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Enantiomorphy and Time

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This article argues that time-asymmetric processes in spacetime are enantiomorphs. Subsequently, the Kantian puzzle concerning enantiomorphs in space is reviewed to introduce a number of positions concerning enantiomorphy, and to arrive at a dilemma: one must either reject that orientations of enantiomorphs are determinate, or furnish space or objects with orientation. The discussion on space is then used to derive two problems in the debate on the direction of time. First, it is shown that certain kinds of reductionism about the direction of time are at variance with the claim that orientation of enantiomorphic objects is intrinsic. Second, it is argued that reductive explanations of time-asymmetric processes presuppose that enantiomorphic processes do not have determinate orientation.

1. Introduction

In the last century, a great deal of literature on the direction of time has accumulated. Much of this work is dedicated to attempts to reduce the direction of time or the time asymmetry of processes to other properties of the processes, usually the dynamical laws governing them, or their boundary conditions. The fact that time-asymmetric processes are enantiomorphs has not attracted much attention in this literature. This article explains what it means for processes to be enantiomorphs, and explores some of the consequences for the debate on the direction of time.

Enantiomorphy of spatial objects is familiar to all of us. We all know that a left hand cannot, by some suitable combination of shifts and twists, be transformed to fit into a right-handed glove. Philosophers may be even more familiar with enantiomorphy due to the argument for the existence of absolute space given by Kant (1768) and the ongoing discussion of this argument in the philosophical literature. The article brings to bear some insights from this discussion on the discussion concerning the direction of time. First, certain kinds of reductionism about the direction of time are seen to be incompatible with the position that enantiomorphic objects have intrinsic orientation.

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Second, reductive explanations of the orientation of processes in time are seen to be at variance with orientations being determinate.

The article falls into three parts: enantiomorphy of processes, enantiomorphy in space, and reductionism. In Section 2, the notion of enantiomorphy is made precise. Section 3 develops the notion of a process as an object in spacetime, and Section 4 then argues that time-asymmetric processes are in fact enantiomorphic objects. Section 5 discusses Kant's puzzle on spatial enantiomorphy and zooms in on the problem that nothing seems to underpin the orientation of enantiomorphic objects. Section 6 discusses the more recent debate over this problem, and arrives at a specific dilemma for both substantivalists and relationists concerning space: either they must reject the position that enantiomorphic objects have determinate orientation, or they must furnish spacetime or processes with further orientation to underpin the determinate orientation of these objects.

Armed with these insights concerning enantiomorphy in space, and with the further fact that time-asymmetric processes are enantiomorphic, the article turns to reductionism about the direction of time. Section 7 argues that reductionism of a certain kind, exemplified by Reichenbach's identification of the direction of time with the entropy gradient, must deny that the orientation of enantiomorphic processes is intrinsic. Following up on this, Section 8 discusses certain reductive explanations of the consistent orientation of enantiomorphic processes. There, the explanations are seen to be incompatible with the view that the orientation of enantiomorphs is determinate.

2. Enantiomorphy

When is a spatial object enantiomorphic? For certain kinds of spaces, this question has a clear-cut answer: an object is enantiomorphic relative to a given space if and only if there is no rigid motion within the space by which the object can be made to coincide with its mirror image. The following illustrates this definition, and elaborates the restrictions to space that make the definition applicable.

Let me first present an exemplary case of enantiomorphy. Consider the three two-dimensional objects in Figure 1, referred to as 'knees' in Nerlich (1973). It is easy to check that knees (a) and (b) can be made to coincide by, for instance, turning knee (b) through π radians about an axis perpendicular to it, and subsequently moving it along the paper. It is also apparent that knees (a) and (c) are mirror images: in a mirror, knee (a) will look exactly like knee (c) as printed on paper. Moreover, knees (a) and (c), like knees (b) and (c), cannot be made to coincide by shuffling and turning them within the paper. Because they are mirror images, and at the same time impossible to match, we call objects (a) and (c), like (b) and (c), incongruent counterparts. Such pairs are then said to have opposite orientation. All three objects, being incongruent counterparts, are called enantiomorphic objects, or enantiomorphs for short.

A rigid motion of an object is a continuous motion that leaves the metrical properties of the object invariant during all the stages of the motion. More specifically, if the object is defined by a set of points and their distances, then a rigid motion of that object is any combination of continuous motions of its points in the given space that leaves

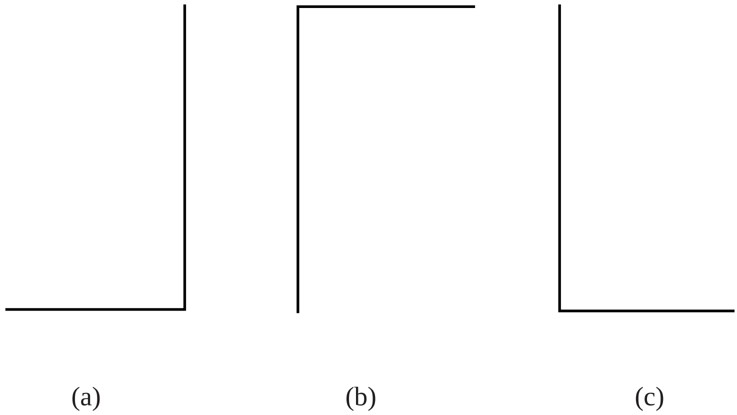

Figure 1 Three knees.

unchanged all distances between the points. For a more elaborate explication of the notion of rigid motion, see Frederick (1991). Because of continuity, points are not allowed to make jumps. In Cartesian space, rigid motions are given by the group of translations and rotations of the object. The shuffling and turning of the three knees above are just these rotations and translations in a space that is isomorphic to R^2. In general, we can make the shuffling precise with the notion of rigid motion.

So it seems that an object is enantiomorphic if and only if it cannot by rigid motions be made to coincide with its mirror image. But this definition is deficient in a number of ways, and it must therefore be restricted to objects in spaces of a certain kind. For one thing, in a space that has variable curvature, rigid motion may be impossible, because the curvature may cause the metrical properties of the object to change during any motion. But it seems wrong to deem objects enantiomorphic solely in virtue of that. In the following, I therefore want to restrict the definition of enantiomorphic objects to the cases in which space has constant curvature, such as the flat metric. However, even within this specific domain of application, there are two further caveats. First, incongruent counterparts can be made to coincide by rigid motions within higher dimensions. Second, such objects can be made to coincide by rigid motions in spaces with a nonstandard topology. These special rigid motions are discussed below.

First, I treat rigid motions within higher dimensions. Consider the example with the knees once again. It is easy to see that knees (a) and (c) can be made to coincide by lifting knee (a) from the paper, turning it through π radians about some axis parallel to the paper sheet, and putting it back on the paper again. In other words, the two-dimensional knees (a) and (c) in the paper sheet, a space isomorphic to R^2, can be made to coincide by rigid motion in the space containing the paper sheet, which is isomorphic to R^3. Should we consequently say that knees (a) and (c) are not enantiomorphs after all? Rather, we will say that the enantiomorphy of an object is a notion relative to the space in which the object is considered. So, the characterization of enantiomorphy becomes: an object is enantiomorphic relative to a space.

