Time for Pancakes: Time Reversal and Ontology

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Abstract

According to the standard account of time reversal, namely the account found in physics books, a time reversal transformation involves a temporal operator T that, when acting on a sequence of states, it inverts the order with which states happen, and suitably changes the properties of the entities in the state as to make the theory time reversal invariant. This 'symmetry first' approach imposes symmetries on the theory: the changes in the states are a consequence of requiring the theory to be time reversal invariant. Some (Albert, Callender) find this view unjustified: we discover a theory has a given symmetry, on the basis of the theory's ontology, not the other way around. So, they propose a 'metaphysics first' approach, sometimes dubbed 'pancake account' of time reversal: T inverts the order of the states but does nothing else. Consequently, since there are no obvious independent reasons for the state to changes as T prescribes to preserve time reversal symmetry, then the theory is not time reversal invariant. In this paper I wish to further motivate the pancake account of time reversal by arguing the standard account is far more problematical than has been suggested. Moreover, I defend in the pancake account from recent objections raised by Roberts. Finally, since I value symmetries, I propose an alternative account, which aims at retaining the best of both approaches: the T operator changes the order of the states, it leaves the state unaffected (like the pancake account), but also makes the theory time reversal invariant (like the standard account).

Keywords: time reversal; quantum theory; classical electrodynamics; primitive ontology

1. Introduction

In this paper I wish to further motivate, defend and improve on the non-standard, or heterodox, account to time reversal symmetry as proposed by Albert (2000) and Callender (2000), which has been recently dubbed by Roberts the pancake account. According to this approach a time reversal transformation is implemented by an operator which simply inverts the order of the physical states. Instead, the standard or orthodox approach is one in which the relevant operator also suitably changes some properties of the entities in the physical state.

In section 2 I discuss the motivations for the standard approach: it is a 'symmetry first'; approach, in the sense that time reversal symmetry, as many others are required or imposed on the theory rather than inferred from the dynamics. This leads directly to the problem for this approach, discussed in section 3, namely that it is 'metaphysics last:' Albert and Callender argue that a scientific realist should take the theory at face value, and therefore read the properties of the theory from its ontology, rather than the other way around. Accordingly, if time reversal is simply seen as reversing the time ordering of events, and if the ontology of the theory is what it is commonly accepted that it is, then there is no reason why it should transform in such a way as to make the theory time reversal invariant.

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The defenders of the standard account have tried to provide these reasons, as presented in section 4, thereby responding to the challenge posed by Albert and Callender. Nonetheless, as I argue in section 5, the standard account is far from being problem free. I discuss several of such difficulties, the most challenging of which are that there is no justification of why the state should change under time reversal, and that the invariance of theories under such definition of time reversal are not worth having.

In section 6, I defend the pancake account from recent criticism by Roberts (2021), and in section 7 I propose and alternative approach, in which I endorse the time reversal operator as defined by the pancake account, but I also restore the time reversal symmetry of the theory by eliminating much of the ontology from the state. I conclude in section 8, in which I evaluate the cost and benefits of each approach.

2. The Standard Account of Time Reversal

Consider a classical system such as a billiard ball on a frictionless table. According to every physics textbook, the state S of the system at a given time, namely what provides its complete description at that time, is given by its position x and its velocity v: $S = (x, v)$. Now consider various transformations the system can go through. For instance, a system can be rotated, or translated in space. Usually, one obtains the transformed system by applying some suitable operator to the original system. This operator is supposed to suitable describe the physical transformation the system goes through, as we observe it. That is, one can actually perform the transformation and later see its result. This is what allows us to select which mathematical operator to use to represent such transformation. For spatial translations, such an operator is one which takes the original system and moves it by an arbitrary constant. Alternatively, one can move oneself by that constant in order to describe the system from a translated frame. So, if one describes an unmoving billiard ball at one instant by its position x at that instant, $S = (x, 0)$, then the coordinate of translated ball will be described by $x + a$, for an arbitrary constant a, such that the transformed state is $S' = (x + a, 0)$. This translated system describes the transformation both passively (the ball seen from a translated frame) and actively (the ball being translated itself). For a rotation of an angle ϑ, the operator implementing the transformation is a suitable matrix R_ϑ: if S is the original state, then the state rotated by ϑ is $R_\vartheta S$.

These are not the only transformations on can perform on a system. Consider now the time reversal operation. A new difficulty arises: how are we supposed to understand this operation? We cannot understand it in the same way as we understood rotations or translations, as we cannot actually reverse time in a physical process. So, it is not entirely obvious what time reversal does to the state of a system: it certainly inverts the order of the instantaneous states, but does it do also something else? To find an answer to this question, and thus to characterize time reversal, one usually resorts to the following metaphor. Imagine filming a body in motion (say, a billiard ball in a frictionless table) and then imagine projecting the resulting movie backwards. The backward projection is the time reversed process. How is this process obtained, starting from the original system? The answer is: not only one reverses the order of the events, but also the velocity changes sign. That is, according to the 'standard account,' namely what one finds in physics textbooks, time reversal operator T is given by the composition of two transformations: 1) T inverts the temporal order with which states happen, that is $t \rightarrow -t$; 2) T changes the state of the system as to invert the direction of the velocities, that is $v \rightarrow -v$. Watching the backward movie suggests T to behave like this, but also the mathematical definition of the velocity as rate of change of position.

