Introduction and Basic Concepts

S. Koltzenburg et al., *Polymer Chemistry*, DOI 10.1007/978-3-662-49279-6_1

Among the many areas of chemistry, polymer science is a comparatively new field. The empirical use of polymeric materials made from natural substances has been documented for centuries; however, only the pioneering work of the late Hermann Staudinger (1926), a Nobel laureate, in the 1920s provided the basis for a systematic understanding of this class of materials. In the decades since then, polymer science has developed to become both technically demanding and industrially extremely important. In particular, polymer science is characterized by its interdisciplinary nature:

- Most technologically relevant macromolecules[1] are based on a carbon backbone and thus belong in the realm of *organic chemistry*.
- Approximately half of all polymers produced today are synthesized using *organometallic* catalysts.
- A description of the behavior of both solid polymers and their solutions is now based on well-established *physical* and *physicochemical theories*.
- Because macromolecules are often used in the area of classical materials, processing and molding of polymers is an essential step in the production of finished products. Thus, *engineering science* is also important. In medical technologies, polymers are used in highly specialized applications, such as artificial heart valves, eye lenses, or as materials for medical devices.

Last but not least, as well as the vast and significant use of synthetic polymers, macromolecules are of crucial *biological* importance. Undoubtedly the most important polymer in the world—without which human existence would not be possible—is DNA. Without its polymeric nature, DNA could not fulfill its essential role as the memory molecule of living systems. If the molecules were not linked to a polymeric strand, DNA would be nothing more than a mixture of four different bases with no defined structure and therefore without biological function. In addition to the millions of tons of natural rubber processed annually, further examples of biopolymers essential to life include proteins that catalyze chemical reactions as enzymes, form membranes, or act as antibodies differentiating between friend and foe.

This chapter deals with the basic concepts and definitions of polymer science and especially the most important question that a natural scientist can ask: “Why?” In particular, why should one take an interest in this field? It is shown that polymers constitute a class of materials that not only make an essential contribution to the existence of life in the form of biological macromolecules, but without which, thanks to their myriad technical applications, our modern daily life would be no longer conceivable.

1.1 Polymers: Unique Materials

Even if we restrict ourselves to the field of non-biogenic, traditional materials, macromolecules are a material class of unparalleled versatility. However, the range of properties covered by polymeric materials is much broader than that of traditional materials. Thus, for example:

---

[1] Originally, a distinction was made between macromolecular substances and polymers. This differentiation has become unnecessary. In this book, these terms are used congruently.

- Glass fiber reinforced plastics can have tensile strengths that rival, e.g., steel, whereas other polymers such as polyurethane foams can be used as soft cushions or mattresses.
- Most plastics are electrical insulators, but highly conjugated polymers have also been synthesized with specific conductivities of the same order of magnitude of those of highly conductive metals (Naarmann and Theophilou 1987).
- The density of porous polymeric materials can be varied across a very wide range. In particular, from polymer foams such as Styrofoam®, extremely lightweight articles can be produced.[2]
- The melting point of polymers can also be greatly modified by varying the macromolecular architecture. Some polymers can be physically described as highly viscous melts even at room temperature, whereas other polymers have melting points of several hundred degrees Celsius, and can be heated to red heat or sintered. Of course, the temperature range of the melting or softening point is critical for the temperature at which a material can be used or processed. On the one hand, a high melting point allows a high service temperature but requires a lot of energy to process the molten material into the final shape. For many materials in everyday life, which are only used at room temperature, a low melting point is an advantage because they can be processed much more resource-efficiently than materials with a high melting point. Here, too, the unrivaled variability that polymers offer is often a decisive and advantageous factor.

Because of their great versatility and their resulting unique material properties, synthetic polymeric materials have become indispensable in our daily lives. Many familiar applications can only be realized using macromolecular materials:

- The electrical and electronics industries in their current form are difficult to envisage without polymers. This statement includes seemingly trivial applications such as the sheathing for electric cables—no other non-polymeric substance class provides materials that are both flexible and at the same time act as electrical insulators. Even in technically much more demanding applications, such as the manufacture of solar cells, LEDs, or integrated microchips, polymers play a crucial role, e.g., as etching masks, protective coatings, dielectrics, or fiber optics.
- The modern automobile would also be unthinkable without polymers. All motor vehicles manufactured today are covered with a polymer layer—the so-called *clearcoat*. In addition, polymers, from which, for example, the tires, dashboard, seat cushions, and bumpers are constructed, make a major contribution to reducing the weight of the vehicle, thus limiting the fuel consumption.
- The construction industry has also benefited enormously from this relatively young class of materials. Polymers in the form of insulating foams reduce the energy consumption of buildings, serve as conduits for water supply and sanitation, and provide a weather-resistant alternative to the use of exterior wood.
- As packaging, polymers are now irreplaceable, especially for food packaging or as shock absorbing material for goods in transit.

Polymers find applications not just as classical *materials* but also as, mostly soluble, *active ingredients* and *functional additives*. As such, they often go unnoticed because

---

[2] Low-density materials such as metal foams or ceramic aerosols can also be produced from non-polymeric materials; these, however, do not have the same breadth of application in everyday life as polymers.

they are not the actual material but rather, often in relatively small amounts, responsible for the appearance of something. Thus, polymers can be found in modern detergents, cosmetics, or pharmaceutical products. They are also used in water treatment and paper production. In the latter capacity, macromolecules as *functional polymers* are discussed in detail in ▶ Chap. 19.

