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BROKEN SYMMETRIES AT THE ORIGIN OF MATTER, AT THE ORIGIN OF LIFE AND AT THE ORIGIN OF CULTURE*

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In earliest cosmic history the university started with matter and not with antimatter. Shortly after the beginning the electroweak interaction — prominent in nuclear β decay — acted as a lefthander. Much later, in prebiotic evolution, optically left-handed amino acids determined the unique signature of following terrestrial organic life. Again ae- ons later, homo sapiens appears as predominantly right handed and creates cultures with many broken symmetries. Along these pathways of history it was essential *that choices were made* — left or right, matter or antimatter — but on several instances it seemed less relevant *which choices* were made. We think that biochirality occurred by global chance; perhaps by local necessity, but without causal links to the PCT theorem. In other cases — *e.g.* the standardization to right-handed screws — the choice will have been made by causal necessity.

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1. Introduction

Broken symmetries occur everywhere: at the origin of matter (not antimatter), in electroweak interactions with left-handed $V - A$ (not right-handed $V + A$) currents, at the origin of terrestrial life with exclusively optically left-handed (L not R) amino acids, in the human body with predominantly though not exclusively the heart to the left and the liver to the right, in Judeo-, Christian-, Islamitic-religion with an attachment to the metaphor "sitting at the right hand of God", in human relationships and in many state and society features.

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Table I shows examples ranging from perfect symmetry as in the case of ab- initio synthesis of chiral molecules in a chemistry laboratory to complete asymmetry as in the case of biochirality and as assumed in the Standard Model (SM) of electroweak interactions.

TABLE I

Broken symmetries

	Symmetry/Asymmetry
CP or T violation:	1 : 1.003 cosmic matter, no anti-matter
Electroweak Interaction; β decay	1 :$\leq 10^{-3}$ experimental (SM assumes 1:0)
Ab-initio chemistry of chiral molecules	1 : 1 or to 17 decimals by theory: 1 : 1.0000000000000000×
Biochirality with L-amino acids:	1 : $10^{-\infty}$ with maximality
Right-handed mankind:	1 : 10^{-1}
Situs Inversus	1 : 10^{-5} (heart at right side)

GLOSSARY:
Amino acids: acids of the type C_n H_{2n1} COOH with NH_2-groups. Twenty amino acids form the 20-syllable language of proteins.
Biochirality: in all organic material on Earth the amino acids are optically left (L) and the sugars optically right (R) handed in a key-and lock mechanism.
Bifurcation: (furca = fork): development towards either one of two possibilities, *e.g.* L either R.
Chiral: (cheir = hand in Greek), handedness, left or right. Of the 20 amino acids 'of Life' only one (glycine) is not chiral.
Chiral polarization of sample of molecules x:

$$\eta = (N_{\times L}\text{-}N_{\times R})/\ (N_{\times L} + N_{\times R}).$$

Enantiomer: the mirrored chiral molecule.
Homochiral: the chiral molecules are either L or R.
Polymers: long chains of smaller molecules.
Racemic materials: $\eta = 0$ with equal probability for L and R.
Radiometric clock: based on radioactive (*e.g.* ^{40}K) decay.
Stereo selectivity: with preference for L either R.

2. At the origin of matter

Mirror the world and your left hand becomes a right hand and vice versa, but all classical forces remain the same: Newtonian mechanics with forces proportional to d^2x/dt^2 are mirror invariant and do not violate Parity (P in Fig. 1a). Transform the elementary particles into their antiparticles, so that all charges Q change sign, but the Coulomb force being proportional with Q^2 remains the same for Charge Conjugation (C in Fig. 1b). Invert the timevector and all movements of elementary particles, but elementary

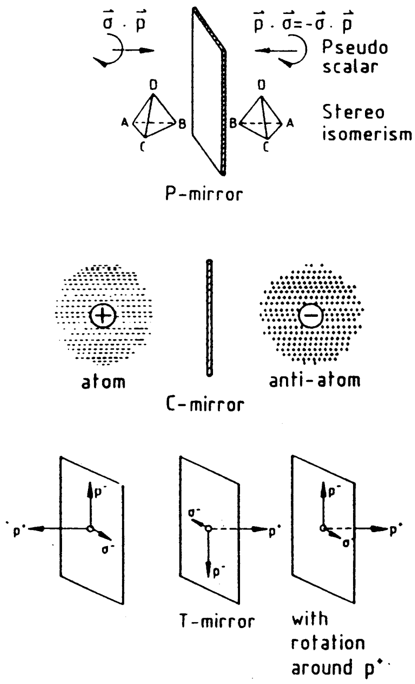

Fig. 1. Discrete transformations.

