A Survivor's Guide to Quantum Physics

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Abstract

As a pointer, and a service to other amateur physicists, I thought it would be useful to sum up the main pitfalls and discoveries I stumbled upon while working my way through Feynman's Lectures – complemented with some other basic material, of course. I call it a Survivor's Guide to Quantum Physics because – at times – it did feel like going through a jungle, or wading through deep water, or climbing a mountain for which there is no map. Indeed, while there is a tendency to present quantum physics as a coherent set of principles and theory, it is not. At best, it is a toolbox with some novel mathematical techniques, approaches and models. At worst, it tries to present itself as an *alternative* to classical physics, which it is not. Quantum physics is, in essence, a combination of Maxwell's equations and the Planck-Einstein relation. That is it. Nothing more. Nothing less. In the QED sector, at least. The one and only quantum is Planck's quantum of (physical) action, and its physical dimension – a force times a distance times a period (cycle time) – is, unfortunately, not always well understood by those who are supposed to understand it – which is why there is a lot of nonsense around.

In short, we hope this short paper might help you to avoid the mistakes I made, and that is to waste time on things you should not waste time on: stuff that is not useful, or plain wrong even. And then I will also try to highlight the little shortcuts or visualizations that may help you to get a much more intuitive grasp of things.

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Introduction

In the *Epilogue* to his *Lectures*, Richard Feynman writes that his intention was to give us "some appreciation of the wonderful world and the physicist's way of looking at it", which he believes to be "a major part of the true culture of modern times." He wrote that back in 1963, so that is almost 60 years ago now. I was born back in 1969 – when men went and walked on the moon, and returned safely home – and I can, therefore, not become older than Feynman's lectures. Hence, I will continue to consider them as modern science – especially his last lecture (on superconductivity) includes an introduction to Josephson junctions, which are used in quantum computing. His treatment of transistors and lasers is also pretty standard, still. Besides, I will mention whatever new discovery was made if and when relevant (think of the 2012 CERN experiments here, or the experimental confirmation of the reality of gravitational waves by Caltech's LIGO Lab in 2016).

The recent discoveries and experiments do not fundamentally alter the way we are looking at the world, indeed. It consists of light, matter, and force fields, and so you want to know what these are – not approximately but *exactly*. That is why you are reading this. What makes this text different is that most texts talk more about deep mysteries (while there are none) than good theories and, therefore, confuse rather than enlighten. There is also a rather absurd tendency to present quantum physics as a coherent set of principles and theory: it is not. At best, it is a toolbox with some novel mathematical techniques, approaches and models. At worst, it tries to present itself as an alternative to classical physics, which it is not. Quantum physics is, in essence, a combination of Maxwell's equations and the Planck-Einstein relation. The one and only quantum is Planck's quantum of (physical) action, and its physical dimension – a force times a distance times a period (cycle time) – is, unfortunately, not always well understood by those who are supposed to understand it – which is why there is a lot of nonsense around.

The difference between bosons and fermions, for example, is a grand generalization which is not all that useful. We will prefer to talk about photons, electrons, protons, neutrinos, etcetera without getting lost in the nitty-gritty of, say, Dirac versus Majorana fermions. We will also explain superconduction without talking about Bose-Einstein condensates: Feynman's explanation of Schrödinger's equation as "the equation of motion" in a "superconducting electron fluid" is what it needs to be: concise and clear. So, yes, this will be a survivor's guide: I want you to avoid the mistakes I made, and that is to waste time on things you should not waste time on: stuff that is not useful, or plain wrong even. And then I will also try to highlight the little shortcuts or visualizations that may help you to get a much more intuitive grasp of things.

Will I succeed? I do not know. That is for you to judge. Let us go for it.

Wavefunctions and the equations of motion for the electron

Are wavefunctions – or wave equations – always equations of motion? No. A quantum-mechanical state is not always a state of motion – but, in many cases, it is and, in such cases, the wavefunction will represent the position of a pointlike charge (think of an electron – for all practical purposes). Or, to be precise, the wavefunction will represent its trajectory, because a pointlike charge usually travels too fast to pinpoint its exact position – so it could be here but also there. This has nothing to do with quantum-

mechanical uncertainty because we know that – at some point in time – it will be here, and if we would know at what point in time *exactly*, we would know when it would be there. The phase is just a fast-running clock (I am simplifying things a lot here, but the essentials are correct): so fast-running, in fact, that we can never quite see the exact position of the hand of this clock: it is always moving, and moving very fast.

How fast? It depends. You can use the wavefunction to model the spin of a free electron in a 'mass without mass' model, in which case the velocity of the pointlike charge will equal the speed of light. We fully developed the model elsewhere, but the basics of it are probably worth a quick recap. We may think of the magnetic moment of a charge being generated by a ring current. Hence, we really think of the electron as a perpetual ring current: a pointlike charge that is going round and round. This motion may or may not be chaotic but it must be regular (otherwise we would not be able to model it as an oscillation). The tangential velocity is given by $c = a \cdot \omega$, and we must assume some centripetal force keeps the pointlike charge in its orbit – as illustrated below.
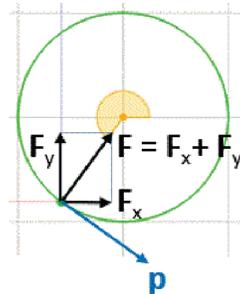

Figure 1: The ring current model of an electron

We effectively think of an electron (and a proton) as consisting of a pointlike elementary charge – pointlike but not dimensionless, perhaps[1] – moving about at the speed of light around the center of its motion. This pointlike charge must have some momentum—if only by virtue of its motion.[2] More importantly in the context of our discussion here, any (regular) oscillation – including this circular oscillation[3] – has a frequency and a cycle time $T = 1/f = 2\pi/\omega$. The Planck-Einstein relation ($E = h \cdot f = \hbar \cdot \omega$) relates f and T to the energy (E) through Planck's constant h (or, when using the reduced form of Planck's equation, $\hbar$). This frequency formula then allows us to use the tangential velocity to

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[1] The slight anomaly in the magnetic moment can be explained by assuming the pointlike charge has a tiny size itself.

