Polymers in Biomedical and Pharmaceutical Systems

Purdue University
Biomedical Engineering

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Little by Little
By Joyce Chisale

Little by little we’ll go…
No matter how far the distance is…
We are not shaken…

Little by little we’ll go and reach our destination…

Little by little we’ll go…
No matter how bumpy the road gets…
We’re not going to turn back…

Little by little we’ll go no matter how narrow the path is…
We are going to force ourselves to pass…

Little by little we’ll go and reach the promised land…
Don’t be shaken…Don’t turn back…

Little by little we’ll go and reach our destination…
The Best Way to Enjoy: See the Big Picture

Thinking inside the box   Thinking outside the box

The First "Outside the Box" Box
1. Introduction
**Polymers: Definitions**

**Polymer** (Macromolecule): A substance whose molecules consist of many parts (or units) (Poly: many; Meros: parts)

**Plastic** (*plastikos* = adapt to shaping or casting): A polymer-based material that can be molded, cast, extruded, drawn, or laminated into objects, films, or filaments. (Pliable & easily shaped)

**Long chain molecular structure**
→ Many unique and useful properties

**Molecular Weight:** $M_n$, $M_w$
Number-average, Weight-average

- Light but stiff, strong, and tough,
- Resilient,
- Resistant to chemicals & corrosion,
- No conductivity (temp & electricity)
- Transparent or opaque
- Easily processible and cheap
Polymers: Unique Properties that the Monomers Do Not Have

Multiple contacts
→ Stronger contacts (higher affinity)

DNA: Individual hydrogen bonding is trivial, but millions of hydrogen bonding is significant.

Hair Suspension Artists

https://www.usatoday.com/story/news/nation-now/2014/05/05/hair-hang-circus-ringling/8719429/
Polyhuman = Poly(human being)

Poly(red man)

Polychild = Polykid = Polymer of kids
Poly(boy-co-girl), Poly(girl-co-boy), Copolymer

Poly(father-co-daughter), Copolymer

Poly(man-co-woman), Random copolymer

Poly(man-co-woman), Block copolymer

Graft copolymer

Branched polymer

Chemically crosslinked Gel = Chemical Gel
Physically crosslinked Gel = Physical Gel

Interpenetrating Polymer Network (IPN)

Semi-Interpenetrating Polymer Network (semi-IPN)

Inamdar 2018, Thermoplastic-toughened high-temperature cyanate esters and their application in advanced composites
A plastic that is transparent, resilient, bulletproof, that doesn’t burn, scorch or melt, and it’s natural, eatable and sweet. It would be marvelous… if it was true.

Each one of the characteristics can be found in several plastics, but no plastic has them all. Maybe a technical plastic with all this characteristics exists nowadays. Notice that the development of this kind of plastics started at the beginning of 1950s, so it means that was an actual topic when the movie was filmed.

http://toldbydesign.com/?portfolio=billy-wilder-sabrina

Sabrina. 1954
“One word. Just one word: Plastics. There’s a great future in plastics.”

The Graduate. 1967
Polymers: The Big Picture

Natural
- Proteins
- Polysaccharides
- Nucleic acids

Water-Insoluble
- Water-Soluble

Synthetic
- Thermoplastics
- Thermosets

Degradable
- Nondegradable

Properties
- Chemical structure
  - Molecular architecture
- Physicochemical
- Mechanical

Applications
- Biomedical
- Pharmaceutical
- Agricultural
- Dietary
- Industrial

Duration
- Long-term
- Short-term
- Single-use

Recycling
- Plastic Pollution
### Natural Polymers

#### Chapter Review

### SUMMARY OF KEY CONCEPTS

**CONCEPT 5.1**

Macromolecules are polymers, built from monomers (pp. 67–68)

- Large carbohydrates (polysaccharides), proteins, and nucleic acids are polymers, which are chains of monomers. The components of lipids vary. Monomers form larger molecules by dehydration reactions, in which water molecules are released. Polymers can disassemble by the reverse process, hydrolysis. An immense variety of polymers can be built from a small set of monomers.

What is the fundamental basis for the differences between large carbohydrates, proteins, and nucleic acids?

**CONCEPT 5.2**

Carbohydrates serve as fuel and building material (pp. 68–72)

- Compare the composition, structure, and function of starch and cellulose. What role do starch and cellulose play in the human body?

**Examples**

- **Monosaccharides**: glucose, fructose
- **Disaccharides**: lactose, sucrose
- **Polysaccharides**:
  - Cellulose (plants)
  - Starch (plants)
  - Glycogen (animals)
  - Chitin (animals and fungi)

**Functions**

- Fuel: carbon sources that can be converted to other molecules or combined into polymers
- Strengthens plant cell walls
- Stores glucose for energy
- Stores glucose for energy
- Strengthens exoskeletons and fungal cell walls

**CONCEPT 5.3**

Lipids are a diverse group of hydrophobic molecules (pp. 72–75)

- Why are lipids not considered to be polymers or macromolecules?

