2023 FQxI Essay Competition: How Could Science Be Different?

How the Nazis Split Modern Physics, and How It Can Be Reunified

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Abstract:

Everyone knows that the Nazis hated Einstein and relativity. I argue that this hostility had a profound influence on the development of quantum mechanics in the 1930s, and how it was taught. Specifically, de Broglie showed that quantum waves derived from special relativity, but political pressures forced German physicists to hide this close connection in the first textbooks. Furthermore, Einstein's objections to aspects of quantum theory (such as entanglement) were ignored. This led to a split in the foundations of physics that has continued to the present, between relativity on the one hand, and quantum theory on the other. It is past time to reunify physics, by reimagining how "quantum relativity" would have developed *without* the influence of the Nazis. This may have important implications for the future of physics, particularly regarding quantum computing.

I. Introduction

Scientists often believe that science is independent of history and culture, but these are really deeply embedded in science, in ways that are difficult to change. The central role of Albert Einstein in the development of special and general relativity is of course well known. But the main point of this essay is the novel proposition that quantum mechanics should really be seen as part of the same theory as relativity, but that strong antipathy toward Einstein by the Nazis in the 1930s prevented this unified theory from being developed. In addition, Einstein's longtime objections to randomness and entanglement in quantum theory were ignored. In the absence of this strong unifying aspect, the defining aspect of quantum mechanics became the abstract mathematical formalism, which has been maintained ever since. If history had been different, the physics could have developed in a remarkably different way.

The history of Einstein and the Nazis is reviewed in Section II, focusing on the Nazi influence in German universities and research institutes, and the pressure on physicists to conform to the party line. This is followed in Section III with the introduction of quantum waves by Louis de Broglie, and how they can only be properly understood as relativistic waves which define time and space. Section IV summarizes Einstein's objections to quantum mechanics, and suggests how a unified foundation of quantum relativity may resolve quantum paradoxes. However, this requires questioning some established quantum phenomena, especially quantum entanglement. The essay concludes with section V, which suggests some implications for the future of physics and technology.

II. Einstein and the Nazis

Einstein was everything that Hitler hated. Einstein was Jewish, but was also left-leaning and anti-militarist. Einstein renounced his German citizenship as a teenager, moving to Switzerland and acquiring Swiss citizenship. When Einstein later became a professor at the University of Berlin, his German citizenship was restored, but he again renounced it when he fled Germany in 1933 after the Nazi takeover of the German government. And worst of all, Einstein was a prominent physicist who was proudly anti-Nazi.

But it wasn't just Hitler and Nazi officials who hated Einstein. Nazi followers were influential in German universities, including in Physics Departments. There was even a movement, led by two German Nobelists (Philipp Lenard and Johannes Stark), to create a new "German Physics", as opposed to the "Jewish Physics" of Einstein.[1] While this movement had limited success even in Germany, it was quite dangerous for German physicists (or those under German occupation) to teach relativity, or say anything good about Einstein or other prominent Jewish physicists. An illustration of the environment was that Werner Heisenberg, probably the leading young physicist in Germany at the time, was investigated by the Gestapo for teaching relativity. The only thing that saved Heisenberg was that his mother was a childhood friend of the mother of Gestapo leader Heinrich Himmler, and intervened on Werner's behalf.[1]

So it would not be surprising that Heisenberg and other German physicists were under great pressure not to mention Einstein or relativity in any way. If it became common knowledge that the new field of quantum mechanics was really a branch of relativity, it would discredit the entire field, and place researchers and students in danger. That is not to suggest that Heisenberg or other German physicists were pro-Nazi (although some were), but they were certainly afraid of the Nazis. It was safer to present quantum mechanics as a completely different theory, with its own mathematical formalism.

This has not been widely recognized by either historians or physicists, but I argue that this is exactly what happened in Germany in the 1930s. And Germany was the center of world physics at the time, so this was bound to be influential. The first textbooks were written in German, and provided the basis for later textbooks. After the Nazis were defeated, there was little incentive for these German physicists to publicly admit their complicity. The orthodox quantum theory was already established and being taught, despite some continuing questions about paradoxes and foundations. So the "de-relativized" quantum picture became the standard, including the mathematical Hilbert-space formalism of John von Neumann. Of course, relativistic quantum mechanics was later introduced for high-energy particles by Paul Dirac (who was British), but this did not change the fundamental nature of "non-relativistic" quantum mechanics.