Second, nonstandard topologies must be taken into consideration. An example of a two-dimensional space with nonstandard topology is the Möbius band. But to get a rough idea, it is perhaps easier to do a folding exercise. Consider the knees in Figure 1. To construct a two-dimensional space with a nonstandard topology, take the lower outside corner of the page on which this figure is printed and loosely fold it over, so that it touches the page just below knee (b), over the whole width of this knee. Then imagine we transport knee (b) by rigid motion over the twisted two-dimensional space we have just created, onto the back of the page.[1] Imagine further that you are able to see through the page. It then appears that object (b) can be made to coincide with object (c). Moreover, in the two-dimensional space R^2 to which the paper is isomorphic, being on the front or the back of a page is not a real difference. Finally, the knee keeps its metrical properties during the motion over the twisted space: the space is curved extrinsically, but internally flat. So we may say that objects (b) and (c) can be made to coincide by rigid motion after all, by placing them in a two-dimensional space with a particular twist.

In reaction to this, one can say that in twisted spaces like the Möbius band, we simply do not find enantiomorphic objects. But it is not unthinkable that someone will want to call oppositely oriented knees on a Möbius strip enantiomorphic after all. To that aim, we may exclude rigid motions over trajectories that cannot be contracted to a point. As far as I can see, this rules out rigid motions over Möbius-type twists. However, the safe option is to restrict the domain of applicability of the definition a bit further, and to remain silent on enantiomorphy in spaces like the Möbius band. The following therefore employs the definition of enantiomorphy only in spaces that are simply connected and thus have a completely standard topology. The restriction is too strong, but for present purposes this is not damaging.[2]

3. Processes in Spacetime

In this section, I define a process as an object in flat Minkowski spacetime. I then discuss time asymmetry of processes, and define the mirror image of a process as the time reversal of that process.

3.1. Processes as Objects

Consider a simply connected and flat Minkowski spacetime M with events $x \in M$, together with a Lorentz coordinate framework relativised to some observer. Over the spacetime, the framework defines a time function $\tau(x)$ of the observer, and a function that assigns every event spatial coordinates, $\xi(x)$. Thus, we can talk of the events in terms of unique observer-relative coordinates $\langle \tau, \xi \rangle$. In this context, it is important to note that the time function does not in any way relate to the direction of time: it is simply a conventional labelling.

Relative to the observer, we may now define a process as an object in spacetime. First, we localise the process in a specific spacetime region, and divide the region into time slices, that is, into parts that have the same time coordinate. Second, the respective times can be associated with states of a certain process in some state space. The process in spacetime is then defined by assigning these states to the time slices with the corresponding times. The following makes this idea precise.

Consider a process p in a limited spacetime region around the origin of the coordinate frame, $M_p = \{x: \tau(x) \in I_p, |\xi| < D_p\}$. Here, $D_p \in R$ is the radius of a spatial sphere, and $I_p = [-T, +T] \subset R$ is the time interval. The region M_p determines the place and interval within which the process p occurs. We can define a time slicing of the region M_p as follows:

> Time slicing $\mathcal{M}_p$: A time slicing for a specific observer is a partition $\mathcal{M}_p$ of the region M_p into subsets $M_p(t)$ such that $\forall x : x \in M_p(t) \Leftrightarrow \tau(x) = t$.

This definition entails that the union of all time slices is again the region, $\cup_t M_p(t) = M_p$, and further that the time slices do not intersect, $\forall t \neq t' : M_p(t) \cap M_p(t') = \emptyset$. Note that the slicing is specific to the observer and her coordinate frame.

The region M_p is supposed to contain a system undergoing some process. Denote the set of state descriptions for the system with $\mathcal{S}$. We can define a process in the state space as follows:

> Process $S(t)$: A process in state space is a function $S : I_p \mapsto \mathcal{S}$ of parameters $t \in I_p = [-T, +T]$ to state descriptions $S(t) \in \mathcal{S}$.

The argument t of the process S signals that state descriptions are assigned to times. We can now situate the process in spacetime by assigning the state descriptions of a process $S(t)$ to the time slicing $M_p(t)$ in the manifold.

> Process p_S: A process p_S in spacetime, for a specific observer, is a function p_S: $\mathcal{M}_p \mapsto \mathcal{S}$ of time slices in a spacetime region, $M_p(t) \in \mathcal{M}_p$, to state descriptions in a state space, $S(t) \in \mathcal{S}$, according to $p_S\,[M_p(t)] = S(t)$.

A process in spacetime p_S thus assigns a state description to every time-slice of the region M_p within which the process takes place.

Note that the process p_S is defined relative to an observer in a specific inertial frame. Events that are simultaneous to one observer may, according to another observer, be part of time slices that are assigned different state descriptions. As a result, one process in spacetime has as many different representations p_S as there are inertial frames. To ensure that transformations from one inertial frame to another do not change the order of the states in the process representation, we must assume that the states $S(t)$ in the state space describe a causal process. If the states describe a so-called pseudo-process, such as the positions of a shadow moving along a wall, the order of the states may differ from one observer to another.

It may finally be noted that the assignment $p_S[M_p(t)]$ does not necessarily result in a full description of the state of affairs in the time-slice $M_p(t)$. The state space $\mathcal{S}$ may consist of thermodynamical properties, while the full state of affairs consists of configurations of particles. This is not a problem as long as the states are connected causally.

3.2. Asymmetry and Mirror Image in Space

Before defining time asymmetry of processes and the time reversal of a process, it is helpful to consider asymmetry and reversal in three-dimensional Cartesian space $\mathcal{C}$.

Let me first define a spatial object b in a way similar to the processes defined above. We can partition space into parallel planes $\mathbb{C}(j)$, perpendicular to a vector j and parametrised by it. To these planes, we can assign the spatial intersections of the object b and other qualities such as colour and weight, summarized in the form descriptions $F(j)$. The object is thus represented by a function $b_F[\mathbb{C}(j)] = F(j)$. Note that the partitioning is assumed to be spaced according to the metric given by j. Note also that there are many different representations of the same object b depending on the initial choice of the vector j, in the same way that there are many representations of a process p depending on the choice of inertial frame. Recall that representations of processes pertain to the same process if they employ the same ordered set of state descriptions. For representations of spatial objects, the equivalence of representations is less obvious, but this need not bother us here.

For spatial objects, it is easy to characterise the notions of asymmetry and mirror image. First, an object is called asymmetric in the direction of j if there is no plane perpendicular to j around which the form descriptions are pairwise identical, that is, if there is no plane $\mathbb{C}(j)$ such that $F(j - j') = F(j' - j)$ for all j'. Second, the mirror image of a spatial object is characterised by a parity transformation of the object with respect to one of the spatial coordinates. In the above representation, a parity transformation with respect to j is effected by changing the vector j into $-j$, leaving the function b_F unchanged. So, the mirror image of an object, denoted b_F^*, is defined by assigning the form descriptions $F(j)$ to the parallel planes $\mathbb{C}(j)$ in opposite order: $b_F^*[\mathbb{C}(j)] = F(-j)$.

Note that whether an object is deemed asymmetric in the above sense is in part determined by the spacing of the vector j. Moreover the spacing must be fixed during the mirror image transformation, because if we allow the spacing to vary, objects with different shapes can be constructed as mirror images of each other. The simplest solution for this is to suppose space to be flat, so that the spacing is equidistant. Note also that the parity transformation is defined for a specific coordinate. It is a further fact about Cartesian space that parity transformations with respect to different coordinates are effectively the same operation. Finally, note that an object is symmetric exactly if there is a plane $\mathbb{C}(j)$ that cuts the object into halves that are mirror images. If the object has more than one plane of symmetry, these halves are identical.