1.2 Definition of Terminology and Basic Concepts

In the following section a brief introduction to the basic concepts of polymer science is given.

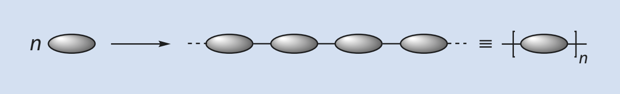
1.2.1 Fundamentals

The term *polymer* refers by definition to molecules formed from a number of building blocks, called *monomers*, usually connected by covalent bonds. The prefix "poly" comes from the Greek word for "many" whereas the Greek prefix "mono" means "single" and refers here to a single block. In the synthesis of many polymers, monomers are linked together in the same manner to form a single chain consisting of covalently connected repeating units (◘ see Fig. 1.1).

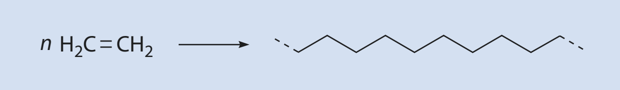
There is no definitive limit on the number of repeating units required to meet the definition of the polymer. In general, it is stipulated that the number n, also referred to as the *degree of polymerization*, must be sufficiently high that the physicochemical properties of the resulting molecule no longer change significantly with each addition of a further repeating unit. This definition is not exact. Macromolecules that are composed of relatively few repeating units do not meet this definition and the term *oligomers* ("oligo" = "few") is used for such molecules.

One example of a polymerization reaction is the reaction of ethene to form polyethylene (◘ see Fig. 1.2). In this reaction, the C=C double bond of the ethylene is converted into a single bond.

From the definition of the term polymer, it follows that in principle any chemical molecule that can form two (or more) bonds can be used as a monomer for the synthesis of macromolecules. This allows a huge variety of accessible structures which barely set a limit to the imagination of the synthetic chemist.



◘ **Fig. 1.1** Schematic structure of a polymer of n repeating units



◘ **Fig. 1.2** Polymerization of ethene to polyethylene

As already mentioned in the introduction to this chapter, the properties of polymers can be varied within a broad range. For the control of these properties, a huge array of adjustments is available to the polymer chemist. The most important are:

- Type of monomers
- The chemical bond between the repeating units—for example, ether vs amide bonds
- Degree of polymerization
- Architecture of the chain—for example, linear or cross-linked
- Incorporation of chemically different monomers along the polymer chains (*copolymerization*)
- Sequence of monomers in a copolymerization—for example, alternately or in long sequences which consist of only one type of monomer (▶ see Sect. 1.3.3)
- Specific interactions between the components of the polymer chain, e.g., hydrogen bonding or dipole–dipole interactions

In addition to these essential questions, many other factors, such as admixtures (*additives*) and material processing, also have an influence on the properties of macromolecules. The aim of this book is to provide, against the background of an almost infinite variety of possible polymer structures, an overview of the essential principles that can be used for the selective synthesis of structures with desired properties.

1.2.2 Polyreactions

In the following, a brief overview of the basic possibilities for the synthesis of polymers (*polyreactions*) is given. These can be classified according to various criteria.

Depending on the manner in which the polymer chains are constructed in the course of the polyreaction of the monomers, a distinction can be made between step-growth and chain-growth reactions.

Step-Growth Reactions

This polymerization process can, in principle, be applied to all organic compounds which have two functional groups capable of forming a chemical bond. Classic examples of this are ester, amide, or urethane bonds (◘ see Fig. 1.3).

The resulting polymers here are referred to as polyesters, polyamides, or polyurethanes. Details on the nomenclature can be found in ▶ Sect. 1.2.3.

Chain-Growth Reactions

In chain-growth reactions, the polymerization can ensue by an addition to a polymerizable group, especially an olefinic double bond, or by the opening of a ring. The essential criterion for chain growth is the existence of a (usually high energy and unstable) active particle, which is able to add to a monomer unit and thereby transfers its active character to the newly incorporated repeating unit. This leads—as with a falling row of dominoes—to a chain reaction in which the growing chain continuously adds additional monomer units until no more monomer is available or side reactions occur.

Vinyl compounds can often be polymerized by a chain-growth mechanism. Here, the double bond is converted into two single bonds (◘ see Fig. 1.4). Because, in the case of carbon, two single bonds have less enthalpy than one double bond, the reaction is exothermic.

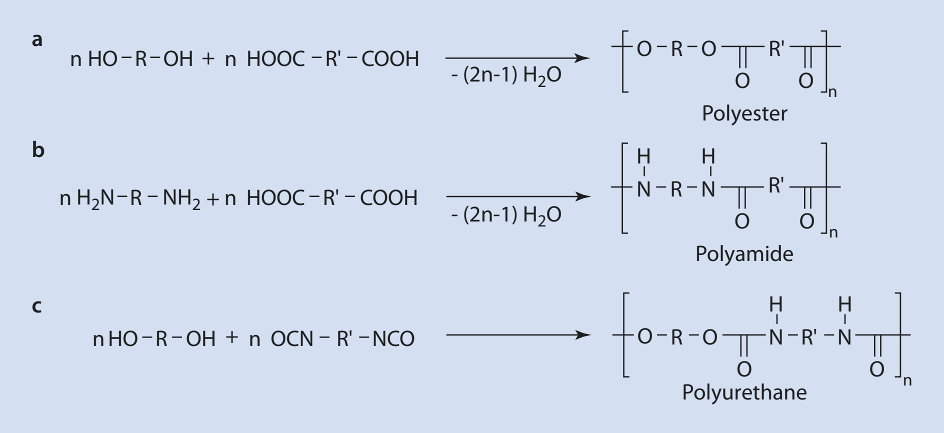


Fig. 1.3 Creation of (**a**) polyester, (**b**) polyamide, and (**c**) polyurethane