But wouldn't Einstein himself have objected to the developing belief that quantum theory was

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[1] See https://en.wikipedia.org/wiki/Deutsche_Physik. See also Philip Ball, Scientific American, 2015, https://www.scientificamerican.com/article/how-2-pro-nazi-nobelists-attacked-einstein-s-jewish-science-excerpt1/

independent of relativity? In fact, Einstein did object, although in the end he was mostly ignored. Einstein identified two major problems with quantum theory: statistical uncertainty ("God does not play dice with the universe") and entanglement ("Spooky action at a distance"). In 1935 Einstein wrote his paper on the EPR paradox questioning entanglement,[2] and Erwin Schrödinger wrote his "cat" paper questioning the logical consistency of coupled quantum states.[3] Einstein was in Princeton at the time, and Schrödinger would soon flee Austria. Neither of them ever accepted the reality of quantum entanglement.

Ironically, the fact that Einstein was publicly criticizing quantum foundations made it easier for physicists in Germany (such as Heisenberg) to claim that the field was independent of relativity. But it should still have been clear to Heisenberg and other leading physicists that relativity and quantum theory really were closely related. Below I present the basis for this unity, and further suggest the outlines of a unified picture of "quantum relativity" that might have been derived in the 1930s, were it not for pernicious influence of the Nazis.

III. De Broglie Waves and Quantum Relativity

1905 was a very good year for Einstein and for physics. One paper established special relativity, with $E = mc^2$ for a particle; another (on the photoelectric effect) established the photon, with $E = h\nu$. In his French Ph.D. thesis in 1924,[4] Louis de Broglie used both of these relations to derive waves for particles with mass. This was unprecedented; while both waves and particles carry energy and momentum, particles are discrete, whereas classical waves are continuous. But a discrete photon seemed to require a particle aspect of an electromagnetic wave, a form of the doctrine that became known as "wave-particle duality".

De Broglie first considered what one would expect if a photon were a relativistic particle with a small mass m. The energy would be given in the standard way by $E^2 = (pc)^2 + (mc^2)^2$, which can also be written as $E = \gamma mc^2$ and $p = \gamma mv$, where $\gamma = (1-v^2/c^2)^{-0.5}$. If one also has $E = \hbar\omega$ (where $\omega = 2\pi\nu$ and $\hbar = h/2\pi$), the corresponding relation for frequency must be $\omega^2 = (kc)^2 + \omega_0^2$, where $p = \hbar k$ and $\omega_0 = mc^2/\hbar$. This corresponds to the wave equation $\partial^2F/\partial t^2 = c^2\nabla^2F - \omega_0^2F$, where F is the electric or magnetic field, which is also known as the Klein-Gordon equation. But this is now a dispersive wave equation, so that the wave velocity is no longer c for all frequencies. The phase velocity ω/k is greater than c, but the group velocity $v_g = \partial\omega/\partial k = c^2k/\omega$ describes the motion of a dispersive wave packet. If one takes $\omega = \gamma\, mc^2/\hbar$ and $k = \gamma\, mv/\hbar$, one obtains $v_g = v < c$, so that the wave packet always moves together with the associated particle. If this were true for a photon, its speed would be smaller for smaller frequencies. For

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[2] Einstein, Podolsky, and Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", Phys. Rev. 47, 777 (1935).

[3] E. Schrödinger, "The Present Status of Quantum Mechanics", Naturwissenschaften, 1935.

[4] L. de Broglie, "Research on the Theory of Quanta" 1924 (in original French). English translation available here.

example, radio waves would travel more slowly than light waves. In fact, the measured speed of light is independent of frequency, indicating that the mass of a photon is virtually zero.

It is only a small conceptual step to suggest that a massive particle might also have wave properties. De Broglie then suggested applying the same analysis for an electron, with mass $m \sim 10^{-30}$ kg in its rest frame. The corresponding frequency $f = mc^2/h \sim 10^{20}$ Hz, which is far too high to observe directly. But the wavelength $\lambda = h/p \sim 0.1$ nm for electrons with atomic-scale velocities ($v << c$), which led to experimental verification of electron wave diffraction.