3.3. Time-Asymmetry and Reversal of Processes

We can now define the notion of time reversal and time-asymmetry as the analogues of the mirror image and asymmetry of an object in a certain direction. As an illustration, take a cooling poker that is first white and very hot, then traverses several shades of red and orange, and finally cools down to black. Let the set of state descriptions consist of a suitable set of colours, conveniently ordered so that we can define the process S as a trajectory in this colour space. As for the spacetime region, take a fixed sphere $|\xi| < D_p$ containing the poker. For convenience, define the period of cooling as $I_p = [-1, +1]$. The assignment of the subsequent colours to the time slices of the selected region, i. e. the sphere at subsequent instances, is the process p_S.

Much like the object b_F, the process p_S is given by an assignment of certain descriptions, consisting of colour states, to a partition, consisting of time slices in a flat Minkowski spacetime. Note that there is no real analogue for the intersections, which are part of the form descriptions $F(j)$, since the spatiotemporal extension of the process is fixed by the region M_p. Also note that the analogue of the direction j in the spacetime case is the direction of the time axis in the inertial frame.

Using this analogy, we say that the process p_S is time-asymmetric if there is no time-slice around which the state descriptions are pairwise identical. Because of the definition of the spacetime region with $I_p = [-1, +1]$, the time slice that cuts the process in halves is $M_p(0)$, so that the identity of the halves comes down to the pairwise identity $S(0 + t) = S(0 - t)$ for all $t \in I_p$. So we say that a process p_S is time-asymmetric if this pairwise identity does not hold. It will be clear that in this definition, the example process comes out as time-asymmetric. With the same analogy, the time-reversed process p_S^* is a function of the partition of time slices $\mathcal{M}_p$ to the state space $\mathcal{S}$ in which the order of the states in $S(t)$ is reversed. That is, the states of $S(t)$ are assigned to the time slices in reverse order: $p_S^* [M_p(t)] = S(-t)$. In the example of the cooling poker, if the process p_S has $S(-1)$ = 'white' and $S(+1)$ = 'black', its reversal p_S^* has the opposite state assignments, $S(-1)$ = 'black' and $S(+1)$ = 'white'. It may be observed immediately that an asymmetric process and its time reversal are therefore not identical in any straightforward manner.

There are some complications with the definition of time reversal when the state descriptions S contain velocities or other change-related state descriptions. In the example, imagine that apart from the colour of the poker, we keep record of whether the poker is cooling down or heating up, so that typical states in the process are ⟨orange, cooling⟩, ⟨red, cooling⟩, and so on. The reversal process then is a rather strange one if considered in the same time direction: the poker changes from 'black' and therefore cool to 'white' and therefore hot, while during this process it is 'cooling' all the time. In other words, state descriptions with change-related properties only seem natural when considered relative to a particular time direction.

One way to avoid this is by leaving such change-related elements out of the state descriptions of the process, as proposed by Albert (2000) and Arntzenius (2000). Another option is to stay closer to the state descriptions of physics, which typically include change-related properties, and associate a transformation of state descriptions with the time-reversal operation. This more common view is defended in Earman (2002) and Smith (2003). While the debate over this issue is certainly not settled, the result of this discussion only becomes relevant to the present article if we say that the change-related state descriptions with opposite temporal orientation differ intrinsically, in which case they supposedly determine the orientation of the process. All this is discussed in more detail below.

4. Enantiomorphic Processes

Having defined time asymmetry and reversals of processes, what can we say of the enantiomorphy of processes? The current section shows that asymmetric processes can be viewed as enantiomorphs. This conclusion directly counters Reichenbach's contention in (1958, 109) that 'time does not have the problem of mirror-image congruence'. The argument is an elaboration and extension of Earman's remark (1971, 13–14), that it is impossible to transform a timelike vector pointing in one direction into a vector pointing in the opposite direction. A comparable but less explicit discussion can further be found in Le Poidevin (1994).

Note first that the setting for processes fulfils the conditions required for the definition of enantiomorphy to apply. The region M_p is a maximal subset of M, in the sense that it has the same number of dimensions. Further, the manifold M has a flat metrical structure, and it is simply connected. So, the question on the enantiomorphy of processes comes down to the question of whether a process can be made to coincide with its mirror image by a so-called continuous rigid motion. It must be stressed that the motions I am concerned with are not ordinary motions happening within spacetime. A rigid motion of the process of a cooling poker is not the same as rigidly moving the poker in space. In the following, I therefore talk of allowed transformations instead of rigid motions, because these do not have the unintended temporal connotation. Finally, as suggested by the above characterisations, the mirror image of a process is taken to be the time reversal of the process.

Now, what transformations are allowed in spacetime? Recall that rigid motions of objects are given by those continuous motions of labelled points in the object that preserve the distances between all the points. Instead of continuous motions, we must talk here of continuous translations. For an object represented with two points, the allowed transformations are therefore exactly those translations of the points that leave the distance between them unchanged. Now, the distance functions for two points in Newtonian and Minkowski spacetime, using 1 space and 1 time dimension, respectively, are as follows:

$$D_N^2 = dx^2 + dt^2,$$
$$D_M^2 = dx^2 - cdt^2.$$

These distance functions define the allowed transformations for objects represented with two points in these respective spaces. Note that the Newtonian spacetime comes down to two-dimensional Cartesian space.

Figure 2 illustrates the difference between the allowed transformations in two-dimensional Cartesian space and those in a Minkowski space with one spatial and one timelike dimension. The lines denote all possible positions for the endpoint of a vector originating in O that can be reached by allowed transformations of the vector, leaving aside transformations that come down to a shift of O. It appears that a vector in Newtonian or Cartesian space, which has $D_C = +1$, can be moved to point in any direction. A timelike vector in Minkowski space, however, that has $D_M = -1$ cannot be transformed continuously into an arrow that is oriented oppositely. The dotted line denotes the endpoints of timelike vectors with $D_M = -1$ that cannot be reached by an allowed transformation. Therefore, in a Minkowski metric, oppositely oriented timelike vectors cannot be made to coincide.

Now consider once again the cooling poker of the previous section. We can represent this process in spacetime with a timelike extended hypercylinder and attach the

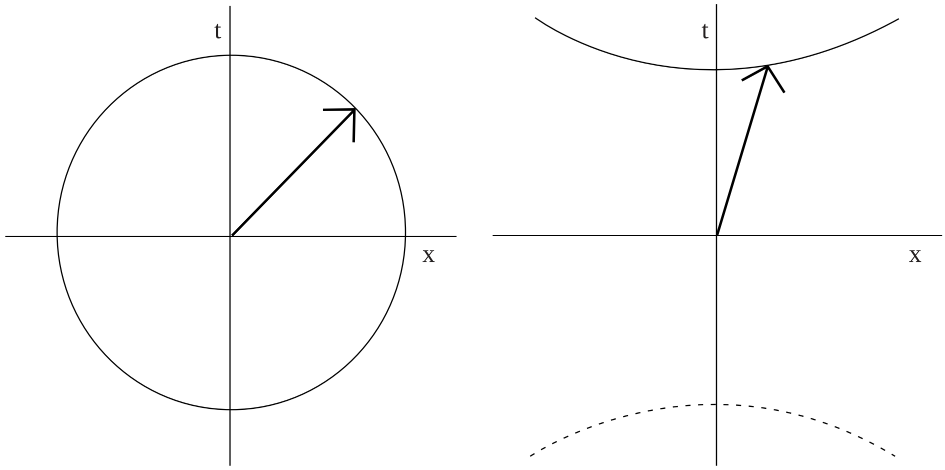

Figure 2 Newtonian and Minkowski metric.

states $S(-1)$ = 'white' and $S(+1)$ = 'black' to the first and last spheres, respectively. And as indicated, we can construct the reversal of this simplified process by attaching the states in opposite order, i. e. $S(-1)$ = 'black' and $S(+1)$ = 'white'. But for the above reasons, the time-like separated black and white spheres can never change place by allowed transformations of the hypercylinder. The process of the cooling poker and its reversal cannot therefore be made to coincide, as shown in Figure 3.

