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Unifying Special Relativity and Quantum Mechanics via Adynamical Global Constraints

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Abstract. Maxwell unified the disparate concepts of electric and magnetic fields with one theory (electromagnetism) and Einstein then unified the disparate theories of electromagnetism and mechanics with one kinematics (Minkowski space of special relativity). In this talk, we will briefly explain how the disparate kinematics of quantum mechanics (finite-dimensional Hilbert space) and special relativity can be unified with one principle (relativity principle). This result follows from the axiomatic reconstruction of quantum mechanics via information-theoretic principles, which has successfully recast quantum mechanics as a principle theory a la Einstein, i.e., the formalism of the theory follows from an empirically discovered fact, just like special relativity. According to the quantum reconstruction program, the empirically discovered fact whence the Hilbert space formalism of quantum mechanics is Information Invariance & Continuity. Of course, the empirically discovered fact whence the Lorentz transformations of special relativity is the light postulate, i.e., everyone measures the same value for the speed of light c, regardless of their relative motions. Obviously, the light postulate can be justified by the relativity principle—the laws of physics are the same in all inertial reference frames—because c is a constant of Nature per Maxwell's electromagnetism. [We label this "NPRF + c" for short, where NPRF stands for "no preferred reference frame."] As we will show, Information Invariance & Continuity can also be justified by the relativity principle by first spatializing the quantum reconstruction program's operational notion of measurement. In that case, Information Invariance & Continuity entails the empirically discovered fact that everyone measures the same value for Planck's constant h, regardless of their relative spatial orientations or locations (Planck postulate). Since Poincaré transformations relate inertial reference frames via spatial rotations and translations as well as boosts, and h is a constant of Nature per Planck's radiation law, the relativity principle justifies the Planck postulate (NPRF + h) just like it justifies the light postulate (NPRF + c). Thus, the kinematics of quantum mechanics and special relativity are unified in that both follow most fundamentally from the relativity principle in the adynamical global constraints NPRF + h and NPRF + c. This approach provides a principle solution to the mystery of quantum entanglement that does not violate locality, statistical independence, intersubjective agreement, or the uniqueness of experimental outcomes and it does not alter quantum mechanics as a principle theory. An ontology consistent with this unification is introduced and we deflate both the 'big' and 'small' measurement problems.

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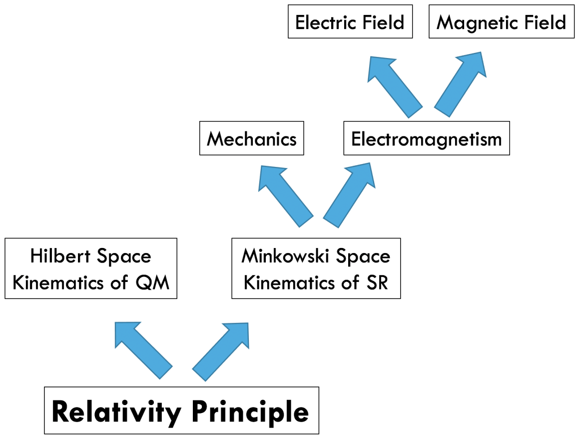

Figure 1: **Increased Unification**.

1 Introduction

It is widely believed that the violation of Bell inequalities in spacelike separated quantum measurement events creates tension or outright conflict between special relativity (SR) and quantum mechanics (QM) [Bell, 1986, Popescu and Rohrlich, 1994, Albert and Galchen, 2009, Maudlin, 2011, Mamone-Capria, 2018]. However, since the Bell state distribution of quantum events in spacetime is independent of the spatial separation and temporal order of the two measurement events in each trial of the experiment, the joint probabilities (and hence the correlations) are invariant under Lorentz boosts. Additionally, Schrödinger's equation (dynamics) of QM, which gives the time evolution of the state vector in a fixed-dimensional Hilbert space, is simply the low-energy approximation of the Lorentz-invariant Klein-Gordon equation [Zee, 2003, p. 172]. Thus, unless one invokes an additional (hidden) causal mechanism beyond the formalism of QM in an attempt to account for Bell-inequality-violating correlations via causal mechanisms and/or dynamical processes (constructively), there is no reason to suspect a conflict with SR.

Indeed, not only is there no necessary conflict between QM and SR, but as we will show in this talk, their kinematics can actually be unified. What we mean by *unification* here is simply "to relate two or more disparate concepts or structures." For example, Maxwell unified the electric and magnetic fields by showing how the electric field can create the magnetic field and vice-versa. Then, Einstein unified Maxwell's electromagnetism and mechanics by showing how both share the same Minkowski space (M4) kinematics of SR. This resolved the true conflict between Lorentz-invariant Maxwell's equations and Galilean-invariant Newtonian mechanics kinematically, since the Galilean-invariant spacetime of Newtonian mechanics follows from M4 in the limit $\frac{v}{c} \ll 1$.

In that spirit, we bring QM into the fold by showing how the disparate kinematic structures of SR (M4) and QM (Hilbert space) follow from the same relativity principle—the laws of physics (including their constants of Nature) are the same in all inertial reference frames. So the historical pattern as shown in Figure 1 is: two disparate concepts (electric and magnetic fields) unified by one theory (electromagnetism) followed by two disparate theories (electromagnetism and mechanics) unified by one kinematics (M4) followed by two disparate kinematics (M4 and Hilbert space) unified by one principle (relativity principle).

This unification follows Einstein's "principle" approach to SR. That is, [Einstein, 1919] defined a *principle theory* as one whose formalism follows from an empirically discovered fact. The Lorentz transformations of SR follow from an empirically discovered fact called the light postulate, i.e., the observer-independence of the speed of light c between Lorentz frames related by boosts, so SR is a principle theory. Obviously, the light postulate can be justified by the relativity principle. We characterize the relativity principle most generally as "no preferred reference frame" (NPRF), so SR as the justification of the light postulate via the relativity principle is written NPRF + c.

Since the relativity of simultaneity with its block universe implication obtains in M4 (Section 4), NPRF + c provides what [Kastner, 2017] calls "a descriptor of static relationships among events" and leads to the paradox of length contraction. That is, when Alice and Bob are in relative motion, Alice's par-

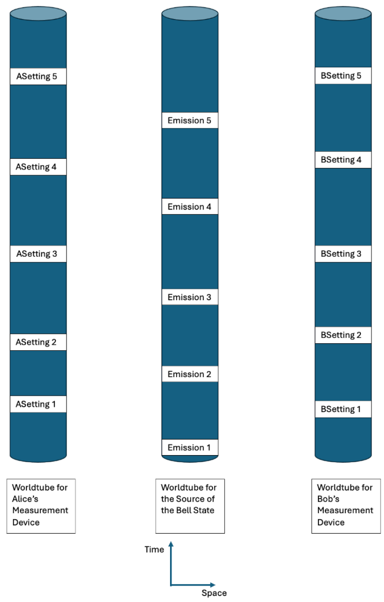

Figure 2: Alice and Bob choose their measurement settings randomly and independently for each trial/emission event of the experiment and the Bell state source is faithfully reproduced in each trial.

tition of spacetime events according to her surfaces of simultaneity shows clearly that Bob's meter sticks are short. But, Bob's partition of those same spacetime events according to his surfaces of simultaneity shows clearly that Alice's meter sticks are short. What causal mechanism is responsible for this length contraction? Whose meter sticks are really short? Physicists widely agree that there is no causal mechanism at work because length contraction is not a dynamical effect, it is a kinematic fact following from NPRF + c. As a kinematic fact, there simply is no objective fact of the matter as to whose meter sticks are short. This adynamical view of the origin of SR (NPRF + c) is so widely accepted that it has made its way into introductory physics textbooks [Serway and Jewett, 2019, Young and Freedman, 2020, Knight, 2022].

