Physical Chirality.
It Feeds on Negative Entropy *

G. Gilat
Department of Physics
Technion, Haifa 32000, Israel
email: gilat@physics.technion.ac.il

Abstract
Chirality is considered by many scientists to be mainly a geometric concept. There exists also a physical aspect of chirality which is largely being overlooked at. Two examples of mechanical devices are introduced here that represent “Physical Chirality”. These are a rotating water sprinkler and a variant of Crookes’ radiometer. When interacting with appropriate media, they both choose only one mode of rotation out of two possible ones. Such a behavior does not obey time-reversal invariance, which is regarded to be a rule in classical mechanics. This is due to their chiral nature. Instead, they do obey a space-time (ST) law of invariance, that is, what is rotating in the opposite direction is the mirror-image of the given device. In a recent experiment of Koumura et al. they discovered a similar behavior of a molecular rotor. The possible biological significance of physical chirality is emphasized hereby, and the conclusion is that chiral molecular systems do not reach readily thermal equilibrium. In other words: “Physical chirality does feed on negative entropy”, and therefore, it may well be of crucial value to life.

1 Introduction
The phenomenon of structural chirality of crystals and molecules has been recognized since the early 19th century when Arago\(^1\) and Biot\(^2\) did demonstrate the effect of optical activity in quartz crystals. Louis Pasteur\(^3\) was the first one to observe chirality on a molecular level and specified it as “dissymmetry”. The term “Chirality” was first introduced by Kelvin\(^4\), who also defined this concept as a property of any object that cannot superimpose, or overlap, completely its own mirror image.

*Published at Fundamentals of Life
© 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved
Eds., G. Palyi, C. Zucchi, L. Caglioti.
3-8 Sep. 2000, Modena, Italy.
The main reason for Kelvin to modify this term came from the fact that chirality did not necessarily imply a total lack of symmetry. Actually, chirality does lack the symmetry property of reflection, but chiral shapes of bodies may also obey so-called continuous symmetry operations such as rotational and/or translational symmetries.

At this point it becomes relevant to point out that the concept of chirality in science is largely considered to be mainly of geometrical nature. Even Kelvin’s definition of chirality concerns mainly the geometric shape of a body, regardless of its physical properties. For this very reason it becomes necessary to point out possible physical aspects of chirality and this becomes one of the main motivations of the present article. A physical body may contain in it various different materials. It may also contain different properties such as colors or magnetic structure. All these are not considered as realistic from geometrical viewpoint. Such properties may have physical aspects and they form the basis for what is referred to as “Physical chirality”. A body that contains this property of physical chirality may operate in a peculiar mode that differs considerably from a regular mode of operation of an achiral body. The source of such an operation comes from a specific type of interaction that exists between various mechanical devices and different media such as flow of air or water and even light radiation. What is special about this type of interaction is the presence of chiral structure in these devices which makes their mode of operation quite different from other interactions which are based on achiral objects such as the Newtonian mass point. Such an interaction is to be labeled “chiral interaction” (CI) and it has already been described and treated in several publications.\textsuperscript{5–7} It is important to note that this phenomenon of physical chirality is largely being ignored and overlooked in classical mechanics, and many physicists are quite unaware of its physical significance in the domain of biophysics.

2 Chiral Interaction in Mechanical Devices

As mentioned above, chiral interaction is not limited to molecular structure only, but there exist various mechanical chiral devices that function according to the same principle. The most obvious chiral device is the rotating water sprinkler (see Fig. 1). When the water stream enters the sprinkler it “knows” immediately in which direction to rotate. This is so due to its chiral structure. What is rotating in the opposite direction is the mirror image of the given sprinkler. Let us define now by D and L the “enantiomers” of the rotating sprinkler according to its direction of rotation being clock or anti clockwise, respectively. Another common chiral device is the windmill. When wind blows at the vanes of the mill it also “knows” instantly to which direction to rotate. This is due to its chiral design. If it did contain reflection symmetry with respect to its axis of rotation, it “would not know” to which direction to rotate. The next example, shown in Fig. 2, is somewhat more sophisticated, and it depends on a different mode of chirality. This device is a simple variant of the Crookes’ radiometer. The active medium in this case is light radiation. The element of chirality here consists of two different colors on both sides of the rotating blades, being black and silver, respectively. This is a special example of a physical rather than a geometric chirality. From a pure geometric sense of view this radiometer contains a complete reflection symmetry and, therefore, it can be regarded as achiral. Physical chirality\textsuperscript{7,8} is presented by the chiral distribution of a physical property rather than by a chiral geometric shape.
Physical chirality differs from a geometric one in its capability of interacting with various media surrounding it. In the case of this special example of a variant of the ordinary Crookes’ radiometer, the physical distribution of the black and silver colors on the blades represents a large difference in the light absorption coefficient of the blades. The silver side reflects back the light, whereas the black side absorbs the light and therefore becomes warmer in comparison to the silver one. This causes the air close to the black side to become heated, and as a result it expands and pushes back the black side, which ends up in rotating the device in the preferred direction of the black side of the blade. The selection of the sense of rotation of the blades is made by the variance of colors on the blades and their interaction with light. The concept of physical chirality here is represented by the distribution of the optical absorption coefficient on the blades and not by their geometric shape.

