

Quantum Mechanics: Keeping It Real?*

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Abstract

This paper is an introduction to and advertisement of Erwin Schrödinger's little-known real-valued wave equation, the first published time dependent Schrödinger equation. I argue that this equation is not merely a historical curiosity. Not only does it show that quantum mechanics need not be viewed as essentially complex-valued, but the real formalism also provides a deep insight into the puzzling nature of time reversal in a quantum world. It is hoped that this observation will stimulate the discovery of other areas where "keeping it real" will prove pedagogically or foundationally useful.

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1 Introduction

It is well-known that when Erwin Schrödinger discovered quantum theory he wanted to interpret the quantum wavefunction ψ as representing a continuous distribution of charge traveling through three-dimensional space. What is less appreciated is that Schrödinger also originally desired that his wavefunction be represented by a real-valued function and not a complex one. In some of the first papers written on quantum theory and in letters to Hendrik Lorenz and Max Planck, Schrödinger describes his progress and struggles with finding a real-valued wave equation, even as he knew the complex-valued equation that

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goes by his name. Eventually he discovered a completely real equation, equivalent to the Schrödinger equation, and referred to it as the ‘*the uniform and general wave equation for the scalar field ψ* ’ ([2020], p. 163). To Planck he characterizes this breakthrough as one of ‘unheard of simplicity and unheard of beauty’ (Przibram [1967], p. 16).

This paper is a kind of advertisement for exploring this form of the Schrödinger equation. Suppose we treat this real equation as another formulation of quantum theory, like the Heisenberg formulation, or even as offering a different ontology, one identifying the real part of the wave function with what J.S. Bell [2004] called a *beable*. Might we regard some open problems differently, and what new problems would arise? After sketching the history and some of the background, I’ll illustrate how using this alternative form can be useful in understanding a problem in quantum foundations. Inspired by a recent paper by Struyve [unpublished], I’ll show how the “real Schrödinger equation” dramatically alters a puzzle about time reversal invariance in quantum theory. My hope is that readers will find other examples like this where “keeping it real” can help.¹

2 Schrödinger’s Struggle for Reality²

Schrödinger grappled with the need for quantum mechanics to use complex numbers as he was developing quantum mechanics in the Spring of 1926. In this period Schrödinger worked intensely, publishing six communications in *Annalen der Physik* that laid the foundations of the new mechanics. These communications include the discovery of his famous equation but also a real-valued version of it. He eventually abandoned the real version. However, from these six articles (which went on to become the first book of quantum mechanics) and several letters to Planck and Lorentz, we know that probably he did so reluctantly.³

Let’s briefly recall Schrödinger’s path to quantum mechanics. Schrödinger wanted deBroglie’s matter waves to emerge as solutions of a wave equation. So he expected to find a second-order wave equation, one similar to what one uses in classical electromagnetism and elsewhere in physics. That equation would describe “matter waves” represented by time-dependent real-valued wave amplitudes and these waves would travel through

¹Some readers may be drawn to the real formalism because they feel that physical quantities should be represented by real numbers. To be clear, that is not my motivation for the present note. I don’t think there is any way in which real numbers are intrinsically better suited to represent the world than complex numbers. Concerning questions of scientific representation, my views are maximally liberal (Callender and Cohen [2006]). So long as it’s practically convenient, I’m happy to represent quantum phenomena with real numbers, complex numbers, quaternionic numbers or even Lego blocks.

²Since I wrote this section a better history of this episode has appeared in Karam [2020b], which includes examination of Schrödinger’s derivation in one of his notebooks. I enthusiastically recommend Karam’s paper to interested readers. My own path to this topic came via the Nobelist Yang’s [1987] note, which in turn led me to Schrödinger’s original papers and Chen’s fascinating series of articles ([1989], [1990], [1991], [1993]).

