Functional differential equations.
6: Quantum Mechanics

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Abstract

Reformulating classical physics using functional differential equations (FDEs) is of significant value in itself. But does it lead to quantum mechanics? Formally, the use of mixed-type FDEs leads to a structure of time, and thence to a quantum logic, and the postulates of quantum mechanics. Here, we give a simple and intuitive account of the structured time interpretation of quantum mechanics (STIQM), that quantum mechanics may be due to advanced interactions. We solve the modified Maxwell's equations in a linear approximation, for both retarded and advanced cases. The solutions show that a free electron oscillates under its own self-action. The oscillations are sustained because both damping and anti-damping are present even in the fully retarded case. Quantitative agreement with the de Broglie wavelength is possible with a simple extra hypothesis, though we do not examine it further here. A structure of time corresponds to many logical worlds, which we explain using the close analogy to parallel computing. With STIQM wave-particle duality does not present any conceptual difficulty. If quantum mechanics is indeed due to advanced interactions then a scalable quantum computer must necessarily be an android.

1   Recap

We have seen that if we do the math correctly, functional differential equations arise in the formulation of the two-body problem of classical electrodynamics. It is invalid to approximate these by ODEs and PDEs as is commonly done, since FDEs lead to fundamental departures from expectations based on ODEs and PDEs.[1] Briefly, FDEs correspond

to a *coupled* systems of ODEs and PDEs. It is hazardous to neglect that coupling, even though it is commonly neglected in everyday physics.[2]

Next we saw that to do the classical hydrogen atom correctly we need to include the radiation reaction. But if we include radiation reaction, even the one body problem of electrodynamics cannot be solved since runaway solutions arise. This state of affairs too needs to be corrected. There is a way to fix those infinities by modifying Maxwell's equations at a microphysical level. (This is similar to the technique used to fix the infinities of quantum electrodynamics.) But this turns even the 1-body equations of motion, with radiation reaction, into FDEs.[3]

Further, FDEs are not restricted to electrodynamics. Compatibility with special relativity requires that Newton's "laws" of motion must be reformulated. But Newton's laws of motion and law of gravitation come as a package deal, so that even gravitation has to be reformulated in a Lorentz covariant way. This leads to the FDEs of retarded gravitation theory (RGT). RGT is theoretically better than Newtonian gravitation (since Lorentz covariant), and practically better than general relativity (since using it makes the many body problem for the galaxy tractable). Even if we accept dark matter as the reason for the failure of Newtonian physics for the galaxy, we must use RGT to calculate its extent, not Newtonian gravitation.[4]

Finally, the existing formulation of physics is not consistent with our everyday experience that *we* create a bit of the future. The easiest way to reformulate physics to allow for the observed ability of living organisms to create some of the future is to allow advanced interactions, or a tilt in the arrow of time. This is not a new hypothesis, but just drops the usual hypothesis of causality. That leads to mixed-type FDEs.[5]

Thus, we have used FDEs for a series of corrections and "tweaks" which leads to a better mathematical formulation of classical electrodynamics, and gravitation, and to a physics more in accord with the mundane experience of both time asymmetry and creativity. That is of substantial value in itself. But will any of this lead to quantum mechanics?

Now the relation of mixed-type FDEs (MFDEs) to quantum mechanics was pointed out long ago[6] in what is called the structured-time interpretation of quantum mechanics (STIQM). However, that connection was established at a very abstract level, which is hard for most physicists. The present article aims to provide a simpler and more intuitive account of STIQM.

2 The base MFDEs

With the modified Maxwellian electrodynamics, retarded and advanced propagators are defined as before.[7] That is,

$$G_a(\mathbf{x}, \mathbf{y}) = \delta((\mathbf{x} - \mathbf{y})^2 + d^2)\theta(y^0 - x^0), \quad (1)$$

is the advanced Green function, while to obtain the field strength we now need to use the derivatives at advanced time instead of retarded time.

