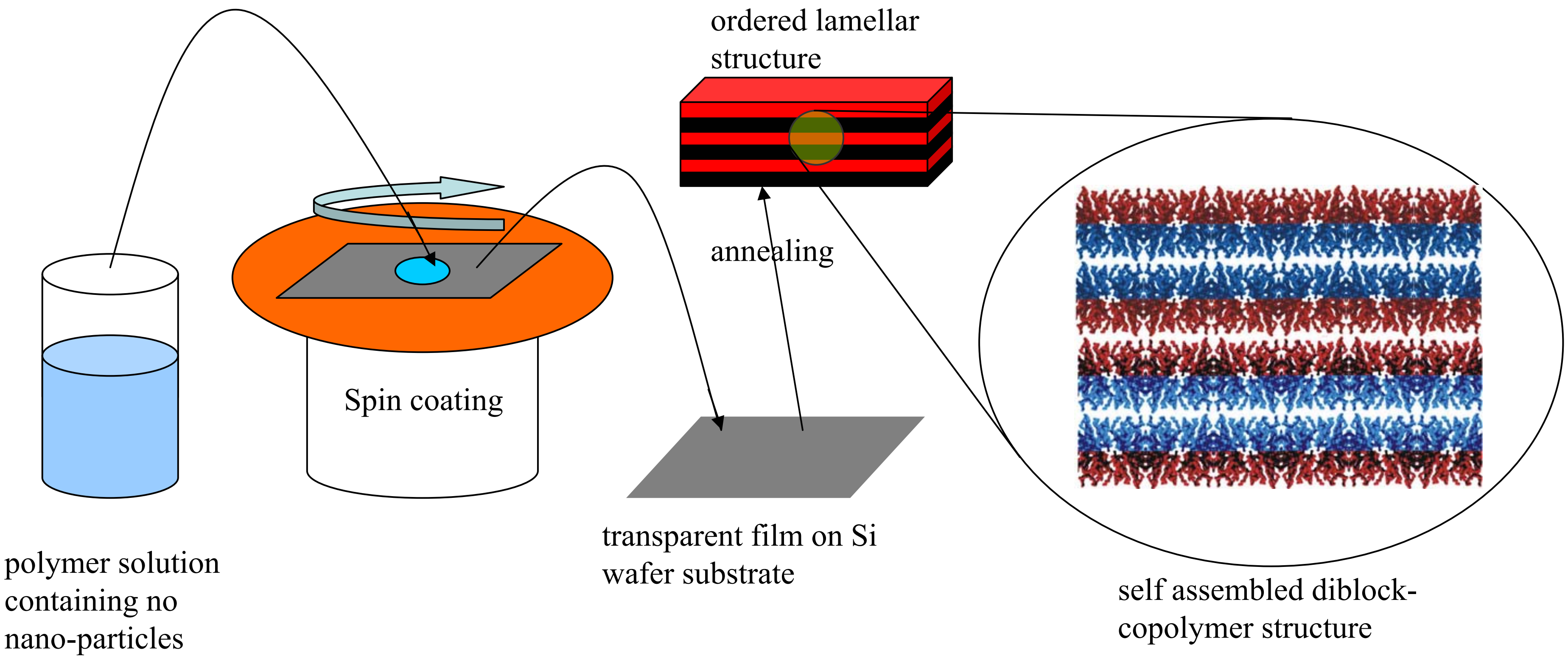
Block copolymer template

template offered by block copolymer nano-structures



ordered lamellar structure

annealing

Spin coating

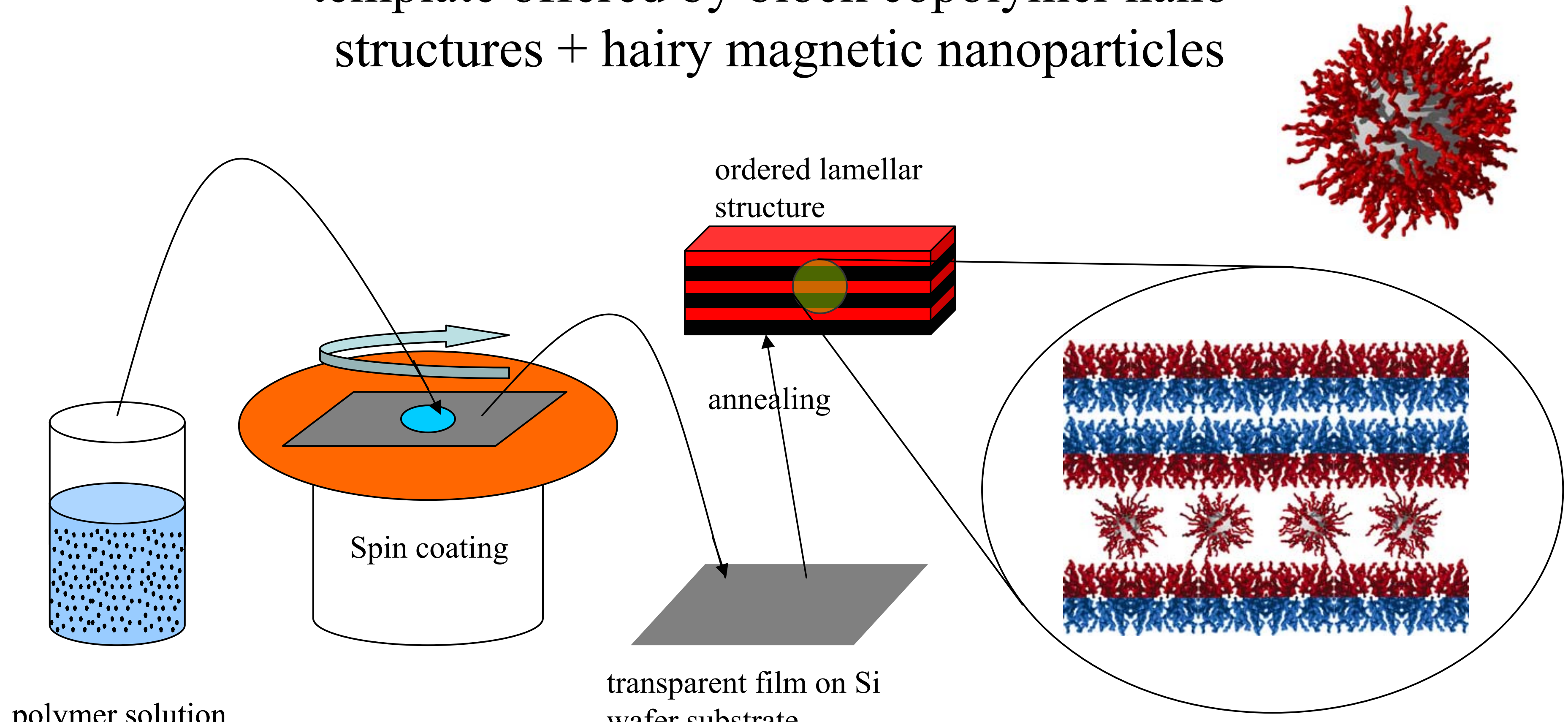
polymer solution containing no nano-particles

