The time reversal invariance of classical electromagnetic theory: Albert versus Malament.

Andrew Holster. Original 2003. Reposted 2023.

1. Introduction.

David Albert (2000) argues that classical EM theory is not time reversal invariant (*non*-TRI), despite what 'all the books' say. David Malament (2003) rejects Albert's arguments, and tries to prove that EM theory is TRI after all, maintaining the long-standing orthodoxy. The controversy centers on the treatment of the time reversal of EM states: in particular, on whether the time reversal operation, *T*, reverses the direction of the magnetic field or not. Albert thinks the magnetic field, like the electric field, must be invariant under time reversal, whereas Malament (like practically everyone else) thinks the magnetic field must be reversed in direction, unlike the electric field. Which view is correct? I conclude here that:

- The conclusion ultimately depends on the *theoretical ontology* we choose to use to interpret EM theory. There is more than one possible and plausible choice.
- Albert and Malament (implicitly) choose different ontologies, and have in mind different theories – or *different versions of EM theory*.
- Neither writer shows that their own interpretation is *the only plausible choice*.
- Neither writer shows clearly what the principles underlying this choice are.
- Albert's account has flaws, but raises crucial questions overlooked by the orthodox account.
- The orthodox account of TRI of EM theory is highly unsatisfactory and misleading, and Malament does not address the key problems.

In the first half of this paper, I discuss some critical points of Albert's and Malament's views about the fundamental concepts involved. Some more technical details about EM theory are summarized in the second half of the paper. The notion of *interpretations* used here is explained in more detail in Holster (2003, b and c), where I propose a certain general treatment of time reversal transformations; this paper expands on comments in the final sections there about EM theory, without the technicalities.

As to the answer to the main question– *is EM theory really time reversal invariant or not?* – I conclude that this is *determined by* the choice of ontology we use to interpret the theory, but there is no 'best choice' for this ontology in general, and two opposite answers are possible. The choice is ultimately based on reasons external to EM theory as such – such as how it combines with other theories, in physics or metaphysics, that we also wish to maintain. I would suggest that the whole *class* of possible interpretations of EM might be taken to be what the theory is about. This is a class of different 'ontological possibilities' that the uninterpreted theory permits or suggests. Plausible variations of the ontology for EM theory give theories with very similar 'causal laws', or even identical observable predictions, but with different logical properties – properties that philosophers and physicists will sometimes argue over with passion.

A further interesting light is thrown on the problem by considering the extension of ordinary EM theory to allow magnetic monopoles, here called the theory *EM**. We can add the possibility of *magnetic monopoles or charges, q*,* as potential sources for magnetic fields, in symmetry with the electric charge and electric field. How does the theory EM* transform under time reversal? From considerations of symmetry, we find that we should transform the *q** charges (magnetic charges) in the same way as the *q* charges (electric charges); but this forces us to conclude that EM* is *decisively time asymmetric,* i.e. *non*-TRI. Consequently, in EM*, we seem to be forced to conclude that (*at least part of) the magnetic field is invariant with time reversal*, and does not reverse its direction. This shows that Albert's arguments cannot be easily dismissed in a general way, as writers like Malament, who support the orthodox account, believe.

2. The definition of time reversal invariance of theories.

I think Albert and Malament (and almost every other writer on this subject) first lose traction on the problem by *failing to provide an accurate conceptual analysis of the meaning of TRI (time reversal invariance) of theories* to begin with. What I mean is a direct *definition* of the property of *time reversal invariance of a theory,* like this (see Holster (2003 a) for details):

> **Definition of TRI**: A theory, **T**, is TRI, just in case it is invariant under the time reversal transformation, *T.* I.e. just in case **T** and *T***T** are *identical theories,* or: **T** = *T***T** for short.

This must be taken in conjunction with a *definition of the time reversal transformation,* which is:

> **Definition of the time reversal transformation.** *T* (time reversal) is a general transformation induced by a (1-1, onto) permutation mapping, of points of time back onto themselves, with a reversal of their order: *T: t→-t.*

And *T* must be explained:

- The key point about *T* is that it *induces a transformation* on any well-defined complex or constructed entity that involves time, *t.* Theories of fundamental physics invariably define many different kinds of complex entities, in a hierarchy of constructions. At the base are certain *fundamental quantities* (like individual particles, positions or spatial manifolds, masses, charges, … and times themselves). Then there are *particle trajectories,* which in Newtonian physics are mappings from particles and moments to points of space (or in special relativity, mappings from particles to space-time points). Then there are *differential properties of trajectories,* such as velocities, accelerations, momenta, energies, etc, essentially based on the construction of *differentials around a moment*. These properties are used to define more general *particle or system states*. Then there are *processes,* usually defined as temporal sequences of states. And most troublesome, there are *propositions, laws*, or *theories,* which are not interpreted rigorously in physics at present (a source of problems), but standardly interpreted in terms of classes of possible processes, or worlds, or models.

But neither Albert nor Malament defines the concept of TRI generally. Both jump to special *applications* of these concepts - using examples and special problems to illustrate them. They each propose *criteria* for judging whether TRI holds of certain kinds of theories, which they misinterpret as *definitions* of the concept of TRI. E.g.

> "The standard account of time reversal invariance goes something like this. A physical theory is said to be *time reversal invariant* if, for any sequence of instantaneous states $S_I, \ldots, S_F$ allowed by the theory, the time reversed sequence $TS_I, \ldots, TS_F$ is allowed as well." (Malament, 2003, p.3[1]).

Malament may be forgiven since he is only explaining the orthodox view here; but he does not propose any better definition of TRI elsewhere in the paper.[2] (However there is nothing generally wrong with Malament's application of this criteria, and his focus is only on showing how the time reversal operation on EM states should proceed, not in defining the property of TRI itself, so this is not a real criticism of any of his arguments).

Albert's introduction to these concepts is more troubling and awkward, especially since in the preface to his *Time and Chance* (2000), he expresses the hope that he has given "an unprecedentedly careful discussion of exactly what it means for a set of dynamical laws to distinguish, or *fail* to distinguish, between the past and the future."

He begins with the idea that a theory is said to be time reversal invariant if it does not distinguish between past and future. His most explicit definition of TRI is:

> "Of course, if any theory whatsoever offers us *both* predictive *and* retrodictive algorithms, and if those two algorithms happen to be *identical,* and if the theory in question entails that a certain process can happen forward, then it will necessarily also entail that the process can happen backward. *That's* what I'll mean, then, from here on, when I speak of a theory as being invariant under time-reversal." (Albert, 2000, p.14).

He has previously defined the notion of a process 'happening backward' by:

> "What is it, then, for something to happen *backward?*
> Simple. Suppose that the true and complete fundamental physical theory of the world is something called **T**. Then any physical process is necessarily just some infinite sequence $S_I, \ldots, S_F$ of instantaneous *states* of **T**. And what it is for that process to happen backward is just for the sequence $S_F, \ldots, S_I$ to occur." (Albert, 2000, p.11).

Note that there is already quite a striking difference between this and Malament's definition given above. Albert's condition does not appear to take recognize the need to take the reversed sequence of *time reversed states* to form the 'backward' process. But this is only because he has imposed a special concept of *'instantaneous states'*,

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[1] I have used the symbol: *T* instead of Malament's super-scripted *R* to signify the time reversal operator on states.

[2] There is a flaw in his definition as it stands. First, it only gives an 'if' condition, no 'only if' condition, so it tells us a *sufficient condition* for a theory being TRI, but not the *necessary conditions.* But it seems to be the wrong way round anyway: the stated condition may be *necessary* for TRI, but it is surely not sufficient, because it does not take into account time-asymmetric probabilistic theories, where reversed *possibilities* of processes exist, but where time asymmetry enters through asymmetric *probabilities.*

which he has *defined* to be invariant under time reversal. I.e. he imposes the following claim:

* $TS_i = S_i$ *for all 'instantaneous states'* S_i

which we may summarize as:

- ***Albert's Main Principle.*** *'Instantaneous states' used in the logical construction of worlds of any theory are always left invariant by time reversal*.