**Examples**

- **Triacylglycerols** (fats or oils): glycerol + three fatty acids
- **Phospholipids**: glycerol + phosphate group + two fatty acids
- **Steroids**: four fused rings with attached chemical groups

**Functions**

- Important energy source
- Lipid bilayers of membranes
- Component of cell membranes (cholesterol)
- Signaling molecules that travel through the body (hormones)

**CONCEPT 5.4**

Proteins include a diversity of structures, resulting in a wide range of functions (pp. 75–83)

- Explain the basis for the great diversity of proteins.

**Examples**

- Enzymes
- Defensive proteins
- Storage proteins
- Transport proteins
- Hormones
- Receptor proteins
- Motor proteins
- Structural proteins

**Functions**

- Catalyze chemical reactions
- Protect against disease
- Store amino acids
- Transport substances
- Coordinate organismal responses
- Receive signals from outside cell
- Function in cell movement
- Provide structural support

**CONCEPT 5.5**

Nucleic acids store, transmit, and help express hereditary information (pp. 84–86)

- What role does complementary base pairing play in the functions of nucleic acids?

**Examples**

- **DNA**
  - Sugar = deoxyribose
  - Nitrogenous bases = C, G, A, T
  - Usually double-stranded

- **RNA**
  - Sugar = ribose
  - Nitrogenous bases = C, G, A, U
  - Usually single-stranded

**Functions**

- Stores hereditary information
- Various functions in gene expression, including carrying instructions from DNA to ribosomes

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Urry 2021, The structure and function of large biological molecules
Cheese is made from milk that has been curdled by the addition of acids and an enzyme from the stomach of calves called rennet. The curds are salted, and moisture pressed out, so the product will not be as easily attacked by bacteria as raw milk would. Thus cheese making is a way of preserving milk.

(http://kitchenscience.scitoys.com/protein)
# Proteins: Amino Acids

## Nonpolar side chains; hydrophobic

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Side Chain</th>
<th>Extended Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycine (Gly or G)</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Alanine (Ala or A)</td>
<td>CH₃</td>
<td>CH₃</td>
</tr>
<tr>
<td>Valine (Val or V)</td>
<td>CH₃</td>
<td>CH₃</td>
</tr>
<tr>
<td>Leucine (Leu or L)</td>
<td>CH₃</td>
<td>CH₃</td>
</tr>
<tr>
<td>Isoleucine (Ile or I)</td>
<td>CH₃</td>
<td>CH₃</td>
</tr>
<tr>
<td>Methionine (Met or M)</td>
<td>CH₃S</td>
<td>CH₃S</td>
</tr>
<tr>
<td>Phenylalanine (Phe or F)</td>
<td>C₆H₅</td>
<td>C₆H₅</td>
</tr>
<tr>
<td>Tryptophan (Trp or W)</td>
<td>C₆H₅</td>
<td>C₆H₅</td>
</tr>
</tbody>
</table>

## Polar side chains; hydrophilic

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Side Chain</th>
<th>Extended Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serine (Ser or S)</td>
<td>CH₂OH</td>
<td>CH₂OH</td>
</tr>
<tr>
<td>Threonine (Thr or T)</td>
<td>CH₂OH</td>
<td>CH₂OH</td>
</tr>
<tr>
<td>Cysteine (Cys or C)</td>
<td>SH</td>
<td>SH</td>
</tr>
<tr>
<td>Tyrosine (Tyr or Y)</td>
<td>OH</td>
<td>OH</td>
</tr>
<tr>
<td>Asparagine (Asn or N)</td>
<td>CO₂H</td>
<td>CO₂H</td>
</tr>
<tr>
<td>Glutamine (Gln or Q)</td>
<td>CO₂H</td>
<td>CO₂H</td>
</tr>
</tbody>
</table>

## Electrically charged side chains; hydrophilic

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Charge</th>
<th>Extended Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspartic acid (Asp or D)</td>
<td>Negatively charged</td>
<td>CO₂H</td>
</tr>
<tr>
<td>Glutamic acid (Glu or E)</td>
<td>Negatively charged</td>
<td>CO₂H</td>
</tr>
<tr>
<td>Lysine (Lys or K)</td>
<td>Positively charged</td>
<td>NH₃⁺</td>
</tr>
<tr>
<td>Arginine (Arg or R)</td>
<td>Positively charged</td>
<td>NH₃⁺</td>
</tr>
<tr>
<td>Histidine (His or H)</td>
<td>Positively charged</td>
<td>NH₃⁺</td>
</tr>
</tbody>
</table>

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**Primary Structure**

- Linear chain of amino acids

**Secondary Structure**

- Regions stabilized by hydrogen bonds between atoms of the polypeptide backbone

**Tertiary Structure**

- Three-dimensional shape stabilized by interactions between side chains

**Quaternary Structure**

- Association of two or more polypeptides (some proteins only)

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*Urry 2021, The structure and function of large biological molecules*

*Ouellette 2014, Amino acids, peptides, and proteins*
Proteins: Gelatin

Hydrogels

Ballistics Gel for Bullet Tests
10% Gelatin gel (250 Bloom):
The density and viscosity of human and animal muscle tissue.
Gelatin Jello

Hydrogels

The major component is water. Jello behaves like a solid.

