

## ADDRESSING THE CONFLICT BETWEEN RELATIVITY AND QUANTUM THEORY: MODELS, MEASUREMENT AND THE MARKOV PROPERTY

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**ABSTRACT:** Twenty-first century science faces a dilemma. Two of its well-verified foundation stones - relativity and quantum theory - have proven inconsistent. Resolution of the conflict has resisted improvements in experimental precision leaving some to believe that some fundamental understanding in our world-view may need modification or even radical reform. Employment of the wave-front model of electrodynamics, as a propagation process with a Markov property, may offer just such a clarification.

**KEYWORDS:** Theoretical physics; EPR paradox; entanglement; modeling; stochastic processes; Markov property; principle of relativity

The first decade of the twentieth century saw two revolutions in science – not only through notable discoveries of new phenomena such as energy quantization, or by proclaiming an amalgam of space and time, but, more importantly for the philosophy of science, the perceived need for radical departures from well-verified modes of classical thought. Historically, the “quantum” and “relativity” theoretical mutations parsed the history of science into distinct eras. Together they brought an abrupt conclusion to that almost unremitting succession of conquests and disclosures of the natural world we now term ‘classical’ physics. The subsequent ‘brave new world,’ of theoretical physics, proved to be the natural domain of a new species of philosopher-scientists, who, unlike their classical forebears, conjectured on fundamental features of the world that suggested not only a radical new ontology, but required a new epistemology when attempting an understanding of phenomena that often seemed enigmatic, even counter-intuitive.

Amongst new and exotic traits of a seemingly reticent natural order, early pioneers of atomic and sub-atomic phenomena began discussing an apparently bizarre phenomenon. In April of 1925, Niels Bohr, in correspondence with Hans Geiger,

expressed his concern about increasing “difficulties to our ordinary space-time description of nature” caused in part by evidence of “a coupling of changes of state of separated atoms.”<sup>1</sup> Apparently, quantum systems that had initially interacted and had been subsequently separated, continued to act as if still one coherent but spatially extended system. Quantum characteristics of the parent superposition remained applicable. Although in accord with newly discovered conservation laws, measurement of one observable (or measurable quantity) in one system appeared to instantaneously determine the measurement of the complementary observable of the other system even when they were deemed ‘space-like’ separated. Here, information about the first measurement, if required as cause of the remote effect, might need to travel faster than the speed of light in vacuum and thus violate the universal velocity constraint imposed by the Minkowski-Einstein space-time formalism of special relativity theory.<sup>2</sup> Later, quantum pioneer, Erwin Schrödinger, was to depict this strange non-classical nexus as “entangled,”<sup>3</sup> a description that has subsequently achieved almost universal acceptance.

On the other hand, although Albert Einstein had pioneered and successfully applied some of the new quantum premises deriving from Max Planck’s early quantization discoveries, the claims resulting from this entanglement phenomenon were, for Einstein, a ‘bridge too far.’ Perceived to be under threat were concepts as fundamental as realism, causality, locality and even the rationale of the scientific enterprise. As Einstein’s opinion became more antagonistic, he derided what he called *spukhafte Fernwirkungen*, or ‘spooky action at a distance.’<sup>4</sup> In further expressing his anxiety, Einstein was to write: “... on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system  $S_2$  is independent of what is done with the system  $S_1$ , which is spatially separated from the former.”<sup>5</sup> In correspondence with his life-long colleague Max Born, he amplified his complaint:

<sup>1</sup> Don Howard, ‘The Early History of Quantum Entanglement, 1905-1935’, in Ikaros Bigi and Martin Faessler, *Time and Matter*, 26 - 31 August 2007, Bled, Slovenia, Laboratory for Astroparticle Physics: University of Nova Gorica, Slovenia 2007, p. 19. (Avail. at [http://tam.ung.si/2007/slides/20070828\\_Howard.pdf](http://tam.ung.si/2007/slides/20070828_Howard.pdf))

<sup>2</sup> One dictum of special relativity maintains that no inertial object, or even a signal, can exceed the universal velocity constant  $c_0$ , the velocity of light (or more correctly, electromagnetic radiation of any frequency) in vacuum.

<sup>3</sup> *verschränkt* in German, which means something like ‘cross-linked.’

<sup>4</sup> Harry Buhrman, Richard Cleve and Wim Van Dam, ‘Quantum Entanglement and Communication Complexity’, *Siam Journal of Computing*, vol. 30, no. 6, 2001, pp. 1829-41, p. 1829.

<sup>5</sup> Albert Einstein, ‘Autobiographical Notes’, in Paul Arthur Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, vol. 1, 2 vols., New York, Harper & Brothers Publishers, 1959, pp. 3-95, p. 85.

I just want to explain what I mean when I say that we should try to hold on to physical reality ... whatever we regard as existing (real) should somehow be localised in time and space. That is, the real in part of space A should (in theory) somehow 'exist' independently of what is thought of as real in space B. When a system in physics extends over the parts of space A and B, then that which exists in B should somehow exist independently of that which exists in A. That which really exists in B should therefore not depend on what kind of measurement is carried out in part of space A; it should also be independent of whether or not any measurement at all is carried out in space A. If one adheres to this programme, one can hardly consider the quantum-theoretical description as a complete representation of the physically real. If one tries to do so in spite of this, one has to assume that the physically real in B suffers a sudden change as a result of a measurement in A. My instinct for physics bristles at this. However, if one abandons the assumption that what exists in different parts of space has its own, independent, real existence, then I simply cannot see what it is that physics is meant to describe.<sup>6</sup>

It was primarily this contention that the description of reality, as advanced by a maturing quantum mechanical theory, was incomplete, that induced Einstein to collaborate with colleague Boris Podolsky and Einstein's then assistant, Nathan Rosen, at Princeton's Institute for Advanced Study. In a paper that has become a significant document for the history and philosophy of science, now generally known as the Einstein-Podolsky-Rosen paradox<sup>7</sup> or simply "EPR paradox," the authors attempted to establish that the entanglement notion would lead to a paradox and must therefore be inadequate. As a remedy, the EPR authors suggested that additional local, but as yet unknown (or "hidden") variables of the interaction, might supply information to the system necessary to restore a more classical compliance.

Intense debate was to follow that polarized the physics community. It was in response to the EPR argument that Erwin Schrödinger, as both philosopher and scientist, supported an alternate view:

When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one*

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<sup>6</sup> Albert Einstein, Hedwig Born and Max Born, *The Born-Einstein Letters: Correspondence Between Albert Einstein and Max and Hedwig Born from 1916 to 1955, With Commentaries by Max Born*, trans. Irene Born, London, Macmillan, 1971, p. 164.

<sup>7</sup> Albert Einstein, Boris Podolsky and Nathan Rosen, 'Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?', *Physical Review*, vol. 47, no. 10, 1935, pp. 777-80.

but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought ...

Another way of expressing the peculiar situation is: the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of all its *parts*, even though they may be entirely separated and therefore virtually capable of being "best possibly known", i.e. of possessing, each of them, a representative of its own. The lack of knowledge is by no means due to the interaction being insufficiently known—at least not in the way that it could possibly be known more completely—it is due to the interaction itself.<sup>8</sup>

Historically, it was not until 1964, that Irish theoretical physicist John Stewart Bell, then working at CERN, proposed an approach generally acclaimed as capable of resolving the issue. Although the EPR paper had spread its enquiry to include issues such as realism and theoretical completeness, for Bell, the more experimentally tractable problem was clear:

The paradox of Einstein, Podolsky and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables [that] were to restore to the theory causality and locality. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a different system with which it has interacted in the past, that creates the essential difficulty.<sup>9</sup>

Creating a formalism now known as “Bell’s Theorem,” the notion of additional but concealed variables required to retain a local realism was mathematically systematized and “shown to be incompatible with the statistical predictions of quantum mechanics [or for any] theory which reproduces exactly the quantum mechanical predictions.”<sup>10</sup> By logical argument, Bell demonstrated that, if EPR-styled supplementary parameters were present, statistically averaged results collected from an appropriate measurement regimen must comply with an algebraic inequality derived from the theorem, now termed “Bell’s Inequality,” and thus, at least in principle, permit adjudication by experiment.<sup>11</sup> If demonstrated, empirical violation of that inequality would support the

<sup>8</sup> Erwin Schrödinger, ‘Discussion of Probability Relations between Separated Systems’, *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 31, no. 4, 1935, pp. 555-63, p. 555.