³For references to these six communications I’ll use a new edition of the *Collected Papers on Wave Mechanics* (Schrödinger [2020]), which is a translation from the second German edition. This collection also contains three additional papers from 1927. For the exchange with Lorentz and Planck, I’ll refer to their English translations in (Przibram [1967]).

three-dimensional space. Schrödinger's road to this equation began with the classical Hamilton-Jacobi equation. He knew that the Hamilton-Jacobi equation could be turned into a second-order wave equation. Letting ψ represent some 'vibration process' in the atom (Schrödinger [2020], p. 19), he could change the former into the latter via the transformation $S = kln\psi$, where $k = h/2\pi$. His idea was that classical Hamilton-Jacobi theory would be the geometric optics limit of this new wave theory of matter.

In his first communication Schrödinger had already discovered what we now consider the time-independent version of the Schrödinger equation:

$$\Delta\psi + \frac{8\pi^2}{h^2}(E - V)\psi = 0$$

where E is the total energy, V the potential energy and h Planck's constant. This equation, however, was not satisfactory, as it 'suffers from the disadvantage that it expresses the law of variation of the "mechanical field scalar" ψ neither *uniformly* nor *generally*' (Schrödinger [2020], p. 162). In an impressively long and detailed letter the seventy-two year old H.A. Lorentz points out various deficiencies of having the equation apply only to a specific energy. It means, for instance, that there will be 'as many wave problems as there are energy values E ' (Przibram [1967], p. 49). Lorentz urged him to eliminate E from the equation in favor of time derivatives of ψ – that way Schrödinger could also handle non-trivial time dependent phenomena. Schrödinger agreed. Fixing these two issues would mean finding a wave equation that was more general and more uniform.

We also know that Schrödinger wanted more, namely, that this equation be real-valued. In his third communication he had introduced a complex wavefunction, intending to use only the real part. In his reply to Lorenz on June 6, he commented that

What is unpleasant here, and indeed directly to be objected to, is the use of complex numbers. ψ is surely a fundamentally real function and therefore in Eq. 35 of my third paper... I should be good and write a cosine instead of the exponential, and ask myself: is it possible in addition to define the imaginary part unambiguously *without reference to the whole behavior of the quantity in time*, but rather referring only to the real quantity itself and its time and space derivatives *at the point in question* (Przibram [1967], pp. 62-63).

The wave equation he desired would be general, uniform and real.

He achieves all three goals by letting the real part of a complex wavefunction have a (periodic) time dependence. Differentiating it twice with respect to time he obtains

$$\frac{\partial^2\psi}{\partial t^2} = -\frac{4\pi^2 E^2}{h^2}\psi$$

which can be re-expressed in terms of a Hamiltonian H as simply $H\psi = E\psi$. Plugging this into the above time-independent equation yields

$$\left(\nabla^2 - \frac{8\pi^2}{h^2}V\right)^2\psi + \frac{16\pi^2}{h^2}\frac{\partial^2\psi}{\partial t^2} = 0$$

which can be expressed compactly via \hbar as

$$\hbar^2 \frac{\partial^2 \psi}{\partial t^2} = -H^2 \psi \quad (1)$$

In his fourth communication he proclaims his version of (1) to be ‘evidently *the uniform and general equation for the field scalar ψ* ’ (Schrödinger [2020], p. 163). This equation is the first published time-dependent Schrödinger equation. It meets all of his desiderata: it is real-valued, general, and time-dependent.⁴ It is real both in the sense that ψ is a real-valued function and in the sense that equation (1) has no imaginary components to it.

Equation (1) is second-order in time like a wave equation, but fourth-order due to the spatial derivatives. That makes it more complicated than the equation with which we’re familiar (which is derived by inserting the first rather than second derivative of a complex rather than real wavefunction into the time-independent equation). That additional complexity by itself probably didn’t bother Schrödinger too much. He seems unfazed by it. The historians Mehra and Rechenberg [1987] write that he ‘was not afraid of mathematical complications of higher order equations; the methods of their solution were well known in principle’ (p. 788) and note that in his work he regularly entertained equations of high order. Indeed, in his letter to Planck, after introducing (1) he immediately notes that it is ‘completely the same type as the equation for a vibrating plate’ (Przibram [1967], p. 17) and he reproduces this equation in a footnote in his fourth communication.⁵

Schrödinger is evidently relieved at having discovered (1). On June 11 he writes to Planck

By the way, during the last few days another heavy stone has been rolled away from my heart....I had considerable anxiety over it...But it all resolved itself with unheard of simplicity and unheard of beauty; it all came out exactly as one would have it, quite straightforwardly, quite by itself and without forcing. (Przibram [1967], p. 16)

What he is referring to is his discovery of (1), which he describes as ‘the true wave equation which is of fourth order in the coordinates’ (17). His goal of a wave equation that is general, uniform and real was achieved.