State of water
Removing water from Jello without melting?

https://chembam.com/resources-for-students/the-chemistry-of/gelatin/
Proteins: Microtubules

Microtubule Motor Protein

https://en.wikipedia.org/wiki/Microtubule
**Natural Polymers: Polysaccharides**

Cellulose = Cellulle (a living cell) + glucose

Cellulose: $\beta(1\rightarrow4)$ linked Dglucose

Ethylcellulose

Carboxymethylcellulose

Hyaluronic acid

Chitosan

Alginic acid

Hydroxypropyl methylcellulose (HPMC, Methocel™)

Aravamudhan 2014, Natural polymers-Polysaccharides
Polysaccharides: Carbohydrate Polymers

Natural Polysaccharides

Pectin

Pectin is a polymer of α-Galacturonic acid with a variable number of methyl ester groups.

Guar Gum

Xanthan Gum

Chen 2021, The past ten years of carbohydrate polymers in ACS Macro Letters
Polysaccharides

Starch: $\alpha(1\rightarrow4)$ linked D-glucose polymer

- Heating the starch:
  At heat and moisture are added, beta-starch incorporates water molecules into its glucose chains and becomes alpha-starch.

- The aging of starch:
  Once the alpha-starch shrivels its water and reverts to a difficult-to-digest mass that is close to its original beta-starch form.

Bread: Soft or Hard

Natural Wood
METHOCEL™ cellulose ether products are available in two basic types: methylcellulose and hypromellose.

**METHOCEL™ A:** Methylcellulose is made using only methyl chloride.

**METHOCEL™ E, F & K:** Hypromellose products are made using propylene oxide in addition to methyl chloride to obtain hydroxypropyl substitution on the anhydroglucose units. This substituent group, -OCH₂CH(OH)CH₃-, contains a secondary hydroxyl on the number two carbon and may also be considered to form a propylene glycol ether of cellulose. These products possess varying ratios of hydroxypropyl and methyl substitution, a factor which influences organic solubility and the thermal gelation temperature of aqueous solutions.
Nucleic acids are composed of monomers known as nucleotides (= polynucleotides)
Each nucleotide consists of a phosphate, a pentose sugar (deoxyribose for DNA and ribose for RNA), and a nitrogenous base.

Scofield 2007, Nucleic acids
DNA

**MOLECULAR STRUCTURE OF NUCLEIC ACIDS**

A Structure for Desoxyribose Nucleic Acid

W. J. Watson and F. H. C. Crick have proposed a structure for desoxyribose nucleic acid (DNA). The structure has several features which are in agreement with the known properties of DNA. The structure consists of two antiparallel polynucleotide chains so arranged that complementary base pairs occur in the interior of the molecule. These base pairs are held together by hydrogen bonds, the nature of which has been determined by the X-ray diffraction studies of D. H. Crowfoot and J. D. Bernal. The two polynucleotide chains are wound around each other in a helical fashion, forming a right-handed double helix. The diameter of the helix is approximately 2 nanometers, and the distance between the two sugar-phosphate backbones is approximately 0.34 nanometers.

**The Double Helix**

Shining a Light on the 'Dark Lady of DNA'

F. H. C. Crick and J. D. Watson, two scientists who were instrumental in the discovery of the structure of DNA, proposed a model for the molecule that has since become known as the double helix. This model was developed through a combination of experimental evidence and theoretical reasoning, and has since been confirmed by a variety of biological and chemical experiments. The discovery of the double helix was a major milestone in the field of molecular biology, and has had a profound impact on our understanding of the nature of life.

**Mysteries of History: Who Was First?**

**FRANKLIN, AS MUCH AS THE MEN CREDITED, DISCOVERED THE CODE**

The crucial X-ray fiber images were taken between 1951 and 1952, and the models of the DNA helix were built in 1953. However, the contribution of Rosalind Franklin to the discovery of the double helix has been largely overlooked. Franklin’s work on X-ray crystallography provided crucial insights into the structure of DNA, but her contributions were not fully recognized during her lifetime. The discovery of the double helix by Watson and Crick was a result of their interpretation of Franklin’s data, and it is now recognized that her work was essential to the development of this important model.
Entering the Crispr Era: DNA Hacking Tool Enables Shortcut to Evolution

The 2010s marked huge advances in our ability to precisely edit DNA, in large part thanks to the identification of the CrisprCas9 system. Some bacteria naturally use CrisprCas9 as an immune system, since it lets them store snippets of viral DNA, recognize any future matching virus, and then cut the virus’s DNA to ribbons. In 2012, researchers proposed that CrisprCas9 could be used as a powerful genetic editing tool, since it precisely cuts DNA in ways that scientists can easily customize. Within months, other teams confirmed that the technique worked on human DNA. Ever since, labs all over the world have raced to identify similar systems, to modify CrisprCas9 to make it even more precise, and to experiment with its applications in agriculture and medicine.