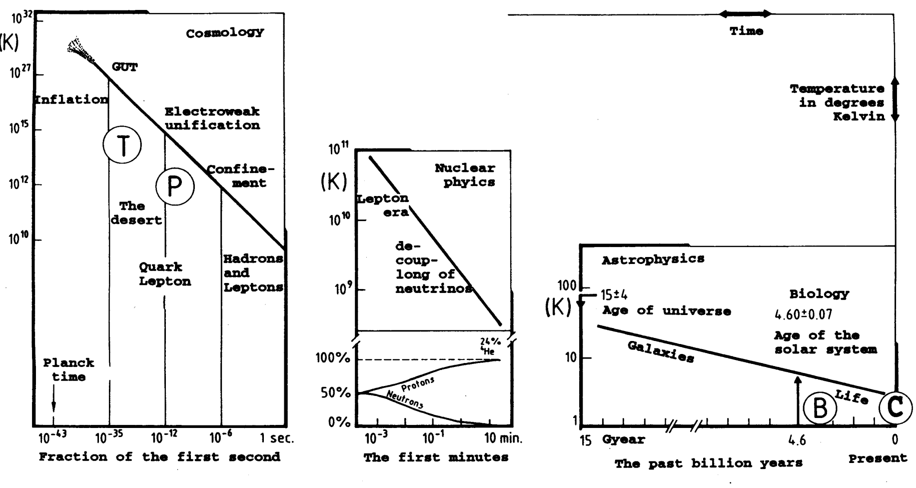

Fig. 2. History of a cooling (vertical axis) and expanding universe in three epochs. The broken symmetries and P are indicated in cosmology and later at the origin of biochirality (B) and culture (C).

processes will not change: they are invariant for Time Reversal (T in Fig. 1c) in classical physics.

However, we know since 1957 that nuclear β decay violates P as well as C with maximality. It looked for a while that these violations occurred together in such a way that there remained invariance for the product PC. But this appeared to be not always true. From kaonic decays followed that PC was violated too, be it not with maximality but very clearly at a level of 0.3%. We will return to the PC issue in a later lecture and mention here only that PC is connected with T through the PCT theorem:

Nature is invariant for the product transformation PCT regardless the possibility of P, C or T violation.

If accepted as true, this theorem implies that the observed PC violation is 'compensated' by T violation. This T violation is thus assumed by inference, but it has never been observed directly.

PC violation has been connected with the origin of matter. In conventional theory matter and antimatter annihilate each other. But with PC violation this annihilation is not exact. Andrej Sakharov [1] was one of the first to connect the baryon asymmetry of the universe with PC violation, suggesting that this violation allowed in earliest Cosmic history for a remnant of matter and for the baryonic (not antibaryonic) mass of the universe in which we live. Shortly thereafter followed the quark-lepton era with the electroweak P violation. Upon cooling down and after the "First Three Minutes" [2] all free neutrons are transformed into protons and 24% ^{4}He. At the beginning of Fig. 2c, atoms become stable, the cosmos becomes transparent and spiral galaxies start to be formed and to move away from each other in an expanding universe. Nowadays all far galaxies move away from us in a uniform way. However, their sense of spiraling is not uniform but random: a count showed within statistics equal numbers of clock and anti-clock wise spiraling galaxies (588 and 529, respectively). This uniform moving away from us combined with our observation of random spiraling implies that P is not violated but conserved in gravitational interaction. Our universe carries no net angular momentum and is not (quadrupole) deformed.

Having located various broken symmetries in cosmic history, we now proceed to a next chapter on biological chirality (B in Fig. 2c).

3. At the origin of Life

From prehistoric times man has wondered why for most of his kin the right hand performed better than the left hand. At a deeper level Louis Pasteur wondered about the unique biological chirality shared by all Life on our planet: the organic amino acids are left and the sugars are right handed. Till today this biochirality remains a mystery, although perhaps no longer as great a mystery as it was in the days of Pasteur.