Symmetries, or invariances, of a given theory are associated with the transformations of the theory's dynamical law. If one wishes to use a quick slogan, one could say that a theory is invariant under a given transformation if and only if 'transformed solutions are still solutions,' where 'solution' means 'solution of the fundamental dynamical law of a theory.' A solution of the fundamental laws expresses a possible way the world can be according to the theory. So, a theory is invariant under a given transformation if and only if both the original description provided by the theory and the transformed descriptions are both possible descriptions of the world. In classical mechanics, under translation and rotation, the coordinates of the system suitably change but the velocity does not: if the ball was moving in the original frame, it was also moving in the translated or rotated frame (even if the characterization of the coordinates of the velocity might change, the vector is the same). So, the state does not change under these transformations. That is, rotations and translations are symmetries of the theory. Or, one could say that the theory is invariant under these transformations. What about time reversal? As in the case of rotation and translation, there is a symmetry connected to the time reversal operator, namely time reversal invariance. A theory is said to be time reversal invariant if and only if both the original description provided by the theory and the time reversed one are possible descriptions of the world according to the theory. In Newtonian mechanics the instantaneous state of the system is given by $S = (x, v)$; if T is the time reversal operator defined above, then the transformed state is $T(S) = (x, -v)$. Newtonian mechanics is time reversal invariant because transformed solutions namely $x(-t)$, are also solutions. A movie of a billiard ball on a frictionless table projected forward and backward both describe ways the world can be. If we *impose time reversal symmetry* on all other fundamental physical theories, then it follows that T, in addition of reversing the order of the states, should also change some of the other properties of the theory. More in detail, given that a temporal sequence of states is a dynamical trajectory, the time reversal operator T acts on trajectories so that:

1) T inverts the order with which states happen $t \rightarrow -t$;

2) T changes the state so that some properties are preserved, and some instead need to change, as illustrated in Table 1 below:

Table 1: Property change under time reversal transformation in the standard account.

Theory	Changed	Preserved
Hamiltonian Mechanics	Momentum $p \rightarrow -p$	Position $\mathrm{x} \rightarrow x$
Classical Electromagnetism	Magnetic field $B \rightarrow -B$	Electric field $E \rightarrow E$
Quantum Mechanics	Spin $\sigma \rightarrow -\sigma$	Kinetic energy $p^2/2m \rightarrow p^2/2m$
	Position wavefunction $\psi(x) \rightarrow \psi^*(x)$	Transition probabilities $\lvert\langle\psi\vert\varphi\rangle\rvert^2 \rightarrow \lvert\langle\varphi\vert\psi\rangle\rvert^2$

In Newtonian mechanics the instantaneous state of the system is given by $S = (x, v)$; if T is the time reversal operator defined above, then the transformed state is $T(S) = (x, -v)$. Newtonian mechanics is time reversal invariant because transformed solutions namely $x(-t)$, are also solutions. In the case of Hamiltonian mechanics, the state is $S = (q, p)$, where q and p may have general meaning, not necessarily position and momentum; the time reversed state is $T(S) = (q, -p)$. If q and p are effectively position and momentum, then Hamiltonian mechanics is time reversal invariant. Transformed solutions $q(-t)$ are also solutions. Now consider relativistic field theories such as classical electrodynamics. The state this time is given by $S = (x, E, B)$; while the transformed state is $T(S) = (x, E, -B)$. If so, then classical electrodynamics is time reversal invariant: with these transformations, the transformed solutions are also solutions. What about standard quantum mechanics? The state is given by the wavefunction, $S = \psi$; and the operator T is such that $T(S) = \psi^*$. It is antiunitary, and antilinear, and this transforms solutions into solutions.

3. Against the Standard Account: The Pancake Account

As we have seen above, the movie analogy and the intrinsic definition of velocity led us to define the time reversal operator so that it would do more than just reordering the states: it also changes something in the state, namely velocity. Then imposing time reversal symmetry on other theories, we find how T should be defined. With this definition, T guarantees time reversal invariant of these theories. However, while this seems straightforward for classical mechanics, the situation is not as clear in the other theories. That is, the last two examples require a little more discussion. What about classical electrodynamics and quantum theory? Why does T the flip the magnetic, $B \rightarrow -B$? Why do we have this: $\psi(x) \rightarrow \psi^*(x)$?

Roberts (2021 and references therein) writes: "we want an operator that preserves position, and reverses momentum" and the magnetic field. But why is that? The idea is that we want the symmetries for the theory, and we define the time reversal operator as to preserve this symmetry for us. For instance, in quantum theory, it is antiunitary because only antiunitarity preserves the Hamiltonian, and the properties transform as they do because it's part of their definition

Albert (2000), Callender (2000), however, find this reasoning question begging: we need to discover whether a theory has a given symmetry, on the basis of the ontology of the theory. Instead, what Roberts proposes is to impose the symmetries to constrain the dynamics of the theory to start with. If instead we adopt an ontology first approach, a theory will have the symmetries that it has, as a consequence of its ontology, rather than an a priori theoretical imposition. In other words, according to Albert and Callender, in the standard approach one postulates the time reversal operator to be defined as such in order to make the theories time reversal invariant. In other words, one postulates that T is defined that way to make the theory invariant. But why is this the right definition of T? What is the physical justification for the changes one would have for the magnetic fields and the wavefunction?

According to Albert and Callender, the time reversal operator should not do anything more than reversing the order of the states, because this is what physically makes sense. Then, once T is defined that way, one can determine whether the theory is time reversal invariant or not.

With such a definition, namely T merely reorders the states, Albert (2000, ch.1) reasons that it makes sense for the velocity to change sign, and thus we can conclude that classical mechanics is time reversal invariant. However, the situation is different in the other theories. Here is why. As we mentioned, in classical mechanics, typically, the state of a given physical system is taken to be constituted by the couple of positions and velocities. Albert instead thinks that such couple should be called the dynamical condition D at an instant. In fact for Albert the state should be complete but also genuinely instantaneous: the description at different times should be independent. Since the velocity depends on the position, it should not be it the state but only in the dynamical condition, as it is needed "in order to bring the full predictive resources of the dynamical laws of physics to bear" (Albert 2000: 17). Rephrasing, the instantaneous state represents what exists in the world at one instant, while the dynamical condition specifies what is needed at one time to determine the state of the system at another time. According to Albert, thus, in classical mechanics, S is given by the particles' positions, while D by the positions and the velocities: $S = (x)$; $D = (x, v)$. Having said that, therefore in classical mechanics, the instantaneous state S remains invariant under T, and therefore classical mechanics is time reversal invariant. The velocity transforms under T according to its definition as a function of x and t: $T(v) = T(dx/dt) = dx/(-dt) = -dx/dt = -v$. However, this does not affect time reversal invariant because the velocity is not in the state. This is no longer true in classical electrodynamics or quantum theory. In fact, when considering classical electrodynamics, instead, Albert believes we need to add to S also "the magnitudes and directions of the electric

(E) and magnetic (B) fields at every point in space" (Albert, 2000:14). That is, the instantaneous state is given by the triplet (x, E, B). The fields are, unlike velocities, logically independent of the particles' positions and therefore they should be added to the state in order to complete the picture of the world at one time. That is, electromagnetic fields are real just as much as the particles are. According to Albert, as we already saw, the instantaneous state should not change under T. The velocity was not in the state and changed under T according to its definition as the rate of change of position. In contrast, magnetic fields are not the rate of change of anything. Rather, they are fields, and as such, he argues, they should be mathematically represented simply by vector functions, whose intensities represent the various field values in space. As such, therefore, there is no reason why they should not change at all under T: $T(x, E, B) = (x, E, B)$. As a matter of fact, though, in order for classical electrodynamics to be time reversal invariant, we need the magnetic field to flip sign under T. But since there is no reason why this would happen, classical electrodynamics is not time reversal invariant.