This leads us to view NPRF + c as an *adynamical global constraint* on the spacetime configuration of worldtubes for bodily objects in M4 (Figure 2). This is a version of "all-at-once" explanation [Stuckey et al., 2008, Silberstein et al., 2018, Stuckey et al., 2024], which has been used by Evans, Liu, Price, and Wharton for retrocausality [Price, 1996, Evans et al., 2010, Wharton, 2015, Wharton and Liu, 2022, Adlam, 2022], Esfeld and Gisin for Bell flash ontology [Esfeld and Gisin, 2013], Hance, Hossenfelder and Palmer for superdeterminism [Hance et al., 2022], and Adlam and Rovelli for relational quantum mechanics [Adlam and Rovelli, 2022].

As is turns out, the quantum reconstruction program (QRP) has rendered QM a principle theory based on the empirically discovered fact called Information Invariance & Continuity (Section 2). QRP has many so-called axiomatic reconstructions of QM based on information-theoretic principles, but in Section 2 we will show that Information Invariance & Continuity entails the observer-independence of Planck's constant h between reference frames related by spatial rotations and translations. Since h is a constant of Nature per Planck's radiation law and inertial reference frames are related by spatial rotations and translations, the relativity principle justifies the observer-independence of h exactly as it justifies the light postulate, giving us the unification of Figure 1.

Notice that this is not a unification of the *dynamics* of QM and SR. That was done via quantum field theory by going to high-energy phenomena where the quantum dynamics allows for transitions between Hilbert spaces of different dimensions (Fock space). Our kinematic unification provides two immediate benefits. First, our unification of QM and SR directly via their kinematics formally accounts for the apparent discrepancy between these kinematics created by QM's Bell-inequality-violating correlations (Section 4). Second, our unification of QM and SR via their kinematics provides a new understanding of the overall unity of physics (Section 5). Ultimately, our unification establishes NPRF as a ground for Einstein's methodological approach to physics articulated in his "Physics and Reality" [Einstein, 1936].

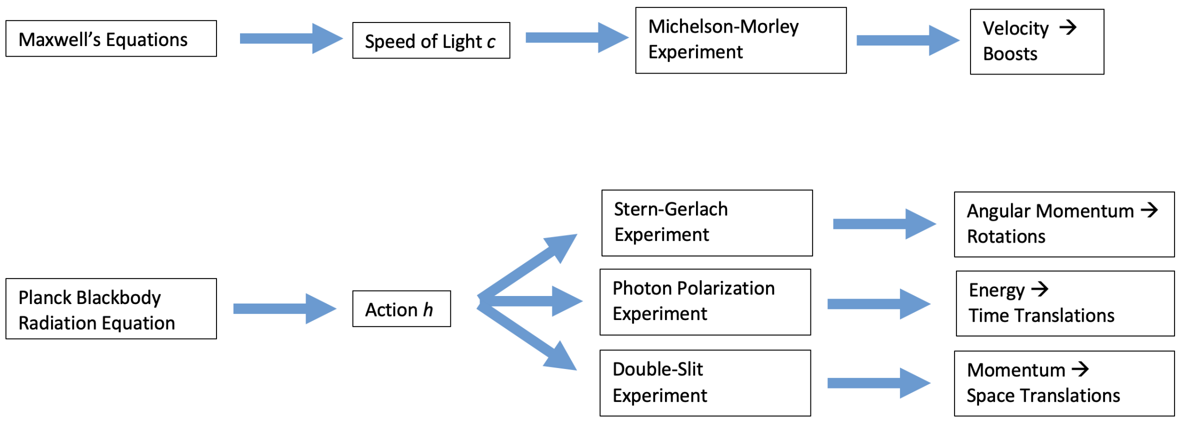

Figure 3: **Two Theories, Two Constants and Four Experiments for a Poincaré Symmetric Ontology.**

To realize the first benefit, we will show how the quantum-mechanical probabilities for the qubit (Section 2) and the joint probabilities for the Bell spin states (Section 3) follow from NPRF + h. We use spin-$\frac{1}{2}$ to illustrate how the qubit structure follows from the observer-independence of h since, as pointed out in Axiom 3 of the [Masanes and Müller, 2011] reconstruction, "All systems that effectively carry the same amount of information have equivalent state spaces." We provide two other experimental examples of the qubit structure per the observer-independence of h using the photon polarization experiment in [Stuckey et al., 2024] and the double-slit experiment in Section 5. We choose these examples because combined with the Michelson-Morley experiment they provide the empirical basis for a Poincaré symmetric ontology, which is already widely accepted in physics (Figure 3).

That is, h establishes a quantum of angular momentum in the Stern-Gerlach experiment, momentum in the double-slit experiment, and energy in the photon polarization experiment. Since angular momemtum generates spatial rotations, momentum generates spatial translations, energy generates time translations, and velocity generates boosts, the observer-independence (invariance) of h and c is associated with the Poincaré symmetry group. Prima facie h is 'quantum', since h is generally associated with the quantization that Planck discovered when he used statistical mechanics to justify the derivation of his radiation law, while c is 'classical', having come from classical electromagnetism. But in fact, both h and c are products of classical physics, since Planck actually first obtained h as necessary for his fit of Wien's law, which he derived from the classical theories of electromagnetism and thermodynamics [Diaz, 2024].

Additionally, we focus on Bell state entanglement because among all QM entanglement it most strongly deviates from classical physics in that it saturates the Tsirelson bound [Stuckey et al., 2019, Stuckey et al., 2020]. In Section 4 we show that the Tsirelson bound and the mystery of Bell state entanglement are consequences of 'average-only' conservation. That is, when Alice and Bob are making their Bell state measurements in different directions, Alice's partition of the Bell state data according to her $+1$ and -1 results shows clearly that Bob needs to average his results in order to satisfy Bell state conservation. But, Bob's partition of that same Bell state data according to his $+1$ and -1 results shows clearly that Alice needs to average her results in order to satisfy Bell state conservation. What nonlocal or superdeterministic or retro causal mechanism is responsible for this 'average-only' conservation? Who really needs to average their data?

Just as with length contraction, 'average-only' conservation is not a dynamical effect, it is a kinematic fact following from NPRF + h. As a kinematic fact, there simply is no objective fact of the matter as to who must average their data to satisfy Bell state conservation. So in total analogy with NPRF + c, we view NPRF + h as an adynamical global constraint over the distribution of quanta among the relevant bodily objects (Figure 4). Accordingly, the relativity principle unifies the disparate kinematics of SR (Minkowski space) and QM (Hilbert space) via the adynamical global constraints NPRF + c and NPRF + h, respectively.

Finally, according to our "all-at-once" explanation, the 'big' measurement problem (non-unitary evolution of the state vector [Bub and Pitowski, 2010]) is deflated trivially, since QM is providing distributions of outcomes throughout M4 in "all-at-once" fashion. Notice that we have solved these mysteries

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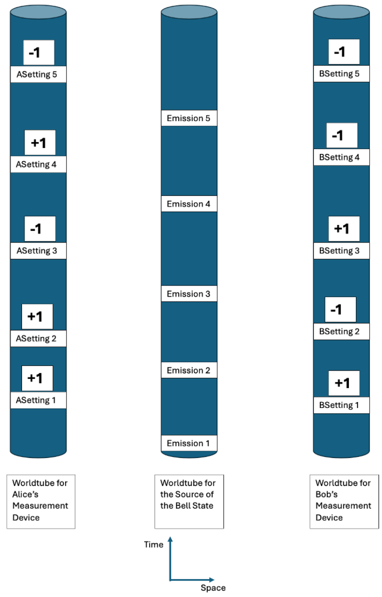

Figure 4: The joint probabilities per our acausal global constraint NPRF + h provide an all-at-once distribution of outcomes throughout spacetime for Alice and Bob's measurement choices over the Bell state source in question.

without violating locality, statistical independence, intersubjective agreement, or the uniqueness of experimental outcomes, and without having to modify QM; QM is as complete as possible given NPRF + h. So, have we actually managed to understand QM without serious consequence to the model of reality per classical physics? No, on the contrary, there is a serious void that remains to be filled and it can best be seen via the 'small' measurement problem ("the problem of explaining the dynamical emergence of an effectively classical probability space of macroscopic measurement outcomes in a quantum measurement process" [Bub and Pitowski, 2010]).