While CrisprCas9’s possible benefits are huge, the ethical quandaries it poses are also staggering. To the horror of the global medical community, Chinese researcher He Jiankui announced in 2018 the birth of two girls whose genomes he had edited with Crispr, the first humans born with heritable edits to their DNA. The announcement sparked calls for a global moratorium on heritable “germline” edits in humans.

https://www.nationalgeographic.com/science/2019/12/top20scientificdiscoveriesofdecade2010s/?cmpid=org-ngp::mc=crmemail::src=ngp::cmp=editorial::add=SpecialEdition_20191229&rid=FF526C1F1B0738788B420FE1D0034350

Watch: Learn—and visualize—how CRISPR technology works in this animated graphic video.
mRNA COVID-19 Vaccine

- Plasmid containing Coronavirus spike protein gene
- Grow modified E. coli
- Harvest and Purify the DNA
- Cut the plasmid
- Transcribe the DNA into mRNA
- Assemble the mRNA vaccine into lipid nanoparticles
- A vaccine for variants


Elia 2021, Design of SARS-CoV-2 hFc-conjugated receptor-binding domain mRNA vaccine delivered via lipid nanoparticles, ACS Nano

Figure 2. Common chemical modifications for RNA oligonucleotides (Ons). The three sites for common modifications of RNA Ons include the nucleobase, the phosphate backbone, and the carbohydrate sugar. Advantageous characteristics of modifications are listed for each site, and chemical modifications which are utilized FDA-approved Ons are listed for each. The 5′-carbon of the nucleobase and the 2′-carbon of the carbohydrate are annotated with their relevant location number. Abbreviations: PS, phosphorothioate; PMO, phosphorodiamidate morpholino oligomer; 2′-OMe, 2′-O-methyl; 2′-O-MOE, 2′-O-methoxyethyl; 2′-F, 2′-fluoro; LNA, locked nucleic acid.

Figure 3. Endocytic uptake and endosomal escape of Ons. The major identified internalization routes of Ons are clathrin-dependent endocytosis, clathrin-independent endocytosis, and macropinocytosis. On is then trafficked sequentially to the early endosome and sequentially to the late endosome, where it is trafficked to the lysosome or to the multivesicular bodies and exocytosed. Late endosome membrane remodeling and transition to MVB or lysosome have been indicated as likely points of endosomal escape. Commonly used endosomal markers are shown. Abbreviations: Rab, Ras-associated protein; EEA1, early endosome antigen 1; LBPA, lysobisphosphatidic acid; LAMP1, lysosomal-associated membrane protein 1.
Aptamer

Fig. 1 Illustration of how (A) aptamer and (B) antibody attaches to proteins and structure of (A) aptamer and (B) antibody

Table 1. The difference between aptamers and antibodies

<table>
<thead>
<tr>
<th></th>
<th>Aptamers</th>
<th>Antibodies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Small (~12-30 KDa)</td>
<td>Relatively Big (~ 50-170 KDa)</td>
</tr>
<tr>
<td>Target</td>
<td>Wide range</td>
<td>Immune related protein</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Simple (chemical synthesis)</td>
<td>Complicate (in vivo production)</td>
</tr>
<tr>
<td>Stability</td>
<td>Stable</td>
<td>Susceptible to temperature and pH</td>
</tr>
<tr>
<td>Modification</td>
<td>Various modification</td>
<td>Limited modification</td>
</tr>
<tr>
<td>Storage Term</td>
<td>Long</td>
<td>Relatively short</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Immunogenicity</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Kim 2021, Design and clinical developments of aptamer-drug conjugates for targeted cancer therapy

Fig. 2 (A) ApDC constructed by Nucleotide Analogs. (B) ApDC by drug and aptamer intercalation (C) ApDC by using linker between drug and an aptamer
Figure 1. Design and preparation of sustainable DNA plastics. (A) Scheme of the formation of DNA/ionomer hydrogel networks. (B) Scheme of the recyclable use of DNA plastics. (C) Digital photos of DNA plastics with the shape of double helix structure of DNA. The wavelength of UV light was 312 nm. (D) Scheme of the modular assembly process to form a plastic cup. (E) Digital photo of a plastic cup. Without special explanation, DNA plastics were stained green and red by SYBR Green I and GelRed, respectively.