transparent film on Si wafer substrate

self assembled diblock-copolymer structure

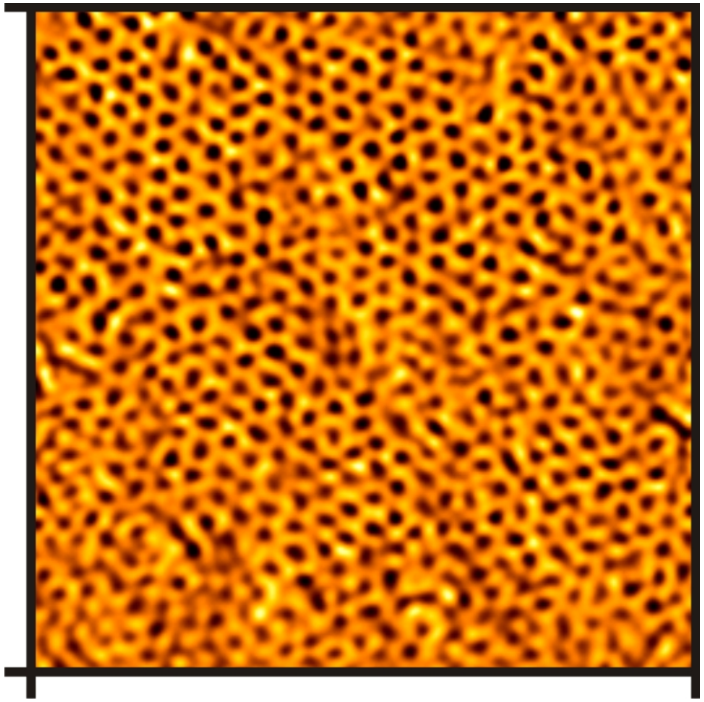
Block copolymer template

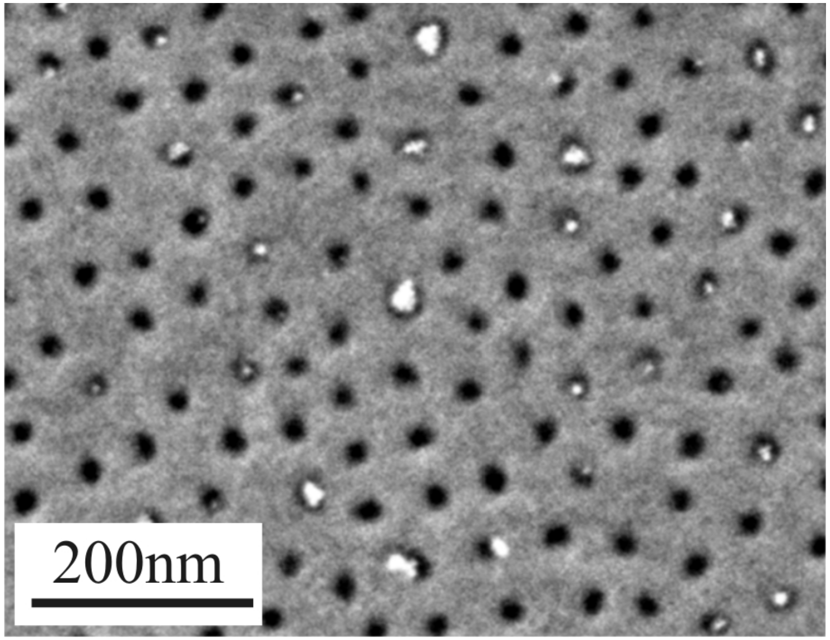
template offered by block copolymer nano-structures + hairy magnetic nanoparticles



nanoparticles distribution inside the layers due to selective affinity to one block