[2] This is *not* the classical moment of the electron or proton as it is moving about classically—with an equally classical velocity *v*. No. The momentum in this illustration is equal to $p = m_\gamma c$: m_γ is the *relativistic* mass of the pointlike charge, whose *rest* mass itself is zero because the naked charge itself has no other properties but its charge. We can use the idea of a centripetal force (**F**) keeping this charge in its orbit to prove this effective mass will be *half* of the electron mass. The other half of the mass or energy of the electron is in the oscillating field which must keep this charge, somehow, in its orbital motion. We know this must sound rather fantastical but we ask you to just go along with it for the time being. We will think about the nature of this force in later developments.

[3] Louis de Broglie's intuition in regard to the wave nature of matter-particles was correct, but he might have tried to think of orbital rather than linear motion – circular rather than linear oscillations. De Broglie may also have been wrong in modeling a particle as a wave *packet*, rather than as a single wave. See our paper on de Broglie's matter-wave for more details

calculate the radius of this orbital motion:

$$a = c/\omega = c\frac{\hbar}{E} = \frac{\hbar c}{mc^2} = \frac{\hbar}{mc} \approx 0.38616 \text{ pm}$$

This effectively corresponds to what we refer to as the Compton *radius* of an electron[4], which, paraphrasing Prof. Dr. Patrick LeClair, we can now understand as "the scale above which the electron can be localized in a particle-like sense."[5] In any case, in the context of this discussion, we should just mention this:

1. The elementary wavefunction (Euler's formula) can be used to represents the motion of the pointlike charge by interpreting $r = a \cdot e^{i\theta} = a \cdot e^{i \cdot (E \cdot t - \mathbf{k} \cdot \mathbf{x})/\hbar}$ as its position vector (the coefficient a is, in this particular case, just the Compton radius $a = \hbar/mc$.[6] Now, we could integrate the concept of spin by thinking about the *direction* of motion, as illustrated below: we can go from the +1 to the −1 position on the unit circle taking opposite directions—as illustrated below.
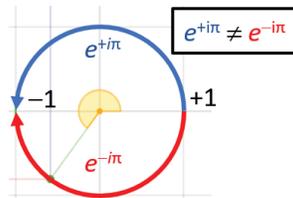

Figure 2: $e^{+i\pi} \neq e^{-i\pi}$

Hence, combining the + and − sign for the imaginary unit with the direction of travel, we get four mutually exclusive structures for our electron wavefunction (see Table 1). Unfortunately, the mainstream interpretation of quantum mechanics does not integrate the concept of particle spin from the outset because the + or − sign in front of the imaginary unit (i) in the elementary wavefunction ($a \cdot e^{-i \cdot \theta}$ or $a \cdot e^{+i \cdot \theta}$) is thought as *a mathematical convention* only. This non-used *degree of freedom* in the mathematical description then leads to the *false* argument that the wavefunction of spin-½ particles has a 720-degree symmetry. Indeed, physicists treat −1 as a *common phase factor* in the argument of the wavefunction.[7] However, we should think of −1 as a complex number itself: the phase factor may be +π or, alternatively, −π: when going from +1 to −1 (or vice versa), it matters how you get there—as illustrated below.[8]

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[4] The Compton *radius* is equal to the reduced Compton wavelength: $a_C = \lambda_C/2\pi$.

[5] See: http://pleclair.ua.edu/PH253/Notes/compton.pdf, p. 10.

[6] You know that, in the context of probability *amplitudes*, one needs to *normalize* coefficients because the sum of all probabilities – as per our mathematical or statistical *convention* – has to add up to 1. However, the reader may already appreciate that we will want to talk about normalization based on physical realities—as opposed to unexplained quantum-mechanical *rules*.

[7] Mainstream physicists therefore think one can just multiply a set of amplitudes – let us say *two* amplitudes, to focus our mind (think of a beam splitter or alternative paths here) – with −1 and get the same *physical states*.

[8] The quantum-mechanical argument is technical, and so I am not going to reproduce it here. I do encourage the reader to glance through it, though. See: *Euler's Wavefunction: The Double Life of − 1*. Note that the $e^{+i\pi} \neq e^{-i\pi}$ expression may look like *horror* to a mathematician! However, if he or she has a bit of a sense for geometry and the difference between identity and equivalence relations, there should be no surprise. If you are an amateur physicist, you should be excited: it is, effectively, the secret key to unlocking the so-called mystery of quantum

Spin and direction of travel	Spin up (J = +ℏ/2)	Spin down (J = −ℏ/2)
Positive *x*-direction	ψ = exp[i(kx−ωt)]	ψ* = exp[−i(kx−ωt)] = exp[i(ωt−kx)]
Negative *x*-direction	χ = exp[−i(kx+ωt)] = exp[i(ωt−kx)]	χ* = exp[i(kx+ωt)]

<div align="center">Table 1: Occam's Razor: mathematical possibilities versus physical realities</div>

