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Chirality across scales

Chiral symmetry breaking in $NaClO_3$ crystals as a model for the study of biological homochirality

Ruptura de la simetría quiral en cristales de $NaClO_3$ como modelo para el estudio de la homoquiralidad biológica

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Abstract

Living systems are composed of chiral molecules. In the absence of asymmetric influences, chemical reactions that generate chiral molecules produce statistically equivalent proportions of left- and right-handed enantiomers (the racemic state). However, biological systems exhibit a marked preference for one enantiomer over the other. The paradigmatic example is the predominant use of L-amino acids in protein synthesis and D-pentose sugars in the synthesis of nucleic acids (DNA and RNA). The asymmetric crystallization mechanisms of sodium chlorate ($NaClO_3$) provide an experimental model for investigating the possible origin of this molecular asymmetry and its relevance to living systems. In this article, we review the mechanisms responsible for the formation of chiral $NaClO_3$ crystals, including amplification and deracemization processes, as well as their potential applications in the production of enantiomerically pure compounds. We also examine the relationship between the chiral asymmetry observed in these inorganic systems and biological homochirality. Finally, we discuss the hypothesis that asymmetric crystallization processes may have occurred on the prebiotic Earth and influenced the molecular dynamics associated with the origin of life. We conclude that $NaClO_3$-based systems provide a useful model for understanding the physical mechanisms capable of generating and amplifying chiral asymmetries from initially symmetric conditions.

Keywords: Homochirality, asymmetric crystallization, deracemization, sodium chlorate ($NaClO_3$), origin of life.

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Resumen

Los seres vivos están constituidos por moléculas quirales. En ausencia de influencias asimétricas, las reacciones químicas que producen moléculas quirales generan proporciones estadísticamente equivalentes de los enantiómeros izquierdo y derecho (estado racémico). Sin embargo, los sistemas biológicos muestran una marcada preferencia por uno de los enantiómeros. El caso paradigmático es el uso predominante de aminoácidos levógiros (L) en la síntesis de proteínas y de azúcares pentosas dextrógiras (D) en la síntesis de ácidos nucleicos (DNA y RNA). Los mecanismos de cristalización asimétrica del clorato de sodio ($NaClO_3$) constituyen un modelo experimental para estudiar el posible origen de esta asimetría molecular y su relevancia para los sistemas biológicos. En el presente artículo revisamos los mecanismos responsables de la formación de cristales quirales de $NaClO_3$, incluyendo los procesos de amplificación y desracemización, así como sus posibles aplicaciones en la obtención de compuestos enantioméricamente puros. Asimismo, analizamos la relación entre la asimetría observada en estos sistemas inorgánicos y la homoquiralidad biológica. Finalmente, discutimos la hipótesis de que procesos de cristalización asimétrica pudieron ocurrir en la Tierra prebiótica e influir en la dinámica molecular asociada con el origen de la vida. Concluimos que los sistemas basados en $NaClO_3$ constituyen un modelo útil para comprender los mecanismos físicos capaces de generar y amplificar asimetrías quirales a partir de condiciones inicialmente simétricas.

Palabras clave: Homoquiralidad, cristalización asimétrica, desracemización, clorato de sodio ($NaClO_3$), origen de la vida.

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1 Introduction

Chirality is a fundamental geometric property wherein an object or system exists in two distinct configurations that are non-superimposable mirror images of each other, precisely analogous to the structural relationship between a left and a right hand (See Figure 1).

In the case of chiral molecules and crystals, these forms are known as enantiomers. Experimentally, enantiomers can be distinguished by their interaction with plane-polarized light, as they rotate the plane of polarization in opposite directions. This property is denoted as $(+)$ or $(-)$, depending on whether the rotation is clockwise or counterclockwise, respectively. Historically, this phenomenon gave rise to the terms levorotatory (L) and dextrorotatory (D); however, in modern chemistry, the designations L and D do not describe optical rotation but instead correspond to a relative structural nomenclature based on the Fischer projection of glyceraldehyde. In contrast, the absolute configuration of a chiral molecule is defined using the R/S (*rectus/sinister*) system, which is assigned according to the Cahn–Ingold–Prelog priority rules (Cleaves, 2023). These rules establish the priority of substituents around a chiral center based on the atomic number (Z) of the atoms directly bonded to it. In the event of a tie, the next atoms along the chain are progressively compared until a difference is found, determining the spatial arrangement of the groups around the chiral center.