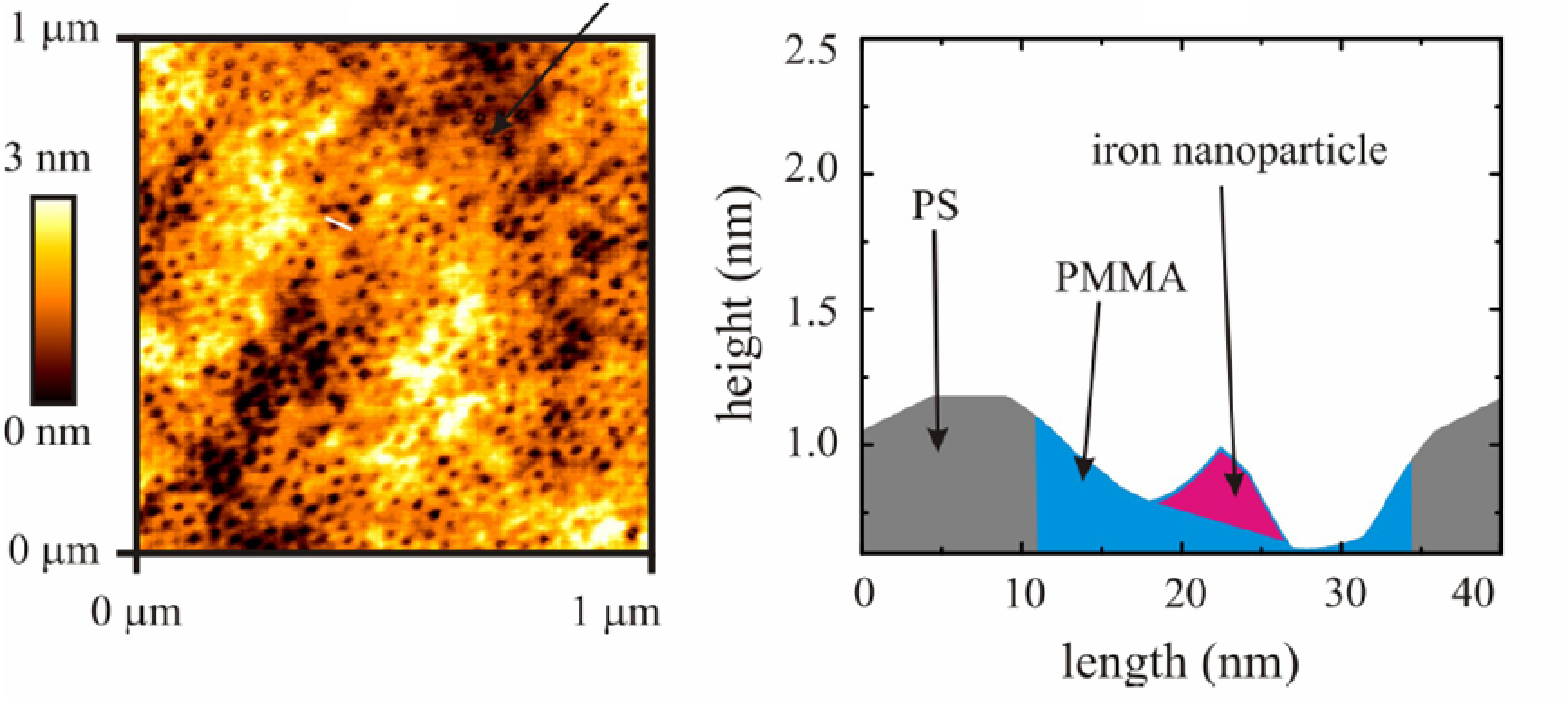
Block copolymer template





Particle cooperative self assembly / directed self assembly

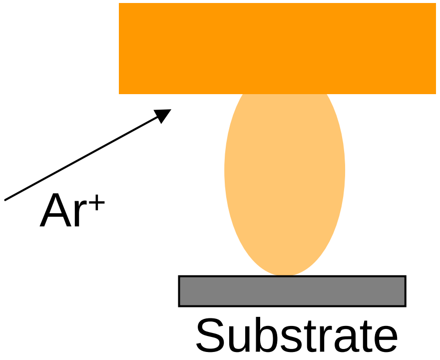
Block copolymer template

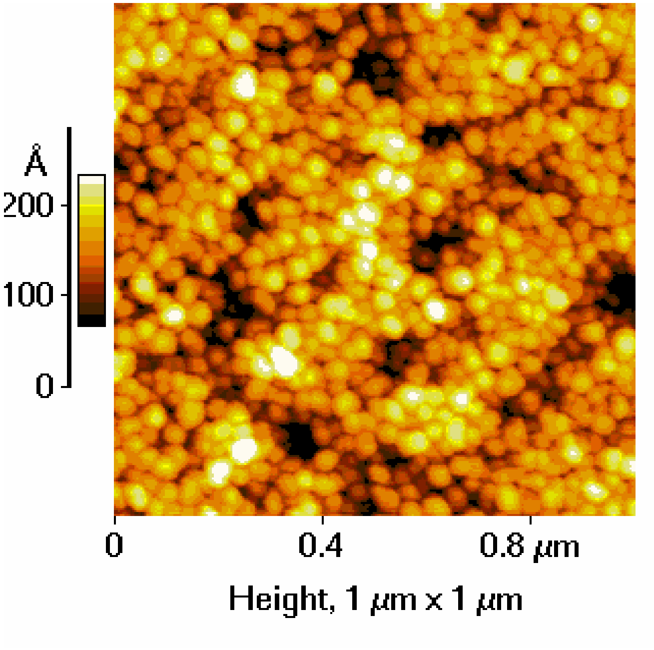


Sputter deposition of iron atoms