Figure 4. Healing and welding of sustainable DNA plastics to form 3D architectures using water. The wavelength of UV light was 312 nm. (A) Digital photos of the healing process of two pieces of triangular prism-shaped plastics that were stained green and red, respectively. (B) Digital photos of the healing process of a fractured dumbbell-shaped specimen. (C) Young’s modulus of original and healed plastic specimens. Results are presented as means ± standard deviation (SD) (n = 3). (D) Digital photos of the healing process of four pieces of plastic puzzles. The puzzles were stained red, green, blue, and green by GelRed, SYBR Green I, carbon dots, and fluorescein, respectively. (E) Preparation of a plastic cup with a cover using waste DNA plastics. (F) Digital photos of the degradation of plastics in DNase I solution (5 U/μL).

Han 2021, Sustainable bioplastic made from biomass DNA and ionomers
(Vinning) Maurice A. Lemoigne, a biologist at the Pasteur Institute of Paris, reported in 1925 that a bacteria produced a polyester with properties similar to those of synthetic plastics. These natural polyesters, or polyhydroxyalkanoates (PHAs), can be melted, molded, and shaped to form articles, like other thermoplastics. In June of 1991, Britain's Imperial Chemical Industries opened a factory containing large fermenters for polymer producing bacteria to grow. Adjusting the mixtures of raw materials fed to the bacteria produces different polyesters with different properties.

Subsequently, Douglas Dennis, a molecular biologist at James Madison University, found that recombinant bacteria could also produce PHAs by identifying and transferring the genes controlling PHA production into a common bacterium, E. Coli. Inspired by this research, scientists at Michigan State University inserted the gene responsible for PHB production into a plant known as the Arabidopsis, or "mouse ear cress". This plant was able to successfully produce polyester. These plastics are completely biodegradable because they are naturally occurring food reservoir for bacteria.

These polymers generally do not trigger an immune response, and they are widely used in medical industry. Unfortunately, they are more expensive than those from conventional petroleumproduced plastics.
Natural Polymers: Polyesters

Polyhydroxyalkanoates (PHAs) are naturally produced.

Poly3-hydroxybutyrate (PHB or PH3B)

Poly3-hydroxyvalerate (PHV)

Poly(3-hydroxy butyrate-co-3-hydroxyvalerate) (PHBV)

McKeen 2012, Renewable Resource and biodegradable polymers, in Film Properties of Plastics and Elastomers (3rd Edn). 14.8. Poly-3-hydroxybutyrate (PHB or PH3B)

Synthetic Polymers

Linear Polymers (1930s)
- Homopolymer
- Copolymer
  - Random copolymer
- Block copolymer

Crosslinked Gel (1940s)

Branched Polymers (1960s)

Dendrimers (1980s)

Linear polymers can pack together very closely, resulting in a high density material.

Branched polymers cannot pack as tightly, resulting in less dense and more flexible material.

Crosslinked polymers can swell in solutions, but cannot dissolve in the solvents unless the crosslinkers are broken.
Additives
When plastics emerge from reactors, they may have the desired properties for a commercial product or not. The inclusion of additives may impart to plastics specific properties. Some polymers incorporate additive during manufacture. Other polymers include additives during processing into their finished parts. Additives are incorporated into polymers to alter and improve basic mechanical, physical or chemical properties. Additives are also used to protect the polymer from the degrading effects of light, heat, or bacteria; to change such polymer processing properties such as melt flow; to provide product color; and to provide special characteristics such as improved surface appearance, reduced friction, and flame retardancy.

Types of Additives
Antimicrobials: used for shower curtains and wall coverings
Antioxidants: for plastic processing and outside application where weathering resistance is needed
Antistats: to reduce dust collection by static electricity attraction
Colorants: for colored plastic parts
Flame retardants: to improve the safety of wire and cable coverings and cultured marble
Foaming agents: for expanded polystyrene cups and building board and for polyurethane carpet underlayment
Lubricants: used for making fibers
Plasticizers: used in wire insulation, flooring, gutters, and some films

Polymer Characterization
• Understanding the relationships between chemical structure and (molecular and bulk) properties of polymers.

• Characterization of molecular and bulk properties

• Use the relationships to design new materials with predictable properties, and to mimic natural substances without need to duplicate their structures in detail.

Past & Present

Existing Polymers
Find Applications

Present & Future

Applications: Specific Polymer Properties
Design New Polymers
Characterization: Polymer Molecules

- **Molecular Weights**
  - Weight average
  - Number average

- **Molecular Structure**
  - Monomers: Single monomer, Comonomers
  - Architecture: Linear, Branched, Dendritic, Crosslinked

- **Solubility**
  - Polymers dissolved in a solvent are used in paints, varnishes, and glues. As a general rule, as the size of a polymer increases, the difficulty with which it dissolves also increases.

[https://chemisyou.blogspot.com/2015/03/polymerchemistrymolecularweightof.html](https://chemisyou.blogspot.com/2015/03/polymerchemistrymolecularweightof.html)
- Size exclusion chromatography/gel permeation chromatography separate based on the hydrodynamic volume.
- Solvation between polymer/solvent, interaction with column also controls the retention time.
- Non-representative standard (typically polystyrene) and the lack of standardized methods mean lab-to-lab differences in GPC measured molecular weights.