Further evidence of electron waves came from quantization of orbital angular momentum around an atom. A single-valued wave must have a phase difference around an atom of $2\pi N$, where N is an integer, corresponding to N wavelengths. For a matter wave rotating around an atom with radius r, this yields an angular momentum $L = rp = (N\lambda/2\pi)(h/\lambda) = n\hbar$, which does indeed correspond to known atomic energy levels.

Even more details of atomic structure were obtained by Schrödinger, who used the non-relativistic energy-momentum relation $E = p^2/2m + V(r)$ for a potential energy V. Taking $E = \hbar\omega$ and $p = \hbar k$ from de Broglie, Schrödinger was able to back-construct a wave equation for operators $E = i\hbar\partial/\partial t$ and $p = -i\hbar\nabla$: $i\hbar\partial\Psi/\partial t = (-\hbar^2/2m)\nabla^2\Psi + V(r)\,\Psi$. This is the famous "time-dependent Schrödinger equation", which he used to successfully derive all of the energy levels and wave functions for an electron in a hydrogen atom.

This seems to represent a non-relativistic equation for a complex electron wave, but Ψ is not the same as the de Broglie wave. In fact, it suppresses the "carrier wave" at mc^2/h, and represents the amplitude and frequency modulation of this wave due to the atomic potential. Mathematically if one simply substitutes $F = \exp(imc^2t/\hbar)\Psi$ into the Klein-Gordon equation, and assumes that $\omega_0 = [mc^2+V(r)]/\hbar$, where $|V| << mc^2$, the Schrödinger equation directly follows. But this simple derivation is never presented in elementary textbooks, because that would make it obvious that a quantum wave is a real relativistic field much like the electromagnetic field, and that the complex field Ψ is just a mathematical construction.

Even more striking evidence that quantum waves are fundamentally relativistic follows from the fact that they exhibit non-simultaneity, which is a central aspect of special relativity. It is well known that events that are simultaneous in one reference frame are *not* simultaneous in other reference frames, due to the Lorentz transform. This is contrary to our classical intuition, whereby events that are simultaneous in one reference frame are *always* simultaneous in all other reference frames. Consider the drawing in Fig. 1, which is copied from the 1947 general-audience history of quantum mechanics by Banesh Hoffmann.[5] Hoffmann was an assistant of Einstein who later edited Einstein's papers and wrote a biography of him. In describing de Broglie waves, Hoffmann pointed out that in its rest frame, all the parts of the wave are

[5] B. Hoffmann, "The Strange Story of the Quantum," 1947, 1959. Available online here.

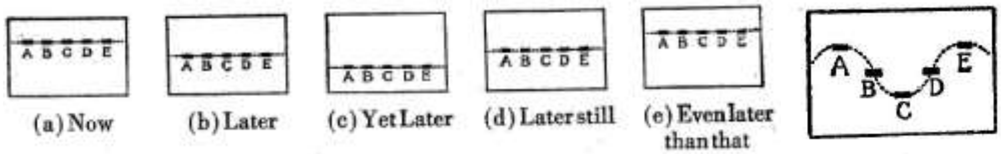


Fig. 1. De Broglie wave in its rest frame (a-e) and when moving (right), from Hoffmann.[5]

oscillating in phase, i.e., their crests and troughs are simultaneous. But in any other (moving) reference frame, time delays create a wave with wavelength $\lambda = h/p$, i.e., the oscillations are no longer simultaneous. This can only be explained by relativity. I suspect that these are Einstein's pictures, which I have not seen elsewhere.

In 1905, Einstein annunciated the principle of relativity, that physical laws should be the same in any reference frame, and applied this to light waves. This led directly to the Lorentz transform for time and space, and to 4-dimensional abstract space-time. Einstein extended this geometrical approach to gravity, and developed general relativity with curved 4D space-time.

The discovery of relativistic quantum waves in the 1920s should have encouraged a new more general interpretation of relativity, with time and space being locally defined by real microscopic clocks and rulers embedded in these quantum waves. This is what I call "quantum relativity". This could have been developed in the 1920s and 1930s. Einstein himself was firmly committed to his geometrical picture. But I suspect that others, particular in Germany and occupied countries, were simply afraid of attracting the anti-Einstein paranoia of the Nazis.

