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BOOK REVIEW

Review of Bryan W. Roberts's *Reversing the Arrow of Time*

Bryan W. Roberts, *Reversing the Arrow of Time*. Cambridge: Cambridge University Press (2022), 252 pp.

Time reversal is a notoriously vexed concept in physics, an oddball symmetry that lacks a canonical statement. Depending on who you ask, time reversal is either a simple or complicated affair. Suppose we have a time-indexed sequence of states

$$\ldots, a_{-1}, b_0, c_1, \ldots$$

that solves the theory's dynamics. According to the simple "time-reflection" camp, a theory is time reversal symmetric when the time-flipped sequence $t \mapsto -t$ of the *same* states

$$\ldots, c_{-1}, b_0, a_1, \ldots$$

is also a solution to the dynamics. On the other hand, the "instantaneous camp" holds that applying the concept requires a theory-specific operator that alters the instantaneous states themselves (e.g., reversing magnetic fields in classical electromagnetism or complex conjugating quantum wave functions; Earman 2002; Malament 2004). Each camp is well motivated. According to the time-reflection camp, our notion of time reversal should be general across physics and not tailored to each theory. However, the instantaneous camp better captures how time reversal is understood and used in contemporary physics. This distinction amounts to extensional disagreements. Defenders of the time-reflection view have argued that theories widely considered to be time reversal symmetric—e.g., classical electromagnetism and quantum mechanics—are in fact not (Albert 2000; Callender 2000).

In *Reversing the Arrow of Time*, Bryan Roberts offers a partial reconciliation of these views. First, instead of viewing $t \mapsto -t$ as reversing time coordinates, he suggests that it should be viewed as reversing the time translation of "evolve forward by t" to "evolve backwards by t." Next, he pulls apart (i) the spacetime group of time translations and (ii) the map of those translations in a system's state space, written as ϕ_t. This takes an initial state s_0 and maps it to a new state under the dynamics $\phi_t(s_0) = s_t$. These two sides are not independent. (i) is related to (ii) by a representation: a structure-preserving homomorphism from the group of spacetime symmetries to state space symmetries. In spacetime, time reversal is the extension of the time translation group to include the automorphism that flips the direction of time translations $\tau : t \mapsto -t$. In state space, a representation of τ involves an operator

T that acts on states such that

$$T\phi_t T^{-1}(s_0) = \phi_{-t}(s_0) = s_{-t}. \tag{1}$$

(1) says that the time-reversed evolution to $-t$ is obtained by transforming s_0 with T^{-1}, evolving forward by t, and then using T to transform back. When such a T exists and is minimal with respect to the surrounding spacetime group structure, the theory is time reversal symmetric.[1] The detailed action of T on states is going to depend on the theory. However, Roberts shows these are not ad hoc additions to each theory, but representations of a specified spacetime symmetry structure. So both camps are correct at different levels of analysis. Per the time-reflection camp, time reversal is the simple *spacetime* reversal of time *translations* $\tau : t \longmapsto -t$. However, per the instantaneous camp, its application in *state space* requires a state operator T that is connected to τ via a representation.

This central and profound insight of *Reversing the Arrow of Time* is well worth the price of admission, which can be high at times. Throughout the book, Roberts makes extensive use of group representation theory, functional analysis, and symplectic/differential geometry. However, the book reads in a familiar and user-friendly manner. Roberts is constantly signposting the relevance of each mathematical result for the coming arguments, and how everything fits within the broader view. I would recommend this book even to those who have not encountered these areas of mathematics before, although supplemental reading would prove useful.

After outlining his "Representation View," the rest of the book applies it to a host of other debates such as the philosophy of symmetry, philosophy of time, and the recent(ish) evidence from particle physics that time itself does contain an asymmetry. In the rest of this review, I will provide a chapter-by-chapter overview, followed by a brief discussion.

Roberts provides some preliminary introductions and motivations in chapter 1. His core proposal is described in chapters 2 and 3, and these make for a standalone read. Chapter 2 sets out the Representation View described above. Roberts then applies the Representation View in chapter 3. Using some minimal assumptions—e.g., that time translations are represented as automorphisms on state space and that energy is bounded from below—Roberts determines the character of the time reversal operator T from time translations in Newtonian, Hamiltonian, Lagrangian, and quantum mechanics. In Newtonian mechanics, T is velocity reversal, in Hamiltonian and Lagrangian mechanics it is an antisymplectomorphism (which entails that it reverses momentum and magnetic fields), and in quantum mechanics it is an antiunitary operator (which conjugates wavefunctions). Although in general there will be many operators T that satisfy (1) for a given theory, we can often use additional spacetime group structure from the theory to fix the unique reference of the T operator, ruling out operators such as joint parity–time reversal.