GPC separation followed by MALLS ($R_g$, MW), Viscometry (intrinsic viscosity), inline dynamic light scattering ($R_h$), and refractive index (concentration).
- Universal calibration, no external standards, no solvation artifacts.
- Light scattering is better for low RI solvents (acetone) than high RI solvents (THF).
- In depth information about PLGA for determination of molecular shape & branching.
Star-Shaped PLGA (Glucose-PLGA)

Glu-PLGA

\[ R = \begin{cases} \text{OR} & \text{or} \quad R = H \\ \text{CH}_3 \end{cases} \]

R represents either PLGA or hydrogen

\[ V_h = \frac{2 [\eta] M}{5 N_A} \]  
(V\(_h\): Hydrodynamic Volume)

Low Molecular Weight  
High Molecular Weight

\[ M_{\text{lin}} = M_{\text{star}} \quad M_{\text{star}} > M_{\text{lin}} \]

\[ V_{h,\text{lin}} > V_{h,\text{star}} \quad V_{h,\text{star}} = V_{h,\text{lin}} \]

\[ f = 3 \quad f = 5 \quad f = 5 \]

\[ \text{PDI}_{\text{star}} \approx \text{PDI}_{\text{lin}} \quad \text{PDI}_{\text{lin}} \leq \text{PDI}_{\text{star}} \]

Fig. 7. Mark-Houwink plots of Glu-PLGAs of Sandostatin LAR, Corbion, E vonik, and Lactel(A), branch standards with triplicate measurements of each sample (B), Glu-PLGAs of Sandostatin LAR (lots 356166 (CandD) in comparison with the branch standards of 2–6 arms.

The branch units of Glu-PLGAs can be determined without any theoretical model from the Mark-Houwink plots, \([\eta]=KM\alpha\) or \(\log[\eta]=\log K+\alpha\log M\), where \([\eta]\) and \(M\) are intrinsic viscosity and molecular weight, respectively.
Polymer Properties
Properties

**Mechanical properties:** Solid, Elastomer, Liquid
- Glass transition temperature \( (T_g) \) & Melting temperature \( (T_m) \)
- Elastic modulus, Flexibility, Tensile strength
- The polymer crystallinity increases its strength, stiffness, and chemical resistance.
- Resilience: The ability of the plastic to resist abrasion and wear

**Permeability:** Polyethylene is used to wrap foods because it is 4000 times less permeable to oxygen than polystyrene.

**Crystallinity:** Amorphous arrangement of polymer chains are usually transparent
- (Contact lenses, windows, headlight lenses, food wrap)
- The higher degree of crystallinity, the less light through the polymer.

**Heat conductivity:** Effective insulators against the flow of heat

**Refractive index:** The extent to which the plastic affects light as it passes through the polymer

**Thermal expansion:** Polymers are usually anisotropic. They contain strong covalent bonds along the polymer chain and much weaker dispersive forces between the polymer chains. As a result, polymers can expand by differing amounts in different directions.

**Resistance to electric current:** Most polymers do not conduct an electric current, except some conducting polymers.
Properties: Amorphous and Crystalline

Thermoplastic materials can be divided into amorphous and semicrystalline.

Amorphous thermoplastic materials are usually clear and stiff material with low shrinkage (e.g., polystyrene, polycarbonate, and poly(methyl methacrylate)).

Semicrystalline thermoplastic materials are generally tougher and less fragile than amorphous thermoplastics. They are translucent, or opaque, and have a high shrinkage and a high specific heat (e.g., polyethylene, polypropylene, poly(ethylene terephthalate), polyamides

Properties: Phase Separation

Phase separation

Schmitt 2016, Polymer ligand–induced autonomous sorting and reversible phase separation in binary particle blends

Kim 2015, Isolation of high-purity extracellular matrix
Polymer Applications
**Applications: Thermoplastics and Thermoset Plastics**

**Thermoplastics** (Secondary bonds between polymer chains)
- **Polyethylene:** Packaging, Electrical insulation, Milk and water bottles, Packaging film, House wrap, Agricultural film
- **Polypropylene:** Carpet fibers, Automotive bumpers, Microwave containers, External prostheses
- **Polyvinyl Chloride:** Sheathing for electrical cables, Floor and wall coverings, Siding, Automobile instrument panels, Credit card

**Thermoset Plastics** (Primary bonds between polymer chains; crosslinked)
- **Polyurethanes:** Mattresses, Cushions, Insulation
- **Unsaturated Polyesters:** Boat hulls, Bath tubs and shower stalls, Furniture
- **Epoxies:** Adhesive glues, Coating for electrical devices, Helicopter and jet engine blades
- **Phenol Formaldehyde:** Oriented strand board, Plywood, Electrical appliances, Electrical circuit boards and switches