Thus in Section 5, we introduce an ontology we call *quantum-classical contextuality* (a form of multiscale contextual emergence [Bishop et al., 2022]) to address this lacuna. In addition to this ontological deviation from the model of reality per classical physics, our kinematic unification of QM and SR violates theoretical reduction, i.e., Figure 1 is misleading in that it looks formally reductive. In Figure 1, we have a compelling fundamental principle (NPRF) justifying two empirically discovered facts (light and Planck postulates) that dictate the kinematics (M4 and Hilbert space) constraining their dynamics (Lorentz-invariant mechanics and Schrödinger state vector evolution in Hilbert space). However, not shown in Figure 1 is the fact that the constants c and h of the light and Planck postulates, respectively, are products of the dynamics. So in Section 5, we present a more accurate depiction of physics that reflects this reciprocal relationship between the dynamics and kinematics. This illustrates the second benefit of our kinematic unification of QM and SR in that it reveals an overall unity of physics based on NPRF. In short, we see that physics is neither physically nor theoretically reductive, but its methodology is grounded in NPRF, which is easily justified by "Physics and Reality" [Einstein, 1936].

2 The Qubit from the Observer-Independence of h

[Rovelli, 1996] advocated a principle approach to QM:

> [Q]uantum mechanics will cease to look puzzling only when we will be able to *derive* the formalism of the theory from a set of simple physical assertions ("postulates", "principles") about the world. Therefore, we should not try to *append* a reasonable interpretation to the quantum mechanics *formalism*, but rather to derive the formalism from a set of experimentally motivated postulates (italics in original).

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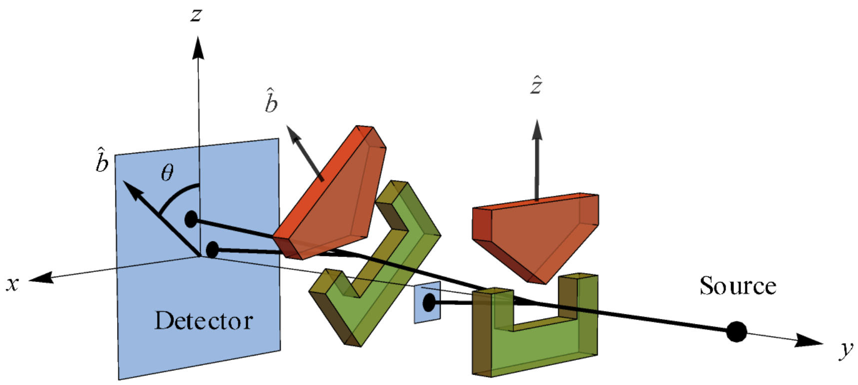

Figure 5: In this setup, the first SG magnets (oriented at $\hat{z}$) are being used to produce an initial spin state $|\psi\rangle = |z+\rangle$ for measurement by the second SG magnets (oriented at $\hat{b}$).

[Rovelli, 1996] was motivated by the success of SR specifically:

> The reasons for exploring such a strategy are illuminated by an obvious historical precedent: special relativity. ... Special relativity is a well understood physical theory, appropriately credited to Einstein's 1905 celebrated paper. The formal content of special relativity, however, is coded into the Lorentz transformations, written by Lorentz, not by Einstein, and before 1905. So, what was Einstein's contribution? It was to understand the physical meaning of the Lorentz transformations.

[Hardy, 2001] was the first to respond with his paper "Quantum Theory from Five Reasonable Axioms" and QRP has since produced many axiomatic reconstructions of QM based on information-theoretic principles. Here we will focus on those based (one way or another) on an empirically discovered fact called Information Invariance & Continuity [Brukner and Zeilinger, 2009]:

> **The total information of one bit is invariant under a continuous change between different complete sets of mutually complementary measurements.**

This is not as transparent as the light postulate, so let us spatialize QRP's notion of measurement by applying this principle specifically to spin-$\frac{1}{2}$ since, "spin-$\frac{1}{2}$ affords a model of the quantum mechanics of all two-state systems, i.e., qubits" [Brukner and Zeilinger, 1999].

Suppose we prepare an initial spin state $|\psi\rangle = |z+\rangle$ for measurement by a subsequent set of Stern-Gerlach (SG) magnets oriented at $\hat{b}$ (Figure 5). Thinking of spin angular momentum as a vector in real space we would expect our SG spin measurement of $|z+\rangle$ along $\hat{b}$ to produce the projection of $+1\hat{z}$ along $\hat{b}$ (in units of $\frac{\hbar}{2}$), i.e., $\cos(\theta)$, as shown in Figure 6. But we never observe anything other the two outcomes "up" or "down" relative to the North magnetic pole, that's the mystery of quantum superposition per the spin-$\frac{1}{2}$ qubit.

Since we are measuring Planck's constant h when we measure the spin of an electron [Weinberg, 2017], the mystery of spin amounts to the observer-independence of h between reference frames related by spatial rotations. That we always obtains ± 1 for an SG spin measurement at any $\hat{b}$ is what Brukner and Zeilinger meant by "The total information of one bit is invariant." If the fundamental unit of information was not "invariant under a continuous change between different complete sets of mutually complementary measurements" (Figure 7), then we would be getting a fraction of h along $\hat{b}$, so we see that Information Invariance & Continuity entails the observer-independence of h under spatial rotations (Planck postulate). But, always obtaining ± 1 rather than fractional outcomes is, as we stated, counterintuitive.

If the classical model of spin was true (Figure 8), then we would be measuring a fraction of h along $\hat{b}$ per Figure 6. But, since h is a constant of Nature per Planck's radiation law, NPRF tells us no fractional values are possible. We can use this to derive the spin-$\frac{1}{2}$ qubit probabilities.

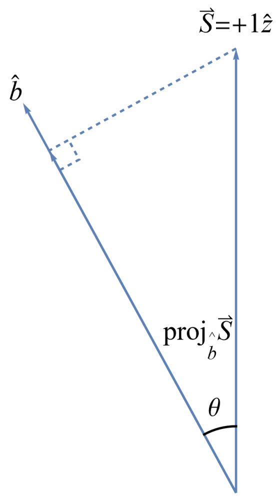

Figure 6: The spin angular momentum $\vec{S}$ projected along the measurement direction $\hat{b}$. This is not what we measure.

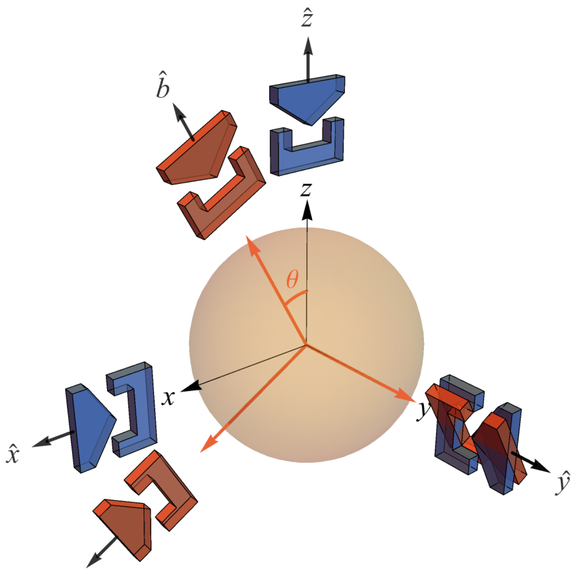

Figure 7: Two reference frames of mutually complementary SG spin measurements.