Combining (*) with the usual condition (as stated by Malament) allows Albert to arrive at his formulation as quoted above. But it is better to split this into two parts, giving the general *concept* of time reversal of a process first, and adding the extra condition (*) separately.

This is where Malament and Albert first part ways. Albert justifies his view by giving a particular theory (p.9-10) of "what it means to give a complete description of the physical situation of the world at an instant", which he defines in terms of what he calls an "instantaneous *state* of the world". He outlines a logical construction of fundamental theories in terms of *instantaneous states or properties;* and argues for the 'principle' above. We turn to this next.[3]

2. Instantaneous states *versus* logical atoms.

Albert's approach to the time reversal of fundamental processes involves these main steps:

(i) fundamental processes are described as sequences of instantaneous states;
(ii) instantaneous states are claimed to be defined in terms of fundamental instantaneous (or time-independent) properties;
(iii) fundamental properties and instantaneous states are claimed to be invariant under time reversal (like position and mass and electric charge).
(iv) time reversals of fundamental processes are defined as reversed-order sequences of the instantaneous states that make up the original sequences.

Applying this to classical EM theory then involves:

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[3] Albert also makes a distinction between whether a theory "entails that whatever can happen can also happen backward" and whether a theory "offers identical *algorithms for inferring* towards the future and the past". (p.11). We will only be concerned with the first kind of property of a theory: its direct implications for processes, states, worlds, etc, and we need not consider any 'algorithms' to make real predictions or measurements here. Albert's distinction of 'predictions' from 'algorithms' seems to allow that 'fundamental theories' are *interpretable* in a 'dual' kind of way: (i) as (theoretically) *classes of propositions,* conceived of as *classes of possible processes,* conceived of as *sequences of instantaneous states,* along with: (ii) as (practically) *classes of predictive and/or retrodictive algorithms* for actually calculating past or future processes on the basis of present observations. This 'dualism' seems to reflect the similar feature evident in ordinary quantum theory, where there is a popular distinction between the deterministic evolution of the wave function, and the probabilistic 'algorithm' used for calculating results of measurement. It also seems to reflect two kinds of interpretation in general: 'realist' and 'instrumentalist' interpretations of meaning, which run in parallel in *orthodox* QM, in the form of a realist interpretation of wave functions (or fields), combined with an instrumentalist interpretation of the measurement of those wave-functions. Seen in this light, the distinction is important. But we need not consider any 'algorithms' here, only the equations of the theory, interpreted realistically as being about one or other kind of fundamental features of worlds. We are only examining classical EM theory, which is a fundamental deterministic theory.

(v) identifying the instantaneous states used to interpret EM theory; then
(vi) checking whether the time reversed EM processes (obtained from (iii) and (iv)) still satisfies EM theory.

I examine Albert's concept of *instantaneous states* in this section, and subsequently consider his particular *identification of the ontology to interpret EM theory*.

My view is that Albert has mixed up two different concepts:

- on the one hand, what logicians call *logical atoms,* (or 'atomic facts', or the corresponding *instantaneous atomic states* of a world constructed from these – which are things used to *interpret a theory*);
- and on the other hand, the quite different concept of an *instantaneous state of a world* (which is defined relative to the interpreted theory, and is the full physical state that obtains at a moment of time in a world, including all the properties of physical objects at that moment of time in that world – which are properties operated on by the causal or dynamic laws).

Albert thinks the latter should be called the *dynamical condition,* and he reserves the term 'instantaneous state' for the first sense. But I think this is wrong, and contradicts the common meanings of the terms. I will use what I think is the more accurate terminology, which inter-translates with Albert's as follows:

Terms used here.	**Albert's corresponding term.**
Logical atom/atomic fact	*- none –*
Instantaneous atomic state	*Instantaneous state*
Instantaneous (general) state	*Dynamical condition*

Albert fails to distinguish properties of the first concept (the notion of *logical atoms,* which he does not explicitly identify as a separate notion) from properties of the second concept (*instantaneous* states). What I have called the 'instantaneous general state', he instead recognizes as the 'dynamical conditions'. These are 'conditions' that hold *at moments of time,* but may be *logically dependant on facts at other moments of time* (e.g. differential properties).

Albert thinks that the latter feature – the *failure* of logical independence from facts about other times - prevents differential properties from being *instantaneous properties;* but I reject this understanding. For instance, velocities are, intuitively, *instantaneous properties* (of particles, at moments), because they are properties that hold of particles *at instants of time*. The fact that these properties impose a 'logical dependence' on facts about *other times* does not prevent them being *instantaneous,* on the usual definition of that term; it affects their *logical independence,* which is a separate logical property, provided by *logical atoms.* I will briefly explain the concept of a 'logical atom' next. It is discussed in more detail in Holster (2003 c).

Logical atoms, worlds, the logical space.

The notion of 'logical atoms' or 'atomic facts' is common in intensional logic. Worlds are commonly regarded as complete classes of basic facts:[4]

[4] Using 'logical atoms' is the simplest device for defining an ontology of *worlds,* and although it is not the most general notion of worlds, it is general enough for theories of Classical physics.

- In the context of a particular fundamental theory, a *world* is defined by a unique class of *logical atoms* (or 'atomic facts'), represented as *n-tuples* of fundamental quantities and times.

A classic example is the interpretation of classical mechanical-type worlds, *W,* by classes of 4-tuplets, like:

$W = \{(t,i,m,\mathbf{r})$: particle i has mass m and position $\mathbf{r}$ at time t in world $W\}$

The 'logical atoms' here are shown with the form:

Form of logical atoms for W: $(t, i, m, \mathbf{r})$

We take the domains of reference of t, i, m and $\mathbf{r}$ to be well-defined '*physical continua'*, with the usual *intrinsic mathematical structures* assumed for classical mechanics. E.g. $\mathbf{r}$ is from a 3-dimensional structure of positions, called '(classical) physical space', and this structure itself has a set of properties. It is a continuum, with a dense set of points, 3-dimensional connectivity, and a *(Pythagorean) distance function,* or *Euclidean metric,* which is a relational property, of pairs of space points. Similarly, the domain of *mass* is a continuum of properties, with a ray-like real-number structure. This kind of 'implicit structure' is brought in with the classes of fundamental entities that we use in the interpretation. The logical atoms themselves may be seen as points in the Cartesian product of all these quantities, although special functional structures may be assumed within this. This raises a question that we must recognize, but we will worry about later:

- There are various possible choices for the ontology to interpret a given theory of physics; and some ontologies are thought to give *better* versions of a theory than others. This means that the choice of fundamental ontology itself plays an explanatory role in the theory. But what are the principles for allowing adaptations to the *ontology?* Can we adapt the ontology at will by imposing complex or ad-hoc 'implicit structures' in the form of additional relations on the basic sets, and transfer apparent contingencies in the 'laws of nature' into 'nomological necessities', or features of the chosen 'nomological space'?

At any rate, we can interpret the classical mechanical-type world as a class of 'atomic facts' of this form: $(i,t,m,\mathbf{r})$. The possible variations of worlds *of this ontological form* then defines the *logical space* of the theory.

It is essential to emphasize that *the class of such worlds that satisfies classical mechanics,* or even kinematics, is only a *tiny* fragment of *the class of logically possible worlds of this type.* (The form of *W* above identifies the *logical form* of classical mechanical worlds, but it does not express the specific *laws of classical mechanics.*)

- The structured class of *all logically possible worlds* formed as *classes of atomic facts of the form (*t, i, m, **r**), i.e. the power-set of the class of atoms, is called the *logical space of classical mechanics.*

We regard all the members of this logical space as ‘logically possible worlds’ *in the context of this specific interpretation of classical mechanics.* It is not a ‘general logical space’ representing all ‘logical possibility’, or logical possibility in natural language. (It seems to me to be natural to call this the *nomological space* for the interpreted theory, but I will not pursue this terminology here.)

Classical mechanics proper.