Figure 1. Chirality is prominently expressed in gastropod anatomy through the direction of shell coiling. The dextral (right-handed) coiling of the shell in most snail species defines a chiral asymmetry, as individuals with sinistral (left-handed) shell coiling are less common. This reversal in shell coiling is caused by mutations that alter the animal's anatomy from the earliest cleavage stages of embryonic development.

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Figure 2 illustrates the assignment of the R/S absolute configuration for lactic acid according to these rules. In both enantiomers, the substituent with the lowest priority is $-$H ($Z = 1$), which is oriented away from the observer. Moving upward in priority, $-CH_3$ is followed by $-CO_2H$. This assignment arises because the atoms directly bonded to the chiral center (the α-carbon) are identical, as both substituents possess a carbon atom with $Z = 6$. To resolve this tie, the next atoms in the chain are compared: hydrogen has $Z = 1$, whereas oxygen has $Z = 8$. Consequently, $-CH_3$ (carbon bonded to H, H, H) holds a lower priority than $-CO_2H$ (carbon bonded to O, O, H). Finally, $-$OH is the substituent with the highest priority because the oxygen atom directly bonded to the chiral center has $Z = 8$. Thus, the overall priority order is OH $>$ CO_2H $>$ CH_3 $>$ H. Based on this sequence, the orientation OH $\rightarrow$ CO_2H $\rightarrow$ CH_3 traced in a counterclockwise direction corresponds to the S configuration, whereas a clockwise sequence corresponds to the R configuration.

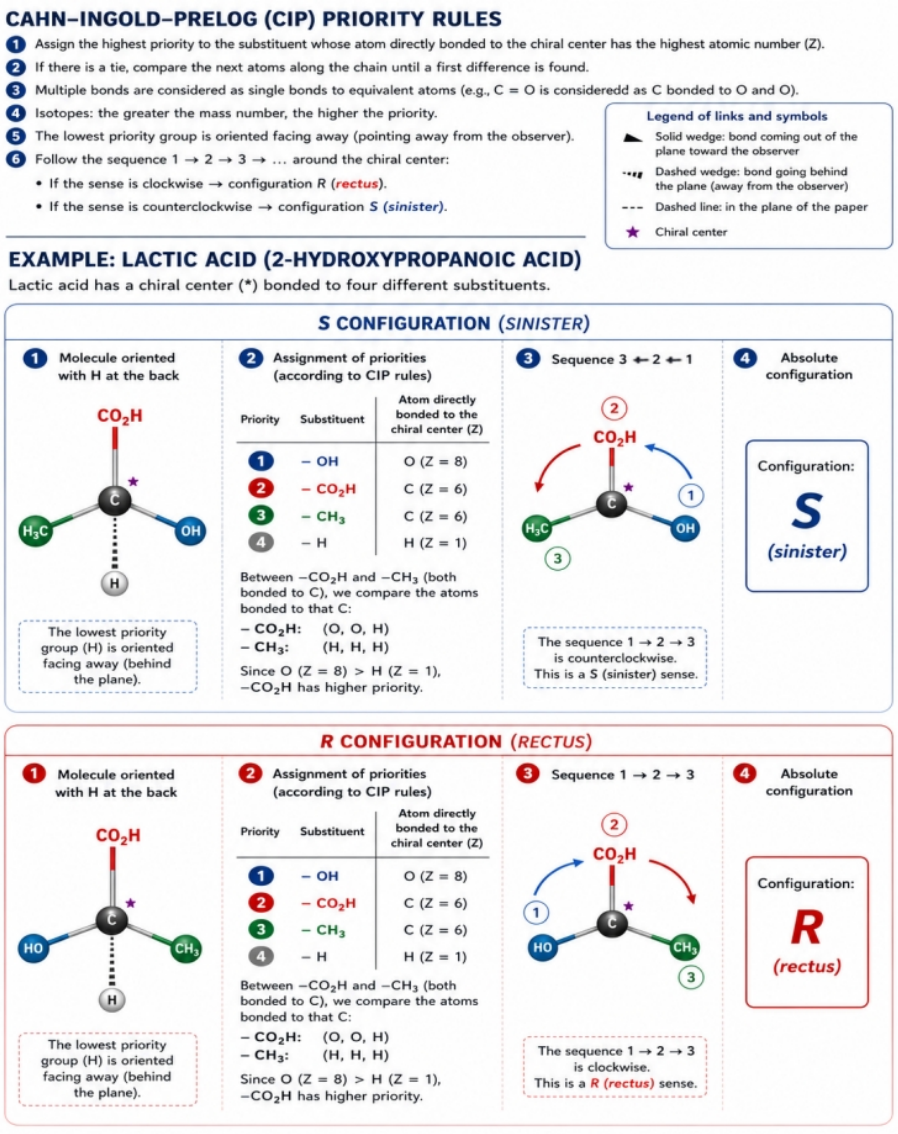


Figure 2. Assignment of the R/S absolute configuration for lactic acid according to Cahn–Ingold–Prelog priority rules.