2. We were talking about fast-running clocks. The cycle time of the electron can be easily calculated as being equal to:

$$T_e = \frac{h}{E_e} = \frac{h}{m_e c^2} \approx \frac{4.135 \times 10^{-15} \, \text{eV} \cdot \text{s}}{511 \times 10^6 \, \text{eV}} \approx 8.1 \times 10^{-21} \, \text{s}$$

So that is, effectively, a time interval which is too small to measure, which – at the occasion of his Nobel Prize lecture – made Dirac state the following about this magneton, ring current or *Zitterbewegung* model[9] of an electron:

> "It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency oscillatory motion of small amplitude superposed on the regular motion which appears to us. As a result of this oscillatory motion, the velocity of the electron at any time equals the velocity of light. *This is a prediction which cannot be directly verified by experiment, since the frequency of the oscillatory motion is so high, and its amplitude is so small.* But one must believe in this consequence of the theory, since other consequences of the theory which are inseparably bound up with this one, such as the law of scattering of light by an electron, are confirmed by experiment." (Paul A.M. Dirac, *Theory of Electrons and Positrons*, Nobel Lecture, December 12, 1933)

Dirac confuses the idea of the electron and the oscillating charge inside here: the pointlike charge is a charge only: it has no other properties. It has no rest mass, for example, and it must, therefore, effectively move at the speed of light (Newton's law tells us the slightest force on it will give it infinite acceleration). However, in an atomic or molecular orbital, the electron – as a whole – will *not* move at lightspeed: it cannot because of the mass it acquires from the *internal* motion of the charge. However, the elementary wavefunction can also be used to model the *circular* Bohr orbitals, i.e. the electron trajectories in an atom. Of course, now you will shout that actual electron orbitals have a very different shape: think of the nice visual representations of electron shells, based on the probabilities we get out of the solutions to Schrödinger's equation. And you are right: we should not limit ourselves to circular orbitals, and that is exactly why the Bohr-Rutherford model of an atom had to be replaced by Schrödinger's model, which is based on a wave equation whose solutions correspond more closely to

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mechanics. Remember Aquinas' warning: *quia parvus error in principio magnus est in fine*. A small error in the beginning can lead to great errors in the conclusions, and we think of this as a rather serious error in the beginning!

[9] The *ring current* or *magneton* model of an electron was first advanced by the British chemist and physicist Alfred Lauck Parson (1915) to explain the magnetic properties of the electron, which had just been discovered. We may refer directly to Ernest Rutherford's remarks on Parson's '*électron annulaire*' (ring electron) and the magnetic properties of the electron in his lecture on '*The Structure of the Electron*' at the 1921 Solvay Conference. The term '*Zitterbewegung*' was coined by Erwin Schrödinger, who found such theoretical local oscillatory motion as a rather trivial solution to Dirac's wave equation for an electron. Of course, we are just writing this so you feel we are in rather good company.

the actual energy levels and the actual shapes of electron orbitals.

However, you should carefully read what we write here: *more closely*. Schrödinger's equation is not perfect, either! It effectively excludes spin and, therefore, we only get the *gross* structure of the electron configurations: the *fine* structure – let alone the hyperfine structure (which arises from the coupling of the spin of the nuclear protons with electron spins) – does *not* emerge from Schrödinger's model. Hence, Schrödinger's wave equation may be more sophisticated than the quantum-mechanical Bohr-Rutherford model but it is *not* essentially different. Let us quickly run through it to get an idea of the velocities and frequencies involved.

The Bohr model has a positively charged nucleus at its center and its electron has an effective rest mass: the radial velocity $v = a \cdot \omega$ of the electron is, therefore, some *fraction* of the speed of light ($v = \alpha \cdot c$). It also has some non-zero momentum $p = m \cdot v$ which we can relate to the electrostatic centripetal force using the simple classical formula $F = p \cdot \omega = mv^2/a$.
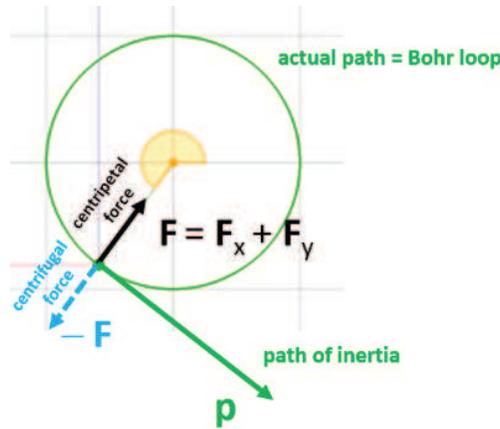

Figure 3: The position, force, and momentum vector in a Bohr loop

We must now apply the quantum-mechanical that angular momentum comes in units of $\hbar = h/2\pi$ or, what amounts to the same, that physical action comes in unit of h. So each cycle – each *rotation* – will pack some energy over some time (the cycle time) or – what amounts to the same – some momentum over some distance (the circumference of the loop). We write:

$$S = h = E \cdot T = p \cdot \lambda = p \cdot 2\pi \cdot r_B$$

Using the $v = \alpha \cdot c$ and $r_C = \alpha \cdot r_B$ relations[10] one can easily verify this for the momentum formulation:

$$S = p \cdot 2\pi \cdot r_B = mv \cdot 2\pi \cdot (r_C/\alpha) = m\alpha c \cdot \frac{2\pi\hbar}{\alpha mc} = h$$

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[10] These relations come out of the model. They are, therefore, not some new hypothesis. The α in the formula is the fine-structure constant. It pops up in (almost) all of the equations we get. As such, it does appear as some magical dimensionless number that relates almost all (physical) dimensions of the electron (radii, circumferences, energies, momenta, etcetera).