Similar reasoning can be made in the case of quantum theory, as proposed by Callender (2000). Why should the wavefunction transform into its complex conjugate under T? The wavefunction, being a function of the particles' coordinates, is naturally understood as a scalar field in configuration space. If so, the wavefunction is not the right kind of object to transform into its complex-conjugate under T : a scalar field should not change its amplitude at all under a time reversal transformation. What the time reversal operator in fact should do is only change the order of the states, and nothing more. Since in order to have time reversal invariance the wavefunction would have to change under T, then the argument concludes, then the Schrödinger equation is not time reversal invariant.

The basic idea is therefore this: first find what is in the instantaneous state, namely the ontology of the theory. Then figure out whether there is a reason for the entities in the state to change under T as needed in order to preserve time reversal invariance. In classical mechanics, by definition, the velocity changes sign under T and in any case it does not matter because it is not even be thought of as belonging to the state. But in classical electrodynamics and quantum theory the situation is different. The magnetic field and the wavefunction are physical fields, mathematically represented as suitable functions of coordinates, and as such there is little reason for them to change during time reversal, Albert and Callender maintain. But if they do not change, then transformed solutions are no longer solutions, and thus the theories are no longer time reversal invariant.

Therefore, here is, schematically, my reconstruction of the argument put forward by Albert and Callender against the standard account, and its consequence for the time reversal invariance of a given theory:

1. The complete instantaneous description of any system is given by its state S;
2. In a given theory, the object X provides the state [this changes from theory to theory, and from one interpretation of the theory to another];

3. We both agree that the time reversal transformation T transforms a sequence of states into their temporally reversed sequence: $S_i, \dots, S_f \ \rightarrow T(S_f), \dots, T(S_i)$;
4. According to the standard account, we should also add that the time reversal transformation T also may need to change the properties in S to map solutions into solutions (to make the theory Time reversal invariant);
5. However, there is no reason why S should change under T: (4) is false;
6. Therefore, whether a theory is time reversal invariant depends on what X: if X does not change under T, the theory is invariant; otherwise, it is not.

In other words, the standard account does not provide us with any reason why properties change due to a time reversal transformation, so, aside any further justification, we should not assume that they do. Albert applies this argument to classical electrodynamics:

1. The complete instantaneous description of any system is given by its state S;
2. In classical electrodynamics the state is given by (E, B) (in addition to position);
3. The time reversal transformation T needs to change B into $-B$ to map solutions into solutions;
4. However, there is no reason why B should change under T: *"It's not the rate of change of anything" (ibid.);*
5. Therefore, classical electrodynamics is not time reversal invariant.

Callender has the same argument for quantum theory:

1. The complete instantaneous description of any system is given by its state S;
2. In quantum mechanics the state is given by the wave function ψ;
3. The time reversal transformation T needs to change ψinto ψ^* to map solutions into solutions;
4. However, there is no reason why ψ should change under T;
5. Therefore, quantum mechanics is not time reversal invariant

(A more accurate conclusion would be to say that the Schrödinger equation is not time reversal invariant. In fact, to argue that the quantum theory, understood as both the Schrödinger equation and the von Neumann collapse rule, is not time reversal invariant, one would also have to show that the von Neumann rule is not time reversal invariant. This is indeed easier to argue for, as it is intrinsically time directed, see Allori 2019a).

At this point, there are at least two possible reactions. Albert and Callender argue that there is no sensible definition for these quantities that would make sense of their change under time reversal transformation. Because of this, they think this argument shows that the proponents of the standard account need to re-think what the time reversal operator does: it does not change the properties of the entities in the state; rather it simply changes the temporal ordering at which the states happen. That is, Albert and Callender identify the time reversal operation as simply an order reversal operator. If so, however, the theories considered here are no longer time reversal invariant.

Some have argued that the two accounts arrive at opposite conclusion because they talk past one another. For instance, Lopez (2019) has suggested that the proponents of the standard account think of time reversal as motion reversal: that is, T is the transformation which reverses the changes which have happened to the object during their forward temporal evolution. If so, then the transformation is not 'time' reversal at all, as it has nothing to do with time as such. This would be another objection of the standard account. Be that as it may, I am going to assume that the two accounts share the same notion of time reversal, and I aim to show that the standard account is not satisfactory.

Proponents of the standard account were obviously not so quick at abandoning it. An obvious way to go is to reject premise 5 of the main argument (or 4 of the theory-specific arguments): find non-obvious reasons why the properties would change under T the way required for time reversal invariant. This is discussed in the next section.

4. Defending the Standard Account

People have proposed ways to explain why the state changes under T as to make the theory retain time reversal symmetry. In the case of classical electromagnetism, this type of approaches includes Arntzenius (2000, 2004), Earman (2002), Malament (2004). In quantum mechanics this route has been taken by Earman (2007), Roberts (2017).

Setting aside subtle differences, the general idea is that given a mathematical object, there is a natural way for it to transform under a particular transformation, which depends on its intrinsic or geometrical definition. This would fill the gap between classical mechanics and electromagnetism and quantum theory: for the velocity we had a reason to change sign under T, based on its definition; now similar definitions are proposed for B and ψ. It is argued that electromagnetic fields are intrinsically defined as to transform under T to make classical electrodynamics time reversal invariant. In fact, it is not correct to think of B as generic function; rather, it is an axial vector, also known as pseudovector. It is because of its so defined geometrical nature that it makes sense that the magnetic field flips sign under T. In fact, by definition a pseudovector behaves like a vector function in many situations, but it changes into its opposite under T. A similar strategy has been proposed for quantum mechanics. In quantum theory, the wavefunction is to be understood not as a field in configuration space but as a ray in Hilbert space, i.e. an equivalent class of vectors related by a phase θ of the form $\psi = \{\psi e^{i\theta}\}$. It is because of this geometrical definition that it makes sense that the wavefunction transforms into its complex conjugate under T.

