Chirality on Surfaces
W.H. Thompson (Lord Kelvin)

“I call any geometrical figure, or any group of points **chiral** (χειρ, greek for hand), and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincidence with itself”.

Baltimore Lectures 1884
Human hands are perhaps the most universally recognized example of chirality: the left hand is a non-superimposable mirror image of the right hand; no matter how the two hands are oriented, it is impossible for all the major features of both hands to coincide. This difference in symmetry becomes obvious if someone attempts to shake the right hand of a person using his left hand, or if a left-handed glove is placed on a right hand.
When used in the context of chemistry, chirality usually refers to molecules. Two mirror images of a molecule that cannot be superimposed onto each other are referred to as enantiomers or optical isomers. Because the difference between right and left hands is universally known and easy to observe, many pairs of enantiomers are designated as “right” and “left-handed”. A mixture of equal amounts of the two enantiomers is said to be a racemic mixture.
Chiral molecules are mostly carbon-containing compounds. If a carbon atom in tetrahedral environment is bounded to four different atoms or groups, then the species will be chiral.
Ammonium sodium tartrate

(+) dextrorotatory, (-) laevorotatory

(-)R,(+)S or (+)R,(-)S

Separation of enantiomorphs of „acide racemique“ in 1848 by Louis Pasteur.
Nomenclature

By configuration: $R$- and $S$-

By optical activity: $(+)$- and $(-)$-

By configuration: $D$- and $L$-
By configuration: \( R - \) and \( S - \)

The \( R/S \) system labels each chiral center \( R \) or \( S \) according to a system by which its substituents are each assigned a \textit{priority}, according to the Cahn-Ingold-Prelog priority rules, based on atomic number. If the center is oriented so that the lowest-priority of the four is pointed away from a viewer, the viewer will then see two possibilities: if the priority of the remaining three substituents decreases in clockwise direction, it is labeled \( R \) (for \textit{Rectus}), if it decreases in counterclockwise direction, it is \( S \) (for \textit{Sinister}).
The Cahn–Ingold–Prelog priority rules, CIP system or CIP conventions are a set of rules used in organic chemistry to name the stereoisomers of a molecule. The steps for naming molecules using the CIP system are often presented as:

Identification of stereocenters

Assignment of priorities to the groups attached to each stereocenter.
Two groups are compared first by atomic number of the atoms directly attached to the stereocenter; the group having the atom of higher atomic number receives higher priority. The rules are more complicated if a chain of atoms is attached to the chiral center.

After assigning the priority, the molecule is so oriented in space that the group with the lowest priority is pointed away from the observer.
If the substituents are numbered from 1 (highest priority) to 4 (lowest priority), then the sense of rotation of a curve passing through 1, 2 and 3 distinguishes the stereoisomers. A center with a clockwise sense of rotation is an \( R \) or \textit{rectus} center and a center with a counterclockwise sense of rotation is an \( S \) or \textit{sinister} center. The names are derived from the Latin for right and left, respectively.
The image shows two chemical structures with the following instructions:

1. For the left structure:
   - Orient the lowest priority group away from the main structure.
   - The clockwise orientation is designated as R.

2. For the right structure:
   - Orient the lowest priority group away from the main structure.
   - The counter-clockwise orientation is designated as S.
By optical activity: (+)- and (−)-

An enantiomer can be named by the direction in which it rotates the plane of polarized light. If it rotates the light clockwise (as seen by a viewer towards whom the light is traveling), that enantiomer is labeled (+). Its mirror-image is labeled (−). The (+) and (−) isomers have also been termed d- and l-, respectively (for dextrorotatory and levorotatory). This labeling is easy to confuse with D- and L-.
An optical isomer can be named by the spatial configuration of its atoms. The D/L system does this by relating the molecule to glyceraldehyde. Glyceraldehyde is chiral itself, and its two isomers are labeled D and L. In this system, compounds are named by analogy to glyceraldehyde, which, in general, produces unambiguous designations, but is easiest to see in the small biomolecules similar to glyceraldehyde. One example is the amino acid alanine, which has two optical isomers, and they are labeled according to which isomer of glyceraldehyde they come from.
D-glyceraldehyde