The *theory of classical mechanics* proper is then represented by a (vastly smaller) *sub-class of the logical space*, which corresponds to an intensional proposition. This proposition is specified by various constrains, like:

- A world, *W,* obeys classical mechanics *only if* every particle, *i,* at every moment, *t,* has a *differential property:* $\mathbf{v}(i) = d\mathbf{r}(i)/dt$.

Connected with this is an even more fundamental property, that:

- A world, *W,* obeys classical mechanics *only if* every particle, *i,* at every moment, *t,* has at most *one position*.

Laws like this are usually called *kinematic laws,* and regarded as logically prior to the more powerful mechanical laws proper. Another simple law is the constancy of particle mass:

- A world, *W,* obeys classical mechanics *only if* every particle, *i,* has the same mass, $m(i)$, at every moment, *t,* at which it has a *position*.

A more familiar example is the law of conservation of linear momentum:

- A world, *W,* obeys classical mechanics *only if* the total linear momentum: $m(i).\mathbf{v}(i)$ summed over all particles in the world is the same at every moment of time.

Introductions to theories of physics usually quickly mention the ‘kinematic properties’, (“we assume that there are point-particles with continuous differentiable trajectories in 3-d space…”), and then take it for granted that these are ‘logical properties’ of ‘particles’; that all possible particles have continuous, differentiable, or analytic trajectories, and so on. This takes it for granted that we are working in a restricted ‘logical space’, where everything is assumed to obey basic kinematics *as a matter of logic*.

The idea that kinematic laws are ‘logical’ properties, or ‘defined’ properties seems to be accepted quite uncritically by physicists; but this is not easily justifiable. The existence of particles having properties of definite trajectories and so on is an empirical and contingent matter in one obvious sense - since these properties were empirically discovered and confirmed (more or less when classical atomism succeeded) - and later disconfirmed when physicists looked at particles much more closely (in quantum mechanics). And it is also contingent in a second sense, which is most important here: that ontologies or logical frameworks, for classical physics at least – certainly the one mentioned above – make kinematic laws *logically contingent* by providing *logically possible worlds in which they are false*.

Given the construction of the classical mechanical worlds from logical atoms, the logical space of possible worlds is neither more nor less than the power-set of the class of atomic facts, and the class of kinematic worlds is generally only the tiniest fragment of this. This raises another question we will acknowledge here and worry about later:

- Is there any way to *improve* the construction of a logical space – e.g. by reducing its size or complexity? In particular, we will find that the size of the kinematic space is an order of infinity smaller than the full logical space; is there any way to reduce the logical space to include only the kinematically valid worlds?.

Instantaneous properties or states.

We have introduced the concept of *logical atoms,* from which worlds are logically constructed. What then are *instantaneous states and properties (of worlds at times)?* These may be introduced in a number of different ways, which initially seem quite plausible. First, we may think to take the full *instantaneous state of W at t* as the class of all atomic facts of *W* that obtain at time *t.* I.e. the class:

* $W^*(t) = \{(t,i,m,\mathbf{r})$: *i* has *m* and $\mathbf{r}$ at *specific time t* in world $W\}$

But this is best described as the *instantaneous class of atomic facts about W at t*. It is actually a kind of *world - a 'minimal instantaneous world'* – having the logical form of a *possible world* with facts at only one moment of time.

However the *state of a world* does not have the same logical form as *a world*. More natural is to take an *instantaneous atomic state at t* to be a mapping from worlds *W* at time *t*, to *the positions and masses of all the particles in W at t.* I.e:

$W(t) = \{(i,m,\mathbf{r})$: *i* has *m* and $\mathbf{r}$ at *specific time t* in world $W\}$

This object, *W(t),* satisfies a special set of *atomic instantaneous properties* of this state-of-*W*-at-*t* – *taking this type of property in turn to be a mapping from worlds W and times t to types of atomic states that satisfy the property. W(t)* defined in this way is a quite different *type* of thing to a world. And note that this second interpretation of a state allows us to identify two distinct worlds, *W* and *W',* as *having the same state at two different times:* i.e. we can have: $W(t) = W'(t')$, where: *t is not equal to t'.* We cannot possible have: $W^*(t) = W'^*(t')$ unless $t = t'$.

So let us take *W(t)* to represent *states.* Albert and Malament both take similar views about this; and both appear to agree that, in EM theory, an *instantaneous world state at time t contains facts about positions, charges, electric fields, and magnetic fields, at time t.* Malament specifically characterizes an EM world as a map from *moments of time, t,* to *instantaneous world states* with the form: $(\mathbf{E}, \mathbf{B}, \rho, \mathbf{j})$ (see p.4). But we should note that neither writer explicitly breaks these world states down further into logical atoms, and consequently, they both fail to specify very clearly what *the logical variation of possible worlds* is.

There is a crucial difference between them as well: while Malament includes electric and magnetic fields in the *instantaneous states,* he does not assume that they *must logically be independent of facts about other times,* or independent of 'time direction', as Albert does, because he does not accept Albert's characterization of 'instantaneous properties'. This is where their views first split.

But it is not just a squabble about the meaning of the term 'instantaneous'. In our present terms, Malament's view requires rejecting either: (i) *Albert's (implicit) view that magnetic fields are part of the atomic states, or logical atoms,* or alternatively, (ii) *Albert's (explicit) view that the atomic states, or logical atoms, are invariant under time reversal* (which I have called 'Albert's main principle above). Malament is not clear about this, and if anything, he seems to suggest that he rejects (ii). But I will argue that he is really rejecting (i), and implicitly interprets the logical atoms for his chosen ontology in a 'minimalist' kind of way which leaves out the **B** fields. By comparison, Albert's interpretation of the logical atoms is very 'rich', and provides a much larger logical space of possible worlds.

Now *W*(t),* or the 'world-slice' at *t*, is called *the class of atomic facts about W at t*. It represents a weak property of *W*, however, in the sense that it represents a property shared by many other worlds (those that have *exactly the same atomic state at t as W*), which nonetheless have many other different properties from *W*. These other worlds have differences from *W* in their pasts or futures; and these represent a much larger class of general properties of *W*. The question is: should any of these other properties be called *instantaneous properties of W at t?*

Of special relevance, of course, are properties like *velocities*, *accelerations*, or *differential properties* of particles at moments of time. These are patently *not* represented by the *atomic instantaneous states* defined above (either by *W(t)* or *W*(t)*). Yet they are clearly defined of particles *at particular moments;* and so why not part of the *instantaneous state* at that moment? The question is:

- *What is the definition of the full class of instantaneous properties of W at t, or the full instantaneous state of W at t?*

I now provide an alternative definition of an *instantaneous property of a particle trajectory*, which seems plausible, but includes differential properties:

Definition: Instantaneous Properties.
A property P of a trajectory $\mathbf{r}(i,t)$ at t_1 is an *instantaneous property of a complete trajectory* $\mathbf{r}(i,t)$ *at* t_1 *in W* just in case it is defined on all points in some arbitrarily small section of **r** on a neighborhood around t_1.

We define the sections of $\mathbf{r}(t)$ between $[t_1-\Delta t, t_1+\Delta t]$ as:

$$\mathbf{r}^*(t_1, \Delta t) = \begin{cases} \mathbf{r}(t), \text{ if } t \text{ is in } [t_1-\Delta t, t_1+\Delta t] \\ Null, \text{ if } t \text{ is not in } [t_1-\Delta t, t_1+\Delta t]. \end{cases}$$

Now of course, ***r*** and ***r**** (for any Δt) are both *temporally extended entities.* Intuitively, we want to capture only *the properties they have at t in W.* This definition means that if P is an *instantaneous property* of $\mathbf{r}(.)$ at t_1, P defines as a property of $\mathbf{r}^*(.)$ at $(t_1, \Delta t)$, *no matter how small we make* Δt. This includes the differential properties, $d\mathbf{r}(t)/dt$, $d^2\mathbf{r}(t)/dt^2$, etc, (whenever these exist), since they are defined precisely in terms of such limits:

$$d\mathbf{r}(t)/dt \;\; = \lim_{dt\to 0} (\mathbf{r}(t+dt)-\mathbf{r}(t))/dt = \lim_{dt\to 0} (\mathbf{r}(t)-\mathbf{r}(t-dt))/dt,$$

(just in case both these limits exist and are finite and equal).