This result easily generalizes to the fact that there is no asymmetric process which can be made to coincide with its time reversal in spacetime. Of any asymmetric process, we can label the temporal endpoints with 'black' and 'white', so that the process and its reversal cannot be made to coincide for the same reason as the example process. The conclusion is that time-asymmetric processes and their time reversals are enantiomorphic objects in Minkowksi spacetime. Each time-asymmetric process comes in two

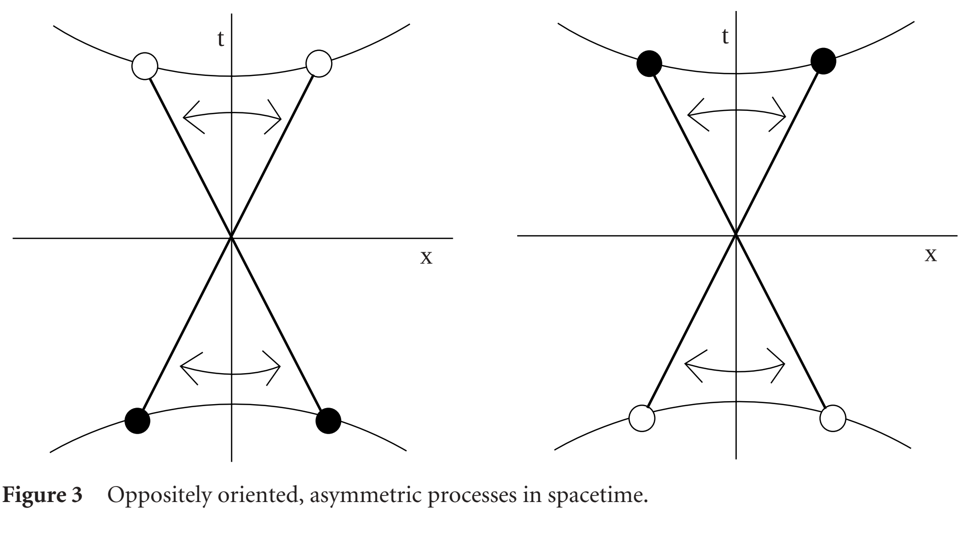

Figure 3 Oppositely oriented, asymmetric processes in spacetime.

versions, which may be labelled + and −. Note that this labelling is deliberately not associated with the notions of past and future, which inherently depend on the temporal perspective of the observer.[3]

5. Enantiomorphy in Space

The first main result of this article is simply that time-asymmetric processes are enantiomorphs in spacetime. The remainder of the article considers some of the consequences of this fact for the discussion on the direction of time. Specifically, it focuses on consequences for reductionism about the direction of time and reductive explanations of the time asymmetry of processes. To this aim, I first bring to the fore some results in the debate on enantiomorphy and space. In particular, this section discusses the well-known argument of Kant in order to introduce some positions and distinctions that concern space and enantiomorphy. It must be emphasized that the aim of this section is not to give a survey of Kant's argument itself.

5.1. The Puzzle and Kant's Argument

Imagine a single hand in an otherwise empty space, and for the moment, assume that the hand is left. We can then ask what property or state of affairs makes this hand left. To answer this question, we may start out citing properties of the hand, such as its weight, temperature, the lengths of the fingers, the distances and angles between them, and so on. But we will not succeed in finding a property that determines whether the hand is left or right, unless we cite something like the property that on the side of the palm, turning the thumb towards the fingers is a clockwise movement. But this sort of property seems to take as basic the orientation we were trying to spell out. It could equally well have read: if viewed from the arm on the side of the palm, the thumb is left of the fingers. It seems that a hand's being left or right, its orientation for short, cannot be based on anything but orientation itself.

The above puzzle has played an important role in the controversy over the existence of absolute space. Kant has used the puzzle in an argument purporting to show that relationism about space is untenable. His later argument concerning the intuitive nature of space is briefly considered in the next subsection. But first I provide a variant of the earlier argument to elaborate the relation between enantiomorphy and various views on space and objects. As indicated, this reconstruction is not faithful to the original text of Kant (1768).

The argument is a reductio ad absurdum. Here is an almost exhaustive list of premises:

- DET: the orientation of an enantiomorphic object is determinate.
- GEO: an orientation of an enantiomorphic object is a geometric property of that object.
- REL: geometric properties of objects are made determinate by relations between objects and their parts, or they are indeterminate.
- ORI-R: relations between objects and their parts do not directly refer to orientation.[4]

GEO-R: without direct reference to orientation, relations between objects and their parts do not make determinate an orientation of an enantiomorphic object.

With relations between objects and their parts I mean both intra-object and inter-object relations. Note that apart from DET, all premises speak of 'an orientation' and not of 'the orientation'

The derivation employs all premisses apart from DET. Together they prove that an enantiomorphic object does not have a determinate orientation. The derivation assumes that the relation 'is made determinate by' is transitive.

⇒ 1: an orientation of an enantiomorphic object is made determinate by relations among objects and their parts, or it is indeterminate (GEO, REL).
⇒ 2: an orientation of an enantiomorphic object is made determinate by relations among objects and their parts that do not refer to orientation, or it is indeterminate (ORI-R, 1).
⇒ 3: an orientation of an enantiomorphic object is indeterminate (GEO-R, 2).

Statement 3 directly contradicts premise DET. One possible reaction to this is to dispose of REL, and thus to claim that relationism fails. While the above is of course an anachronistic and simplifying reconstruction, the conclusion of Kant's (1768) argument is indeed that REL has to be rejected. Kant further contended that by using absolute space, the orientation of a lone hand can be determined unproblematically.

5.2. Two Aspects of the Puzzle

Below we come back to this contention, and to the alleged problem for relationism. In this subsection I want to draw attention to certain aspects of the above argument, relating to two possible meanings of being determinate, and to the further specification of the orientation of enantiomorphic objects as an intrinsic property.

First, let me present the eventual solution of Kant to the puzzle and, by means of that, distinguish two problems inherent to it. In his 1783 argument, Kant arrives at the conclusion that space is c. '…the form of the external intuition of this sensibility', where sensibility refers to the capacity to frame and organise sense experience of things in a spatial scheme. The rough idea is that space, which is external to us, is the form of a capacity that we observers have, internally, to frame and organise experiences. Our internal capacity to frame things is thus made constitutive of the things as they appear to us, that is, of the things as spatial objects. This move enables Kant to solve the puzzle of enantiomorphy. In an anachronistic reformulation, it is in the cognitive act of framing an enantiomorphic object that it has a determinate orientation, and moreover, this framing is constitutive of the object.