Fig. 1.4 Polymerization of an olefinically unsaturated compound

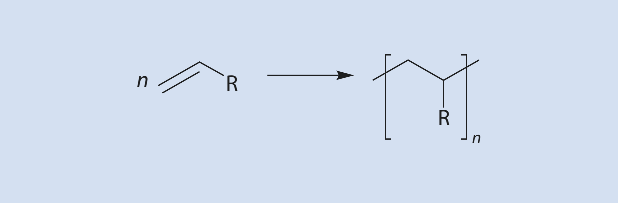
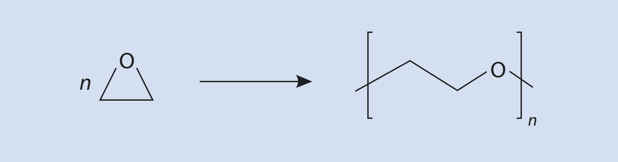


Fig. 1.5 Ring-opening polymerization using the example of ethylene oxide



Ring-opening polymerizations also generally involve a chain-growth mechanism (see Fig. 1.5). Here, the driving force is the release of the ring strain. Thus, for instance, three membered rings, such as ethylene oxide (oxirane), undergo facile polymerization.

As with small molecule organic chemistry, chain-growth reactions are classified according to whether they involve radical, positively, or negatively charged reactive species. In these cases, one refers to a *radical*, *cationic*, or *anionic* polymerization, respectively. Another important class of chain-growth polymerizations are those involving transition metal compounds, referred to as *transition-metal catalyzed (catalytic)* or *coordinative* polymerizations.

It follows from Figs. 1.3–1.5 that there are three basic possibilities for the formation of a covalent chemical bond as the result of a polyreaction:

- Addition to a multiple bond
- Elimination of (mostly low-molecular) fragments
- Opening of a ring

These are referred to as *polyaddition, polycondensation*, or *ring-opening polymerization*, respectively.

The latter differentiation makes a stringent subdivision of the different types of polymerizations difficult, in particular in the field of chain reactions. Thus, for example, ring-opening polymerization is possible by both catalytic and ionic mechanisms. Likewise, they can occur both via step-growth reactions and chain-growth reactions. However, there is little value in making this distinction between polycondensation and polyaddition and this is not being pursued further here.

This difficulty has been accounted for in this book by the inclusion of a separate chapter on ring-opening polymerization (▶ see Chap. 12), and the basic mechanisms are discussed in the preceding chapters.

A detailed overview of methods for synthesizing macromolecules can be found in ▶ Chaps. 8–12.

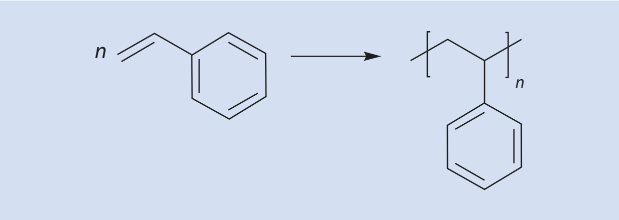
1.2.3 Nomenclature of Polymers

The basic principle of polymer nomenclature rests on the designation of the monomer or repeating unit set in brackets, in conjunction with the prefix "poly." For example, poly(styrene) is produced from styrene. Whether one uses the name of the monomer or the repeating unit is rather arbitrary. Thus, for example, the polymerization product of styrene is mostly referred to as poly(styrene), whereas that of ethene, after the repeating unit, usually as poly(ethylene). For reasons of clarity, the brackets are generally omitted with polymers that consist only of a single monomer type (so-called *homopolymers*), and are only used with *copolymers*, i.e., polymers composed of at least two chemically different monomers (▶ see Sect. 1.3.3).

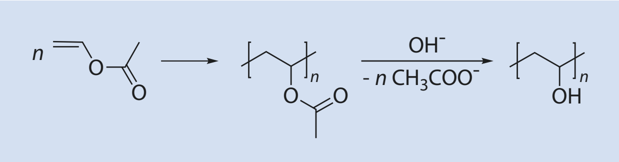
In the formula, the repeating unit is placed in square brackets (▣ see Fig. 1.6). For more complex structures it has also become common practice to indicate with dotted lines that the molecule is further extended (▣ see Fig. 1.9).

If the repeating unit is further altered after polymerization by a chemical reaction (▶ see Chap. 15), the resulting polymer is often designated according to a formal monomer, but one that was not used in the polymerization. For example, the product of hydrolysis of polyvinyl acetate is referred to as polyvinyl alcohol, even though it is not accessible via the direct polymerization of the (unstable) vinyl alcohol (▣ see Fig. 1.7).