L-glyceraldehyde
The D/L labeling is unrelated to (+)/(−); it does not indicate which enantiomer is dextrorotatory and which is levorotatory. Rather, it says that the compound's stereochemistry is related to that of the dextrorotatory or levorotatory enantiomer of glyceraldehyde—the dextrorotatory isomer of glyceraldehyde is, in fact, the D isomer.
The $R/S$ system has no fixed relation to the $(+)/(−)$ system. An $R$ isomer can be either dextrorotatory or levorotatory, depending on its exact substituents. The $R/S$ system also has no fixed relation to the D/L system. For example, the side-chain one of serine contains a hydroxyl group, $-\text{OH}$. If a thiol group, $-\text{SH}$, were swapped in for it, the D/L labeling would, by its definition, not be affected by the substitution. But this substitution would invert the molecule's $R/S$ labeling, because the CIP priority of $\text{CH}_2\text{OH}$ is lower than that for $\text{CO}_2\text{H}$ but the CIP priority of $\text{CH}_2\text{SH}$ is higher than that for $\text{CO}_2\text{H}$. 
For this reason, the D/L system remains in common use in certain areas of biochemistry, such as amino acid and carbohydrate chemistry, because it is convenient to have the same chiral label for all of the commonly occurring structures of a given type of structure in higher organisms. In the D/L system, they are all L; in the $R/S$ system, they are mostly $S$ but there are some common exceptions.
Unknown Origin of Homochirality in Terrestrial Life

Enantioselectivity in Processes Involving Biologically Important Chiral Molecules

Heterogeneous and Enzimatic Enantioselective Catalysis
Photochemical Asymmetric Syntheses
Drug Activity
Properties of enantiomers

Enantiomers are identical with respect to ordinary chemical reactions and properties (i.e., identical NMR spectra, identical IR spectra), but differences arise when they are in the presence of other chiral molecules or objects. Different enantiomers of chiral compounds often taste and smell differently and have different effects as drugs.

One chiral 'object' that interacts differently with the two enantiomers of a chiral compound is circularly polarised light: An enantiomer will absorb left- and right-circularly polarised light to differing degrees. This is the basis of circular dichroism (CD) spectroscopy.
Polarized light

Linearly polarized light is polarized in a certain direction (that is, the magnitude of its electric field vector oscillates only in one plane, similar to a sine wave). In circularly polarized light, the electric field vector has a constant length, but rotates about its propagation direction. Hence it forms a helix in space while propagating. If this is a left-handed helix, the light is referred to as left circularly polarized, and vice versa for a right-handed helix.
Since circularly polarized light itself is "chiral", it interacts differently with chiral molecules. That is, one of the two types of circularly polarized light are absorbed to different extents. In a CD experiment, equal amounts of left and right circularly polarized light are radiated into a (chiral) solution. One of the two types is absorbed more than the other one and this wavelength-dependent difference of absorption is measured, yielding the CD spectrum of the sample.
Circular dichroism (CD) is a form of spectroscopy based on the differential absorption of left- and right-handed circularly polarized light. It can be used to help determine the structure of macromolecules (including the secondary structure of proteins and the handedness of DNA). CD was discovered by the French physicist Aimé Cotton in 1896.
Complex organic molecules at metal surfaces:
bonding, organisation and chirality
Surface science techniques have now reached a stage of maturity that has enabled their successful deployment in the study of complex adsorption systems. A particular example of this success has been the understanding that has been gained regarding the behaviour of multi-functional organic molecules at metal surfaces. A single organic molecule–metal system can exhibit a wide-ranging and flexible approach to its environment, leading to a variety of adsorption phases, according to the prevailing temperature and coverage conditions.
Interest has recently focused on the property of chirality that can be bestowed at an achiral metal surface by the adsorption of these complex organic molecules. The creation of such architectures offers the opportunity for ultimate stereocontrol of reactions and responses at surfaces. We have, therefore, specifically examined the various ways in which chirality can be expressed at a surface and provide a framework for classifying chiral hierarchies that are manifested at surfaces, with particular attention being paid to the progression of chirality from a local to a global level.
Of the various attributes that an organic molecule can bring to a metal surface, there is the ultimate selectivity function of chirality. Chirality is simply a geometric property which dictates that the mirror transformation of an object is a non-identity operation, i.e. the object and its mirror image are non-superimposable by any translation or rotation. Clearly for this to hold, the object must not possess any inverse symmetry elements (i.e. centre of inversion or reflection planes). The property of chirality has profound effects in physics, chemistry and biology, ranging from parity violations for weak forces, to the exclusive use of one mirror form of amino acids by all life forms on earth.
Chiral expression at surfaces has only attracted increasing attention in recent years, despite the fact that it is actually easier to create chirality in a 2D system since a surface cannot possess a centre of inversion and can only maintain reflection mirror symmetry planes normal to the surface. Although intrinsically chiral metal surfaces can be created by cutting to expose step and kink sites that are chiral, the interesting point for the organic/inorganic interface is how the adsorption of organic molecules bestows chirality to a previously non-chiral surface.
In fact, surface chirality can be manifested in a number of ways and a hierarchy of surface chirality can be identified. We suggest the following classification of surface chiral systems that includes both the creation of local chiral motifs by single adsorption events (i.e. point chirality) and the creation of chiral domains arising from the chiral arrangements of the individual motifs (i.e. organisational chirality). We also differentiate between molecule-induced chirality and adsorption-induced chirality and between expressions of local and global chirality. A summary of the classification is shown in Fig. 1.2 and a description of how chirality can be manifested at non-chiral surfaces is given below.
## Non-chiral molecules