The Kantian solution signals the merger of two essentially distinct problems in the puzzle. Following similar distinctions in Hoefer (2000), Huggett (2000) and Pooley (2003), I will distinguish the epistemic and the ontological variant. The epistemic problem addresses what conceptual or cognitive tool makes the orientation of an enantiomorphic object determinate for us. The ontological problem addresses what element of reality makes the orientation of an enantiomorphic object determinate for itself. Kant solves the epistemic problem, and, with the Kantian move to take modes of cognition as constitutive of the things for us, claims the ontological problem solved, too. Now I do not want to assess this eventual solution here. I bring it up because it highlights that there are really two distinct problems in the puzzle. This runs parallel to the fact that in the above argument, the term 'determinate' can be given two different meanings, which reflect these two problems: one concerns the determination relative to a conceptual scheme, and the other concerns the determination of properties of a thing in the world. What I want to emphasize here is that the following concerns the ontological determinateness only.

The second aspect concerns the notion of ontological determinateness in relation to whether the orientation of enantiomorphic objects may be called intrinsic. In the original puzzle of Kant, the subject matter is not just any enantiomorphic object, but more specifically a single object in otherwise empty space, namely a lone hand. If anywhere, the ontological basis for the orientation of the hand must therefore be located in the hand itself. It may thus seem natural to provide an underpinning for the premise DET in terms of intrinsic properties, according to

INT: an orientation of an enantiomorphic object is an intrinsic property.
IND: intrinsic properties are determinate independently of other objects or facts.

From these two premises, we can easily derive DET. Moreover, following Le Poidevin (1994), we may take IND as a definition. In that case, denying DET comes down to an immediate denial of INT.

The explication of determinateness in terms of intrinsic properties is not wholly unproblematic. First of all, the working definition IND may well run into problems when used in combination with the Kantian perspective proposed in the 1783 argument. In this perspective, the orientation of an enantiomorphic object is intrinsic but at the same time related to the spatial scheme that we use to frame the object. Note also that the intrinsicality of orientation is logically stronger than the determinateness. Maintaining the determinateness of orientation does not mean that the orientation is also taken to be intrinsic, because the determinateness of orientation may be due to space itself or other objects in it. The following will take care to separate arguments in which the intrinsicality of orientation is at stake from stronger arguments that only concern the determinateness.

Summing up, this article focuses on the ontological aspect of enantiomorphy: not the epistemic determination of orientation, but the ontological basis of the determinateness, is at stake in the arguments. Moreover, this ontological basis may reside in the enantiomorphic object itself, in which case the determinateness may be spelled out in terms of intrinsic properties, but also in the relation the object has to space, as a substance or a construction of relations, or other objects. These two possibilities become relevant for the way in which the positions in this argument carry over to the discussion of enantiomorphic processes in spacetime.

6. A Dilemma on Enantiomorphy

This section elaborates on determinateness as defined in the above argument, and shows that the argument presents a problem to both relationists and substantivalists with respect to space. Specifically, both positions are confronted with a dilemma: either it must be accepted that the orientation of enantiomorphs is indeterminate, or an independent notion of orientation to objects, space or spatial relations must be introduced. This latter option is connected to a denial of reductionism with respect to orientation, which leads up to the next two sections on enantiomorphy and reductionism about the direction of time and orientation in time.

6.1. Indeterminate Orientation

Kant uses the argument of the preceding section to argue against relationism, as voiced in REL. In an attempt to save REL, Remnant (1963) advances the idea that a relationist can deny DET. To this aim, he reconsiders the example Kant used to explain the determinateness of the orientation of a hand, imagining a handless and perfectly symmetrical human body to determine where the hand fits. He then argues: '… even though it is quite determinate which arm the hand belongs on, it remains completely indeterminate whether this is a right or a left arm and consequently indeterminate whether the hand is right or left'. It must first be noted that the presence of the handless human body does not alter the import of the argument by Kant, which, strictly speaking, concerns lone hands. The symmetric human body cannot be used to make the orientation of the lone hand determinate, so that relationism is still at risk.

As indicated in the quote, Remnant accepts that the lone hand is an enantiomorph, and thus fits only one particular arm. So he accepts that the hand has an orientation. But he denies that it is determinate which arm the hand fits on, and thus whether the hand is left or right. To appreciate this, it is important to distinguish yet again two ways of having determinate orientation, next to its epistemic and ontological meanings: an enantiomorphic object is by its very nature determinate in having some orientation as opposed to not having any orientation at all, whereas it need not be determinate in having a particular orientation as opposed to having the opposite orientation. According to Remnant, Kant is wrong in holding that the hand has a determinate orientation in the latter sense. Remnant concludes that absolute space need not be invoked to explain anything.

6.2. Relationist Dilemma

The move of Remnant has elicited several responses,[5] of which I will mention those of Nerlich (1973) and Earman (1971).

Nerlich distinguishes between the two above ways of having a determinate orientation and argues that the argument against relationism can still be run using the fact that certain objects are enantiomorphs: it is perhaps not the particular orientation of a lone hand that needs an explanation, but the fact that such a hand is an enantiomorph remains. It is up to the relationist to give an explication of this. However, as suggested by Pooley (2003), the relationist can react to Nerlich in a way that is similar to the response of Remnant. She may deny that single objects in otherwise empty space are enantiomorphic.

The objection of Earman is that the absence of other oriented objects can never cause the lone hand to suddenly stop having a particular orientation: 'the parity operation … for the room I am now sitting in would not collapse if all the objects in it save one hand were to vanish'. The point is that the parity operation, which turns any object into its mirror image and which for a hand is surely not equal to identity in full space, cannot suddenly turn into identity because space is evacuated.[6] Minimally, the relationist must give an explication of the parity operation in which this is made clear.

It is not clear that the suggestion of Earman harms the relationist who denies DET. For a relationist like Remnant, when it comes to the ontological aspect of enantiomorphy, orientations of enantiomorphic objects are indeterminate in the vicinity of other objects just as well. A relationist description of both a left and a right hand in otherwise empty space, as long as it only employs distances, does not encode which of the two is the left one either. There is no need for the relationist to explain the magical disappearance of the element of reality that determines the orientation of one hand if the other hand is removed, because according to at least some relationist conceptions, there is no such element of reality.

In any case, there is no need to rely on the relationist reactions above. Also for less radical relationists, who want to admit that a lone hand is determinate in being enantiomorph or that a hand is determinate in having a particular orientation in the presence of its counterpart, the responses of Nerlich and Earman do not rule out a relationist denial of DET. At best, they indicate that a relationist explication of enantiomorphy and spatial notions like parity and orientability has not yet been given. Nerlich and Earman have not shown that a relationist can never give these explications. Once their challenges are taken up, as they are by Pooley (2003) and Huggett (2003), it seems quite possible to deny DET. The other possibility for the relationist, suggested in Earman (1989) and more elaborately discussed in Pooley (2003), is to deny ORI-R, and to accept a relation such as 'left of' in the range of possible geometric relations. This comes down to supplying the relationist conception of space with further oriented relations that fix the orientation. A final relationist escape from the argument may be to deny GEO. I know of no such attempt in the literature and will myself not follow that track either.