Mixed-type propagators are defined as a convex combination of retarded and advanced propagators

$$G_m = aG_a + (1-a)G_r \quad 0 < a < 1, \quad (2)$$

so that for the fields we have

$$F_m = aF_{adv} + (1-a)F_{ret} \quad 0 < a < 1. \quad (3)$$

With this expression for the field, the equations of motion of even a single classical charged particle are MFDEs.

2.1 The locally linear approximation

There are *no* general methods of solving this type of nonlinear MFDE. However, a simple way to obtain an approximate solution, called the locally linear approximation, was suggested long ago.[1] The idea is to approximate the nonlinear MFDE locally by an equation *of the same type*, a linear MFDE with constant coefficients and constant deviation of the argument.

To obtain this linear MFDE the coefficients are frozen in the neighbourhood of a particular point of time, as are the delay and advance. We know how to solve such linear MFDEs with constant coefficients and constant deviation of arguments. We then continue the solution by using this locally linear approximation in neighbourhoods around different

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[1]C. K. Raju, "Simulating a tilt in the arrow of time", paper presented at the seminar on "Some Aspects of Theoretical Physics", Indian Statistical Institute, Calcutta, 14–15 May 1996 (unpublished).

points of time, and patching together solutions at different times. This may not result in a globally continuous or unique solution, but that is not a requirement.

2.2 A linear approximation: retarded case

Let us start by explicitly working out this linear approximation in the retarded case. It is helpful to convert from proper time to coordinate time, and to use 3 vectors and a 3+1 decomposition.

A straightforward but tedious calculation gives for the electromagnetic field strength $\boldsymbol{E}$

$$\boldsymbol{E} = \frac{qc\tau}{4\pi\epsilon_0\big(c^2\tau - (\boldsymbol{v}\cdot\boldsymbol{\chi})\big)^3}$$
$$\Big(-\boldsymbol{a}\big(c^2\tau - (\boldsymbol{v}\cdot\boldsymbol{\chi})\big) + \boldsymbol{u}(c^2 - v^2 + \boldsymbol{\chi}\cdot\boldsymbol{a})\Big) \quad (4)$$

where $\boldsymbol{v}$, $\boldsymbol{a}$ are the 3 vectors corresponding to velocity and acceleration respectively (both at retarded time), $(\tau, \boldsymbol{\chi}) = \zeta$ is the 3+1 decomposition of the retardation vector ζ. Further, $\boldsymbol{u} = \frac{1}{\tau}\boldsymbol{\chi} - \boldsymbol{v}$, is analogous to the vector defined in elementary texts [Griffiths]. However, recall that, unlike the Maxwellian case, ζ is no longer a null vector, since interaction takes place along a hyperboloid. Consequently, $\frac{1}{\tau}\boldsymbol{\chi} \neq \hat{\boldsymbol{\chi}}$. Instead, we now have

$$\chi^2 + d^2 = c^2\tau^2. \quad (5)$$

For the case of self-action, let us approximate the retardation 3-vector χ as

$$\boldsymbol{\chi} \approx \boldsymbol{v}\tau. \quad (6)$$

This gives from (5) that

$$\tau = \gamma \frac{d}{c}. \tag{7}$$

Since $\boldsymbol{\chi} \approx \boldsymbol{v}\tau$ we actually have $\boldsymbol{u} \approx 0$ for the case of self action, and we can also use (6) to simplify the expression due to the dot product $\zeta \cdot \dot{\alpha}$

$$c^2\tau - \boldsymbol{v} \cdot \boldsymbol{\chi} = (c^2 - v^2)\tau \tag{8}$$

To derive our approximate linear equation, let us further neglect the force due to the magnetic field. The self-force on the charge due to the electric field is $\boldsymbol{F} = q\boldsymbol{E}$, and the equation of motion is

$$\ddot{\boldsymbol{x}} = \frac{q}{m}\boldsymbol{E} \tag{9}$$

Recalling that $\boldsymbol{u} = 0$ for the case of self-action, and recalling that we are neglecting the magnetic field in this approximation, the equation (9) reduces to the simple equation

$$\ddot{\boldsymbol{x}} = -k_r \boldsymbol{a} \tag{10}$$

where

$$k_r = \frac{q^2 c\tau}{4\pi\epsilon_0 m(c^2\tau - \boldsymbol{v} \cdot \boldsymbol{\chi})^2}. \tag{11}$$