Not long after, however, he became worried about the introduction of time varying potentials. Terms such as $\partial V/\partial t$ demanded ‘caution’ (Schrödinger [2020], p. 164). Another path was possible, he noted, one ‘extraordinarily convenient for the calculation’ (194). This equation, of course, was the second-order equation that we now refer to as the Schrödinger equation. The price of this simplicity was the introduction of complexity. By the time of his sixth communication he decided to use the complex equation. At this point it’s clear that he regarded his namesake as a kind of surrogate for the entirely real fourth-order equation. At the very end of this paper he writes:

⁴See Karam [2020b] for discussion of Schrödinger’s derivation of this equation in his notebook.

⁵The equation for a classical vibrating plate is of the form $\nabla^2 \nabla^2 u + \partial^2 u/\partial t^2 = 0$.

Meanwhile, there is no doubt a certain crudeness at the moment in the use of a *complex* wave function. If it were unavoidable *in principle*, and not merely a facilitation of the calculation, this would mean that there are in principle *two* wave functions, which must be used *together* in order to obtain information on the state of the system. This somewhat unacceptable inference admits, I believe, of the very much more congenial interpretation that the state of the system is given by a real function and its time derivative. (Schrödinger [2020], p. 194)

Although he used the complex equation at the end of this important period, he viewed it as a kind of convenient substitute for a real function and its time derivatives.

It is not known how long Schrödinger’s belief in the “reality” of quantum mechanics persisted nor precisely why he abandoned the real equation. Chen [1989] holds that Schrödinger’s difficulties in finding a non-conservative version was a major hurdle (but shows how it is surmountable); Karam [2020b] suggests that the lack of a physical interpretation for the real part may have been a problem and that the growing use of $\psi^*\psi$ as the charge density, which is real, may have satisfied him. Recall that Schrödinger never accepted the statistical interpretation of the wavefunction. Also, note that his real-valued wavefunction still “lives” in high-dimensional configuration space, just like the complex-valued wavefunction; so the move to real values doesn’t by itself help one interpret it as an object or field in three-dimensional space. To me it’s plausible that the combination of issues caused him to put the problem aside. After all, what he originally wanted was (a) hard to use, (b) still difficult to interpret, and (c) to some extent almost achieved because $\psi^*\psi$ was real.⁶

In any case, almost exactly a year (June 10, 1927) later Schrödinger writes in a footnote that

The wave function has to be regarded as essentially complex (Schrödinger [2020], p. 216).

However, he doesn’t explain what he means by ‘essentially’ here. There are certainly many plausible interpretations of this statement that are consistent with his earlier position. The physicist Chen, who has done the most to investigate this real Schrödinger equation, reports that V.F. Weisskopf wrote to him that ‘Schrödinger persisted in his belief in the real wavefunction until his last days’ (Chen [1990]). Minus the context, this too can be interpreted various ways.

That said, there is another hint that perhaps Schrödinger held this desire for reality for quite some time. As late as 1952 Schrödinger wrote a note in *Nature* pointing out that contrary to ‘widespread belief’, charged fields do not need to be represented by complex numbers. Schrödinger shows that by a change of gauge the wavefunction used in the Klein-Gordon-Maxwell equations of motion can be made real (Schrödinger 1952). He

⁶As Yang [1987] notes, it’s interesting in this context to recall that Born’s original expression of the probability density occurred in a footnote (in a paper received June 21, 1926) and left off the now familiar absolute value symbols. The reason? Born used real wavefunctions for both his incoming and scattered wavefunctions.

finds it interesting that in this real formulation the electromagnetic potential becomes proportional to the current, just as in Dirac’s recently proposed theory (for more recent work on this, see Akhmeteli [2011]).⁷ That Schrödinger was still considering real wavefunctions just nine years prior to his death is suggestive of Chen’s claim, although hardly definitive.