![Figure 1](image_url)

Figure 1: (A) Two rotating water sprinklers are shown as examples of chiral devices. The sprinkler rotating in clock-wise direction when looking at it from above is marked by D and its mirror image by L. At the bottom, both sprinklers are shown from above. These provide for an excellent example of time irreversible macro chiral device. (B) At the bottom it is shown that by reversing the direction of the flow of water, the vectorial difference of the water flow momentum at the bending of the sprinkler, does still rotate the sprinkler in the same direction. This is why the rotating water sprinkler is space-time (ST)-invariant.
One of the main objectives for carefully analyzing the action of chiral mechanical device is to point out a certain unusual result that is derived from their operation. The choice of only one direction of rotation by these devices is not readily acceptable in classical mechanics. Actually, the meaning of this mode of operation is that chiral interaction does not obey time-reversible invariance. By reversing the direction of motion of the interacting media, such as the flow of water in the sprinkler (see Fig. 1), or the direction of the light radiation in the case of the radiometer (see Fig. 2), the direction of rotation of the devices does not change, it remains the same. This is the main effect of chirality in these cases. What does rotate in the opposite direction is the mirror-image of each of these chiral devices. This effect happened also to irritate Richard Feynman who tried to reverse the direction of flow of water in the sprinkler and caused a flood in his laboratory at Los Alamos. Actually, by looking carefully at the bending of the sprinkler, where the direction of the momentum of the water is varying and it creates an angular momentum to the sprinkler with respect to its axis. It can now be readily deduced that the difference in the water momentum will create the same direction of angular momentum, regardless of which side the water is flowing from (see Fig. 1).

Figure 2: A variant of Crookes’ radiometer is an example of the operation of chiral interaction (CI). The asymmetry in the optical absorption coefficient between the black and the silver blades generates a temperature difference between them when light is shining at the device. This expands the air on the side of the black blade which, in turn, pushes it around the axis AB in the preferred direction towards the black vane. This is an example of a physical rather than of a geometric chirality where the chirality is in the colors of the blades and not in their geometric shape.
A similar conclusion is derived from the action of the radiometer. It always rotates in the direction of the black blade regardless of the direction from which the light is shining at. In what follows this phenomenon is further treated on.

To summarize the main features of chiral interaction (CI) in mechanical-devices, let us notice that in all these examples there exists a specific medium with which the chiral device is interacting and this is always happening at an interface separating the device from the active medium. The physical chirality is built into this very interface. CI is a process by which energy is transferred from the active medium into the chiral device which causes a rotational motion, being usually of mechanical nature. The most significant aspect of the chiral interaction process is its mode of selecting only one direction of rotation out of two possible ones, which is to be attributed to the chiral nature of the device. The mirror image of the given chiral device, interacting with the same medium, does produce the same rotational motion in the opposite direction. This is to be regarded as a main feature of chiral interaction.

The effect of chiral interaction (CI) on a molecular level is less recognizable in comparison to that of macro-chiral devices. The main reason for this is that CI occurs mainly within the chiral system, or molecule, in the form of rather small perturbations which are not easy to detect experimentally. In a recent experiment by Koumura et.al they observed also a similar behavior of chiral interaction on a molecular level of “monodirectional molecular rotor”. Much more recognizable are the physical effects associated with molecular chiral structure, such as optical activity and related effects. These are to be regarded as “chiral scattering”, rather than CI, since the observable effect concerns the polarized light being scattered away from the chiral molecule, rather than its effect on the molecule itself which is intrinsic and cannot be readily detectable. This is chiral interaction.