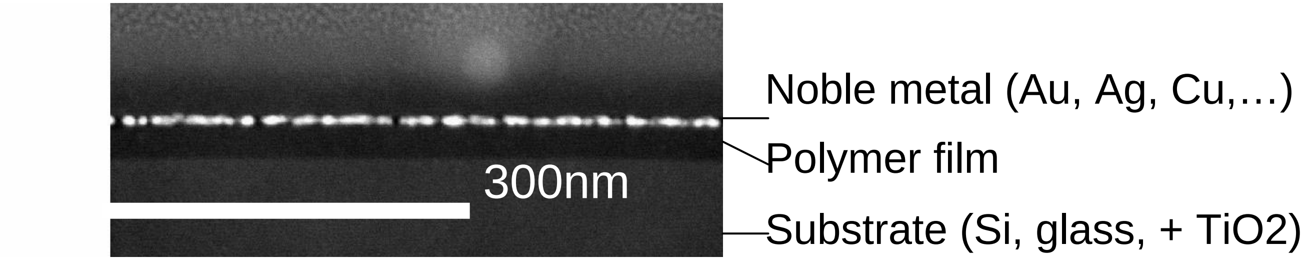
Polymer-Metal Nanocomposites: Production

Sputter deposition:





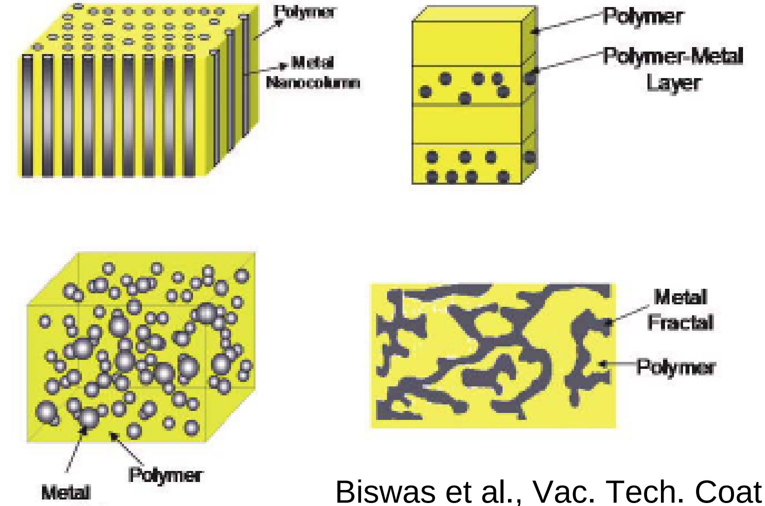
- Nice clusters, too
- Fast deposition method
- Usually broader size distribution
- self-assembly: Au-Au interaction much stronger than Au-Polymer interaction