Note that on the definition, position $\mathbf{r}(i,t_1)$ is trivially an instantaneous property at t_1. Note also that differential limits taken only from above, or from below, are also instantaneous properties on this definition. We must also wonder whether this definition is *complete*, but I will not try to answer that question here.

An essential point about this definition of *instantaneous properties* is that they still *exclude ordinary temporal relations* between points at a finite distance on a trajectory.

E.g. a trajectory $\boldsymbol{r}$ may have the values $\boldsymbol{r}(t_1) = \boldsymbol{r}_1$ and $\boldsymbol{r}(t_2) = \boldsymbol{r}_2$, where t_1 and t_2 differ by a finite interval. Then the trajectory $\boldsymbol{r}$ has a 'relational property' (a relation across time), for instance, that: $\boldsymbol{r}(t_1) = \boldsymbol{r}(t_2) + (\boldsymbol{r}_1 - \boldsymbol{r}_2)$, which we can describe as "the position at t_2 is a distance $(\boldsymbol{r}_1 - \boldsymbol{r}_2)$ from the position at t_1". But this time-relation property is not determined by the *local* properties at t_1 *or* t_2, and is *not an instantaneous property* at either time on this definition.

It seems only natural and normal use of language to include velocities, accelerations, etc, as 'instantaneous properties', holding at moments of time. They are the appropriate properties to engage with *the laws of nature at time t.* The *kinds* of fundamental laws of nature we know of have a particular kind of temporal 'locality': they operate on *local or instantaneous properties of particles, systems, or worlds.* None of our classical theories, at least, recognize theories with fundamental laws of nature that require operating across *multiple world-states taken at different times.*

The notion of an 'instantaneous state' is thus loaded with a kind of metaphysical presupposition that it is the appropriate kind of thing to be acted on by the laws of nature. And in this sense, the deterministic laws of classical physics require the wider concept of instantaneous state – using positions and velocities and accelerations as meaningful instantaneous quantities. This at least implicitly affirms that *particles in the world* have differential properties at moments of time – even though, of course, they only have them *in virtue of their temporally extended trajectories.*

At any rate, I think it is anti-intuitive to deny this broader interpretation of 'instantaneous states', and Albert's terminology will cause needless disagreements. But this point is no real challenge to Albert's argument, which only depends on what we are calling instead *atomic states,* and on their construction and role. The key points Albert wants to make are now readily seen in these terms.

(A) Albert (implicitly) recognizes that while we can take *logical atoms* of the form: $(i,t,m,\boldsymbol{r})$, for instance, we *cannot take logical atoms of the form:* $(i,t,m,\boldsymbol{r},\boldsymbol{v})$, where $\boldsymbol{v}$ is a velocity property of i at t, because in this case, *we cannot take any arbitrary class of such atoms as a world.* If we take a world to be defined from atoms: $(i,t,m,\boldsymbol{r})$, then the differential properties, $\boldsymbol{v}$**,** are already *determined.* Hence, including properties like $\boldsymbol{v}$ in the logical atoms is redundant.

The key feature of logical atoms is that they are used to *define the logical space of possible worlds* that we use to interpret the theory. This is not, as Albert says first (p.9, point (a)), that they must be 'genuinely *instantaneous'*: rather, as he says second, that they have "the appropriate sort of conceptual or logical or metaphysical independence of one another, that a perfectly explicit and intelligible *sense* can be attached to *any temporal sequence whatever* of the sorts of descriptions we have in mind.". If we tried to use atoms like: $(i,t,m,\boldsymbol{r},\boldsymbol{v})$ then they can no longer play this role of being *logical atoms*.

(B) Second, Albert would maintain that *the time reversal of a logical atom* is given in general simply by *reversing the moment t in it,* and *leaving all other quantities invariant.* In the simplest example, the time reversal of: $(i,t,m,\boldsymbol{r})$ is: $(i,-t,m,\boldsymbol{r})$, and there is no dispute about this. But what is disputed is that this must apply to *any kind of entities or quantities that we use to construct atoms.* In particular, if we choose to include magnetic field strengths, **B**¸ in atoms, for EM theory, then *should we – or must we - take* ***B*** *to be invariant under time reversal*? (The same question may be asked of other quantities like intrinsic spin in quantum mechanics.)

Now point (B) is perhaps the most difficult - and I will argue later that it is far from indisputable. Albert's reasons for it come back to his view that what we are calling *logical atoms* can only involve 'genuine *instantaneous'* quantities or properties, which have no reference to *time,* or no 'intrinsic' temporal construction. The velocity properties ***v*** for instance have an intrinsically temporal construction – being rates of change, by definition. Albert therefore dismisses them as possible elements in the logical atoms. About the **B**-field, he says:

> "Magnetic fields are *not* the sorts of things that any proper time-reversal transformation can possibly turn around. Magnetic fields are not – either logically or conceptually – the *rates of change* of anything." (Albert, 2000, p.20).

While I think his general arguments about this 'principle' are not generally correct, I think his main conclusions are convincing in the limited context he discusses. We return to this subsequently; but let us now turn to consider the assumptions Albert has made about *the logical atoms for classical EM theory* in the first place, and whether there are plausible alternatives.

3. Logical Atoms for EM worlds: Albert's ontology.

Albert's argument proceeds by identifying a particular form of *logical atoms* for interpreting the ontology of EM theory – i.e. a particular logical construction of EM worlds. His choice is that:

> "What counts as an instantaneous state of the world according to classical electrodynamics is … a specification of the positions of all the particles and of the magnitudes and directions of the electric and magnetic fields at every point in space. And it isn't the case that for any sequence of such states $S_I \ldots S_F$ which is in accord with the dynamical laws of classical electrodynamics, $S_F \ldots S_I$ is too. And so classical electrodynamics is *not* invariant under time-reversal." (Albert, 2000, p.20).

Albert uses the concept of the 'instantaneous state' without explicitly considering its logical construction in terms of logical atoms, but the logical atoms used to construct the states he has in mind are intuitively of two different forms: one to represent (charged) particle trajectories: ($i,t,m,q,\boldsymbol{r}$), with q being electric charges[5], and another to express electric and magnetic fields at points of space: ($t,\boldsymbol{r},\mathbf{E},\mathbf{B}$). A world is then a collection of both (charged) particle trajectories and electromagnetic field-strengths at points of space.

This ontology represents *particles* and *fields* as logically independent. It also makes the electric and magnetic fields logically independent. This is seen by considering Maxwell's laws (see 1-4 below). These laws relate electric and magnetic fields to the distributions and motions of charged particles, and to each other. In the present ontology, these relationships are all definitely *contingent,* because there are logically possible worlds which contradict the relationships. E.g. for any arbitrary set of particle trajectories, we can add an arbitrary set of electromagnetic field strengths, and they need not satisfy the Maxwell equations (nor the Lorentz force equation,

[5] We can use q instead of charge densities, ρ, if we assume discrete point charges.

which relates particle accelerations to the electromagnetic fields). We can make worlds that have electric fields but no magnetic fields at all.

And on this choice, Albert's conclusion that EM theory is *non*-TRI is very convincing. Of course, for that conclusion, we must first accept that the time reversal of an atom: (*t*,***r***,**E**,**B**) is the atom: (-*t*,***r***,**E**,**B**), and *not* the atom: (-*t*,***r***,**E**,-**B**), as the orthodox account supposes. But this is at least very plausible, because, as Albert argues, this ontology provides no logical or metaphysical connections between **B**-values and time. The logical independence of the magnetic field strengths from electric fields or particle trajectories really seems to force this conclusion: it is built into the 'metaphysics' behind this choice of logical atoms, because this metaphysics means that electric and magnetic fields are logically independent of each other and of time and of any dynamic properties. And for any possible world, this ontology provides a time reversed image of that world, exactly as Albert claims, with both particle positions and electric and magnetic fields taken simply in their reversed sequence.

