

Review

# Functional Chirality: From Small Molecules to Supramolecular Assemblies

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**Abstract:** Many structures in nature look symmetric, but this is not completely accurate, because absolute symmetry is close to death. Chirality (handedness) is one form of living asymmetry. Chirality has been extensively investigated at different levels. Many rules were coined in attempts made for many decades to have control over the selection of handedness that seems to easily occur in nature. It is certain that if good control is realized on chirality, the roads will be ultimately open towards numerous developments in pharmaceutical, technological, and industrial applications. This tutorial review presents a report on chirality from single molecules to supramolecular assemblies. The realized functions are still in their infancy and have been scarcely converted into actual applications. This review provides an overview for starters in the chirality field of research on concepts, common methodologies, and outstanding accomplishments. It starts with an introductory section on the definitions and classifications of chirality at the different levels of molecular complexity, followed by highlighting the importance of chirality in biological systems and the different means of realizing chirality and its inversion in solid and solution-based systems at molecular and supramolecular levels. Chirality-relevant important findings and (bio-)technological applications are also reported accordingly.

**Keywords:** chirality; enantiomorphism; deracemization; supramolecular chirality; chirality inversion; chiral supramolecular assemblies; chiral polymers



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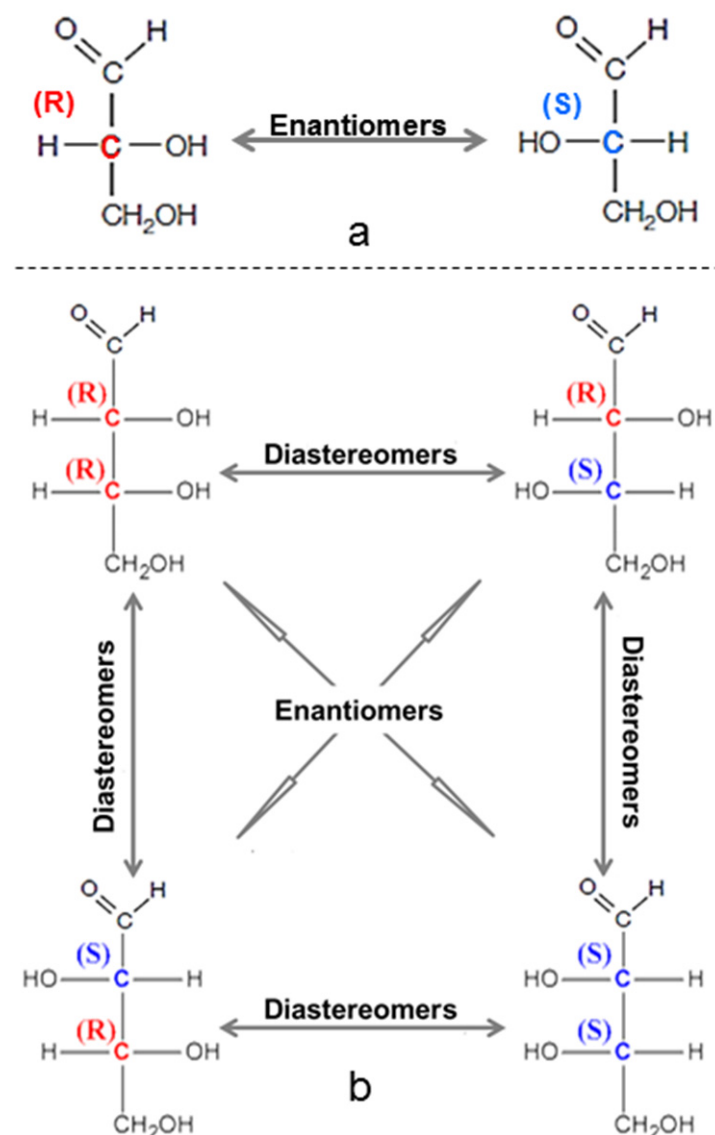
## 1. Introduction

### 1.1. Chirality and Vital Rules for its Identification

Pasteur concluded that homochirality forms the only sharply defined boundary between the chemistry of dead and living matter [1]. Our right and left hands look symmetric and are mirror images of each other but cannot be superimposed onto each other, and this is the simplest example of *enantiomers* [2]. Pairs of enantiomers are often designated as right- and left-handed. Chiral molecules have non-planar structures (usually tetrahedral), and they always have one or more chiral centers (usually around an asymmetric carbon atom). The number of chiral centers within a specific chiral molecule determines whether there is only an *enantiomeric pair* of this molecule or more possibilities of enantiomers and *diastereomers* (non-superimposable mirror images of one another) (Figure 1). For instance, 17 out of the 20 amino acids possess one chiral center. For each of them there are two possibilities: an enantiomeric pair. Threonine and isoleucine have two chiral centers, and they have two enantiomers and two diastereomers.

Glycine is the smallest amino acid and has no chiral centers and therefore it is *achiral*. An enantiomeric pair is two molecules or compounds that are identical in their chemical structure and physical properties but have exactly the opposite orientation (absolute opposite configuration). Diastereomers show similar but not exact chemical properties, whereas their physical properties are completely different. As all chiral molecules are optically active, enantiomers are also called *optical isomers*. The primary difference between the members of an enantiomeric pair can be detected by the way they rotate the plane of the

polarized light when they are optically active [3]. If the light is rotated clockwise, then this enantiomer is labeled (+) and its mirror image is labeled (−).



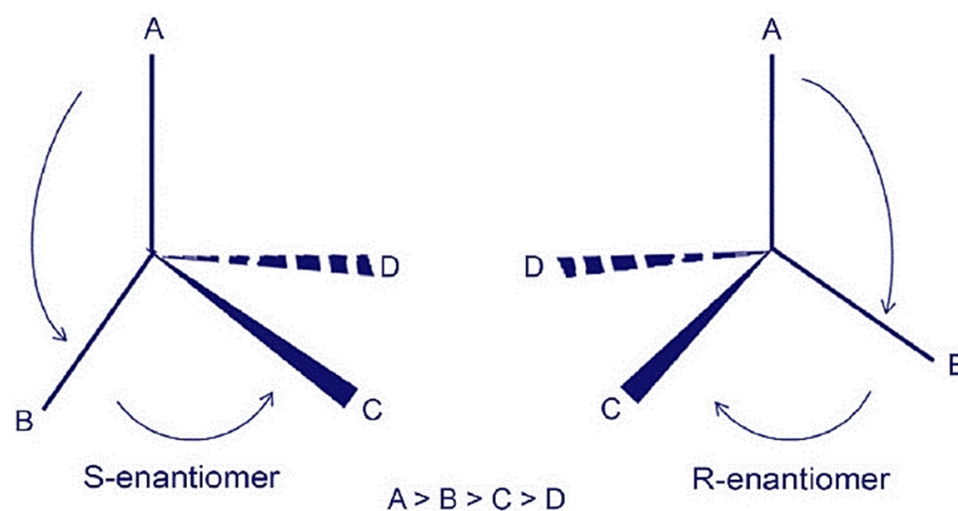
**Figure 1.** If the compound has only one chiral center, then there is a possibility of having only one pair of enantiomers (a). In case of the presence of two or more chiral centers, enantiomers and diastereomers could exist (b).

Another way of determining the orientation or the handedness of the molecules is by applying the Cahn-Ingold-Prelog priority rule [4]. Using this rule, the group/atoms are attached to the chiral center (stereo-center) and bearing the lowest molecular weight are held backward out of the plane and the other groups/atoms are ordered from the group/atoms by the highest priority (molecular weight). If the direction of this order is clockwise, then the molecule is "R" (from *rectus*, right-handed); if the order direction is counterclockwise, then the molecule is "S" (from *sinister*, left-handed) (Figure 2).

### 1.2. Other Forms of Chirality

Other forms of chirality include the axial chirality [5], also called *helicity*. In this case, the molecules do not have a stereogenic center, but an axis, about which the molecular groups are held in a spatial arrangement (helical, propeller, or screw-shaped geometry) that cannot be superimposed on its mirror image. A molecule with a helical morphology is termed P (standing for "plus") or  $\Delta$  enantiomer if it is a right-handed helix and M (standing

for “minus”) or  $\Lambda$  enantiomer, if it is a left-handed helix. While chiral molecules are not planar molecules, they can exhibit planar chirality [4,6], which is another form of chirality existing in chiral molecules that have no asymmetric carbon atoms but possess two non-coplanar rings that are each dissymmetric and thus cannot rotate around the chemical bond connecting them.



**Figure 2.** Cahn-Ingold-Prelog priority rule for determining the handedness of molecules. Solid lines represent bonds that are in the plane of the paper. Dotted lines represent bonds out of plane away from the reader, whereas wedge-shaped lines are projected towards the reader. Molecular weight, and thus priority, of the four groups is such that  $A > B > C > D$ . The group of the lowest priority (D) is projected behind the plane containing the groups A, B, and C. The handedness direction is clockwise (R) in the enantiomer on the right and anticlockwise (S) in the enantiomer on the left.

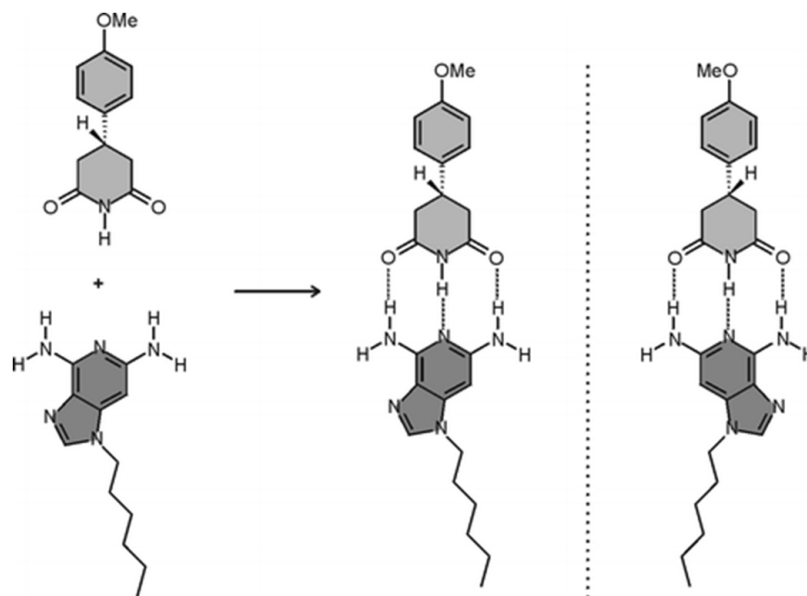
### 1.3. Enantiomorphism and Supramolecular Chirality

Enantiomers represent chirality at the molecular level. However, chirality at the molecular level is not a prerequisite to observe chirality at the macroscopic level. In fact, there are hierarchical levels of chirality in which the building blocks need not be chiral themselves (Figure 3). This generates what is widely known as *enantiomeric* and *diastereomeric assemblies*. Supramolecular chirality is initiated by the properties of the contributing components. A supermolecule can be chiral if one or more of its constituents are asymmetric or there is an association among the achiral components so that their assembly has no symmetry elements. In this case, the chiral supermolecule does not superimpose on its mirror image [7]. For instance, sodium chlorate ( $\text{NaClO}_3$ ) is an achiral chemical compound that assembles in a chiral crystalline space group ( $P2_13$ ) [8–10]. A crystal of a certain handedness and its mirror image are called enantiomorphs. The term enantiomorph is commonly reserved for all macroscopic objects possessing handedness [11].

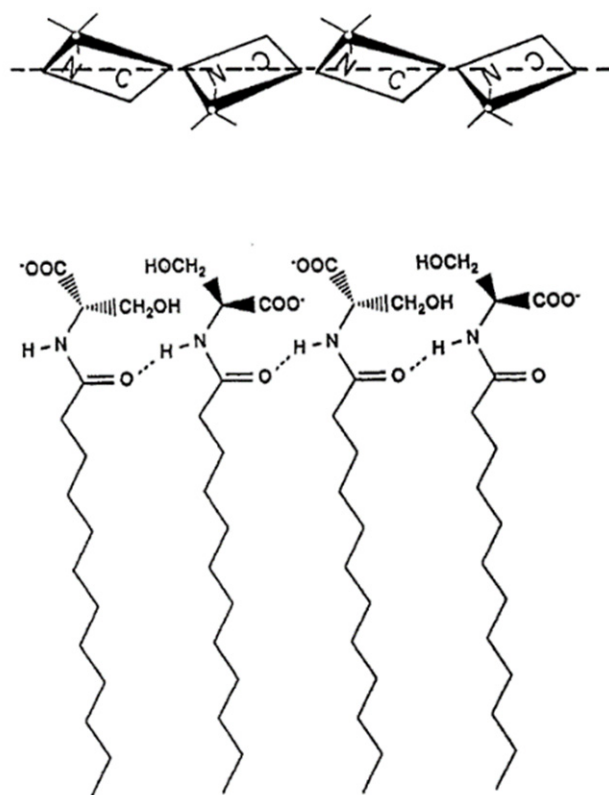
At the 2D level of condensed matter, supramolecular chiral surfaces of a monomolecular thickness can be assembled in a confined 2D crystallization process. For instance, chiral monolayers of an ester (N-stearoylserine methyl ester) are assembled at the air-water interface such that the long hydrocarbon chains are aligned parallel to each other at the air phase, whereas the chiral head groups are closely packed to form the condensed phase (Figure 4) [13]. Dipotassium folate has also been shown to form a self-assembled hexagonal lyotropic liquid crystalline phase in water, which generates supramolecular objects with a chiral columnar shape [14].

Molecules can also self-assemble through non-covalent interactions to form helical supramolecules. It was shown that there is a plausible interrelation between the torsion angle between the hydrogen bond donor and acceptor groups in those molecules and the handedness of hydrogen bonded supramolecular helices formed in the solid state. This correlation is suggested to be in the form of translation of certain conformation (OCCN torsion angles) of the unit molecules into the O-H...N hydrogen bonded helical networks

with specific handedness [15]. Other chiral 3D supramolecular assemblies are well defined complexes of molecules in the form of spheres, rods, and sheets, with dimensions from nano- to micrometer range [16].



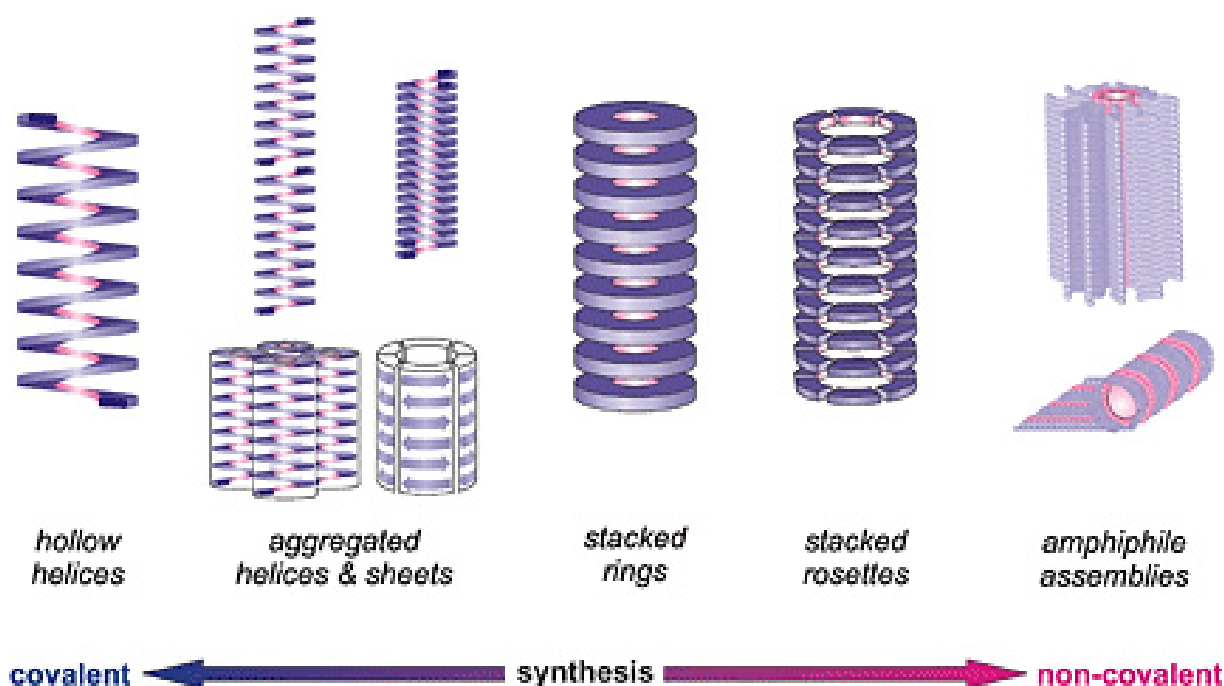
**Figure 3.** An example for the assembling process of two achiral molecules that result in the formation of a chiral supermolecule, because the symmetry planes are normal to the molecular components. (Reprinted from Reference [12]).



**Figure 4.** Upper and side views of an assembly of four adjacent N-stearoyl-L-serine molecules in a micellar aggregate. The top view depicts the inter-amide chiral spine of the same segment, including the asymmetric centers. A 2-dimensional crisscross network of such spines will create a chiral surface (reprinted with permission from Reference [13]). Copyright 1993 American Chemical Society.

#### 1.4. Complex Chiral Structures

Rosette nanotubes (RNTs) are a bioinspired and biocompatible class of nanomaterials that can provide tunable chiroptical properties [17–20]. Through hierarchical spontaneous self-assembly, RNTs are obtained from a synthetic heterobicyclic Guanine-Cytosine (G/C) motif by the formation of six-membered supermacrocyces (rosettes), which then stack up under the effects of temperature and concentration to form the very long nanotubes. Functional groups can be covalently attached to G/C motif and can be expressed on the surface of the nanotubes, and this provides a robust built-in strategy for varying the physical and biological properties of RNTs for specific medical or biological applications [21–23]. Other forms of organic nanotubes are also possible through combinations of covalent and non-covalent interactions (Figure 5) [24].