With these definitions for the relevant objects, it is argued, one can provide reasons why they change the way they do under T, and therefore one can restore time reversal invariance in these theories.

5. More Objections for the Standard Account

I am not convinced. Indeed, I think that there are more problems with the standard account than the one granted by Albert and Callender. In this section I discuss first why I think that the defense provided is insufficient, and then I argue that the overall approach is too costly to be worth it.

5.1. No Independent Reasons

I think that the response provided above by the defender of the standard account begs the question. What has been shown is that there is another way of thinking of the electromagnetic fields are the wavefunction that is compatible with the invariance of classical electrodynamics or quantum mechanics. Nonetheless, no reason has been provided just yet as to why this new definition should be considered the correct one. In other words, one needs to provide additional, *independent* reasons to believe that the true nature of the magnetic field (of the wave function, or whatever) is the one captured by the mathematics of an axial vector (of a ray, or whatever), so that the theory turns out invariant. And no such additional reason has not been provided so far. In any case, I think that even if one can provide independent reason, the standard account would still be extremely problematical, as discussed in the next subsection.

5.2. Unjustified Changes in the Ontology

In this subsection I am going to argue that Albert and Callender have been too kind with the standard account. In fact, their objection to the standard account was that there is no (obvious) reason why S should change under T. If this were the real problem, then one could simply provide some non-obvious reasons, as discussed in the last section, and save the account. Now instead, I wish to argue that the situation is much worse than it has been suggested so far. I wish to argue that S cannot change under T, otherwise one would have to provide a different meaning of what the state represents. If I am correct, and it does not make much sense for the state to change under time reversal, then the standard account has no chance of being fixed, providing further motivation to the alternative account to time reversal proposed by Albert and Callender.

Here is the reason why I think that it makes no sense for the state to change under a time reversal transformation. Assume that the standard account is correct and that T changes the content of the state adjusting the properties so that the theory will turn out to be time reversal invariant. However, think of what the state is supposed to represent. By definition, the state represents an instantaneous description of the world, namely it represents a picture of the world at one time. In other words, *the state gives you the instantaneous ontology of the theory.* This is what Albert assumes and no one in the standard account seems not to be willing to deny. However, if that is the case, namely if T changes the content of the state at one time, then this means that T changes the ontology of the system at that time. In other words, what the world looks like depends on whether the picture of it we are looking at is taken from the movie going backwards or going forward. By why should it be like that? It would be as if, when playing 'Back to the Future' forward in time, Marty McFly is interpreted by Michael J. Fox, but when we play it backwards it is interpreted by Keanu Reeves. Or in forward 'Star Wars' Yoda is small and green but in backward 'Star Wars' he is tall and blue. Nothing can possibly justify such a change under a transformation labelled time reversal. In a nutshell, if the state of a system at one time represents the ontology of that system at that time, then the state cannot change under T because that would amount of changing the ontology, which is absurd.

5.3 Unmotivated Definition of Time Reversal

The proponents of the standard account may want to deny that this absurdity. However, doing that, the burden of proof would be on them: the need to explain why the ontology changes under time reversal. That is, they need to explain what makes time reversal, which is supposed to reverse time, do something else entirely. In other words, now the question is about the time reversal transformation itself, and the question is: *why should we think that T, as time reversal operator, changes the ontology, while, say, the translation operator does not?* We would not accept a translation operator such that it moves the body on the left, say, of a given distance, but also colors it all red. So, why should we accept something similar for T? What is special about T? At best, there is a mystery to be solved. Notice that one cannot reply by saying that this is the way to make the theory time reversal invariant, because we have not yet provided any reason why one would want symmetries to start with. Since there seems to be no reason to have a time reversal operator defined as such other than to preserve time reversal symmetry to this change in ontology, I think we should reject this definition of time reversal operator.

5.4 No Value in Time Reversal Invariance within the Standard Account

In addition, I wish to argue that even if with the standard account of time reversal theories turn out to be time reversal invariant, nonetheless there is no value in the symmetry so defined. To explain this, let me elaborate on why we want symmetries.

Some people have argued that symmetries are worth having because they are often used in theory construction: especially in quantum field theories, symmetries are imposed on the formal structure to select among the various possibilities, Symmetries are also used in theory evaluation: theories with more symmetries are usually preferred, all things being equal, to theories with less symmetries. Others have argued that symmetries are important because of their connection with conservation laws. However, I think that the most important reason why symmetries are worth having is that they reflect our desire of providing a perspective free description of the phenomena. When we require that a theory is rotation invariant, we mean that the description the theory provides of the phenomenon does not depend on whether we are observing the phenomenon from this frame of reference, or a frame rotated with respect to this. The principle of relativity, that the form of the law should be valid in all (inertial) reference frames, just reflects this idea: the frame we are in should not influence our description of the phenomenon. In other words, the more symmetries a theory has, the less dependent on our point of view it is, and the more objective its description of the world is.

If that's the case, however, and if a time reversal transformation is defined as to change the ontology of the system, then requiring a theory to be invariant under such T does not help at all our search for the most perspective free description, so we have no reason for requiring such a symmetry. In fact, this invariance does the *opposite* of what we want, namely it changes the description of a phenomenon depending on how we look at it. Instead, what we should want is a theory to be time reversal invariant because in such a theory it would not be important whether we are gathering information about the world from its forward or its backward movie. In fact, we would want the instantaneous description not to change depending on whether it is taken from the backward or the forward movie, because we want our theory to be as perspective free as possible. In other words, requiring time reversal invariance does not seem to make sense in the standard account, if the reason why we want symmetries is to make the theory as objective as possible. In fact, the time reversal operator as defined in the standard account makes the description provided by the theory perspective dependent, which was exactly what we wanted to prevent by requiring symmetries.