4. Logical atoms for EM theory: a minimalist orthodox ontology.

But the real question is whether this the only ontology we can choose? I will now propose an alternative, which *does* make both the electric and magnetic fields logically dependant on the motions of charged particles – but still leaves electrodynamics as a contingent theory. The logical atoms for this are restricted to the *charged particle trajectories* alone: (*i*,*t*,*m*,*q*,***r***). We make no independent place for atoms involving electric or magnetic fields at all. A possible world is defined as any possible collection of (*i*,*t*,*m*,*q*,***r***) atoms.

This is a very 'minimal' ontology compared to Albert's choice above. I will summarize some important points about this choice here, and go on in subsequent sections to give more technical details.

Electric and magnetic fields are not fundamental quantities at all in this 'minimal ontology'. Instead we introduce electric and magnetic fields by treating Maxwell's laws as implicit *definitions* of these quantities. That is to say, electric and magnetic fields are *defined* purely in terms of sources which ultimately lie in charged particles and their motions. The dynamics of the theory is then expressed through the Lorentz force law, which governs how charged particles respond (accelerate) in the presence of such fields. This dynamics will be contradicted by some possible worlds – where the particle motions are not in accordance with the Lorentz force law, applied to the EM fields *defined* through Maxwell's laws. So the theory is still contingent with respect to particle motions, but not with respect to the laws relating to the appearance of EM fields.

Now if we can indeed successfully adopt this interpretation, then classical EM theory turns out, after all, to be TRI – and magnetic fields will turn out to reverse on time reversal, while electric fields will be invariant, as in the orthodox account. The reason for this is straightforward enough[6]. First, we have adopted the Maxwell equations as definitions, so they are invariant under time reversal. Second, magnetic fields now arise (by definition) from charged particle motions, and the consequent differentials of electric fields, and these reverse just as in the standard account. And

[6] It is confirmed by Albert's own observation that classical EM theory is invariant under a kind of 'motion reversal'.

electric fields arise from particle distributions (not velocities), and are invariant in the appropriate way. And given these transformation, if the Lorentz force equation holds of a world *W*, it will also hold of the time reversed world *TW*, because in *TW* both velocities, ***v***, and magnetic fields, **B**, reverse.

But is this a plausible, or logically coherent, interpretation? One immediate problem is that it *denies the existence of EM fields as entities, independently of charged particles.* This has some initial plausibility because we can argue that we do not detect or observe electric or magnetic fields directly: we only detect *particle motions* directly, and infer the presence of EM fields from these. But there are serious questions about this idea. For instance, what about free EM fields, or photons? Can't we detect the existence of these quite independently of their sources in charged particle motions? Indeed, couldn't there be photons that do not have sources in charged particle motions at all, but are instead additional 'fundamental particles' in the world, independent of any others? And given that we can detect the existence of photons as independent particles, don't we have to assign an independent reality to EM fields as such?

I think we can get around these objections, but it requires adopting a 'strong' logical interpretation of EM theory. We must deny that photons or free EM fields ever exist *except as they are generated by charged particle motions.* If we follow any photon back far enough in history, we maintain that it will have a source as electromagnetic radiation created originally from the acceleration of some charged particle sources. This is surely acceptable as an empirical postulate forming part of classical EM theory. But the ontology we have adopted here has a special *logical* effect on this postulate (just as it does on the Maxwell equations): it makes the laws governing the *existence of EM* fields – and hence, governing the existence of photons - true analytically, or 'by definition'. This is because this ontology cuts down the range of *logically possible worlds* so that there are simply *no logically possible worlds in which free EM fields (or photons) exist independently of charged particle motions.*

Within this choice of ontology, we cannot even *express* the alternative postulate that independent EM fields exist. But doesn't this contradict the fact that this is a *contingent or empirical postulate?*

I do not think this is a valid objection, because *the theory as a whole* remains contingent. This view of *interpretations* forces us to recognize, in the first place, that the logical formulation of the theoretical ontology is not itself a *logical or analytic fact about the world* – it is only correct *if the world itself has a logical construction corresponding to the theoretical ontology.* On this view, we actually perform experiments and so on to try to determine whether *the theoretical ontology itself is empirically adequate* – because, for instance, classical mechanics and quantum mechanics have quite different forms of ontology, but experimental evidence shows that the very form of the classical ontology is empirically wrong, being too simple in certain respects to represent various facts about physical reality evident from quantum theory.

Once we adopt a specific ontology of this kind to *express a theory,* we then have to recognize a secondary division, within the framework of the theory, between logical (or analytic) propositions, and contingent propositions. Various laws of dynamics, for instance, remain *contingent in the theoretical ontology,* whereas other laws become *analytic within the theoretical ontology.*

An even clearer example of this is the existence of magnetic charges or magnetic monopoles. The ordinary theory, of course, states that there are no magnetic sources. This is clearly an empirical postulate in a broad sense: scientists have searched for magnetic monopoles, and failed to find them. But in the context of the minimalist *ontology* considered here, this result is *analytic*, because we have made no provision for the *possible existence* of magnetic charges. To do so, we would need to expand the logical atoms for representing particles from: ($i,t,m,q,\boldsymbol{r}$), to something like: ($i,t,m,q,q^*,\boldsymbol{r}$), where q^* are magnetic charges. In such an expanded theory, we can represent the orthodox theory by setting: $q^* = 0$ for every particle that *obeys the classical theory*. Then this law would be theoretically contingent – there are logically possible worlds in the expanded ontology where particles do have magnetic charges.

But instead of representing this law as a *contingency within the logical space*, the minimalist ontology represents it through the structure of the logical space itself, making it *theoretically analytic* – by reducing the logical atoms from ($i,t,m,q,q^*,\boldsymbol{r}$) to ($i,t,m,q,\boldsymbol{r}$), there is no theoretical representation of magnetic monopoles at all.

It should be noted that this technique is actually a common practice in physics, e.g. in the adoption of *relational space* instead of *absolute space* to represent classical physics. The relational ontology *changes the representation of space,* so that only facts about spatial relations between pairs of particles are representable as facts. In the relational ontology*, there simply are no facts about absolute positions of particles in space.* Yet, of course, this reflects what is undoubtedly an *empirical* postulate – that there is no special point of space, or special direction of space, or more generally, that the Galilean symmetries obtain.

There is a further problem about the independent existence of EM fields, which is obvious as soon as we recognize that the sources of all the EM fields that exist at the present moment *lie in the past, not in the present.* I.e. the instantaneous atomic state, in our minimal ontology, with atoms like: ($i,t,m,q,\boldsymbol{r}$), *does not determine the present EM fields.* They are only determined (in the 'retarded sources' version of EM theory) by *the (charged) particle trajectories throughout the past*.

Now this seems to raise a problem: the EM fields at the present time certainly seem to be *real* (we can test them by observing the motions of test charges), and they certainly seem to be *instantaneously real.* They exist *now*, and we do not need to know what the *source* of a present EM field was to know or measure that there *is* a particular field. So shouldn't they be included in the *present instantaneous state*?

Now I agree that they should be – but this does not mean that they must be included in the instantaneous *atomic state,* as Albert effectively maintains. Rather, on the definition of the *instantaneous general state* proposed above, which includes differential properties at *t,* it is intended that the EM fields will be determined as part of the present general instantaneous state after all (like velocities, accelerations, etc).

But there is a difference between the EM fields and the instantaneous differential properties. The EM fields *depend on events in the distant past,* i.e. events a finite time ago, whereas the differentials only depend on what happened an 'infinitesimal' time ago. Do the EM fields really qualify as elements of the 'general instantaneous state', on our current definition?

But I think this problem is solved easily enough, through the fact that we have adopted the Maxwell equations as *definitions of the EM states.* In any EM worlds, there is a continuum of differential EM field properties, all the way through the past to the sources, which determine their present values as *instantaneous states.* The present fields are continuously connected by differential quantities; and this allows us to include them as instantaneous states, even though their sources are remote in time.