To sum up, in response to the Kantian puzzle, the relationist can deny either DET or ORI-R. This is the basic dilemma for relationists. Now, it seems that the latter option is in direct opposition to reductionist views on orientation. But before making this precise, let me discuss the dilemma for substantivalists in the next subsection.

6.3. Substantivalist Dilemma

Earman (1971) challenges Kant's (1768) contention concerning the use of absolute space in determining the orientation of a lone hand. He notes, as Kant himself seems to do in (1783), that supplying the setting of the lone hand with the further presence of space substance is of itself not sufficient to solve the puzzle. Just as distances between parts of the hand do not suffice to determine orientation, distances between the hand and spatial points outside the hand will not do the job, either. But what else, Earman asks, can be the special property of absolute space that allows for the determination of a lone hand as having a particular orientation? Kant's suggestion that it is 'universal space as a unity of which every extension must be regarded as a part' is notoriously unhelpful. Earman concludes that thus far, no satisfactory answer to this question has been given.

Nerlich makes clear that there is a way in which absolute space determines enantiomorphy: it is because space is three-dimensional and simply connected that we call certain objects enantiomorphs. So, one interpretation of the above suggestion of Kant is that absolute space determines the lone hand in being enantiomorphic. Moreover, as indicated above, it seems possible to restate the argument against relationism, so that it is concerned with being enantiomorphic. One may even conjecture that Kant intended the argument like that, although this is certainly not the claim of Nerlich. However, no matter how we read the original argument by Kant, it is simply not the case that substantival space determines a lone hand in having a particular orientation. The reformulation which Nerlich proposes does not help against that.

Hoefer (2000) picks up this line of argument. He shows that if space points are supposed to have primitive identity, a substantivalist can determine the orientation of an enantiomorphic object after all. With this additional insight, we are in the position to reiterate the argument of Section 5.1 for substantivalists. The premise REL must be replaced with

SUB: geometric properties of objects are made determinate by the points they occupy in substantival space, or they are indeterminate.

The premise that relationists do not employ relations that refer to orientation must be replaced with the premise that absolute space does not have primitive identity of space points. That is, we must replace ORI-R and GEO-R with

ORI-S: points in space do not have primitive identity.
GEO-S: without primitive identity of points in space, absolute space does not make determinate an orientation of an enantiomorphic object.

With the adapted argument, we can force the substantivalist into a dilemma as well, namely to reject DET or ORI-S. That is, space must be decorated with primitive identity for the points, or the determinateness of orientations will have to be denied.

There is an obvious similarity between the premises ORI-R and ORI-S. In both cases, their denial comes down to a denial of a kind of reductionism about orientation. For a relationist, accepting relations that directly refer to orientation means that orientation is included in the basic ontology of spatial relations. And similarly for a substantivalist, saying that space points have primitive identity also means that orientations in space have a primitive identity. We may therefore say that substantivalists and relationists face the same dilemma, which is to deny a kind of reductionism about orientation, in the following referred to with RED, or to deny that enantiomorphic objects have determinate orientation, denoted DET.

7. Reduction of Time Direction

In the remaining sections, I employ the positions and dilemma of the foregoing in a discussion on reductionism in time and enantiomorphic processes. Specifically, this section deals with a certain kind of reductionism about the direction of time. The exemplary case is Reichenbach's attempt to reduce the direction of time to the entropy gradient. Other examples are reductions of the direction of time to cosmological processes, as in Hawkings' article in Halliwell, Perez-Mercader, and Zurek (1994). I argue that such reductionism is at variance with INT, the claim that orientation of enantiomorophic objects is intrinsic. The argument employs the relation between the intrinsicality of orientation and its being determinate, and assumes the above characterisations of several positions regarding enantiomorphy.

7.1. Reichenbach's Proposal

Reichenbach (1956) aims to reduce the direction of time to the global entropy gradient. His claim is that any further feature of processes pertaining to a particular orientation in time can ultimately be traced back to the global asymmetry of entropy increase in the large-scale physical process of which these processes are part. The fact, for instance, that pokers on earth always decrease in temperature in the future direction can be reduced to the asymmetry of a more global entropy gradient. Figure 4 depicts the reduction that Reichenbach has in mind. The curve shows the possibility that the entropy gradients are zero or oppose each other globally.

Following Sklar (1995), I stress two features of the intended reduction. First, the reduction is scientific as opposed to epistemological. It is not the epistemic access we have to time direction or some inner sense of tense that is at stake. The reduction aims at a veritable bridge law between time direction and entropy gradient. Second, according to Sklar, the reduction of past–future to the entropy gradient resembles the reduction of up–down to the gravitational gradient on earth rather than the reduction of the left–right distinction to violation of parity symmetry in weak nuclear interactions.

As an example of the latter kind of reduction, dexterity of humans may be said to reduce to this symmetry breaking in the sense that this dexterity can be explicated using

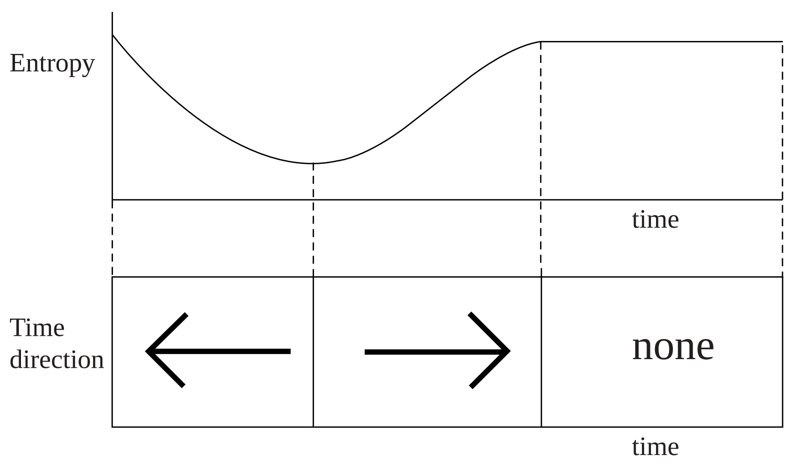

Figure 4 Global entropy curve and resulting time direction.

weak interactions which violate parity symmetry. That is, if we had to communicate the dexterity of humans to extraterrestrials by radio communication, describing an experiment with such weak interactions can be used to get this information across. Apart from the fact that we may object to this being called a reduction, the identification of time direction with the entropy gradient is more than such a contingent correlation. The claim is that all further time-asymmetric features can be traced back to the entropy gradient, as is the case in the reduction of up–down to the gravitational gradient. As in the up–down case, the entropy gradient is supposed to be foundational for any directionality that resides in natural processes.

One further remark must be made to qualify the reductionism that is at stake. The reduction of the direction of time to the entropy gradient is a reduction of direction in the sense of elimination: in the reducing theory, there is no reference to directions of time or orientation in time. We may decide to reduce the direction of time to, for example, the direction of causal efficacy, as discussed in Le Poidevin (1994). Such causal reductions do not run into the problems discussed below, because they refer to a primitive notion of direction in time. However, such reductions do not eliminate the notion of direction. The reductionism at stake in this article does not include reductions of this latter kind.