The formation of organic polymers and the origin of self-replication of molecules has to be sought in the early terrestrial oceans. The history of Earth and Moon started 4.6 Gy ago with the condensation of Sun and planets. Radiometric age determinations reveal a clear picture: melting by plate tectonics has frequently reset the terrestrial clocks, so that they rarely indicate ages as old as 3.6 Gy (Fig. 3). The smaller Moon had a more quiet history, resulting in preservation of older moon rocks. However, it were the undisturbed meteorites which determined the 4.6 Gy age of the solar system.

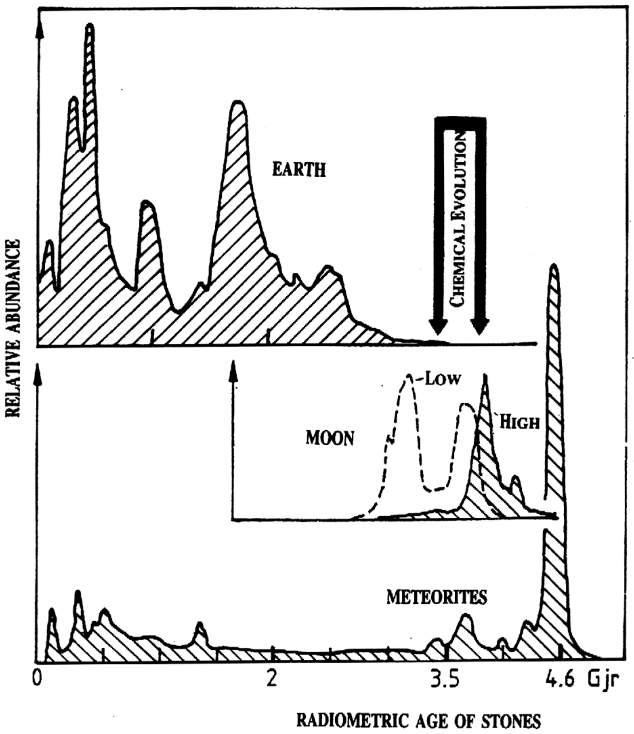

Fig. 3. Radiometric ages.

The surface of the young Earth suffered from violent meteoric impacts and from vulcanism, and cannot have been hospitable for a genesis of organic macro molecules before the time of 4 Gy ago. However, shortly thereafter and perhaps already before 3.6 Gy ago, there were algae as documented by fossils recognized in oldest terrestrial sediments. A chemical evolution, in which biochirality played its important role, must have preceded the appearance of these algae and this prebiotic evolution must have taken place within a time interval possibly shorter than 0.5 Gy. Concerning their chirality there has been a growing consensus in the last decades on two basic points:

(i) *The broken symmetry with its preference for L-amino acids occurred by chance and not by global necessity through electroweak parity violation* [3,4]: *a causal link between the broken symmetries B and P in Fig. 2 is unlikely.*

(ii) *The change of an originally racemic media into a homochiral one preceded the beginning of self-replication of organic molecules* [5] *in the early terrestrial oceans.*

The two points are important, but leave unanswered the epochal question *how* to arrive from initial racemity at chiral purity? That topic deserves first an introduction to *bifurcation.*

4. Bifurcation, racemization and a supernova hypothesis

The early oceans amassed substantial amounts of carbon-based molecules from outer space, molecules which are still found nowadays in interstellar dust and in chondritic meteorites. They occur in essence as racemic and they occur exponentially less with increasing complexity; two features indicating their formation by stochastic chemical reactions. Symmetry breaking is described by bifurcation [4,5] leading to hyper selectivity for left or right handed molecules in auto-catalytic chemical reactions. Fig. 4 illustrates the development in time of a medium with increasing concentration of molecules A and B which can combine to chiral enantiomers X_L and X_R with a chiral polarization η. When passing a critical bifurcation point t = b the originally racemic medium with $\eta = 0$ can become homochiral: L with $\eta = 1$ or R with $\eta = -1$.

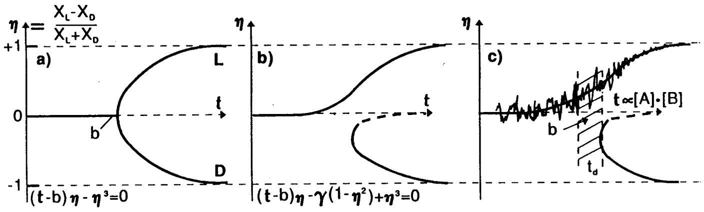

Fig. 4. Bifurcation of original racemity with $\eta = 0$ at low concentrations towards homochirality with $\eta = \pm 1$ at high concentrations after passing the critical bifurcation point b; a — steered by chance, b — steered by chiral selectivity γ, c — with noise.