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In biological systems, homochirality is a property of functional asymmetry associated with the flow of information at the cellular level (Carroll, 2009; Cruz-Rosas et al., 2020). It is a distinctive characteristic of life that extends across different levels of biological organization (Cruz-Rosas et al., 2022; Inaki et al., 2016). During the synthesis of informational biopolymers, ribosomes recognize only *L*-amino acids (except glycine, which is achiral), whereas RNA polymerase and DNA polymerase recognize only nucleotides containing *D*-ribose and *D*-deoxyribose—a phenomenon strictly referred to as biohomochirality. Nevertheless, the presence of *D*-amino acids and *L*-sugars has been reported to play important roles in certain biological processes (Bitchagno et al., 2022; Forsman and Leino, 2011; Fuchs et al., 2005; Genchi, 2017). Conversely, the synthesis of mirror proteins and mirror nucleic acids—achieved by polymerizing *D*-amino acids and *L*-nucleotides—has been accomplished only under laboratory conditions, requiring synthetic mirror enzymes (Harrison et al., 2023; Young et al., 2019).

Thus, the strict homochirality involved in the synthesis of proteins and nucleic acids is not maintained universally outside these core processes. However, the preferential use of one enantiomer over the other remains a consistent characteristic of biological systems (Franco-Rodríguez et al., 2023). Interestingly, inorganic systems also exhibit chiral asymmetry, displaying biases toward either right-handed or left-handed configurations that range from the weak interactions within atoms to the rotation of spiral galaxies like the Milky Way (Pavlov and Klabunovskii, 2014), thereby demonstrating that chiral asymmetry is a widespread feature of nature.

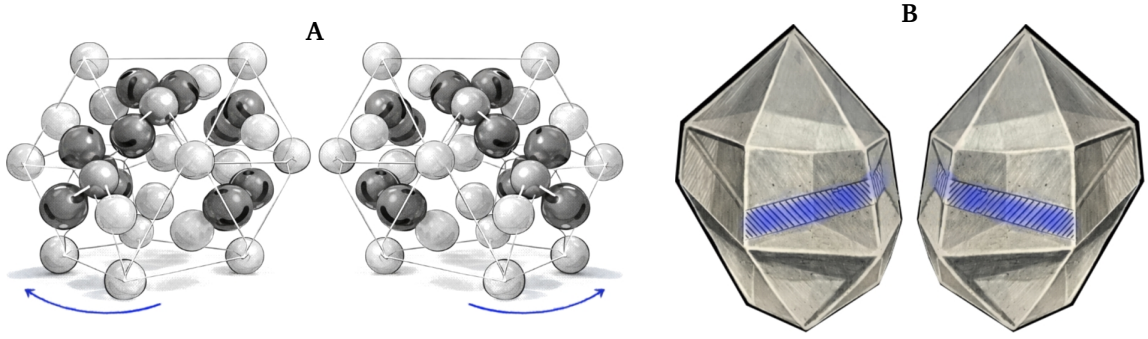


Figure 3. Schematic illustration of chirality observed in crystals. A) Enantiomorphs in which chirality emerges because of the spatial arrangement of the chemical units. B) Enantiomorphs in which chirality is observed as inclined striations on the surface of one of the crystal faces.

The stable, disordered, and most probable state of a chiral system is the racemic state, which represents an equimolar mixture of both enantiomers (50 % left-handed and 50 % right-handed). Consequently, biohomochirality represents a distinct state of molecular asymmetry and order in biology. Even non-living biological systems, such as viruses, must be homochiral to interact with the cells they infect. In crystalline systems composed of inorganic compounds, where molecular order follows a periodic pattern, chirality does not necessarily reside in the individual chemical units; instead, it emerges as a collective property of the spatial arrangement of the crystal lattice and its space group symmetry (Flack, 2003; Valentín-Pérez et al., 2022). These arrangements can manifest as helices rotating either clockwise or counterclockwise, as seen in sodium chlorate ($NaClO_3$) (Dickinson and Goodhue, 1921), or as striations on crystal faces that incline to the left or right relative to the observer, as observed in the hemihedral faces of sodium tartrate (Gal, 2011) (Figure 3).