While we will likely never know how long Schrödinger’s belief in a real wavefunction lasted, we can appreciate that his desire to keep quantum mechanics real-valued was quite natural given the time period. Of course he was accustomed to using complex functions and equations from classical mechanics. As his research evolved he found himself increasingly using complex numbers, especially when he was confronted with Heisenberg’s theory. But in the physics he studied prior to the development of quantum mechanics, ultimately one always connected the real parts of complex equations to experiment, as in linear circuit theory. All of his experience of physics to date suggested that the imaginary was employed for convenience but ultimately dispensable.

3 The Real Schrödinger Equation

We are often taught that in quantum mechanics the use of imaginary numbers is essential, but that is not true.⁸ One can represent what quantum theory has to say using real numbers, complex numbers and quaternions, and there are plenty of formulations of the theory that are entirely real. That said, the existence of a real-valued quantum wave equation may be surprising for it’s an elementary mathematical fact that the real part of a complex number underdetermines the complex number of which it is a part. The real part is leaving out “half” the information of the complex function. So it’s worth briefly explaining how there can be a real equation with a real-valued wavefunction.

While there are some tricky mathematical details, the core idea is easy to understand. As is well-known, the complex Schrödinger equation is equivalent to two coupled differential equations for two real variables (Bohm [1951]). The present idea simply uses this coupling to put everything in terms of one variable. The two equations are rewritten in terms of one variable and its time derivative.

The complex Schrödinger equation is

$$i \frac{\partial \psi}{\partial t} = H_t \psi \tag{2}$$

where ψ is complex, $\hbar = 1$, and $H_t \equiv ((1/2m)\nabla^2 - V(x))$. Dub $u(x, t)$ and $v(x, t)$ the real and imaginary parts of ψ , respectively, so that $\psi(x, t) = u(x, t) + iv(x, t)$ holds. Inserting this into the complex equation (2) and separating yields two real equations

$$\frac{\partial u}{\partial t} = H_t v \tag{3}$$

⁷Schrödinger’s idea is valid beyond the context of Klein-Gordon-Maxwell electrodynamics. It can also be applied to the Klein-Gordon equation in an electromagnetic field and for the original (nonrelativistic) Schrödinger equation in electromagnetic field, as Andrey Akhmeteli kindly points out to me.

⁸Karam [2020a] surveys some interesting rationales for the complexity of quantum mechanics.

$$\frac{\partial v}{\partial t} = -H_t u \quad (4)$$

Note, crucially, that the two equations are coupled.

Using this coupling, we recognize the possibility of expressing everything in terms of one equation of u and $\partial u/\partial t$. One can try to isolate v by integrating with respect to time. This will bring out an arbitrary function, which is presumably what bothered Schrödinger ('integration with respect to time would involve an undetermined wave function. I do not know yet whether this can be fixed in a rational way', (Przibram [1967], p. 96)). One can answer this problem, but another method is to find a unique inverse operator $(H_t)^{-1}$ of H_t in (4), so that

$$v = (H_t)^{-1} \frac{\partial u}{\partial t}$$

. In the energy representation this operator is $(H_t)^{-1} = [\hbar/E_i(t)]\delta_{ij}$ (Chen [1989], equation 6).⁹ Using this relationship allows one to write everything in terms of u .

Note that an analogous move is not possible in classical mechanics. Although not widely recognized, classical mechanics can be described by a complex first-order but nonlinear "classical Schrödinger" equation (Rosen [1964], Schiller [1962], Schleich et al [2013]). One can try a similar trick and insert a complex wavefunction into this equation and separate real and imaginary parts. When one does, however, the two equations are not coupled as in quantum theory, eliminating the possibility of exploiting the coupling to eliminate the second real-valued function.

Recall that Schrödinger had concerns about the extension to non-conservative cases. Sparing the details, Chen [1989] discovered the equation Schrödinger sought,

$$\frac{\partial^2 u}{\partial t^2} = -H_t^2 u + \frac{\partial V}{\partial t} H_t^{-1} \frac{\partial u}{\partial t} \quad (5)$$

where everything is written explicitly in terms of u and its time derivative. When V doesn't depend on time (5) reduces to the simpler (1).