<sup>9</sup> John S. Bell, ‘On the Einstein Podolsky Rosen Paradox’, *Physics*, vol. 1, no. 3, 1964, pp. 195-200, p. 195.

<sup>10</sup> *ibid.*, p.195

<sup>11</sup> Evaluation of Bell’s expression for the class of local realist theories shows that it must be  $\leq 2$ , whereas the quantum mechanical expectation should be experimentally distinguishable at  $2\sqrt{2}$ . ( $\approx 2.828$ ) It should be noted however, that many different versions and inequalities, with family resemblances, were

non-classical correlations purported for quantum entanglement and reinforce its tension with classical separability and locality suppositions.

In his conclusion Bell claimed that, “for at least one quantum mechanical state, the ‘singlet’ state ... the statistical predictions of quantum mechanics are incompatible with separable predetermination,” and thus inconsistent with EPR assumptions. However, missing from Bell’s observation was a means of practical implementation. Although no methodology was suggested, Bell nevertheless claimed that his theorem “had the advantage that it requires little imagination to envisage the measurements involved actually being made.”<sup>12</sup> Further, to be valid, Bell insisted that any proposed experimental procedures must include a provision noted by Bohm and Aharonov, wherein experimental settings should only be changed during the flight of test particles.<sup>13</sup> Writing later in 1969, John Clauser and his associates generalized Bell’s theorem - the Clauser-Horne-Shimony-Holt (CHSH) inequalities<sup>14</sup> – in a more experimentally realizable form that subsequently fostered a range of experimental approaches during the next decade. Unfortunately, pioneering strategies as used at Berkeley, Harvard, and Texas A&M, were analytically limited and far from ideal. However, the use of an improved laser and optical technology produced encouraging results.<sup>15</sup> Eventually, a more stringent approach specifically configured to investigate the Einstein-Podolsky-Rosen-Bohm deliberations and exploit the utility of the CHSH inequalities, found its first practical expression in trials by Alain Aspect and his associates of the Institute of Theoretical and Applied Optics at the University of Paris, Orsay, in 1982.<sup>16</sup> Such empirical results were assessed as providing strong evidence in favour of quantum mechanics. Utilizing time-varying angled analysers to maximize practical non-conformity to EPR locality and causality expectations, Aspect and his team claimed that the “results are in good agreement with quantum mechanical

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inspired by the 1964 paper and are subsumed under the general ‘Bell’s Theorem’ and ‘Bell’s Inequality’ nomenclature.

<sup>12</sup> *ibid.*, p199

<sup>13</sup> David Bohm and Yakir Aharonov, ‘Discussion of Experimental Proof for the Paradox of Einstein, Rosen and Podolsky’, *Physical Review*, vol. 108, no. 4, 1957, pp. 1070-6, p. 1070.

<sup>14</sup> John F. Clauser, *et al.*, ‘Proposed Experiment to Test Local Hidden-Variable Theories’, *Physical Review Letters*, vol. 23, no. 15, 1969, pp. 880-4. The CHSH inequality states that a classically compliant value must lie between -1 and 0. By contrast, the maximum value, of 0.112 allowed by quantum mechanics occurs when the polarization analysers are orientated with an angle between them of 22.5 or 67.5 degrees.

<sup>15</sup> Alain Aspect, Philippe Grangier and Gérard Roger, ‘Experimental Tests of Realistic Local Theories via Bell’s Theorem’, *Phys. Rev. Lett.*, vol. 47, no. 7, 1981, pp. 460-3.

<sup>16</sup> Alain Aspect, Jean Dalibard and Gérard Roger, ‘Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers’ *ibid.*, vol. 49, no. 25, 1982, pp. 1804-7.

predictions” but most importantly “violate Bell’s inequalities by 5 standard deviations.”<sup>17</sup>

Subsequently, however, what were to become known as ‘loopholes,’ disputing the empirical integrity of these approaches, were to cloud their unambiguous interpretation and uncritical acceptance. James Franson raised a criticism based on the quantum ‘measurement problem’,<sup>18</sup> whereas others defended a possible ‘detection’ or ‘fair sampling’ loophole deriving from acknowledged detector inefficiencies. Yet others raised a ‘communication’ or “lightcone” reservation, suggesting that detection locations might not prove to be unambiguously space-like separated. One by one, over a period of years, technological advances substantially raised detector efficiency from < 30% to above an 83% requirement for fair sampling.<sup>19</sup> Franson compliant optical-fibre layouts with detector separations of up to tens of kilometres, and that demonstrated inequality violations of up to 30 standard deviations while running continuously for over twenty four hours, were eventually claimed to have successfully disposed of legitimate criticisms.<sup>20</sup> More recently, infringement of Bell-based inequalities have been recorded for a diverse range of systems involving photons, protons, *K* mesons, ions, neutrons, *B* mesons, heterogeneous atom-photon systems, and atomic ensembles. Entanglement, as a now accepted feature of a mature quantum theory,<sup>21</sup> is routinely incorporated into practical quantum-based technologies, giving birth to serviceable applications such as quantum information exchange,<sup>22</sup> quantum computing, cryptography, and quantum key distribution systems.

<sup>17</sup> Ibid. p. 1804. The statistically significant CHSH value reported by Aspect’s group was  $0.101 \pm 0.020$ , which is five standard deviations away from the limit imposed by realistic, local theories.

<sup>18</sup> James D. Franson, ‘Bell’s Theorem and Delayed Determinism’, *Phys. Rev. D*, vol. 31, no. 10, 1985, pp. 2529-32.

<sup>19</sup> M. A. Rowe, *et al.*, ‘Experimental Violation of a Bell’s Inequality with Efficient Detection’, *Nature*, vol. 409, no. 6822, 2001, pp. 791-4.

<sup>20</sup> Daniel Salart, *et al.*, ‘Testing the Speed of Spooky Action at a Distance - Supplementary Information’ *ibid.*, vol. 454, no. 7602, 2008b, pp. 1-4.

<sup>21</sup> “as experimental accuracy has improved by orders of magnitude, quantum physics has correspondingly been confirmed to one part in  $10^{18}$ ” Bob Doyle, *Einstein-Podolsky-Rosen, The Information Philosopher*, 2013. Accessed 4 July 2013, Available from <http://www.informationphilosopher.com/solutions/experiments/EPR/>. The speed of a so-called “quantum information transfer” or “spooky action at a distance” between well-separated but entangled quantum components has been reported as greater than 10,000 times the speed of light. Daniel Salart, *et al.*, ‘Testing the Speed of ‘Spooky Action at a Distance’’, *Nature*, vol. 454, no. 7206, 2008a, pp. 861-4.

<sup>22</sup> Quantum information, as physical information held in the ‘state’ of a quantum system, is to be distinguished from classical digital, or discrete, information. Quantum information can be quantitatively evaluated in ‘qbits,’ employing the “Von Neumann” entropy as an analogue of the classical “Shannon” entropy, advanced by Claude E. Shannon in 1948, in which the ‘bit’ (binary digit) is the unit.

For his part, Bell assessed the available results at CERN in 1990 with his comments that:

... I cannot say that action at a distance is required in physics. But I can say that you cannot get away with no action at a distance. You cannot separate off what happens in one place and what happens in another. Somehow they have to be described and explained jointly. Well, that's just the fact of the situation; the Einstein program fails, that's too bad for Einstein, but should we worry about that? So what?<sup>23</sup>

Bell's question was not rhetorical. In partial answer to his own question, he noted that the notion of causality as required by special relativity theory, was jeopardized:

According to [special] relativity, the notion of simultaneity is relative... we have a puzzle, because we would not like what [someone] does here to have an effect there, before it is done here ... [however] if I set up a traditional causal model, where the cause effects are allowed to be nonlocal, in the sense of propagating instantaneously over large distances, in some frame of reference the cause will come before the effect.