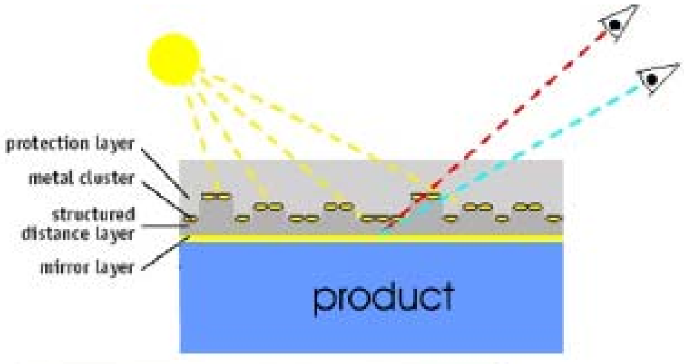


Roth et al., Appl. Phys. Lett. **88**, 021910 (2006)

Block copolymer template

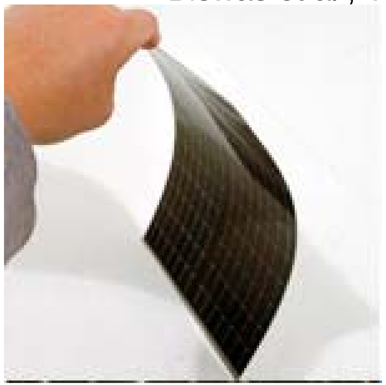
Polymer-Metal Nanocomposites



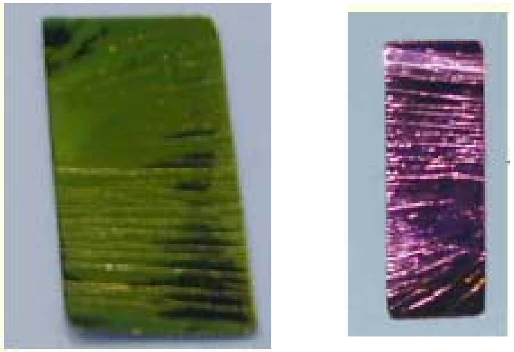


Bauer et al., Nanotechnology 14,1289 (2003)

Biswas et al., Vac. Tech. Coat. **7**, 54 (2006).