Using (8), this simplifies to

$$k_r = \frac{q^2 c}{4\pi\epsilon_0 m\tau(c^2 - v^2)^2}$$
$$= \frac{q^2}{4\pi\epsilon_0 mc^3\tau(1 - \frac{v^2}{c^2})^2} \tag{12}$$

If the charged particle is an electron so that $m = m_e$, the last equation can be rewritten

$$k_r = \frac{q^2}{4\pi\epsilon_0 m_e c^3\tau(1 - \frac{v^2}{c^2})^2}$$
$$= \frac{r_e}{c} \cdot \frac{1}{\tau} \cdot \gamma^4$$
$$= \frac{\tau_{\text{relax}}}{\tau}\gamma^4$$
$$= \frac{r_e}{d}\gamma^3, \tag{13}$$

where $r_e = \frac{q^2}{4\pi\epsilon_0 m_e c^2}$ is the classical radius of the electron, $\tau_{\text{relax}} = \frac{r_e}{c}$ is the so-called relaxation time of the electron (time taken by light to travel across the classical electron radius), and d is the separation parameter in the modified Maxwell equations. If $d \approx r_e$, we have $k_r \approx 1$.

3 Oscillatory solutions

For our immediate purpose, we can, without loss of generality, further simplify the above equation to an equation in a single dimension (so that x is a scalar, not a vector). (There is no loss of generality because in the vector case we simply apply the following reasoning to each component of the vector.)

To begin with, since $k_r \approx 1$, we set $k_r = 1$, in (10) and solve the simple equation

$$\ddot{x} = -\ddot{x}(t - \tau) \tag{14}$$

We look for pure imaginary roots of the characteristic quasi-polynomial. That is, we substitute $x = e^{\iota\omega t}$ in (14), to obtain

$$-\omega^2 x = \omega^2 x e^{-\iota\omega\tau}. \tag{15}$$

Cancelling $\omega^2 x$ from both sides, we see that we are seeking a solution of

$$e^{-\iota\omega\tau} = -1. \tag{16}$$

Such a solution is easily found. Taking real and imaginary parts we see that we need the simultaneous solution of

$$\cos\omega\tau = -1,$$
$$\sin\omega\tau = 0. \tag{17}$$

The solution is evidently given by

$$\omega\tau = \pi + 2n\pi, \quad n = 0, \pm 1, \pm 2, \ldots$$
$$= (2n+1)\pi, \quad n = 0, \pm 1, \pm 2, \ldots \tag{18}$$

In general, this equation has an infinity of roots. Each pure imaginary root corresponds to an undamped oscillatory motion of the particle. Thus, the solution of (14) is

$$x(t) = e^{\iota\omega t}$$
$$\omega = (2n+1)\frac{\pi}{\tau}, \quad n = 0, \pm 1, \pm 2, \ldots \tag{19}$$

Thus, we see that a single free charged particle will, under its own self-action, oscillate. While there is no rest frame for such a particle, we may consider as a "zero" frame a frame where the particle does not drift off, and has zero average velocity. As seen from a frame which it is moving with respect to the zero frame, so that the particle has an average velocity V, the particle will correspond to a travelling wave, say,

$$x = Vt + A\sin(\omega t). \tag{20}$$

However, for the wavelength λ of such a travelling wave we will have

$$\lambda = VT, \tag{21}$$

where $T = \frac{2\pi}{\omega}$ is the time period of the sinusoidal oscillation. Since $T \propto \tau = \frac{\gamma d}{c}$, we see that quantitative agreement with the de Broglie formula requires an additional hypothesis

$$d \propto \frac{1}{E}, \tag{22}$$

where E is the average energy, and we neglect the γ factor, for simplicity. For a free particle $E = \frac{1}{2}mV^2$, so, with this hypothesis, from (21) we get

$$\lambda \propto \frac{1}{mV}. \tag{23}$$

Now the parameter d is not specified by the theory. Roughly speaking, it relates to the "interior" of the electron, where anything at all might happen. The above hypothesis about it looks simple enough. Nevertheless, any attempt to justify it would bring in ramifications far beyond the scope of this article, which aims to give a simple an intuitive account of the structured-time interpretation of quantum mechanics (STIQM). Therefore, for the purposes of this article let us proceed with qualitative agreement alone: some sort of oscillatory or wave motion is naturally associated with a free charged particle.