To show we are not doing anything outrageously crazy here, we can also calculate S by calculating the force, and then we can multiply the force with the distance and the time. The force is just the (centripetal) electrostatic force between the charge and the nucleus:

$$F = \frac{q_e{}^2}{4\pi\varepsilon_0 r_B{}^2} = \alpha \cdot \frac{\hbar c}{r_B{}^2}$$

We can then recalculate S as:

$$S = F \cdot r_B \cdot T = \alpha \cdot \frac{\hbar c}{r_B{}^2} \cdot r_B \cdot \frac{2\pi r_B}{v} = \alpha \cdot \frac{hc}{\alpha c} = h$$

All is consistent. Of course, you *really* want to be sure, and so we should also calculate the energy. If we do so, we get what we expect to get: the ionization energy of hydrogen.

$$S = h = E \cdot T = E \cdot \frac{2\pi r_B}{v} = E \cdot \frac{\frac{h}{\alpha m c}}{\alpha c} \Leftrightarrow E = \alpha^2 m c^2$$

To be precise, this is *twice* the ionization energy of hydrogen ($E_R = \alpha^2mc^2/2^{11}$), and it is also *twice* the (non-relativistic) kinetic energy ($\hbar^2/2ma^2 = \alpha^2mc^2/2$). If you read any of my papers, then you might think this is because we are modeling orbitals for *two* electrons: we effectively believe the solutions that come out of Schrödinger's equation are solutions for an electron *pair* because – as mentioned above – Schrödinger's equation does *not* incorporate spin.[12] However, the explanation is much more subtle, and also tells us why Euler's function – the wavefunction – models oscillations in two dimensions so perfectly: any circular oscillation can effectively be analyzed as the sum of two linear oscillations. That is why we write the force as **F** = **F**$_x$ + **F**$_y$ (both in **Figure 1** as well as in **Figure 3**). The point is this: when calculating the energy of the system, we are adding not only the kinetic but also the *potential* energy in the two oscillators.

We were talking velocities and cycles times. Unsurprisingly, α^2mc^2 is a *very* tiny fraction of the rest energy of the electron: $\alpha^2 \approx 0.00005325$. It is easy to generalize the result we just obtained to all electron orbitals. Doing so yields the well-known formula for the energy *difference* between the various orbitals, which corresponds to the energy of the photon that is emitted or absorbed when an electron goes from one orbital (n_1) to another (n_2):

$$\Delta E = \left(\frac{1}{n_1{}^2} - \frac{1}{n_2{}^2}\right) \cdot E_R$$

Let us now generalize our formulas for all of the Bohr orbitals:

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[11] The reader can (and, therefore, *should*) check the conversion of the Rydberg energy in terms of the fine-structure constant and the rest mass (or rest energy) of the electron:

$$E_R = \frac{\alpha^2 m c^2}{2} = \frac{1}{2}\left(\frac{q_e{}^2}{2\varepsilon_0 hc}\right)^2 mc^2 = \frac{q_e{}^4 m}{8\varepsilon_0{}^2 h^2} \approx 13.6 \text{ eV}$$

[12] Because of this, we do think Schrödinger's equation is relativistically correct: the 1/2 factor in the equation is *not* related to non-relativistic kinetic energy or the rather confusing concept of the effective mass of an electron.

Table 2: Generalized formulas for the Bohr orbitals

Orbital electron (Bohr orbitals)
$S_n = nh$ for $n = 1, 2, \ldots$
$E_n = -\dfrac{1}{2}\dfrac{\alpha^2}{n^2}mc^2 = -\dfrac{1}{n^2}E_R$
$r_n = n^2 r_B = \dfrac{n^2 r_C}{\alpha} = \dfrac{n^2}{\alpha}\dfrac{\hbar}{mc}$
$v_n = \dfrac{1}{n}\alpha c$
$\omega_n = \dfrac{v_n}{r_n} = \dfrac{\alpha^2}{n^3\hbar}mc^2 = \dfrac{\frac{1}{n^2}\alpha^2 mc^2}{n\hbar}$
$L_n = I \cdot \omega_n = n\hbar$
$\mu_n = I \cdot \pi r_n{}^2 = \dfrac{q_e}{2m}n\hbar$
$g_n = \dfrac{2m}{q_e}\dfrac{\mu}{L} = 1$

The reader can easily verify these formulas – by googling them, doing the calculations himself or, preferably, just doing some simple substitutions in the formulas we already gave you. Let us calculate the angular momentum, for example:

$$L_n = I \cdot \omega_n = m \cdot r_n{}^2 \cdot \frac{\alpha^2}{n^3\hbar}mc^2 = m \cdot \frac{n^4}{\alpha^2}\frac{\hbar^2}{m^2c^2} \cdot \frac{\alpha^2}{n^3\hbar}mc^2 = n\hbar$$

So what do these formulas actually *mean*? The table below shows what happens with radii, velocities, frequencies, and cycle times as we move out. The velocities go down, all the way to zero for n → ∞, and the corresponding cycle times increases as the *cube* of *n*. Using totally non-scientific language, we might say that, as the electron moves out, it loses interest in the nucleus so as to get ready to just wander about as a free electron. 😊

Table 3: Functional behavior of radius, velocity, and frequency of the Bohr orbitals

n	1	2	3	4	5	6	7	8	9
$r_n \propto n^2$	1	4	9	16	25	36	49	64	81
$v_n \propto 1/n$	1	0.500	0.333	0.250	0.200	0.167	0.143	0.125	0.111
$\omega_n \propto 1/n^3$	1	0.125	0.037	0.016	0.008	0.005	0.003	0.002	0.001
$T_n \propto n^3$	1	8	27	64	125	216	343	512	729