http://www.siliconsolar.com

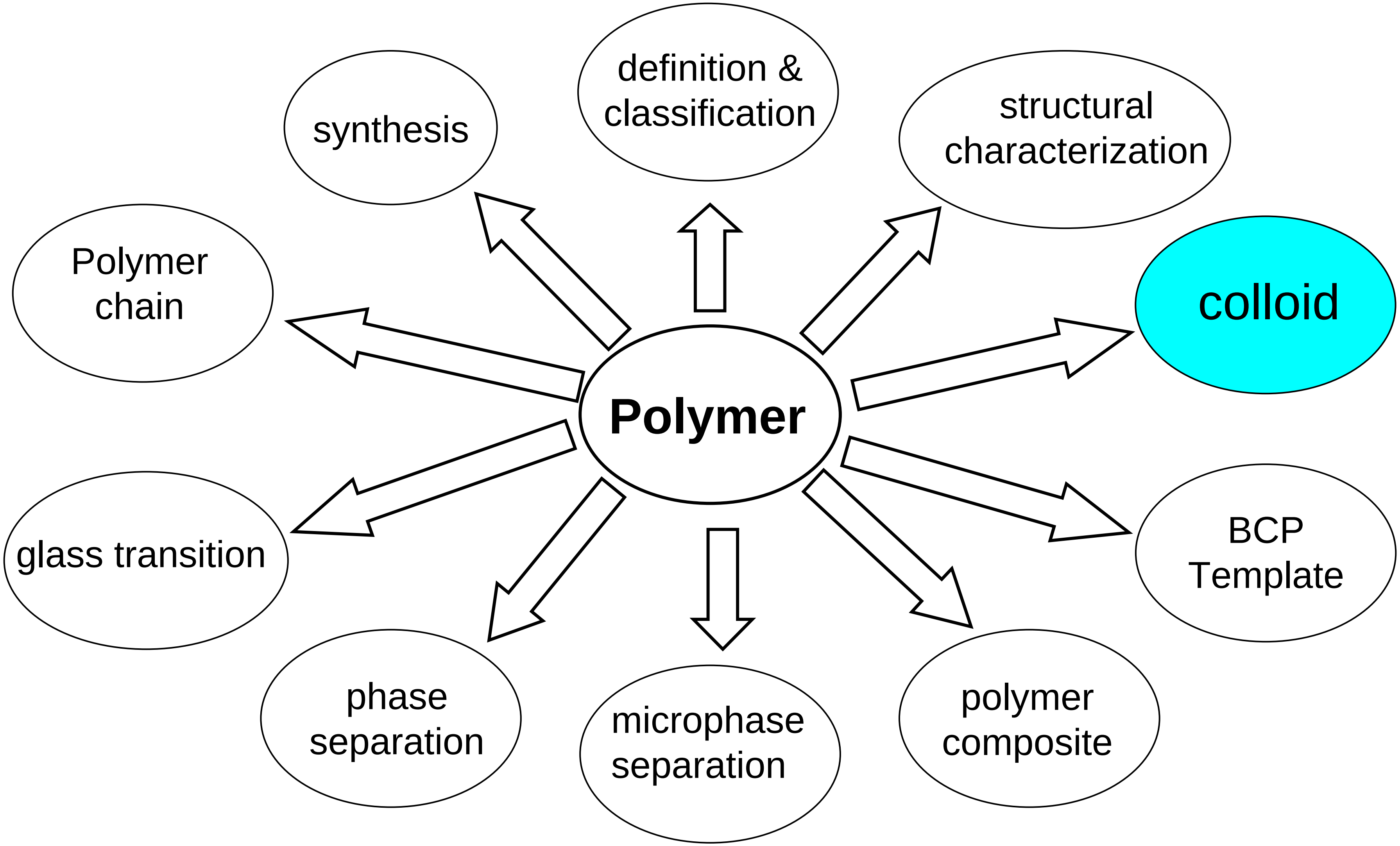


14° 90°

High-frequency filters
Solar cells

$\nu_{lim} \sim \rho/R^2$

Anti-counterfeiting
Biosensors



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Colloids

A **colloid** is a type of mixture of two separate phases: a *dispersed phase* (or *internal phase*) and a *continuous phase* (or *dispersion medium*). A colloidal system may be solid, liquid or gas.

- Polymers
- Metals

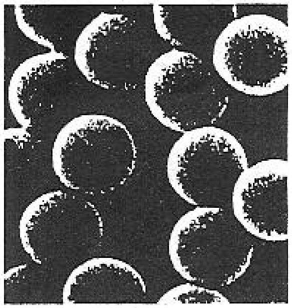
- Small particles, dispersed in liquid phase
- Size: nm….µm
- Wall paints, milk
- Polymers: Spheres

Emulsion polymerization: Example latex particles (styrene/butadiene)