Note that we have an infinite (discrete) spectrum of possible frequencies *in classical physics*. That is obviously not possible in classical *mechanics* or with ODEs. If we were to do the same for a system of ODEs, no matter how many particles are involved, we would end up with a polynomial with a finite number of roots, never a quasi polynomial with an infinity of roots. On the theory of Fourier series, this means that we are not restricted

to sinusoidal oscillations, and can have any general period function.

4 Damping and anti-damping

The significance of pure imaginary roots of the characteristic quasi-polynomial is that pure imaginary roots correspond to stable or un-damped oscillations. However, in arriving at the simplified equation (14) above we as-sumed that $k_r = 1$, although from the last of the equations (13) it is clear that that can never *exactly* be the case.

So, let us go to the next level of complexity, and solve the equation after putting back the value of k_r but supposing it to be a constant, possibly different from 1. That is, we solve the equation

$$\dddot{x} = -k_r \ddot{x}(t - \tau), \qquad (24)$$

obtained by neglecting just the magnetic field, and treating k_r as a constant.

We now take as a trial solution

$$x = e^{zt}, \quad \text{where}$$
$$z = u + \imath\omega. \qquad (25)$$

Substituting in (24), and cancelling $z^2 e^{zt}$ as before, we are led to the characteristic quasi-polynomial equation

$$e^{-z\tau} = -\frac{1}{k_r}, \qquad (26)$$

in place of (16). Equating real and imaginary parts as before, we arrive at

$$e^{-u\tau}\cos\omega\tau = -\frac{1}{k_r}, \qquad (27)$$
$$\sin\omega\tau = 0. \qquad (28)$$

in place of (17). This can be solved by choos-ing ω as before as a solution of (17) and choos-ing u as the solution of

$$e^{-u\tau} = \frac{1}{k_r}. \qquad (29)$$

That is,

$$u = \frac{1}{\tau}\log k_r \qquad (30)$$

Thus, the solution of (24) is given by

$$x(t) = e^{ut}.e^{\imath\omega t} \qquad (31)$$

with ω as before given by (18) and u given by (30).

Thus, we now have oscillations which are damped *or* anti-damped by a factor of e^{ut} where $u = \frac{1}{\tau}\log k_r$. Damping holds if $u < 0$, or $k_r < 1$, that is, for large values of d or τ ($d > \gamma^3 r_e$ or $\tau > \gamma^4 \tau_{\text{relax}}$). If the reverse inequality holds ($k_r > 1$), that is for small values of d or τ ($d < \gamma^3 r_e$ or $\tau < \gamma^4 \tau_{\text{relax}}$) we will have anti-damping. This should be noted, because on intuition built on classical mechan-ics there is no possibility of anti-damping with purely retarded radiation.

In particular as $d \to 0$, it is anti-damping which prevails, and we recover the runaway solutions as in the theory with point masses. That is, the method of deriving radiation re-action by a limiting procedure is not valid, be-cause in the process of taking the limit there is an unexpected switch from damping to anti-damping.

4.1   Self-excited oscillations

The existence of both damping and anti-damping raises the possibility of self-excited oscillations. Indeed, $k_r = \frac{r_e}{d}\gamma^3$, is velocity dependent. For constant $\frac{r_e}{d}$, as $v \to c$ we have $\gamma \to \infty$, so k_r will increase, and anti-damping will set in. In an oscillatory motion, v will decrease and become zero. During this time, we have $\gamma \to 1$, so if $\frac{r_e}{d} < 1$, damping will set in. *Thus, both damping and anti-damping may be present in the course of a single oscillation.*

What will be the effect of this? We cannot write down a formula for this case, where the damping factor is velocity dependent, but the numerical solution is given below. The solution is stable, or at least semi-stable, corroborating the possibility of self-excited oscillations, though the frequency of the oscillation is no longer given exactly by (17).