A physical model of chiral interaction (CI) in soluble proteins and amino-acids has already been developed and described in detail in several publications. The description here contains only a few main features of this model. The active medium in this model consists of a random motion of ions, including protons, throughout the solvent, being mostly regular water. The chiral element that interacts with these ions is an electric dipole moment that exists in the protein structure. This interaction causes a moving ion to be deflected away from its original track of motion, which creates a continuous perturbation along the α-helix of which the proteins consist, and this perturbation moves along the helix in one preferred direction out of two possible ones. Such a perturbation of each ion is energetically rather small, but they add up together for the whole protein molecule and become comparable to the size of thermal energy. This is an abbreviated description of the model of CI that occurs in soluble proteins. A more detailed description appears in earlier publications. The perturbation resulting from this CI is of electric nature, rather than a mechanical one. Another interesting aspect of this CI is that it is happening at an interface separating the interior of the protein molecule from the solvent. This is due to the globular structure of the soluble protein. It is well known that all soluble proteins become globular before they can function as enzymes.

As mentioned above chiral interaction is not easy to observe experimentally on a molecular level due to the small size of this effect. Nevertheless, there exists a certain strong supporting evidence for its existence owing to an experiment performed by Careri et al. This experiment concerns the effect of dehydration on the protonic, or ionic, motion through-
out the hydration layers surrounding soluble proteins. The amount of water around each protein is crucial for free protonic motion around the molecule, which is also crucial for chiral interaction. By dehydrating these water layers, a level is being reached when protonic motion becomes awkward and stops, and so does also, simultaneously, the enzymatic activity of the protein molecule. On re-hydrating the molecule, protonic motion becomes possible again and this, in turn, causes also the onset of enzymatic activity of the protein molecule. This experiment shows that free ionic motion around soluble protein molecules, which is a necessary condition for chiral interaction, is also necessary for their enzymatic activity.

3 Physical Aspects and Biological Significance

The main objective of the present article is to draw several physical conclusions from the phenomenon of chiral interaction in macro-chiral devices, which are quite different from the regular rules that exist in classical mechanics. The source of these differences arises from the presence of physical chirality as a major feature, instead of the achiral environment that plays a basic role in classical mechanics. From these conclusions analogies can be drawn for the function of molecular chiral systems, which may well be of considerable significance in molecular biology.

The first conclusion concerns the symmetry operation of time-reversibility that exists in many examples of classical physics. As mentioned before, in the case of chiral interaction time-reversibility cannot be conserved. The rotating water sprinkler, rotates about its axis in a single preferred direction due to its chiral design. What is rotating in the opposite direction is the mirror-image of the given sprinkler. The meaning of this mode of symmetry operation is that a rotating water sprinkler is not time-reversible, but it obeys space-time invariance.

The meaning of this conclusion is not very common in classical mechanics. The reason for this is that the physical nature of chirality has not been so far well recognized and treated in mechanics. In particular, the fact that it does not obey time invariance. As shown before, this can be readily deduced by a simple momentum consideration for the operation of a rotating water sprinkler. The vectorial velocity of the stream of water changes its direction at the bending of the sprinkler, and the momentum change caused by this is transferred to the sprinkler, which determines the sense of rotation of the sprinkler (see Fig. 1). Upon “reversing” time, the stream of water “reverses” its direction of flow. Let us now analyze briefly the situation if the stream of water reverses, its direction of flow. Let \( \vec{v}_1 \) and \( \vec{v}_2 \) be the velocity vectors of the original flow of water before and behind the sprinkler bending, respectively, and \( \Delta \vec{v} = \vec{v}_1 - \vec{v}_2 \) be the change in these velocities, which is proportional to the momentum transfer to the sprinkler. Now let \( \vec{u}_1 \) and \( \vec{u}_2 \) be the opposite velocities, respectively, upon reversing the direction of the water stream. It is obvious that \( \vec{u}_1 = -\vec{v}_2 \) and \( \vec{u}_2 = -\vec{v}_1 \). Let \( \Delta \vec{u} = \vec{u}_1 - \vec{u}_2 \), then

\[
\Delta u = \vec{u}_1 - \vec{u}_2 = (-\vec{v}_2) - (-\vec{v}_1) = \vec{v}_1 - \vec{v}_2 = \Delta \vec{v}
\]