Finally, let me consider the reach of the problems discussed here. First, it must be admitted that Reichenbach is not the most recent proponent for the kind of reductionism at stake. However, his reduction is relatively simple, and most suitable for illustrating the more general conclusion in this section. Second, it may be argued that there are very few proponents of the strong form of reductionism discussed here. But it is probably more appropriate to say that those in favour of reducing the direction of time to other notions are not always explicit on the points considered above. Finally, it is notable that in physics, as in Wald (1984, 60, chap. 8), it is standard usage to supply spacetime with further oriented structure. However, this cannot be taken as the endpoint of discussions on reductionism about the direction of time and orientation in time, since we may still ask for the physical principles underlying this direction. The following argues that in answering this question, we run into trouble with enantiomorphy.

7.2. Problems for Reductionism

I now turn to the problems that the intrinsic orientation of time-asymmetric processes poses for the above form of reductionism. The key ingredients are the features of the intended reduction emphasized above: the reduction being foundational, the fact that a notion of global direction is not present in the reducing theory, and associated with that, the possibility of globally opposing directions of time. The problems can be illustrated with Figure 5, in which objects with black and white circular ends represent several processes of pokers cooling down or heating up. The directions of time derive from Figure 4.

Since the reduction is supposed to be foundational, the orientation of the processes in the above spacetime is determined by the direction of time defined in it. However, on the above assignment of directions, this leads to problematic scenarios in the

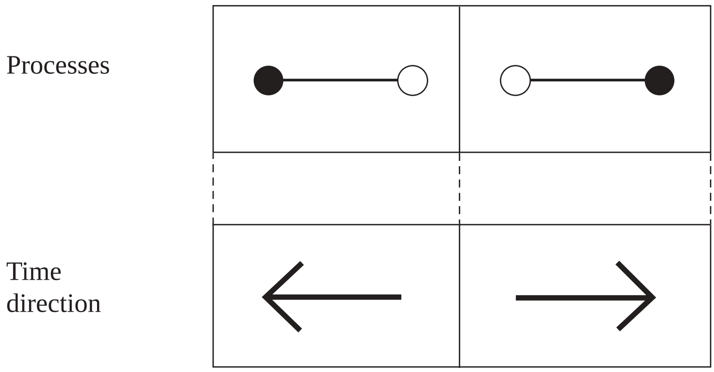

Figure 5 Time directions and mirror-image processes.

regions of spacetime in which there is a direction of time. For instance, the two processes depicted there come out as having the same orientation: in relation to the time direction of the spacetime region, both processes are oriented identically. But we can move one process and bring it over to the other segment by continuous translation over a timelike line, which is an allowed transformation, and after this translation the processes turn out to be incongruent counterparts. Similarly, if we imagine the two regions with opposite time direction as containing two processes (which, according to the local time directions, have opposing orientations), then these orientations can be made the same by moving one process to the other region.

Both scenarios are at variance with the view that the orientation of a process is intrinsic, as voiced in INT. The general point is simply that time-asymmetric processes cannot have intrinsic orientation if this orientation depends on a locally defined direction of time. But let me make this a bit more specific. First, in accordance with the reduction being scientific rather than epistemic, the foregoing concerns the ontological basis for the intrinsic orientation of the processes. Second, this ontological basis is not just about the processes being enantiomorphic but about their having a specific and determinate orientation. Third, the fact that the orientation is supposed to be intrinsic means that time-asymmetric processes have a determinate orientation that is independent of spacetime or other objects in it, and thus also independent of convention, setting or perspective. However, following the examples above, orientations of time-asymmetric processes are not independent of other processes if we employ the reduction of the direction of time to the entropy gradient. The conclusion must be that the reduction only works if we deny INT in the first place.

It is important to keep in mind that the problem derives its force from the enantiomorphic character of processes, and not just from their being time-asymmetric. The parallel with spatial enantiomorphy is very useful here. Imagine a symmetric chair facing away from the entrance of an office, and consider the case in which we rigidly move this chair into the office on the opposite side of the corridor. This other office is oppositely oriented in space, and since we have rigidly moved the chair, it now faces towards the entrance. In this sense, the orientation of the chair has changed. But it will be clear that this is not the kind of orientation change that makes the above scenario with processes problematic. After all, we still want to say that the moved chair is the very same chair. The problem with moving the enantiomorphic processes is more like rigidly moving a right slipper to the other office and noticing, stupefied, that in the other office the slipper is left. It is because we feel the orientation to be intrinsic to the slipper, or at least determinate independently of the office in which the slipper is situated, that this scenario is problematic.

7.3. Reductionist Replies

As a first reaction to this conclusion, a reductionist may claim that, apart from the entropy gradient, we still have some kind of metrical notion of time direction to discern incongruent counterpart processes. But remember that Reichenbach intended to identify time direction with the entropy gradient, and that this gradient was supposed to be foundational for all other directionality of processes in time, as in the up–down reduction. Certainly, it remains a possibility for the reductionist to reduce only some of the aspects of directionality to the entropy gradient, and leave others aside, but in my view this must be considered as a withdrawal.

As a second reaction, one can reply that the problem emerges only if the universe contains opposite entropy gradients. Such universes can of course be excluded, but as long as the time direction is defined locally, the existence of globally opposing entrophy gradients presents a fundamental possibility. Moreover, simply ruling out universes with globally opposing time directions seems an ad hoc move to escape a systematic problem.

Related to this second point, it may be noted that the above problems can be avoided by respecting the principle of precedence PP, as formulated in Earman (1974), in carrying out the reduction. This principle states that in an orientable spacetime, continuous time-like transport of an orientation takes precedence over any method[7] of fixing time direction. This principle is rightly criticized by Matthews (1979), but sticking to INT exactly undercuts the reasons given by Matthews for discarding the principle. If we take the orientation of enantiomorphs to be intrinsic, local definitions of time direction are problematic. Since a local definition opens up the possibility of directions that oppose each other globally, we then allow that enantiomorphs which have opposite temporal orientations within a certain region have the same temporal orientation after translation of one of them. So, holding onto INT is a good reason for endorsing PP. In any case, adopting this principle means that, at least partly, we give up the reduction of time direction.

Recall that in the discussion on time asymmetry, it mattered whether processes are characterised with state descriptions that contain change-related properties. Let me briefly come back to this to relate it to the intrinsic orientation of processes and their role in this discussion. It is convenient to distinguish two possibilities. The first is that the change-related properties reflect only between the perspective of the observers. In that case, there is no intrinsic difference between a state and the transformed, temporally opposite state. The use of change-related properties in state descriptions is then irrelevant to the discussion in this section. The second possibility is that states and their temporal opposites differ intrinsically. Using change-related properties in state descriptions then amounts to supplying a process with intrinsic orientation via its state descriptions. But in that case, these state descriptions must accord with the locally defined direction of time, which means that we can reiterate the above problems. If, on the other hand, the state descriptions do not accord with the locally defined direction of time, we have simply not managed to perform the reduction.

These last remarks reveal the structure of the problem for reductionism in its most elementary form: it is impossible to reduce the direction of time to other notions while at the same time maintaining that the orientation of processes in time is somehow intrinsic, and therefore independent of these notions.

8. Reductive Explanations of Asymmetry

This section considers explanations of the consistent orientation of time-asymmetric processes. It turns out that such explanations are facing the same dilemma as derived for enantiomorphy in space. Reductive explanations of time asymmetry are therefore tied to the view that the orientation of the asymmetric processes is ontologically indeterminate.