Thirdly, even $\tau = \frac{\gamma d}{c}$ is γ dependent. So long as the values of v are small relative to c this does not seem to make much of a difference, and the numerical solution remains almost the same.

Thus, on classical physics (with FDEs) an electron is not just a mass point which sits idly waiting for an external force to move it as in Newtonian mechanics. Under its own retarded self-action it undergoes a rapid self-excited oscillation, during which its momentum and energy also vary, though there is no net loss or gain of energy due to radiation.
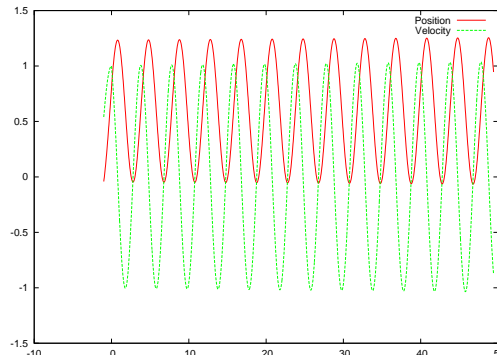

Figure 1: Solution of the retarded equation (24) with the velocity dependence of k_r and τ taken into account. The x-axis is time in units of τ_{relax} (deci-yocto seconds). The y-axis does double duty. For velocity it is in units of $\frac{c}{30}$ (or $\frac{c}{300}$) dfm/dys, for position it is in corresponding units of distance (deci-femto meters).

4.2   The equations of motion for self-action: mixed case

We now take up the mixed-type case, where the propagator is a convex combination of advanced and retarded propagators. Working exactly as above, we arrive at the approximate equations of motion for a charged particle as,

$$\ddot{x} = ak_r\dddot{x}(t + \tau) - bk_r\dddot{x}(t - \tau), \quad a + b = 1, \tag{32}$$

where the weight of the advanced component $a \ll 1$, so that the weight of the retarded component $b \approx 1$. To solve this equation, assuming k_r constant, we proceed as before and take as a trial solution $x = e^{zt}$, with $z = u + \imath\omega$. Substituting in (32), and cancelling $z^2 e^{zt}$ as

before, we are now led to the characteristic quasi-polynomial equation

$$1 = ak_r e^{z\tau} - bk_r e^{-z\tau}. \qquad (33)$$

Taking real and imaginary parts as before, we now obtain

$$ak_r e^{u\tau} \cos \omega\tau - bk_r e^{-u\tau} \cos \omega\tau = 1 \qquad (34)$$

$$ak_r e^{u\tau} \sin \omega\tau + bk_r e^{u\tau} \sin \omega\tau = 0. \qquad (35)$$

If ω is a solution of (17), then $\sin \omega\tau = 0$ so the equation (35) is satisfied, and, since $\cos \omega\tau = -1$, (34) reduces to

$$ae^{u\tau} - be^{-u\tau} = -\frac{1}{k_r}. \qquad (36)$$

This can be solved by setting $y = e^{-u\tau}$ so that $u = -\frac{1}{\tau} \log y$. This leads to the quadratic equation

$$\frac{-1}{k_r} = \frac{a}{y} - by \qquad (37)$$

Explicitly the quadratic is $by^2 - \frac{1}{k_r}y - a = 0$ and this has the solution

$$y = \frac{1 \pm \sqrt{1 + 4abk_r^2}}{2bk_r}. \qquad (38)$$

We need a positive root since we need the log of y. Approximately, this is given by

$$y \approx \frac{2}{2bk_r} + \frac{2abk_r^2}{2bk_r}, \qquad (39)$$

so that

$$y \approx \frac{1}{bk_r} + ak_r \qquad (40)$$

Since $b \approx 1$ we have as before $y \gtrless 1$ almost according as $k_r \gtrless 1$. Thus, the solution in the mixed-type case is

$$x(t) = e^{ut}.e^{\iota\omega t} \qquad (41)$$

with ω as before given by (18) and $u = -\frac{1}{\tau} \log y$ with y given by (40).