In chapter 4, Roberts applies the Representation View to various debates in the philosophy of symmetry using the guiding insight that symmetries must be split into their spacetime and state space components. For example, Roberts extends existing arguments for the direct empirical significance of continuous symmetries to also

[1] To illustrate this minimality condition, in the Poincaré and Galilei groups, T should not also include parity reversal because this corresponds to a different symmetry.

include discrete symmetries. By treating discrete symmetries (e.g., time reversal) as automorphisms of a continuous symmetry group (e.g., time translations), direct empirical evidence for continuous symmetries is also direct empirical evidence for their discrete companions.

In chapters 5 and 6, Roberts argues that many purported arrows of time are not in fact arrows of time itself. Chapter 5 includes a rejection of several candidate arrows: the radiation arrow of electromagnetism, the statistical mechanical entropic arrow, various cosmological arrows, and quantum collapse. Chapter 6 argues that thermodynamics also provides no arrow of time. By "arrow of time," Roberts means something subtle: that fundamental temporal structure is directed/asymmetric, rather than merely the arrangement of matter across spacetime. However, the Representation View again shows spacetime structure and matter arrangement are not independent but are connected by a representation. For Roberts, because the background theories in these cases are time reversal symmetric in state space, these asymmetries can be traced back to asymmetric boundary conditions, informal heuristics, or omitted information and not a fundamental temporal asymmetry. Once this subtlety is understood, the claims made in these chapters are much less surprising than they first appear.

Chapters 7 and 8 then argue that this type of arrow of time is supplied by the violation of time reversal symmetry of the weak interaction in quantum field theory. In chapter 7, Roberts cites both direct and indirect lines of evidence obtained from particle physics for time reversal violation. Chapter 8 then considers whether other symmetries such as CPT (charge conjugation, parity, time reversal), CP, or PT should be considered the proper T operator of the standard model. Although quantum theory guarantees that we can always find some antiunitary operator T that satisfies (1) (see Proposition 8.1 on p. 196), Roberts argues that these candidates fail to fit appropriately within the surrounding spacetime structure to occupy the role reserved for bare time reversal. As the results from chapter 7 show, nothing can be found that occupies that role.

Throughout *Reversing the Arrow of Time*, Roberts attempts to give a precise analysis of time reversal that is philosophically compelling without maiming its use in physics practice. For example, the view simultaneously explains magnetic field reversal in electromagnetism and complex conjugation in quantum theory, while also respecting the consensus that the weak interaction is asymmetric in time. On those joint criteria, the Representation View is highly (and perhaps uniquely) successful.

This relates to my central worry about the Representation View. By viewing spacetime and state space structure as two faces of the same issue, the Representation View offers an interpretive flexibility not available to competitors. When and why should we hold spacetime structure as fixed while revising our account of state space, rather than revising our account of spacetime to fit the dynamics on state space? Throughout the book, Roberts reasons in both directions. In chapter 3, Roberts treats the spacetime symmetry groups as fixed when deriving T operators. This includes an extension of the traditional notion of state space automorphisms for Hamiltonian mechanics (from symplectomorphisms to both symplectomorphisms and antisymplectomorphisms) to accommodate time reversal (pp. 67, 110). Then, in chapters 7 and 8, an asymmetry from state space evolution is used to argue for an asymmetry in temporal structure. Many will not find these arguments objectionable; in both places I took Roberts to be closely following the reasoning of mainstream physics. However, if the premises of these arguments are themselves at issue, even those who agree with Roberts's basic framework might disagree on the direction of individual arguments and subsequent conclusions about spacetime structure and the extension of time reversal symmetry.

Even if there is potential to dispute the starting and ending points of individual arguments, *Reversing the Arrow of Time* is a remarkable achievement. Roberts's book distills a huge amount of physics and philosophy reflection about time reversal into a single view. It offers not only a persuasive solution to the problem of time reversal but an insightful reorganization of the landscape into something more fruitful for future research. For these reasons, it is likely to remain a touchstone on this topic for many years to come.

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