Quantum waves are similar to electromagnetic waves in that both are vacuum fields. One could equally well derive the Lorentz transform by applying the principle of relativity to quantum waves. Since everything in the universe is built out of fundamental quantum waves, this enables a universal foundation not specifically focused on electromagnetic waves. The speed c is not just the speed of light; it is also the maximum speed of quantum waves.

Furthermore, every microscopic quantum wave (with $m>0$) acts as a clock with time $\tau = 2\pi/\omega_0 = h/mc^2$ and a ruler with length $\Lambda = h/mc$ in its rest frame. Together, these define the local speed of light $c = \Lambda/\tau$. One can focus on the electron wave, since that for other fundamental particles (such as quarks) should scale the same way. From this point of view, time and space are not abstract quantities, but rather are locally defined by real microscopic objects in space. Space has 3 dimensions, and no more. Time is not a dimension; it is just a measure of oscillating waves. Neither is absolute, so that time intervals and lengths will differ in different reference frames (time dilation and length contraction). The mathematical theory of 4-dimensional space-time simply reflects the equation $\omega^2 - (kc)^2 = \omega_0^2$, a constant. This is an alternate interpretation of special relativity that was not available in 1905, since quantum waves were unknown. One can even regard the Lorentz transform as primarily an equation for the Doppler shift of microscopic quantum waves.

This quantum relativity picture also provides an alternative interpretation of general relativity.

The negative gravitational potential energy reduces the total rest energy, thus decreasing ω_0 and increasing τ, leading to gravitational time dilation. Similarly, $\Lambda \propto \omega_0$, leading to gravitational length contraction. (This dependence appears slightly different from the standard formulas of general relativity, but they are identical in the tested limit of weak gravitational potentials.) Remarkably, the speed of light is *not* a constant: $c = \Lambda/\tau \propto \omega_0^2$, and gets smaller in a gravitational potential such as that close to the sun. (Any local measurement gets the standard speed by definition.) From this point of view, relativistic bending of light is simply classical refraction associated with a spatially varying index of refraction. No consideration of curved 4D space-time is needed, and can be misleading.

Quantum relativity can be viewed as more general and less abstract than either special relativity or general relativity. Any interaction, not just gravity, that changes ω_0 for a quantum wave, also alters the local time and space references. This is consistent with our modern pragmatic view of time – it is whatever our atomic clocks tell us. For example, the global positioning system (GPS) is based on precision timing with atomic clocks, which ultimately are based on electron waves. The system works only because of consistent relativistic time corrections due to both satellite speed and altitude.

IV. Einstein's Objections and Quantum Paradoxes

Einstein was one of the early founders of quantum mechanics (after Max Planck), with his identification of the photon with relation $E = h\nu$. But by the 1930s, Einstein was one of the main critics of quantum mechanics. His objections focused on two main aspects – intrinsic uncertainty and quantum entanglement. Einstein's relativity is built on deterministic trajectories of locally real objects, and quantum mechanics seemed to violate both of these. More specifically, the quantum wave function was believed to be *not* a real physical wave, but rather a mathematical probability distribution. Pairs of wave functions were believed to be coupled *not* through a real-space physical interaction, but through a mathematical correlation (quantum entanglement), even when they were far apart. This "spooky action at a distance" is incompatible with special relativity. Einstein believed that the quantum theory was incomplete, and that a deeper theory consistent with relativity would eventually be found. Einstein did not find this underlying theory, but no one else was looking for it. I suspect that Nazi threats prevented German physicists from addressing these issues, and Einstein's criticisms led others to believe that quantum mechanics did not depend on relativity.

I believe that Einstein was correct with his criticisms, and that quantum relativity provides the "missing link" that ties relativity to quantum theory, without uncertainty and entanglement. But how did uncertainty and entanglement first enter the theory? Uncertainty was built on the paradox of wave-particle duality, which was present from the beginning of quantum theory. Was a photon or an electron a wave, a particle, or both? De Broglie believed that an electron was both a physical point particle and a physical guiding wave. In contrast, in the Copenhagen interpretation of Bohr and Heisenberg, an electron was a point particle, with a position distributed statistically by $|\Psi|^2$. But a point particle is a singularity, a mathematical abstraction, and a probability wave was never present in prior theories of physics.