The important thing is the energy formula, because it should explain the Rydberg formula – and it does:

$$E_{n_2} - E_{n_1} = -\frac{1}{n_2{}^2}E_R + \frac{1}{n_1{}^2}E_R = \left(\frac{1}{n_1{}^2} - \frac{1}{n_2{}^2}\right)\cdot E_R = \left(\frac{1}{n_1{}^2} - \frac{1}{n_2{}^2}\right)\cdot\frac{\alpha^2 mc^2}{2}$$

We could continue the calculations but that is not the point here. No. It is a survival guide, so it should be short. The point is this: you should *not* think you are solving some God-given equation when doing the arithmetic. No! Schrödinger's wave equation came out of Schrödinger's mind, and it models the motion of the elementary charge in an electromagnetic field. It is just a bit difficult to immediately see this because we are used to calculate forces from the electric and magnetic fields **E** and **B** but, in quantum mechanics, we need to switch our thinking in terms of electric and magnetic fields to thinking in terms of scalar and vector potential. So let us quickly run through so as to make you feel more comfortable next time you see all of those equations.

Schrödinger's equation as *the* wave equation

Because we must assume you are familiar with the basics of electromagnetic theory, we will be *very* brief. The **E** and **B** vectors have three components each: E_x, E_y, E_z and B_x, B_y, B_z respectively, each of which is a function – obviously – of **x** = (x, y, z) and t, in our reference frame, obviously (there is no need to switch to some other reference frame right now). **E** and **B** appear in Maxwell's equations, and so we could keep analyzing things in terms of **E** and **B** but we can and, therefore, *should* simplify the math so we can do stuff using relativistically correct four-vector notation. You should note we can only do this because **E** and **B** behave pretty regularly mathematically and we can, therefore, apply a few theorems (Gauss and Stokes) and conventions[13] and effectively rewrite Maxwell's equations in terms of the *scalar* potential Φ and the *vector* potential **A** = (A_x, A_y, A_z). So we have four variables depending on **x** and t now instead of six. Now, Φ and **A** can be combined using four-vector notation – A_μ = (Φ, **A**) = (Φ, A_x, A_y, A_z) – and then all of the physics in Maxwell's equations can be written in one single equation:

$$\Box^2 A_\mu = \frac{j_\mu}{\epsilon_\mu}$$

As Feynman notes, the beauty of this equation is that it shows the invariance of electrodynamics under a Lorentz transformation, because four-vector dot products are invariant: they have the same value in every reference frame.[14] To put it simply: **this equation represents the *reality* of electromagnetic fields, regardless of how we *measure* them.**

Now, four variables are not always easier to work with than six, but quantum physicists prefer the four, so it is the scalar and vector potentials Φ and **A** that are used in, say, Schrödinger's equation for a

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[13] You will probably have heard about *gauge* theories – the need to *choose* a gauge when developing your field theory. In this particularly simple context, it amounts to the following. The whole derivation starts by writing **B** as the curl of some other vector field: **B** = ∇×**A**. Now, any **A**' = **A** + ∇ψ (where ψ is any scalar field) will do, so we need to make some *choice*. This combines with some other choice we need to make when rewriting **E** in terms of a Φ (scalar potential) and an **A** (vector potential). We refer to Feynman's from [Feynman's *Lectures*](), II-18-6 for the full development, but the point is this: we will choose a *gauge* for electromagnetics by choosing ∇·**A** to be equal to ∇ · **A** = $-\frac{1}{c^2}\frac{\partial \phi}{\partial t}$. It is referred to as the Lorenz gauge – without t in the name because the man who thought of this is not H.A. Lorentz from the Netherlands, but the Danish physicist [Ludvig Lorenz](). I am grateful to a reader who pointed this out to me because the t is usually there – in the original 1963 print edition of the *Lectures*, for example!

[14] The reasoning should be somewhat more subtle here – the dot product is *not* very obvious here! – but the reader should be able to easily fill the gap in the explanation.

particle with charge q moving in some electromagnetic field. Now that we are here, we may as well write it down[15]:

$$-\frac{\hbar}{i}\frac{\partial\psi}{\partial t} = \text{H}\psi = \frac{1}{2m}\left(\frac{\hbar}{i}\boldsymbol{\nabla} - q\boldsymbol{A}\right)\cdot\left(\frac{\hbar}{i}\boldsymbol{\nabla} - q\boldsymbol{A}\right)\psi + q\boldsymbol{A}\psi$$

$$\Leftrightarrow i\hbar\frac{\partial\psi}{\partial t} = -\frac{1}{2m}(i\hbar\boldsymbol{\nabla} + q\boldsymbol{A})^2\psi + q\boldsymbol{A}\psi$$

$$\Leftrightarrow \text{H} = i\hbar\frac{\partial}{\partial t} = -\frac{1}{2m}(i\hbar\boldsymbol{\nabla} + q\boldsymbol{A})^2 + q\boldsymbol{A}$$

Again, physicists – Feynman included – will tell you this equation is non-relativistic (and, yes, that it excludes the idea of spin), but that is only because the 1/2 factor comes out of some weird interpretation of the *effective* mass of an electron[16], which has nothing to do with it. As for the issues in regard to spin, the solutions to Schrödinger's equation for electron orbitals are actually solutions for orbitals with *two* electrons, so that is what explains it: Schrödinger's equation for an atom – with the electrostatic potential and the 1/2 factor works perfectly fine because it models electron orbitals for two electrons. Those two electrons have opposite spin, and the mechanism that makes superconducting electrons (Cooper pairs) or electron pairs in atomic/molecular orbitals move in pairs is exactly the same: by aligning spin, they can lower the energy of the *ensemble*. The Pauli exclusion principle might and should, therefore, probably be rephrased in terms in terms of the pairing mechanism of elementary particles with opposite spin.[17]