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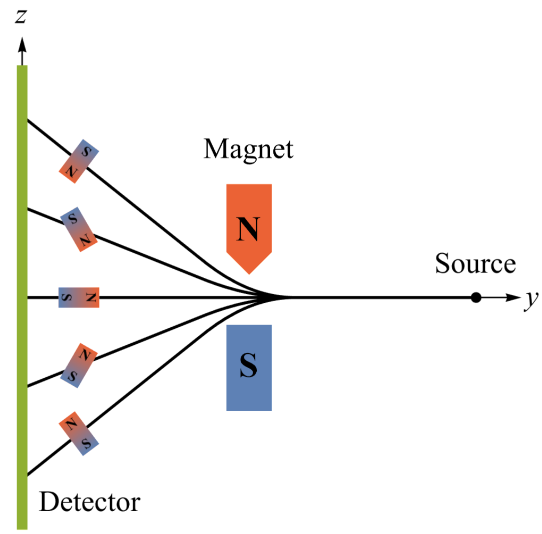

Figure 8: The classical model of the Stern-Gerlach experiment. If the atoms enter with random orientations of their 'intrinsic' magnetic moments (due to their 'intrinsic' angular momenta), the SG magnets should produce all possible deflections.

The angle between $\hat{z}$ (for $|\psi\rangle = |z+\rangle$) and $\hat{b}$ (for $|b+\rangle$) in Figure 5 is θ while the angle between $|z+\rangle$ and $|b+\rangle$ in Hilbert space is $\frac{\theta}{2}$. So, QM says our qubit probabilities are $P(b+|\theta) = \cos^2\left(\frac{\theta}{2}\right)$ and $P(b-|\theta) = \sin^2\left(\frac{\theta}{2}\right)$ giving an average (expectation value) of

$$(+1)\cos^2\left(\frac{\theta}{2}\right) + (-1)\sin^2\left(\frac{\theta}{2}\right) = \cos(\theta).$$

We can derive these qubit probabilities using NPRF + h and the closeness requirement [Dakic and Brukner, 2009] by first demanding

$$(+1)P(b+|\theta) + (-1)P(b-|\theta) = \cos(\theta).$$

Again, the outcome we expect for the measurement/projection of $|\psi\rangle = |z+\rangle$ along $\hat{b}$, given our classical understanding of angular momentum as a vector, is $\cos(\theta)$ (Figure 6). But, since the measurement at $\hat{b}$ must produce ± 1 just like any other direction in space per NPRF + h, we can only *average* this expected projection. And, the closeness requirement [Dakic and Brukner, 2009] says that classical properties obtain on average over a large number of their corresponding, coherent quantum states. The quantum-mechanical probabilities for our qubit then follow uniquely from that equation and normalization

$$P(b+|\theta) + P(b-|\theta) = 1.$$

Now let's see how the joint probabilities for a Bell spin state can be derived from NPRF + h.

3 'Average-Only' Conservation

The Bell spin singlet state represents a spin-entangled pair of particles with anti-aligned spins in any direction of space. The Bell states in general represent the quantum conservation of some property; here that property is spin angular momentum. So, when Alice and Bob both happen to make their SG measurements of this state in the same direction of space, they always get opposite outcomes consistent with a total spin angular momentum of zero. In the z basis, it is written

$$|\psi_-\rangle = \frac{|z+\rangle \otimes |z-\rangle - |z-\rangle \otimes |z+\rangle}{\sqrt{2}}$$

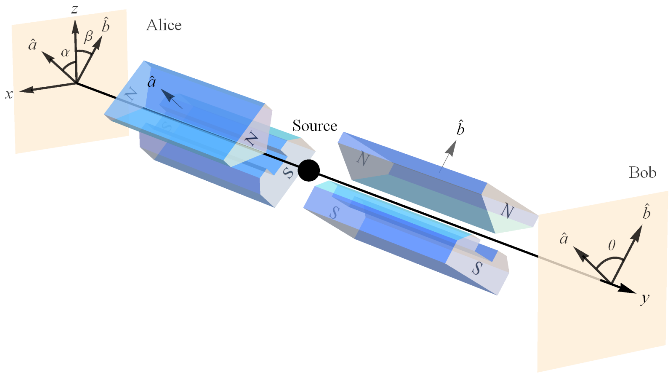

Figure 9: Alice and Bob making spin measurements on a pair of spin-entangled particles with their Stern-Gerlach (SG) magnets and detectors.

Likewise, the three Bell spin triplet states in the z basis

$$|\psi_+\rangle = \frac{|z+\rangle \otimes |z-\rangle + |z-\rangle \otimes |z+\rangle}{\sqrt{2}}$$
$$|\phi_-\rangle = \frac{|z+\rangle \otimes |z+\rangle - |z-\rangle \otimes |z-\rangle}{\sqrt{2}}$$
$$|\phi_+\rangle = \frac{|z+\rangle \otimes |z+\rangle + |z-\rangle \otimes |z-\rangle}{\sqrt{2}}$$

represent a pair of spin-entangled particles with aligned spins in any direction of space for their respective symmetry planes. So, when Alice and Bob both measure along the same direction in the relevant plane of symmetry they will always get the same outcomes consistent with a total spin angular momentum of ± 2. Let's look at the correlation functions to clarify that.

If Alice is making her spin measurement σ_1 in the $\hat{a}$ direction and Bob is making his spin measurement σ_2 in the $\hat{b}$ direction (Figure 9), we have

$$\begin{aligned} \sigma_1 &= \hat{a} \cdot \vec{\sigma} = a_x\sigma_x + a_y\sigma_y + a_z\sigma_z \\ \sigma_2 &= \hat{b} \cdot \vec{\sigma} = b_x\sigma_x + b_y\sigma_y + b_z\sigma_z \end{aligned} \tag{1}$$

where $(\sigma_x, \sigma_y, \sigma_z)$ are the Pauli spin operators. The correlation functions are then given by

$$\begin{aligned} \langle\psi_-|\sigma_1\sigma_2|\psi_-\rangle &= -a_xb_x - a_yb_y - a_zb_z \\ \langle\psi_+|\sigma_1\sigma_2|\psi_+\rangle &= a_xb_x + a_yb_y - a_zb_z \\ \langle\phi_-|\sigma_1\sigma_2|\phi_-\rangle &= -a_xb_x + a_yb_y + a_zb_z \\ \langle\phi_+|\sigma_1\sigma_2|\phi_+\rangle &= a_xb_x - a_yb_y + a_zb_z \end{aligned} \tag{2}$$

You can see that the correlation function for the singlet state is $-\cos(\theta)$ while the correlation function for a triplet state is $\cos(\theta)$ in a particular plane, e.g., that symmetry plane for $|\psi_+\rangle$ is the xy plane. Let's look at a triplet state in its symmetry plane.

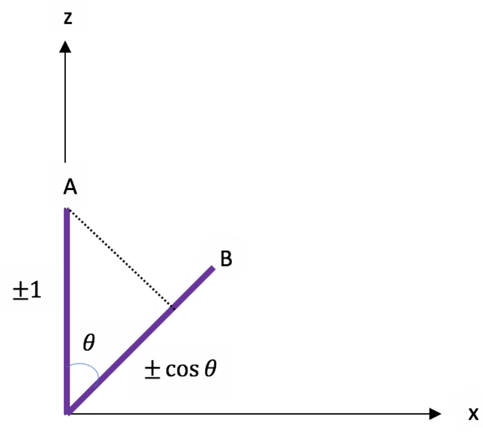

Figure 10: Per Alice, Bob should be measuring $\pm\cos(\theta)$ when she measures ± 1.