Let me first characterise reductive explanations of the consistent orientation of time-asymmetric processes. Explanations of this kind are widespread in physics, in particular for thermodynamical and radiative processes. One of the earliest examples is the branching hypothesis by Reichenbach, which explains the consistent orientation of thermodynamical processes by reference to a global time-asymmetric process. Other reductive explanations can be found in Davies (1977), Horwich (1987), Zeh (1992), Halliwell, Perez-Mercader, and Zurek (1994), Savitt (1995), and Price (1996). The general characteristic of the explanations is that they give an account of the alignment of the orientation of certain time-asymmetric processes in terms of an underlying theory that does not refer to a specific direction of time or a specific orientation in time. The following argues that these cannot be combined with the view that the orientations of the processes are determinate, as expressed in the claim DET.

The conflict becomes apparent once we recall that enantiomorphy in space leads to a dilemma: we must either deny DET or in some way accept orientation as a basic notion, and thus deny the reductionist tenet RED. Now, in the case of time-asymmetric processes in spacetime, we are presented with the very same dilemma, and there are again a number of ways to choose the second option. We may give primitive identity to spacetime points and deem one end of spacetime 'the future', or incorporate relations between processes that refer, explicitly or implicitly, to orientation. However, if we assume reductive explanations of the consistent orientation of time-asymmetric processes, the option to deny RED does not seem available: the account of the processes is not supposed to include any reference to orientation as a basic notion. It therefore seems that within such reductive explanations, we are forced to embrace the view that orientations are indeterminate.

It is important to keep in mind the import of the claim that the orientation of processes is determinate, as elaborated in Sections 5 and 6. Recall that the determinateness is supposed to be ontological. This means that the processes come in two distinct orientations, say + and –, and that, possibly relativised to the setting, there is an element of reality that corresponds to the specific orientation of each process. It must be noted that this is not to deny the point of Huggett (2000, 224) and Pooley (2003, 257) that labelling an enantiomorph with a particular orientation involves an element of convention. I do not contend that once we have two oppositely oriented enantiomorphs available, we can provide a consistent labelling for all the enantiomorphs. To assert this possibility is to say that we can consistently identify the orientations, but it is not to say that there is a fact of the matter, or an element of reality, to the specific orientation of enantiomorphic objects once the incongruent counterparts are both present. In fact, both Huggett and Pooley seem to deny the existence of such an element of reality.

It may be argued, independently from the labelling, that the mere existence of oppositely oriented processes in spacetime can provide the ontological basis for the orientations. But, following the discussion of Remnant, I do not see how this can work. If we imagine a lone hand in otherwise empty space without further orientation, the problem is fairly clear. There is nothing that can base the orientation of the hand, so maintaining DET, by saying that the lone hand is, for example, a left one, is problematic. Now imagine two hands in otherwise empty space. What can be the reason for the one, and not the other, to come out as the left hand? It seems that conceptually, we have not gained anything with the presence of a second hand. Certainly, with two oppositely oriented hands in space, it is indisputable that the hands are enantiomorphic objects, and incongruent counterparts of each other. But there is simply nothing in a relationist account without oriented relations, or in an account using space points without primitive identity, that determines one of the hands as left. The same holds for processes in spacetime, or so I argue. In a reductionist account of processes, the orientations are ontologically indeterminate, simply because the ontological basis for the orientations is lacking. The presence of multiple, oppositely oriented processes in spacetime does not help against that.

Here, it is perhaps illuminating to consider the attempt to define a global direction of time in terms of the orientation of a specific asymmetric process, namely the evolution of the universe. As the evolution of the universe is by definition a single process in otherwise empty spacetime, the above problem is analogous to the original puzzle of Kant concerning the lone hand. The point is that in any reductive account, it is impossible to distinguish this evolution from its incongruent counterpart. Of course, no sentient being will ever notice the difference between a time-asymmetric evolution and its incongruent counterpart. But it is a different thing to say that there is no such difference. Again, employing the analogy with spatial enantiomorphy, we may be happy to deny the difference between oppositely oriented office chairs in otherwise empty space, but denying the difference between a left and a right slipper is, prima facie, not as uncontroversial.[8]

Finally, there is an interesting connection between problems with reductive explanations of the consistent orientation of time-asymmetric processes on the one hand, and explanations of the consistent orientation of the violation of parity symmetry in subatomic physics, as discussed in Hoefer (2000) and Pooley (2003), on the other. Let me repeat how Hoefer (2000, 252) puts it, for the moment ignoring the anthropomorphic character of the expression: it is something of an explanatory mystery how B-mesons manage to select the same orientation for their mirror-asymmetric decay consistently. Now, in the case of time-asymmetric processes, the reductive explanations do account for the fact that the orientations align. But as I have argued here, in explaining the eventual orientation of time-asymmetric processes, we are facing the very same mystery as in B-meson decay.

9. Conclusion

This article discusses the enantiomorphic character of processes in spacetime, and with insights deriving from the debate on spatial enantiomorphy, it presents some problems for reductionism in the discussion of the direction of time.

In more detail, I first show that on a certain definition of processes, time-asymmetric processes are enantiomorphic objects in spacetime. Then, I discuss the problem of enantiomorphs in space, in order to introduce some positions concerning enantiomorphy, and to show that it entails the dilemma of either denying reality to the orientation of enantiomorphs, or supplying space or objects with further oriented properties. This discussion is subsequently carried over to the discussion on time, where I show that reductionists about the direction of time are tied to a denial of orientation being intrinsic. I further show that reductive explanations of time-asymmetric processes presuppose that the orientation of enantiomorphic processes is indeterminate.

The two results on reductionism are probably best taken as a further motivation to adopt the position that incongruent counterparts are not intrinsically different, and further that their orientation is not determinate. This already seems to be the consensus view among philosophers, and the price for maintaining INT and DET in the spacetime case again seems high: the impossibility of a locally defined time direction, and problems with reductive explanations of the orientation of processes in time. Still, against the above theoretical reasons, the firm intuition of most philosophically untrained minds remains that a hand is determinate in being left or right, and made determinate by its very constitution.

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Notes

[1] If the folding exercise is confusing, it is also possible to imagine knee (b) going round a Möbius band by rigid motion.

[2] It seems possible to provide a definition of enantiomorphy that does not depend on rigid motions, along the lines of Möbius (1991): an object is enantiomorphic in *n*-dimensional

space if and only if it is not uniquely characterised by $\binom{n+1}{2}$ distances between its labelled parts. But for the present purpose, this definition is less suitable.

[3] The present result may be connected to the remark of Wittgenstein (1921) in Tractatus 6. 36111: 'Das Kantsche Problem von der rechten und linken Hand…besteht schon…im eindimensionalen Raum'. It is because in Minkowski spacetime, the time component is in a sense a separate one-dimensional space that time-asymmetric processes are enantiomorphic.

[4] It seems that in an n-dimensional space, a relation that refers to orientation must involve at least $n + 1$ points. We may make ORI-R more specific by means of this.

[5] Smart (1964) advances an argument comparable with that of Remnant. The same responses apply to his position.

[6] As a nice parallel, this is just as counterintuitive as Mach's view on the inertia of mass, which is also supposed to suddenly vanish when there are no other masses present in the universe.

[7] Matthews (1979) quotes Earman as saying 'any other method' and accuses Earman of suggesting that PP is a method, too, while PP is just a consistency requirement. But Earman's text reads 'any method'.

[8] The difference may give rise to an argument similar to Leibniz's argument against Newtonian absolute space: there is no sufficient reason to create either the universe or its incongruent counterpart.

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