Equation (5) is a single equation and entirely real: neither u nor the equation contains an i . (5) looks a lot like a classical wave equation. Like such equations, it is second-order in time and takes Cauchy initial data, u and $\partial u/\partial t$. Unlike classical wave equations, however, it is fourth order due to the spatial derivatives (in the H^2 term). On this picture, the real part of the wavefunction is roughly like the configuration variable and the imaginary part is like its velocity.¹⁰

⁹Note that v 's dependence upon u is apparently nonlocal. See Chen [1989] for the concern and Chen [1991] for explanation.

¹⁰How a complex wavefunction is split into real and imaginary parts is to some extent arbitrary. This arbitrariness is a kind of gauge invariance. Let $\psi(x, t) = u(x, t) + iv(x, t)$. Then if u, v satisfy equations (3) and (4) above, then u' and v' will satisfy the primed counterparts of these equations if $u = u' \cos\theta - v' \sin\theta$ and $v = v' \cos\theta - u' \sin\theta$. Chen [1990] shows that this transformation is independent of the Hamiltonian of the system.

4 Multiple Routes: Discussion

Schrödinger saw that he had essentially three choices in how to represent his theory.

- A Use the second-order complex equation (2) for which he is known.
- B Use two coupled real equations, such as (3,4) above.
- C Use the fourth-order real equation (1).

For option B I write ‘such as’ because there are more illuminating real equations one can use, as Schrödinger knew. In particular, a more natural version of this strategy that fits his path of discovery would have been to pick two different real equations, a modified Hamilton-Jacobi type equation and a Van Vleck continuity equation. This form of quantum mechanics was used by Bohm [1952] in his derivation of the de-Broglie-Bohm interpretation of quantum mechanics and is nicely discussed by both Holland [1998] and Schleich et al [2013]. These two coupled equations are derived by expressing the complex wavefunction in polar coordinates as $\psi = Ae^{iS}$, where the amplitude A and phase S are real-valued, and then separating into real and imaginary parts.

Two initial values are necessary in all three presentations. The first requires the real and imaginary parts of the complex wavefunction; the second requires two real functions; and the third requires one real function and its temporal derivative. The i in (2) enforces the coupling between these two real functions—without it the two functions would decouple and we’d have too much freedom, as we could then specify u , $\partial u/\partial t$, v and $\partial v/\partial t$ (Bohm [1951], p. 86). So by going complex both in the wavefunction and the wave equation one eliminates two types of initial data. That coupling, we saw, is then used to get the single real wave equation.

What should we make of this “new” option? One can imagine what we might call *weak* and *strong* interpretations. On the weak interpretation, we regard Option C as simply another way of expressing the same theory. Just as Newton’s second law can be written as $F = ma$, or $F = dp/dt$, or $F = d(mv)/dt$, or $F = -\nabla V(x)$, so too Schrödinger’s theory can be written many ways. All three options pick out the same models of the physical universe, so one is not right and the others wrong. Our selection is instead dictated by so-called “pragmatic” virtues, such as ease of use, fruitfulness, elegance, context, and purpose. Like Holland [1998] and Schleich et al [2013], I often find option B (in its modified Hamilton-Jacobi form) preferable to A in pedagogical contexts. It provides insight into the historical origin of quantum mechanics, Schrödinger’s discovery, the classical-to-quantum correspondence, and the deBroglie-Bohm interpretation. Confronting option C, one question we might have is whether there are contexts where this form is similarly useful. I’ll give an example where I think it is in a moment.

On this weak interpretation, I think it’s fair to say that the choice Schrödinger and history made excels. Equation 2 of option A is a single compact expression of low order, unlike the equations of options B and C. It is likely the lowest order single equation that can characterize the set of worlds allowed by non-relativistic quantum mechanics (for arguments along these lines, see Bohm [1951]). Furthermore, if we look past the choice

of wave equation to the full theory, we will find that the extraction of probabilities from the wave equation (2) is incredibly elegant and easy via Born’s rule; by contrast, it will be comparatively messy or artificial via option C.