The leftside figure is described by $(t - b)\eta - \eta^3 = 0$, while the middle one appears after adding a quadratic term $\gamma(1 - \eta^2)$ for chiral selectivity. In reality there is noise (right side) which makes that a critical (hatched) zone has to be passed. With Δ E = 10^{-18} eV and kT = 0.1 eV (at room temperature) the steering parameter $\gamma = \Delta$ E/kT becomes as small as 10^{-17}. Should this amount to one standard deviation in the number of reacting molecules, then an unrealistic number of 10^{34} primary molecules would be needed. However, a more detailed treatment [6] shows that during a slow passage of the zone the L and R molecules appear to be separated by a difference proportional with $\gamma^{1/3}$, which is larger than γ. But even then the process still requires 10^{24} molecules. Goldanskii *et al.* [5] judge it unlikely that such an amount stays undisturbed during more than 10^5 years in the bifurcation zone because *racemization* will occur with a typical time scale of 10^4 years.

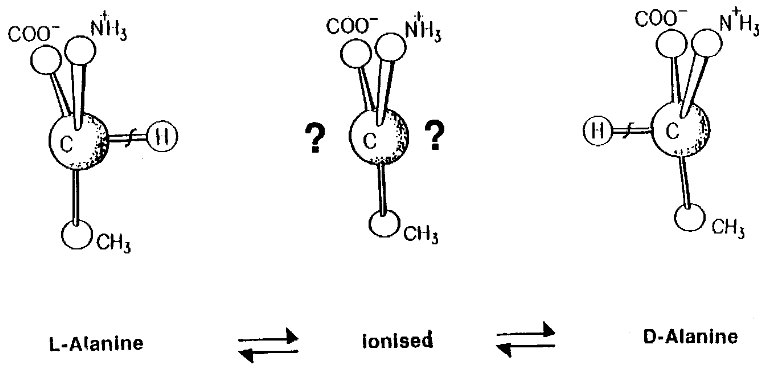

Fig. 5. Racemization can be visualized as a process in which an L-side hydrogen atom is changed into one at an R-side.

Racemization is a process by which homochiral samples of chiral molecules return by themselves to racemity within a typical halflife of 10^4 years. In a simplified picture (Fig. 5) an hydrogen atom gets occasionally unbound from a more or less planar alanine molecule (at left). The ionized molecule will immediately grasp another H from the water solution, be it on the same L side or on the other R side. The process, more appropriately described as *chemical tunneling*, is a severe obstacle in finding a mechanism to arrive at homochirality in prebiotic evolution. Citing Bonner [7] "all conceived theories to amplify molecular chirality have racemization as their ultimate Nemesis". The genesis of a homochiral medium seems to require a constant influx of molecules with a definite sign of chiral polarization.

There have been expectations that such an influx took place, and during writing of this treatise this has been affirmed by Engel and Macko [8]. They sampled minute amounts of amino acids from meteorites and reported deviations from racemity of extra-terrestrial origin as evidenced by ^{15}N-enrichments in the amino acids. Such enrichments (larger than 10%) cannot have been caused by terrestrial contamination.

A fascinating extra-terrestrial origin! But the questions persist: how did the chiral polarization originate and why did it, once originated, not disappear again by racemization?

There is at least one scenario (I know of no other) which may offer an explanation. It hypothesizes a supernova explosion (SN) shortly before the condensation of a presolar cloud into the Solar System 4.6 Gy ago. The SN will develop into a neutron star which in turn becomes a strong emitter of UV-light created by electrons spiraling in its magnetic field of $\sim 10^{13}$ Gauss. When emitted in a direction outside the plane of rotation of the neutron star this UV light will be circularly polarized, behaving like the pseudo scalar $\vec{p} \cdot \vec{\sigma}$ in Fig. 1 with opposite sign of the polarization at both sides of the plane. When shining upon the condensing Solar Cloud at one or the other side of the plane the UV light performs asymmetric photo- dissociation of macro molecules in interstellar dust and leaves a residue of molecules with one or the other sign of chiral polarization η. In this way photolyses to 50% can create $\eta \geq 0.01$. At interstellar temperatures between 10 and 20 K this η is in essence not reduced by racemization as it would be at 300 K. A steady influx on Earth of such molecules can steer the bifurcation in the early oceans.