I will now turn to some of the technical details before returning to complete the discussion of Albert's and Malament's views.

5. Details of the EM interpretations.

Let us start with the set of (simplified) Maxwell equations:

1. $$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
2. $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
3. $$\nabla \cdot \mathbf{B} = 0$$
4. $$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$$

These relate the EM fields to their sources and to each other. We obtain the implications for the behavior of a charged test-particle from the Lorentz force law:

5. $$\mathbf{F}_q = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Equation 5 is usually split into two components, and frequently taken as a *definition* of the meaning of electric and magnetic fields. The electric field, at least, is commonly *defined* as producing a particular type of acceleration or force on charged 'test-particles': **F** = *q***E**. (The *definition* of the **B**-field is more obscure: most often, it is taken as defined through Ampere's law of magnetic induction, i.e. through Maxwell's equations. But if treated like the **E**-field, the **B**-field would also be defined by the Lorentz law, Eq.5.)

Maxwell's equations 1-4 are most often taken as contingent or empirical laws, governing how EM fields are actually produced by motions of charged matter.

But is this necessary? Instead, we might take Equations 1-4 as providing *reductive definitions of EM fields in terms of the trajectories of source charges*, and propose Eq.5 as a contingent postulate about the effects of such fields. Or we might even consider taking all of these as independent contingent postulates. Which interpretation is correct? How do we decide such questions? Is it merely 'conventional'? I want to point that:

- The interpretation of which equations are logically true (or true by definition), and which are contingent, is (at least partly) *determined by our choice of the logical atoms for the theory.* That choice determines the *logical space* for interpreting the theory, and hence it determines what are definitions and what are contingent propositions.

To see how this works, let us compare results from alternative ontologies for EM.

Albert's 'rich' ontology.

World:
*W = {(i,t,m,q,**r**)} U {(**r**,t,**E**,**B**)}*

Time-reversed World:
*TW = {(i,-t,m,q,**r**)} U {(**r**,-t,**E**,**B**)}*

- In this ontology, the equations 1-5 *must all be contingent*, because there are logically possible worlds where they are all contradicted – since we can set the trajectory properties quite independently of both electric and magnetic field properties.

- On this interpretation, EM theory is *time asymmetric* (*non*-TRI) as long as we accept the principle that including **B** as *a logical atom* entails that: $T\mathbf{B} = \mathbf{B}$. Equations 2, 4 and 5 are then non-TRI or irreversible. I agree with Albert that this is the correct conclusion, *given this ontology*.

Minimalist orthodox ontology (implicitly held by Malament).

World:
$W = \{(i,t,m,q,\boldsymbol{r})\}$

Time-reversed World:
$TW = \{(i,-t,m,q,\boldsymbol{r})\}$

- In this ontology, *not all the equations 1-5 can be contingent.* The ontology does not contain anything corresponding directly to the **E** or **B** fields, and they must be introduced *by definition* from facts about the charges and trajectories.
- The most obvious way to read this is to take Eqs.1-4 as definitions of the EM fields. These serve to completely determine the EM fields, given the world-history of trajectories provided in the logical atoms. Then Eq.5 must be taken as an additional contingent proposition – since we can always define worlds in which the trajectories of charged particles contradict Eq.5.

There is a question about this though, because we might instead want to define the EM fields from Eq.5, and propose Eq. 1-4 as contingent laws, relating the fields defined by Eq.5. to sources. But there is a problem with this alternative. Whereas the history of the world serves to *determine the present EM fields, if we take Eq.1-4 as definitions,* it does not serve to *determine the EM fields if we only take Eq. 5 to define the EM fields.* The reason is that the law in Eq.5 covers *counterfactuals about what would happen if you placed a test-particle in a certain motion in the EM system* - but few such counterfactuals will be *actually realized in the history of a particular world*, and so the use of Eq.5 applied to the *actual history* will radically underdetermine facts about the present EM state. Eqs.1-4, on the other hand, fully determine the present EM state, which is required here.[7]

- On this interpretation, EM theory is *time symmetric* (TRI) because Eqs. 1-4 are invariant (being definitions), and they require that: $T\mathbf{B} = -\mathbf{B}$, so that Eq. 5 is also invariant under T as usual.

Another orthodox ontology.

World:
$W = \{(i,t,m,q,\boldsymbol{r})\} \cup \{(\boldsymbol{r},t,\mathbf{E})\}$

Time-reversed World:
$TW = \{(i,-t,m,q,\boldsymbol{r})\} \cup \{(\boldsymbol{r},-t,\mathbf{E})\}$

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[7] E.g. see Wangsness, 1979, p.58: "We can thus regard the calculation of **E** as providing us with a sort of contingency statement distributed throughout space in the sense that **E**(***r***) combined with [Coulomb's law] tells us what *would* happen *if* we were to put a point charge *q* at ***r***.*"*

- In this ontology, the electric field is regarded as independently real, but the magnetic field is defined from the electric fields and charges. We must take Eq.1 as *contingent.* We may take Eqs. 2, 3 and 4 (along with the world-history of trajectories) to define **B**, and Eq. 5 is contingent as in the 'minimalist onotlogy'.
- On this interpretation, EM theory is still *time symmetric* (TRI), because treating Eqs.2-4 as *definitions* means we must take: *T***B = -B,** and then all equations are invariant under *T* as usual.

The key point this reveals is that the time symmetry of EM theory depends upon whether the ontology we choose to represent the theory *takes the magnetic field as part of the atomic properties or states.* This is not read off or determined by the equations (1-5) themselves. It depends on whether magnetic field strengths are *included in the logical atoms of the theory.* We seem more or less compelled to take *electric charges, q,* as atomic properties, and the 'minimalist ontology' makes EM theory TRI. We can also include electric field strengths as well, and EM still remains TRI on a fully realistic treatment of electric fields. But if we take *q,* **E**¸*and* **B** in the logical atoms, the theory is *necessarily non-TRI.*

It must be emphasized also that the 'choice' that has to be made to decide the TRI property of EM is *not a choice of how to interpret the concept of TRI*, but instead, *a choice of how to interpret the theory.* Once *the theory is fully interpreted*, then (I maintain) *its TRI property is also fully determined.*

6. Magnetic monopoles.

I now consider an extension to ordinary EM to EM*, which allows both electric and magnetic monopoles, and treats electric and magnetic charges in a similar way. This theory turns out to be *non*-TRI, even on the most minimalist ontology.

Minimalist ontology for EM* (EM with magnetic monopoles).

World:	***Time-reversed World:***
$W = \{(i,t,m,q,q^*,\boldsymbol{r})\}$	$TW = \{(i,-t,m,q,q^*,\boldsymbol{r})\}$

Here we expand the minimalist ontology to include magnetic charges, q^*. We must expand the ordinary set of laws as well, to incorporate these, obtaining a theory like this[8]:

1*. $$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

2*. $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} - \mathbf{J}^*$$

3*. $$\nabla \cdot \mathbf{B} = \rho^*$$

[8] We may be able to choose between variants of EM* theory, depending on how we assign dimensions and constants for **B** charges, and depending on whether we assign positive or negative values to given magnetic charges., but these choices do not affect the TRI property. E.g. see Lorrain, Corson and Lorrain, 1988, p. 510.