<table>
<thead>
<tr>
<th>Adsorption induced chiral motifs.</th>
<th>Overall racemic</th>
</tr>
</thead>
<tbody>
<tr>
<td>-alignment of molecule breaks the reflection symmetry axes of surface: <em>local point chirality</em> (i.e. belongs to a chiral point group).</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Adsorption induced chiral arrangements (or domains).</th>
<th>Overall racemic</th>
</tr>
</thead>
<tbody>
<tr>
<td>-the ordered domains possess a chiral space group: <em>local organisational chirality</em>.</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
### Chiral molecules

**Molecule induced chiral motifs.**

- intact preservation of chiral centre upon adsorption i.e. creates local chiral point group: **global point chirality.**

**Adsorption induced chiral arrangements.**

1. **Asymmetric lateral interactions**
   - e.g. mediated by groups that are non-chiral
   - reflectional domains allowed:
     - **global point**
     - **local organisational chirality.**

2. **Chiral lateral interactions**
   - no reflectional domains allowed:
     - **global point**
     - **global organisational chirality**

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**Overall chiral**

- **pseudo reflection**

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**Overall chiral**

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Surface chirality from adsorption of non-chiral molecules

Point chirality: adsorption-induced chiral motifs.

Organisational chirality: adsorption-induced chirally ordered domains.
Surface chirality from adsorption of chiral molecules

Point chirality: molecule-induced chiral motifs

Organisational chirality
Table 1
Various combinations of chiral manifestations at surfaces along with the type of chiral surface created$^a$

<table>
<thead>
<tr>
<th>Molecular chirality</th>
<th>Manifestations of chirality</th>
<th>Chirality of surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point chirality</td>
<td>Organisational chirality</td>
</tr>
<tr>
<td></td>
<td>(chiral motif forms on adsorption)</td>
<td>(domains form with molecules in chiral arrangements)</td>
</tr>
<tr>
<td></td>
<td>chiral image created</td>
<td>mirror image also created</td>
</tr>
<tr>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