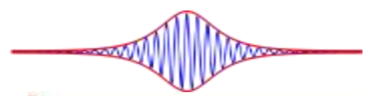
Consider the Heisenberg uncertainty principle, which is presented in quantum textbooks as a mathematical proof that a quantum wave cannot have a definite position and a definite momentum at the same time, leading to fundamental uncertainty. However, this assertion is highly misleading, and in fact the "proof" is a standard mathematical theorem of Fourier analysis, proving that a classical wave cannot be localized in less than half a wavelength. This mathematical theorem says nothing at all about uncertainty. A classical wave-packet can in fact have both a definite momentum and a definite position (its center of energy). The only connection with uncertainty is the interpretation that a quantum wave function represents a statistical distribution of point particles. A more logical explanation is that the quantum wave is a real vector field, just like the electromagnetic wave, with no point particles present. So an electron is a distributed wave packet, which has a size, but no uncertainty is present.

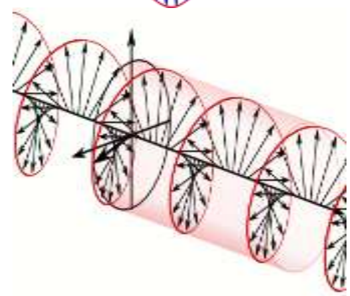
The mathematics of linear wave equations was well known to physicists in the early 20^{th} century. Consider, for example, a vibrating string. It can have multiple solutions with different resonant frequencies, and the general solution is the linear combination of the single-frequency solutions. But the physical solutions of the Schrödinger equation correspond to exactly 0, 1, or 2 electrons in a given resonant frequency, rather than continuous amplitudes. This requires an additional restriction, known as the "exclusion principle", and is a central aspect of electrons in atoms.

In 1925, Wolfgang Pauli proposed an unusual mathematical construction to explain the exclusion principle. Consider electron 1 with wave Ψ_A and electron 2 with wave Ψ_B. Assume that the combined state is the product of the two states, $\Psi_A(1)*\Psi_B(2)$. In classical physics, one never takes products of waves, but if one assumes that these are really independent probabilities rather than waves, this almost makes sense. But given quantum uncertainty, one should also consider this with the particles reversed, $\Psi_B(1)*\Psi_A(2)$. Pauli suggested taking the difference of the two configurations: $\Psi_A(1)*\Psi_B(2) - \Psi_B(1)*\Psi_A(2)$. Note that if $\Psi_A = \Psi_B$, this difference becomes identically zero. Mathematically, this has the effect of ensuring that only a single electron can be present in a given quantum state, thus reproducing the exclusion principle. This construction was quickly accepted as the proper explanation of the exclusion principle, so much so that it is still called the "Pauli exclusion principle". Subsequently similar linear combinations of product states became established throughout quantum theory. But note that if these two electrons move far apart, they remain coupled in this strange way. If one electron is measured to be in state Ψ_A, the other electron immediately is in state Ψ_B. States of this type are said to be "entangled", and this is inconsistent with "local reality". In special relativity, instantaneous action-at-a-distance cannot occur, since nothing travels faster than the speed of light.

But what if there is an alternative explanation for the exclusion principle, without relying on Pauli's entangled states? That would eliminate the need for entangled states in quantum theory, making it more compatible with relativity. One such explanation relies on nonlinear wave equations, which were not well known to physicists in the early 20th century. Specifically, certain nonlinear wave equations have solutions call "solitons", which behave very much like electrons. A soliton is a localized wave-packet that moves through space without attenuation or dispersion, with a fixed amplitude for which the nonlinearities cancel out, making the motion appear linear. A soliton cannot split in two, and two solitons close to each other will repel. When the solution has multiple solitons in different locations, this is a simple sum of the independent soliton waves; no product states or entangled waves are present.

The Schrödinger equation is a linear dispersive wave equation, where frequency components have different velocities, so that a wave packet would spread out or even split. That cannot happen with solitons. From this viewpoint, the linear Schrödinger equation is only an approximation for the true underlying nonlinear equation, valid only for quantized electrons. While the full nonlinear equation is hidden and remains unknown, this provides a realistic microscopic basis for quantum relativity. Without the nonlinear equation, the theory is incomplete.