In these cases, each crystal form is the mirror image of the other and is referred to as an enantiomorph (Flack, 2003). Notably, this chirality occurs at the supramolecular level, largely independent of the chirality of the units constituting the lattice. This is exemplified by sodium chlorate, an achiral molecule that gives rise to a chiral helical lattice,

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further demonstrating that chirality is an emergent property determined by the spatial arrangement of a system's components. Therefore, chirality can be observed at different levels of organization in nature without necessarily being present at the preceding level.

The emergence of chirality in a molecular system depends on physicochemical forces and processes that may have operated on the prebiotic Earth, influencing the origin or the earliest evolutionary stages of life and determining, from a very early stage, the subsequent development toward present-day biohomochirality. Therefore, studying these forces and processes may provide important insights into the mechanisms that led to the emergence of living systems. Furthermore, research focused on the pathways that induce chiral asymmetry is interesting for understanding the origin and functioning of biological processes, with implications that are not only theoretical but also highly practical.

An example of this is the development of medical therapies based on the fact that biohomochirality represents a fundamental structural order enabling stereospecific recognition among biomolecules. This principle has been exploited in the design of chiral nanomaterials capable of selectively recognizing molecular structures of biomedical interest, with applications in diagnostics, targeted drug delivery, and medical therapies (Sun et al., 2026; Zhao et al., 2024). The development of enantiomerically specific drugs is also an area of research based on molecular chirality, aiming to minimize adverse effects while enhancing physiological activity through the stereoisomer with the appropriate biological action (Nguyen et al., 2006).

To achieve these objectives, various research groups employ simple molecular models, such as the formation of chiral crystals to understand the mechanisms by which chiral symmetry breaking can be induced and to investigate their implications for biology. On this basis, the present study highlights the relevance of investigating the crystallization of $NaClO_3$ and the mechanisms underlying its chiral symmetry breaking as a simple and useful experimental model for approaching the possible asymmetric conditions under which the earliest living systems were assembled.

2 Sodium Chlorate ($NaClO_3$): An Experimental Model

Sodium chlorate is an achiral inorganic salt that crystallizes to form chiral conglomerates. This chirality does not reside in the individual chemical units but rather emerges because of the three-dimensional arrangement of the Na^+ and ClO_3^- ions within the crystal lattice. Specifically, the crystal belongs to a chiral space group ($P2_13$), in which the structural units are arranged along helical axes, giving rise to left- or right-handed enantiomorphic structures (Buhse et al., 2021; Flack, 2003; Florent et al., 2023). An important consequence of this arrangement is that the crystals exhibit optical activity; i.e., they are capable of rotating the plane of plane-polarized light. As a result, when observed through polarized filters, crystals of opposite handedness interact differently with light, allowing opposite chiral conglomerates to be visually distinguished.

If the polarizing plates are initially crossed (their polarization planes oriented perpendicularly to each other at $90°$) and the upper plate (analyzer) is rotated to the right, the polarized light passes through the crystal mixture, causing the L-crystals of $NaClO_3$ to appear brighter than the D-crystals. Conversely, if the analyzer is rotated to the left, the appearance of the conglomerates is reversed, and the D-crystals appear brighter. This phenomenon is illustrated in Figure 4, where the arrows indicate clockwise and counterclockwise rotations and the corresponding effect on the pair of crystals. The lower images show the appearance of the L and D conglomerates, respectively, because each enantiomorph interacts differently with the direction of the polarized light passing through the crystal mixture. There is no direct relationship between the clockwise or counterclockwise rotation of the analyzer and the chirality of each enantiomorph. Therefore, this method does not determine the absolute configuration of each conglomerate but rather serves as a technique for distinguishing between left- and right-handed crystals, as well as from achiral crystals (Niinomi et al., 2014).

A particularly interesting feature of $NaClO_3$ crystallization is that when a supersaturated solution is prepared from previously formed crystals—whether composed exclusively of left-handed crystals, right-handed crystals, or a racemic mixture—

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the chirality associated with the crystal lattice is entirely lost upon dissolution. Consequently, the formation of new crystals from this solution yields a racemic mixture. This demonstrates that the racemate is the natural equilibrium state of the system's dynamics, to which it recurrently returns. Under certain conditions, however, this equilibrium can be broken, leading to non-racemic growth and the clear predominance of one of the enantiomorphic crystal forms (Buhse et al., 2021; Noble-Terán et al., 2023).