Even for a theory endowed with appropriate EPR hidden variables, Bell noted that an impasse remained since "there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant."<sup>24</sup> The outcome of the 'Bell tests' has presented a responsible philosophy of science with a crisis originating from a dilemma. As Maudlin saw it: "We cannot simply accept the pronouncements of our best theories, no matter how strange, if those pronouncements contradict each other. The two foundation stones of modern physics, Relativity and quantum theory, appear to be telling us quite different things about the world."<sup>25</sup> The Frigg and Hartman injunction must then logically follow that: "if several theories of the same system are predictively

<sup>23</sup> John S. Bell, 'Indeterminism and Nonlocality. (transcription by R. W. Nowak, from video of a talk presented on 22 January 1990 at CERN on invitation of the Center for Quantum Philosophy, Geneva, organized by Antoine Suarez)', in Alfred Driessen and Antoine Suarez (eds.), *Mathematical Undecidability, Quantum Nonlocality and the Question of the Existence of God*, Kluwer Academic Publishers, 1997, pp. 83-100. Transcript available online as "1997-Bell-Kluwer-indeterminism.doc" at <http://www.quantumphil.org/Bell-indeterminism-and-nonlocality.pdf>, p 5-6. Video avail. at <http://www.youtube.com/watch?v=V8CCfOD1iu8>

<sup>24</sup> i.e. remain unchanged under Lorentz transformations which, in special relativity theory, algebraically express the spacetime relationships obtaining between physical quantities in relatively moving frames of reference. Bell, 1964, p. 199.

<sup>25</sup> Tim Maudlin, *Quantum Non-Localities and Relativity: Metaphysical Intimations of Modern Physics*, Vol. 13, 2nd ed., Chichester, John Wiley & Sons - Blackwell, 2002, p. 24.

successful and if these theories are mutually inconsistent, they cannot all be true, not even approximately.”<sup>26</sup> Elsewhere Bell concluded, “we have an apparent incompatibility, at the deepest level, between two fundamental pillars of contemporary theory ... It may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal.”<sup>27</sup> Similar sentiments are found in recent discussions:

The greatest worry about nonlocality ... has been that it intimates a profound threat to special relativity as we know it. In the past few years this old worry – finally allowed inside the house of serious thinking about physics – has become the centrepiece of debates that may finally dismantle, distort, reimagine, solidify or seed decay into the very foundation of physics ... The status of special relativity, just more than a century after it was presented to the world, is suddenly a radically open and rapidly developing question.<sup>28</sup>

It is in such a context that an observation by Wolfgang Pauli becomes relevant: “If new features of the phenomena of nature are discovered that are incompatible with the system of theories assumed at that time, the question arises, which of the known principles ... are general enough to comprehend the new situation and which have to be modified or abandoned.”<sup>29</sup>

In common scientific practice, complex phenomena, such as electromagnetism, are usually approached by the use of scientific models.<sup>30</sup> Depending on the complexity involved, a number of different, and possibly contradictory, models might be employed, where each as a partial picture represents groups of related features of the phenomena. As such, the complex constitution of electrodynamics is found depicted by rays, beams, waves, quanta, photons, wave packets, particles and wavefronts. Such

<sup>26</sup> Roman P. Frigg and Stephan Hartmann, *Models in Science*, Spring (27 Feb) 2006, The Stanford Encyclopedia of Philosophy, Accessed 7 July 2007, Available from <http://plato.stanford.edu/archives/spr2006/entries/models-science/.Sec.5.1>

<sup>27</sup> John S. Bell, ‘Speakable and Unspeakable in Quantum Mechanics (1984)’, in Simon Capelin (ed.), *J.S. Bell, Collected Papers on Quantum Philosophy: Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 1987, pp. 169-72, p. 172.

<sup>28</sup> David Z. Albert and Rivka Galchen, ‘A Quantum Threat to Special Relativity’, *Scientific American*, vol. 300, no. 3, 2009, pp. 26-33, pp. 28, 33.

<sup>29</sup> Wolfgang Pauli, ‘Einstein's Contributions to Quantum Theory’, in Paul Arthur Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, vol. 1, 2 vols., New York, Harper & Brothers Publishers, 1959, pp. 149-60, p. 149.

<sup>30</sup> Frigg and Hartmann, *Models in Science*. Here, two general definitions apply to the term ‘model’ in the scientific literature. In common scientific practice, a model is deemed to be a representational vehicle picturing in part or whole a ‘real-world’ system under consideration, whereas, in set-theory logic, a model represents that underlying structure “that makes all the sentences of a theory true, where a theory is taken to be a ... set of sentences in a formal language.”



modelling communities are termed *multiple-models idealizations* by Barrett,<sup>31</sup> and employ simplifications, idealizations and analogies as representational strategies in their attempt to render a complex subject matter more tractable. Historically, however, the modeling of electrodynamics has been further simplified by two apparently contradictory modeling categories: ‘waves’ and ‘particles,’ often termed simply ‘wave-particle duality,’ and reflecting one of the most ancient of philosophical contentions – whether the fundamental constitution of the world is discrete or continuous. It was specifically this conceptual discord, yet supported by empirical evidence, that Bohr addressed with his proposal of *complementarity*. This principle, as Bohr expressed it,<sup>32</sup> claimed that although an object may exist with multiple seemingly contradictory and thus mutually exclusive properties, experiment can only exhibit one such property at any one time. For an exploration of radiation, different experimental approaches would suggest either a wave-like model<sup>33</sup> or a particle-like model, as the most appropriate for each circumstance, but not simultaneously.

Although it is generally recognized that a philosophy of science offers more than simply separating science from non-science, it is also well recognized as a critic of the logic underwriting methodologies employed in the cause of scientific enquiry and entailing the construction of scientific theory. It is in consonance with this, however, that the supporting role of models has proven to be among its most valuable contributions to the conduct of science. It is particularly in preliminary processes of theory construction, such as problem and hypothesis formulation, that some observers identify a potent modelling role. Giere asserts that in the realization of this role “scientists use designated similarities between models and aspects of the world to form both hypotheses and generalizations.”<sup>34</sup> In similar vein, Hartmann, who describes the dynamic process of physics as “the continuous endeavour of theory construction,”

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<sup>31</sup> Michael Weisberg, ‘Three Kinds of Idealization’, *The Journal of Philosophy*, vol. 104, no. 12, 2007, pp. 639-59.

<sup>32</sup> At the International Physical Congress held in September 1927, at Como, Bohr “advocated a point of view conveniently termed ‘complementarity,’ suited ... to clarify the peculiar aspects of the observational problem in the field of experience ... evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as *complementary* ...” Niels Bohr, ‘Discussion with Einstein on Epistemological Problems in Atomic Physics’, in Paul Arthur Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, vol. 1, 2 vols., New York, Harper & Brothers Publishers, 1959, pp. 201-41, pp. 209, 10.

<sup>33</sup> The ‘wave’ model of light is a general abstraction from many familiar phenomena that are only geometrically similar such as water waves, sound waves in air, and displacement of a taut string or stretched membrane. “In each case there is some ‘field’ quantity varying smoothly in 1, 2, or 3 dimensions.” E. H. Carlson, *Wave-Particle Duality: Light*, 1 Feb. 2000, Michigan State University, 2000. Accessed 21 June 2009, Available from [http://www.physnet.org/modules/pdf\\_modules/m246.pdf](http://www.physnet.org/modules/pdf_modules/m246.pdf).