$^a$Note that for a chiral molecule with a chiral adsorption motif with no mirror image and a chiral organisation with no mirror image this leads to the special case of global organisational chirality.
Extended surface chirality from supramolecular assemblies of adsorbed chiral molecules
The increasing demand of the chemical and pharmaceutical industries for enantiomerically pure compounds has spurred the development of a range of so-called `chiral technologies', which aim to exert the ultimate control over a chemical reaction by directing its enantioselectivity. Heterogeneous enantioselective catalysis is particularly attractive because it allows the production and ready separation of large quantities of chiral product while using only small quantities of catalyst.
Heterogeneous enantioselectivity is usually induced by adsorbing chiral molecules onto catalytically active surfaces. A mimic of one such catalyst is formed by adsorbing (R,R)-tartaric acid molecules on Cu(110) surfaces: this generates a variety of surface phases, of which only one is potentially catalytically active, and leaves the question of how adsorbed chiral molecules give rise to enantioselectivity.
Here we show that the active phase consists of extended supramolecular assemblies of adsorbed (R,R)-tartaric acid, which destroy existing symmetry elements of the underlying metal and directly bestow chirality to the modified surface. The adsorbed assemblies create chiral `channels' exposing bare metal atoms, and it is these chiral spaces that we believe to be responsible for imparting enantioselectivity, by forcing the orientation of reactant molecules docking onto catalytically active metal sites.
Figure 1 The active chiral phase created by (R,R)-TA on Cu(110). Shown is local adsorbate geometry and extended two-dimensional ordering. A, Schematic diagram showing the local bonding and orientation of the adsorbed bitartrate species on a Cu(110) surface. B, Low-energy electron diffraction (LEED) pattern observed at 31 eV for the ordered (90, 12) bitartrate phase of (R,R)-TA on Cu(110). C, Scanning tunnelling microscope (STM) image (150 Å × 200 Å) showing the ordered (90, 12) bitartrate phase formed by (R,R)-tartaric acid adsorption on Cu(110) at 405 K ($V_{tb} = -1.7$ V; $I_{tb} = 1.18$ nA).

The two-dimensionally ordered structures are described in matrix notation with reference to a and b, the unit vectors along (110) and along the (001) directions on the Cu(110) surface. For convenience, the matrix is represented throughout the text as ($G_{11}$, $G_{12}$, $G_{21}$, $G_{22}$). STM and LEED experiments were performed in ultrahigh vacuum chambers. Atomically clean Cu(110) surfaces were exposed to tartaric acid by direct sublimation of the 99% pure compounds into the chamber.
The STM images reveal that the bitartrate molecules are self-assembled in rows of three, each row stacking in parallel with others to form long chains. This molecular growth direction has the effect of destroying all the symmetry elements of the underlying metal, leading directly to the creation of a chiral surface that is non-superimposable on its mirror image. This observation suggests that cooperative behaviour of the adsorbed bitartrate molecules plays a central role in bestowing chirality, or `handedness', to the achiral metal surface.
We attribute this selfassembly to the close proximity of the a-hydroxy groups on neighbouring bitartrate molecules, leading to intermolecular hydrogen-bonding interactions that extend across the surface. The growth direction of this supramolecular assembly is dictated solely by the conformation of the a-hydroxy groups on the adsorbed bitartrate species. We note that in order to restrict supramolecular growth along one particular direction, the locations of the hydroxy groups need to be constrained in space. The bitartrate form meets this requirement by its two-point attachment to the surface via its carboxylate groups, which imparts a rigid and defined adsorption geometry.
Figure 2 STM images showing mirror chiral surfaces created by (R,R)- and (S,S)-TA adsorbed on Cu(110). Shown are 108 Å × 108 Å STM images of the (9 0, 1 2) (R,R)-TA bitartrate phase (a; $V_{tip} = -1.7$ V; $i_{tip} = 1.18$ nA) and the (9 0, -1 2) (S,S)-TA bitartrate phase (b; $V_{tip} = -2.73$ V; $i_{tip} = 1.02$ nA). Below each STM image is a schematic diagram displaying the position of the molecular features observed relative to the Cu(110) surface.
We also investigated the behaviour of the mirror-image modifier, (S,S)-tartaric acid, in order to verify that directed supramolecular assembly is the pivotal factor in enabling modifiers to bestow chirality. The active (S,S)-TA bitartrate phase was created under identical conditions used for (R,R)-TA. Significantly, the chirality of the surface has now been switched, as illustrated by the STM images: the (9 0, -1 2) phase of (S,S)-TA on Cu(110) is a true mirror image of the (9 0, 1 2) phase obtained for (R,R)-TA. That is, the (S,S)-TA adsorbed layer shows chain growth in the mirror direction, and the alignment of individual molecules in each row of three has also been switched to the mirror orientation.
This chiral switching can be explained in terms of molecular structure and its effect on supramolecular assembly. Both TA enantiomers possess defined and rigid adsorption geometries arising from their two-point bonding with the metal surface. The only difference between them is the spatial orientation of their OH groups. For (R,R)-TA, the positions of the OH groups and the directionality of intermolecular hydrogen-bonds leads to a molecular chain alignment along one particular direction. For (S,S)-TA, the mirror positioning of the hydroxy groups now naturally forces chain growth along the mirror direction, explaining why the mirror unit mesh is formed.
Figure 3 The spatial alignment and intermolecular hydrogen-bonding interactions of the α-hydroxy groups on the two enantiomers of tartaric acid. Left column, (R,R)-TA; right column, (S,S)-TA. The short, thick lines show extended hydrogen-bonding interactions: in a, these interactions dictate the direction of long chain growth; in b, they ‘weave together’ the three molecular chains.
Our findings demonstrate that it is possible to sustain a single chiral domain across an extended surface, provided that reflection domains of opposite handedness are removed by a rigid and chiral local adsorption geometry, and that inequivalent rotation domains are removed by successful matching of the rotational symmetry of the adsorbed molecule with that of the underlying metal surface.
Cysteine/Au(110): top surface imaging