Another central paradox in quantum mechanics is the nature of spin. In the standard theory, an electron or a photon is a point particle that also carries quantized angular momentum. But a point cannot spin. Quantum relativity implies a much simpler picture: quantum spin is due to rotating vector fields. In fact, a circularly polarized classical electromagnetic wave is known to carry angular momentum distributed through the wave. In such a wave, the **E**-field follows a helical trajectory of fixed amplitude. Both the energy density $\mathcal{E}$ and the spin density $\mathcal{S}$ are proportional to $\mathbf{E}^2$, where $\mathcal{S} = \mathcal{E}/\omega$ follows from Maxwell's equations. If one integrates over a wave packet with energy $E = \hbar\omega$, then $S=\hbar$ falls out automatically. Alternatively, if one *assumes* a total spin of $\hbar$, then $E=\hbar\omega$ follows as a consequence. So this is a consistent quantum relativity picture of a single photon. Note that angular momentum is a Lorentz invariant, so that the spin of a photon is always $\hbar$ in any reference frame.

In the same way, an electron can also consist of a coherently rotating vector field about a fixed axis, with a total spin of $\hbar/2$. Indeed, all fundamental "particles" (quarks, etc.) are rotating vector fields with either $\hbar$ or $\hbar/2$ quantized total spin. It is natural to assume that the underlying nonlinear quantum wave equation has two different forms, which quantize these two values. Indeed, soliton-like rotating vector fields with quantized spins should be the *only* stable solutions of these equations. That would enable a complete quantum theory, without uncertainty or entanglement, in line with Einstein's vision.

V. The Future of Physics Without Entanglement

I have suggested above that quantum relativity can form a unified foundation for relativity and quantum mechanics, but quantum entanglement stands in the way of this unification. Entanglement is embedded in the mathematical foundation of quantum mechanics, and is firmly believed by most physicists. That is despite Einstein's arguments that entanglement violates relativity. In fact, most results of quantum mechanics depend on the single-particle Schrödinger equation, which contains no entanglement. The exclusion principle is interpreted to require Pauli's entangled mathematical construction, but a locally realistic picture based on solitons and nonlinear wave equations may provide an alternative explanation without any entanglement.

But there were also experimental tests of photon correlations, starting in the 1970s, which claimed to prove quantum entanglement. These experiments were based on the analysis of John Bell, who proposed a set of inequalities in the 1960s to test quantum entanglement, of which he was a skeptic. These experiments all involved measurements of linearly polarized single photons and coincidence detectors, and confirmed the predictions of quantum entanglement. But according to the spin picture described above, all single photons must be circularly polarized, corresponding to spin $\pm\hbar$. There are no linearly polarized single photons! From this viewpoint, the experiments may be measuring linearly polarized 2-photon states, following from stimulated emission in the photon sources, which may exhibit the correlations observed, without requiring entanglement. This alternative could be tested experimentally using modern single-photon detectors.

Finally, the biggest future test of quantum entanglement is quantum computing. Quantum computing promises exponentially fast digital computing based on quantum entanglement. Specifically, quantum computing predicts effective parallelism of 2^N, where N is the number of entangled quantum bits (qubits). When N is 300, 2^N is greater than the number of atoms in the known universe, suggesting a performance far beyond what could ever be achieved using classical computers. Because of the widespread belief that this is achievable, many governments, corporations, and investors around the world have poured billions of dollars into research programs to demonstrate quantum computing. No such exponential speedup has actually been demonstrated thus far, but the success of quantum computing would validate the fundamental basis of quantum entanglement. In contrast, the complete failure of quantum computing in the next few years would suggest serious problems in quantum foundations, which may encourage the physics community to be more receptive to alternative formulations such as the quantum relativity picture presented here. Time will tell!

In conclusion, this essay has suggested that the foundations of physics were split in the 1930s, due at least in part to the ideological antipathy of the Nazi regime to Albert Einstein. The relativistic basis for quantum mechanics was hidden, focusing instead on uncertainty and entanglement, aspects that Einstein criticized. I believe that Einstein was right, but overturning orthodox quantum theory will require a major violation of expectations. If quantum computing fails, that may open the door to consideration of a unified foundation based on relativistic local reality on all scales. That would truly vindicate Einstein and represent the final defeat of Nazi ideology.