However, in this case there is one more solution. We can choose $\cos(\omega\tau) = 1$ in (34), so that $\omega = \frac{2n\pi}{\tau}$. In this case, instead of (36) we have the equation

$$ae^{u\tau} - be^{-u\tau} = \frac{1}{k_r}. \qquad (42)$$

With y defined as before by $y = e^{-u\tau}$ we now get the quadratic $by^2 + \frac{1}{k_r}y - a = 0$, which has the solution

$$y = \frac{-1 \pm \sqrt{1 + 4abk_r^2}}{2bk_r}. \qquad (43)$$

Further analysis shows that this solution is unstable since permanently anti-damped (unless some assumptions fail), hence we discard it.

5 STIQM

That brings us to a very fundamental issue, at the core of STIQM.[6] The difference between MFDEs and retarded FDEs is not just a matter of slightly differing rates of damping. With MFDEs past does not determine future. Indeed, the existence of advanced interactions allows the future to communicate with the past, so that even the past is not fully determinate. However, since advanced interactions are rare, the indeterminacy of the past is very small compared to that of the future.

The question now is this: how does one *model* such indeterminacy? A structure of

time helps us to model indeterminacy. In Newtonian mechanics a dynamical variable has a definite value at one instant of time. A structure of time means that it may have more than one value at one instant of time.

Because the structure of time in STIQM arises from the use of MFDEs with only a tiny advanced component, a retarded FDE model still remains a good first approximation. The world is still approximately deterministic, and the indeterminacy relates typically to a microphysical level. That is, STIQM involves a *microphysical structure of time.* We can expect advanced effects to be most readily manifest at the level of single particles.

It may seem illogical to say of a dynamical variable that $q = 3$ is true, and also that $q = 4$ is true, but logic itself depends on the nature and structure of time.[8] A change in logic is a key *required* feature in modeling the indeterminacy of qm; it is well-known that the logic obeyed by quantum mechanics is not Boolean like 2-valued logic.

In terms of probabilities, quantum probabilities are different from classical probabilities, just because quantum probabilities are defined on a different logic, and *hence* do not admit a joint probability distribution of canonically conjugate variables. In the von-Neumann formulation of qm, the representation of dynamical variables by operators may be understood as relating to random variables as measurable functions defined on the non-Boolean lattice or logic of subspaces of a Hilbert space, also called a quantum logic.

The temporal logic corresponding to a structured time is neither 2-valued, nor 3-valued; it is quasi truth-functional. That is we cannot always assign a truth value to the statement $q = 3$. A subtle but important point here is that this is NOT the same thing as saying that $q = 3$ has the truth value "indeterminate", as in, say Lukasiewicz's 3-valued logic.[6, chp. 1] In that 3-valued logic, the logical connectives remain functions of the 3 truth values; that is no longer the case with quasi truth-functional logic.

Roughly speaking, in 3-valued logic we assign *neither* truth value (true, false) to a proposition; in quasi truth-functional logic we may assign *both* truth values (at one "instant" of time). It is not the case that Schrödinger's cat is either alive or dead, and we don't know which is the case; rather it is the case that Schrödinger's cat is both alive and dead (at one "instant" of time). The 3-valued logic used by Reichenbach[9] or Kothari[10] does not lead to a valid interpretation of qm. A key result of STIQM, however, is this: a quasi truth-functional logic is a quantum logic. Though this result is formally proved only in the book[6], and not in the related series of articles in this journal, let us try to understand it here in simple intuitive terms.

As already noted, the key aspect of quantum probabilities is that joint probability distributions do not exist for canonically conjugate variables. This is mathematically linked to the non-commutativity of operators, with dynamical variable defined as random variables, with probability defined on the lattice of subspaces of a separable Hilbert space instead of a usual Boolean algebra. The key requisite feature of the lattice of projections on a Hilbert space is that the distributive law of "and" over "or" fails.