RT-deposition and diluted at 340 K for 15 min.
Here we report scanning tunnelling microscopy studies of cysteine adsorbed to a (110) gold surface, which show that molecular pairs formed from a racemic mixture of this naturally occurring amino acid are exclusively homochiral, and that their binding to the gold surface is associated with local surface restructuring. Density functional theory calculations indicate that the chiral specificity of the dimer formation process is driven by the optimization of three bonds on each cysteine molecule.
These findings thus provide a clear molecular-level illustration of the well-known three-point contact model for chiral recognition in a simple bimolecular system.

The mercapto or thiol group -SH binds to gold with high affinity, and a rich literature on the adsorption of self-assembled thiol monolayers on gold surfaces exists. Of the 20 naturally occurring amino acids, only cysteine (HS-CH$_2$-CH(NH$_2$)-COOH) contains a mercapto substituent, making this chiral amino acid interesting for studying adsorption on gold surfaces.
Schematic illustrations of the structural features of the amino acid and the gold surface used in this study are given in Fig. 1a and b. Figure 1c shows a scanning tunnelling microscope (STM) image of the gold surface with a low density of adsorbed L-cysteine molecules. The deposition of cysteine leads to the formation of bright protrusions at the sides of the close-packed gold atom rows. The protrusions always exist as pairs, and we ascribe each of the protrusions to an individual cysteine molecule. We have not observed any unpaired protrusions that could be interpreted as isolated molecules.
The main axis running through the two bright lobes of these characteristic double-lobe features is always rotated 20 degrees clockwise with respect to the close-packed direction. The adsorbed cysteine pairs thus break the mirror symmetry of the gold surface. When the mirror-image form of the molecules, D-cysteine, is deposited, we observe similar molecular pairs, but these are rotated 20 degrees anticlockwise with respect to the surface direction (Fig. 1d). The breaking of the mirror symmetry of the gold surface must therefore result from the chirality of the cysteine molecules themselves, with the STM measurements allowing us to identify the chiral conformation of individual, enantiomERICALLY pure molecular pairs.
When depositing a racemic mixture of cysteine onto the gold surface, we observe molecular dimers (see Fig. 1e) identical to those seen in the previous measurements using pure enantiomers, that is, they are either of the LL form (rotated clockwise) or of the DD form (rotated anticlockwise). New structures that could be ascribed to the pairing of molecules of opposite chirality are not observed. This result suggests that the dimerization of the cysteine molecules is highly stereoselective, with each molecule binding exclusively to partners that have an identical enantiomeric form.
We have performed ab initio density-functional theory (DFT) calculations. Starting with pairs of cysteine molecules interacting in the gas phase, we find stable bimolecular complexes held together through (1) single or double OH-O hydrogen bonds formed between carboxylic groups on the two molecules, (2) one or two OH-N hydrogen bonds formed between carboxylic and amino groups, or (3) an S-S bond between two cysteinates (-SCH$_2$- CH(NH$_2$)-COOH). The interaction involving the carboxylic groups leads to the most stable configuration. We also draw upon the general knowledge that thiols at Au surfaces undergo dissociation to thiolates, followed by binding to the surface through a S-Au bond.
The most favourable adsorption configuration calculated for an LL dimer adsorbed on a four-atom-vacancy structure in the gold rows is shown in Fig. 3a. For comparison, the figure also shows a simulated STM image of this LL dimer. Distinct, bright lobes are found over each of the molecules, in agreement with the experimental STM image (Fig. 1c). Because D- and L-cysteine are related by mirror symmetry, a DD dimer is formed by mirroring of the LL dimer in the (001) crystal plane through the gold close-packed row, yielding an STM image in accordance with the experimental DD dimer image (Fig. 1d).
Figure 4 Illustration of the three-point contact model for enantioselectivity in intermolecular interactions. The molecule on the left with contact points A, B and C matches the corresponding receptor sites A', B' and C'. The mirror-imaged enantiomeric form of the molecule (right) does not match this receptor, thereby enabling chiral discrimination.
The DFT studies indicate that the preferred formation of homochiral dimers is driven by the optimization of three bonds on each cysteine molecule (sulphur-gold, amino-gold, and carboxylic-carboxylic). By directly pinpointing the three bonds involved in the chiral recognition process, our results constitute a direct molecular-level demonstration of the generic, conceptual three-point contact model for chiral recognition, illustrated in Fig. 4.
CD
Circular Dichroism