▣ **Fig. 1.6** Polymerization of styrene to polystyrene



▣ **Fig. 1.7** Synthesis of polyvinyl alcohol from polyvinyl acetate



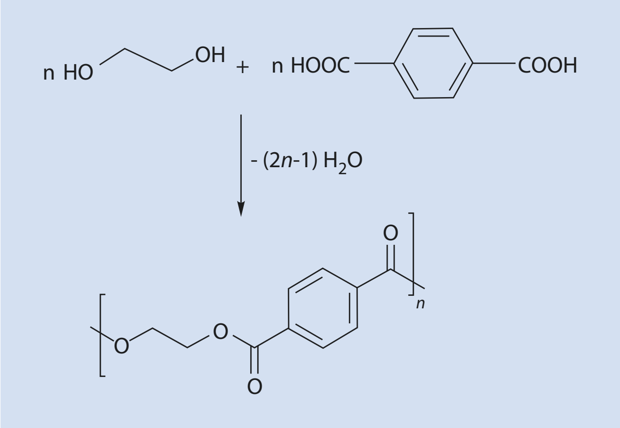


Fig. 1.8 Synthesis of polyethylene terephthalate (PET) from ethylene glycol and terephthalic acid

For polymers resulting from a reaction of a dicarboxylic acid with a diol, common names, based on the name of the corresponding ester, have become usual. For example, the polyester resulting from the complete esterification of ethylene glycol with terephthalic acid (◘ see Fig. 1.8) is referred to as polyethylene terephthalate (abbreviated PET).

1.3 Polymer Architectures

An overview of the different structural principles according to which a polymer can be built is provided below. Several structural variants need to be distinguished:

- Unbranched (linear) and branched polymers
- Isomerism of the repeating units
- Copolymers

1.3.1 Linear and Branched Macromolecules

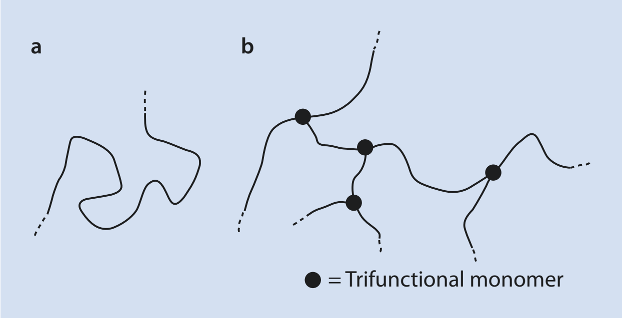
In addition to their chemical diversity, polymers can also differ substantially from each other in their molecular architecture. The result, as can be readily seen, of the above-discussed polycondensation of ethylene glycol and terephthalic acid (► see Sect. 1.2.3), is a linear, unbranched macromolecule with exactly two ends.[3] However, if one was to add, for example, a small amount of trifunctional acid to the monomer mixture, a branching point can develop at those locations where this molecule is incorporated into the polymer (◘ see Fig. 1.9). When an excess of one functional group, for example the OH function, is used, a molecule is produced after the complete reaction of the other functional group which has only alcohol functions as terminal groups which cannot sustain further polycondensation—that is, the polymerization comes to a halt.

In this quite simple architecture it already becomes clear that there are limits to a plain formula for polymers and that, for an exact description of the molecule, one requires more accurate information than just the name(s) of the monomer(s).

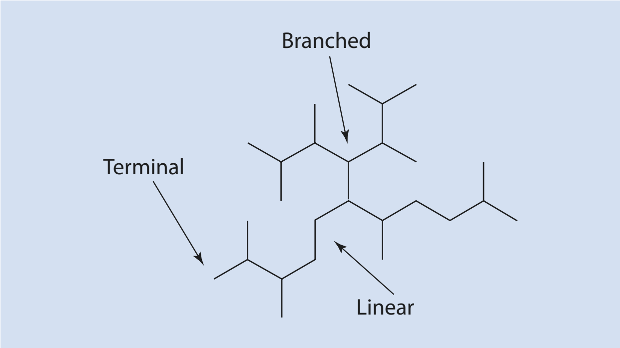
---

[3] To a lesser extent, macrocyclic rings can form when one terminal acid group reacts with the terminal alcohol group of the same molecule.

◘ **Fig. 1.9** Schematic representation of (**a**) a linear polymer chain and (**b**) a branched macromolecule



◘ **Fig. 1.10** Coexistence of linear, terminal and branched segments in a highly branched polymer (schematic)