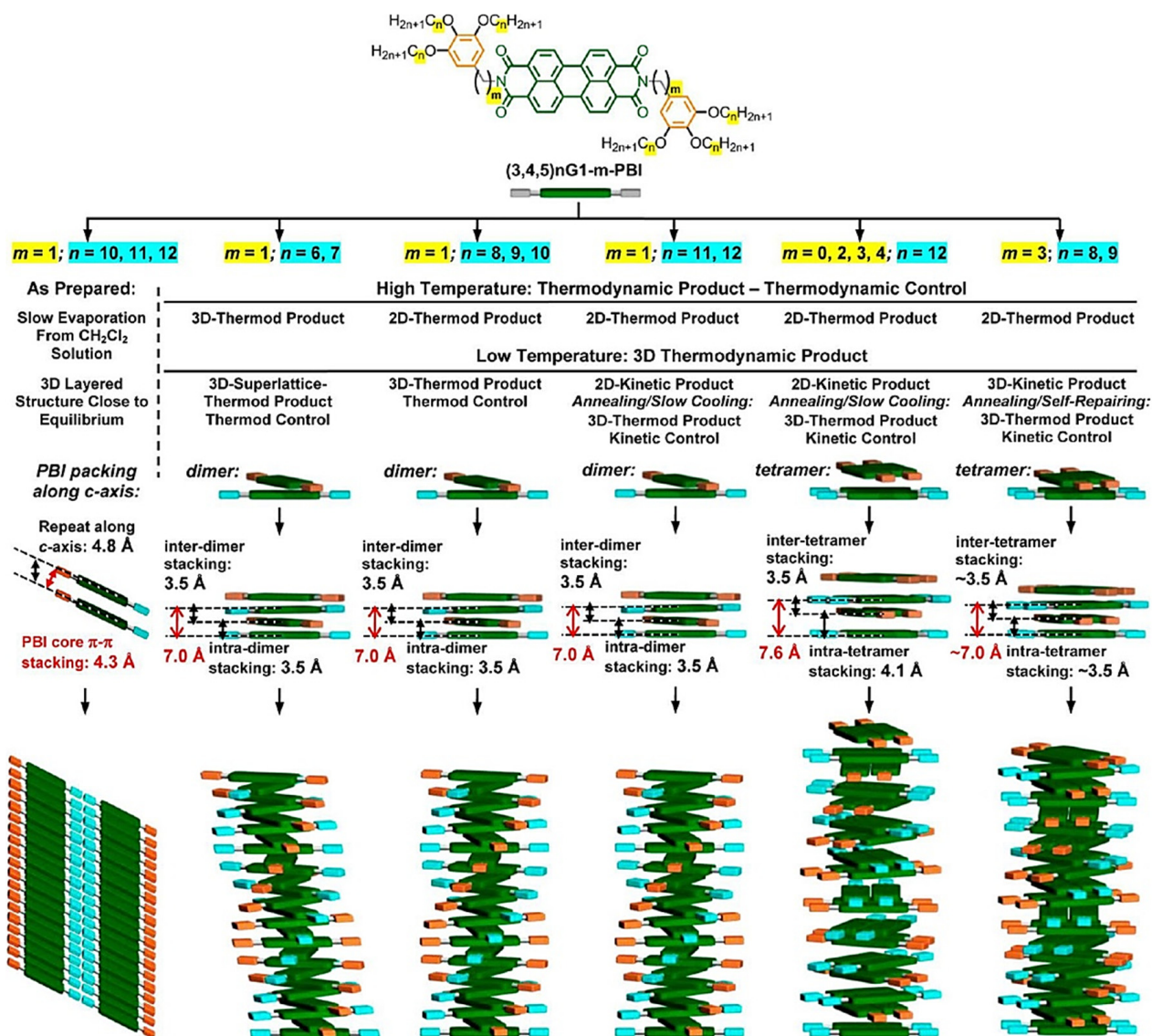


**Figure 5.** A schematic diagram showing the different forms of organic nanotubes (reprinted from Reference [24] with kind permission from Springer Science and Business Media, License number: 3610670481704).

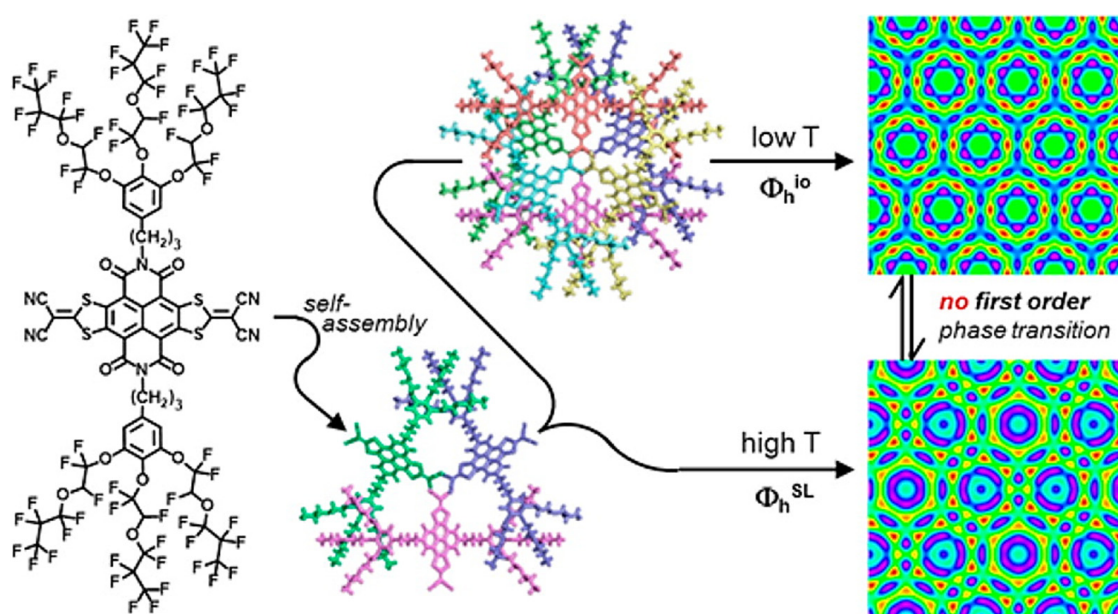
Among the chiral 3D supramolecular assemblies exist the dendrons [25], dendrimers [26,27], and other more complex dendritic building blocks, which provide vital architectural motifs. Chirality (helicity) in these complex structures emerges through the transfer of structural information from the molecular level, passing by the supramolecular level up to the (quasi-)periodic array level of crystals [28–32]. The intrinsic propensity of self-assembling dendrimers with three-fold symmetry has been exploited to form diverse three-dimensional columnar, tetragonal, and cubic arrays of helical supramolecular structures [33]. Using a series of perylene bisimide (PBI) derivatives (versatile electron-accepting building blocks dendronized with two first generation self-assembling minidendrons) [34–36], it was revealed that the crystallization of the supramolecular assembly can be transformed from a kinetically controlled process into a thermodynamically controlled process. This could facilitate easy access to their equilibrium states and the determination of their structures, notwithstanding the thermal history of the sample (Figure 6) [37].

The thermodynamically controlled assembly of supramolecules has also been reported for another group of strong electron-accepting building blocks: naphthalene bisimide (NBI) derivative functionalized and dendronized with an environmentally friendly chiral racemic semi-fluorinated group. The resultant NBIs have undergone either self-organization into lamellar crystals or self-assembly into complex and ordered columns that subsequently self-

organize in a columnar hexagonal periodic array and eventually as a columnar hexagonal super-lattice (Figure 7) [38]. These NBIs are expected to be used as alternatives for fullerene acceptors in organic photovoltaics [39–41] and other electronic applications [42–44]. In addition, they could be utilized in fluorosis chemistry, as well as in organic, supramolecular, macromolecular, and biomolecular fluorine-containing compounds [45–50] that are neither toxic nor biopersistent [51–55].



**Figure 6.** A schematic diagram of the self-assembly of dendronized PBIs. (3,4,5)nG1-m-PBI with  $m = 0, 1, 2, 3, 4$  and  $n = 14$  to 4, ( $n$  = number of carbons in the alkyl groups;  $m$  = number of methylenic units between the dendron and the imide group of PBI). Reprinted with permission from Reference [37]. Copyright 2013 American Chemical Society.



**Figure 7.** A schematic diagram describes the self-assembly of dendronized NBI at three methylenic units into an unprecedentedly complex and ordered column that self-organizes in a columnar hexagonal periodic array. This array undergoes a continuous transition to a columnar hexagonal superlattice that does not display a first-order phase transition during differential scanning calorimetry analysis at heating and cooling rates of 10 and 1 °C/min. Reprinted with permission from Reference [38]. Copyright 2015 American Chemical Society.

## 2. Importance of Chirality in Biological Systems

The origin of chiral homogeneity of biological molecules is somehow connected to the origin and evolution of life [56–66]. Molecular chirality plays a vital role in chemistry and biology, and many chiral molecules are known to display enantioselective effects in biological systems. Chiral molecules exist widely in nature, such as in amino acids, sugars, and nucleotides. Except cysteine, all-natural amino acids are S: left-handed. Supramolecular chirality is abundant in many biological structures, e.g., the triple helix of collagen [67], the  $\alpha$ -helical coil of myosin [68], and the DNA double helix [69], which, together with RNA, are long helical polymers formed from complex connections of sugar units with the same absolute chirality. Biological supramolecular structures result from chiral molecular recognition [70] and chiral self-assembly [71].

It has long been known that, in biological systems, the cells use only left-handed proteins and phospholipids and right-handed sugars [72]. This has recently been realized to be inaccurate, when D-aminoacids were found in living organisms as free aminoacids, peptides, and proteins [73] that have even been linked to the progression of the big threat of dementia [74,75]. Since amino acids and sugars are themselves chiral, the proteins and glycoproteins, which constitute enzymes, receptors, and carrier macromolecules, are also chiral. For instance, to activate or block a certain receptor, the correct structural orientation is necessary to effectuate the necessary function. This causes a stereospecificity and selective affinity in these structures and their dynamics. In consequence, R and S enantiomers can be very different in their (bio-)chemical effectiveness or have very different functions. Synthetic chiral molecules are very crucial in pharmaceutical applications [76]. In the pharmaceutical industry, different enantiomers may greatly affect the pharmacokinetic processes, such as absorption, tissue distribution, plasma protein binding, metabolism, and elimination [77,78]. An enantiomer can even cause adverse effects if wrongly existed instead of its mirror image [79]. Therefore, it is vital to prepare enantiomerically pure forms of the molecules intended for the production of pharmaceutical drugs [80]. For these reasons, different approaches for the synthesis and purification of enantiopure molecules

and chiral supramolecular assemblies have been constructed. The chiral drugs can be prepared using chiral precursors through different routes, such as asymmetric (biased) synthesis or enzymatic transformation, chiral resolution, or preparative enantiomeric segregation [81–87].

### 3. Towards Pure Enantiomeric Compounds and Supramolecular Assemblies

Synthesizing chiral molecules from achiral precursors in the absence of inductive chiral agents leads to the formation of equal portions of enantiomers, the so-called *racemic mixture* or *racemate* [88,89]. In case of solid-liquid equilibria phases, racemic mixtures can crystallize as pairs of enantiomers that act as a single phase, which cannot be segregated without the use of a chirality breaking operation. Most crystalline racemates (90–95%) are racemic compounds in which the enantiomeric pair exists orderly and evenly in every unit cell. Only about 5–10% of crystalline racemates can crystallize in the form of racemic *conglomerates* [90], which are a mechanical mixture of crystals, each of which contains only one of the two enantiomers present in a racemate, i.e., the enantiomers crystallize separately as separate phases from each other, and, therefore, the different enantiomers can be easily separated by crystal picking, as in the pioneering experiment of Louis Pasteur with a salt of tartaric acid [91]. A more complicated form of assembly exists in *solid solutions* in which the enantiomeric pair crystallizes randomly within one crystal.

In natural biopolymers, homochiral polymers do not efficiently assemble in a racemic solution of its monomers [92]. This was explained through a theoretical analysis, which suggested that the addition of monomers of the wrong chirality blocked the polymerization through an enantiomeric cross-inhibition process [93]. This is indeed a relief from very many unwanted and even dangerous mutations on the biological level. Fortunately, the same process does not exist when attempts are made to generate homochiral synthetic polymers, because homochirality in this case is not a prerequisite [94].

The chiral purity is measured by calculating the optical purity [95], also called *enantiomeric excess* (*ee*), which reflects the degree to which a mixture contains one enantiomer in greater amounts than the other, using the following equation:

$$ee = \frac{[R] - [S]}{[R] + [S]} \times 100$$

where [R] and [S] (also called [P] and [M], respectively) are the respective fractions of the separate enantiomers in the mixture. A racemic mixture has an *ee* of 0%, while an enantiopure sample has an *ee* of 100%.

The methodologies implemented to induce the formation of pure enantiomers (*ee*  $\approx$  100%) are categorized into two main approaches; the chiral approach, based on the synthesis of pure enantiomeric compounds, and the racemic approach, based on chiral resolution through separation of enantiomeric mixtures [96,97]. Among the chiral methods, deracemization has shown an impressive progress [98], whereas cocrystallization is from the racemic methods that resulted in several remarkable outputs [99].

### 4. Deracemization and Chiral Amplification

Except for conglomerates, other racemic mixtures require a *deracemization*: an enantiomers separation process, also known as *resolution*.

For racemic mixtures, a dynamic absolute resolution requires two main steps: *chiral symmetry breaking*, followed by *chiral amplification* [100].

Chiral symmetry breaking is a process by which a small chiral bias is introduced into a racemic mixture, with *ee* of 0% to increase it to a value  $\leq 1\%$ . This bias can be induced by adding a catalyst that leads to a kinetic (chemical) resolution [101], by the presence of a natural chiral impurity, by seeding with either one of the enantiomers, or the addition of a (tailor-made) non-racemic stereogenic element into some molecular fragment in the racemic mixture. The latter may inhibit the nucleation of one of the enantiomers in case of condensed matter. This process, in which one enantiomer is preferentially



selected over its mirror image, is also known as a *stereo-selective*, or more specifically *enantioselective process*. Generally, chiral resolution is facilitated by different methods, which can be categorized into two main routes: crystallization-assisted chiral resolution in solid solutions [102] or chiral synthesis in solutions.

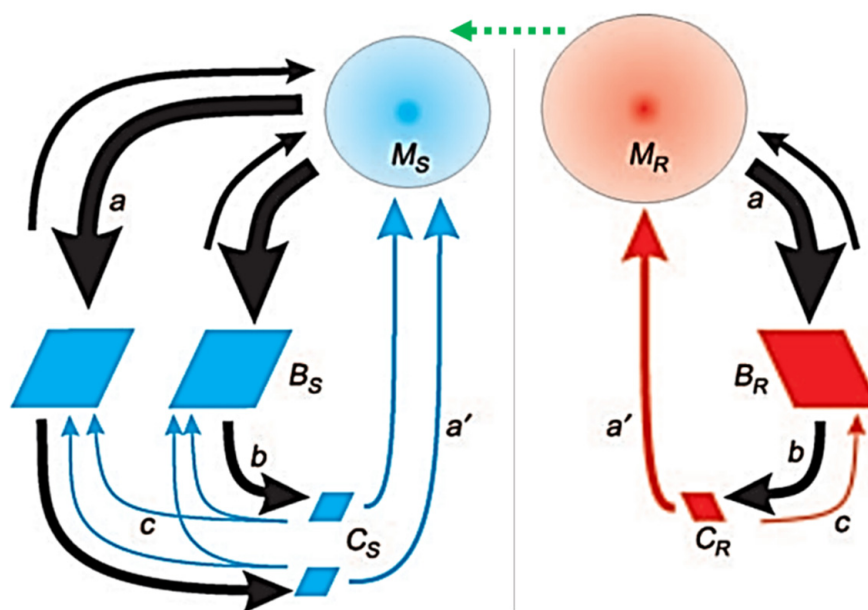
#### 4.1. Crystallization-Assisted Chiral Resolution in Solid Phase

Spontaneous absolute asymmetric synthesis, by which the statistical formation of enantio-enriched compounds from achiral reagents takes place, without the intervention of any chiral auxiliaries, has been proposed as one of the origins of chirality [64,103]. Chiral resolution can rarely occur through *spontaneous resolution*, in which the two enantiomers condense (crystallize) as two separate phases (conglomerates) [104,105]. Enantiomeric resolution can be initiated via the transformation of a metastable polymorphic form using the solvent-assisted solid-to-solid route into a thermodynamically stable polymorph during the crystallization from the supersaturated solution of certain kinds of racemic mixed crystals [106].

As mentioned earlier, enantiomers are similar in their physical properties, while diastereomers are not. Therefore, one way of purifying an enantiomeric pair from each other is by adding a chiral resolving agent to their racemic mixture. This leads to the formation of a complex, usually diastereomeric salt with the racemic mixture entities (so called diastereomeric salt formation). Therefore, a difference in physical properties (such as solubility) occurs, and accordingly, the resultant diastereomers can now be separated through crystallization [107,108]. Afterwards, the chiral agent can be removed to give the pure enantiomers. This method is known as *diastereomeric resolution*. Unfortunately, this approach will only result in a 50% yield.

On the other hand, *mechanical flow* has been proven to efficiently induce complete resolution for solid crystals, as was highlighted by the work of Viedma [98,109,110]. The latter and others have shown that stirring with attrition (grinding the crystals in saturated solution with glass or ceramic beads), so called *Viedma ripening* [111,112], accomplishes both the chiral bias and amplification [113–118]. By increasing the attrition intensity during Viedma ripening, the effect of inherent chiral impurities (which influence Viedma ripening and lead to a preference of one enantiomer over the other) is suppressed and deracemization yield each enantiomer with equal probability [119]. The chiral amplification in Viedma ripening is enhanced by what is considered as an accelerated form of *Ostwald ripening* [120], which involves dissolution of minor crystals in the crystallization solution and their participation, as dissolved species, as growth units on the surfaces of larger crystals. In terms of chirality, the solid phase (crystals) of certain (usually major) handedness dissolves to very small clusters and then redeposits on the surface of larger crystals of the same handedness. Consequently, a higher fraction of clusters of the opposite minor handedness dissolve, resulting in an increment in the proportion of molecules bearing this handedness in the solution phase. Under racemizing conditions, this proportional difference provides a net flux of molecules of the minor handedness to those of the major chirality. Thus, the final result is a complete conversion into crystals of the chirality that initially forms the major population (Figure 8). The method was proven to be effective without the need of adding any catalyst, as was the case for isoindolinones (a compound of common use for pharmaceutical drugs), for which complete deracemization was accomplished, starting from a racemic mixture of conglomerate crystals [121,122]. Nevertheless, the prerequisite for a racemization step is a major limiting factor for applying Viedma ripening, and many attempts were made to overcome this bottleneck. Successful approaches that resulted in complete deracemization were made through the combination of grinding with physical factors, such as temperature gradients [123], temperature cycling [124], chiral additives [125], UV-light [126], and continuous solvent exchange, with which the very important antimalaria drug Mefloquine was deracemized [127]. Moreover, Vlieg et al. showed that Viedma ripening is also effective for obtaining a single enantiomer, not only for compounds with a single stereocenter, but also from a mixture of stereoisomers with

two (or more) different stereocenters, in a process that should be preceded by epimerization of stereocenters, and crystallization of the most stable pair of enantiomers as a racemic conglomerate [128].