Electric Dipole / Electric Quadrupole Interaction

Electric Dipole / Magnetic Dipole Interaction

$10^{-3}$

CDAD
Circular Dichroism in the Angular Distribution of Photoelectrons

Electric Dipole Interaction

Chiral molecules in gas phase
(1990) 255

Handedness in the experiment
G. Schönhense, Physica Scripta T31
Asymmetry = \text{CD} = CDAD = \frac{I_+ - I_-}{I_+ + I_-} \quad + : \text{ right handed polarization}
- : \text{ left handed polarization}
Considerations on experimental geometry in case of linear achiral molecules on a surface

J. Bansmann et al, PRB 46, 13496 (1992)

Measurement on out-of-plane causes chiral geometry
High coverage (3x2) phase

Alanine on Cu(110)

M. Polcik et al., PRL 92, 236203 (2004).
2,3-Butanediol on Si(100)

J.W. Kim et al.

(S,S) on Si(100) dimer in a six-membered ring

- Surface features of clean Si(100) are reduced completely.
- Most apparent change occurs on O 2p levels from the free molecule.
Butanediol on Si/ Si 2p spectra

Clean Si(100)
hv=130 eV

Second layer(0.24 eV)
Up-dimer (-0.51 eV)

Butanediol/Si(100)
hv=130 eV

Second layer plus Si-H(0.23 eV)
Si-O (0.97 eV)
Butanediol on Si/ C 1s spectra

C 1s
\( h\nu = 330 \text{ eV} \)

Intensity (arb. unit)

Binding Energy (eV)

RCP
LCP

(R,R)
(S,S)
(R,S)

normal emission
Butanediol/Si(100) - angular distribution of CD

(R)-Methyloxirane

assignment from Gaussian calculation
Methyl oxirane/Si(100) C 1s XPS

Methyl oxirane/Si(100) Si 2p XPS

Methyl oxirane/Si(100) valence

Methyl oxirane/Si(100) adsorption geometries

(a)  (b)
Methyl oxirane/Si(100) C 1s XPS

CD effect in core level photoemission from adsorbed chiral molecules.

In-plane geometry: No contribution due to experimental handedness.

Results are invariant under a parity operation which changes photon helicity and handedness of the molecule.

\[ I(+,R) = I(-,S) \Rightarrow \text{Asymmetry changes sign} \]