# Applications: Polymers for Packaging

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Properties</th>
<th>Applications</th>
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<tbody>
<tr>
<td>High density polyethylene</td>
<td>Excellent resistance to most solvents Relatively stiff material with useful temperature capabilities.</td>
<td>Bottles for milk, water, juice, cosmetics, shampoo, dish and laundry detergents, and household cleaners. Bags for groceries and retail purchases. Cereal box liners.</td>
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<tr>
<td>Low density polyethylene</td>
<td>Good combination of properties for packaging applications requiring heat-sealing. Can be made into thin films.</td>
<td>Bags for dry cleaning, newspapers, bread, frozen foods. Shrink wrap and stretch film. Coatings for paper milk cartons and hot and cold beverage cups. Container lids. Squeezable bottles (e.g., mustard)</td>
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<tr>
<td>Poly(ethylene terephthalate)</td>
<td>Clear, tough, and has good gas and moisture barrier properties. Cleaned, recycled PET pellets are used for spinning fiber for carpet yarns and producing fiberfill and geotextiles.</td>
<td>Plastic bottles for soft drinks, water, juice, sports drinks, beer, mouthwash, catsup, and salad dressing. Food jars for peanut butter, jelly, jam, and pickles. Ovenable film and microwavable food trays</td>
</tr>
</tbody>
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https://www.plasticpackagingfacts.org/plasticpackaging/resinstypesofpackaging/  
https://www.bbc.co.uk/bitesize/guides/ztr7b82/revision/2
# Applications: Polymers for Packaging

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<td>Polystyrene</td>
<td>Rigid or foamed. Relatively low melting point. Excellent moisture barrier for short shelf life products. Significant stiffness in both foamed and rigid forms. Low thermal conductivity and excellent insulation properties in foamed form.</td>
<td>Typical applications include protective packaging, food service packaging, bottles, and food containers. PS is often combined with rubber to make high impact polystyrene (HIPS) which is used for packaging and durable applications requiring toughness, but not clarity</td>
</tr>
</tbody>
</table>
Applications: BulletProof Glass

- **Clarity and Strength**
  Polycarbonate: Strong, light weight, UV resistant, scratch resistant, heat resistant, transparent.
  Used in safety glasses, airline windows, riot police shields, bullet-proof glass

- **Lexan®**
  Made by GE. Tough, transparent, high tensile strength, temperature-resistant, light weight.
  Used in bicycle, motorcycle, and football helmets, automobile and aircraft equipment, safety glass, unbreakable glass, signs, race car exterior.
Polyarylates are a family of aromatic polyesters. The repeat units consists of ester groups (chemical formula -CO-O-) and aromatic rings. They are produced by polycondensation of a diacid chloride derivative of a dicarboxylic acid with a phenolic compound. The dicarboxylic acid is usually terephthalic or isophthalic acids and the phenol is Bisphenol A or a derivate of it. The bulky aromatic rings and the absence of methylene groups in the polymer backbone greatly stiffen the polymer chain by interfering with the rotation of the repeat units around the ester linkages. The two most common polyarylates are poly(-p-hydroxybenzoate) and polybisphenol-A terephthalate. The chemical structure of these arylates is given below.

Polybisphenol-A terephthalate is the most common polyarylate. It has one of the highest-levels of heat resistance among transparent resins. For example, its deflection temperature under 1.8 MPa load is about 175 °C (345 °F) (Ardel Polyarylate). It also has high transparency and excellent resistance to degradation from ultraviolet radiation. The material undergoes a molecular rearrangement resulting in the formation of a protective layer that essentially serves as a UV stabilizer. Because UV irradiation increases the UV-blocking property of the polymer, it exhibits excellent weather resistance without addition of any stabilizers. (Although some yellowing occurs, there is hardly any change in physical properties.) Arylates have a transparency as high as PC or PMMA, transmitting almost 90% light. The polymer exhibits excellent elastic recovery and has a high tolerable strain ratio. It also has excellent creep resistance and retains its properties for an extended period of time. For these reasons, the polymer can be used as springs.

Some other noteworthy arylate monomers are 4-acetoxybenzoic acid, 4-hydroxybenzoic acid, hydroxynaphthalene-2-carboxylic acid, and 4-pivaloyloxybenzoic acid. The polymer Ekonol produced by Saint-Gobain, is based on 4-hydroxybenzoic acid. It is a highly crystalline linear thermoplastic polymer with no melting point and virtually no creep below 350 °C. It retains good stiffness at temperatures up to 315°C and, at temperatures around 425°C, it undergoes a second-order transition and becomes malleable and can be forged like ductile metals. Some other properties are high heat resistance, dielectric strength, elastic modulus, thermal conductivity, and good resistance to wear and solvents. It is also good machinable. Poly(hydroxybenzoate) can be blended with polytetrafluoroethylene (PTFE). This composite material is self-lubricating and has excellent temperature and wear resistance. Another important polyarylare is the Vectran fiber, manufactured by Kuraray. It is produced by polycondensation of 4-hydroxybenzoic acid and 6-hydroxynaphthalene-2-carboxylic acid and has similar good properties.
Applications: Polypropylene