<sup>34</sup> Ronald N. Giere, ‘How Models Are Used to Represent Reality’, *Philosophy of Science*, vol. 71, 2004, pp. 742-52, p. 742.

affirms his comprehensive thesis: “As a major tool for theory construction, scientists use models.”<sup>35</sup>

Given such functionalism apportioned to representational models, it seems pertinent to paraphrase Pauli’s previously noted observation to also ask: Which of the models of complex systems are appropriate to represent a new situation and which might need to be modified or abandoned? One of the first of the quantum pioneers to apply the intent of this question to the emergence of entanglement was Bohr:

In general, I believe that these difficulties [including the existence of quantum coupling] exclude the retention of the ordinary space-time description of phenomena to such an extent that ... conclusions about a possible corpuscular nature of radiation lack a sufficient basis.<sup>36</sup>

Reference to “a possible corpuscular nature of radiation,” was specifically intended to refer to Einstein’s 1905 characterization of the photo-electric effect.<sup>37</sup> Planck had pictured the light quantum as having reality, if it was to have any at all, only during the event-like processes of absorption and emission, whereas elsewhere radiation had only a continuum wave-like character. “Einstein departed completely from this tentative position that sought a compromise between classical physics and the new quantum hypothesis ... [by going] over entirely to a quantum theory.”<sup>38</sup> Einstein’s radiation was not just discrete, and separable, but composed of “... independent entities emitted by the sources of light, exactly as in the Newtonian emission theory of light.”<sup>39</sup> Here, locality was pre-eminent: “... the most natural interpretation seems to me to be that the occurrence of electromagnetic fields of light is associated with singular points ... It is not out of the question that in such a theory the entire energy of the electromagnetic field might be viewed as localized in these singularities.”<sup>40</sup> Further, when suggesting that “... the Newtonian emission theory of light seems to contain

<sup>35</sup> Stephan Hartmann, ‘Models as a Tool for Theory Construction: Some Strategies of Preliminary Physics’, in William E. Herfel, Wladyslaw Krajewski, Ilkka Niiniluoto and Ryszard Wojcicki (eds.), *Theories and Models in Scientific Processes*, vol. 44, Amsterdam, Rodopi, 1995, pp. 49-67, p. 49.

<sup>36</sup> Howard, p. 19

<sup>37</sup> Albert Einstein, ‘On a Heuristic Point of View Concerning the Production and Transformation of Light (*Annalen der Physik* 17, 1905, pp. 199-206)’, in John Stachel (ed.), *The Collected Papers of Albert Einstein*, trans. Anna Beck and Peter Havas, vol. 2: The Swiss Years: Writings, 1900-1909, (Doc. 14), Princeton, New Jersey, Princeton University Press, 1989a, pp. 86-103.

<sup>38</sup> Henry A. Boorse and Lloyd Motz, ‘Einstein’s Legacy’, in Henry A. Boorse and Lloyd Motz (eds.), *The World of the Atom*, vol. 1, Part VI, 2 vols., New York, Basic Books, Inc., 1966a, pp. 533-612, p. 539.

<sup>39</sup> Albert Einstein, ‘On the Development of Our Views Concerning the Nature and Constitution of Radiation (*Deutsche Physikalische Gesellschaft, Verhandlungen* 7, 1909, pp. 482-500, and *Physikalische Zeitschrift*, vol. 10, 1909, pp. 817-826)’, in John Stachel (ed.), *The Collected Papers of Albert Einstein*, trans. Anna Beck and Peter Havas, vol. 2: The Swiss Years: Writings, 1900-1909, (Doc. 60), Princeton, New Jersey, Princeton University Press, pp. 379-94, p. 383.

<sup>40</sup> *ibid.* p. 394

more truth than does the wave theory,"<sup>41</sup> Einstein moved his discussion more into the domain of propositions which, unlike representations, are properly responsive to questions of realism and truth. Among Einstein's contemporaries it appears to have been generally accepted that a particle (or later 'photon')<sup>42</sup> model was the more appropriate for particular phenomena such as the photo-electric effect, the Compton effect and photochemical reactions, whereas interference, refraction, diffraction and polarization were generally conceded to be phenomena where wave-like modeling remained the more effective. By 1911, Einstein's realist particle conviction was to provide grounds for robust academic debate and one that opened a division between Einstein and his colleagues. As Born recollected the first Solvay Conference: "Most of the discussion was devoted to the [light quantum]; Einstein insisted that it be recognized as a real physical particle, but the majority was willing to accept it only as an artificial device for clarifying certain radiation phenomena."<sup>43</sup> In contrast to the joint citizenship and mutual respect offered to antagonistic models by such as a Bohr-styled multiple-models complementarity, Einstein's local particle claim appears increasingly unilateral and unequivocal.

Given Einstein's inflexible 1905 stance on the constitution of radiation, and the antithetical issues later raised by quantum entanglement, it seems reasonable to ask whether a local and separable characterization of radiation, as necessarily also employed by Einstein in the contemporaneous construction of the special relativity theory, would still be thought an appropriate predisposing model for its theoretical development. The question is one of more than simple academic curiosity. Following a model-theory relationship as researched by such as McMullin, a model supporting a theoretical development that is subsequently found to sponsor an invalid hypothetical prediction or inter-theoretical inconsistency, is recognized as being in need of either modification or replacement.<sup>44</sup> However, any alternate representation would also need to acknowledge the nonlocal and non-separable attributes of radiation now established as aspects of the real world. It then becomes of importance that such attributes are to be recognized in the wave-front model of light.

<sup>41</sup> *ibid.* p. 387

<sup>42</sup> the designation of the 'light quantum' or 'light particle' by the term 'photon,' was first introduced by the professor of physical chemistry at the University of California at Berkeley, Gilbert N. Lewis, in late 1926, "'The Conservation of Photons'", from Letters to the Editor, *Nature Magazine*, vol. 118, Part 2, Dec. 18, 1926, pp. 874-875', in J. Walker (ed.), *The Origin of the Word "photon"*, Science and Philosophy, NoBeliefs.com, 2006.

<sup>43</sup> Max Born cited in Henry A. Boorse and Lloyd Motz, 'The Wavelengths of Particles: Prince Louis V. de Broglie (1892-1987)', in Henry A. Boorse and Lloyd Motz (eds.), *The World of the Atom*, vol. 2, part XII: Wave Mechanics, 2 vols., New York, Basic Books, Inc., 1966b, pp. 1041-8, p. 1046.

<sup>44</sup> Ernan V. McMullin, 'Galilean Idealization', *Studies in History and Philosophy of Science, Part A*, vol. 16, no. 3, 1985, pp. 247-73. pp. 261, 264

Historically, although completed in 1678, it was in 1690, that the eminent Dutch scientist Christiaan Huygens finally published his *Traité de la Lumière*, (*Treatise on Light*) as a fitting sequel to an already prodigious scientific career.<sup>45</sup> Although a contemporary of Newton, and despite Newton's emphatic claims as to a corpuscular constitution of light, in his own exposition, Huygens elaborated on a continuum approach to optical problems, now known as "Huygens' principle." Although often referred to as "Huygens' wave theory of light," it would be more correctly described as a model of the process of light-energy transmission by the formation of a spreading spherical wave-front. As envisaged by Huygens, a disturbance in an elastic medium should communicate the vibration to its immediate neighbourhood where adjacent elements of the medium should become new, or secondary, sources of the disturbance. In this way, each adjacent element becomes, in effect, the centre of a new spherical emanation. Pursuing the fate of this ever increasing myriad of 'secondary' wavelets with a detailed geometrical analysis, Huygens hypothesized that they would cancel each other within the domain of an inflating sphere, yet become perceptible where they concur at their common tangent, thereby forming an expanding spherical surface of constant phase. His principle is now understood as comprehending the "principle of action-by-proximity" whereas the superposition of secondary wavelets is separately describable as "Huygens' construction." Nevertheless, despite being praised by Leibniz,<sup>46</sup> Huygens' work sank into obscurity for more than a century, eclipsed by Newton's prestige and domination of the physical sciences.

The first significant breach of Newtonian theoretical monopoly was claimed early in the nineteenth century by Thomas Young whose historical ripple tank and 'double-slit' experiments advanced powerful arguments supporting a wave model of light through the principle of interference. Young further advocated a transverse wave model that then paved the way for optical polarization as was subsequently, yet independently, advanced by Augustin-Jean Fresnel in 1821. Extending Huygens' original model, Fresnel introduced the periodicity of wave trains and was able to

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<sup>45</sup> Christiaan Huygens, 'Treatise on Light, In which are explained the causes of that which occurs In REFLEXION, & in REFRACTION And particularly In the strange REFRACTION OF ICELAND CRYSTAL, trans Silvanus P. Thompson, from Christiaan Huygens, 'Treatise on Light,' New York, Dover, 1912'. The Project Gutenberg eBook (#14725), January 18, 2005. His reputation was so great that in 1665 Louis XIV offered him a pension if he would live in Paris, from where he became a founder and then overseer of the *Académie Royale des Sciences* in 1668. Recently, an atmospheric entry probe that landed on Saturn's moon Titan on January 14, 2005, as part of NASA's *Cassini-Huygens* space mission, was named in his honour.