**Figure 8.** A schematic diagram showing the actual mechanism of Viedma ripening. Blue and red parts indicate the major and minor enantiomers, respectively. Circles and large rhombi indicate dissolved enantiomers and enantiomeric crystals, respectively. Small rhombi indicate subcritical nanocrystals that mostly undergo dissolution, but also participate more effectively in the crystal growth for the major enantiomer. Thick arrows indicate crystal growth. The green dotted arrow indicates the driving steady flow to major enantiomer in the solution that results in chiral purity. Reprinted with some additions with permission from Reference [120]. Copyright 2015 John Wiley and Sons. License number: 3610860077640.

#### 4.2. Synthetically-Assisted Chiral Resolution in Solutions

**Asymmetric autocatalytic reactions** [129,130], an auto-multiplication process, can efficiently effectuate chiral amplification, because the chiral product itself acts as a catalyst for the production of more of this product. Therefore, unlike asymmetric catalysis, in which the structure of the product is completely different from the catalyst, the separation of the catalyst from the product is not required [131,132]. An empirical and stochastic analysis of several parallel experiments was performed to investigate the nature of the autocatalytic reactions, and it was found that the initial steps of the reaction might be controlled by simple normal distribution (“coin tossing”) formalism. However, the advanced stages of the reaction appear to be of a more complicated nature, with a high probability of being up to three cooperating catalytic cycles [133].

**Physical forces**, such as sublimation [134] and light, namely, circularly polarized light [64,135–142], have been also reported to effectuate chiral amplification. Single handed circularly polarized light has been shown to induce preferred-handed helical conformation in a thin film form of a virtually achiral main-chain conjugated polymer without the use of chemical auxiliaries, but the induction was reversible [143].

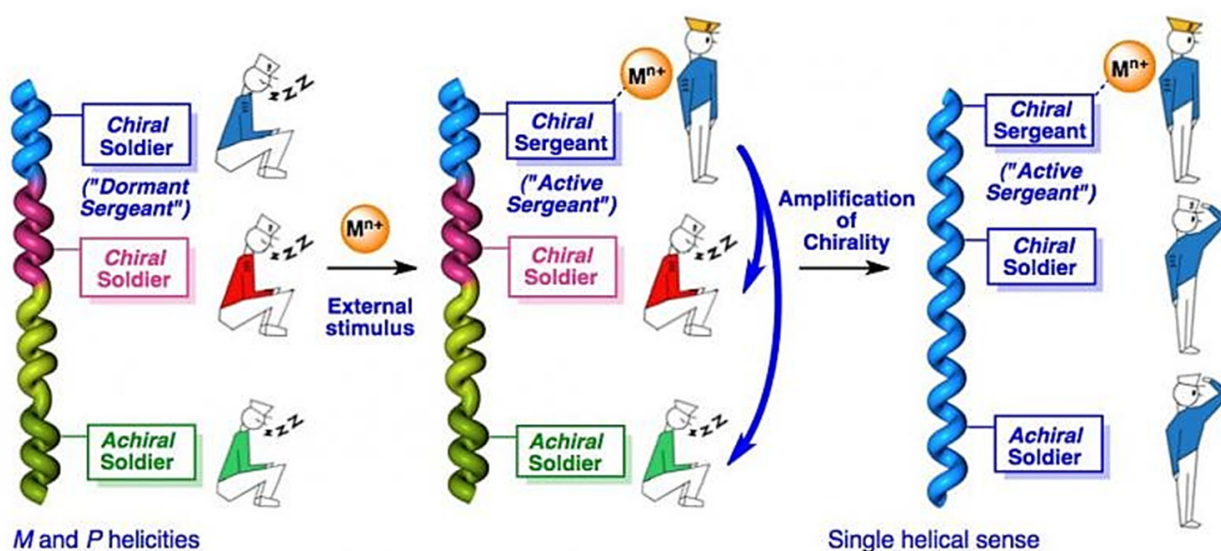
On the supramolecular level, synthetic hydrogen-bonded assemblies were reported to display supramolecular chirality in solution [144] and solid states [145]. In particular, helical architectures are required, because they are the central structure motif in biopolymers. The first successful example of the self-assembly of building blocks into helical superstructures via non-covalent interactions was reported in 1998 [146]. Chiral polymers bearing defined secondary structures and chiral macromolecular assemblies arising from polymer aggregation were thoroughly reviewed elsewhere [94,147]. Asymmetric induction

of supramolecular chirality is extensively studied in polymeric superstructures [148–150] and especially in solvents [151]. It has so far been achieved in inorganic metal-coordinated systems [152,153], organic hydrogen-bonded assemblies [149], and organic gels [154,155].

Amplification of chirality in helical covalent and supramolecular copolymers, which are unlike bio-helical polymers, have no chiral information in their building blocks, can occur via two main assembly routes: the *sergeants-and-soldiers* or the *majority-rules principles* [156,157]. Both effects are triggered by a chiral bias between the left- and right-handed helical bonds [158].

#### 4.2.1. Sergeant-and-Soldiers Principle and Related Approaches

Sergeant-and-soldiers chiral amplification was first proposed in the field of polymer chemistry in the 1960s [159]. Two decades later, it became described with this term when a big control of a few chiral co-monomer (sergeants) was observed on the optical properties (a strong nonlinear response) of the (achiral) monomers (soldiers) in the helical assembly of poly(*n*-hexyl isocyanate) [156]. Few research groups broadened the scope of this concept to include different aspects of supramolecular and polymer chemistry [148,160–167], and many supramolecular structures were released [168–175]. A prerequisite for the sergeant and soldiers' approach is that the chiral guest (sergeant) molecules are chiral analogues of the achiral component (soldiers) [160,176–179]. A large number of bonds with the helicity sense preferred by the chiral monomers was then formed (Figure 9).



**Figure 9.** A schematic diagram showing the activation of the “dormant sergeant” by an external stimulus. Reprinted with permission from Reference [180] License number: 1172323-1.

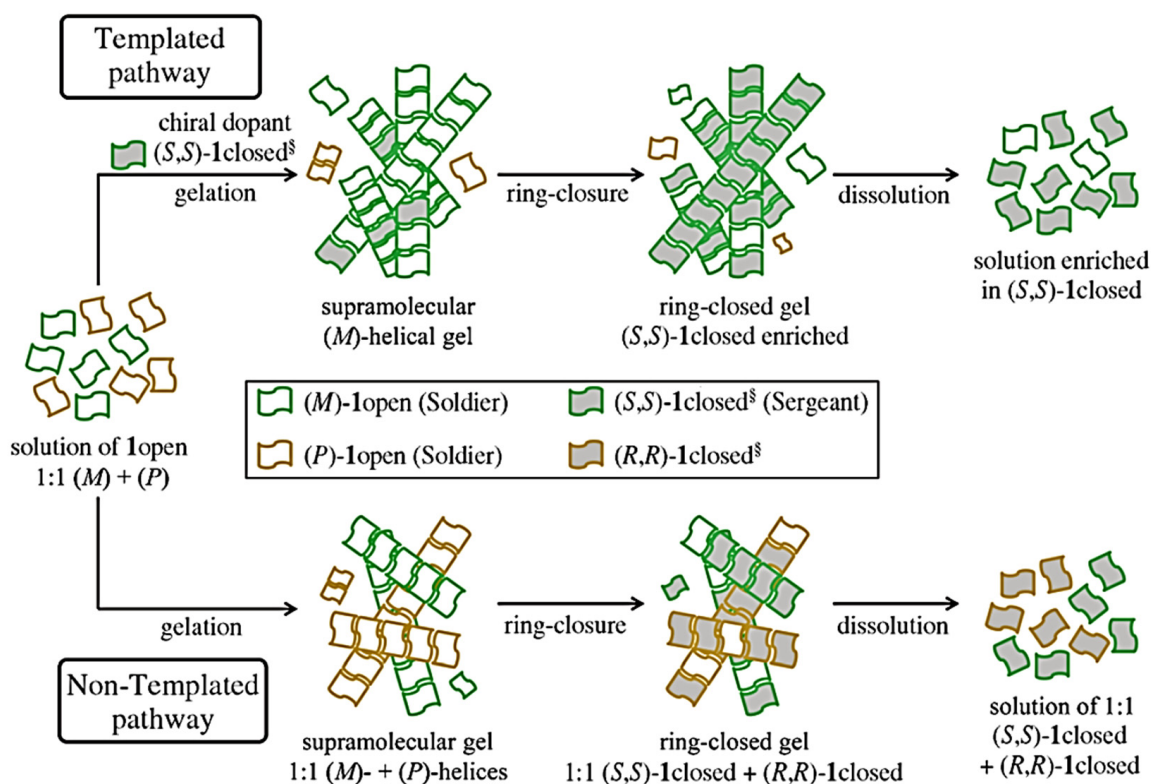
If the chiral guests (auxiliaries) differ in the structure from the achiral component, or if they are chiral solvents, the amplification mode is called the *chiral auxiliaries approach* [18,164,181–184]. The idea of adding an auxiliary chiral component (chiral supramolecular auxiliary approach) has also been used to assemble 1D and 2D chiral structures. The resultant assemblies retain their structure even after the removal of the auxiliary chiral components, thus revealing a memory effect of the chiral auxiliary component in the production of chiral structures. This was shown in the stereoselective non-covalent synthesis of 1D helical self-assembled stacks of achiral monomers that resulted in homochiral helical stacks, which maintain the preferred helicity after the removal of the chiral auxiliary, even after encountering a temperature change [185].

Induction of global chirality in an achiral 2D monolayer, initially assembled into only chiral rows of hydrogen bonded domains in a racemic structure at the liquid-solid interface, has been also accomplished by the addition of a chiral auxiliary, which interacts with

the dimers through hydrogen bonding. Upon removal of these chiral molecules (volatile solvent), the surface remains in its chiral form [186]. Many other examples of amplification of homochirality at solid surfaces [187,188], as well as in isotropic liquids [189], have been reported.

A third approach for preparing chiral monolayers, called the *giant sergeant-and-soldiers* approach, has been also reported. The giant sergeant is the covalent analogue of a cyclic supramolecular hexamer of sergeant molecules, which co-adsorbs on the surface without affecting the supramolecular organization. This approach is expected to have an impact on the supramolecular synthesis of on-surface materials through the formation of mixed assemblies, by applying the first compound on the surface, removing the excess material, and then adding the second component [190].

Moreover, it has been reported that *auto-amplification* of molecular chirality can be accomplished through the induction of supramolecular chirality, which proceeds by means of the sergeant and soldiers' approach (Figure 10). This amplification process was reported for the solution of prochiral, ring-open diarylethenes (soldiers), in which a small amount of their chiral, ring-closed counterpart was added. Hydrogen bonding facilitates the molecules' co-assembly into helical fibers, while the handedness of the fibers is biased by the chiral, ring-closed diarylethene. Subsequent photochemical ring closure of the open diarylethene yields extra chiral of the ring-closed product [191].



**Figure 10.** A schematic diagram showing the concept for auto-amplification of molecular chirality through the induction of supramolecular chirality. Adding a small fraction of chiral dopant (S,S)-Iclosed<sup>S</sup> to a mixture of prochiral photo switches [(M)-Iopen and (P)-Iopen], prior to gelation and UV light activation, made all the difference. Reprinted with permission from Reference [191]. Copyright 2014 John Wiley and Sons. License number: 3610870899092.

#### 4.2.2. Majority-Rules Principle and Related Approaches

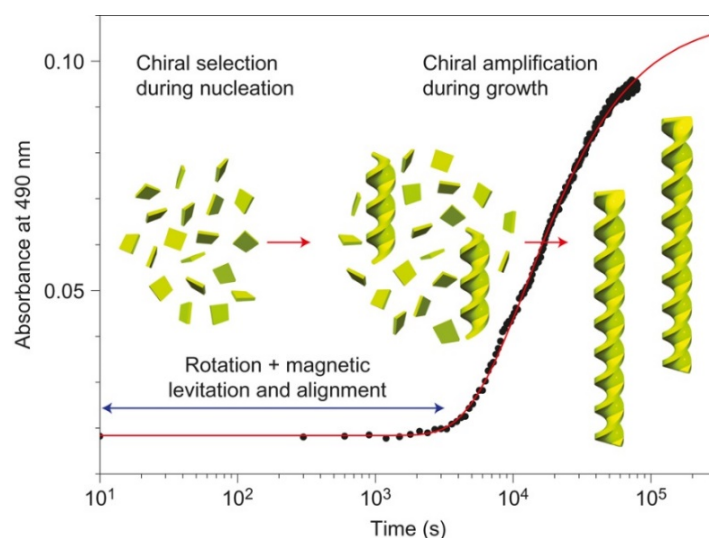
In the absence of a chiral co-monomer, the helical assembly can equally be in one or the other handedness, and many helical reversals along the polymeric chain can occur. For chains consisting of both enantiomeric forms of a chiral monomer, one of which is present in (small) excess, the majority-rules principle is the way to chiral amplification [157]. In

this case, a slight majority, shown by a small  $ee$ , leads the helical preference toward its helical sense. Subsequently, fewer helical reversals occur, because of the lower energy of the helical directionality of the majority units compared to the minority helical sense. These reversals were also shown to be negligible in the copolymer of a ratio of 56/44 of one mirror image unit to the other but became significant with a ratio of 51/49 [157]. The effect of chemical structure on the amplification of chirality has been investigated in order to determine the limits of the majority-rules principle, and it was found that helix reversal penalty is constant; the mismatch (energy) penalty could be directly related to the number of stereocenters present in the molecules [192]. The validation of the 'majority-rules' for the homochirality control of achiral molecules at the liquid/solid interface was first demonstrated when global homochirality was induced in 2D enantiomorphous networks of achiral molecules via co-assembly with chiral co-absorbers. Even after the replacement of the chiral co-absorber by other achiral co-absorber, the resultant global homochirality was memorized and showed nonlinear dependence on the enantiomeric excess of the chiral co-absorber in the solution phase [193].

Although the majority-rules approach of chiral amplifications has been demonstrated by several examples [194–196], it has been discovered, in contrary to common knowledge that, for several combinations of supramolecular polymers, the helical preference is governed by the helicity preference of minority enantiomer. This effect has been dubbed the '*minority-rules*' approach [197].

Another extraordinary finding has been reported, in which four-component supramolecular, propeller-like architectures were constructed through co-assembly of an achiral disk-shaped molecule and chiral amino acid derivatives driven by intermolecular hydrogen bonding. Chiral amplification in this system was shown to be explainable by both the "sergeants-and-soldiers" principle and "majority-rules" effect [198].

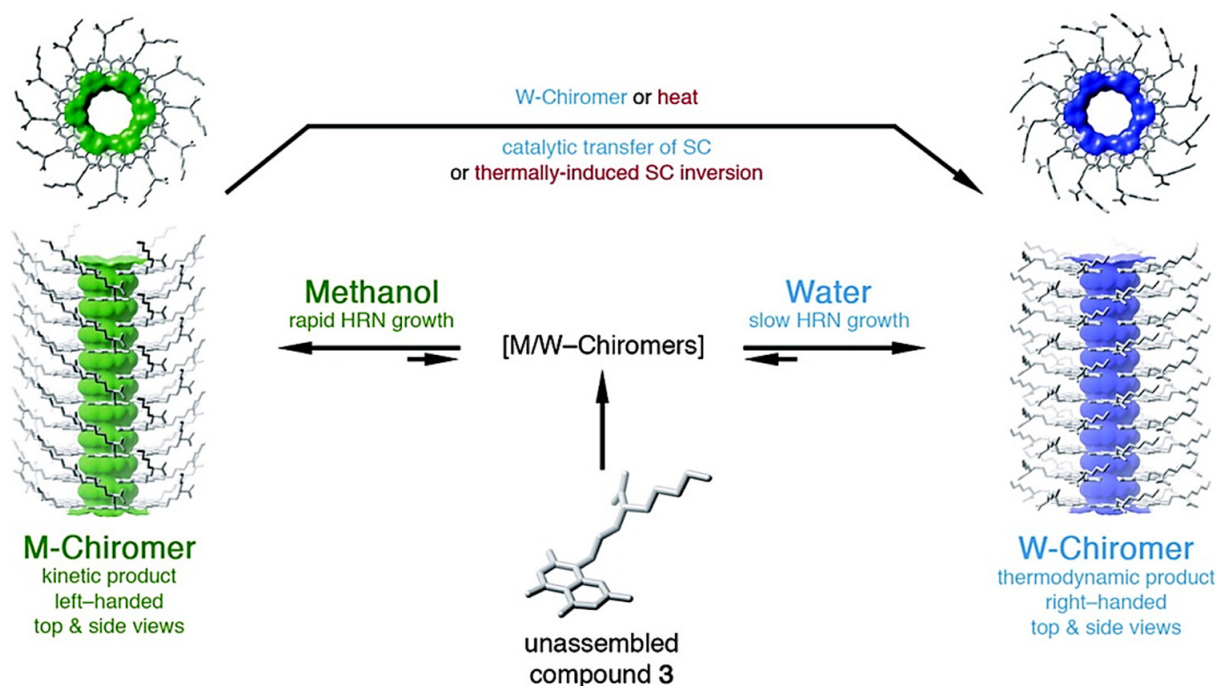
Moreover, in a breakthrough in the knowledge about the preferred helicity of naturally occurring helical supramolecular assemblies, it has been demonstrated that the chirality of helical supramolecular aggregates formed by achiral molecules can be assisted by applying rotational, gravitational, and orienting forces during the self-assembly process. The application of these external forces only during the nucleation step of the aggregation is shown to be sufficient to achieve chiral selection. This finding proved that an almost instantaneous chiral distress can be passed on and amplified throughout the growth of supramolecular self-assemblies and represents evidence that a falsely chiral influence is able to induce absolute enantioselection (Figure 11) [199].