4*. $\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$

These relate the EM* fields to their sources and to each other. The Lorentz force law may also be expanded to:

5*. $\mathbf{F}_q = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ and: $\mathbf{F}_{q*} = q*(\frac{\mathbf{B}}{\mu_0} + \varepsilon_0(\mathbf{v} \times \mathbf{E}))$

- In this ontology, as in the minimalist EM ontology considered above, we take Eqs.1*-4* as *definitions of the EM fields,* (reducing the fields logically to the *q* and *q** trajectories). We take Eq.5 as *contingent*.
- The natural interpretation of the time reversal of an atom: *T*(*i,t,m,q,q*,**r***) = (*i,-t,m,q,q*,**r***). This means that *magnetic charges are invariant under T.*
- By equation 3* (a definition), the **B** field generated by a magnetic source charge, *q*,* is invariant under *T* (exactly as the electric field **E** generated by an electric source *q* is invariant).
- But what about the **B** fields generated by the motion of electric charges, as in ordinary QM? And equally, what about the **E** fields now generated by the motions of magnetic charges? Given that Eqs.1-4 are all *definitions*, and must therefore be invariant under time reversal, it seems that we will have to reverse *both these quantities.*
- To represent this, we can indicate the two different kinds of *sources for electric and magnetic fields,* by writing: **E**(*q*) (for the **E** field generated from the electric charge *q*), and: **E**(*q**) (for the **E** field generated from the magnetic charge *q**), and similarly: **B**(*q)* and **B**(*q**)[9]. Then the equations split into a dual pair, like this:

1. $\nabla \cdot \mathbf{E}(q) = \frac{\rho}{\varepsilon_0}$ 1**. $\nabla \cdot \mathbf{E}(q*) = 0$

2. $\nabla \times \mathbf{E}(q) = -\frac{\partial \mathbf{B}(q)}{\partial t}$ 2**. $\nabla \times \mathbf{E}(q*) = -\frac{\partial \mathbf{B}(q*)}{\partial t} - \mathbf{J}*$

3. $\nabla \cdot \mathbf{B}(q) = 0$ 3**. $\nabla \cdot \mathbf{B}(q*) = \rho*$

4. $\nabla \times \mathbf{B}(q) = \frac{1}{c^2}\frac{\partial \mathbf{E}(q)}{\partial t} + \mu_0 \mathbf{J}$ 4**. $\nabla \times \mathbf{B}(q*) = \frac{1}{c^2}\frac{\partial \mathbf{E}(q*)}{\partial t}$

With a force law:

$5_{(q)}$. $\mathbf{F}_q = q(\mathbf{E}(q) + \mathbf{v} \times \mathbf{B}(q))$ $5_{(q)}$.** $\mathbf{F}_q = q(\mathbf{E}(q*) + \mathbf{v} \times \mathbf{B}(q*))$

$5_{(q*)}$. $\mathbf{F}_{q*} = q*(\frac{\mathbf{B}(q)}{\mu_0} + \varepsilon_0(\mathbf{v} \times \mathbf{E}(q)))$ $5_{(q*)}$.** $\mathbf{F}_{q*} = q*(\frac{\mathbf{B}(q*)}{\mu_0} + \varepsilon_0(\mathbf{v} \times \mathbf{E}(q*)))$

(Note that: **J**(*q*) = **J**, **J**(*q**) = 0, **J**(*q*) = 0, and **J**(*q**) = **J***.)

[9] This is meant to be similar in kind to the usual distinction of *free currents* and *magnetization currents*, and the corresponding distinction of **B** (magnetic flux vector) from **H** (electric field), with **H** generated from the free current alone

- To maintain that these Eqs.1-4 and 1**-4** *are all true by definition,* it seems that we must adopt the following definitions of time reversals for the different kinds of components of the EM* fields:

$T(\mathbf{E}(q)) = \mathbf{E}(q)$	As usual.
$T(\mathbf{B}(q^*)) = \mathbf{B}(q^*)$	In symmetry with the electric charges.
$T(\mathbf{E}(q^*)) = -\mathbf{E}(q^*)$	In symmetry with the magnetic fields.
$T(\mathbf{B}(q)) = -\mathbf{B}(q)$	As usual.

- So in this version, it seems that we have to choose *different time reversal transformations for different 'elements' of the electric and magnetic fields, according to their sources.*

These different transformations are needed because they are the only choice that leaves all of Eqs.1-4 and 1**-4** *true by definition* while also satisfying the fundamental choice: $T(i,t,m,q,q^*,\boldsymbol{r}) = (i,-t,m,q,q^*,\boldsymbol{r})$, i.e. invariance of charges. That choice, and Eqs. 1 and 3* already compel us to take: $T(\mathbf{E}(q)) = \mathbf{E}(q)$ and: $T(\mathbf{B}(q^*)) = \mathbf{B}(q^*)$. Now suppose that we take the orthodox view that *all electric fields are invariant under T,* and hence try to take: $T(\mathbf{E}(q^*)) = \mathbf{E}(q^*)$. But then Eq.2* fails to be invariant. The only way to make it invariant is by adopting the previous transformations, which *distinguish different sources for the EM fields.*

- EM* is not TRI, because Eq.5* is not invariant.

It is seen that the partial equations: $5_{(q)}$ and $5_{(q^*)}$** are both TRI (as in the usual interpretation of EM), but $5_{(q)}$** and $5_{(q^*)}$ are now both non-TRI. E.g. $5_{(q)}$** states that: $\mathbf{F}_q = q(\mathbf{E}(q^*) + \mathbf{v} \times \mathbf{B}(q^*))$, but this transforms to the anti-symmetric version: $T5_{(q)}$**: $\mathbf{F}_q = q(-\mathbf{E}(q^*) - \mathbf{v} \times \mathbf{B}(q^*))$.

This example illustrates that there is no *general* prescription about how time reversal transforms **E** or **B** at all – in this case, they are transformed differently according to their *sources,* not according to their identities as fields of a certain type. I also note:

- There is no ontology for EM* theory that makes it TRI, as long as we (a) include both electric and magnetic charges in the logical atoms *and* (b) insist that quantities in the logical atoms are invariant under *T*, except *t* itself of course[10].

To conclude here, we should also note that:

- On the minimalist ontology for EM*, i.e. using atoms like: (i,t,m,q,q^*,r), ordinary EM still turns out to be TRI (just as in the orthodox minimalist interpretation).

[10] The possibility still remains, however, that we might define logical atoms which *are themselves time dependant* – and maintain that some elements in the atoms change values with *T*. I consider this in the next section.

This is clear because ordinary EM makes all the values of **E**(q*) and **B**(q*) equal to zero, so that the entire *T*-transformations on the EM fields are given by the usual: *T*(**E**) = *T*(**E**(q)) = **E**(q) = **E**, and: *T*(**B**) = *T*(**B**(q)) = -**B**(q) = **B**.

7. Albert's Principle of Time Independence of Logical Atoms.

I now briefly reconsider Albert's principle (formulated slightly differently) that *the operation of time reversal on instantaneous atomic states leaves them invariant.* I have appealed to this in considering some of the previous ontologies, but I have doubts about it as a general principle. It works, I think, *only if we define atomic states through properties or quantities that are explicitly time independent.* But this may not be necessary. It would not hold, for instance, if we defined atomic states *using velocity properties,* because we would have to reverse velocities. Now Albert rules out using velocity properties *and trajectory properties simultaneously* to characterize the 'fundamental facts' about a world, because these are not *logically independent.* And he is quite right: more generally:

- We cannot use facts about a 'time differential property', say: *dZ/dt,* as *atomic facts* if we have already included the facts about the quantity *Z* at every moment of time as part of the specification of worlds.

But this does not mean that we must *always* use the *Z's* rather than the *dZ/dt's* for atomic properties. In fact, I can presently see three potential ways of escaping from Albert's general conclusion.

(A) First, what if we include a quantity: *dZ/dt* among the atomic facts, without including *Z* itself? Why should *Z* necessarily be considered more 'fundamental' than its derivative?

(B) Second, what if we decide to simply *interpret an ordinary quantity like **B** as the differential of another quantity,* **Z**¸ where: *d***Z**/dt = **B**, and take ***Z*** as the 'invariant' property w.r.t. time reversal. E.g. why not consider the magnetic field like this, as intrinsically a *time differential* – of another quantity, **Z**, that needs only to be defined by saying that: *d***Z**/dt = **B**.

(C) Third - and more radically - I suggest that we can interpret 'atomic states of worlds' in physics as '*instantaneous general states'* - without temporal extension. The time variable *t* is then no longer an index for atomic states at all: rather, *facts about other times in a given world at a moment* are given by either logical relations, or are truly contingent – or do not even exist.