We can contemplate a stronger interpretation, one that Schrödinger probably initially entertained. So far I have said nothing about the interpretation of quantum mechanics. An interpretation is a mapping between the representation and the world. In the context of quantum mechanics, it’s common to refer to the ontology of a theory as a *beable*. The question then arises as to what the beables of quantum mechanics are. Do they include the wavefunction? More—such as GRW mass density or Bohmian particles? And if the wavefunction, we now see that we have a new option – adopting the position that only the real part of the wavefunction is a beable (and the imaginary part its “velocity”). Call this *Re(ψ) Realism*. According to *Re(ψ) Realism*, the real-valued wave represents what is real.

I think it’s plausible that Schrödinger was a *Re(ψ) Realist*, at least in June 1926. As has been chronicled many times elsewhere, we know that Schrödinger held that his wave equation described a genuine field in the world. He did not share Heisenberg’s positivist inclinations about ontology. He also felt that the use of imaginary numbers in quantum theory would turn out to be understood in the way in which he was familiar classically, namely, as dispensable. But note also that classically one never regards the imaginary parts of complex representations as representing the ontology. It’s not just that classical mechanics associates experimental outcomes with the real parts of complex representations (if used), it also associates the ontology of particles or fields with the real parts. The complex representation, for Schrödinger, represented a real field described by the real part of the wavefunction and its time derivative.

I’m not advocating such a position here. I note, however, that it may be attractive to some even today. Advancing the so-called “multi-field” interpretation of the wavefunction, Romano [forthcoming] opts for path B above in part because the two fields it posits are real-valued. The real-valuedness makes it easier, he thinks, to understand how to relate these two real fields to measurement outcomes. Path C arguably provides the same benefit but in a more parsimonious manner, positing one real-valued field as opposed to two. A similar advantage may appear in attempts to “nominalize” quantum theory, such as Chen [unpublished]. Something like path C also appears in the reduced phase space formulation of Schrödinger theory and may be helpful in considering possible beables for Bohmian field theory (Struyve [2010]).

In what follows I’ll describe one benefit of path C. This can be interpreted in a strong or weak way, as a consideration in favor of *Re(ψ) Realism* or as simply a pedagogical insight due to representing quantum theory via path C.

5 The Puzzle of Time Reversal Invariance in Quantum Theory

Quantum mechanics is widely proclaimed to be time reversal invariant. Yet this is a very puzzling claim. Let us assume that we use a time reversal invariant Hamiltonian such as

$H = p^2/2m + V(x)$. Then the Schrödinger equation is not time reversal invariant in the usual sense (Albert [2000]; Callender [2000]). Normally one associates time reversal in classical spacetimes with the physical operation corresponding to a temporal reflection about a spatial axis: the past is swapped for the future. Then, in natural coordinates, time reversal corresponds to the action $T : t \rightarrow -t$. Yet if we apply this operation to the Schrödinger equation, one immediately sees that it is not time reversal invariant. Temporal reflection brings out a negative sign in front of the equation because (2) is first-order in time and nothing else changes. Thus it is typically the case that if $\psi(t)$ is a solution then $\psi(-t)$ is not.

To drive the point home, note that the heat equation has the form

$$\frac{\partial\psi}{\partial t} = \kappa\nabla^2\psi \tag{6}$$

where κ is a real-valued coefficient. The heat equation is the *paradigmatic* non-time reversal invariant equation—it describes the irreversible diffusion of heat through a medium. And as we would expect of such an equation, we can readily see that if $\psi(t)$ is a solution then $\psi(-t)$ is not. The equation is not invariant under a temporal reflection. The only relevant formal difference between (6) and the Schrodinger equation (2) is that (2) has an i in it. But why should an i – which is just a number – matter? A physical operation in spacetime, a temporal reflection, should not affect dimensionless numbers.

Quantum textbooks sometimes address this point and claim that in quantum mechanics time reversal invariance is to be given by *two* operations, a temporal reflection and the operation of complex conjugation $K : \psi \rightarrow \psi^*$. This idea can be traced back to Wigner [1931]. With this understanding quantum mechanics is indeed time reversal invariant. But it's also clear that this combined operation, however one refers to it, is different than merely a temporal reflection. It is also a very strange symmetry, as it is the only one in quantum theory represented by an anti-unitary operator. Its introduction demands some explanation and justification. After all, what physical symmetry is represented by complex conjugation, and what does it have to do with time reversal?