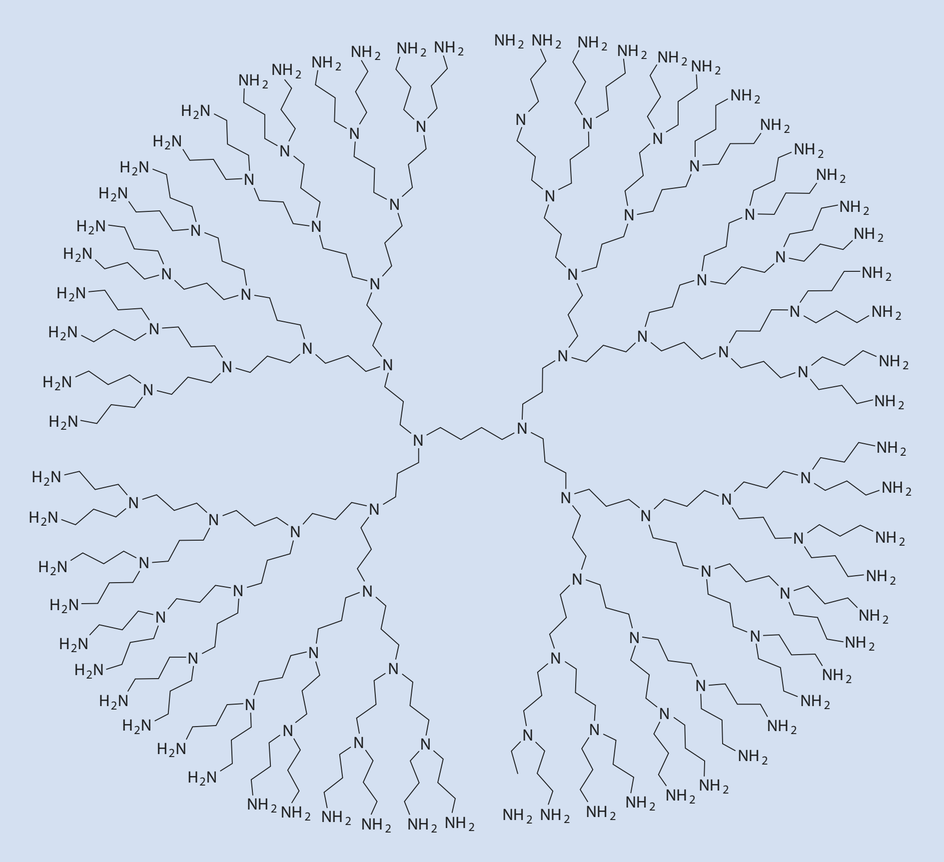


If the number of branches in the macromolecule is increased, one eventually reaches a class of so-called highly branched polymers. These molecules can be notionally divided into linear segments, branches, and so-called *terminal* end segments (◘ see Fig. 1.10). An example of such a highly branched polymer is polyethyleneimine, discussed in ▸ Chap. 19.

The greater the ratio of branched to linear segments, the greater the degree of branching of the material. Ideally, there is a perfectly branched, symmetrical macromolecule which grows outward from a central point, resembling a family tree, until the spatial density of branches on the surface of the (generally in good approximation, spherical) molecule is so high that further growth is no longer possible (◘ see Fig. 1.11). Because of the similarity with trees, such molecules are referred to, after the Greek word "dendron" for "tree," as *dendrimers* (Buhleier et al. 1978).

Because of the branched polymer's strong outward increase in segment density, its interior contains cavities which can be used for the storage of guest molecules such as dyes or agents. However, the loading density is quite low because of the small number of these cavities. In addition, the synthesis of such perfectly branched systems is only possible in multistep reaction sequences and therefore very time consuming, so dendrimers have, up to now, achieved only limited technical significance (▸ see Chap. 8).

Although highly branched or dendritic polymers represent individual, discrete macromolecules, the synthesis of *polymer networks* leads to the formation of a covalent, branched network within which all of the molecules available in the system are incorporated.



◘ **Fig. 1.11** Schematic representation of a dendrimer

Such a network emerges, for example, if higher-functional monomers (i.e., those with more than two reactive groups) are caused to react and the reaction exceeds a certain level of monomer conversion (► see Sect. 8.3.4). Such a network can be described as a single molecule which occupies the entire reaction space (◘ see Fig. 1.12).

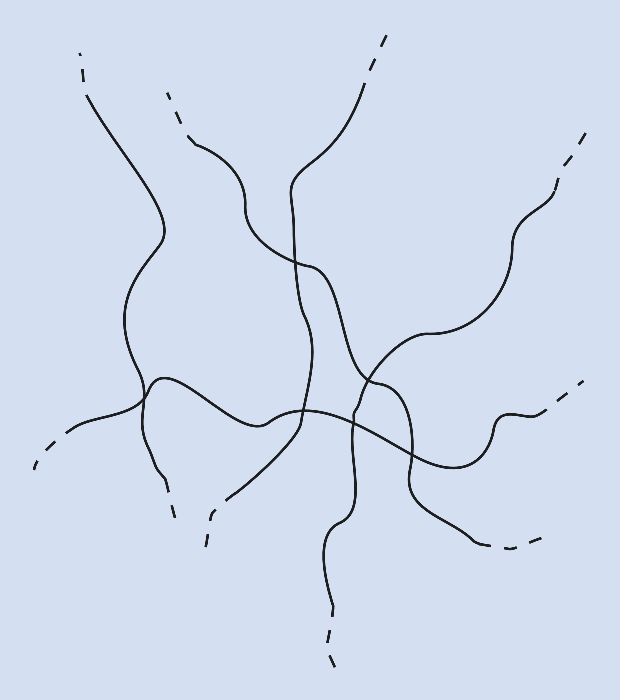
1.3.2 Isomerism in Polymers

As with small molecules, macromolecules can also exist as isomers. Here, the following cases, which are particularly important from the viewpoint of the polymer chemist, are *structural-*, *stereo-*, and *conformational isomerism*.

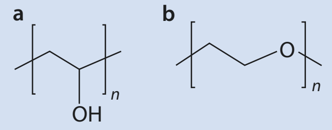
Structural Isomerism

With *structural isomerism* (also referred to as *constitutional isomerism*), the nature of the covalent linkage of the atoms with each other differs, similar to the low-molecular isomers acetone and propionaldehyde. For example, polyvinyl alcohol and polyethylene oxide (◘ see Fig. 1.13) are structurally isomeric polymers.