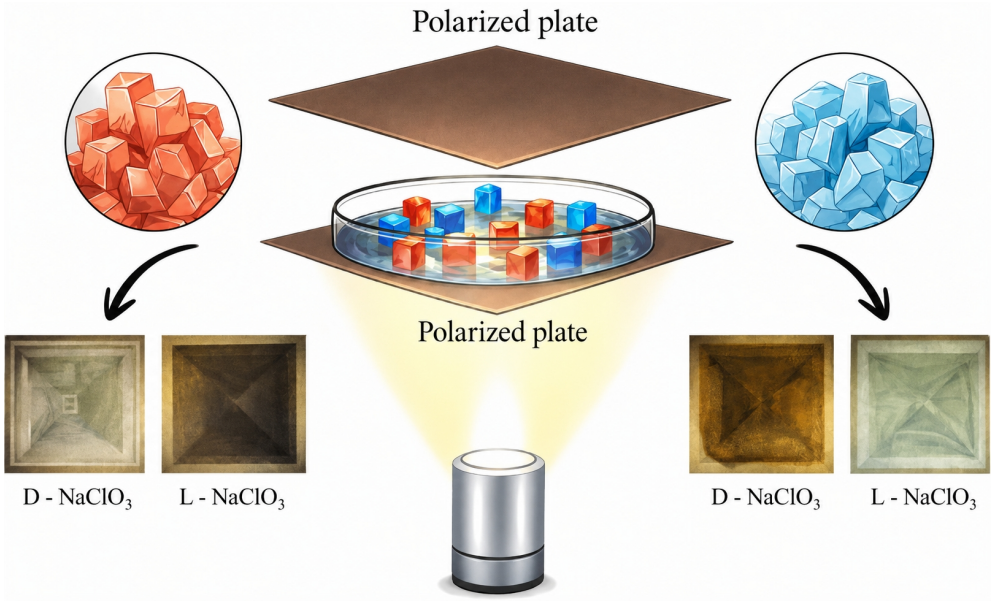


Figure 4. Asymmetric interaction of L- and D-$NaClO_3$ crystals with plane-polarized light. When the upper polarizing plate is rotated clockwise (to the right) relative to the lower polarizing plate, the L-$NaClO_3$ crystals appear brighter. When the upper polarizing plate is rotated counterclockwise (to the left), the D-$NaClO_3$ crystals appear brighter. Original image: Heidi García Quintana. Colors are for illustrative purposes only.

3 Chiral Symmetry Breaking and Non-Racemic Growth

Non-racemic growth refers to any process that results in a significant excess of one enantiomer over the other (in this case, one enantiomorphic crystal form of a given handedness over the other). Both stochastic (random) and deterministic mechanisms can cause this phenomenon.

3.1 The Effect of Spontaneous Conglomeration and Viedma Ripening

Viedma ripening operates through the spontaneous formation of chiral crystals resulting from a dynamic process of conglomeration, fragmentation, and recycling, in which a chiral nucleus induces the incorporation (adsorption) of structural units compatible with the configuration of the growing enantiomorph, thereby giving rise to crystals with a defined chirality. Under static conditions, the crystallization of $NaClO_3$ produces left-handed and right-handed conglomerates in a symmetric (racemic) state. From this spontaneous conglomeration, the Viedma ripening mechanism (Viedma, 2005) makes it possible to obtain a homochiral crystal population (100 % enantiomorphs of the same handedness) from a supersaturated racemic solution.

The system is subjected to a continuous cycle of dissolution and growth of the crystal conglomerates. This process can be induced in two ways. The first involves the mechanical fragmentation of crystals through the presence of glass beads that act as a grinding medium under continuous stirring, causing the smaller, less stable conglomerates to dissolve preferentially. This favors an Ostwald ri-

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pening process, in which the dissolved material is incorporated into the larger crystals, thereby promoting their growth (Noorduin et al., 2009). The second approach involves thermal fluctuations, in which cycles of heating and cooling induce crystal dissolution and growth, respectively (Noorduin et al., 2008).

The key to this mechanism lies in the fact that $NaClO_3$ ions transition from the crystal phase into the aqueous phase during dissolution and are subsequently adsorbed again by either of the two enantiomorphic crystal forms. This solid–liquid–solid interconversion is reversible and exhibits no preference for the formation of crystals of a particular chirality, since $NaClO_3$ is achiral in solution and its ionic units (Na^+ and ClO_3^-) can be incorporated into either enantiomorph. However, owing to stochastic fluctuations, a slight excess of one handedness may arise at a given moment. As the cycles of crystal dissolution and growth continue, the enantiomorph present in greater abundance has a higher probability of adsorbing the ions released by crystals that have dissolved after reaching a size below the critical threshold (Noorduin et al., 2008). This dynamic constitutes a symmetry-breaking process in the formation of the two enantiomorphs and establishes a positive feedback loop that ultimately leads to the complete disappearance of the minority enantiomorph and the formation of a homochiral crystal population (Noble-Terán et al., 2023).