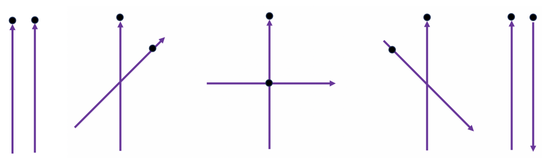

Figure 11: Average View for the Triplet State. Reading from left to right, as Bob rotates his SG magnets (rotating purple arrow) relative to Alice's SG magnets (purple arrow always vertically oriented) for her $+1$ outcome (black dot at tip of her arrow), the average value of his outcome (black dot along his arrow) varies from $+1$ (totally up, arrow tip) to 0 to -1 (totally down, arrow bottom). This obtains per conservation of spin angular momentum on average in accord with NPRF. Bob can say exactly the same about Alice's outcomes as she rotates her SG magnets relative to his SG magnets for his $+1$ outcome.

Suppose Alice obtains $+1$ at $\hat{a}$ and Bob measures at $\hat{b} \neq \hat{a}$ ($\theta \neq 0$). We have the exact same situation here between $\hat{a}$ and $\hat{b}$ for two particles that we had in Section 2 between $\hat{z}$ and $\hat{b}$ for one particle. Using the same reasoning here, Alice says Bob's measurement outcome should be $\cos(\theta)$, since obviously he would have also gotten $+1$ for his particle if he had measured at $\hat{b} = \hat{a}$, as required to conserve spin angular momentum (Figure 10). The problem is, that would mean Alice alone measures h while Bob measures some fraction of h, which means Alice occupies a preferred reference frame. Since Bob must also always measure h per NPRF, Bob's ± 1 outcomes can only *average* to $\cos(\theta)$ at best (Figure 11). That means from Alice's perspective, Bob's measurement outcomes only satisfy conservation of spin angular momentum *on average* when Bob is measuring the spin of his particle in an inertial reference frame rotated relative to hers.

We can write this 'average-only' conservation for Alice's $+1$ outcomes as

$$2P(++)(+1) + 2P(+-)(-1) = \cos(\theta).$$

Likewise, for Alice's -1 outcomes 'average-only' conservation is written

$$2P(-+)(+1) + 2P(--)(-1) = -\cos(\theta).$$

This 'average-only' conservation plus normalization per NPRF

$$P(++) + P(+-) = \frac{1}{2}$$
$$P(-+) + P(--) = \frac{1}{2}$$

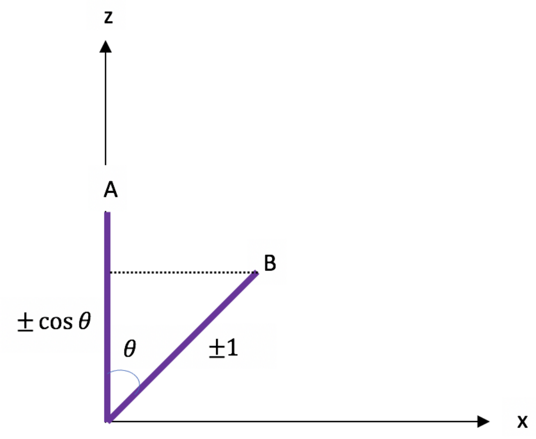

Figure 12: Per Bob, Alice should be measuring $\pm\cos(\theta)$ when he measures ± 1.

Alice's Partition		Bob's Partition	
Bob	Alice	Bob	Alice
+1	+1	+1	+1
-1	+1	+1	-1
+1	+1	+1	+1
+1	+1	+1	+1
-1	-1	-1	-1
+1	-1	-1	+1
-1	-1	-1	-1
-1	-1	-1	-1

Figure 13: Example collection of eight data pairs when Alice and Bob's measurement settings in the symmetry plane for a Bell spin triplet state differ by 60°. Alice partitions the data according to her ± 1 results to show that Bob's measurement outcomes only *average* the required $\pm\frac{1}{2}$ for conservation of spin angular momentum. But, when Bob partitions the data according to his ± 1 results (by switching rows 2 and 6 shown with blue arrows) he can show it is *Alice's* measurement outcomes that only average the required $\pm\frac{1}{2}$ for conservation of spin angular momentum.

gives precisely the QM joint probabilities $P(++) = P(--) = \frac{1}{2}\cos^2\left(\frac{\theta}{2}\right)$ and $P(+-) = P(-+) = \frac{1}{2}\sin^2\left(\frac{\theta}{2}\right)$. It is a simple matter to repeat this derivation for the single state and obtain $P(++) = P(--) = \frac{1}{2}\sin^2\left(\frac{\theta}{2}\right)$ and $P(+-) = P(-+) = \frac{1}{2}\cos^2\left(\frac{\theta}{2}\right)$. Of course, Bob can make the exact same argument about Alice's outcomes (Figure 12) and derive the joint probabilities from his perspective.

In this view, the mystery of Bell state entanglement and, relatedly, the Tsirelson bound reside in the symmetric, 'average-only' conservation that results from the observer-independence of h between inertial reference frames related by spatial rotations (Figure 13). Accordingly, the mystery is easily solved by justifying the empirically discovered fact responsible for the mystery with the relativity principle, NPRF + h.

4 Kinematic Facts, Not Dynamical Effects

As we stated in Section 1, this 'average-only' conservation is totally analogous to the mystery of length contraction resulting from the observer-independence of c between inertial reference frames related by boosts. There, Alice's measurements show clearly that Bob's meter sticks are shorter than hers while Bob's measurements show clearly that Alice's meter sticks are shorter than his.

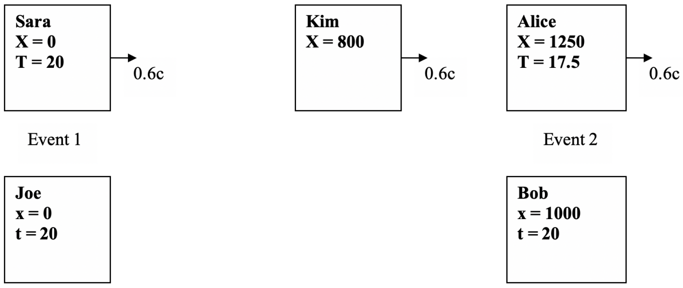

Figure 14: The girls are the same age in their reference frame and the boys are the same age in their reference frame. We exaggerate the time differences for effect. The temporal origin corresponds to being 20 years old and -0.0025 s corresponds to being 2.5 years younger than 20 years old, i.e., 17.5 years old, and so on. The distances are in km. This figure shows Events 1 and 2 occurring simultaneously from the boys' perspective, which leads them to conclude that the girls are not the same age and their meter sticks are clearly shorter.

For example, consider the following three events adapted from [DeWitt, 2004] (who adapted his version from Mermin) using exaggerated time differences:

- Event 1: 20 year-old Joe and 20 year-old Sara meet.
- Event 2: 20 year-old Bob and 17.5 year-old Alice meet.
- Event 3: 22 year-old Bob and 20 year-old Kim meet.

The girls and the boys agree on the facts contained in these three events. Further, Joe and Bob see the girls moving in the positive x direction (Figure 14), so the girls see the boys moving in the negative X direction at the same speed (Figure 15). Additionally, the boys are the same age in their reference frame and the girls are the same age in their reference frame. This establishes simultaneity for each set, i.e., events are simultaneous (coexist) for the boys if the events occur when the boys are the same age, e.g., Events 1 and 2 above. Likewise for the girls, e.g., Events 1 and 3 above. This is known as the *relativity of simultaneity* and motivates the block universe interpretation of M4 [Silberstein et al., 2018].

To appreciate this, we note that Einstein specifically defined time using simultaneity [Einstein, 1905]:

> We have to take into account that all our judgments in which time plays a part are always judgments of *simultaneous events* (italics in original).

where his notion of simultaneity was that of the synchronicity of *stationary* clocks, which was established by exchanging light signals [Einstein, 1905]:

> Thus with the help of certain imaginary physical experiments [associated with the exchange of light signals] we have settled what is to be understood by synchronous stationary clocks located at different places, and have evidently obtained a definition of "simultaneous," or "synchronous," and of "time." The "time" of an event is that which is given simultaneously with the event by a stationary clock located at the place of the event, this clock being synchronous, and indeed synchronous for all time determinations, with a specified stationary clock. ...
>
> It is essential to have time defined by means of stationary clocks in the stationary system, and the time now defined being appropriate to the stationary system we call it "the time of the stationary system."