To conclude this section: these arguments, in addition to the original argument by Albert and Callender, in my opinion show that the time reversal operator should only reverse the order of the states rather than messing around with its content, like proposed in the standard account.

6. Criticisms to the Pancake Account and Replies

If it is the case that the state should not change, because it is an instantaneous picture of the worlds, then we need to postulate that the time reversal operator simply flips the order of the states but leaves them unaffected. This approach has been dubbed the 'pancake' account' because the states are stacked onto one another, like a stack of pancakes, without any connection with one another (Roberts 2019). I think that the name is meant to suggest that the account is too naïve to work. Nonetheless, I think this is the case in which simplicity is mistaken for naivete, understood as oversimplification. Anyway, if this is being simple-minded, I like naivete (and pancakes too), so I happily endorse the name.

Nonetheless, Roberts (2021) has recently criticized the originally proposed pancake account. In this section, I discuss these criticisms and provide my replies.

6.1 Misguided Motivation

According to Roberts, the original motivation for the account was that it did not make any sense for the magnetic field to change under T because "it is not the rate of change of anything." However, Roberts points out properties can flip in this way without being rates of change. In order to show this, he uses the following example. Consider a soldier going to war. Assume he has the property of being brave, as he runs towards the enemy. If we take a movie of this and we time reverse it, what the soldier does, namely running away from the enemy, can be characterized as 'cowardice.' If the pancake account were correct, it is argued, then we could not characterize the soldier as coward in the backward movie, and this seems wrong. Roberts also says that the same thing can be said for other, more physically interesting properties such as spin. So, the pancake account is mistaken.

As a first reply to this objection, let me notice that it is unclear in what sense 'cowardice' is the time reversed counterpart of 'bravery.' Both of these properties are much more than simply 'running towards' or 'running away' from the enemy. After all, someone could run towards the enemy for a variety of reasons: they may because they are brave, but also because they are being fool-heated, or reckless, or irresponsible. Or also they may run towards the enemy because they are forced to do so, or they do it without realizing where they are going, just to mention few obvious possibilities.

Regardless, I think that the 'backward' soldier cannot be described as 'coward' in any sensible sense: they run away from the enemy but probably the enemy is also running away from them in the other directions, bombs are un-exploding, bullets are existing bodies to 'run towards' guns and rifles. That is, nothing makes sense in the usual language in the time reverted movie, and that is because the macroscopic world is irreversible: we can tell which, among the forward and the backward movie, is physically possible, and the backward one is not. That is, not only one cannot characterize the backward soldier as coward, rather the backward soldier is not soldier at all.

Moreover, for this argument to work we need 'cowardice' and 'bravery' to be alike the magnetic field, the wavefunction, and spin. The natural way of thinking of cowardice and bravery is of thinking of them as dispositional properties. If so, then, also the magnetic fields, the wavefunction and spin should be understood in the same way. That is, they are dispositional properties of matter rather than part of matter themselves. Indeed, one may think that they would be more alike to velocity than we originally realized: they are properties with the suitable definition which lets them transform as needed as to preserve time reversal invariance. And since velocity is a property of matter, the magnetic field and the wavefunction are properties of matter too. In this way, as we classified velocities in D, rather than in S, we should do the same for the fields are the wavefunction as well. However, this would be a very unorthodox view. For starters, if the wavefunction is a property, what is matter made of in quantum theory? One could say particles, within the pilot-wave theory, but such an answer is not available within the standard theory. In turn, within classical electromagnetism this view would also imply a radical way of thinking about the fields. In fact, the magnetic field is not understood, as usual, as part of the ontology of classical electrodynamics but rather as a dispositional property of the ontology which presumably is given by particles. I have nothing against such a view (indeed, I am going to discuss it favorably later). Nonetheless, it would be a peculiar view to hold by someone who wants to defend the orthodoxy of the standard account.

In any case, this is question begging: just noticing that some stuff can be seen as doing what we want does not explain much. The point is to explain why certain objects have the properties that they do: why is spin flipping sign? Why is the magnetic field? Why does the wavefunction turn into its complex conjugate? What is the physical significance of a pseudovector? What is the physical significance of a ray in Hilbert space? What do they tell us about the nature of the world? In other words, if one wishes to take the theory ontologically seriously, one should be able to justify why the fields and the wavefunction are defined as they are. Instead, the standard account does not explain these features.

6.2 Incoherence

Roberts also argues that the pancake account is incoherent because it does not make sense of the transformation of the momentum under time reversal in Hamiltonian mechanics. Remember that on the pancake account the content of the state is left unchanged, only the order of the states is reversed. In Hamiltonian mechanics the state is (q, p), so the time reversed state is the same, hence the momentum p does not change under T. However, since the velocity v is a rate, then it changes sign under T, even in the pancake account. So, the momentum p, given that $p = mv$, should change too, by definition. However, this contradicts what we have just seen, hence the pancake account is incoherent.

In reply, one could insist that this is just a misunderstanding of the pancake account: as we have seen earlier, according to the pancake account velocities are not in the state, they are in the dynamical condition D, and T can change D as long as what is in D is defined in a way that makes sense for them to change, like velocities. In this case, also momentum is a rate, hence the incoherence charge dissolves. (A counter reply could be that this means that Hamiltonian mechanics isn't an effective description of classical mechanics. However, the defender of the pancake account could simply deny this, as also in classical mechanics velocity is not in the state. Alternatively, one could bite the bullet and say that the Hamiltonian formalism is not physically significant: it is just a useful mathematical tool.)

6.3 Underdetermination

A third objection is that in the pancake account it is no longer clear why time reversal is implemented by $t \to -t$ and not some other transformation, like for instance $t \to \sqrt[3]{a - t^3}$. In the standard account the first transformation is selected by the requirement that T is an involution, i.e., if it is performed again, it brings back to where one started. Instead, in the pancake account one only requires that the transformation inverts the time ordering. In this case, both transformations invert the order of the states, so why the former instead of the latter?