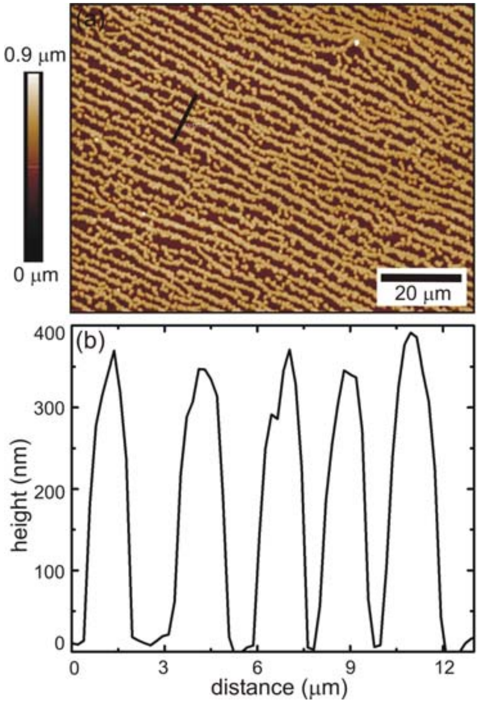
Polymer colloids

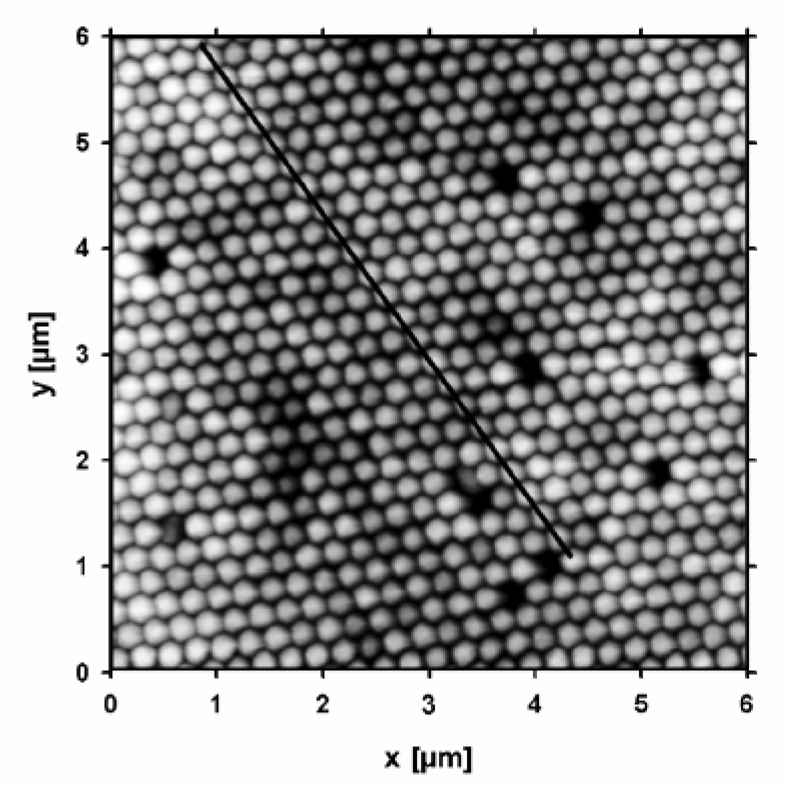
… and you obtain nice spheres:

… which you can nicely arrange here in 2D:



[Springer]





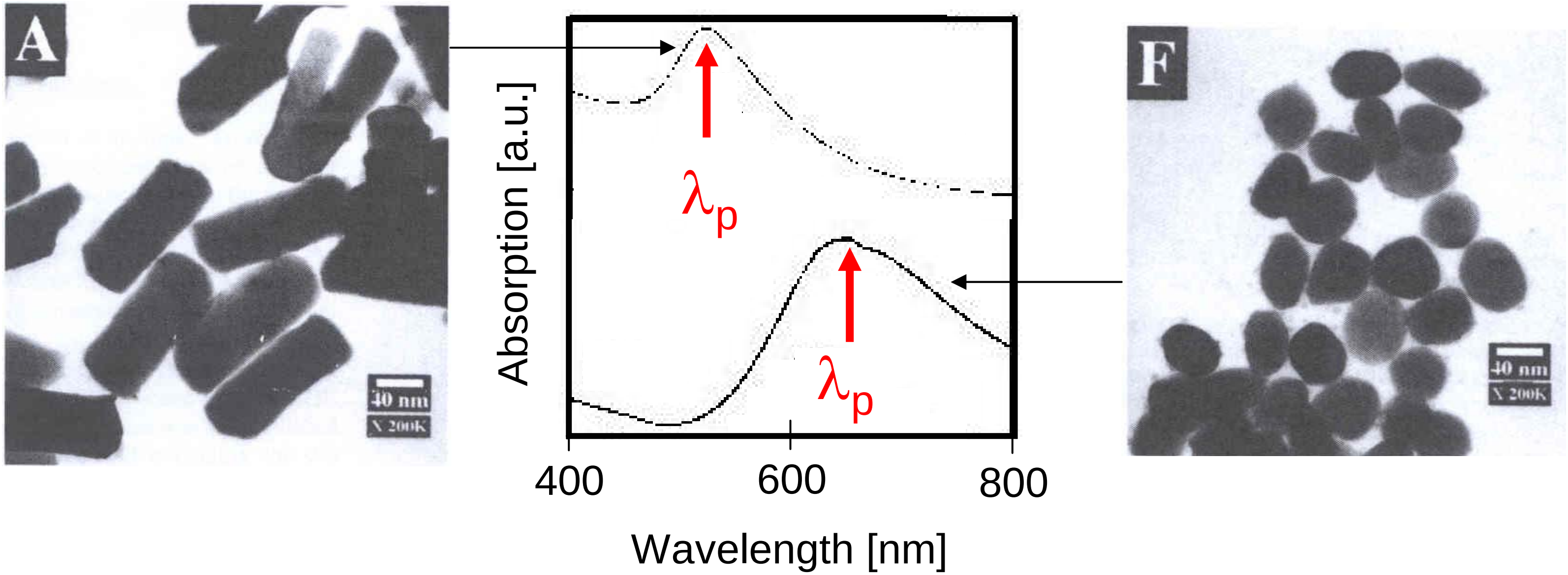
[Frömsdorf, J. Chem. Phys. (2006)]