<sup>46</sup> Leibniz to Huygens, Oct. 1690, cited in Alan E. Shapiro, 'Kinematic Optics: A study of the Wave Theory of Light in the Seventeenth Century', *Archives for History of Exact Sciences*, vol. 11, 1973, pp. 134-266, p. 246.

account not only “for the rectilinear propagation of light of very short wave-length and the laws of reflection and refraction, but also for certain diffraction phenomena.”<sup>47</sup> Prorogue of a particle-emission domination of optical modeling was then completed in 1850:

Fresnel’s work had put the wave theory on such a secure foundation that it seemed almost superfluous when in 1850 Foucault and Fizeau and [independently] Breguet undertook a crucial experiment ... The corpuscular theory explains refraction in terms of the attraction of the light-corpuscles at the boundary towards the optically denser medium, and this implies a greater velocity in the denser medium; on the other hand the wave theory demands, according to Huygens’ construction, that a smaller velocity obtains in the optically denser medium. The direct measurement of the velocity of light in air and water decided unambiguously in favour of the wave theory.<sup>48</sup>

It remained then for the German physicist Gustav Robert Kirchhoff, to consolidate the Huygens-Fresnel principle by resolving residual difficulties and to present it as a general representation of radiation and diffraction processes and derivable from Maxwell’s electromagnetic equations. So successful were Kirchhoff’s syntheses, simplifications and insights that the “*Huygens-Fresnel-Kirchhoff wave-front diffraction formulation*” has survived the revolutions and paradigm changes visited upon the physical sciences in the ensuing century and a half, with almost no need for further modification.

In modern physics, and following Feynman’s developments and using appropriate field operators such as Green’s functions, Huygens’ principle also finds exact mathematical expression through the Chapman-Kolmogorov equation,<sup>49</sup> which is the equation of motion of Markov processes. According to Enders, such a derivation is as exact as Kirchhoff’s formula but has the advantage of easier generalization to other propagation phenomena. In respect of this approach, “Huygens’ principle is understood as a *universal* principle governing not only the propagation of light,” but further, such a “formulation leads to a *unified* formal representation of not only classical and Schrödinger (matter) waves<sup>50</sup> as well as diffusive transport, but of virtually *all*

<sup>47</sup> Bevan B. Baker and E. T. Copson, *The Mathematical Theory of Huygens’ Principle*, third ed., New York., Chelsea Publishing Company, 1987, p. 20.

<sup>48</sup> Max Born and Emil Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, seventh (expanded) ed., Cambridge University Press, 1999, pp. xxviii-xxix.

<sup>49</sup> The equation was arrived at independently by both the British mathematician Sydney Chapman and the Russian mathematician, Andrey Kolmogorov.

<sup>50</sup> Quantum theorist Erwin Schrödinger employed Huygens’ principle in his development of “wave mechanics” which now stands as an integral component of quantum theory. Erwin Schrödinger, ‘An

propagation phenomena, which can be described through *explicit* differential and difference equations, respectively.”<sup>51</sup> As a consequence Huygens’ principle has found its place as the predisposing model of choice, sponsoring theory construction not only in optics, but also in such diverse fields as medical ultrasound imaging, seismology, acoustics and quantum electrodynamics.

Given that Huygens’ principle in its modern form, presents as a highly potent and successful representation of electromagnetic propagation, yet equally presents as both nonlocal and non-separable, such a depiction may then be thought to recommend itself as the model of choice for a possible reformulation of the special relativity theory in a post-EPR context. However, beyond its conformity to the implications of entanglement, the wave-front model offers representations of a different subset of optical characteristics to that traditionally incorporated by an isolatable particle model.

Of significance is a difference in portrayal of an optical ray. Historically, the Newtonian perception was of a real physical entity as the reified rectilinear locus of light stuff, and consequently as the notionally countable components of a light beam. In a wave-front context, a ray is an abstraction – a radius<sup>52</sup> of an expanding spherical optical surface and thence, the geometrical normal to that surface. Such a conceptual disparity fuelled many of the heated confrontations dogging optical development in the early nineteenth century:

While waves ... were replacing particles of light as tools of explanation, wave-fronts were also beginning to replace rays as tools of analysis. This second process was at least as difficult for many people as the first one because it required them to alter many fundamental optical concepts concerning the nature of a *ray* and its relation to a *beam* ... many people had immense difficulty understanding that the *wave-front* is irreconcilable with the concept of an *isolatable ray* – that [such] rays must be abandoned entirely as physical objects in their own right in order to deploy the mathematical apparatus of the wave theory... In the emergence of the wave theory ... one finds a profound dichotomy in understanding as well as in conception: a dichotomy between the most elementary images of the nature of a

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Undulatory Theory of the Mechanics of Atoms and Molecules’, *Physical Review*, vol. 28, no. 6, 1926, pp. 1049-70, p. 1052.

<sup>51</sup> Peter Enders, ‘Huygens’ Principle and the Modelling of Propagation’, *European Journal of Physics*, vol. 17 no. 4, 1996, pp. 226-35, p. 226.

<sup>52</sup> In the 17th century, English philosopher and geometer, Thomas Hobbes, specified the significance of his geometrical pulse-front treatment of a ray and its distinction from medieval atomist modelling to the extent that he “abandoned the term ‘ray’ (*radius*) and introduced the new term ‘radiation’ (*radiatio*).” Shapiro, p. 151

ray, on the one hand, and a dichotomy between the physical models of light as particles and light as waves ...<sup>53</sup>

In keeping with the need to distinguish between distinctive ray formulations, the term “speed of light” also begs a certain disambiguation. Whereas in a particle-emission model, the term may also be expressed as the “velocity of light” insofar as it may reference both the speed and direction, or vectorial trajectory of an individual, in a wave-front model, the term references the scalar rate of radial expansion of the spherical light complex. Given the modern predilection for acronyms, the speed of light in isotopic media might then benefit from being denoted the *Electromagnetic Radial Inflation Constant*, or ERIC.<sup>54</sup> This speed has a specific value for each light-bearing medium, including the vacuum of space, and is conventionally denoted ‘*c*’.<sup>55</sup> In physical terms this speed derives from just two intrinsic properties of the medium – its *electric permittivity* and its *magnetic permeability*. The refractive index of any medium is then defined as the ratio of the (phase) speed of radiation in vacuum to the (phase) speed of radiation in the medium itself.

It is, however, in the domain of information theory that the most profound model-specific differences become apparent. If Einstein found the nonlocal correlations of entanglement confronting, he was to also find acute philosophical difficulty with the probabilistic interpretation of quantum events. Einstein had shown aptitude in the use of statistical approaches when interpreting the molecular randomness seething beneath the superficial appearance of the bulk phenomena of liquids and gasses, however, averaged results demonstrated regularities that appeared to conform to the expectations of a classical determinism. Nevertheless, chance alone seemed to epitomise the outcome of individual sub-atomic interactions.<sup>56</sup> It was this frank indeterminism that prompted one of Einstein’s more memorable quips, that “God does not play dice,”<sup>57</sup> expressing his disquiet at the extent to which quantum

<sup>53</sup> Jed Z. Buchwald, *The Rise of the Wave Theory of Light: Optical Theory and Experiment in the Early Nineteenth Century*, Chicago, The University of Chicago Press, 1989, p. xiv.

<sup>54</sup> Gareth Boardman, *An Information Theory Interpretation of Relativistic Phenomena*, PhD Thesis, Swinburne University of Technology, Australasian Digital Theses collection, 2012. p. 249 Avail at: <http://hdl.handle.net/1959.3/231831>

<sup>55</sup> Deriving possibly from English ‘*constant*’ or Latin ‘*celeritis*’ (meaning swiftness). The “speed of light” in free space is more properly denoted  $c_0$  and since 1983, has been defined as 299,792,458 metres per second.