■ **Fig. 1.12** Schematic representation of a polymer network



■ **Fig. 1.13** Structural isomerism using the example of (**a**) polyvinyl alcohol and (**b**) polyethylene glycol



An important case of structural isomerism occurs in the polymerization of conjugated dienes such as isoprene (2-methylbut-1,3-diene). During the polymerization of this monomer, as discussed in more detail in ▶ Sect. 14.10, each monomer unit can be added to the macromolecule in different ways. These are shown in ■ Fig. 1.14.

The isomers shown rarely occur as pure forms in practice. Most often the polymers formed are composed of different structural variations within the same polymer chain. In addition to the isomers shown here, 1,4-polyisoprene also exists as *cis* and *trans* isomers (see below).

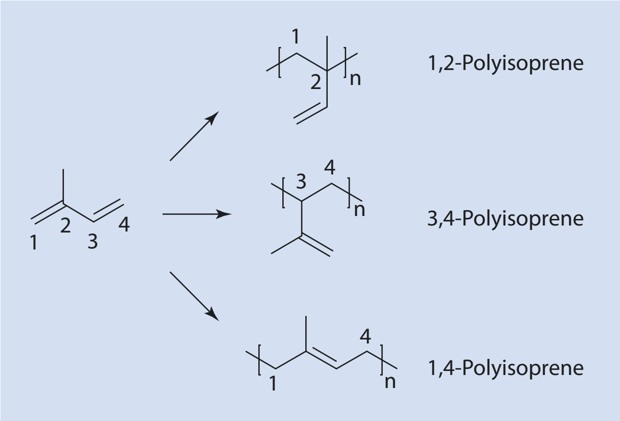
Stereoisomerism

In analogy to small molecule organic substances, constitutionally identically macromolecules may differ in their spatial form. Notably relevant for polymers are *cis-trans* isomers and enantiomers.

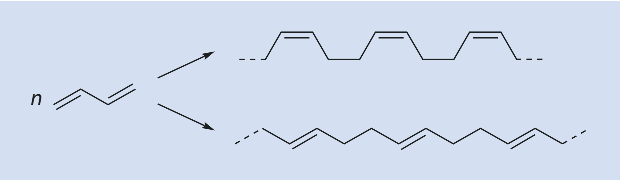
The *cis-trans* isomerism is particularly important for polymers with a double bond in the main chain. The simplest example of this are *cis-* and *trans*-1,4-polybutadiene (■ Fig. 1.15).

As in the field of low-molecular organic chemistry, they differ in their physicochemical properties. This effect is generally very pronounced in macromolecules. *cis*-1,4-

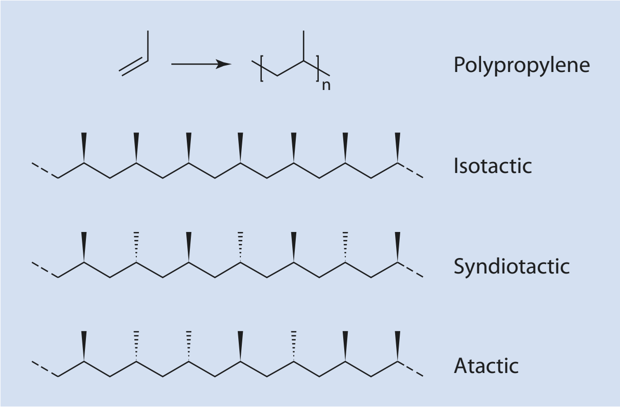
▣ **Fig. 1.14** Structural isomers of polyisoprene



▣ **Fig. 1.15** *cis-trans* isomerism using the example of (**a**) *cis*-1,4-polybutadiene and (**b**) *trans*-1,4-polybutadiene



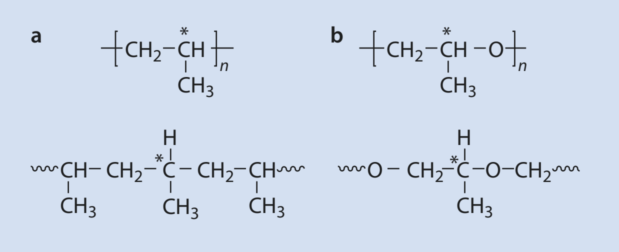
▣ **Fig. 1.16** Stereoisomerism using the example of polypropylene: isotactic, syndiotactic, and atactic polypropylene



Polybutadiene (butadiene rubber), for example, is an amorphous, sticky material, whereas the *trans* isomer is a (partially) crystalline material with a high melting point. The situation is similar for the *cis* and *trans* isomers of isoprene (▶ see Sect. 14.10.3). The *cis* isomer is a soft and, in its non-vulcanized state, sticky material which is known as natural rubber, whereas the *trans* isomer, which is referred to as gutta-percha, is a non-sticky and much harder material.

A technically very important case of a polymer exhibiting enantiomerism is polypropylene (PP). In the polymerization of propene (▶ see Chap. 11) a macromolecule is created whose main chain—the so-called polymer backbone—could formally be placed in a plane, whereas the methyl groups of the C_3 carbon point upwards or downwards relative to this plane (▣ see Fig. 1.16). Depending on whether the stereochemistry at the C_2 atom

Fig. 1.17 Pseudo-asymmetry using the example of (**a**) polypropylene compared to optical activity in (**b**) polypropylene oxide



is regularly (*stereoregular*) or statistically configured, different stereoisomers result, which are referred to as isotactic, syndiotactic, or atactic polypropylene.