As a reply, I would say that in the pancake account the justification of T being $t \rightarrow -t$ is not the one provided. Rather, this transformation has a physical significance, while the other one does not. That is, we already know what the variable t stands for, and what the minus sign does, so why are we asking for more? To me, to ask for further justification is just like asking why the transformation $x \rightarrow -x$ represents a mirror transformation on the x axis, or why the transformation $x \rightarrow x + a$, where a is a constant, represents a translation along the x axis of a quantity equal to a. In these cases, we do not ask why we have, say, $x \rightarrow x + a$ rather than some other transformation, and this is because we know what this transformation represents. Why should the case of time reversal be different? In other words, why should we even think that the transformation $t \rightarrow \sqrt[3]{a - t^3}$ represent something physical at all, given that we already have specified what the various variables and the operations stand for?

6.4 Unwelcomed Results

Another charge to the pancake account is that it makes classical electrodynamics and quantum theory no longer invariant under time reversal. This is supposed to be problematical because, as anticipated already, symmetries have been considered important features for a theory.

As we have seen in the last section, however, if we want symmetries because they are an indication of how objective a description is, then the time reversal operator as defined in the standard account does not qualify as a valuable symmetry in this respect: we should be looking for a theory with most symmetries because such a theory would be as perspective free as possible, but T as defined in the standard account makes the ontology change. That is, the ontology would be perspective dependent, because what we would say exists and their features depend on whether we are looking at the backward or the forward series. This is the exact opposite of what we look for. So, going to the standard account to preserve symmetries would not be any help in this at all. What one would need is a theory to be invariant under the pancake account of time reversal, and so far, this is not what happens.

The proponents of the pancake account can of course bite the bullet and argue that the importance we give to symmetries is exaggerated and without much of a foundation. Nonetheless, it is a very radical step to make.

7. The Best of Both Words

I am convinced that the time reversal operator should be defined as proposed by the pancake account, namely as ordering operator. However, I also think that the symmetry objection poses a real problem for the pancake account, as I value symmetries for the reasons discussed earlier. The question now become the following: is there a way to recover symmetries but also maintain the pancake account? In other words, we have a dilemma. In the standard account of time reversal, theories are invariant under time reversal, but we have the problem that the state, namely the ontology, changes depending on whether we take the state from the forward and the backward movie of the world. That is, this account is true to the symmetries (with qualifications, as we have seen), but not to the ontology. On the other hand, however, in the pancake account the state does not change but the theories lose time reversal symmetry. That is, this account is true to the ontology but not to the symmetries. The goal is now to find an account of time reversal and of the ontology that keeps the best of both words: changes the order of the states without changing the ontology, but also maps solutions into solutions. I think that this goal can be achieved by keeping the definition of T of the pancake account (reverse the order but does not change the states) but *redefining what is in the state*. Just proceed as Albert did in classical mechanics: put everything but x in the dynamical condition, out of the state.

Here's the situation so far. Both the standard account and the pancake account agree that in classical electrodynamics the state is $S = (x, E, B)$, and in quantum theory one has $S = \psi$. What if we challenge this? Albert already did this in classical mechanics: the velocity is in the dynamical condition D, not in S. Let's see what happens. Set aside quantum theory for the moment and focus on classical electromagnetism. Assume that the fields are not in the state, they are in the dynamical condition. That is, assume that there are only particles, so that $S = x$. If we start from this hypothesis, then T reverses the order of states but does not change them (as in the pancake account, *contra* the standard account). Because now the fields are no longer in the state, then classical electrodynamics is time reversal invariant (as in the standard account, *contra* the pancake account). In this way we get both time reversal invariance and no odd transformation for the ontology. Given that the electromagnetic fields are no longer in the state, they are no longer part of the ontology, so the ontology does not change by time-reversing the history of the world.

There is an obvious problem with this way of seeing things: if the electromagnetic fields are not in the state, then what are they? Are they even real? Aren't we used to think that fields are real? Isn't there energy associate to fields that suggests that they are, indeed real?

As a reply, one could simply accept that they are real without being in the ontology of matter. That is, one could maintain that the electromagnetic fields are objective features of the world without thinking that they constitute something material. Fields should be understood as we understand forces or potentials: they are objective without being what tables and chairs are made of. They represent therefore, some 'nomological' rather than 'material' facts: they 'tell' matter how to move, but they are not matter. In this approach, the ontology comes first, and symmetries are imposed on the nomology. So, in virtue of the role fields have in the theory, one can explain why B flips (*contra* the standard account): it is in D, it is an axial vector, and the reason why it is one is that such a definition allows it to change as to preserve the time reversal invariance of the theory. This is compatible with the 'geometrical' transformation account: physicists defined B as an axial vector because in this way time reversal symmetry is preserved.

Arguably, this is similar to the way in which fields have been originally introduced during the 19th century. The idea was to use them as a fiction to make interaction among particles local, mediated by the fields rather than in terms of forces acting at a distance and not through any intermediary matter. Charged particles were considered as giving rise to an electromagnetic field, which had a value in every point in space. "Nobody, however, thought of fields, early on, as anything more than a matter of bookkeeping. They were not considered a part of the fundamental ontology of the world, not something you might, say, stub your toe on, not (most certainly) *a real thing*" (Albert and Galchen 2009). Later on, however, the situation changed into what now we know as Maxwell's classical electrodynamics. It was observed that the energies and momenta of systems of particles were sometimes not conserved, unless one would add the energies and momenta of the fields. This suggested that fields are real, in contrast with what previously thought. This suggestion was reinforced by the fact that one can write an evolution equation for the fields, which have solutions independently of the presence of any particle. Also, the fact that these free fields could interact with themselves and that they oscillate at a velocity which is identical to the speed of light strongly suggested that they should be identified as light themselves.

So, the approach that I am now proposing is going back to the original way of understanding electromagnetism, in which conservation laws are broken and light is no longer identified as the oscillation of these fields (because there aren't any). This requires a lot of re-assessing, and it is certainly not cost free. Still, we know that classical electrodynamics is not the final theory, so one may hope that in future theories these difficulties might even out.