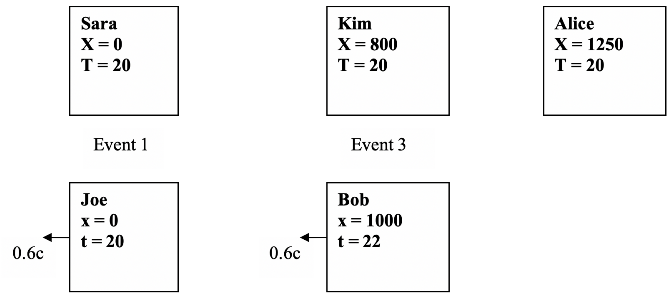

Figure 15: The girls say Events 1 and 3 are simultaneous, so the boys are not the same age and their meter sticks are clearly shorter.

So, the boys' clocks (mechanical and biological) are stationary and synchronized with respect to each other and establish "the time of [their] stationary system" while the same is true for the girls' clocks (mechanical and biological). Accordingly, the boys are the same age in their stationary system and say they coexist when they are the same age while the girls are the same age in their stationary system and would make the same claim about their coexistence.

This motivated [Geroch, 1978, p. 20–21] to write:

> There is no dynamics within space-time itself: nothing ever moves therein; nothing happens; nothing changes. In particular, one does not think of particles as moving through space-time, or as following along their world-lines. Rather, particles are just in space-time, once and for all, and the world-line represents, all at once, the complete life history of the particle.

Consequently, we introduced the term "all at once" explanation in [Stuckey et al., 2008] to describe the 4-dimensional (4D) global distribution of quantum outcomes among the 4D configuration of worldtubes for the experimental equipment (beam splitters, mirrors, sources, SG magnets, detectors, etc.). Accordingly, NPRF + h is an adynamical global constraint on the distribution of quanta in the worldtubes of the experimental equipment configured per the adynamical global constraint NPRF + c (Figures 2 and 4).

As we pointed out in Section 1, there is no need to invoke causal mechanisms to explain the paradoxical kinematic facts, i.e., length contraction and 'average-only' conservation. These kinematic facts follow necessarily from the adynamical global constraints NPRF + c and NPRF + h, respectively.

5 Physics and Reality

At first glance, the unification scheme proposed here (Figures 1 and 16) looks formally reductive. We have a compelling fundamental principle (NPRF) justifying two empirically discovered facts (light and Planck postulates) that dictate the kinematics (M4 and Hilbert space) constraining their dynamics (Lorentz-invariant mechanics and Schrödinger state vector evolution in Hilbert space). However, hidden in this hierarchy is the fact that the constants c and h of the light and Planck postulates, respectively, are products of the dynamics. So, a more accurate depiction of physics would show this reciprocal relationship between the dynamics and kinematics, as we have done in Figure 17.

Figure 17 extends Figure 1 by showing (via blue arrows) that Lorentz-invariant Mechanics (which subsumes Newtonian mechanics) is grounded in the Minkowski Space Kinematics of SR, and Mechanics is used for Statistical Mechanics, whence Thermodynamics. [We'll come back to General Relativity below.] Quantum Field Theory (which subsumes quantum electrodynamics, quantum chromodynamics, and the Standard Model of particle physics) is connected via blue arrows from the Hilbert Space Kinematics of QM and the Minkowski Space Kinematics of SR, since it is the Lorentz-invariant, high-energy extrapolation of QM. Obviously, Figure 17 does not depict a unification of the formalism for all of this physics, that unification does not exist. Rather, Figure 17 depicts a network of conceptual relationships for physics as a whole, showing how they are all grounded in NPRF.

As for the constants, Figure 17 shows that c comes from the electric permittivity ϵ_o and the magnetic permeability μ_o of free space per Maxwell's equations of Electromagnetism. Again, h is generally associated with the quantization that Planck discovered when he used statistical mechanics to justify the derivation of his radiation law, but Planck actually first obtained h as necessary for his fit of Wien's law, which he derived from the classical theories of electromagnetism and thermodynamics. Consequently, the

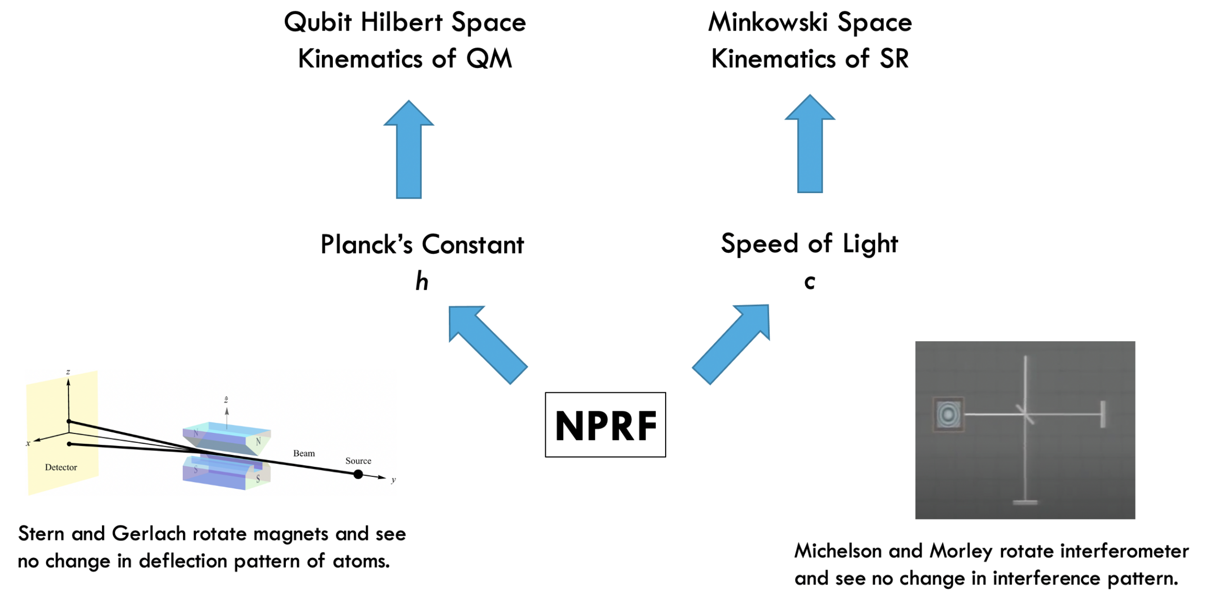

Figure 16: **The Relativity Principle at the Foundation of QM and SR.**

blue arrow for h in Figure 17 should really be coming from both Thermodynamics and Electromagnetism, but that would clutter the figure, so we show it coming only from Thermodynamics.

Also shown in Figure 17 are the Boltzmann constant k_B and Newton's gravitational constant G, which is related to c and $\hbar$ by another constant η. This new constant η is the constant of proportionality between the variations of entropy and causal horizon area in the [Jacobson, 1995] derivation of Einstein's equation of general relativity ("Thermodynamics of Spacetime: The Einstein Equation of State"). [Aside: This is the same approach Planck used to derive his radiation law via electromagnetism and thermodynamics (before justifying that derivation with statistical mechanics) [Diaz, 2024].] That is why we have General Relativity connected (conceptually) to Thermodynamics in Figure 17.