Some distinguished books find this task very difficult. Paul Roman, for example, writes that ‘we should like, even if only by some artifice, to achieve full covariance [time reversal invariance]’ (Roman [1950], p. 266). Sachs [1987] offers one of the more careful treatments one can find and plausibly insists that time reversal should leave the kinematical structure of the theory intact; however, a crucial part of his argument – like that of many others – is that complex conjugation is necessary if time reversal is to reverse momentum and spin. That's true but it just pushes the question back, for momentum and spin are both spatial in quantum mechanics. Momentum is a spatial derivative and spin lacks time-dependence and is sometimes understood as a form of space quantization. Neither gets reversed by taking a temporal reflection.

Work in the philosophical foundations of physics also struggles to produce a defensible justification. In an elegant paper Roberts [2017] shows that if one assumes that there exists at least one non-trivial time reversal invariant quantum physical system then Wigner's operation follows. But in this context this assumption is a large one for it's up in the air whether quantum mechanics is time reversal invariant. Roberts [forth-

coming] and some other commentators argue that the combined operations of temporal reflection and complex conjugation better merit the denomination “time reversal invariance” than temporal reflection does. That’s fine as far as it goes, but why does what *we call* the operation matter? Call it what you like, Wigner’s reversal is different from a temporal reflection. Taking the complex conjugation of a state doesn’t follow by logic or definition alone from a temporal reflection. Classical mechanics is invariant under temporal reflections (so long as friction and other non-conservative forces aren’t included). Quantum theory a la the Schrödinger equation (2) is not if we treat like for like. We can agree to call the combined operations “time reversal invariance” but that doesn’t make the problem go away. Callender [2000] uses the classical correspondence and Ehrenfest’s theorem to tie Wigner reversal to classical time reversal invariance. This approach, I think, helps explain why Wigner’s transformation is so important. But I don’t think it gets to the heart of the puzzle: demonstrating by logic or definition alone how to go from temporal reflections to complex conjugation.

Schrödinger’s real realism offers insight here. Although he does not tie it to Schrödinger, Struyve [forthcoming] considers altering the ontology of classical electromagnetism and quantum theory in various ways to see what effect this has on time reversal invariance. Because a symmetry leaves the ontology of a theory intact, it is natural to expect the fate of symmetries to hang on the choice of ontology (and perhaps vice versa, inasmuch as symmetries may play a role in the selection of ontology). Struyve shows that this is indeed so for time reversal invariance if one adopts what I’m calling $\text{Re}(\psi)$ Realism.

Suppose that the ontology of quantum theory is given by the real part of the wavefunction and the main governing law of nature is best formulated as Schrödinger’s real equation, (1) above. Perform a temporal reflection on (1). Because it is second order in time and nothing else changes (as we’ll see, and assuming, as usual, a time reversal invariant Hamiltonian), it is manifestly time reversal invariant. Use the complex wavefunction and (2), by contrast, and the theory is not invariant under a temporal reflection. There is no paradox here because the ontology is not the same in the way we’re imagining things. This is an interesting example of Struyve’s point that the symmetry changes with the ontology.

Can this case provide insight into our puzzle? Yes. Suppose we introduced the above puzzle about time reversal to Schrödinger in June 1926. Let’s call him Real Schrödinger. How might Real Schrödinger understand and react to our problem?

Recall that Real Schrödinger would view the introduction of i into the wave equation as the price one pays for going lower order in type of differential equation and thereby getting something ‘extraordinarily convenient for the calculation’. The i plays an absolutely central role in allowing (2) to express the same theory as (3,4) and also (1). So when considering time reversal invariance, Real Schrödinger would want to “unwind” the transformation of his theory into a complex representation and understand time reversal in terms of the real formalism and u and $\partial u/\partial t$. Looking at that formulation, we’ve already seen that

$$v = (H_t)^{-1} \frac{\partial u}{\partial t} \tag{7}$$

holds. The imaginary part of the wavefunction contains the information about the time dependence of the real part. Here, Real Schrödinger will think, is my time dependence of u . The imaginary part is roughly like the velocity of the real part—due to the presence of $(H_t)^{-1}$ the imaginary part is not fully analogous to velocity. The important point is that $(H_t)^{-1}$ will not flip under time reversal. Hence by definition alone v must flip under time reversal.¹¹