Polypropylene is referred to as isotactic polypropylene (it-PP) if all of its tertiary carbon atoms are configured identically. Syndiotactic polypropylene (st-PP) has an alternating configuration of its methyl groups along the chain, whereas in atactic polypropylene (at-PP) the spatial orientation of the methyl groups is irregular.

The three types of polypropylene mentioned above are diastereomers. Whereas it-PP is a highly crystalline material with a melting point of ca. 160 °C, at-PP cannot crystallize because of its irregular structure and it is an amorphous, sticky material. The control of stereochemistry is thus of considerable importance (▶ see Chap. 11).

However, in contrast to substances composed of small molecules, stereoregular polyolefins are usually not optically active. This is because the two polymeric chains attached to the chiral center are very large and thus indistinguishable from a physicochemical point of view. A mirror plane can thus be placed approximately through the chiral center. This is also referred to as *pseudo-asymmetry*. In contrast to this, no mirror plane can be placed through the molecule of polypropylene oxide (◘ see Fig. 1.17) because of the additional oxygen atom. Therefore, this macromolecule can exhibit optical activity if one succeeds in producing a stereoregular product and separating the stereoisomers.

Conformational Isomerism

Even with macromolecules, individual molecular groups can rotate around a single bond. Consider the case of polyethylene as the simplest organic polymer. The *trans* conformation is approximately 4 kJ/mol more favorable than the *gauche* conformation. Therefore, the all-*trans* conformation is the enthalpically most favorable conformation. However, the number of possible *trans* and *gauche* conformations of n single bonds is 3^n, i.e., a very large number for polymers. For this reason, an all-*trans* conformation is enthalpically favorable, but extremely unlikely, with the result that this conformation is entropically unfavorable. In addition, the enthalpy difference of 4 kJ/mol, which corresponds to about 1.5 times $k_B T$ (k_B: Boltzmann constant, T: absolute temperature) at room temperature, is not particularly large. From simple considerations, it follows that at room temperature the *trans* configuration is only approximately 1.6 times more likely than the *gauche* configuration. A significant number of bonds therefore exist in the *gauche* configuration, and the molecule adopts a spatial arrangement quite different from the extended form, which resembles rather a ball of wool (◘ see Fig. 1.18).[4] Details of this are discussed further in ▶ Chap. 2.

---

[4] Recent work shows that for isolated chains this picture becomes even more complex: additional forces such as dispersion forces have to be considered, leading to substantial chain-length-dependent influence on the chain architecture; see, e.g., Lüttschwager NOB, Wassermann TN, Mata RA, Suhm MA (2013) The Last Globally Stable Extended Alkane. Angew. Chem. Int. Ed. 52:463–466.

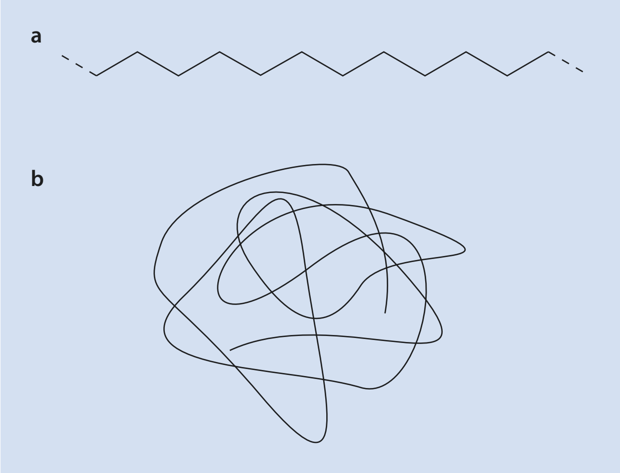


Fig. 1.18 All-*trans* conformation (**a**) and "ball of wool" conformation (**b**) of polyethylene

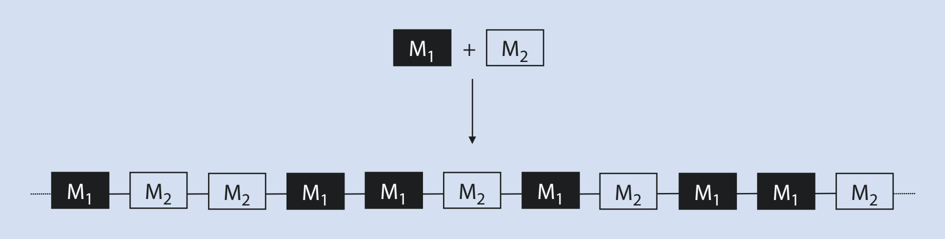


Fig. 1.19 Statistical copolymer consisting of two monomers M_1 and M_2

1.3.3 Copolymers

Copolymers are polymers composed of at least two chemically different monomers. In principle, with copolymerization of different monomers in various quantities, an infinite variety of different macromolecules can be synthesized. This chemical diversity is increased by the various possibilities available for incorporating the *comonomers* into the chain as well as their sequences. These are discussed below.

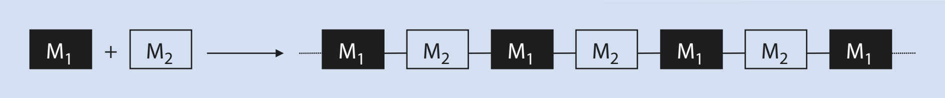
Statistical Copolymers

If two chemically different monomers M_1 and M_2 are polymerized in a random, statistically determined sequence to each macromolecule, this is referred to as a *statistical copolymer* (see Fig. 1.19).