So, again, Schrödinger's equation is what Dirac was looking for: the equations of motion for charged particles! So the solutions to Schrödinger's equation (not Dirac's[18]) gives us electron orbits – for paired-up electrons with opposite spin. Schrödinger's equation works when modeling a hydrogen atom (atomic orbitals), and it also works in the context of perpetual currents in superconductors. In fact, it should work generally but, yes, academics could usefully spend more time on this to show it does! We made a start with that[19], but we readily admit we are still operating more on the basis of intuition – it cannot be anything else, can it? – than on the basis of firm mathematical proof. But, yes, equations of motion of charged particles in static and/or dynamic electromagnetic fields. No mystery. No hocus-pocus. In fact, lest you forget, Feynman concludes as much himself at the very end of his *Lecture* on superconductivity:

> "Schrödinger's equation for the electron pairs in a superconductor gives us the equations of motion of an electrically charged ideal fluid. Superconductivity is the same as the problem of the hydrodynamics of a charged liquid. If you want to solve any problem about superconductors you

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[15] See: Feynman's Lectures, III-21-1. The transformation (1/*i* equals −*i*, and we also separate the operators from the wavefunction ψ) and the writing of it as an equality of operators is ours. Please do check for any mistake that may or may not have been made in the formulas.

[16] See my paper on matter-waves, signals, and amplitudes.

[17] As for wavefunction (and, therefore, wave equations) not incorporating the concept of spin, see: Euler's Wavefunction and the Double Life of −1.

[18] Dirac's equation for free electron does not work, as he admits himself: it gives us 'run-away electrons' (Dirac's terms for the dissipating wave packets). We elaborate on the why and how here in our paper on de Broglie's matter-wave: concept and issues.

[19] See: A geometric interpretation of Schrödinger's wave equation.

take these equations for the fluid [or the equivalent pair, Eqs. (21.32) and (21.33)], and combine them with Maxwell's equations to get the fields."

So, end of story. Next topic. 😊

OK. Maybe not. [...] Before I move on, one more remark on the current topic: wavefunctions as equations of motion. You may wonder: why can I be so sure these wavefunctions represent the position of an electron? It is because of the operators. We can apply operators so as to get averages and probabilities on position, energy, angular momentum, and whatever other classical variable (the 'observables', as physicists refer to these variables). Hence, the information on the position must be there – because that is how you calculate all the rest.[20]

The strong force and quantum field theory

So you can consider the QED sector (quantum electrodynamics) to be solved. But what about the QCD sector? Here you are basically on your own, but it might help to know there are not definite answers here, and that everyone is struggling with it: the 'mysteries' in the QED sector are, effectively, all pretty clear and obvious now[21], but the QCD sector is and remains the realm of dreamers, gurus, geniuses and fools – disguised as academics or not. Dirac wrote this about the nascent theories modeling what may or may not be going on inside of the nucleus[22]:

> "Quantum mechanics may be defined as the application of equations of motion to particles. [...] The domain of applicability of the theory is mainly the treatment of electrons and other charged particles interacting with the electromagnetic field – a domain which includes most of low energy physics and chemistry. Now there are other kinds of interactions, which are revealed in high-energy physics and are important for the description of atomic nuclei. These interactions are not at present sufficiently well understood to be incorporated into a system of equations of motion. Theories of them have been set up and much developed and useful results obtained from them. But in the absence of equations of motion these theories cannot be presented as a logical development of the principles set up in this book. We are effectively in the pre-Bohr era with regard to these other interactions. It is to be hoped that with increasing knowledge a way will eventually be found for adapting the high-energy theories into a scheme based on equations of motion, and so unifying them with those of low-energy physics." (Paul A.M. Dirac, The Principles of Quantum Mechanics, 4th edition (1958), p. 312)

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[20] We warmly recommend Feynman's discussion of operators (Vol. III, Chapter 20) because it sticks pretty close to this interpretation too. It is, therefore, much better than, say, the online MIT/edX course on quantum physics.
[21] We refer to our papers on the anomalous magnetic moment, or Mach-Zehnder self-interference of a photon, or on the Lamb shift, etcetera: do not believe academics who say you need quantum field theory for that!
[22] Of course, Dirac wrote this back in 1958 – but he maintained this point of view till his death (1984). The Wikipedia article on Dirac usefully quotes from his last paper, aptly titled *The Inadequacies of Quantum Field Theory* (1984): "These rules of renormalization [in quantum field theories] give surprisingly, excessively good agreement with experiments. Most physicists say that these working rules are, therefore, correct. I feel that is not an adequate reason. Just because the results happen to be in agreement with observation does not prove that one's theory is correct." The paper ends with the words: "I have spent many years searching for a Hamiltonian to bring into the theory and have not yet found it. I shall continue to work on it as long as I can and other people, I hope, will follow along such lines." Personally, I hope so too (note that we presented the final Hamiltonian for the QED sector in this paper, at least!) but, unfortunately, that is everything but the focus of mainstream physicists.