<sup>56</sup> Although quantum theory dictates a limited number of possible outcomes for an interaction, the state assumed is randomly selected for any event, yet equally conforms to a definite probability calculable for assuming that state. Paul Adrien Maurice Dirac, ‘The Principles of Quantum Mechanics’, *The International Series of Monographs on Physics*, vol. 27, 4th, Oxford, Oxford Science Publishers, 1958, p. 6.

<sup>57</sup> “On his side, Einstein mockingly asked us whether we could really believe that the providential authorities took recourse to dice-playing (‘... *ob der liebe Gott würfelt*’)” Bohr, 1959, p. 218

mechanics apparently repudiated a causal account in space and time that had long served as a fundamental tenet of classical mechanics.

It is in the context of such a classical ‘cause and effect’ account of the world that in recent appraisals of classical mechanics, some prominent physicists, including Stanford theorist Leonard Susskind, have claimed that “information conservation is perhaps the most fundamental law of basic classical physics.”<sup>58</sup> Outranking conservation of energy or momentum, invariance of the information content of a (idealised) mechanical system is here valued as underwriting the fundamental tenet of causal determinism and with concepts of exact predictability, and reversibility, as necessary corollaries. However, whereas earlier accounts of the world, by such as French mathematician Pierre-Simon Laplace,<sup>59</sup> held that a classical determinism monopolised scientific understanding, the later recognitions of entropy, the second law of thermodynamics, and quantum indeterminacy have amply demonstrated a more complex natural order. In modern mathematics, the study of ‘stochastic’ (random, non-deterministic, non-reversible), systems or processes, comprises a significant arena within the domain of probability theory. Processes modeled as stochastic time series include audio and video signals, stock market fluctuations, financial exchange rates, and the perhaps familiar “Brownian motion”<sup>60</sup> or ‘pedesis,’ in which small particles suspended in a liquid or gas, are observed to undergo a ‘random walk,’ or succession of random steps, due to bombardment from arbitrary molecular motions.

Processes such as Brownian motion are, however, further classifiable as Markov<sup>61</sup> processes, identifiable as satisfying the memoryless or Markov property. In general, a process satisfies the Markov property if one can make predictions for the future of the process based solely on its present state, its past history having no relevance since, in

<sup>58</sup> Leonard Susskind, ‘Modern Physics: The Theoretical Minimum - Classical Mechanics; PHY 25, Lecture 1, October 15, 2007’, Stanford on iTunes U, 2007. Avail. as “PHY 25 Lecture 1 (October 15, 2007).mp4”

<sup>59</sup> Known historically as *Laplace’s demon* or sometimes *Laplace’s Superman*, Laplace conjectured, on the basis of a strict causal or scientific determinism, that if a suitable intellect at a certain moment knew all the forces that set nature in motion, together with the precise location and momentum of every atom in the universe, then “for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.” Pierre-Simon Laplace, *A philosophical essay on probabilities (1814)*, trans. F.W. Truscott and F.L. Emory, New York, John Wiley & Sons, 1902, p. 4.

<sup>60</sup> Named after Scottish biologist Robert Brown (1773-1858), who, in 1827, was one of the first to describe the phenomenon when observing microscopic pollen grains suspended in water. However, the Roman atomist, Lucretius, appears to accurately describe the motion as seen in dust particles, in his scientific poem “*De Rerum Natura*” (*The Nature of the Universe*) written circa 60 B.C. Titus Lucretius Carus, *De Rerum Natura (Book I - VI)*, Department of the Classics, Tufts University, Sept 2000 Accessed 6 May 2008, Available from <http://www.perseus.tufts.edu/cgi-bin/ptext?lookup=Lucr.+1>.

<sup>61</sup> After Russian mathematician Andrey Andreyevich Markov (1856-1922)



accordance with its random status it has no deterministic influence on how the current state was obtained.<sup>62</sup> A corollary of the Markov property then asserts that no examination of a state in such a stochastic process can reveal information concerning any prior state. Such processes are thus not information conserving. For Huygens construction, identified as a continuous process with a Markov property, this means that the secondary wavelets, each acting in effect as new sources of disturbance, derive their spreading motion afresh each instant solely from local properties of the medium under consideration, independent of all previous history. For free space, it is the electric and magnetic constants of vacuum alone that continuously determine the expansion rate of the secondary sources and thus the wave-front. For a material medium, it is the refractive index, deriving ultimately from the unique electric permittivity and magnetic permeability of the medium, that is the fiducial factor. It then follows that appearances of velocity constancy reflect only an isotropy and homogeneity of the medium. It is in these respects that, for a wave-front model of light, propagation in the memoryless Markov sense is incommensurate with inertial motion in the Newtonian mechanical sense.

Although modeling as a scientific strategy was not yet well understood, a review would suggest that it was the multiplicity and disparity of optical models that effectively worked to generate a plethora of attempted theoretical constructions in the decades around the beginning of the twentieth century. At issue was the perceived need to amalgamate, or at minimum, to reconcile, the newly emergent electromagnetic paradigm of such as Faraday, Hertz and Maxwell, with the clock-work mechanical world-view that had ruled science for centuries. For many, the problem was pursued using wave-like modeling. However, such efforts were hampered, perhaps we may venture to say, corrupted, by a prevailing belief that electromagnetic radiation must have a separate and real detectable medium for its transmission through empty space - a luminiferous aether. The modeling was further complicated in that different aethers were then conjectured for different electromagnetic phenomena. Maxwell, Cauchy, Stokes, Thomson and Planck all postulated aethers with differing properties and by the end of the nineteenth century, "light, heat, electricity and magnetism all had their respective ethers."<sup>63</sup> Wave modeling was to be further conflicted when the Michelson-Morley interferometer

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<sup>62</sup> Crispin W. Gardiner, *Handbook of Stochastic Methods for Physics, Chemistry and the Natural Sciences*, Hermann Haken (ed.), 3rd ed., Berlin and New York, Springer-Verlag, 2004, pp. 42-4.

<sup>63</sup> John J. O'Connor and Edmund F. Robertson, *Mathematical Physics: Special Relativity*, The MacTutor History of Mathematics archive, School of Mathematics and Statistics, University of St. Andrews, 1996. Accessed 7 Sep 2013, Available from [http://www-history.mcs.st-andrews.ac.uk/HistTopics/Special\\_relativity.html](http://www-history.mcs.st-andrews.ac.uk/HistTopics/Special_relativity.html).

experiment in 1887, cast serious doubt on the existence of such a transport medium.<sup>64</sup> On the other hand, emission and ballistic styled solutions began reappearing. For some, a particle or projectile picture, requiring no transport medium, avoided the mounting difficulties then surrounding waves-in-aether speculations. Included in the neo-atomist resurgence were disparate formulations advanced by Sir J.J. Thomson, (1903), Albert Einstein, (1905),<sup>65</sup> Walter Ritz, (1908), Richard Tolman and Daniel Comstock, (1910), Oskar Stewart, (1911), and Jakob Kunz (1914).

For Einstein, after a troubled decade of indecisions and false starts, discovery of a universal principle appeared necessary in order to establish a stable theoretical base.<sup>66</sup> Casting notions of a light-bearing aether aside as irrelevant for a particle approach, Einstein postulated the speed of light in vacuum in the role of an independent universal constant. The concept of light-speed constancy was not of itself new. Prominent in prior deliberations of such as Irish physicist, Sir Joseph Larmor, Dutch physicist Hendrik A. Lorentz and the French polymath Henri Poincaré, had been a group of equations relating electrodynamics and the dimensions of classical mechanical motion, and in which the vacuum speed of light featured as a local constant. This group was gratuitously named by Poincaré for Lorentz as the ‘Lorentz transformations.’ The Einstein interpretation, however, bypassed what had previously appeared to Poincaré as philosophically tenuous,<sup>67</sup> to require a literalist, yet counter-intuitive, interpretation of the Lorentz transforms. Here, vacuum light-speed would measure as a universal constant independent of either source or observer. Consequently the previously acclaimed absolutes of time and spatial dimensions would become relative quantities - later denoted as ‘time dilation’ and the ‘Fitzgerald-Lorentz contraction’ - their quantification now dependent on the relative motion of the measurer.