Indeed, what about other theories, like quantum mechanics? If this approach is correct, then the wavefunction is not in the state. Rather, it is part of the dynamical condition. But how can we even begin to make sense of this approach if the wavefunction is all there is in quantum theory? What is left in the ontology? We need to move beyond of standard quantum theory. Indeed, we already knew that, albeit our reasons were different, as they were connected to the measurement problem. The measurement problem is the problem of dealing with unobserved macroscopic superpositions without imprecise rules such as von Neumann's collapse rule. This leads to the pilot-wave theory, the spontaneous localization theory and the many-worlds theory. Now instead the motivation comes from thinking about ontology alone, and the way in which it makes sense to transform it. We have already seen this, but this is a different way of putting this: if we think that the ontology should not change during a time reversal transformation, and if we also think that the wavefunction transforms under time reversal transformation into its complex conjugate (because this is the way in which we can ensure that the theory is time reversal invariant), then it follows that the wavefunction cannot be in the state (as we have seen, one can get around this by denying that the wavefunction actually transforms the way books say, and this is what Albert and Callender propose, at the price of the theory being no longer time reversal invariant). If so, however, what can be in the state in place of the wavefunction?

For the pilot-weave theory, the answer is clear: it is a theory of particles so that $S = x$. For the other two theories instead, it is not clear at all, as they are both theories about the behavior of the wavefunction. So, to make sense this approach needs to postulate the existence of other things which should be thought the ontology of the theory, in place of the wavefunction which is no longer in the state. This is indeed what the proponents of the primitive ontology approach do (Allori et al 2008, Allori 2013 a,b): GRW and many-worlds are not theories of the wavefunction, but they need to be 'supplemented' with some other ontology, such as particles, a matter field, or spatiotemporal events. In this way, the state could instantaneously describe them, rather than the wavefunction. There are other reasons to have something other than the wavefunction. One of them is provided by the so-called primitive ontology approach, which was developed to preserve the classical explanatory schema based on composition and dynamical reduction (Allori 2015a). To guaranteed that such a reductive explanation is possible, one needs the ontology to be (suitably) microscopic and in spacetime. Thus, one needs to go beyond the wavefunction, as it is neither (obviously) macroscopic nor in spacetime. Here instead the argument has to do with symmetries: if the wavefunction transforms the way the textbooks say, then the theory is time reversal invariant in both accounts of time reversal operator. However, only if you think of the time reversal operator as in the pancake account then it makes sense why the wavefunction transforms that particular way: it is because it does not belong to the state. To be clear, in this approach the wavefunction has disappeared from the state, namely it is not part of the ontology of matter. However, it should still be regarded as encoding something objective about the feature of the world, just like velocities in classical mechanics. Also, like in the case of electromagnetic fields, the wavefunction is not material but is better understood as expressing some nomological fact (see Allori 2021 for an account of what the wavefunction could be in this framework).

8.Evaluation

To summarize, we have seen three approaches: the standard approach, the pancake account, and the primitive ontology approach. None of them is perfect, namely in each of the costs are not light, otherwise we would have no debate at all.

In the standard account, we have the advantage that theories are invariant under time reversal, but the cost is that we need to define the time reversal operator in such a way that the ontology changes depending on whether the state of a system belongs to the forward or the backward history of the world. This, I think, is a serious objection because it undermines the whole symmetry first strategy: the time reversal invariance so obtained does not do what we would like symmetries to do, namely to provide us with a perspective free description. In the pancake approach, one does not have this issue, but by keeping certain quantities in the ontology the theory loses time reversal symmetry. Finally, in the modified pancake account, in which one pairs the pancake account of time reversal with a bare understanding of the ontology, one has both time reversal symmetry and the ontology behaving sensibly and restoring the value of symmetries. However, we have the problem of understanding the status of the entities which are not in the state but they are in D, namely they still encode objective information about the world, such as the electromagnetic fields and the wavefunction.

People will disagree about which approach is to be preferred based on which desiderata they care for more, and depending on the costs they are more likely to swallow. So, very generally, I think we can conclude that we cannot have everything we want. That is, the three following claims (which we want all to be true) are incompatible (for more on this paradox, see Allori 2015b):

1. time reversal is a symmetry of the theory;
2. the ontology does not change under time reversal transformation;
3. fields and wavefunction are in the state.

We can select the features we care about more, but we cannot have them all: one of them will have to go. This is the cost that each approach has. In fact, if, as both in the original and the modified pancake account, someone cares about an ontology which does not change under transformations like T, then they have to reject either 2 or 3. So, either, as in the pancake account, one accepts that the theory is not longer time reversal invariant (rejecting 1). Otherwise, as in the modified pancake account, one has to assume that the fields and wavefunction are no longer in the state (rejecting 3).

Instead, if, as in the standard and pancake accounts, someone wants to keep fields and wavefunction in the state (thereby holding on to 3), then they have two other options. Either, as in the pancake account, one accepts that the theory is no longer time reversal invariant (rejects 1). Or, as in the standard account, one accepts that the ontology changes under T (rejecting 2).

Finally, if someone cares about symmetries, as both in the modified pancake and the standard accounts, then the options are the following. Either, as in the primitive ontology account, one can reject 3, namely accept that the fields and wavefunction are no longer in the state. Or, as in the standard account, one can reject 2, namely accept that the ontology changes under T.

My personal evaluation is the following. I think that allowing the ontology to change under T is too high of a cost, threatening the coherence of the whole symmetry first strategy, and therefore I rule out the standard account, also considering that the T operator as defined does not provide an invariance we can care for. Between the two alternative pancake accounts, I favor the modified one because I value symmetries, so allowing that the fields and the wavefunction are not in the state seems to me as an acceptable cost. This is true especially in the case of quantum mechanics, in which I think there is already evidence that the wavefunction is not in the state. In other words, I think that it is much less problematical to make sense of the wavefunction not being in the state instead of the electromagnetic fields. In fact, the wavefunction not being in spacetime, thereby disrupting the classical explanatory schema based of compositionality and dynamical reduction, provides already a reason to reject the wavefunction as being part of the ontology (see Allori 2019b). This instead cannot be said for the electromagnetic fields, which are in spacetime. Moreover, the reasons we had to think of the fields as part of the ontology do not hold for the wavefunction. That is, the reasons we had to think of fields are part of the ontology were that fields carry energy, and that fields affect, and they are affected by particles. This is not the case for the wavefunction: it does not carry its own energy, and even if it affects the particles, it is not affected by them. The second fact indeed is one of the proclaimed mysteries of the pilot-wave theory: it is said that the theory is problematical because it does not explain why the wave acts on the particles, but the particles do not act back. In this framework instead this asymmetry makes perfect sense: particles do not act back because there is no physical entity to act back on.