which proves that the change of velocity at the sprinkler bending remains the same regardless of the water flow reversal. This is also shown in detail in Fig. 1. A similar situation exists also for the rotating radiometer. No matter from which direction the light is shining, at its blade, it does rotate always in the direction of the black wing owing to the existing physical
situation. Such a behavior does not obey time reversal invariance, but rather space-time invariance. Let us now express the space-time inversion by $S$ and $T$, respectively: then a rotating water sprinkler does obey the ST-invariance. The same is true for all the examples given here of macro-chiral devices. The same is also true for the protein molecule example. A similar rule of PT-invariance (or CPT invariance) is recognized in physics due to the presence of a spin in quantum mechanics, but it is absent in classical physics because the concept of physical chirality has been so far completely overlooked at. In particular, its mechanical aspects. This concept of chirality appears much more in chemistry due to the presence of many chiral molecules in organic compounds, but chirality is mostly regarded and treated in chemistry in terms of geometric shape, rather than in its physical properties and contents. For this reason the concept of chiral interaction has so far been largely ignored in researches concerning chirality.

Such space-time symmetry operations for chiral devices may contain also a certain aspect of practicality. This is so in contrast to their presence in the domain of elementary particles in physics. From this viewpoint any time-reversible process is almost completely useless from any aspect of practicality. For instance, any machine operation that produces a certain function or object, or any information transfer process, are completely time-irreversible. These include also biomolecular functions such as enzymatic activity and other processes which are totally time-irreversible. For such reasons of practicality, the function of chiral devices, or molecules, may be of special significance in comparison to time reversible phenomena.

The next consideration involves the mode of selection, where only one direction of rotation is excited by chiral interaction, whereas the opposite direction remains largely inactive. Judging it from a thermodynamical aspect, what is happening here is that only one half of the energy that can be activated by the device is excited by CI, whereas the other half remains mostly inactive. On a molecular level this means that only one half of the energy states of the system that are populated by CI become active, whereas the other half remain relatively empty. In other words, the system does not readily reach thermal equilibrium. This conclusion is of very substantial and significant meaning for living systems because reaching thermal equilibrium practically means death.

Another way of looking at this effect is from the viewpoint of ergodicity. This concept was introduced by Boltzmann about a century ago, and it considers the mode of approaching thermal equilibrium of a single particle. This is done as a process of time average, instead of a statistical average of a large ensemble of particles. In view of this, the average velocity of such a particle, in any given direction, approaches zero as a function of time. This is not the case if, for instance, the average angular velocity of a rotating water sprinkler is regarded as a function of time. This is, actually, true for any effect of CI, when averaged as a function of time. The selection of one direction of motion out of two possible ones, which is typical of CI, makes its mode of motion to become a non-ergodic entity, which again causes it to avoid thermal equilibrium. This property of CI on a microscopic level is, apparently, one of the most crucial advantages that chirality, or CI, does contribute to molecular biology. It does postpone thermal equilibrium, or death, for a considerable length of time, so that the biological function of these molecules can go on and not be affected by approaching thermal equilibrium.

In this context it is significant to mention also Schrödinger, who became interested in the phenomenon of life and wrote a book $^{15}$ “What is Life?” in 1944. His main conclusion in this
book was: “It feeds on negative entropy”. This expression becomes also quite appropriate for the function of physical chirality and this is the reason for borrowing it as part of the title of the present article. This is exactly what chiral interaction is performing in its mode of selecting only one direction of motion. Such a mode of activity reduces considerably the entropy of the system. In relation to the phenomenon of non-ergodicity it is also important to mention its relevance to the process of evolution, which is crucial in biology. It is reasonable to deduce that systems that reach readily thermal equilibrium never do undergo the process of evolution and remain basically unchanged forever. Non-ergodic molecular systems have a better chance to undergo evolutionary changes.