**Figure 11.** A schematic diagram for a model proposed for the chiral selection and amplification. Reprinted with permission from Reference [199]. License Number 3701990420728. Copyright 2012 Nature Publishing Group.

## 5. Inversion of Chirality

The chiral assembly of supramolecular structures is as vital as the capability of inverting their chiral pattern. The inversion of supramolecular chirality is expected to facilitate chiral transmission (and thus information) and provide the possibility of mimicking biological superstructures, such as DNA, which can encounter a helical reverse as a result of a small change in its molecular packing. Inversion of the self-assembled structures' helicity can be realized by varying the preferences toward the available intermolecular interactions such as hydrogen bonding,  $\pi$ - $\pi$  stacking, and hydrophobic forces that arise from the typical nature of molecular systems [200–202]. These variations can be induced by changing the solvent [200], temperature [203], or concentration of the co-assembling chiral dopant molecules (Figure 12) [204]. This chiral inversion has been accomplished by applying external heat and ultrasonic stimuli to an organic chromophoric system, which in turn induced the formation of aggregates with ordered molecular packing and enhanced optical chirality [205]. In a very different approach than the kinetically and thermodynamically-driven approaches, a thermal-reversible chirality inversion has been patterned by the symmetry change of the self-organized 3D packing [33].



**Figure 12.** A schematic diagram for the catalytic and thermodynamic pathways for the formation of chiromer and their interconversion in methanol (left) and water (right). Reprinted with permission from Reference [200]. Copyright 2007 American Chemical Society.

## 6. Supramolecular Chirality and (Bio-)Technological Applications

Many polymers cannot form crystals, and thus the investigations to determine their structures always lacks important details. The assembly of these polymers in chiral helices provides an alternative means to study their exact structure using X-ray diffraction. In addition, local guidance, usually by manipulating the chiral properties, plays an important role in supramolecular structure formation. Controlled construction of different levels of chirality in helical structures using chiral molecules is a necessity for exploring the new properties of functional materials. Because supramolecular polymeric structures are assembled through hydrophobic interactions, hydrogen-bonding, metal-ligand bonding,  $\pi$ - $\pi$  stacking, or host-guest interactions, they offer crucial properties related to their reversible nature (in terms of their structure, shape, and function, in response to external stimuli) that cannot be obtained with classical, or covalent polymers [206]. These smart

material properties include low viscosity in the melt phase, amphiphilicity [207], the potential to self-heal [208,209], and reciprocity to the dynamics of living tissues [210,211].

In a leading structure-dynamics-property study, it has been shown that the inclusion of homochirality in aqueous supramolecular polymers imparts a higher level of internal ordering, which does not affect the basic dimensions of the supramolecular fibers but the equilibrium dynamics of the polymers differ by almost one order of magnitude [212]. This result is important for the implementation of the chiral supramolecules in biomedical applications.

### 6.1. Technological Applications for Chiral 2D Surfaces

The induction and amplification of chirality in 2D surfaces are relevant for many vital chemical processes, including asymmetric heterogeneous catalysis, chiral resolution, and enantio-enrichment in crystal chemistry. Chiral assemblies results in important properties when the building blocks assemble in periodic 2D structures [213]. This is because of the resultant strong optical activity [214,215], circular dichroism [216], and negative refraction [217–220]. Several applications in physics, including electronic (semiconducting nanofibers [221,222] and nanotubes [194]), photonic and opto-electronic applications, have been enormously developed by using these chiral 2D structures. Other applications include optical communication and sensing [223–227], which require a sort of 2D periodic chirality, and holographic lithography-based and vectorial holographic techniques [213,228]. Moreover, remote chiral communication in 2D supramolecular assembly at a liquid/solid interface has been explored at the molecular level [229]. It was also shown that the stereochemical information in a chiral co-adsorber was transmitted over five methylene groups' lengths to a 2D supramolecular assembly of achiral building units, with the association of certain hydrogen bonds between the chiral co-adsorber, achiral building units, and the confinement effect during 2D crystallization. In addition, an odd-even effect was found when the stereogenic center encountered a change in position, with respect to the stereocontrolling functional groups. In such a case, a stereogenic center closer to the stereocontrolling moiety transmitted more readily the stereochemical information to the 2D supramolecular assembly [229].

### 6.2. Functions Provided by Chiral 3D Supramolecular Assemblies

Transmission of chirality from the molecular to the 3D supramolecular level is an important topic in organic chemistry [230], enantioselective organo-catalysis [231–234], and metal and bio-catalysis [235–237]. In that respect, chiral guest encapsulation has been shown to result in high diastereoselectivity of a dissymmetric capsule, which resembles an enzyme with a binding pocket, in an approach that may provide rational means for the synthesis of a molecular machine capable of manipulating chiral information encoding in a supramolecular structure [238].

### 6.3. Applications of Synthetic Chiral Polymers

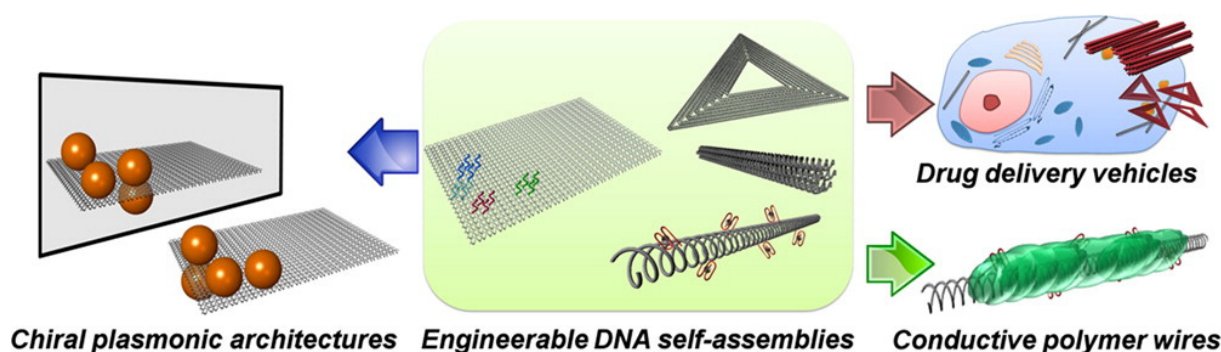
Artificial chiral polymers have a wide variety of potential applications [224,239–242]. Chirality of some polymers can be switchable using chemical [243–245] and light [135–137,141,143,246–248] stimuli. Artificial double-stranded helical oligomers (foldamers) and polymers have been also developed [235,241,249,250]. However, the structural motifs for these structures are still limited to helicates [251] (and a double helix of two strands with opposite chirality) [252], peptide nucleic acids (PNAs) [253], aromatic oligoamides [254], and oligoresorcinols [255]. However, more studies are dedicated to the construction of complementary double-stranded helical oligomers and polymers linked by a variety of linkages with a controlled helical sense [256–261]. The controlled modulation of the chiral properties of the self-assembled polymeric aggregates is expected to help in the design of optical devices based on organic nanostructures with the desired chiroptical properties.

#### 6.4. Plausible Functions for Dendrons and Dendrimers Based Supramolecular Assemblies

As we described above, these assemblies provide vital architectural motifs that have a remarkable impact on the field of science at the interface between chemistry, biology, physics, and complex ordered soft-condensed matter [262,263]. The high level of control in designing supramolecular helical structures, generated from synthetic dendrons, dendrimers, and other structurally similar macromolecules, draws the attention to these assemblies, essentially because of the ability to precisely incorporate functional groups in various parts in their helices [264,265]. These structures are of wide interest in different applications [266], including molecular recognition [267], folding [249,268], nanotubes [18,194,269], nanomachines [270], porous protein mimics [25], optics [271–273], and/or organic electronics [42,274,275].

#### 6.5. Exploiting the Chiral Nature of DNA in Technological Applications

DNA is a biologically abundant double helical chiral supramolecular assembly that has been used beyond its genetic role as a building block for the construction of nano-engineered materials (Figure 13). The spatial arrangement of heterogeneous components, using DNA nanostructures as the templates, is expected to facilitate the fabrication of outstanding functional materials. Moreover, nucleic strands can be designed to extend out of the DNA superstructures to interact with nanoscale targets through specific recognition. Metal and semi-conductor nanoparticles has been positioned on the surface of DNA nanostructures with nanometer precision for chiral response applications (chiral plasmonic nanostructures) [276,277]. Moreover, DNA origami nanostructures have been shown to guide the assembly of achiral, spherical, and metallic nanoparticles into nature-mimicking chiral geometries through hybridization between complementary DNA strands on the surface of nanoparticles and DNA scaffolds to generate a circular dichroism (CD) response in the visible light region [278,279]. In addition, DNA has been successfully applied in biosensors [280–282], molecular machines [283,284], and other complex nano-architectures [278,279]. Furthermore, the regulation of DNA self-assembly and hybridization on chiral molecule modified gold surfaces has been performed. The study has shown that the short-chain DNA has a larger adsorption quality and better covalent assembly on the L-surface than the D-surface, but the D-surface has larger hybridization efficiency [285]. These developments require the study of the covalent immobilization of DNA and further investigation of the DNA hybridization on chiral molecule modified surfaces.



**Figure 13.** A schematic diagram summarizes the current possibilities of utilizing DNA as building blocks for the construction of engineering materials in different applications. Reprinted with permission from Reference [278]. Copyright 2014 American Chemical Society.

## 7. Conclusions

Homochirality is the selection that has been easily, but indeed wisely, chosen for nature. Learning from this choice and attempting to become accustomed to its demands to synthesize compounds and supramolecular assemblies for important chiral-based technological and biologically relevant pharmaceutical applications is currently a very vital topic of research. To date, attempts are ongoing to define the rules and develop and improve



methodologies by which chiral selection and amplification can be implemented. In this review, the essential basics, as well as recent foundations and applications, in this field of research are reported. Indeed, there is no single universal methodology suitable for the production of pure enantiomers for all super(molecules) and assemblies. However, an enormous development in science of chirality does exist and is still attracting a lot of research appeal, owing to the prospective of very important applications.

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## References

1. Oparin, A.I. *Life, Its Nature, Origin and Development*; Academic Press: New York, NY, USA, 1961.
2. Wilkinson, A.; McNaught, A. *IUPAC Compendium of Chemical Terminology, (the "Gold Book")*; International Union of Pure and Applied Chemistry: North Carolina, NC, USA, 1997.
3. Barker, T.V.; Marsh, J.E. LXXXV.-Optical activity and enantiomorphism of molecular and crystal structure. *J. Chem. Soc. Trans.* **1913**, *103*, 837–847. [[CrossRef](#)]
4. Cahn, R.S.; Ingold, C.; Prelog, V. Specification of Molecular Chirality. *Angew. Chem. Int. Ed. Engl.* **1966**, *5*, 385–415. [[CrossRef](#)]
5. Carballeira, J.; Krumlinde, P.; Bocola, M.; Vogel, A.; Reetz, M. Directed evolution and axial chirality: Optimization of the enantioselectivity of *Pseudomonas aeruginosa* lipase towards the kinetic resolution of a racemic allene. *Chem. Commun.* **2007**, *19*, 1913–1915. [[CrossRef](#)] [[PubMed](#)]
6. Ruble, J.C.; Latham, H.A.; Fu, G.C. Effective Kinetic Resolution of Secondary Alcohols with a Planar–Chiral Analogue of 4-(Dimethylamino)pyridine. Use of the Fe(C5Ph5) Group in Asymmetric Catalysis. *J. Am. Chem. Soc.* **1997**, *119*, 1492–1493. [[CrossRef](#)]
7. Havinga, E. Spontaneous formation of optically active substances. *Biochim. Biophys. Acta* **1954**, *13*, 171–174. [[CrossRef](#)]
8. Kipping, F.S.; Pope, W.J. LXIII.-Enantiomorphism. *J. Chem. Soc. Trans.* **1898**, *73*, 606–617. [[CrossRef](#)]
9. Niedermaier, T.; Jr, W.S. Zur optischen Aktivität der Natriumchlorat- und Natriumbromat-Kristalle (Studies on the Optical Activity of Sodium Chlorate and Sodium Bromate Crystals). *Chem. Ber.* **1972**, *105*, 3470–3478. [[CrossRef](#)]
10. Barron, L.D. An introduction to chirality at the nanoscale. In *Chirality at the Nanoscale*; Amabilino, D.B., Ed.; Wiley: New York, NY, USA, 2009; pp. 1–27. [[CrossRef](#)]
11. Eliel, E.L.; Wilen, S.H. *Stereochemistry of Organic Compounds*; John Wiley & Sons: New York, NY, USA, 1994.
12. Mateos Timoneda, M.A. Functional Chiral Hydrogen-Bonded Assemblies. Ph.D. Thesis, University of Twente, Enschede, The Netherlands, 2005.
13. Shinitzky, M.; Haimovitz, R. Chiral surfaces in micelles of enantiomeric N-palmitoyl- and N-stearoylserine. *J. Am. Chem. Soc.* **1993**, *115*, 12545–12549. [[CrossRef](#)]
14. Bonazzi, S.; DeMorais, M.M.; Gottarelli, G.; Mariani, P.; Spada, G.P. Self-Assembly and Liquid Crystal Formation of Folic Acid Salts. *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 248–250. [[CrossRef](#)]
15. Tsang, M.Y.; Di Salvo, F.; Teixidor, F.; Viñas, C.; Choquesillo-Lazarte, D.; Giner Planas, J.; Vanthuyne, N. Is molecular chirality connected to supramolecular chirality? The particular case of chiral 2-pyridyl alcohols. *Cryst. Growth Des.* **2015**, *15*, 935–945. [[CrossRef](#)]
16. Green, M.M.; Cheon, K.S.; Yang, S.Y.; Park, J.W.; Swansburg, S.; Liu, W. Chiral Studies across the Spectrum of Polymer Science. *Acc. Chem. Res.* **2001**, *34*, 672. [[CrossRef](#)]
17. Fenniri, H.; Mathivanan, P.; Vidale, K.L.; Sherman, D.M.; Hallenga, K.; Wood, K.V.; Stowell, J.G. Helical rosette nanotubes: Design, self-assembly, and characterization. *J. Am. Chem. Soc.* **2001**, *123*, 3854–3855. [[CrossRef](#)]
18. Fenniri, H.; Deng, B.L.; Ribbe, A.E. Helical rosette nanotubes with tunable chiroptical properties. *J. Am. Chem. Soc.* **2002**, *124*, 11064–11072. [[CrossRef](#)]
19. Fenniri, H.; Deng, B.-L.; Ribbe, A.E.; Hallenga, K.; Jacob, J.; Thiyagarajan, P. Entropically driven self-assembly of multichannel rosette nanotubes. *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 6487–6492. [[CrossRef](#)] [[PubMed](#)]
20. Datta, S.; Takahashi, S.; Yagai, S. Nanoengineering of Curved Supramolecular Polymers: Toward Single-Chain Mesoscale Materials. *Acc. Mater. Res.* **2022**, *in press*. [[CrossRef](#)]
21. Suri, S.S.; Fenniri, H.; Singh, B. Nanotechnology-based drug delivery systems. *J. Occup. Med. Toxicol.* **2007**, *2*, 16. [[CrossRef](#)]
22. Journeay, W.S.; Suri, S.S.; Morales, J.G.; Fenniri, H.; Singh, B. Rosette nanotubes show low acute pulmonary toxicity in vivo. *Int. J. Nanomed.* **2008**, *3*, 373.
23. Seabra, A.B.; Duran, N. Biological applications of peptides nanotubes: An overview. *Peptides* **2013**, *39*, 47–54. [[CrossRef](#)] [[PubMed](#)]