The first two suggestions may appeal to Malament and other writers who wish to support the orthodox interpretations of TRI. There are some interesting points in connection with this, but in the present context, they hardly change our present conclusion that the TRI properties of EM *depend on the choice of ontology,* and this is not determined simply by the equations of a theory, but by the choice of interpretation.

The third suggestion is much more radical, and relates to the assumption we have made so far about the representation of *time itself* in the logical atoms. So far we have assumed that the logical atoms are *indexed by time.* Since a world is defined by a collection of logical atoms, and these can represent facts about different times, we find naturally enough that *world are temporally extended objects.* This is entirely consistent with the 'block universe' or space-time-manifold conception of worlds. But I think that a quite different kind of ontology is possible: one which identifies *worlds as classes of present facts – with no temporal extension.*

To do this, we *must drop the time index from the logical atoms altogether.* Instead, we can make our worlds and logical atoms like, for instance:

$$W = \{(i, m, \mathbf{r}, d\mathbf{r}/dt, d^2\mathbf{r}/dt^2, \ldots)\}$$

On the usual 'block universe' view of things, this is not a *world* at all, but instead just the *instantaneous general state* of a (classical mechanical) world. We need a complete temporal sequence of such states to form a bloc universe world.

But the intention here is to deliberately *contradict* this 'bloc universe' conception of worlds, and impose instead a definition where 'the world' is something which exists instantaneously – but which *changes*. Time is introduced through the concept of *changes of the world (changes of what exists),* rather than being defined as a kind of *quantity within worlds.*

Now there are some obvious objections to this kind ontology. First, what do we mean by *'the same world at different times'*, if *worlds* are *defined by their present states?* Second, how do worlds satisfy propositions about *past or future facts,* if they are defined purely by *present facts?*

I am not going to try to defend this conception in any detail here, although I think these objections can be overcome. First we must distinguish the notion of 'the same world at different times', which we do simply by identifying equivalence classes of *worlds at different times that are transformed into each other by change.*

The key device to do this is to identify the notion of *analytic trajectories,* and hold that it is part of the definition of differential properties that they entail certain kinds of *change,* and that worlds with analytic trajectories are *logically connected to other worlds,* which we interpret as 'the same world at a different time'.

However, if it not my purpose here to try to justify this possible alternative type of ontology in any detail, merely to raise this a potential example where Albert's general prescription may fail.

In general, however, few physicists or philosophers would disagree with Albert's assumptions of a 'block universe' ontology, or with the logical independence of atoms across time; and his arguments, in the context of his own discussion, turn out to be quite robust.

8. Conclusions.

Malament.

Malament's argument against Albert ultimately misses the point. He gives an argument that the orthodox treatment of EM theory is correct - but he fails to realize that this conclusion depends on something that goes beneath the surface: the choice of ontology. It is evident in his appeal (twice) that his treatment depends on recognizing that the **B**-field is an 'axial vector', rather than an 'ordinary' vector. But this is no more than a *definition* of the transformation property he wants to confirm, not a *reason* to confirm that transformation property. This is also evident because the second part his paper, where he gives a technical treatment of the 'orthodox transformations', fails to expose the reason underlying the choice of transformations (the choice of ontology). Malament's treatment is a valuable *exposition* of the orthodox treatment, but it ultimately fails to deal with the *problems* that Albert raises.

Albert.
Unfortunately, despite its merits, I think Albert's discussion also fails to expose this critical point adequately, and his conclusion that EM theory is *absolutely* or *indisputably* non-TRI is not justified (and not correct) for exactly the same reason that Malament's conclusion (that EM theory is *absolutely* TRI) is not correct. To repeat: it depends on the choice of ontology, and Albert does not establish that his choice is definitive. But Albert's arguments show, at least, that there is a serious *problem* here, which the orthodox analysis fails to recognize.

Summary.
As Albert maintains, the orthodox treatment of time symmetry and TRI in physics is plagued with severe conceptual flaws. These first appeared unnoticed in the earlier work of pioneering physicists, who gave intuitive treatments of the symmetries of various theories, and were consolidated into orthodoxy by early philosophical pioneers in this area - most notably Reichenbach, Grunbaum, and Mehlberg. They have been subsequently impressed on the scientific consciousness as the 'conclusive results of physics', through persuasive expositions by authorities such as Davies, Zeh, Sachs, Hawking, and many others. However, a number of writers have found fault with these analyses over the last 50 years or so. Most important, in my opinion, is the work of Satosi Watanabe, which has been sadly neglected; and on one point or another, Schrodinger, Racah, de Beauregard, McCall, Earman, Healey, Penrose, Price, Albert, and Callender have all detected conceptual flaws in the orthodox treatment of TRI and current explanations of time directionality or irreversibility in physics.

Writers committed to the current orthodox ideology will no doubt defend the prevailing orthodoxy for some time yet; and (as Kuhn, Feyeraband and Lakatos have shown in other areas) they may very well succeed in maintaining the current ideology for some time, no matter what its flaws. But I think they are ultimately doomed to failure, because they have simply got the answers wrong. I believe the whole subject of the directionality of time in physics needs to be *completely reconsidered* by a new generation of philosophers of physics. Physics is nowhere near the end of this problem yet: it is only belatedly starting to recognize what the problems are.

I would add that a critical philosophical point for young researchers to begin with is a recognition of *the failure of instrumentalist/positivist/operationalist theories of meaning and conceptual analysis,* which are still naively embraced by many leading writers. This is a point of deeper ideological conflict in the philosophy of physics, which is still to be adequately addressed. The weight of popular opinion among physicists themselves (and more importantly, among 'philosophers of physics' who are converted from being professional physicists, rather than being professionally trained in philosophy) is still firmly on the side of positivism. Yet the overwhelming weight of opinion among the most sophisticated *professionally trained philosophers of science and semantics* – and the overwhelming weight of evidence, I would say – is that the positivist theories of meaning have decisively failed. Indeed, this failure has been evident for the last fifty years.

The failures in the orthodox account of time symmetry are a prime illustration of the dangers that positivism poses to conceptual analysis - and it should be noted that positivist ideology provides a ready-made reply to the critical points I have made here and elsewhere. The positivist can simply *deny that there is any meaningful difference between two interpretations of a theory on the basis of two different ontologies,* as described above, given that the 'observable predictions' of the theory turn out the same on both interpretations. For positivism identifies 'meaning' with 'observable implications', or 'empirically verifiable predictions', or something equivalent. Semanticists have long pointed out that this view of meaning undermines any attempt to give realistic conceptual or logical analysis; but this does not appear to register with the positivist. Deeper concerns about the correct logical analysis of time symmetry are relegated to the disparaged category of 'metaphysical pseudo-problems', and dismissed as 'mystery mongering'. [11] At this point, communication between positivists and realists breaks down altogether, and no shared *objective* grounds for conducting the debate remain. This appears to be a deeper source of current impasses in the subject; and because of this deeper conflict of ideologies about the nature of *meaning* and *logical analysis* itself, I would hardly expect *any* arguments to make any impression on the views of writers who are typically committed to the orthodox interpretation of time symmetry in physics. On the other hand, I still think there are *objective answers* to these problems, whether or not scientists or philosophers can agree on them.

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[11] In reply to another kind of critical argument first given by Watanabe (1955), and summarized in Holster (2003 a), positivists tend to take a different tack, and claim that the 'meaning of time symmetry' is merely a 'convention'. For instance, they claim that the only thing that matters are the 'observable implications' of theories, and we are merely playing with the 'names' we want to give to symmetries. They seek to discredit the idea that there is anything *important* about correctly identifying time symmetry properties – although it may be observed that this lack of importance only seems to occur to them after their own analysis has been criticised - to begin with, they regard the orthodox identification of time symmetry properties as very important. These kinds of responses have proved to be common in a majority of referees' reports on papers I have submitted to journals; but unfortunately, I have been refused permission from any journals to quote from any of these.

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