The Viedma mechanism is stochastic, giving rise to homochiral populations of either the left-handed or the right-handed enantiomorph following a binomial probability distribution, without preference for either handedness (Kondepudi et al., 1990; Viedma, 2005) (Figure 5). However, it is possible to control the direction of chiral symmetry breaking, thereby making the system deterministic, either by applying unidirectional stirring to the solution (Ribó et al., 2001) or by using chiral initiators, also referred to as chiral seeds, such as crystals of the same compound or molecules dissolved in the medium (Putman and Armstrong, 2022). In this context, controlling the handedness of the resulting homochiral state has implications that are not only theoretical for the origin of life but also practical, for example, in the food and pharmaceutical industries.

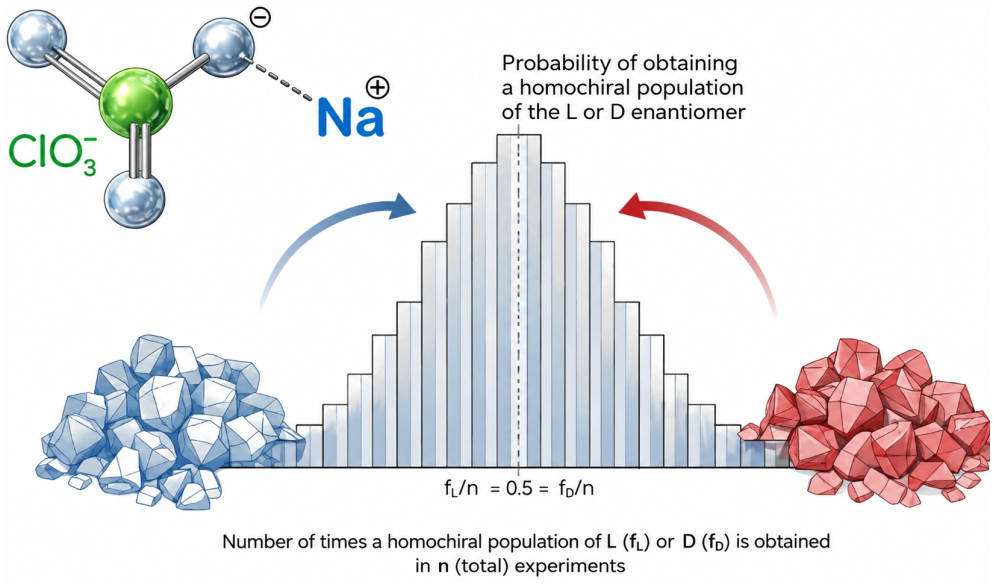


Figure 5. Example of a binomial distribution. An idealized histogram is shown with symmetric probabilities of obtaining homochiral populations of left-handed and right-handed crystals, each having a maximum probability of 50 %. Colors are for illustrative purposes only.

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3.2 Chiral Symmetry Breaking by Secondary Nucleation

This mechanism, observed in salts such as $NaClO_3$, is based on the growth of crystals from previously formed crystals. During primary nucleation, the stochastic formation of the first crystals gives rise to a racemic mixture (Kondepudi et al., 1990). As the initial crystals continue to grow in solution, they may induce secondary nucleation: small fragments detached from the parent crystals act as new crystallization nuclei, inheriting their structure and, consequently, their chirality (Noorduin et al., 2008).

This mechanism may constitute a source of asymmetry if either a left-handed or a right-handed crystal becomes slightly larger or more active by incorporating more ions into its crystal lattice, thereby generating more secondary nuclei of the same chirality. These newly formed crystals, in turn, generate additional crystallization nuclei with the same handedness, thus establishing an autocatalytic process. This cascade effect can rapidly lead to the predominance of a single enantiomorph in the crystallization medium. Under appropriate conditions, these mechanisms can produce crystal populations with enantiomeric purities approaching $100\,\%$ (Viedma, 2005).