24. Balbo Block, M.; Kaiser, C.; Khan, A.; Hecht, S. Discrete Organic Nanotubes Based on a Combination of Covalent and Non-Covalent Approaches. In *Functional Molecular Nanostructures*; Schlüter, A.D., Ed.; Topics in Current Chemistry; Springer: Berlin/Heidelberg, Germany, 2005; Volume 245, pp. 89–150.
25. Percec, V.; Dulcey, A.E.; Balagurusamy, V.S.K.; Miura, Y.; Smidrkal, J.; Peterca, M.; Nummelin, S.; Edlund, U.; Hudson, S.D.; Heiney, P.A.; et al. Self-assembly of amphiphilic dendritic dipeptides into helical pores. *Nature* **2004**, *430*, 764–768. [[CrossRef](#)]
26. Donnio, B.; Buathong, S.; Bury, I.; Guillon, D. Liquid crystalline dendrimers. *Chem. Soc. Rev.* **2007**, *36*, 1495–1513. [[CrossRef](#)]
27. Soininen, A.J.; Kasëmi, E.; Schlüter, A.D.; Ikkala, O.; Ruokolainen, J.; Mezzenga, R. Self-Assembly and Induced Circular Dichroism in Dendritic Supramolecules with Cholesteric Pendant Groups. *J. Am. Chem. Soc.* **2010**, *132*, 10882–10890. [[CrossRef](#)] [[PubMed](#)]
28. van Gorp, J.J.; Vekemans, J.A.; Meijer, E. C<sub>3</sub>-symmetrical supramolecular architectures: Fibers and organic gels from discotic trisamides and trisureas. *J. Am. Chem. Soc.* **2002**, *124*, 14759–14769. [[CrossRef](#)] [[PubMed](#)]
29. Alam, M.A.; Motoyanagi, J.; Yamamoto, Y.; Fukushima, T.; Kim, J.; Kato, K.; Takata, M.; Saeki, A.; Seki, S.; Tagawa, S.; et al. “Bicontinuous Cubic” Liquid Crystalline Materials from Discotic Molecules: A Special Effect of Paraffinic Side Chains with Ionic Liquid Pendants. *J. Am. Chem. Soc.* **2009**, *131*, 17722–17723. [[CrossRef](#)]
30. Percec, V.; Imam, M.R.; Peterca, M.; Wilson, D.A.; Graf, R.; Spiess, H.W.; Balagurusamy, V.S.K.; Heiney, P.A. Self-Assembly of Dendritic Crowns into Chiral Supramolecular Spheres. *J. Am. Chem. Soc.* **2009**, *131*, 1294–1304. [[CrossRef](#)] [[PubMed](#)]
31. Percec, V.; Imam, M.R.; Peterca, M.; Wilson, D.A.; Graf, R.; Spiess, H.W.; Balagurusamy, V.S.K.; Heiney, P.A. Self-Assembly of Dendronized Triphenylenes into Helical Pyramidal Columns and Chiral Spheres. *J. Am. Chem. Soc.* **2009**, *131*, 7662–7677. [[CrossRef](#)] [[PubMed](#)]
32. Cordovilla, C.; Coco, S.; Espinet, P.; Donnio, B. Liquid-Crystalline Self-Organization of Isocyanide-Containing Dendrimers Induced by Coordination to Gold(I) Fragments. *J. Am. Chem. Soc.* **2010**, *132*, 1424–1431. [[CrossRef](#)]
33. Peterca, M.; Imam, M.R.; Ahn, C.-H.; Balagurusamy, V.S.K.; Wilson, D.A.; Rosen, B.M.; Percec, V. Transfer, Amplification, and Inversion of Helical Chirality Mediated by Concerted Interactions of C<sub>3</sub>-Supramolecular Dendrimers. *J. Am. Chem. Soc.* **2011**, *133*, 2311–2328. [[CrossRef](#)]
34. Würthner, F. Perylene bisimide as versatile building blocks for functional supramolecular architectures. *Chem. Commun.* **2004**, 1564–1579. [[CrossRef](#)]
35. Huang, C.; Barlow, S.; Marder, S.R. Perylene-3,4,9,10-tetracarboxylic Acid Diimides: Synthesis, Physical Properties, and Use in Organic Electronics. *J. Org. Chem.* **2011**, *76*, 2386. [[CrossRef](#)]
36. Görl, D.; Zhang, X.; Würthner, F. Molecular Assemblies of Perylene Bisimide Dyes in Water. *Angew. Chem. Int. Ed.* **2012**, *51*, 6328. [[CrossRef](#)]
37. Percec, V.; Sun, H.-J.; Leowanawat, P.; Peterca, M.; Graf, R.; Spiess, H.W.; Zeng, X.; Ungar, G.; Heiney, P.A. Transformation from Kinetically into Thermodynamically Controlled Self-Organization of Complex Helical Columns with 3D Periodicity Assembled from Dendronized Perylene Bisimides. *J. Am. Chem. Soc.* **2013**, *135*, 4129–4148. [[CrossRef](#)]
38. Wu, Y.-C.; Leowanawat, P.; Sun, H.-J.; Partridge, B.E.; Peterca, M.; Graf, R.; Spiess, H.W.; Zeng, X.; Ungar, G.; Hsu, C.-S. Complex Columnar Hexagonal Polymorphism in Supramolecular Assemblies of a Semifluorinated Electron-Accepting Naphthalene Bisimide. *J. Am. Chem. Soc.* **2015**, *137*, 807–819. [[CrossRef](#)]
39. Schmidt-Mende, L.; Fechtenkötter, A.; Müllen, K.; Moons, E.; Friend, R.H.; MacKenzie, J.D. Self-Organized Discotic Liquid Crystals for High-Efficiency Organic Photovoltaics. *Science* **2001**, *293*, 1119–1122. [[CrossRef](#)] [[PubMed](#)]
40. Pho, T.V.; Toma, F.M.; Chabinyk, M.L.; Wudl, F. Self-Assembling Decacyclene Triimides Prepared through a Regioselective Hextuple Friedel–Crafts Carbamylation. *Angew. Chem. Int. Ed.* **2013**, *52*, 1446–1451. [[CrossRef](#)]
41. Hartnett, P.E.; Timalisina, A.; Matte, H.S.S.R.; Zhou, N.; Guo, X.; Zhao, W.; Facchetti, A.; Chang, R.P.H.; Hersam, M.C.; Wasielewski, M.R.; et al. Slip-Stacked Perylenediimides as an Alternative Strategy for High Efficiency Nonfullerene Acceptors in Organic Photovoltaics. *J. Am. Chem. Soc.* **2014**, *136*, 16345–16356. [[CrossRef](#)] [[PubMed](#)]
42. Percec, V.; Glodde, M.; Bera, T.K.; Miura, Y.; Shiyonovskaya, I.; Singer, K.D.; Balagurusamy, V.S.K.; Heiney, P.A.; Schnell, I.; Rapp, A.; et al. Self-organization of supramolecular helical dendrimers into complex electronic materials. *Nature* **2002**, *419*, 384. [[CrossRef](#)]
43. Anthony, J.E.; Facchetti, A.; Heeney, M.; Marder, S.R.; Zhan, X. n-Type Organic Semiconductors in Organic Electronics. *Adv. Mater.* **2010**, *22*, 3876. [[CrossRef](#)] [[PubMed](#)]
44. Facchetti, A.  $\pi$ -Conjugated Polymers for Organic Electronics and Photovoltaic Cell Applications. *Chem. Mater.* **2011**, *23*, 733–758. [[CrossRef](#)]
45. Banks, R.E.; Smart, B.E.; Tatlow, J.C. *Organofluorine Chemistry. Topics in Applied Chemistry*; Springer: Boston, MA, USA, 1994.
46. Gladysz, J.A.; Curran, D.P.; Horváth, I.T. *Handbook of Fluorous Chemistry*; Wiley: New York, NY, USA, 2005. [[CrossRef](#)]
47. Krafft, M.P.; Riess, J.G. Chemistry, Physical Chemistry, and Uses of Molecular Fluorocarbon—Hydrocarbon Diblocks, Triblocks, and Related Compounds—Unique “Apolar” Components for Self-Assembled Colloid and Interface Engineering. *Chem. Rev.* **2009**, *109*, 1714–1792. [[CrossRef](#)]
48. Berger, R.; Resnati, G.; Metrangolo, P.; Weber, E.; Hulliger, J. Organic fluorine compounds: A great opportunity for enhanced materials properties. *Chem. Soc. Rev.* **2011**, *40*, 3496–3508. [[CrossRef](#)]
49. Cametti, M.; Crousse, B.; Metrangolo, P.; Milani, R.; Resnati, G. The fluorous effect in biomolecular applications. *Chem. Soc. Rev.* **2012**, *41*, 31–42. [[CrossRef](#)] [[PubMed](#)]

50. Priimagi, A.; Cavallo, G.; Metrangolo, P.; Resnati, G. The Halogen Bond in the Design of Functional Supramolecular Materials: Recent Advances. *Acc. Chem. Res.* **2013**, *46*, 2686–2695. [[CrossRef](#)]
51. Renner, R. Growing Concern Over Perfluorinated Chemicals. *Environ. Sci. Technol.* **2001**, *35*, 154A–160A. [[CrossRef](#)]
52. Renner, R. Sorting out sources of perfluorinated chemicals. *Environ. Sci. Technol.* **2006**, *40*, 2866–2867.
53. Guo, J.; Resnick, P.; Efimenko, K.; Genzer, J.; DeSimone, J.M. Alternative Fluoropolymers to Avoid the Challenges Associated with Perfluorooctanoic Acid. *Ind. Eng. Chem. Res.* **2008**, *47*, 502–508. [[CrossRef](#)]
54. Zhang, W. Green chemistry aspects of fluororous techniques-opportunities and challenges for small-scale organic synthesis. *Green Chem.* **2009**, *11*, 911–920. [[CrossRef](#)]
55. Wilson, C.J.; Wilson, D.A.; Feiring, A.E.; Percec, V. Disassembly via an environmentally friendly and efficient fluororous phase constructed with dendritic architectures. *J. Polym. Sci. Part A Polym. Chem.* **2010**, *48*, 2498–2508. [[CrossRef](#)]
56. Kondepudi, D.K.; Nelson, G.W. Weak neutral currents and the origin of biomolecular chirality. *Nature* **1985**, *314*, 438–441. [[CrossRef](#)]
57. Mason, S.F.; Tranter, G.E. The electroweak origin of biomolecular handedness. *Proc. R. Soc. Lond. A Math. Phys. Sci.* **1985**, *397*, 45–65. [[CrossRef](#)]
58. Weissbuch, I.; Addadi, L.; Leiserowitz, L.; Lahav, M. Total asymmetric transformations at interfaces with centrosymmetric crystals: Role of hydrophobic and kinetic effects in the crystallization of the system glycine/.alpha.-amino acids. *J. Am. Chem. Soc.* **1988**, *110*, 561–567. [[CrossRef](#)]
59. Mason, S. Biomolecular homochirality. *Chem. Soc. Rev.* **1988**, *17*, 347–359. [[CrossRef](#)]
60. Bonner, W. The origin and amplification of biomolecular chirality. *Orig. Life Evol. Biosph.* **1991**, *21*, 59–111. [[CrossRef](#)]
61. Keszthelyi, L. Origin of the homochirality of biomolecules. *Q. Rev. Biophys.* **1995**, *28*, 473–507. [[CrossRef](#)]
62. Avetisov, V.; Goldanskii, V. Mirror symmetry breaking at the molecular level. *Proc. Natl. Acad. Sci. USA* **1996**, *93*, 11435–11442. [[CrossRef](#)]
63. Siegel, J.S. Homochiral imperative of molecular evolution. *Chirality* **1998**, *10*, 24–27. [[CrossRef](#)]
64. Feringa, B.L.; Van Delden, R.A. Absolute asymmetric synthesis: The origin, control, and amplification of chirality. *Angew. Chem. Int. Ed.* **1999**, *38*, 3418–3438. [[CrossRef](#)]
65. Eschenmoser, A. Chemical Etiology of Nucleic Acid Structure. *Science* **1999**, *284*, 2118–2124. [[CrossRef](#)]
66. Avalos, M.n.; Babiano, R.; Cintas, P.; Jiménez, J.L.; Palacios, J.C. From parity to chirality: Chemical implications revisited. *Tetrahedron Asymmetry* **2000**, *11*, 2845–2874. [[CrossRef](#)]
67. Okuyama, K.; Okuyama, K.; Arnott, S.; Takayanagi, M.; Kakudo, M. Crystal and molecular structure of a collagen-like polypeptide (Pro-Pro-Gly) 10. *J. Mol. Biol.* **1981**, *152*, 427–443. [[CrossRef](#)]
68. Warrick, H.M.; Spudich, J.A. Myosin: Structure and function in cell motility. *Annu. Rev. Cell Biol.* **1987**, *3*, 379–422. [[CrossRef](#)] [[PubMed](#)]
69. Dickerson, R.E.; Drew, H.R.; Conner, B.N.; Wing, R.M.; Fratini, A.V.; Kopka, M.L. The anatomy of a-, b-, and z-DNA. *Science* **1982**, *216*, 475–485. [[CrossRef](#)]
70. Pirkle, W.H.; Pochapsky, T.C. Chiral molecular recognition in small bimolecular systems: A spectroscopic investigation into the nature of diastereomeric complexes. *J. Am. Chem. Soc.* **1987**, *109*, 5975–5982. [[CrossRef](#)]
71. Feiters, M.C.; Nolte, R.J.; Gokel, G. Chiral Self-assembled Structures of Biomolecules and Synthetic Analogues. *Adv. Supramol. Chem.* **2000**, *6*, 41–156.
72. Chela-Flores, J. The origin of chirality in protein amino acids. *Chirality* **1994**, *6*, 165–168. [[CrossRef](#)]
73. Fujii, N.; Saito, T. Homochirality and life. *Chem. Rec.* **2004**, *4*, 267–278. [[CrossRef](#)]
74. Lin, C.-H.; Yang, H.-T.; Lane, H.-Y. D-glutamate, D-serine, and D-alanine differ in their roles in cognitive decline in patients with Alzheimer’s disease or mild cognitive impairment. *Pharmacol. Biochem. Behav.* **2019**, *185*, 172760. [[CrossRef](#)]
75. Piubelli, L.; Murtas, G.; Rabattoni, V.; Pollegioni, L. The Role of D-Amino Acids in Alzheimer’s Disease. *J. Alzheimer’s Dis. JAD* **2021**, *80*, 475–492. [[CrossRef](#)] [[PubMed](#)]
76. Maier, N.M.; Franco, P.; Lindner, W. Separation of enantiomers: Needs, challenges, perspectives. *J. Chromatogr. A* **2001**, *906*, 3–33. [[CrossRef](#)]
77. Nguyen, K.T.; Stephens, D.P.; McLeish, M.J.; Crankshaw, D.P.; Morgan, D.J. Pharmacokinetics of thiopental and pentobarbital enantiomers after intravenous administration of racemic thiopental. *Anesth. Analg.* **1996**, *83*, 552–558. [[CrossRef](#)]
78. Mitra, S.; Chopra, P. Chirality and anaesthetic drugs: A review and an update. *Indian J. Anaesth.* **2011**, *55*, 556. [[CrossRef](#)]
79. Kocher-Becker, U.; Kocher, W.; Ockenfels, H. Teratogenic activity of a hydrolytic thalidomide metabolite in mice. *Naturwissenschaften* **1982**, *69*, 191–192. [[CrossRef](#)] [[PubMed](#)]
80. McConnell, O.; He, Y.; Nogle, L.; Sarkahian, A. Application of chiral technology in a pharmaceutical company. Enantiomeric separation and spectroscopic studies of key asymmetric intermediates using a combination of techniques. *Phenylglycidols. Chirality* **2007**, *19*, 716–730. [[CrossRef](#)] [[PubMed](#)]
81. Francotte, E.R. Enantioselective chromatography as a powerful alternative for the preparation of drug enantiomers. *J. Chromatogr. A* **2001**, *906*, 379–397. [[CrossRef](#)]
82. Beck, G. Synthesis of Chiral Drug Substances. *Synlett* **2002**, *2002*, 0837–0850. [[CrossRef](#)]
83. Andersson, S.; Allenmark, S.G. Preparative chiral chromatographic resolution of enantiomers in drug discovery. *J. Biochem. Biophys. Methods* **2002**, *54*, 11–23. [[CrossRef](#)]

84. Kellogg, R.M.; Nieuwenhuijzen, J.W.; Pouwer, K.; Vries, T.R.; Broxterman, Q.B.; Grimbergen, R.F.P.; Kaptein, B.; Crois, R.M.L.; de Wever, E.; Zwaagstra, K.; et al. Dutch Resolution: Separation of Enantiomers with Families of Resolving Agents. A Status Report. *Synthesis* **2003**, *2003*, 1626–1638. [[CrossRef](#)]
85. Kaptein, B.; Vries, T.; Nieuwenhuijzen, J.; Kellogg, R.; Grimbergen, R.; Broxterman, Q. Continuous developments in classical resolution: Dutch resolution and asymmetric transformation. *Life Sci. Adv. Syn. Catal. Pharmachem.* **2003**, *2*, 17–22. [[CrossRef](#)]
86. Marino, S.; Stachurska-Buczek, D.; Huggins, D.; Krywult, B.; Sheehan, C.; Nguyen, T.; Choi, N.; Parsons, J.; Griffiths, P.; James, I.; et al. Synthesis of Chiral Building Blocks for Use in Drug Discovery. *Molecules* **2004**, *9*, 405–426. [[CrossRef](#)]
87. Patel, R.N.; Goswami, A.; Chu, L.; Donovan, M.J.; Nanduri, V.; Goldberg, S.; Johnston, R.; Siva, P.J.; Nielsen, B.; Fan, J.; et al. Enantioselective microbial reduction of substituted acetophenones. *Tetrahedron Asymmetry* **2004**, *15*, 1247–1258. [[CrossRef](#)]
88. Pasteur, L.C. New method of separating racemic acid into dextro- and Izvo- tartaric acid. *Comptes Rendus De L'académie Des Sci.* **1848**, *26*, 535–538.
89. Kauffman, G.; Myers, R. Pasteur's Resolution of Racemic Acid: A Sesquicentennial Retrospect and a New Translation. *Chem. Educ.* **1998**, *3*, 1–4. [[CrossRef](#)]
90. Jacques, J.; Collet, A.; Wilen, S. *Enantiomers, Racemates and Resolutions*, 3rd ed.; Krieger: Malabar, FL, USA, 1994.
91. Pasteur, L.C. Transformation des acides tartriques en acide racémique—Découverte de l'acide tartrique inactif. Nouvelle méthode de séparation de l'acide racémique en acides tartriques droit et gauche. *Compte-Rendus De L'académie Des Sci.* **1953**, *37*, 162–166.
92. Joyce, G.; Visser, G.; Van Boeckel, C.; Van Boom, J.; Orgel, L.; Van Westrenen, J. Chiral selection in poly (C)-directed synthesis of oligo (G). *Nature* **1984**, *310*, 602–604. [[CrossRef](#)] [[PubMed](#)]
93. Avetisov, V.A.; Goldanskii, V.I.; Kuz'min, V.V. Handedness, origin of life and evolution. *Phys. Today* **1991**, *44*, 33–41. [[CrossRef](#)]
94. Cornelissen, J.J.; Rowan, A.E.; Nolte, R.J.; Sommerdijk, N.A. Chiral architectures from macromolecular building blocks. *Chem. Rev.* **2001**, *101*, 4039–4070. [[CrossRef](#)]
95. Kagan, H.B.; Balavoine, G.; Moradpour, A. Can circularly polarized light be used to obtain chiral compounds of high optical purity? *J. Mol. Evol.* **1974**, *4*, 41–48. [[CrossRef](#)] [[PubMed](#)]
96. Lorenz, H.; Seidel-Morgenstern, A. Processes To Separate Enantiomers. *Angew. Chem. Int. Ed.* **2014**, *53*, 1218–1250. [[CrossRef](#)]
97. Shemchuk, O.; Grepioni, F.; Leyssens, T.; Braga, D. Chiral Resolution via Cocrystallization with Inorganic Salts. *Isr. J. Chem.* **2021**, *61*, 563–572. [[CrossRef](#)]
98. Viedma, C. Chiral Symmetry Breaking During Crystallization: Complete Chiral Purity Induced by Nonlinear Autocatalysis and Recycling. *Phys. Rev. Lett.* **2005**, *94*, 065504. [[CrossRef](#)]
99. Springuel, G.; Leyssens, T. Innovative Chiral Resolution Using Enantiospecific Co-Crystallization in Solution. *Cryst. Growth Des.* **2012**, *12*, 3374–3378. [[CrossRef](#)]
100. Amabilino, D.B. Chiral Organic Nanomaterials. In *Organic Nanomaterials*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2013; pp. 59–77.
101. Robinson, D.E.J.E.; Bull, S.D. Kinetic resolution strategies using non-enzymatic catalysts. *Tetrahedron Asymmetry* **2003**, *14*, 1407–1446. [[CrossRef](#)]
102. Brands, K.M.; Davies, A.J. Crystallization-induced diastereomer transformations. *Chem. Rev.* **2006**, *106*, 2711–2733. [[CrossRef](#)] [[PubMed](#)]
103. Mislow, K. Absolute asymmetric synthesis: A commentary. *Collect. Czechoslov. Chem. Commun.* **2003**, *68*, 849–864. [[CrossRef](#)]
104. Pérez-García, L.; Amabilino, D.B. Spontaneous resolution under supramolecular control. *Chem. Soc. Rev.* **2002**, *31*, 342–356. [[CrossRef](#)] [[PubMed](#)]
105. Pérez-García, L.; Amabilino, D.B. Spontaneous resolution, whence and whither: From enantiomeric solids to chiral liquid crystals, monolayers and macro-and supra-molecular polymers and assemblies. *Chem. Soc. Rev.* **2007**, *36*, 941–967. [[CrossRef](#)] [[PubMed](#)]
106. Tamura, R.; Iwama, S.; Takahashi, H. Chiral symmetry breaking phenomenon caused by a phase transition. *Symmetry* **2010**, *2*, 112–135. [[CrossRef](#)]
107. Coquerel, G. Review on the heterogeneous equilibria between condensed phases in binary systems of enantiomers. *Enantiomer* **2000**, *5*, 481–498.
108. Fogassy, E.; Nógrádi, M.; Kozma, D.; Egri, G.; Pálovics, E.; Kiss, V. Optical resolution methods. *Org. Biomol. Chem.* **2006**, *4*, 3011–3030. [[CrossRef](#)]
109. Viedma, C. Selective chiral symmetry breaking during crystallization: Parity violation or cryptochiral environment in control? *Cryst. Growth Des.* **2007**, *7*, 553–556. [[CrossRef](#)]
110. Viedma, C.; Ortiz, J.E.; Torres, T.d.; Izumi, T.; Blackmond, D.G. Evolution of solid phase homochirality for a proteinogenic amino acid. *J. Am. Chem. Soc.* **2008**, *130*, 15274–15275. [[CrossRef](#)]
111. Noorduyn, W.L.; Vlieg, E.; Kellogg, R.M.; Kaptein, B. From Ostwald ripening to single chirality. *Angew. Chem. Int. Ed.* **2009**, *48*, 9600–9606. [[CrossRef](#)]
112. Sogutoglu, L.-C.; Steendam, R.R.E.; Meekes, H.; Vlieg, E.; Rutjes, F.P.J.T. Viedma ripening: A reliable crystallisation method to reach single chirality. *Chem. Soc. Rev.* **2015**, *44*, 6723–6732. [[CrossRef](#)] [[PubMed](#)]