Looking at the complex formulation, Real Schrödinger will see that this time dependence has been disguised by its complex clothing. He would know that he needs to invert v . In the complex formulation the way to do this is to change $\psi = u + iv$ to $\psi = u - iv$ or vice versa. So he would have to change ψ to ψ^* . He would do this not because a dimensionless quantity like i mysteriously flips under time reversal, but simply because v is a disguised first derivative in time. Put picturesquely, envision the wavefunction as expressed in a complex space spanned by its real and imaginary axes. Changing the sign of the imaginary part of the wavefunction will force the real part to rotate in the opposite direction.

This solves our puzzle. Seen through the prism of the real formalism, we can understand why complex conjugation is connected to temporal reflection. Formulated in the real theory version, a temporal reflection essentially reverses the velocities. But now if we express the theory in its complex formulation, we see that the definitional counterpart of reversing the velocities is taking the complex conjugate of the full wavefunction. Complex conjugation of the full wavefunction is just another way of expressing a temporal reflection of the real part of the wavefunction. Although the Schrödinger equation and the heat equation look almost the same, that similarity turns out to be superficial. The complex wavefunction interacting with the i in the general wave equation masks a time dependence that has no counterpart in the heat equation.

I emphasize that I am not saying that we either know quantum theory is or isn't time reversal invariant nor am I advocating for a particular ontology. The choice of correct ontology and its symmetries is a large one depending on many factors. What I am saying is that this real formalism provides greater insight into the conventional claim that quantum theory is time reversal invariant than I've seen elsewhere. For me, this explanation provides a far more satisfying justification for thinking quantum theory time reversal invariant than I've previously encountered. It doesn't demand that we call one symmetry another because that is intuitive, nor does it rely on arguments that don't survive much scrutiny (that momentum must alter sign, despite being a spatial derivative), nor does it merely inform us that Wigner reversal is important. Instead, it explicitly connects complex conjugation with temporal reflection. Just as the second path via two real wave equations can be illuminating when discussing the classical correspondence and much

¹¹Let me spell this out. Unlike a normal velocity, the temporal derivative in (7) is modified by an operator. It is crucial that this operator not bring out another minus sign under temporal reflection. To see that it doesn't, (7) can be expressed as $v = \int G \frac{\partial u}{\partial t} dx'$, where G is the Green's function of the *time-independent* Schrödinger equation (Chen [1991], equation 7). The Green's function for the time independent Schrödinger equation doesn't flip under time reversal. For a free particle in one dimension, for example, $G = G(x, x') = (|x - x'|)^{-1}$, which is unaffected by a temporal reflection.

else, path C can teach us about time reversal invariance.¹²

In fact it is possible that looking at time in quantum mechanics through this perspective will be useful elsewhere too. Could it provide new insights into how to understand stationary states? The CPT theorem? We'll leave these questions for future work.

6 Conclusion

This paper has been an introduction to and advertisement of Schrödinger's real wave equation, the first published time dependent Schrödinger equation. I introduced two ways of interpreting this equation, one weak, one strong. And I have shown how this equation is not merely a historical curiosity. It provides new insight into the nature of time reversal in a quantum world and it might provide an attractive option for some kinds of wavefunction realist. It is my hope that this marketing brochure for the real wave equation will lead to the discovery of other examples where it proves to be useful.

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¹²Does it still teach us this lesson if we're not $\text{Re}(\psi)$ Realists like Schrödinger of June 1926? I think so, although I admit that this is a difficult question. The question is whether we can justify a transformation in one formalism via a justification in a formally equivalent one. Suppose we adopt the usual interpretation. Then if Albert and Callender are correct, we lack a justification for the usual interpretation of complex conjugation as time reversal. Yet we would still see that the counterpart of complex conjugation is what we would naturally call time reversal in a formally equivalent theory. If that turns out to be merely an "insight" as opposed to a "justification" then I maintain that it is still an insight worth making.

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