We effectively do not think very highly of the invention of the concept of strangeness by Murray Gell-Man and Kazuhiko Nishijima in the 1950s. Indeed, Feynman's treatment of it in his 1963 Lectures on Physics shows that the concept of strangeness – and the related conservation law – is a rather desperate assumption to explain the decay of K-mesons (kaons) which – in our not-so-humble opinion – should probably not be explained in terms of a weak force but in terms of non-equilibrium states. Unfortunately, the concept of strangeness – and this weird idea of virtual particles mediating forces[23] – started a strange life of its own and would effectively later serve as the basis for the quark hypothesis which – for a reason we find even stranger than the concept of strangeness itself – was officially elevated to the status of a scientific dogma by the Nobel Prize Committee for Physics. Of course, the question is: is there an alternative?

We are not sure, but we think there must be. Why? You may or may not know that there is currently no real theory as to why the precisely measured charge radius of a proton is what it is: 0.8414 ± 0.0019 fm, more or less.[24] 😊 So mainstream physicists have no idea.[25] It should not surprise us, of course – because they still analyze elementary particles as point particles – denying what is obvious to amateurs: elementary particles have internal structure, and the idea of circulating or moving charge – as Dirac tried to do all of his life – should not be abandoned. So let us see where we get with our ring current model.

When applying the $a = \hbar/mc$ radius formula to a proton, we get a value which is 1/4 of the *measured* proton radius: about 0.21 fm, as opposed to the 0.83-0.84 fm charge radius which was established by

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[23] Of course, the Planck-Einstein relation also implies fields must be quantized, and they are. We *know* for sure because of the since 1961 (the experiments by Deaver and Fairbank in the US and, independently, by Doll and Nabauer in Germany[23]), we know this field is quantized. To be precise, the product of the charge (q) and the magnetic flux (Φ), which is the product of the magnetic field B and the area of the loop S, will always be an integer (n) times h: q·Φ = q·B·S = n·h. However, this quantization does *not* imply that we should assume that the magnetic field itself must, somehow, consist of (discrete) *field quanta*. Not at all, really. The magnetic field is just what it is: a finite quantized magnetic field. There is absolutely no need whatsoever to think of virtual particles or other nonsense here. Now that we are throwing a formula in, we may as well quickly show why and how the Planck-Einstein relation applies to superconductors and perpetual currents (it is something we did *not* see elsewhere – otherwise we would not mention it). Because electrons form Cooper pairs in superconductors, q in the equation above is *twice* the electron charge, the equation above tells us that the basic flux unit is equal to $h/2q_e$. Now we have a circular current here, and this current loop will have a magnetic moment (μ) equal to the product of the current and the surface area of the loop: μ = I·π·a^2 = I·S. Now, the current in such loop is equal to the charge times the frequency of the orbit (I = q·f), so we can re-write the magnetic moment as μ = q·f·S. Now, we also know the (potential) magnetic *energy* is calculated as the product of the magnetic moment and the magnetic field: U_{mag} = μ·B. We can, therefore, show that the Planck-Einstein relation is valid here again. Indeed, the (magnetic) energy is an integer multiple of Planck's constant times the frequency of the current:

$$E = U_{mag} = \mu \cdot B = q \cdot f \cdot S \cdot \frac{n \cdot h}{q \cdot S} = n \cdot h \cdot f$$

[24] This is the 2018 CODATA value for the proton radius, which takes all past measurements into account but gives very high weightage to the measurements of Pohl (2010) and Antognini (2013). The recent (2019) precision measurement by the PRad team at Jefferson Lab basically confirms this value.

[25] I actually wrote both Prof. Dr. Pohl as well as Prof. Dr. Gasparian (spokesman and principal researcher for the PRad team), and both confirmed theorists have no clue really. As for my calculation, both thought it was interesting, but with Prof. Dr. Pohl adding it did look like 'numerology' – so I am waiting for him to come up with something better than 'numerology'. As for Prof. Dr. Gasparian, he wrote lattice theory might come up with something but also admitted that it might take a while. For a discussion, see one of our papers on the proton radius.

Professors Pohl, Gasparan and others over the past decade.[26] We get this radius from using a modified Planck-Einstein relation (E = 4*hf* = 4$\hbar$ω) for the orbital frequency of the charge:

$$a = c/\omega = c\,\frac{4\hbar}{E} = \frac{4\hbar c}{mc^2} = \frac{4\hbar}{mc} \approx 0.84 \text{ fm}$$

Writing the Planck-Einstein relation using an integer multiple of *h* or $\hbar$ (E = *n·h·f* = *n·$\hbar$·*ω) is not uncommon. You should have encountered this relation when studying the black-body problem, for example, and it is also commonly used in the context of Bohr orbitals of electrons. But why is *n* equal to 4 here? Why not 2, or 3, or 5 or some other integer? We do not know: all we know is that the proton is very different. A proton is, effectively, *not* the antimatter counterpart of an electron—a positron. It is much smaller (smaller than the radius we calculated for the *Zitterbewegung* charge) and – somewhat counterintuitive, perhaps[27] – its mass is about 1,836 times that of the electron. Why is that so? Why is a proton even smaller than the α·a_e radius of the pointlike *Zitterbewegung* charge (which is nothing but the classical electron radius)? We do not know, but we may offer some reflections which you may or may not find useful.

One set of reflections effectively revolves around the idea of some strong(er) force inside of a proton – some force inside electrons and protons, whose nature may *not* be electromagnetic. However, I am not thinking of quarks and gluons here (I think one gets lost in all kinds of metaphysics here, which I instinctively dislike, just as Dirac did), and so I think we should probably further try to analyze this very different *form factor*: we have a formula for the radius of a proton which suggests its angular momentum is *four* times that of an electron. Its moment of inertia must, therefore, be quite different and so, yes, a much stronger force. Any case – this is the realm of pure speculation and so I should refer you to my more speculative papers here.[28]

To wrap up our introduction, we should say a few words about uncertainty. Uncertainty is *real*, isn't it? Yes. Uncertainty is there. So let us look at it.