113. Kaptein, B.; Noorduin, W.L.; Meekes, H.; van Enkevort, W.J.; Kellogg, R.M.; Vlieg, E. Attrition-Enhanced Deracemization of an Amino Acid Derivative That Forms an Epitaxial Racemic Conglomerate. *Angew. Chem. Int. Ed.* **2008**, *47*, 7226–7229. [[CrossRef](#)] [[PubMed](#)]
114. Noorduin, W.L.; Meekes, H.; van Enkevort, W.J.; Millemaggi, A.; Leeman, M.; Kaptein, B.; Kellogg, R.M.; Vlieg, E. Complete Deracemization by Attrition-Enhanced Ostwald Ripening Elucidated. *Angew. Chem. Int. Ed.* **2008**, *47*, 6445–6447. [[CrossRef](#)]
115. Noorduin, W.L.; Izumi, T.; Millemaggi, A.; Leeman, M.; Meekes, H.; Van Enkevort, W.J.; Kellogg, R.M.; Kaptein, B.; Vlieg, E.; Blackmond, D.G. Emergence of a single solid chiral state from a nearly racemic amino acid derivative. *J. Am. Chem. Soc.* **2008**, *130*, 1158–1159. [[CrossRef](#)]
116. Noorduin, W.L.; Kaptein, B.; Meekes, H.; van Enkevort, W.J.; Kellogg, R.M.; Vlieg, E. Fast attrition-enhanced deracemization of naproxen by a gradual in situ feed. *Angew. Chem. Int. Ed.* **2009**, *48*, 4581–4583. [[CrossRef](#)]
117. Noorduin, W.L.; van der Asdonk, P.; Meekes, H.; van Enkevort, W.J.; Kaptein, B.; Leeman, M.; Kellogg, R.M.; Vlieg, E. Complete Chiral Resolution Using Additive-Induced Crystal Size Bifurcation During Grinding. *Angew. Chem. Int. Ed.* **2009**, *48*, 3278–3280. [[CrossRef](#)] [[PubMed](#)]
118. Tarasevych, A.V.; Sorochinsky, A.E.; Kukhar, V.P.; Toupet, L.; Crassous, J.; Guillemin, J.-C. Attrition-induced spontaneous chiral amplification of the  $\gamma$  polymorphic modification of glycine. *CrystEngComm* **2015**, *17*, 1513–1517. [[CrossRef](#)]
119. Steendam, R.R.; Harmsen, B.; Meekes, H.; Enkevort, W.J.v.; Kaptein, B.; Kellogg, R.M.; Raap, J.; Rutjes, F.P.; Vlieg, E. Controlling the effect of chiral impurities on Viedma ripening. *Cryst. Growth Des.* **2013**, *13*, 4776–4780. [[CrossRef](#)]
120. Noorduin, W.L.; van Enkevort, W.J.P.; Meekes, H.; Kaptein, B.; Kellogg, R.M.; Tully, J.C.; McBride, J.M.; Vlieg, E. The Driving Mechanism Behind Attrition-Enhanced Deracemization. *Angew. Chem.* **2010**, *122*, 8613–8616. [[CrossRef](#)]
121. Steendam, R.R.E.; Brouwer, M.C.T.; Huijs, E.M.E.; Kulka, M.W.; Meekes, H.; van Enkevort, W.J.P.; Raap, J.; Rutjes, F.P.J.T.; Vlieg, E. Enantiopure Isoindolinones through Viedma Ripening. *Chemistry* **2014**, *20*, 13527–13530. [[CrossRef](#)] [[PubMed](#)]
122. Steendam, R.R.E.; Kulka, M.W.; Meekes, H.; van Enkevort, W.J.P.; Raap, J.; Vlieg, E.; Rutjes, F.P.J.T. One-Pot Synthesis, Crystallization and Deracemization of Isoindolinones from Achiral Reactants. *Eur. J. Org. Chem.* **2015**, *2015*, 7249–7252. [[CrossRef](#)]
123. Viedma, C.; Cintas, P. Homochirality beyond grinding: Deracemizing chiral crystals by temperature gradient under boiling. *Chem. Commun.* **2011**, *47*, 12786–12788. [[CrossRef](#)]
124. Belletti, G.; Meekes, H.; Rutjes, F.P.J.T.; Vlieg, E. Role of Additives during Deracemization Using Temperature Cycling. *Cryst. Growth Des.* **2018**, *18*, 6617–6620. [[CrossRef](#)]
125. Engwerda, A.H.J.; van Schayik, P.; Jagtenberg, H.; Meekes, H.; Rutjes, F.P.J.T.; Vlieg, E. Deracemization of a Racemic Compound by Using Tailor-Made Additives. *Chemistry* **2018**, *24*, 2863–2867. [[CrossRef](#)]
126. Belletti, G.; Tortora, C.; Mellema, I.D.; Tinnemans, P.; Meekes, H.; Rutjes, F.P.J.T.; Tsogoeva, S.B.; Vlieg, E. Photoracemization-Based Viedma Ripening of a BINOL Derivative. *Chemistry* **2020**, *26*, 839–844. [[CrossRef](#)]
127. Engwerda, A.H.J.; Maassen, R.; Tinnemans, P.; Meekes, H.; Rutjes, F.P.J.T.; Vlieg, E. Attrition-Enhanced Deracemization of the Antimalaria Drug Mefloquine. *Angew. Chem. Int. Ed.* **2019**, *58*, 1670–1673. [[CrossRef](#)]
128. Engwerda, A.H.J.; Mertens, J.C.J.; Tinnemans, P.; Meekes, H.; Rutjes, F.; Vlieg, E. Solid-Phase Conversion of Four Stereoisomers into a Single Enantiomer. *Angew. Chem. (Int. Ed. Engl.)* **2018**, *57*, 15441–15444. [[CrossRef](#)]
129. Podlech, J.; Gehring, T. New Aspects of Soai's Asymmetric Autocatalysis. *Angew. Chem. Int. Ed.* **2005**, *44*, 5776–5777. [[CrossRef](#)] [[PubMed](#)]
130. Soai, K.; Kawasaki, T. Discovery of asymmetric autocatalysis with amplification of chirality and its implication in chiral homogeneity of biomolecules. *Chirality* **2006**, *18*, 469–478. [[CrossRef](#)]
131. Steendam, R.R.E.; Verkade, J.M.M.; van Benthem, T.J.B.; Meekes, H.; van Enkevort, W.J.P.; Raap, J.; Rutjes, F.P.J.T.; Vlieg, E. Emergence of single-molecular chirality from achiral reactants. *Nat. Commun.* **2014**, *5*, 5543. [[CrossRef](#)] [[PubMed](#)]
132. Kawasaki, T.; Nakaoda, M.; Takahashi, Y.; Kanto, Y.; Kuruhara, N.; Hosoi, K.; Sato, I.; Matsumoto, A.; Soai, K. Self-Replication and Amplification of Enantiomeric Excess of Chiral Multifunctionalized Large Molecules by Asymmetric Autocatalysis. *Angew. Chem. Int. Ed.* **2014**, *53*, 11199–11202. [[CrossRef](#)]
133. Barabás, B.; Zucchi, C.; Maioli, M.; Micskei, K.; Pályi, G. Stochastic and empirical models of the absolute asymmetric synthesis by the Soai-autocatalysis. *J. Mol. Modeling* **2015**, *21*, 1–13. [[CrossRef](#)] [[PubMed](#)]
134. Viedma, C.; Noorduin, W.L.; Ortiz, J.E.; de Torres, T.; Cintas, P. Asymmetric amplification in amino acid sublimation involving racemic compound to conglomerate conversion. *Chem. Commun.* **2011**, *47*, 671–673. [[CrossRef](#)] [[PubMed](#)]
135. Nikolova, L.; Todorov, T.; Ivanov, M.; Andruzzi, F.; Hvilsted, S.; Ramanujam, P.S. Photoinduced circular anisotropy in side-chain azobenzene polyesters. *Opt. Mater.* **1997**, *8*, 255–258. [[CrossRef](#)]
136. Li, J.; Schuster, G.B.; Cheon, K.-S.; Green, M.M.; Selinger, J.V. Switching a helical polymer between mirror images using circularly polarized light. *J. Am. Chem. Soc.* **2000**, *122*, 2603–2612. [[CrossRef](#)]
137. Iftime, G.; Labarthe, F.L.; Natansohn, A.; Rochon, P. Control of Chirality of an Azobenzene Liquid Crystalline Polymer with Circularly Polarized Light. *J. Am. Chem. Soc.* **2000**, *122*, 12646–12650. [[CrossRef](#)]
138. Noorduin, W.L.; Bode, A.A.; van der Meijden, M.; Meekes, H.; van Etteger, A.F.; van Enkevort, W.J.; Christianen, P.C.; Kaptein, B.; Kellogg, R.M.; Rasing, T. Complete chiral symmetry breaking of an amino acid derivative directed by circularly polarized light. *Nat. Chem.* **2009**, *1*, 729–732. [[CrossRef](#)]
139. Katayama, K.; Hirata, S.; Vacha, M. Circularly polarized luminescence from individual microstructures of conjugated polymer aggregates with solvent-induced chirality. *Phys. Chem. Chem. Phys.* **2014**, *16*, 17983–17987. [[CrossRef](#)]

140. Zinna, F.; Giovanella, U.; Bari, L.D. Highly Circularly Polarized Electroluminescence from a Chiral Europium Complex. *Adv. Mater.* **2015**, *27*, 1791–1795. [[CrossRef](#)]
141. Natansohn, A.; Rochon, P. Photoinduced Motions in Azobenzene-Based Amorphous Polymers: Possible Photonic Devices. *Adv. Mater.* **1999**, *11*, 1387–1391. [[CrossRef](#)]
142. Vera, F.; Serrano, J.L.; De Santo, M.P.; Barberi, R.; Ros, M.B.; Sierra, T. Insight into the supramolecular organization of columnar assemblies with phototunable chirality. *J. Mater. Chem.* **2012**, *22*, 18025–18032. [[CrossRef](#)]
143. Wang, Y.; Sakamoto, T.; Nakano, T. Molecular chirality induction to an achiral [small pi]-conjugated polymer by circularly polarized light. *Chem. Commun.* **2012**, *48*, 1871–1873. [[CrossRef](#)]
144. Mateos-Timoneda, M.A.; Crego-Calama, M.; Reinhoudt, D.N. Supramolecular chirality of self-assembled systems in solution. *Chem. Soc. Rev.* **2004**, *33*, 363–372. [[CrossRef](#)]
145. de Jong, J.J.; Lucas, L.N.; Kellogg, R.M.; van Esch, J.H.; Feringa, B.L. Reversible optical transcription of supramolecular chirality into molecular chirality. *Science* **2004**, *304*, 278–281. [[CrossRef](#)] [[PubMed](#)]
146. Cornelissen, J.J.; Fischer, M.; Sommerdijk, N.A.; Nolte, R.J. Helical superstructures from charged poly (styrene)-poly (isocyanodipeptide) block copolymers. *Science* **1998**, *280*, 1427–1430. [[CrossRef](#)] [[PubMed](#)]
147. Huang, S.; Yu, H.; Li, Q. Supramolecular Chirality Transfer toward Chiral Aggregation: Asymmetric Hierarchical Self-Assembly. *Adv. Sci. (Weinh)* **2021**, *8*, 2002132. [[CrossRef](#)]
148. Wilson, A.J.; Masuda, M.; Sijbesma, R.P.; Meijer, E. Chiral amplification in the transcription of supramolecular helicity into a polymer backbone. *Angew. Chem. Int. Ed.* **2005**, *44*, 2275–2279. [[CrossRef](#)]
149. Wilson, A.J.; van Gestel, J.; Sijbesma, R.P.; Meijer, E. Amplification of chirality in benzene tricarboxamide helical supramolecular polymers. *Chem. Commun.* **2006**, 4404–4406. [[CrossRef](#)]
150. van Gestel, J.; van der Schoot, P.; Michels, M. Growth and chirality amplification in helical supramolecular polymers. In *Molecular Gels*; Springer: Berlin/Heidelberg, Germany, 2006; pp. 79–97.
151. Fujiki, M. Supramolecular Chirality: Solvent Chirality Transfer in Molecular Chemistry and Polymer Chemistry. *Symmetry* **2014**, *6*, 677–703. [[CrossRef](#)]
152. Brunet, E.; de la Mata, M.J.; Juanes, O.; Alhendawi, H.M.; Cerro, C.; Rodríguez-Ubis, J.C. Solid-state reshaping of nanostructured crystals: Supramolecular chirality of layered materials derived from polyethylenoxa-pillared zirconium phosphate. *Tetrahedron Asymmetry* **2006**, *17*, 347–354. [[CrossRef](#)]
153. Alhendawi, H.M. Synthesis and structural characterization of a new chiral porous hybrid organic–inorganic material based on  $\gamma$ -zirconium phosphates and l-(+)-phosphoserine. *J. Solid State Chem.* **2013**, *201*, 24–28. [[CrossRef](#)]
154. Lascialfari, L.; Berti, D.; Brandi, A.; Cicchi, S.; Mannini, M.; Pescitelli, G.; Procacci, P. Chiral/ring closed vs. achiral/open chain triazine-based organogelators: Induction and amplification of supramolecular chirality in organic gels. *Soft Matter* **2014**, *10*, 3762–3770. [[CrossRef](#)]
155. Duan, P.; Cao, H.; Zhang, L.; Liu, M. Gelation induced supramolecular chirality: Chirality transfer, amplification and application. *Soft Matter* **2014**, *10*, 5428–5448. [[CrossRef](#)] [[PubMed](#)]
156. Green, M.M.; Reidy, M.P.; Johnson, R.D.; Darling, G.; O’Leary, D.J.; Willson, G. Macromolecular stereochemistry: The out-of-proportion influence of optically active comonomers on the conformational characteristics of polyisocyanates. The sergeants and soldiers experiment. *J. Am. Chem. Soc.* **1989**, *111*, 6452–6454. [[CrossRef](#)]
157. Green, M.M.; Peterson, N.C.; Sato, T.; Teramoto, A.; Cook, R.; Lifson, S. A Helical Polymer with a Cooperative Response to Chiral Information. *Science* **1995**, *268*, 1860–1866. [[CrossRef](#)] [[PubMed](#)]
158. van Gestel, J. Amplification of chirality in helical supramolecular polymers: The majority-rules principle. *Macromolecules* **2004**, *37*, 3894–3898. [[CrossRef](#)]
159. Carlini, C.; Ciardelli, F.; Pino, P. Optical activity and conformation in solution of stereoregular copolymers of(S)-4-methyl-1-hexene with 4-methyl- 1-pentene. *Makromol. Chem.* **1968**, *119*, 244. [[CrossRef](#)]
160. Palmans, A.R.A.; Vekemans, J.A.J.M.; Havinga, E.E.; Meijer, E.W. Sergeants-and-Soldiers Principle in Chiral Columnar Stacks of Disc-Shaped Molecules with C3 Symmetry. *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2648–2651. [[CrossRef](#)]
161. Brunsveld, L.; Lohmeijer, B.G.G.; Vekemans, J.A.J.M.; Meijer, E.W. Chirality amplification in dynamic helical columns in water. *Chem. Commun.* **2000**, 2000, 2305–2306. [[CrossRef](#)]
162. Prince, R.B.; Moore, J.S.; Brunsveld, L.; Meijer, E.W. Cooperativity in the Folding of Helical m-Phenylene Ethynylene Oligomers Based upon the ‘Sergeants-and-Soldiers’ Principle. *Chemistry* **2001**, *7*, 4150–4154. [[CrossRef](#)]
163. Fernández, Z.; Fernández, B.; Quiñoá, E.; Freire, F. Merging Supramolecular and Covalent Helical Polymers: Four Helices Within a Single Scaffold. *J. Am. Chem. Soc.* **2021**, *143*, 20962–20969. [[CrossRef](#)]
164. George, S.J.; Tomović, Ž.; Smulders, M.M.J.; de Greef, T.F.A.; Leclère, P.E.L.G.; Meijer, E.W.; Schenning, A.P.H.J. Helicity Induction and Amplification in an Oligo(p-phenylenevinylene) Assembly through Hydrogen-Bonded Chiral Acids. *Angew. Chem. Int. Ed.* **2007**, *46*, 8206–8211. [[CrossRef](#)]
165. Smulders, M.M.J.; Schenning, A.P.H.J.; Meijer, E.W. Insight into the Mechanisms of Cooperative Self-Assembly: The “Sergeants-and-Soldiers” Principle of Chiral and Achiral C3-Symmetrical Discotic Triamides. *J. Am. Chem. Soc.* **2008**, *130*, 606–611. [[CrossRef](#)]
166. De Greef, T.F.A.; Smulders, M.M.J.; Wolffs, M.; Schenning, A.P.H.J.; Sijbesma, R.P.; Meijer, E.W. Supramolecular Polymerization. *Chem. Rev.* **2009**, *109*, 5687–5754. [[CrossRef](#)] [[PubMed](#)]