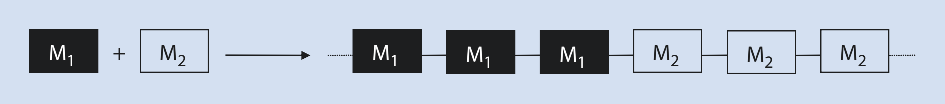
Here, the incorporation of the monomers into the polymer main chain is determined by the relative reactivity of the monomers and obeys statistical laws (▶ see Chap. 13). The copolymer is referred to as poly(M_1-*stat*-M_2)[5].

---

[5] The expression of *random copolymers* (used mostly incorrectly) is often found instead of statistical copolymers. The term *statistical copolymer* should, however, be preferred.



■ **Fig. 1.20** Alternating copolymer consisting of two monomers M_1 and M_2



■ **Fig. 1.21** Block copolymer consisting of two monomers M_1 and M_2

Alternating Copolymers

With alternating copolymers, two monomers M_1 and M_2 are built into the polymer main chain in regular alternation. This results in the structure shown in ■ Fig. 1.20.

These polymers are referred to as poly(M_1-*alt*-M_2). Such polymers result from the polymerization of monomers that can react with one another but not with themselves. One example is the polycondensation of a diol and a diacid (■ see Fig. 1.3). Alternating copolymers result from vinyl polymerizations only when the reactivity of the individual monomers with the other monomer is much greater than with itself. Details are discussed in ▶ Sect. 13.3.

Block Copolymers

In block copolymers, the comonomers are arranged along the polymer backbone in blocks of consecutive identical monomers (■ see Fig. 1.21).

Depending on the number of blocks in the polymer backbone, one refers to, for example, di-, tri-, or multiblock copolymers. The nomenclature for these macromolecules is PolyM_1-*block*-PolyM_2, as, for example, in polystyrene-*block*-polybutadiene. Colloquially, the designation Poly(M_1-*block*-M_2) has become common; e.g., poly(styrene-*block*-butadiene).

Graft Copolymers

Polymers in which a side chain of M_2 is linked to the main chain of M_1 are called *graft copolymers* of the monomers M_1 and M_2 (■ see Fig. 1.22). These macromolecules are referred to as PolyM_1-*graft*-PolyB. Here, PolyM_1 is the main chain, the so-called *graft stock*, and PolyM_2 is the grafted side chain.

Copolymers for which only the monomers are to be designated but in whose name no particular copolymer architecture is to be specified are generally referred to as Poly(M_1-*co*-M_2).

The following chapters present a deeper discussion of the properties and the synthesis of polymeric materials. This is structured as follows:

- ▶ Chapters 2 and 3 present the size and shape of polymers, as well as methods for determining their molar mass
- In ▶ Chapters 4–7, the properties of solid polymeric materials are discussed
- ▶ Chapters 8–13 are devoted to the synthesis of polymers
- ▶ Chapters 14–17 deal with important classes of polymers, chemical reactions of polymers, and procedures for the manufacture and processing of macromolecules

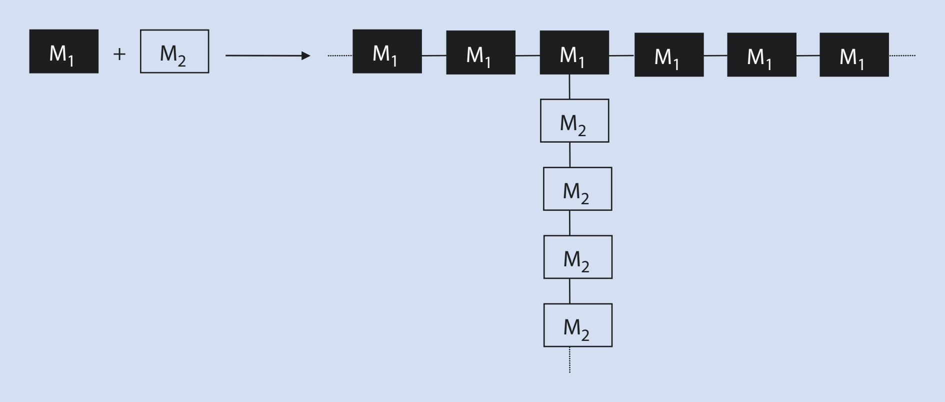


Fig. 1.22 Graft copolymer consisting of two monomers M_1 and M_2

- ► Chapters 18–20 are dedicated to special classes of materials (elastomers, functional polymers, and liquid crystalline polymers)
- The textbook concludes with some environmental aspects of synthetic macromolecules (► see Chap. 21) and a brief presentation of current trends in polymer chemistry (► see Chap. 22)

References

Staudinger H (1926) Die Chemie der hochmolekularen organischen Stoffe im Sinne der Kekuléschen Strukturlehre. Ber Dtsch Chem Ges 59:3019–3043

Naarmann H, Theophilou N (1987) New process for the production of metal-like, stable polyacetylene. Synth Met 22:1–8

Buhleier E, Wehner W, Vögtle F (1978) “Cascade”- and “nonskid-chain-like” syntheses of molecular cavity topologies. Synthesis 1978:155–158