<sup>64</sup> Albert Abraham Michelson and Edward W. Morley, ‘On the Relative Motion of the Earth and the Luminiferous Ether’, *American Journal of Science - Third Series*, vol. 34, no. 203, 1887, pp. 333-45.

<sup>65</sup> Albert Einstein, ‘On the Electrodynamics of Moving Bodies (*Annalen der Physik*, 17, 1905, pp. 891-921)’, in John Stachel (ed.), *The Collected Papers of Albert Einstein*, trans. Anna Beck and Peter Havas, vol. 2, *The Swiss Years: Writings, 1900-1909*, (Doc. 23), Princeton, New Jersey, Princeton University Press, 1989c, pp. 140-71.

<sup>66</sup> “All my attempts ... to adapt the theoretical foundation of physics to this [new type of] knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built.” Einstein, *Autobiographical Notes*, p. 566

<sup>67</sup> Henri Poincaré, ‘Science and Hypothesis (trans. from "La science et l'hypothèse," 1902)’, London and Newcastle-On-Tyne, The Walter Scott Publishing Co. Ltd., 1905. Avail. as The Project Gutenberg eBook [#37157] at: <http://www.gutenberg.org/files/37157/37157-pdf.pdf>

Although the Einstein approach, later denoted the “special theory of relativity,”<sup>68</sup> was to eventually prevail as the preferred interpretation of a mechanical-electrodynamic synthesis, its publication attracted sharp criticisms from prominent physicists such as Ernest Rutherford, now honoured as ‘father of nuclear physics,’ Oliver Heaviside, and Ernst Mach. Later, Nobel laureate Frederick Soddy and Louis Essen, inventor of the atomic clock, and expert in matters of time and measurement, condemned it as both practically and philosophically reprobate.<sup>69</sup> On the other hand, as experimental precision increased, an eclectic array of empirical results appeared to confirm Einstein’s version<sup>70</sup> of space, time, and universal light-speed constancy, to ever greater levels of accuracy. More recently, specialist laboratories pursue greatly improved precision for kinematical tests of special relativity theory in terms of local Lorentz invariance, as prescribed by the Robertson-Mansouri-Sexl (RMS) test theory<sup>71</sup> that utilizes, as both necessary and sufficient, the modern analogues of three earlier experimental procedures.<sup>72</sup> It is the extraordinary degree of empirical compliance now demonstrable that presents modern science with both paradox and dilemma. Such compliance is normally judged as verification of theoretical validity. Conversely, the Maudlin appraisal stands that: “Something has to give: either Relativity or some foundational element of our world-picture must be modified.”<sup>73</sup>

<sup>68</sup> Denoted “special” insofar as it encompasses only force-free (non-accelerated or inertial) motions.

<sup>69</sup> Louis Essen, ‘Relativity - Joke or Swindle? Louis Essen Re-states His View that Einstein’s Theory of Relativity Contains Basic and Fatal Flaws.’, *Electronics & Wireless World*, 1988, pp. 126-7. Here, in part, Essen said “I am inclined to agree with Soddy that it is a swindle; and I do not think Rutherford would have regarded it as a joke had he realised how it would retard the rational development of science.” p 127.

<sup>70</sup> In 1907, although initially rejected by Einstein, his former mathematics tutor, Hermann Minkowski, proposed ‘spacetime’ as a reconciliation of space and time that interpreted time as a virtual orthogonal fourth spatial dimension, from which the Lorentz transformations and other relativistic machinery would necessarily follow. Special relativity theory, as currently held, is more correctly the Minkowski-Einstein theory. Hermann Minkowski, ‘Das Relativitätsprinzip (*previously unpublished lecture before the Göttingen Mathematical Society, 5 November, 1907, as submitted for publication by A. Sommerfeld.*)’, *Annalen Der Physik*, vol. 352, no. 15, 1915, pp. 927-38.

<sup>71</sup> H. P. Robertson, ‘Postulate Versus Observation in the Special Theory of Relativity’, *Reviews of Modern Physics*, vol. 21, no. 3, 1949, pp. 378-82. Reza Mansouri and Roman U. Sexl, ‘A Test Theory of Special Relativity: III. Second Order Tests’, *General relativity and Gravitation*, vol. 8, no. 10, 1977, pp. 809-14.

<sup>72</sup> The 1887 ‘aether-drift’ interferometer experiment by Michelson and Morley that tests for isotropy of space; the 1932 Kennedy and Thorndike interferometer experiment, that claims a test for independence of the speed of light from the velocity of the laboratory; and the 1938 and 1941 Ives-Stilwell Doppler spectroscopy experiments, that quantitatively assess the *relativistic* Doppler shift as a test of time dilation and is sometimes referred to as *Doppler, clock-comparison*, or *one-way speed of light* experiments.

<sup>73</sup> Maudlin, [2002, p. 242](#)

One of the earliest indications for a potential break in the ranks of a later interpretive solidarity, and, in effect, conjecture that an alternative modeling of light might nourish a less counter-intuitive theoretical explanation, seems apparent in papers by Richard Tolman. In 1910, he felt it necessary to speculate on the possible destruction of an original velocity of light after passage through stationary media such as a lens or the earth's atmosphere.<sup>74</sup> Although merely a footnote, in 1912 he again aired a speculation that the velocity of light might "suffer permanent change in velocity on passing through a lense."<sup>75</sup> Coincident with Tolman's speculations, Paul Ewald studied physics at Munich University's Institute for Theoretical Physics under Arnold Sommerfeld, already notable as a pioneer of the study of wave propagation through dispersive media. Ewald's investigations extended application of the propagation of a wave-front beyond Huygens' earlier considerations of birefringence in Iceland spar, to also include electrodynamic dispersion in crystalline structures now known to be built from arrangements of atoms acting as electromagnetic dipole resonators. Independently but contemporaneously, Carl Oseen, in Oslo, published a complementary but more general examination of dispersion in isotropic media deriving directly from Maxwell's electrodynamics. Common to both works was the conclusion that an "incident optical wave is actually prevented from entering [a] crystal because of the modification produced in the field of the crystal by the introduction of a boundary."<sup>76</sup> In modern optics, the formal statement of the "*Ewald-Oseen Extinction Theorem*" is recognized as a special case of a "rigorous formulation of Huygens' principle,"<sup>77</sup> and although not apparently recognised at the time by either researcher, is now readily apparent as a specific application of the memoryless Markov property for a wave-front mode of propagation.

Implications of the Extinction theorem and its implicit warning of potentially inconclusive, or outright invalid, light-speed procedures and conclusions, went apparently ignored for decades. Such implications warned that rays of light, thought to originate from a moving source, such as the interferometer use of starlight, Tolman's light rays deriving from opposite limbs of the sun, and de Sitter's rays thought to

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<sup>74</sup> Richard Chase Tolman, 'The Second Postulate of Relativity', *Physical Review (Series I)*, vol. 31, no. 1, 1910, pp. 26-40, pp. 33, 5-6.

<sup>75</sup> Richard Chase Tolman, 'Some Emission Theories of Light', *Physical Review*, vol. 35, no. 2, 1912, pp. 136-43. p. 136, fn. 1

<sup>76</sup> Paul P. Ewald, 'Postscript 1970: Developments Arising out of Parts I and II On the Foundations of Crystal Optics', in L. M. Hollingsworth (ed.), *On the Foundations of Crystal Optics*, 26 Aug. 1970, Bedford, Massachusetts, Air Force Cambridge Research Laboratories, 1970, pp. A1-A14.

<sup>77</sup> Heidi Fearn, Daniel F. V. James and Peter W. Milonni, 'Microscopic Approach to Reflection, Transmission, and the Ewald-Oseen Extinction Theorem', *American Journal of Physics*, vol. 64, no. 8, 1996, pp. 986-95.

originate from rotating double stars, probably never entered experimental equipment for empirical assessment. Reinforcing the dire implications of the memorylessness of the continuous refracted propagation process in itself, any dielectric boundary encountered that changed the electromagnetic field properties of the optical pathway, such as a lens of glass or even of a gas such as air, would necessarily cause an irremediable optical amnesia. Extinguished would be propagation velocity information that a subsequent examination was potentially intended to reveal. The refracted ray actually entering into empirical examination was to be seen as a later generation, differing fundamentally from its ancestor: not only would its assessable propagation rate become unique to new local dielectric properties, examination of this later generation could give no clue as to a 'relative velocity' its progenitor might or might not have had prior to engagement with experimental detection.