167. Smulders, M.M.J.; Nieuwenhuizen, M.M.L.; de Greef, T.F.A.; van der Schoot, P.; Schenning, A.P.H.J.; Meijer, E.W. How to Distinguish Isodesmic from Cooperative Supramolecular Polymerisation. *Chemistry* **2010**, *16*, 362–367. [[CrossRef](#)] [[PubMed](#)]
168. Nelson, J.C.; Saven, J.G.; Moore, J.S.; Wolynes, P.G. Solvophobic driven folding of nonbiological oligomers. *Science* **1997**, *277*, 1793–1796. [[CrossRef](#)]
169. Prince, R.B.; Okada, T.; Moore, J.S. Controlling the secondary structure of nonbiological oligomers with solvophobic and coordination interactions. *Angew. Chem. Int. Ed.* **1999**, *38*, 233–236. [[CrossRef](#)]
170. Bushey, M.L.; Hwang, A.; Stephens, P.W.; Nuckolls, C. The Consequences of Chirality in Crowded Arenes—Macromolecular Helicity, Hierarchical Ordering, and Directed Assembly. *Angew. Chem. Int. Ed.* **2002**, *41*, 2828–2831. [[CrossRef](#)]
171. Nam, S.R.; Lee, H.Y.; Hong, J.-I. Control of Macroscopic Helicity by Using the Sergeants-and-Soldiers Principle in Organogels. *Chemistry* **2008**, *14*, 6040–6043. [[CrossRef](#)] [[PubMed](#)]
172. Monti, D.; De Rossi, M.; Sorrenti, A.; Laguzzi, G.; Gatto, E.; Stefanelli, M.; Venanzi, M.; Luvidi, L.; Mancini, G.; Paolesse, R. Supramolecular Chirality in Solvent-Promoted Aggregation of Amphiphilic Porphyrin Derivatives: Kinetic Studies and Comparison between Solution Behavior and Solid-State Morphology by AFM Topography. *Chemistry* **2010**, *16*, 860–870. [[CrossRef](#)]
173. Anderson, T.W.; Sanders, J.K.M.; Pantos, G.D. The sergeants-and-soldiers effect: Chiral amplification in naphthalenediimide nanotubes. *Org. Biomol. Chem.* **2010**, *8*, 4274–4280. [[CrossRef](#)]
174. Maeda, K.; Wakasone, S.; Shimomura, K.; Ikai, T.; Kanoh, S. Chiral Amplification in Polymer Brushes Consisting of Dynamic Helical Polymer Chains through the Long-Range Communication of Stereochemical Information. *Macromolecules* **2014**, *47*, 6540–6546. [[CrossRef](#)]
175. Hosono, N.; Palmans, A.R.; Meijer, E. “Soldier–Sergeant–Soldier” triblock copolymers: Revealing the folded structure of single-chain polymeric nanoparticles. *Chem. Commun.* **2014**, *50*, 7990–7993. [[CrossRef](#)] [[PubMed](#)]
176. Prins, L.J.; Neuteboom, E.E.; Paraschiv, V.; Crego-Calama, M.; Timmerman, P.; Reinhoudt, D.N. Kinetic stabilities of double, tetra-, and hexarosette hydrogen-bonded assemblies. *J. Org. Chem.* **2002**, *67*, 4808–4820. [[CrossRef](#)] [[PubMed](#)]
177. García, F.; Viruela, P.M.; Matesanz, E.; Ortí, E.; Sánchez, L. Cooperative Supramolecular Polymerization and Amplification of Chirality in C<sub>3</sub>-Symmetrical OPE-Based Trisamides. *Chemistry* **2011**, *17*, 7755–7759. [[CrossRef](#)]
178. Helmich, F.; Smulders, M.M.; Lee, C.C.; Schenning, A.P.; Meijer, E. Effect of stereogenic centers on the self-sorting, depolymerization, and atropisomerization kinetics of porphyrin-based aggregates. *J. Am. Chem. Soc.* **2011**, *133*, 12238–12246. [[CrossRef](#)]
179. Veling, N.; van Hameren, R.; van Buul, A.M.; Rowan, A.E.; Nolte, R.J.; Elemans, J.A. Solvent-dependent amplification of chirality in assemblies of porphyrin trimers based on benzene tricarboxamide. *Chem. Commun.* **2012**, *48*, 4371–4373. [[CrossRef](#)]
180. Bergueiro, J.; Freire, F.; Wendler, E.P.; Seco, J.M.; Quiñoá, E.; Riguera, R. the ON/OFF switching by metal ions of the “Sergeants and Soldiers” chiral amplification effect on helical poly(phenylacetylene)s. *Chem. Sci.* **2014**, *5*, 2170–2176. [[CrossRef](#)]
181. von Berlepsch, H.; Kirstein, S.; Böttcher, C. Controlling the helicity of tubular J-aggregates by chiral alcohols. *J. Phys. Chem. B* **2003**, *107*, 9646–9654. [[CrossRef](#)]
182. Xiao, J.; Xu, J.; Cui, S.; Liu, H.; Wang, S.; Li, Y. Supramolecular helix of an amphiphilic pyrene derivative induced by chiral tryptophan through electrostatic interactions. *Org. Lett.* **2008**, *10*, 645–648. [[CrossRef](#)]
183. Zeng, L.; He, Y.; Dai, Z.; Wang, J.; Cao, Q.; Zhang, Y. Chiral Induction, Memory, and Amplification in Porphyrin Homoaggregates Based on Electrostatic Interactions. *ChemPhysChem* **2009**, *10*, 954–962. [[CrossRef](#)] [[PubMed](#)]
184. Haketa, Y.; Bando, Y.; Takaishi, K.; Uchiyama, M.; Muranaka, A.; Naito, M.; Shibaguchi, H.; Kawai, T.; Maeda, H. Asymmetric Induction in the Preparation of Helical Receptor-Anion Complexes: Ion-Pair Formation with Chiral Cations. *Angew. Chem.* **2012**, *124*, 8091–8095. [[CrossRef](#)]
185. George, S.J.; de Bruijn, R.; Tomović, Z.E.; Van Averbeke, B.; Beljonne, D.; Lazzaroni, R.; Schenning, A.P.H.J.; Meijer, E. Asymmetric noncovalent synthesis of self-assembled one-dimensional stacks by a chiral supramolecular auxiliary approach. *J. Am. Chem. Soc.* **2012**, *134*, 17789–17796. [[CrossRef](#)]
186. De Cat, I.; Guo, Z.; George, S.J.; Meijer, E.; Schenning, A.P.; De Feyter, S. Induction of chirality in an achiral monolayer at the liquid/solid interface by a supramolecular chiral auxiliary. *J. Am. Chem. Soc.* **2012**, *134*, 3171–3177. [[CrossRef](#)]
187. Ernst, K.-H. Amplification of Chirality at Solid Surfaces. *Orig. Life Evol. Biosph.* **2010**, *40*, 41–50. [[CrossRef](#)]
188. Nuermair, A.; Bombis, C.; Knudsen, M.M.; Cramer, J.R.; Lægsgaard, E.; Besenbacher, F.; Gothelf, K.V.; Linderoth, T.R. Chiral Induction with Chiral Conformational Switches in the Limit of Low “Sergeants to Soldiers” Ratio. *ACS Nano* **2014**, *8*, 8074–8081. [[CrossRef](#)]
189. Dressel, C.; Reppe, T.; Prehm, M.; Brautzsch, M.; Tschierske, C. Chiral self-sorting and amplification in isotropic liquids of achiral molecules. *Nat. Chem.* **2014**, *6*, 971–977. [[CrossRef](#)]
190. Xu, H.; Ghijssens, E.; George, S.J.; Wolffs, M.; Tomović, Ž.; Schenning, A.P.; De Feyter, S. Chiral induction and amplification in supramolecular systems at the liquid–solid interface. *ChemPhysChem* **2013**, *14*, 1583–1590. [[CrossRef](#)] [[PubMed](#)]
191. van Dijken, D.J.; Beierle, J.M.; Stuart, M.C.; Szymański, W.; Browne, W.R.; Feringa, B.L. Autoamplification of Molecular Chirality through the Induction of Supramolecular Chirality. *Angew. Chem. Int. Ed.* **2014**, *53*, 5073–5077. [[CrossRef](#)]
192. Smulders, M.M.J.; Stals, P.J.M.; Mes, T.; Paffen, T.F.E.; Schenning, A.P.H.J.; Palmans, A.R.A.; Meijer, E.W. Probing the Limits of the Majority-Rules Principle in a Dynamic Supramolecular Polymer. *J. Am. Chem. Soc.* **2010**, *132*, 620–626. [[CrossRef](#)] [[PubMed](#)]
193. Chen, T.; Yang, W.-H.; Wang, D.; Wan, L.-J. Globally homochiral assembly of two-dimensional molecular networks triggered by co-absorbers. *Nat. Commun.* **2013**, *4*, 1389. [[CrossRef](#)] [[PubMed](#)]

194. Jin, W.; Fukushima, T.; Niki, M.; Kosaka, A.; Ishii, N.; Aida, T. Self-assembled graphitic nanotubes with one-handed helical arrays of a chiral amphiphilic molecular graphene. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 10801–10806. [[CrossRef](#)]
195. van Gestel, J. Amplification of chirality of the majority-rules type in helical supramolecular polymers: The impact of the presence of achiral monomers. *J. Phys. Chem. B* **2006**, *110*, 4365–4370. [[CrossRef](#)] [[PubMed](#)]
196. Lohr, A.; Würthner, F. Evolution of Homochiral Helical Dye Assemblies: Involvement of Autocatalysis in the “Majority-Rules” Effect. *Angew. Chem.* **2008**, *120*, 1252–1256. [[CrossRef](#)]
197. Stals, P.J.; Artar, M.; Vendrig, P.; Palmans, A.R.; Meijer, E. Consequences of Subtle Chiral Effects: From ‘Majority-Rules’ to ‘Minority-Rules’. *Aust. J. Chem.* **2014**, *68*, 622–626. [[CrossRef](#)]
198. Nie, B.; Zhan, T.-G.; Zhou, T.-Y.; Xiao, Z.-Y.; Jiang, G.-F.; Zhao, X. Self-Assembly of Chiral Propeller-like Supermolecules with Unusual “Sergeants-and-Soldiers” and “Majority-Rules” Effects. *Chemistry* **2014**, *9*, 754–758. [[CrossRef](#)]
199. Micali, N.; Engelkamp, H.; van Rhee, P.; Christianen, P.; Scolaro, L.M.; Maan, J. Selection of supramolecular chirality by application of rotational and magnetic forces. *Nat. Chem.* **2012**, *4*, 201–207. [[CrossRef](#)]
200. Johnson, R.S.; Yamazaki, T.; Kovalenko, A.; Fenniri, H. Molecular Basis for Water-Promoted Supramolecular Chirality Inversion in Helical Rosette Nanotubes. *J. Am. Chem. Soc.* **2007**, *129*, 5735–5743. [[CrossRef](#)]
201. Xie, J.; Qiu, H.; Che, S. Handedness inversion of chiral amphiphilic molecular assemblies evidenced by supramolecular chiral imprinting in mesoporous silica assemblies. *Chemistry* **2012**, *18*, 2559–2564. [[CrossRef](#)]
202. Usov, I.; Adamcik, J.; Mezzenga, R. Polymorphism Complexity and Handedness Inversion in Serum Albumin Amyloid Fibrils. *ACS Nano* **2013**, *7*, 10465–10474. [[CrossRef](#)] [[PubMed](#)]
203. Fujiki, M. Helix Magic. Thermo-Driven Chiroptical Switching and Screw-Sense Inversion of Flexible Rod Helical Polysilylenes. *J. Am. Chem. Soc.* **2000**, *122*, 3336. [[CrossRef](#)]
204. Ajayaghosh, A.; Varghese, R.; Mahesh, S.; Praveen, V.K. From Vesicles to Helical Nanotubes: A Sergeant-and-Soldiers Effect in the Self-Assembly of Oligo(p-phenyleneethynylene)s. *Angew. Chem. Int. Ed.* **2006**, *45*, 7729. [[CrossRef](#)] [[PubMed](#)]
205. Kumar, J.; Nakashima, T.; Kawai, T. Inversion of Supramolecular Chirality in Bichromophoric Perylene Bisimides: Influence of Temperature and Ultrasound. *Langmuir* **2014**, *30*, 6030–6037. [[CrossRef](#)] [[PubMed](#)]
206. Aida, T.; Meijer, E.; Stupp, S. Functional supramolecular polymers. *Science* **2012**, *335*, 813–817. [[CrossRef](#)] [[PubMed](#)]
207. Gillissen, M.A.; Koenigs, M.M.; Spiering, J.J.; Vekemans, J.A.; Palmans, A.R.; Voets, I.K.; Meijer, E. Triple helix formation in amphiphilic discotics: Demystifying solvent effects in supramolecular self-assembly. *J. Am. Chem. Soc.* **2013**, *136*, 336–343. [[CrossRef](#)]
208. Cordier, P.; Tournilhac, F.; Soulie-Ziakovic, C.; Leibler, L. Self-healing and thermoreversible rubber from supramolecular assembly. *Nature* **2008**, *451*, 977–980. [[CrossRef](#)]
209. van Gemert, G.M.L.; Peeters, J.W.; Söntjens, S.H.M.; Janssen, H.M.; Bosman, A.W. Self-Healing Supramolecular Polymers In Action. *Macromol. Chem. Phys.* **2012**, *213*, 234–242. [[CrossRef](#)]
210. Capito, R.M.; Azevedo, H.S.; Velichko, Y.S.; Mata, A.; Stupp, S.I. Self-assembly of large and small molecules into hierarchically ordered sacs and membranes. *Science* **2008**, *319*, 1812–1816. [[CrossRef](#)]
211. Dankers, P.Y.W.; Hermans, T.M.; Baughman, T.W.; Kamikawa, Y.; Kieltyka, R.E.; Bastings, M.M.C.; Janssen, H.M.; Sommerdijk, N.A.J.M.; Larsen, A.; van Luyn, M.J.A.; et al. Hierarchical Formation of Supramolecular Transient Networks in Water: A Modular Injectable Delivery System. *Adv. Mater.* **2012**, *24*, 2703–2709. [[CrossRef](#)]
212. Baker, M.B.; Albertazzi, L.; Voets, I.K.; Leenders, C.M.; Palmans, A.R.; Pavan, G.M.; Meijer, E. Consequences of chirality on the dynamics of a water-soluble supramolecular polymer. *Nat. Commun.* **2015**, *6*, 6234. [[CrossRef](#)]
213. Ruiz, U.; Pagliusi, P.; Provenzano, C.; Shibaev, V.P.; Cipparrone, G. Supramolecular Chiral Structures: Smart Polymer Organization Guided by 2D Polarization Light Patterns. *Adv. Funct. Mater.* **2012**, *22*, 2964–2970. [[CrossRef](#)]
214. Plum, E.; Fedotov, V.A.; Schwanecke, A.S.; Zheludev, N.I.; Chen, Y. Giant optical gyrotropy due to electromagnetic coupling. *Appl. Phys. Lett.* **2007**, *90*, 223113. [[CrossRef](#)]
215. Decker, M.; Ruther, M.; Kriegler, C.E.; Zhou, J.; Soukoulis, C.M.; Linden, S.; Wegener, M. Strong optical activity from twisted-cross photonic metamaterials. *Opt. Lett.* **2009**, *34*, 2501–2503. [[CrossRef](#)]
216. Decker, M.; Klein, M.W.; Wegener, M.; Linden, S. Circular dichroism of planar chiral magnetic metamaterials. *Opt. Lett.* **2007**, *32*, 856–858. [[CrossRef](#)] [[PubMed](#)]
217. Shelby, R.A.; Smith, D.R.; Schultz, S. Experimental Verification of a Negative Index of Refraction. *Science* **2001**, *292*, 77–79. [[CrossRef](#)] [[PubMed](#)]
218. Li, B.; Sui, G.; Zhong, W.-H. Single Negative Metamaterials in Unstructured Polymer Nanocomposites Toward Selectable and Controllable Negative Permittivity. *Adv. Mater.* **2009**, *21*, 4176–4180. [[CrossRef](#)]
219. Plum, E.; Zhou, J.; Dong, J.; Fedotov, V.A.; Koschny, T.; Soukoulis, C.M.; Zheludev, N.I. Metamaterial with negative index due to chirality. *Phys. Rev. B* **2009**, *79*, 035407. [[CrossRef](#)]
220. Zheludev, N.I. The Road Ahead for Metamaterials. *Science* **2010**, *328*, 582–583. [[CrossRef](#)]
221. Schenning, A.P.H.J.; Meijer, E.W. Supramolecular electronics; nanowires from self-assembled [small pi]-conjugated systems. *Chem. Commun.* **2005**, 3245–3258. [[CrossRef](#)]
222. Palmer, L.C.; Stupp, S.I. Molecular Self-Assembly into One-Dimensional Nanostructures. *Acc. Chem. Res.* **2008**, *41*, 1674–1687. [[CrossRef](#)]