Figure 17 relates beautifully to Einstein's methodological approach to physics in "Physics and Reality" [Einstein, 1936]. Therein, he meticulously lays out the practice of physics beginning with some methodological and phenomenological facts, i.e., facts about "sense experiences" that apply to everyone doing physics. Specifically, Einstein's first point is the obvious fact that physics deals most fundamentally with our observations, i.e., physics is an empirical science. Einstein's second point is that these observations involve interacting "bodily objects" like balls, trees, cars, etc., that have worldlines (or worldtubes if you take into account their spatial extent) in a spacetime diagram. So, each person makes observations personally and with data collection devices that they use to create a personal (subjective) spacetime model of reality for the interacting bodily objects of their empirical data. Einstein's third point is that working collectively with their joint data, physicists are trying to discover patterns in the relationships between, and events involving, the bodily objects of their empirical investigations. [Einstein, 1936] writes:

> ... the totality of our sense experiences is such that by means of thinking (operations with concepts, and the creation and use of definite functional relations between them, and the coordination of sense experiences to these concepts) it can be put in order ... .

So, the practice of physics deals fundamentally with observers who collect, exchange, and coherently synthesize the information from their individual data collection devices into an objective spacetime model of reality that subsumes all the individual (subjective) spacetime models.

As long as the data collection device is inertial, we have no reason to treat its data differently from the data of any other data collection device in any other inertial reference frame. However, the world might be such that the data from different inertial reference frames does not conform to the same laws of physics, i.e., some law or constant might only take its 'correct' form or value in a particular inertial reference frame. Indeed, that is exactly what physicists believed when they postulated the preferred

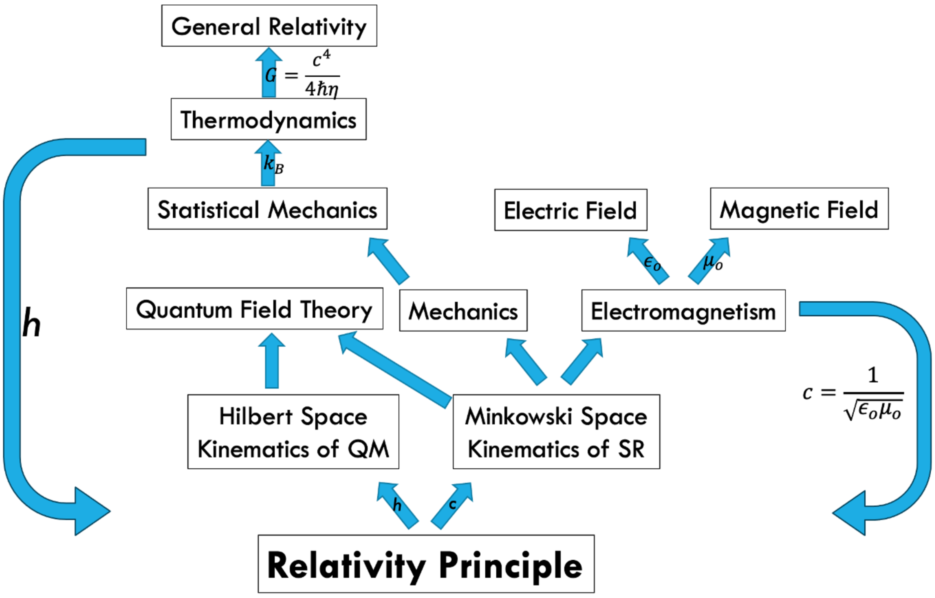

Figure 17: **The Big Picture**.

frame of the luminiferous ether in response to the observer-independence of c. Even Einstein participated in such efforts before giving up, writing [Einstein, 1949]:

> By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results.

Of course, that universal formal principle is the relativity principle. Even [Lorentz, 1916, p. 230] conceded that:

> By doing so, [Einstein] may certainly take credit for making us see in the negative result of experiments like those of Michelson, Rayleigh and Brace, not a fortuitous compensation of opposing effects, but the manifestation of a general and fundamental principle.

Our point here is that given the emphasis on intersubjective agreement between observers in different inertial reference frames in the methodological approach to physics, and given the historical success of the relativity principle in spawning new physics (Galileo to Newton to Einstein), it is not surprising that physicists find NPRF to be a compelling fundamental principle for physics [Norton, 2004, Darrigol, 2022]. Implications for new physics in this new extension of the relativity principle include dark matter, dark energy, and quantum gravity [Stuckey et al., 2024]. Beyond physics there are also implications for consciousness studies [Silberstein and Stuckey, 2022]. This is the second benefit of our kinematic unification of QM and SR.

Finally, we point out that the 'big' measurement problem is deflated trivially in this "all-at-once" explanation. Again, the 'big' measurement problem is to explain "how individual measurement outcomes come about dynamically" [Bub and Pitowski, 2010]. Obviously, that question is a nonstarter when the formalism is used to produce distributions of outcomes atemporally in a 4D global, "all-at-once" fashion (Figure 4). As it turns out, the 'small' measurement problem is also deflated by our adynamical view per quantum-classical contextuality.

Again, the 'small' measurement problem as defined by [Bub and Pitowski, 2010] in Section 1 is "the problem of explaining the dynamical emergence" of 'classical objects' from quantum systems. They state that the 'small' measurement problem is resolved dynamically by decoherence, but while decoherence localizes each quantum system in a classical object, those systems can be "collectively spread over a *macroscopic distance*" [Bacciagaluppi, 2020]. Bacciagaluppi goes on to note "this raises the question of whether quantum mechanics can account for the appearance of the everyday world even apart from the measurement problem." Thus, we believe the 'small' measurement problem arises from an insistence on dynamism and reductionism.

As we explain in [Stuckey et al., 2024], we think that QM and relativity are telling us that reality is fundamentally 4D, i.e., 4D adynamical or acausal global constraints are fundamental to constructive causal patterns and dynamical laws. And, as suggested by Kochen-Specker, Pusey–Barrett–Rudolph, and other theorems and experiments [Lewis and Silberstein, 2024], the universe is inherently contextual in nature in that the 4D constraints range over 'exchanges' of quanta in classical contexts. We refer to this as *quantum-classical contextuality*, which is a subset of what we call *multiscale contextual emergence*. Such a world violates what [Weinberg, 1995] calls "constituent reductionism" or "petty reductionism," i.e, it is not inherently compositional in nature. Weinberg dismisses petty reductionism as follows:

> Petty reductionism is not worth a fierce defense. Sometimes things can be explained by studying their constituents – sometimes not. ... In fact, petty reductionism in physics has probably run its course ... . It is also not possible to give a precise meaning to statements about particles being composed of other particles. We do speak loosely of a proton as being composed of three quarks, but if you look very closely at a quark you will find it surrounded with a cloud of quarks and antiquarks and other particles, occasionally bound into protons.

In our opinion, Weinberg does not go far enough because he still presupposes that the arrow of explanation will always be bottom-up from smaller scales to larger ones, and that fundamental explanation will be constructive. We think relativity and QM are telling us otherwise. We use the term "multiscale contextual emergence" because it suggests that determination relations between smaller and larger scales can be either from larger to smaller or smaller to larger. Contextual emergence emphasizes the explanatory and ontological fundamentality of 4D and other global constraints operating over entities at multiple scales whose existence and properties are inextricably interdependent. As it turns out, this is a unifying fact about the nature of reality [Bishop et al., 2022] and QM exhibits a specific kind of multiscale contextual emergence we call quantum-classical contextuality.

In our model of reality, there can be no classical objects in space and time without exchanges of quanta and vice-versa. [Grangier et al., 2024] reach a similar conclusion, "based on a century of theoretical and experimental progress, our conclusion is that classical physics and quantum physics can neither function nor even be conceived one without the other." Given contextual emergence, it can happen that states of affairs at larger scales provide necessary conditions for the existence of micro-entities and their properties at smaller scales. For example, as we noted with the closeness requirement in our derivation of qubit probabilities, QM is designed to give classical results on average. And states of affairs at smaller scales sometimes provide only necessary and not sufficient conditions for states of affairs at larger scales. For example, the qubit distribution of photons in the interference pattern of the double-slit experiment (the double-slit experiment can also be done with electrons, neutrons, etc.).