The suggested "last minute SN" is not entirely hypothetical [9]. A last-minute presolar flare has once been advocated by Cameron [10] as being perhaps conditional to the origin of the solar system. The suggestion was based on observed overabundances in meteorites of ^{26}Mg, the decay product of 0.7-My ^{26m}Al produced in SNs. However, such anomalies may stem from earlier cosmic events.

At present we consider — strongly motivated by the biochirality perspective — a search for signals of a shortly presolar SN event by looking for isotopes which are produced in SNs, in specific by looking for isotopes with a halflife shorter than the 4.6 Gy age of the solar system, but long enough to be retraced by sophisticated accelerator mass spectrometry at the single-atom level. Upon investigation I found two (no more) candidates: ^{146}Sm and ^{244}Pu. When still observable, these isotopes offer evidence for their shortly presolar synthesis. Surviving primordial ^{146}Sm nuclei can be detected in a unique way with the ESR storage ring at GSI [11], which ring can store and cool heavy ions for 40 h with super resolution M/Δ M of order 10^6.

5. Mankind, crossbills and culture

Broken symmetries remain fascinating not only at the level of amino acids, but also when they appear in the formation of helixes of RNA and DNA, in the L-spiraling of most (not all) seashells, in the winding of climbing plants, in the asymmetry of many lobsters and crab fishes, in the typical (but not exclusive; Table I) left-side position of the human heart, and in the right handedness of mankind.

As said above mankind of all times, and far before the days of Louis Pasteur, has been wondering about his predominant right-handedness. Numerous medical treatises of varying scientific merit have been dealing with the issue. The nowadays often accepted explanation is that the unborn child is positioned in the mothers womb such that its left-side brain is developing better. This agrees with statistics on identical twins which have a good chance of opposite fetal positions and which show as a consequence a higher percentage of L-R symmetry and thus a larger than usual percentage of lefthanders. Here it is interesting to compare the human species with a bird species: the Crossbill (Loxia curvirostra). This species developed its crossed bill to feed on pine cones. Crossing “L over R” or “R over L” is for that purpose not essential. The young birds develop not inside a womb but inside an egg and show no preference for the way in which they cross their bill (Fig. 6). Had the Crossbill developed to culture, the species would not have been burdened by a prejudice of R with respect to L or vice versa.

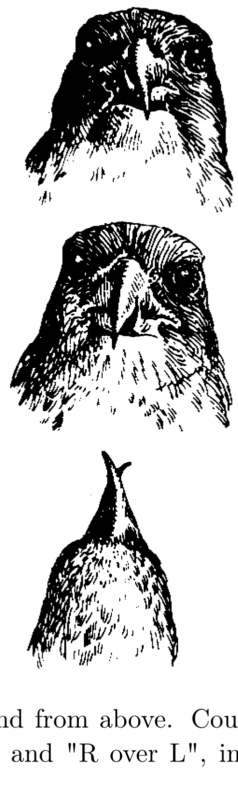

Fig. 6. Crossbill from front and from above. Counts on many birds show about equal numbers of" L over R" and "R over L", independent of the bills of their parents.

6. By chance or by necessity?

For the individual Crossbill it is essential that *a* choice is made; *which* choice does not matter. For traffic regulation the making of a choice (not which choice) has been essential too. Does this not hold in a broader scope of many social and cultural structures? Rules and customs seem needed, which rules and customs can often be debated. In other cases - seashells, right-handedness of mankind, society conventions - the need for a choice is even not evident, but a choice has been made nevertheless. Needed or not needed, the question remains whether choices have been made by chance or by causal necessity. I found examples o both. Sects. 3 and 4 mentioned the feeling that the biochirality occurred by global chance, but that local causality via a last-minute SN explosion, is a realistic possibility. The right-handedness of mankind, probably originating prenatal from fetal positioning (Sect. 5), is by itself again causal to many L-R adaptations in human society. In other cases there may be no direct causality, but once made a choice between L and R can be frozen in by tradition or by ritual, establishing at the time prejudices and discrimination in cultrues, arts and religions. Not too long ago, and even day, the left-handers among us know about this. Examples:

Causal Adaptations: In architecture and in technology the choices follow in many cases in a rational way from the predominant right-handedness of mankind: winding staircases of old castles will spiral in such a way that a usually right-handed attacker from below will be in disadvantage with respect to the defenders from aboave. That technology and industry chose in a previous century for R screws as standard becomes quite evident when one tries to get by hand a woodscrew of wrong helicity in tough material.