Quantum-mechanical uncertainty

Let us be specific and, therefore, talk about something specific. The idea of a particle includes the idea of a more or less well-known position, right? But so we know there is uncertainty, so how should we think of that? We may not fully know the position of a particle for one or more of the following reasons:

1. The precision of our measurements may be limited: this is what Heisenberg initially thought it was, and he referred to it as an *Ungenauigkeit*.
2. Our measurement might disturb the position and, as such, cause the information to get lost and, as a result, introduce an uncertainty: this is what we might refer to as an *Unbestimmtheit* (we need some other term because it is a different *type* of uncertainty).
3. The uncertainty may be inherent to Nature, in which case we might prefer the term

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[26] For the exact references and contextual information on the (now solved) 'proton radius puzzle', see our paper on it: https://vixra.org/abs/2002.0160.
[27] The *a* = $\hbar$/mc = $\hbar$c/E formula tells us the *Zitterbewegung* or *Compton* radius is *inversely* proportional to the energy (or the equivalent mass) of the elementary particle. This relation is, obviously, *not* as intuitive as the easy *a* = *c*/ω or ω = *c*/*a* relations.
[28] My Principles of Physics paper offers some thoughts and references to other crazy papers.

Ungewissheit.

So what *is* the case, then? In his interventions at the (in)famous Solvay Conference of 1927 (and even before[29]), Hendrik Antoon Lorentz claimed it is either the first or the second – or a combination of both – and that the third proposition is a philosophical statement which we can neither prove nor disprove. I cannot see anything logical (in the theories) or practical (in the experiments) that would invalidate this point. I, therefore, intend to write a basic book on quantum physics from what I hope would be Lorentz' or Einstein's point of view. So that book should have a chapter on uncertainty, right? Yes. So let me give you a preview of that by summarizing how I think of uncertainty.

From what we wrote above, it is pretty obvious we think of spin as angular momentum: spin angular moment and/or orbital angular momentum. It is something real: the angular momentum of a charge that rotates around its own axis (spin) or around some other axis (orbital momentum). Hence, spin is a *real* vector. An *axial* vector, yes, but axial vectors are as real as polar vectors.[30] Now, that makes us think the Planck-Einstein relation should be written as a vector equation – as opposed to the usual scalar equation you have seen so many times now. And we should go all the way when we do this, so we get this *vector* dot product[31]:

$$E = \hbar \cdot \boldsymbol{\omega}$$

This brings us, in turn, to the relation between the Planck-Einstein relation (E = $h \cdot f$ = $\hbar \cdot \omega$) and the *de Broglie* relation (λ = h/p $\Leftrightarrow$ h = p·λ). We can, effectively, write Planck's quantum of action as the product of some energy and a cycle time (E = $h \cdot f$ $\Leftrightarrow$ h = E/f = E·T) but we can also write it as the product of some momentum (p) and some *length*—linear or circular, perhaps: think of the wavelength of light, or the circumference of the orbital motion of the pointlike charge. If we denote such length by λ and, keeping in mind that (linear) momentum is a vector too, we can write the *de Broglie* relation as a vector relation[32]:

$$\mathbf{p} = \frac{\boldsymbol{h}}{\lambda}$$

The point is this: we are actually thinking of the reduced Planck constant ($\hbar$ = $\boldsymbol{h}$/2π) as a proper angular momentum, which can and should be written as $\hbar$ = $I \cdot \boldsymbol{\omega}$: the product of an *angular mass* (the rotational inertia I) and an orbital angular frequency ($\boldsymbol{\omega}$). This, then, also gives meaning to the concept of *spin* (which is either up or down).

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[29] Unfortunately, he died shortly after the 1927 Solvay Conference so he could not contribute much after that.
[30] The reader should be familiar with the concepts of axial and polar vectors. Polar vectors (think of a position or radius vector, for example) are sometimes referred to as real vectors, while axial vectors (think of angular momentum or the magnetic moment) are often referred to as pseudovectors, but they are equally *real* in a physical sense, of course! Their mathematical behavior is different, however. That is because they can be written as the cross-product of two other vectors. Real vectors reverse sign when a coordinate axis is reversed. Pseudovectors do *not*. We will let the reader *google* the nitty-gritty here. The definition crucially matters because it is used in *core* quantum-mechanical arguments. We may refer, for example, to Feynman's chapter on symmetries and conservation laws.
[31] The boldface notation is subtle but powerful!
[32] The symbol is obvious in the context of a linear wavelength but much less so when denoting a circumference—which we want you to think of as a *circular* wavelength!

Now this is the crux of the matter: you should note **there is no uncertainty in all of these concepts except for the uncertainty in regard to the *plane* of oscillation** (which is given by the *direction* of $\hbar$ and ω) *in the absence of an external electromagnetic field*. Indeed, the oscillatory motion of the charge generates a classical magnetic moment which – equally classically – will precess in an external electromagnetic field. Hence, it is only in the *absence* of an electromagnetic field that we cannot know what the plane of oscillation will be. This is quite consistent from an epistemological point of view: how would we define up or down, left or right, back and front – space itself, actually – in the absence of an electromagnetic field?

Is that it? Yes. For the time being. We may add to it in the next version of this paper.

Jean Louis Van Belle, 20 October 2020