4 Discussion and Conclusions

Another aspect of chiral interaction regards the nature of this effect, as well as the size of energy that is involved in such a process. In discussing this case it is not relevant to consider macro-chiral devices, and our main concern is chiral interaction of biomolecular systems. Unfortunately, our knowledge at present, of this effect is quite limited and this is mainly because of the small amount of energy involved in this effect, which is quite difficult to observe experimentally. This may evoke criticism as to its possible significance. Such a criticism is rather common among scientists who tend to attribute significance to energy according to its size. What may be much more significant than the amount of energy involved in living processes, is its quality, or degree of sophistication. This is particularly so in complex systems such as certain biomolecules, proteins for example. The feature of time-irreversibility of CI does contribute a degree of sophistication to the activity of biomolecules. In addition to this, there exist quite a few examples of highly sophisticated modes of energy which do require rather minute quantities of energy. For instance, an information transfer process requires a high degree of sophistication in wave modulation, but its size of energy is relatively small. In comparison, boiling a kettle of water requires much more energy, but what is its degree of sophistication? Another example is the small amount of energy required to switch on and off a much larger source of energy. This example can be regarded as a mode of control mechanism energy, which may also be the of significance to CI in biology. Another, rather cruel example, concerns the magnitude of energy change that occurs over a short time interval during which a creature ceases to live. The change in energy is rather small but its significance is very impressive. In these examples and many others, the amount of energy involved in their performance is of little interest, but their main effect is in their degree of sophistication.

The experiment of Koumura et al.\textsuperscript{9} is a significant and important progress on a molecular level. This is the first successful proof that a monodirectional molecular rotor can be fabricated. The chiral interaction leading to this operation is based on light radiation. This experiment supplies for a beginning of support for the assumption of non-ergodic nature of chiral interaction on a molecular level, being the basis for its negative entropy and therefore for its avoiding readily thermodynamical equilibrium. In addition to this there exists also the analysis of behavior of globular proteins\textsuperscript{5–7,10–12} which also react in a monodirectional manner. The experiment of Careri et al.\textsuperscript{13} provides for a supporting evidence for the significance of CI in the enzymatic activity of proteins. It is quite reasonable to assume that in
biology, or in any living substance, the presence of such modes of highly sophisticated and low energy signals may have an important function in its life process.

In conclusion, let us mention again the significance and importance of the phenomenon of chirality in biology. In particular the features of chiral interaction (CI) that differ largely from those of classical physics that do not contain chiral structures in their interactions. These include the ST-invariance of chiral interaction, which causes it to be time-irreversible. The selectivity nature of CI by preferring one mode of motion out of two possible ones, enables CI to become non-ergodic (or, more specifically, to delay considerably its reaching thermal equilibrium), which is a crucial element in life processes and biological evolution. In other words: “it feeds on negative entropy”, as Schroedinger wrote in his book.

Acknowledgement

The author wishes to thank Sharon and Yoram Yihyie for producing the figures in this article as well as Gila Etzion for their help in completing this article.

References

[1] Arago F., “Memoires de la Classe des Sciences Math. et Phys. de l’Institut Imperial de France”, Part 1, (1811) 93.
[2] Biot J.B., “Memoires de la Classe des Sciences Math. et Phys. de l’Institut Imperial de France, Part 1, (1812) 371.
[3] Pasteur L., Ann. Chim. 24, (1848) 457.
[4] Kelvin W.T., “Baltimore Lectures”, C.J. Clay & Sons, London (1904).
[5] Gilat G., Chem. Phys. Lett. 121, (1985) 9.
[6] Gilat G., Mol. Eng. 1, (1991) 161.
[7] Gilat G., “The Concept of Structural Chirality”, in “Concepts in Chemistry”, Ed. D.H. Rouvray (Research Studies Press and Wiley & Sons, London, New York, (1996) 325.
[8] (a) Gilat G., J. Phys. A22 (1989) L545. (b) ibid Found. Phys. Lett. 3, (1990) 189.
[9] Koumura N., Zijlstra R.W.J., van Delden R.A., Harada N. and Feringa B.L., Nature 401, (1999) 152.
[10] Gilat G., Schulman L.S., Chem. Phys. Lett. 121 (1985) 13.
[11] Gilat G., Chem. Phys. Lett. 125, (1986) 129.
[12] Gilat G., “On the Biological Advantage of Chirality”, in “Advances in Biochirality”, Palyi G., Zucchi C., Caglioti L. (Eds.), Elsevier Science S.A., (1999) 47.
[13] Tschesche H., “Globular Proteins” in “Biophysics”, Hoppe W., Lohmann W., Markl H., Ziegler H. (Eds.), Springer Verlag, Berlin (1983) 37.

[14] Careri G., Giasanti A., Rupley J.A., Phys. Rev. A37, (1988) 2703.

[15] Schrödinger E., “What is Life”, Cambridge University Press, Cambridge, 1944.