4 Some Implications for the Pharmaceutical and Food Industries

In the pharmaceutical industry, the production of enantiomerically pure substances is important because biological systems exhibit stereospecific recognition and utilization of chiral molecules. Consequently, enantiomers of the same drug may display different pharmacological properties. There are several examples, one of the most famous being thalidomide, which causes severe malformations during embryonic development if the S-enantiomer is administered; however, both enantiomers interconvert under physiological conditions, undergoing *in vivo* racemization, which makes it difficult to use them as enantiomerically pure compounds (Hutt and Tan, 1996). Another example is ibuprofen, where the S-enantiomer is the physiologically active form in humans (and, in general, in mammals). This anti-inflammatory drug can be obtained as a racemate, in which the R-enantiomer (right-handed) is physiologically inactive but is converted to the S-enantiomer in blood plasma. If the racemic mixture is administered, the effective dose increases because the R-enantiomer is partially converted to the active S-form in the body by liver enzymes, which can potentially lead to kidney damage (Nguyen et al., 2006).

In many cases, enantiopure drugs are obtained through enantioselective synthesis or chiral resolution. From an alternative perspective, chiral crystallization processes can be explored as potential methods for the separation of enantiomers; however, most chiral organic compounds, including ibuprofen, crystallize as racemic compounds (where both S- and R-ibuprofen are part of the same crystal lattice) rather than as enantiomeric aggregates, which limits the direct application of these methods. Research into the mechanisms of asymmetric nucleation, such as the Viedma mechanism or secondary crystallization, remains an open field for the development of industrial processes aimed at obtaining aggregates of these substances with high enantiomeric purity.

In the food industry, a similar situation occurs because sensory chemoreceptors recognize chiral molecules differently depending on the specific enantiomer. Since smell and taste are closely linked, there are numerous examples starting with the classic case of limonene, where it is often claimed that $S(-)$-limonene is perceived as the scent of lemon, while $R(+)$-limonene is recognized as the scent of orange (Brenna et al., 2003). However, the validity of this widely cited example has been questioned. In a study on aroma characteristics, it is argued that $R(+)$-limonene is actually the primary terpene present in the essential oil of all citrus fruits (including both lemons and oranges), and that the $S(-)$-limonene historically obtained from lemon peel may have been contaminated with citral. This contamination likely produced the reported lemon aroma—making it an artifact of the experimental method used—an error that has since persisted in the scientific literature (Sell, 2014).

Leaving the debate about limonene aside for now, chiral organic molecules are consistently found in asymmetric proportions within living organisms. Menthol, obtained from certain species of

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herbaceous plants of the genus *Mentha*, is naturally produced as $(-)$-menthol, which corresponds to the $(1R, 3R, 4S)$ configuration because the molecule possesses three chiral centers. This notation indicates that each of the three chiral centers has an absolute configuration of R or S, describing the three-dimensional arrangement of substituents around each center; for menthol, this structural complexity results in 8 stereoisomers. $(-)$-Menthol is responsible for the characteristic mint flavor and cooling sensation when recognized by sensory chemoreceptors in the mucous membranes. Conversely, $(+)$-menthol, which corresponds to the $(1S, 3S, 4R)$ configuration, is perceived as having an artificial, medicine-like flavor and actively interferes with the receptor recognition of $(-)$-menthol when both are present together. Although the extraction of $(-)$-menthol from peppermint oil (primarily from the species *Mentha canadensis*) remains the primary source of this monoterpenoid, its industrial synthesis can occur via chiral precursors such as $(+)$-limonene, or achiral precursors such as β-pinene, followed by isolation of the pure compound through the crystallization of $(-)$-menthol (Kamatou et al., 2013). In this regard, research into the mechanisms of crystal formation with high enantiomeric purity—such as Viedma ripening or secondary crystallization—represents an active field that could lead to new, economically feasible industrial processes.

5 Implications for the Origin of Biological Chirality

Regarding the origin of biohomochirality, both the Viedma mechanism and secondary nucleation demonstrate that simple processes based on crystallization–dissolution cycles and statistical fluctuations can lead to homochiral states in inorganic systems. This may imply the existence of sites or local environments exhibiting chiral asymmetry on mineral surfaces of the prebiotic Earth, or within the environments in which the earliest living systems assembled and began their evolutionary process. The transfer of chiral bias from inorganic crystals to organic molecules such as amino acids and sugars constitutes a field of research that can be framed within Curie's principle of symmetry: "When certain causes produce certain effects, the symmetry elements of the causes must be found in the effects produced" (quoted by Chalmers, 1970). Accordingly, inorganic chiral asymmetry would impose geometric constraints on molecular dynamics, biasing organic molecular systems toward one of the enantiomers.