223. Holtz, J.H.; Asher, S.A. Polymerized colloidal crystal hydrogel films as intelligent chemical sensing materials. *Nature* **1997**, *389*, 829–832. [[CrossRef](#)]
224. Vogelaar, L.; Nijdam, W.; van Wolferen, H.A.G.M.; de Ridder, R.M.; Segerink, F.B.; Flück, E.; Kuipers, L.; van Hulst, N.F. Large Area Photonic Crystal Slabs for Visible Light with Waveguiding Defect Structures: Fabrication with Focused Ion Beam Assisted Laser Interference Lithography. *Adv. Mater.* **2001**, *13*, 1551–1554. [[CrossRef](#)]
225. Kang, J.-W.; Kim, M.-J.; Kim, J.-P.; Yoo, S.-J.; Lee, J.-S.; Kim, D.Y.; Kim, J.-J. Polymeric wavelength filters fabricated using holographic surface relief gratings on azobenzene-containing polymer films. *Appl. Phys. Lett.* **2003**, *82*, 3823–3825. [[CrossRef](#)]
226. Lee, Y.J.; Braun, P.V. Tunable Inverse Opal Hydrogel pH Sensors. *Adv. Mater.* **2003**, *15*, 563–566. [[CrossRef](#)]
227. Huang, J.; Hu, X.; Zhang, W.; Zhang, Y.; Li, G. pH and ionic strength responsive photonic polymers fabricated by using colloidal crystal templating. *Colloid Polym. Sci.* **2008**, *286*, 113–118. [[CrossRef](#)]
228. Hung, Y.-J.; Lee, S.-L.; Pan, Y.-T.; Thibeault, B.J.; Coldren, L.A. Holographic realization of hexagonal two dimensional photonic crystal structures with elliptical geometry. *J. Vac. Sci. Technol. B* **2010**, *28*, 1030–1038. [[CrossRef](#)]
229. Chen, T.; Li, S.Y.; Wang, D.; Yao, M.; Wan, L.J. Remote Chiral Communication in Coadsorber-Induced Enantioselective 2D Supramolecular Assembly at a Liquid/Solid Interface. *Angew. Chem. Int. Ed.* **2015**, *54*, 4309–4314. [[CrossRef](#)] [[PubMed](#)]
230. Shinkai, S.; Roy, B.; Noguchi, T.; Tsuchiya, Y.; Yoshihara, D.; Yamamoto, T. Molecular Recognition Directed Supramolecular Control over Perylene-bisimide Aggregation Resulting in Aggregation Induced Enhanced Emission (AIEE) and Induced Chiral Amplification. *J. Mater. Chem. C* **2015**, *3*, 2310–2318.
231. List, B.; Yang, J.W. The Organic Approach to Asymmetric Catalysis. *Science* **2006**, *313*, 1584–1586. [[CrossRef](#)]
232. Hatano, M. Design of Tailor-Made Conformationally Flexible Chiral Supramolecular Catalysts Beyond Enzymes. *J. Synth. Org. Chem. Jpn.* **2012**, *70*, 1242–1254. [[CrossRef](#)]
233. Yang, W.; Jiang, K.Z.; Lu, X.; Yang, H.M.; Li, L.; Lu, Y.X.; Xu, L.W. Molecular Assembly of an Achiral Phosphine and a Chiral Primary Amine: A Highly Efficient Supramolecular Catalyst for the Enantioselective Michael Reaction of Aldehydes with Maleimides. *Chem.-Asian J.* **2013**, *8*, 1182–1190. [[CrossRef](#)] [[PubMed](#)]
234. Monaco, M.R.; Poladura, B.; Diaz de Los Bernardos, M.; Leutzsch, M.; Goddard, R.; List, B. Activation of Carboxylic Acids in Asymmetric Organocatalysis. *Angew. Chem. Int. Ed.* **2014**, *53*, 7063–7067. [[CrossRef](#)]
235. Jin, Q.; Zhang, L.; Cao, H.; Wang, T.; Zhu, X.; Jiang, J.; Liu, M. Self-Assembly of Copper(II) Ion-Mediated Nanotube and Its Supramolecular Chiral Catalytic Behavior. *Langmuir* **2011**, *27*, 13847–13853. [[CrossRef](#)]
236. Ouyang, G.-H.; He, Y.-M.; Fan, Q.-H. Podand-Based Dimeric Chromium(III)–Salen Complex for Asymmetric Henry Reaction: Cooperative Catalysis Promoted by Complexation of Alkali Metal Ions. *Chemistry* **2014**, *20*, 16454–16457. [[CrossRef](#)] [[PubMed](#)]
237. García-Simón, C.; Gramage-Doria, R.; Raoufmoğhaddam, S.; Parella, T.; Costas, M.; Ribas, X.; Reek, J.N.H. Enantioselective Hydroformylation by a Rh-Catalyst Entrapped in a Supramolecular Metallo cage. *J. Am. Chem. Soc.* **2015**, *137*, 2680–2687. [[CrossRef](#)] [[PubMed](#)]
238. Tsunoda, Y.; Fukuta, K.; Imamura, T.; Sekiya, R.; Furuyama, T.; Kobayashi, N.; Haino, T. High Diastereoselection of a Dissymmetric Capsule by Chiral Guest Complexation. *Angew. Chem. Int. Ed.* **2014**, *53*, 7243–7247. [[CrossRef](#)]
239. Okamoto, Y.; Hatada, K. Resolution of enantiomers by HPLC optically active poly(triphenylmethyl methacrylate). *J. Liq. Chromatogr.* **1986**, *9*, 369–384. [[CrossRef](#)]
240. Okamoto, Y.; Nakano, T. Asymmetric polymerization. *Chem. Rev.* **1994**, *94*, 349–372. [[CrossRef](#)]
241. Yashima, E.; Maeda, K.; Iida, H.; Furusho, Y.; Nagai, K. Helical Polymers: Synthesis, Structures and Functions. *Chem. Rev.* **2009**, *109*, 6102–6211. [[CrossRef](#)]
242. Okamoto, Y. Chiral Polymers for Resolution of Enantiomers. *J. Polym. Sci. Part A* **2009**, *47*, 1731–1739. [[CrossRef](#)]
243. Okamoto, Y.; Mohri, H.; Nakano, T.; Hatada, K. Stereomutation of optically active poly(diphenyl-2-pyridylmethyl methacrylate). *J. Am. Chem. Soc.* **1989**, *111*, 5952–5954. [[CrossRef](#)]
244. Yashima, E.; Maeda, K.; Okamoto, Y. Memory of macromolecular helicity assisted by interaction with achiral small molecules. *Nature* **1999**, *399*, 449–451. [[CrossRef](#)]
245. Yamamoto, T.; Yamada, T.; Nagata, Y.; Suginome, M. High-Molecular-Weight Polyquinoxaline-Based Helically Chiral Phosphine (PQXphos) as Chirality-Switchable, Reusable, and Highly Enantioselective Monodentate Ligand in Catalytic Asymmetric Hydrosilylation of Styrenes. *J. Am. Chem. Soc.* **2010**, *132*, 7899–7901. [[CrossRef](#)] [[PubMed](#)]
246. Sakamoto, T.; Fukuda, Y.; Sato, S.-i.; Nakano, T. Photoinduced Racemization of an Optically Active Helical Polymer Formed by the Asymmetric Polymerization of 2,7-Bis(4-tert-butylphenyl)fluoren-9-yl Acrylate. *Angew. Chem. Int. Ed.* **2009**, *48*, 9308–9311. [[CrossRef](#)]
247. Fujiki, M.; Yoshida, K.; Suzuki, N.; Zhang, J.; Zhang, W.; Zhu, X. Mirror symmetry breaking and restoration within  $\mu\text{m}$ -sized polymer particles in optofluidic media by pumping circularly polarised light. *RSC Adv.* **2013**, *3*, 5213–5219. [[CrossRef](#)]
248. Nakano, T. Tricks of Light on Helices: Transformation of Helical Polymers by Photoirradiation. *Chem. Rec.* **2014**, *14*, 369–385. [[CrossRef](#)]
249. Hill, D.J.; Mio, M.J.; Prince, R.B.; Hughes, T.S.; Moore, J.S. A Field Guide to Foldamers. *Chem. Rev.* **2001**, *101*, 3893–4012. [[CrossRef](#)]
250. Haldar, D.; Schmuck, C. Metal-free double helices from abiotic backbones. *Chem. Soc. Rev.* **2009**, *38*, 363–371. [[CrossRef](#)]
251. Pigué, C.; Bernardinelli, G.; Hopfgartner, G. Helicates as Versatile Supramolecular Complexes. *Chem. Rev.* **1997**, *97*, 2005–2062. [[CrossRef](#)]

252. Korevaar, P.A.; Grenier, C.; Meijer, E. Toward model-driven engineering of supramolecular copolymers. *J. Polym. Sci. Part A Polym. Chem.* **2015**, *53*, 385–391. [[CrossRef](#)]
253. Nielsen, P.E. Peptide nucleic acid. A molecule with two identities. *Acc. Chem. Res.* **1999**, *32*, 624–630. [[CrossRef](#)]
254. Zhang, D.-W.; Zhao, X.; Hou, J.-L.; Li, Z.-T. Aromatic Amide Foldamers: Structures, Properties, and Functions. *Chem. Rev.* **2012**, *112*, 5271–5316. [[CrossRef](#)] [[PubMed](#)]
255. Goto, H.; Furusho, Y.; Miwa, K.; Yashima, E. Double Helix Formation of Oligoresorcinols in Water: Thermodynamic and Kinetic Aspects. *J. Am. Chem. Soc.* **2009**, *131*, 4710–4719. [[CrossRef](#)] [[PubMed](#)]
256. Tanaka, Y.; Katagiri, H.; Furusho, Y.; Yashima, E. A Modular Strategy to Artificial Double Helices. *Angew. Chem. Int. Ed.* **2005**, *44*, 3867–3870. [[CrossRef](#)]
257. Hasegawa, T.; Furusho, Y.; Katagiri, H.; Yashima, E. Enantioselective Synthesis of Complementary Double-Helical Molecules that Catalyze Asymmetric Reactions. *Angew. Chem. Int. Ed.* **2007**, *46*, 5885–5888. [[CrossRef](#)] [[PubMed](#)]
258. Ito, H.; Furusho, Y.; Hasegawa, T.; Yashima, E. Sequence- and Chain-Length-Specific Complementary Double-Helix Formation. *J. Am. Chem. Soc.* **2008**, *130*, 14008–14015. [[CrossRef](#)]
259. Ito, H.; Ikeda, M.; Hasegawa, T.; Furusho, Y.; Yashima, E. Synthesis of Complementary Double-Stranded Helical Oligomers through Chiral and Achiral Amidinium–Carboxylate Salt Bridges and Chiral Amplification in Their Double-Helix Formation. *J. Am. Chem. Soc.* **2011**, *133*, 3419–3432. [[CrossRef](#)]
260. Yamada, H.; Wu, Z.-Q.; Furusho, Y.; Yashima, E. Thermodynamic and Kinetic Stabilities of Complementary Double Helices Utilizing Amidinium–Carboxylate Salt Bridges. *J. Am. Chem. Soc.* **2012**, *134*, 9506–9520. [[CrossRef](#)]
261. Makiguchi, W.; Kobayashi, S.; Furukawa, K.; Iida, H.; Furusho, Y.; Yashima, E. Homo-double helix formation of an optically active conjugated polymer bearing carboxy groups and amplification of the helicity upon complexation with achiral and chiral amines. *J. Polym. Sci. Part A Polym. Chem.* **2015**, *53*, 990–999. [[CrossRef](#)]
262. Lee, C.C.; MacKay, J.A.; Frechet, J.M.J.; Szoka, F.C. Designing dendrimers for biological applications. *Nat. Biotech.* **2005**, *23*, 1517–1526. [[CrossRef](#)]
263. Rosen, B.M.; Wilson, C.J.; Wilson, D.A.; Peterca, M.; Imam, M.R.; Percec, V. Dendron-Mediated Self-Assembly, Disassembly, and Self-Organization of Complex Systems. *Chem. Rev.* **2009**, *109*, 6275–6540. [[CrossRef](#)]
264. Percec, V.; Barboiu, B.; Grigoras, C.; Bera, T.K. Universal Iterative Strategy for the Divergent Synthesis of Dendritic Macromolecules from Conventional Monomers by a Combination of Living Radical Polymerization and Irreversible TERminator Multifunctional Initiator (TERMINI). *J. Am. Chem. Soc.* **2003**, *125*, 6503–6516. [[CrossRef](#)] [[PubMed](#)]
265. Elemans, J.A.A.W.; Rowan, A.E.; Nolte, R.J.M. Mastering molecular matter. Supramolecular architectures by hierarchical self-assembly. *J. Mater. Chem.* **2003**, *13*, 2661–2670. [[CrossRef](#)]
266. Astruc, D.; Boisselier, E.; Ornelas, C. Dendrimers Designed for Functions: From Physical, Photophysical, and Supramolecular Properties to Applications in Sensing, Catalysis, Molecular Electronics, Photonics, and Nanomedicine. *Chem. Rev.* **2010**, *110*, 1857–1959. [[CrossRef](#)] [[PubMed](#)]
267. Lehn, J.M. Perspectives in supramolecular chemistry—From molecular recognition towards molecular information-processing and self-organization. *Angew. Chem.-Int. Edit. Engl.* **1990**, *29*, 1304–1319. [[CrossRef](#)]
268. Percec, V.; Won, B.C.; Peterca, M.; Heiney, P.A. Expanding the Structural Diversity of Self-Assembling Dendrons and Supramolecular Dendrimers via Complex Building Blocks. *J. Am. Chem. Soc.* **2007**, *129*, 11265–11278. [[CrossRef](#)]
269. Yang, W.-Y.; Lee, E.; Lee, M. Tubular Organization with Coiled Ribbon from Amphiphilic Rigid–Flexible Macrocycle. *J. Am. Chem. Soc.* **2006**, *128*, 3484–3485. [[CrossRef](#)]
270. Percec, V.; Rudick, J.G.; Peterca, M.; Heiney, P.A. Nanomechanical Function from Self-Organizable Dendronized Helical Polyphenylacetylenes. *J. Am. Chem. Soc.* **2008**, *130*, 7503–7508. [[CrossRef](#)]
271. Shibaev, V.; Bobrovsky, A.; Boiko, N. Photoactive liquid crystalline polymer systems with light-controllable structure and optical properties. *Prog. Polym. Sci.* **2003**, *28*, 729. [[CrossRef](#)]
272. Brettar, J.; Bürgi, T.; Donnio, B.; Guillon, D.; Klappert, R.; Scharf, T.; Deschenaux, R. Ferrocene-Containing Optically Active Liquid-Crystalline Side-Chain Polysiloxanes with Planar Chirality. *Adv. Funct. Mater.* **2006**, *16*, 260–267. [[CrossRef](#)]
273. Campidelli, S.; Brandmuller, T.; Hirsch, A.; Saez, I.M.; Goodby, J.W.; Deschenaux, R. An optically-active liquid-crystalline hexa-adduct of [60] fullerene which displays supramolecular helical organization. *Chem. Commun. (Camb. Engl.)* **2006**, 4282–4284. [[CrossRef](#)] [[PubMed](#)]
274. Nguyen, T.Q.; Martel, R.; Bushey, M.; Avouris, P.; Carlsen, A.; Nuckolls, C.; Brus, L. Self-assembly of 1-D organic semiconductor nanostructures. *Phys. Chem. Chem. Phys.* **2007**, *9*, 1515. [[CrossRef](#)]
275. Murphy, A.R.; Fréchet, J.M.J. Organic semiconducting oligomers for use in thin film transistors. *Chem. Rev.* **2007**, *107*, 1066. [[CrossRef](#)]
276. Kuzyk, A.; Schreiber, R.; Fan, Z.Y.; Pardatscher, G.; Roller, E.M.; Hoge, A.; Simmel, F.C.; Govorov, A.O.; Liedl, T. DNA-Based Self-Assembly of Chiral Plasmonic Nanostructures with Tailored Optical Response. *Nature* **2012**, *483*, 311–314. [[CrossRef](#)]
277. Shen, X.B.; Asenjo-Garcia, A.; Liu, Q.; Jiang, Q.; de Abajo, F.J.G.; Liu, N.; Ding, B.Q. Three-Dimensional Plasmonic Chiral Tetramers Assembled by DNA Origami. *Nano Lett.* **2013**, *13*, 2128–2133. [[CrossRef](#)]
278. Wang, Z.G.; Ding, B.Q. Engineering DNA self-assemblies as templates for functional nanostructures. *Acc. Chem. Res.* **2014**, *47*, 1654. [[CrossRef](#)] [[PubMed](#)]

279. Sharma, J.; Chhabra, R.; Cheng, A.; Brownell, J.; Liu, Y.; Yan, H. Control of self-assembly of DNA tubules through integration of gold nanoparticles. *Science* **2009**, *323*, 112. [[CrossRef](#)] [[PubMed](#)]
280. Pei, H.; Zuo, X.L.; Pan, D.; Shi, J.Y.; Huang, Q.; Fan, C.H. Scaffolded biosensors with designed DNA nanostructures. *NPG Asia Mater.* **2013**, *5*, e51. [[CrossRef](#)]
281. Giljohann, D.A.; Seferos, D.S.; Daniel, W.L.; Massich, M.D.; Patel, P.C.; Mirkin, C.A. Gold nanoparticles for biology and medicine. *Angew. Chem. Int. Ed.* **2010**, *49*, 3280. [[CrossRef](#)] [[PubMed](#)]
282. Sassolas, A.; Leca-Bouvier, B.D.; Blum, L.J. DNA biosensors and microarrays. *Chem. Rev.* **2008**, *108*, 109. [[CrossRef](#)] [[PubMed](#)]
283. Gennerich, A. Molecular motors: DNA takes control. *Nat. Nanotechnol.* **2014**, *9*, 11. [[CrossRef](#)]
284. Wilner, O.L.; Willner, I. Functionalized DNA Nanostructures. *Chem. Rev.* **2012**, *112*, 2528. [[CrossRef](#)] [[PubMed](#)]
285. Wei, B.; Liu, N.; Zhang, J.; Ou, X.; Duan, R.; Yang, Z.; Lou, X.; Xia, F. Regulation of DNA self-assembly and DNA hybridization by chiral molecules with corresponding biosensor applications. *Anal. Chem.* **2015**, *87*, 2058–2062. [[CrossRef](#)] [[PubMed](#)]