As a final remark, let me notice that, as Struyve (2022) has also discussed, the ontology of a theory is underdetermined by the formalism and whether a theory is time reversal invariant depends on the ontology one considers, even with the same understating of what the time reversal operator does. For instance, classical electrodynamics can be written in terms of the electric field alone. In this case, the theory is time reversal invariant also for the pancake account, because the electric field does not need to change sign under T in order to map solutions into solutions. Similarly, quantum theory can be written as a theory of the real part of the wavefunction alone, and in this case, again, the theory would be invariant also within the pancake account (see also Callender 2020). Thus, if we had a justification for considering classical electrodynamics as a theory about the electric field only, or quantum theory as a theory with the real wavefunction only, we would bypass the objection that these theories are not time reversal invariant, and the ontology would still not change under T. So, why would we one even need to kick the fields and the wavefunction out of the state? In other words, if one can read these theories in this way, then the paradox presented above does not arise, as we can have the three of them: time reversal symmetry, fields and wavefunction in the state and ontology not changing arbitrarily. So, why don't we obviously choose this? In reply, let me grant that we may not need to adopt the modified pancake account, and that we can make amends to the pancake account without losing symmetries as long as we re-interpret the relevant theories with enough ingenuity. However, the whole point rests on the viability of considering electrodynamics as a theory of the electric field alone, or quantum theory as a theory of the real component of the wavefunction. As also granted by Struyve, it is far from clear whether these theories are merely possible constructions or have a physical significance. For starters, one might also want other symmetries, in addition to time reversal, such as Galilean invariance or, preferably, Lorentz invariant. The viability of this approach is therefore strictly dependent on whether the ontology which makes the theory time reversal invariant under the pancake account is the same ontology which makes the theory also Lorentz invariant, because if the answer is negative, then the approach is hopeless. The same objection does not apply to the modified pancake account, as symmetries are constraints on the nomology, and not on the ontology, and the nomology is designed to change as needed in order to present the various symmetries. So, a time reversal quantum theory is one in which a Schrödinger evolving wavefunction changes into its complex conjugate as to map solutions into solutions; a Lorentz invariant quantum theory is one in which a (e.g.) Dirac evolving wavefunction transforms as needed as to map solutions into solutions, and so on. Be that as it may, let me conclude as follows. If these theories, namely classical electromagnetism and quantum mechanics respectively interpreted as theories of electric fields and real wavefunction alone, lack physical significance, then the argument proposed so far is an additional argument to favor the modified pancake account over the original one. If instead these interpretations turn out to be viable physical interpretation of these theories, then there is no additional argument for my proposed view coming from symmetry considerations.

In any case, these observations do not change the fact that the pancake account, in one form or the other, should be favored to the standard account.

References

- Albert, D. Z. 2000. *Time and Chance*. Cambridge, MA: Harvard University Press
- Albert, D.Z., Galchen, R. 2009. "A Quantum Threat to Special Relativity." *Scientific American* 300: 32–39.
- Allori, V. 2021. "Wave-Functionalism." *Synthese* 199: 12271–12293.
- Allori, V. 2019a. "Scientific Realism without the Wave-Function." In: J. Saatsi, S. French (eds.) *Scientific Realism and the Quantum*: 212-228. Oxford University Press.
- Allori, V. 2019b. "Quantum Mechanics, Time and Ontology." *Studies in History and Philosophy of Modern Physics* 66: 145-154.
- Allori, V., Goldstein, S., Tumulka, R. and Zanghi, N. 2008. "On the Common Structure of Bohmian Mechanics and the Ghirardi-Rimini-Weber Theory" *The British Journal for the Philosophy of Science* 59 (3): 353-389.
- Allori, V. 2015a. "Primitive Ontology in a Nutshell." *International Journal of Quantum Foundat ions* 1 (3): 107-122.
- Allori, V. 2015b. "Maxwell's Paradox: Classical Electrodynamics and its Time Reversal Invar iance." *Analytica* 1:1-19.
- Allori, V. 2013a: "Primitive Ontology and the Structure of Fundamental Physical Theories." In: D.Z. Albert, A. Ney (eds.), *The Wave Function: Essays in the Metaphysics of Quantum Mecha nics*: 58-75. Oxford University Press.
- Allori, V. 2013b: "On the Metaphysics of Quantum Mechanics." In: S. Lebihan (ed.), *Precis d e la Philosophie de la Physique*: 116-151. Paris: Vuibert.
- Arntzenius, F. 2000. "Are there Instantaneous Velocities?" *The Monist* 83: 187-208.
- Arntzenius, F. 2004. "Time-Reversal Operation, Representation of the Lorentz Group and the Direction of Time." *Studies in Histories and Philosophy of Modern Physics* 35(1): 31-43.
- Callender, C. 2020. "Quantum Mechanics: Keeping It Real?" *The British Journal for the Philosophy of Science*. https://doi.org/10.1086/715032
- Callender, C. 2000. "Is Time 'Handed' in a Quantum World?" *Proceedings of the Aristotelian Society* 100: 247-269.
- Earman, J. 2002. "What Time-reversal Invariance is and Why it Matters." *International Studies in the Philosophy of Science* 16: 245-264.
- Lopez, C. A. 2019. "Roads to the Past: How to Go and *Not* to Go Backward in Time in Quantum Theories." *European Journal for Philosophy of Science* 9: 27
- Malament, D. B. 2004. "On the Time Reversal Invariance of Classical Electromagnetic Theory." *Studies in History and Philosophy of Modern Physics* 35: 295-315.
- Roberts, B. W. 2017. "Three Myths about Time Reversal Invariance." *Philosophy of Science* 84 (2): 315-334.
- Roberts, B. W. 2021. "Time Reversal." In E. Knox, A. Wilson (eds.), *The Routledge Companion to Philosophy of Physics:* 605-619. Routledge.
- Struyve, W. 2022. "Time Reversal Invariance and Ontology."*British Journal for the Philosophy of Science.*