The chiral symmetry breaking observed during $NaClO_3$ crystallization demonstrates that simple processes, independent of biological dynamics, can generate homochiral states. This asymmetry in inorganic systems may have contributed to determining biological chiral asymmetry under one of two general scenarios: first, as a condition preceding the origin of life; or second, as an environmental factor that influenced evolutionary processes during the earliest stages following the emergence of living systems. In both cases, one hypothesis linking these phenomena to life proposes that chiral crystals may have acted as the earliest agents of selection and amplification of molecular chirality, either before or after the origin of life.

The non-racemic growth of chiral minerals or prebiotic organic compounds (such as amino acids that crystallize as conglomerates) may have provided the earliest local environments on the primitive Earth with a significant enantiomeric excess. Unlike other hypotheses, such as molecular panspermia (Bonner, 1991; Bonner and Rubenstein, 1987; Rubenstein et al., 1983) or the Oparin–Haldane hypothesis (Schopf, 2024), chiral symmetry breaking during $NaClO_3$ crystallization did not require cosmic radiation or a source of circularly polarized light to induce asymmetric growth; statistical fluctuations and amplification alone were sufficient.

One of the simplest proposed mechanisms is that crystal surfaces exhibiting chiral asymmetry may have functioned as reaction surfaces, displaying asymmetric interactions based on molecular geometric affinities with one enantiomer of organic molecules. For example, a homochiral crystal could preferentially promote the binding and polymerization of amino acids, in this case *L*-amino acids, or sugars such as *D*-ribose and *D*-deoxyribose. This process could have led to the formation of the first oligopeptides or oligonucleotides with a chiral bias, which, once molecular life became autonomous, perpetuated this initial asymmetry (Vogl, 2011).

Several research groups have reported the se-

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lective adsorption of one enantiomer by mineral surfaces exhibiting chiral asymmetry. Examples include the preferential adsorption of *L*-amino acids onto mineral surfaces such as calcite (Hazen et al., 2001) and the selective adsorption of *D*-ribose onto mineral surfaces (Delidovich et al., 2014).

Along the same lines, cross-amplification may also have played an important role. A slight excess of *L*-amino acids or *D*-ribose, perhaps generated by a homochiral population of inorganic crystals, could subsequently have been amplified by other mechanisms, such as asymmetric catalysis on mineral surfaces or autocatalytic reaction systems such as the Soai reaction, ultimately leading to the homochirality observed in living systems today (Barron, 2008).

6 Conclusion: Inorganic Asymmetry and Biological Asymmetry

The crystallization of $NaClO_3$ into enantiomorphic conglomerates demonstrates that chirality can emerge at the supramolecular level from an achiral molecular system. Furthermore, secondary nucleation and Viedma ripening demonstrate that an initially racemic condition can generate a state of pure homochirality through simple physicochemical processes (crystallization, dissolution, mechanical energy, or thermal energy). No initial external asymmetric influence is required; only statistical fluctuations are sufficient. These processes may therefore represent an abiotic mechanism capable of inducing chiral symmetry breaking in organic molecules, particularly in amino acids and pentose sugars (such as ribose and deoxyribose), thereby determining the chiral bias observed in biological systems.

Therefore, it is plausible that on the prebiotic Earth, mineral surfaces subjected to cycles of humidity and temperature, or hydrothermal systems, experienced crystallization processes analogous to Viedma ripening, which acted as the turning point that biased the system toward the predominance of *L*-amino acids or *D*-sugars. Although these mechanisms explain the generation and amplification of chiral asymmetry in simple physical systems, the transition toward its incorporation and fixation in self-replicating chemical systems remains an open question in studies on the origin of life. Nevertheless, the scenario presented here may have formed part of the process that transformed the asymmetry of abiotic chemistry into the functional asymmetry of living organisms, the latter in the sense that organisms maintain their fundamental biological processes because they are organized on the basis of their homochiral state (Cruz-Rosas et al., 2022; Cruz-Rosas and Miramontes, 2021).

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Declaration on the Use of Artificial Intelligence

The authors DECLARE that, during the preparation of the article entitled "Chiral Symmetry Breaking in $NaClO_3$ Crystals as a Model for the Study of Biological Homochirality," generative artificial intelligence tools were used exclusively to generate and/or edit the images accompanying this manuscript. The final version of these visual elements is the result of manual editing by the authors. These tools were not used for data analysis or interpretation, generation of results, formulation of conclusions, or as a substitute for the authors' academic and scientific judgment.

The authors assume full responsibility for the content, originality, integrity, and final version of the article.

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Author Contributions

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