- **Greasy, Oily, and Fairly Stiff**
  Polypropylene: Hydrophobic, greasy, oily, fairly stiff, transparent, inexpensive
  Used in laminations, automobile interiors, automobile battery cases, textiles, toys, bottle caps, carpeting, street signs

**Top 5 Common Uses of Polypropylene**

1. Flexible and Rigid Packaging
2. Flexible and Rigid Packaging
3. Medical Applications
4. Consumer Products
5. The Automotive Industry

https://totebagfactory.com/blogs/news/commonusesofpolypropylene
Applications: Biomedical Polymers

- **Biomedical Applications**
  Artificial Heart. Tissue engineering

- **Cosmetic Applications**
  Hyaluronic acid filler, PLGA filler
  Botulinum toxin

- **Adhesives**

Six Million Dollar Man

https://www.youtube.com/watch?v=0CPJ-AbCsT8

The Bionic Woman
https://www.youtube.com/watch?v=Pz_DT54sfAo
**Applications: Products for Daily Use**

**Polymer Molding**

Polymer Molding

**Materials**

Using Polymers

Polyethylene formed in the polymerization reaction is extruded, dried, and converted into a convenient pellet form. The pellets are then fed into an extruder—essentially a giant screw—rotating within a metal barrel. Heating elements in the extruder melt the polymer, and as the screw turns, the molten polymer is forced under increasing pressure. A hollow tube of molten, pressurized polymer emerges from the extruder. This is fed into a die, where jets of air force the walls of the tube against the die. This form of molding, known as extrusion blow molding, is commonly used in the manufacture of plastic pipes and bottles.

**Extrusion**

To make plastic into simple or simple articles, a method called extrusion is used. Plastic pellets are taken by a luer wire to a chamber which melts them and then forces them into a thin, waxy liquid. This is sprayed through a specially shaped hole called a die to form a tube or a sheet. When this passes through a cooler, it is quickly hardened.

**Rubber**

Rubber, a gum extracted from tropical trees, is a natural polymer. Its molecules have chains and loops in them. The gel colloids in solution are rubbery; they are coiled up. When molecules are not connected together, to make these links, it is heated with sulfur in a process called vulcanization. The tangled rubber elasticities now snap and stretch without breaking. Molds or shaping can be made by mixing rubber with other materials.

**Molding**

One way of forming plastic into special shapes is by a method called molding. A raw polymer is placed through a machine where it is heated. The hot, liquid, plastic flows from a mold into a mold. Once the mold is open, the plastic sheet is removed and shaped.

**Recycling Plastics**

Some plastics can be melted, Pelletized by extrusion (P.E.T.) to give résolubles, which can be collected into tubes, cleaned, and then recycled into chips that can be recolored. Many bottles are made from a polymer of a sugar, glasine. Recycled soda bottles may be broken down into carbon dioxide and water.

**Find out more**

- Carbon 40
- Organic Chemistry
- Chemical Properties of Oil Products
- Science of the Environment
- Earth Science

**Facts Under 3.**
Applications: Foods

Bread: Starch (Yeast, Kneading)

Milk: Lactose-intolerant
Yogurt

Marshmallow

Artificial meat

Kneading is the process of working a dough mixture to form a smooth and cohesive mass. It can be done by hand or mechanically. Proper kneading is essential for the formation of dough with adequate viscoelastic properties including gas retention capacity.
Polymer Recycling
Recycling

Plastic Types
After the plastics are separated from other materials, they need to be stored by type. The separated plastics can be reused easily, as those are far superior to mixed plastics. The separated plastics are washed (and optionally sterilized), and ground or shredded into a pellet (small piece) or flake form that can be melted and molded for new use.

Importance of Separating Different Types of Plastics
Single type of polymers produce high quality products compared with blended polymers.

Separation of Different Plastics
Bar codes encoding each plastic, Spectroscopic analysis, Density (in solution), by Consumers

Removing Dirt from Plastics
The presence of dirt can be critical for spinning recycled plastics into fibers, as the dirt may block the pores of the spinners easily. Washing may not remove all dirt. Dissolving and filtering is difficult and expensive.

Recycled Plastics
They can be used for many applications, especially where tensile strength is not critical.
Plastic Pollution: Our Urgent Problems

Microplastics & Nanoplastics
Steeping a single plastic teabag at brewing temperature (95 °C) releases approximately 11.6 billion microplastics and 3.1 billion nanoplastics into a single cup of the beverage. The composition of the released particles is matched to the original teabags (nylon and polyethylene terephthalate) using Fouriertransform infrared spectroscopy (FTIR) and Xray photoelectron spectroscopy (XPS).
Polymer in History
4 Billion Years of Evolution in 40 Seconds.

History of the Entire World

https://www.youtube.com/watch?v=UX-10v5EBAs

https://www.vox.com/world/2017/5/15/15641594/worldhistoryvideobillwurtz

carlsagan.com
Van Gogh’s “Starry Night”: The Best Way to Enjoy