Let us try to understand this in simple and intuitive terms. Consider a two slit experiment with two slits A and B. Consider the two propositions:

1. The electron reached the screen AND passed through slit A OR the electron reached the screen AND passed through slit B.

2. The electron reached the screen AND passed through slit A OR slit B

The two statements are equivalent on a Boolean logic. However, they are *physically* different, since in the first case one observes a mixture of two gaussians, and in the second case one observes an interference pattern. Hence, the distributive law fails, and a quantum logic must be non-Boolean.

The lattice of projections on a Hilbert space is such a non-distributive lattice. If P_1 and P_2 are two projection on subspaces S_1 and S_2 respectively, we define $P_1 \wedge P_2$ as the projection on the intersection $S_1 \cap S_2$, and $P_1 \vee P_2$ as the projection on the span of $S_1 \cup S_2$. If P_x and P_y and P_{xy} are projections on the x-axis, y-axis and the line $x = y$ respectively, then $(P_{xy} \wedge P_x) \vee (P_{xy} \wedge P_y) = 0$, whereas $P_{xy} \wedge (P_x \vee P_y) = P_{xy}$, so that "and" $(\wedge)$ is not distributive over "or" $(\vee)$.

The explanation of non-distributivity with quasi truth-functional logic is much easier to understand. The two statements above are not equivalent because the OR in proposition 1 is exclusive, while the OR in proposition 2 is inclusive. That is, we allow for the possibility that the electron passed through both slits. The electron is a particle, it did not divide into two halves like a wave; but it is time which split into two threads to allow for both possibilities simultaneously.

The formal mathematical way to make a quasi truth-functional logic meaningful is to interpret it in terms of logical (2-valued) "worlds". A logical world, in the sense of Wittgenstein, is "all that is the case". That is, a logical world corresponds to an assignment of binary truth values "true" or "false" to any proposition. This understanding of the word "world" must be clearly distinguished from the loose way in which the word "world" is used in, say, the many-worlds interpretation of quantum mechanics. In STIQM, there is only one physical world. Multiple logical worlds are just a semantic device we use to make its description easily comprehensible in natural languages. In particular, these logical worlds may interact with one another.

Parallel computers provide a concrete model of the use of quasi truth-functional logic. The parallel computer is analogous to the single physical world we have. It, however, consists of multiple processing units, each of which runs a sequential execution "thread" or sequential process,[11] and thus each processor constitutes a logical world. These worlds interact with one another. Each execution thread itself is a thread or branch of structured time. Now suppose we want to debug a parallel program, and break its execution. This would give us the "state" of the physical world at one "instant". However, it is perfectly possible that we find Schrödinger's cat is alive in one processor, and dead in another, there is no paradox in that. A quasi truth-

functional logic is needed to understand such debugging.[12]

When the STIQM was developed, almost a quarter century ago, parallel computing was in its infancy, and OCCAM was being used as the language of parallel computing, since there was nothing much then by way of parallel Fortran or parallel C. An example computer program in OCCAM illustrating the above considerations (and using the indeterministic ALT construct of OCCAM) is given in [6].

5.1 Two sources of uncertainty

Thus, the use of FDEs brings in *two* novel sources of uncertainty. First, unlike the case in Newtonian mechanics, a particle such as an electron does not stay at rest. Even with purely retarded FDEs, and under its own self-action the particle oscillates. As such its position and momentum are not fixed, but are constantly varying.

Secondly, with MFDEs the future, and even the present and past really are uncertain at the microphysical level. This corresponds to a microphysical structure of time. While this situation can be described as multiple parallel "worlds", in STIQM, unlike the many-worlds interpretation, these are only parallel *logical* worlds. There is only one physical world, as in one computer performing concurrent computation.

Note that the existence of these parallel worlds follows from classical physics done correctly, by addressing problems neglected over the last century.

5.2 Wave particle duality

An interesting feature emerges when we combine both sources of uncertainty, or both the features of (a) an oscillating particle which (b) exists in multiple sub-threads of time.