That is, suppose we have a laser of wavelength λ illuminating a pair of slits in a membrane with equal intensity and in phase. Since the classical configuration dictates the qubit state, which is constructed so as to yield the classical result on average, the qubit state is $(|\text{Slit 1}\rangle + |\text{Slit 2}\rangle)/\sqrt{2}$. Now position the detector screen immediately behind the slits to make a 'which slit' (position, x) measurement and reduce the power of laser emission to energy $E = \frac{hc}{\lambda}$ per unit time. According to classical physics that momentum $p = \frac{h}{\lambda}$ should be divided evenly between the two slits, but that would mean h has been cut in half between the two reference frames related by spatial translation, so instead that momentum must all appear in the image of Slit 1 or Slit 2 (NPRF dictates quantization here as it did for spin-$\frac{1}{2}$). However, that alone does not suffice to give us a qubit rather than a classical bit.

The classical bit would have the quantum behave as a particle, so that when the detector screen is moved far from the slits (compared to the slit separation) a particle pattern would result. That is to say, the probability state 50% Slit 1 + 50% Slit 2 is a mixed state not a pure state for the classical bit. Instead, we obtain an interference pattern, which is the pure state outcome of the 'interference' (momentum, p) measurement. This is a necessary (but not sufficient) condition for the production of the interference pattern as a whole. That is, the eigenstate $(|\text{Slit 1}\rangle + |\text{Slit 2}\rangle)/\sqrt{2}$ of the momentum measurement only says every photon will land in a constructive interference fringe, it does not give the probability distribution along the interference pattern. The QM formalism requires more information from the classical configuration to obtain that distribution, e.g., a path integral computation of the amplitude (which uses the classical action) at each point along the detector screen for the 'interference' measurement configuration.

One should keep in mind that the qubit is an idealization at the foundation of QM akin to Newton's first law of motion, "An object in motion tends to remain in motion," at the foundation of Newtonian

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mechanics. Such idealizations are useful: 1) to the extent that they can be approximated physically, e.g., interference pattern for double-slit experiment and frictionless planes for Newtonian mechanics, and 2) beyond that where they establish a grounding for higher-level concepts in the theory associated with more complex/realistic physical situations, e.g., diffraction overlay for interference pattern in double-slit experiment and air resistance for an object sliding along a frictionless plane.

You can see why the relationship between QM and classical physics isn't strictly reductive in the double-slit example, i.e., QM requires input from classical physics at each step. However, it is true that the classical pattern obtains in the aggregate of QM outcomes, so an obvious question is, "Should we expect to ever see violations of classical physics due to statistical variation in the underlying QM results?" The short answer is "no." That's because h is very small, so classical physics involves many many quanta and that means deviations of several sigma are still very very close to the average (classical physics prediction). Let's look at a back-of-the-envelope calculation to get a sense of how that works.

Equally illuminate a pair of 650nm-wide slits separated by 0.5mm with a 650nm, 1mW, 1.5mm-beam-width laser placed 1m away from the slits (beam width at slits = 2.5mm). Simple calculations show that approximately 2×10^{12} photons per second are passing through the slits (combined), so a classical pattern obtains in one second. Let Slit 1 have a value of $+1$ and Slit 2 have a value of -1 for our qubit, then QM predicts an average of zero over the Slit 1 and Slit 2 outcomes (which is, again, the classical result). Can we expect to ever observe the pattern of 2×10^{12} photons accumulate unequally between the slits in violation of classical physics due to statistical variation?

We have $\mathrm{n} = 2 \times 10^{12}$ photons in each sample and the Central Limit Theorem says sigma in the (nearly) normal distribution of infinitely many such samples is $\frac{1}{\sqrt{\mathrm{n}}}$. [Obviously, the mean of any sample can't be less than -1 or more than $+1$, so a Gaussian distribution of means is only an approximation, but as we will see for these samples, it's a very good one. It's also only an approximation because the distribution of means is discrete not continuous, but with n this large it's a very good one.]

So, with $\mathrm{n} = 2 \times 10^{12}$ for a (classical) sample, we have sigma $= 7.07 \times 10^{-7}$. The probability that an average/mean lies in the range ± 9 sigma is 1.000000000000000, i.e., certainty to 16 significant figures. Now how much deviation from our classically expected value of zero does that range represent? Any average over n trials that gave an answer between -0.00000636 and +0.00000636 is in that range. Would we be able to detect such a small deviation in the intensity between slits? Even if we did, would we attribute it to statistical variation? Or would we rather attribute it to a very small misalignment of the laser beam with the slits or some other very minor imperfection in the setup? That's why the size of h and the demand that QM reproduce classical physics on average (again, QM is made that way) means we can't expect to see violations of classical physics due to QM statistical variation.

Of course there is some sense in which classical objects are made of atoms, but whether or not an atom behaves in a classical or a quantum fashion is a function of the 4D quantum-classical context. For example, silver atoms in the SG experiment behave as qubits while 100,000 photons per second were used to create "a rubidium atom stuck in an atomic trap" with commuting position and momentum [Chu, 2016]. This is not just true for atoms, but for everything! So, the existence and behavior of all classical objects do not merely supervene on their parts and their properties at a particular time, but rather on the 4D 'exchanges' and 'interactions' of quanta with other classical objects.

By contrast, in some constructive interpretations of QM the "beables" represent what [Allori, 2015] and others call a *primitive ontology*, i.e., one that cannot be directly inferred from the formalism of QM. So, a primitive ontology is more fundamental than even textbook quantum particles, fields, or waves. The goal is to provide a constructive ontology in spacetime that can account for definite measurement outcomes, Bell-inequality-violating correlations, and the existence of classical, localized objects such as measuring devices. In our realist all-at-once approach there is no need to posit any primitive ontology. As [Healey, 2017] notes for example, QM does not have an ontology of its own, i.e., it just piggybacks on whatever classical theory you're quantizing.

Contrary to various QM contextuality no-go theorems, it is sometimes further claimed that such primitive beables must have some metaphysical autonomy/independence (their existence requires no interactions with anything else) and some intrinsic properties that are faithfully and objectively represented by measurements (such properties and their values do not only exist relative to a measuring device in a certain setting). We have provided an account of QM that requires no primitive ontology whatsoever, including the wavefunction. Our non-primitive ontology as derived from textbook physics embraces and affirms contextuality. The point is that we need not posit some hidden variables or undetected metaphysical weirdness hiding behind the reality of our observations to explain QM phenomena.

This is all very much in keeping with recent attempts to undergird psi-epistemic accounts of QM such as QBism and pragmatic accounts with phenomenology or radical empiricism. These are sometimes called "experience-first" accounts [Berghofer and Wiltsche, 2024]. However, unlike those accounts, our view does not have subjectivism, instrumentalism, anti-realism, metaphysical quietism, etc., as a consequence. And unlike those other views, we have a mind and theory independent ontology, we deflate both measurement problems, and we explain QM entanglement with none of the usual posited weirdness such as nonlocality, retrocausation, superdeterminism, etc. Just as Einstein did with SR, it turns out one can embrace the "experience-first" perspective without falling into those other traps.

Quantum-classical contextuality is a crazy thing to think if one is a petty reductionist and thus assumes constructive explanation is fundamental. Indeed, if one is not careful, quantum-classical contextuality may sound like instrumentalism or something Bohr would say. However, the co-dependence and co-determination of the quantum and the classical as given by global 4D constraints ranging over what is truly a 4D universe is another story. Accordingly, one needs to think of reality analogous to a crossword puzzle with the words (4D distribution of mass-energy in spacetime) filled in self-consistently as given by the clues (the 4D adynamical/acausal global constraints), rather than a chess game or finite automota like Conway's game of life. We say much more about the adynamical perspective in [Silberstein et al., 2018] and [Silberstein et al., 2021], but hopefully this suffices to provide an overview of a general ontology consistent with our adynamical/acausal global constraints NPRF + c and NPRF + h unifying the kinematics of SR and QM, respectively.

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