Random Adaptations. A choice once is made can perpetuate in communities and can be transferred easily to others which have not yet made a choice. With more difficulties this type of bifurcation can continue too when one community feels obliged or is forced to change and to confirm to a choice made by a majority of neighboring communities. This happens in traffic regulations. The left or right choice had to be made some centuries ago by perhaps at first a town (Rome?), then by a state, by continents, and in the future perhaps by the world.

Customs, prejudices and discrimination. In ancient tribal patterns the customs was often adjusted to the common; all that deviates from the common had a good chance of being treated with suspicion and in the end with disapproval. In the Judeo-Christian-Islamitic tradition and in other major religions the lefthander falls into that category; the right-hand position is the place of honor ("sitting at the right hand of God"). Some chemistry books denote *left* not by L but by S from Sinister and *right* not by R but by D from Dexter related to the positive word *dexterous.*

Arts: Concerning ancient cave paintings, the artists draw in the dark caves and not in situ their animals mostly running from left to right. I noticed that this is not always the case in (Scandinavian) rock carvings in the open air. There the artists could depict the animals in situ on the rock along which they had been moving in reality either from left to right or vise versa.

Concerning medieval arts, it is said that they depict the devil as a left-hander (Fig. 7). Like many statements on L or R preferences, this is not always true according to my own notes: Jeroen Bosch (∼1450-1516) painted *e.g.* multitudes of devils, but his figures are in essence always right handed. Vincent Van Gogh wrote once to his brother Theo that he judged the mirror version of the Potato Eaters, his most famous painting, artistically unacceptable.

Fig. 7. Left-handed Devil.

There is a paper in Nature by McManus and Humphrey [12] claiming that portrait painters have tended to paint the left cheek rather than the right one, the percentages being 68% for women and 56% for men ($P < 0.001$ on χ^2 test).

Arts and Sciences. I allow myself some skepticism about possible hidden science in Ref. [12] as well as in the statement by van Gogh. McManus and Humphrey present a story on kings having strong feelings about which side of their royal face they wished to put on show. King Edward VII had misgivings about coins made with the right-side of his face, arising from a firm conviction that the left-side features were superior. "Superior by chance or by necessity?" becomes then again an interesting question. However, the likely reality will be that the first actor chooses at random and that others follow. In any case, I counted Roman coins depicted in a catalogue [13] and found opposite evidence: 85% show R- and 15% L-side faces of sturdy self-reliant Roman Emperors. Later 16th-19th century European coins follow according to my counting less pronounced but still in majority (69% R; 31% L) the Roman example.

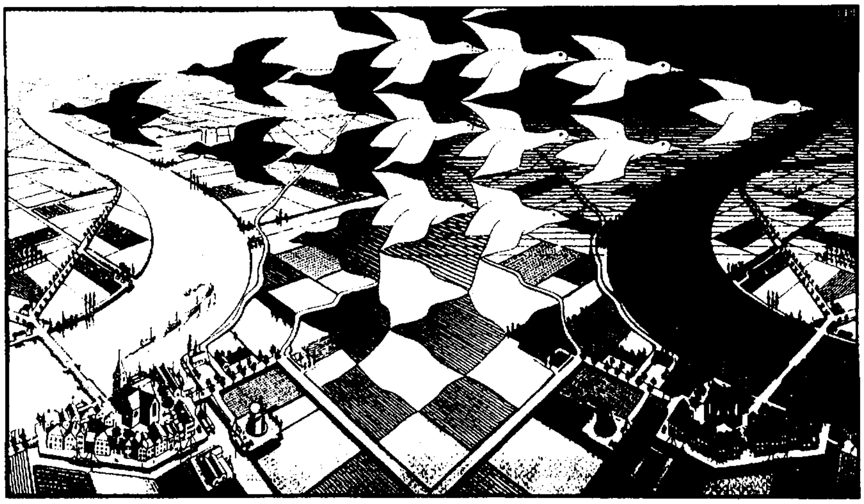

Fig. 8. Escher: Time reversal.

Let me end by showing a famous Escher [14] of beauty and nature in the Low Countries where he made the picture which may evoke in our minds reminiscences of the Time Reversal at the beginning of this lecture.

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