Consider again the classical two-slit experiment with an electron. If the electron behaves as a free particle *before* the slits, then there are two sub-threads of time, one in which the electron comes from slit A and another in which it comes from slit B. These multiple past possibilities will reflect in multiple future solutions between the slits and screen. It is clear that the two solutions will, in general, travel different distances to reach a given point on the screen. Accordingly, there will be a phase difference between the two oscillations. Since there is only one physical world, what we will observe is a superposition of the two oscillations corresponding to the two sub-threads. Since both solutions concern one and the same electron, this is a *coherent* superposition. Accordingly, we will see an interference pattern.

If, however, we observe which slit an electron goes through (delayed choice is irrelevant) then we destroy the possibility that the electron goes through both slits. That is, we change the past data. Consequently, the solution changes also between the slits and the screen. (Note that STIQM is explicitly nonlocal, since it is all about advanced effects, and it is not a hidden-variable theory, since the uncertainties in it cannot be eliminated, as the very notion of a structure of time indicates.[6, chp. 6a])

Thus, with a structure of time obtained through the use of MFDEs, wave particle duality does not present any *conceptual* problem. What about quantitative agreement? Will the observed interference pattern correspond to the de Broglie wavelength? To reiterate the answer above, such quantitative agreement can be obtained by supposing that (22) of some equivalent hypothesis holds. But justifying that very simple hypothesis involves ramifications beyond the scope of this article.

6 Schrödinger equation

It has long been known that, using Koopman's formalism, the representation of dynamical variables by operators on a Hilbert space can also be used in classical statistical mechanics. The critical issue related to qm is the non-commutativity of the operators. That, as explained above, connects to a change of logic, which may be understood using the STIQM.

But what about Schrödinger's equation? Now Schrödinger's equation gives us unitary evolution in Hilbert space; this is possible even with Koopman's formalism. Further, Schrödinger's equation holds only in equilibrium, and as pointed out in my first interpretation of quantum mechanics[13] unitary evolution is equivalent to stationarity which corresponds to equilibrium or indifference to the origin of time. Either way, unitary evolution in Hilbert space does not by itself present any fundamental difficulty.

The critical issue is about the Hamiltonian, or the infinitesimal generator of the unitary group. Why is the quantum Hamiltonian the same function of the dynamical variables as the classical Hamiltonian (when the latter exists)? This indicates that qm and classical physics are not just two different theories; they are closely connected. We will not go further into this question here, except to point out that the STIQM is the best way currently available to connect classical physics to quantum physics.

7 Concluding remarks

Classical physics done correctly, i.e., with MFDEs, exhibits many of the most puzzling conceptual features of quantum mechanics. Those puzzling features are the expected consequences of the existence of advanced interactions.

We emphasize that we have not *derived* qm from classical physics, nor was such derivation ever a goal. At the least some extra phenomenology will be required to obtain the Planck constant or the fine structure constant to obtain quantitative agreement.

We do not claim to have derived qm from classical physics also since classical physics with MFDE's is *not* identical to qm. It is a self-contained theory with many of the features of qm, but distinct from qm. Thus, with MFDEs non-locality central: the theory can be tested by testing for the existence of advanced interactions.

Nevertheless, the understanding acquired above, that key features of qm can be explained as advanced "effects", is important for the technology of quantum computing, considered vital to the future. The key current

problem with that technology is the problem of decoherence or the inability to scale up a quantum computer.

The speed-up provided by a quantum computer is due to parallelism, which on the above understanding relates to a structure of time. And that, according to STIQM is due to advanced effects. So, is there a way to scale up tiny advanced effects to some reasonable macrophysical level? Living organisms (and only living organisms) seem to be able to do that. We do not today understand how that happens. For such understanding we would, at the least, need to simulate the interactions of biological macromolecules using MFDEs in place of the ODEs as is done today.

However, on the structured-time interpretation of quantum mechanics, we can safely conclude that scaling advanced effects would necessarily involve living organisms. (Recall that time travel is *impossible* with machines.[5])Hence, a (scalable) quantum computer would necessarily be an android (not as in the popular operating system, but as in half-live, half-machine); it would involve at least biological macromolecules.

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