Colloids

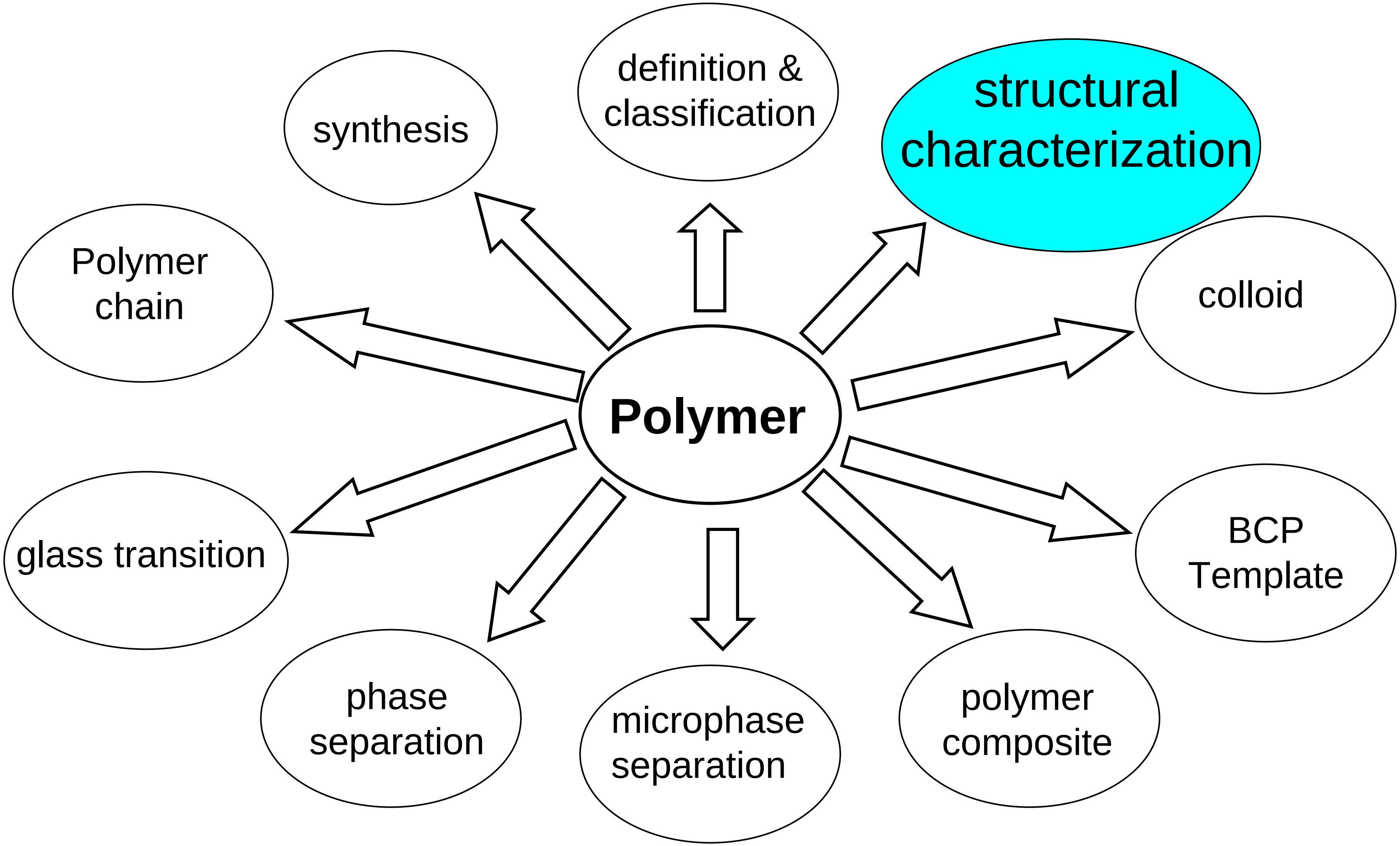
Application

Optical properties: sharp resonances ⟺ plasmon resonances

(visible light) cluster arrangement & shape



J.C. Hulteen et al., J Phys. Chem. B 101, 7727 (1997)



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Structural Characterization

1. Optical microscopy (OM)
2. Atomic force microscopy (AFM)
3. Scanning electron microscopy (SEM)
4. Transmission electron microscopy (TEM)
5. Small-angle X-ray scattering (SAXS)
6. Ultra small-angle X-ray scattering (USAXS)
7. Grazing incidence small-angle X-ray scattering (GISAXS)
8. Grazing incidence ultra small-angle X-ray scattering (GIUSAXS)
9. Wide-angle X-ray scattering (WAXS)
10. X-ray reflectivity (XRR)
11. Dynamic light scattering (DLS)
12. Ellipsometry