It was 1962 before John G. Fox was to publish a detailed, yet cautious, criticism of "a particular class of direct experimental evidence" purporting to prove the Einstein universal light-speed postulate. After checking all the experiments involving moving light sources and mirrors that claimed proof of the light postulate, as listed in Pauli's 1958 *Theory of Relativity*, Fox concluded that, in every case, light generated by the source "was in fact extinguished in one way or another before its velocity was measured." Here, Fox cited the extinction theorem of Ewald and Oseen as the determining factor:

... the extinction theorem of dispersion theory ... shows that an incident light wave is extinguished at the surface of a dielectric. This may mean that information about the velocity of light from a moving source would be lost if the light passed through intervening transparent, stationary material before it was measured. All past laboratory measurements ... from moving light sources ... were made only after the light had passed through stationary material. Thus de Sitter's proof [of the light postulate] may not be conclusive. It is concluded that there may not exist any sure experimental evidence for the second [light-speed] postulate of special relativity.<sup>78</sup>

That so much historical material should prove unreliable was, for Fox, "a surprising situation in which to find ourselves half a century after the inception of special relativity."<sup>79</sup> Regrettably, and in apparent disregard for the integrity of any useful philosophy of science, the warning went mostly unheeded.<sup>80</sup> By 1967, Fox felt

<sup>78</sup> John G. Fox, 'Experimental Evidence for the Second Postulate of Special Relativity' *ibid.*, vol. 30, no. 4, 1962, pp. 297-300, p. 279.

<sup>79</sup> *Ibid.* p. 299

<sup>80</sup> one exception being an experimental report: Petr Beckmann and Peter Mandics, 'Test of the constancy of the velocity of electromagnetic radiation in high vacuum', *Journal of Research of the National Bureau of Standards: Sec. D., Radio Science*, vol. 69D, no. 4, 1965, pp. 623-8.

impelled to castigate more recent experiments that continued to ignore a potential extinction-based prorgue:

certain recent experiments ... ignore an important aspect of the propagation of light through matter ... which is the extinction of the primary radiation and its replacement by secondary radiation ... Because of this omission, the conclusions of these authors are of little or no value. The whole history of the matter of proving the constancy of  $c$  has involved an unusually large number of errors ... It is to be hoped that time will not be wasted in future on additional experiments or arguments which are nullified by extinction.<sup>81</sup>

Elsewhere, summary reports of the evidence claimed for special relativity, by such as Holton, (1962) Newman *et. al.* (1978) or Schleif (1998) equally failed to mention the topic. Of particular concern, on-going reports of results for RMS tests claiming high precision confirmation of special relativity, have also consistently failed to acknowledge that all known variants of Ives-Stilwell type moving source test procedures, both historical and contemporary, appear invalidated by the Markov property and boundary extinction at some stage of the collection process prior to evaluation of the experimental output beam.<sup>82</sup>

It was not until a 2007 revision that the subject was first briefly, and inadequately included by Roberts and Schleif as a potential constraint on ‘some experimental procedures’ or as possibly invalidating some unspecified light-speed constancy claims.<sup>83</sup> Their summary additionally attempted to exclude, as had Fox, all experimental arrangements employing high energy radiation such as hard X-rays and gamma rays, claiming that such phenomena acted only as highly penetrating particles. Repudiation of such claims is, however, amply demonstrated by the 1996 invention and then routine inclusion of “transfocators” in high energy beamlines at the *European Synchrotron Radiation Facility* at Cedex, France.<sup>84</sup> Such devices implement the wave-front model of radiation in ways similar to conventional visible-light optical refracting systems, to

<sup>81</sup> John G. Fox, ‘Constancy of the Velocity of Light’, *Journal of the Optical Society of America*, vol. 57, no. 7, 1967, pp. 967-8, p. 967.

<sup>82</sup> Modern experiments of the Ives-Stilwell (IS) type include Mössbauer rotor experiments, two photon and saturation spectroscopy experiments on atoms or ions. The most recent version of the IS experiment is in principle very similar to the original experiment. It uses collinear saturation spectroscopy on  $7\text{Li}^+$  ions moving at  $v/c = 0.064$  in the heavyion storage ring TSR in Heidelberg. Michael Edmund Tobar, *et al.*, ‘New methods of testing Lorentz violation in electrodynamics’, *Phys.Rev. D*, vol. 71, 2005, pp. 025004.

<sup>83</sup> Tom Roberts and Siegmur Schleif, ‘What is the Experimental Basis of Special Relativity?’, in Don Koks (ed.), *The Physics and Relativity FAQ: Relativity and Cosmology*, Sept., 2009, Physics Newsgroups, 2007. avail. at <http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html>

<sup>84</sup> Gavin B.M. Vaughan, *et al.*, ‘X-ray transfocators: Focusing devices based on compound refractive lenses’, *Journal of Synchrotron Radiation*, vol. 18, no. 2, 2011, pp. 125-33.

directly focus both X-rays and gamma rays. However, since the phase speed of such wave-fronts, in a variety of metals and non-metals, is slightly faster than the phase speed of radiation in vacuum, the refractive index is less than unity, and lenses need to be convex rather than concave. For practical implementation, compound refractive lenses are created wherein fine holes are drilled in a line in blocks of the selected medium with the intervening material between each hole acting as a convex refracting lens.<sup>85</sup> The notable success of such devices allows the claim that the wave-front model of radiation, and thus the memoryless Markov property, is equally applicable to all known frequencies of the electromagnetic spectrum.

#### CONCLUSION:

Although Einstein's interpretation of the Lorentz Transformations is held as consistent with, and validated by, almost all available high precision evidence, closer examination of experimental methodologies reveals that verification of the light-speed postulate, upon which the consistency of the interpretation ultimately depends, lacks unambiguous support. One case for ambiguity turns on a single issue: the suitability of the chosen information carrier for the specific task. In this connection we may conveniently recall the prior research efforts of Claude Shannon in 1948.<sup>86</sup> Effectively, such work on information theory facilitated identification, reduction, and control of the entropy of information, particularly in symbolic form, endemic in its flow through a variety of real-world channels. Such attention to the properties and conditioning of channels, ensuring their suitability as reliable information carriers, ultimately facilitated the creation of an information technology age, with its plethora of computers, internet, CD's, DVD's mobile information phones, tablets, and the like. It would then seem one of the great ironies of science that a similar attention to channel properties and application suitability is rarely found in the appropriation of electromagnetic radiation, although valued as the most ubiquitous of information carriers. And the more so when found pressed into service in attempts to verify an extraordinary and counter-intuitive claim crucial to a theory held as foundational to

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<sup>85</sup> Low atomic weight metals such as lithium, beryllium, magnesium, and aluminium have proven successful, as have boron nitride, pyrographite, plexiglass, polycarbonate, polyoxymethylene, and Vespel (a DuPont plastic). By 1998, development of compound arrays could claim a focal length of 1 metre using 856 holes of 0.25 mm radius drilled in PS (plexiglass) and focusing hard 40 keV X-radiation to a focal spot of 0.25mm. Aluminium (371 lenses), and Magnesium (561 lenses), were found to give equivalent results. B. Lengeler, *et al.*, 'Transmission and Gain of Singly and Doubly Focusing Refractive X-ray Lenses', *Journal of Applied Physics*, vol. 84, no. 11, 1998, pp. 5855-61.

<sup>86</sup> Claude E. Shannon, 'A Mathematical Theory of Communication', *The Bell System Technical Journal*, vol. 27, no. July, October, 1948, pp. 379-423, 623-56. Shannon also acknowledged the prior work of H. Nyquist (1924) and R.V.L. Hartley (1928)

modern science. It might be that we need to be reminded that the cosmos is indifferent to human aspirations - that unimpeded access to authentic information is not vouchsafed to us - that responsibility for the applicability and suitability of any methodology employed in our inquiry into the natural order ultimately rests with ourselves alone.

However, whereas properties of a wave-front model of radiation cast doubt on empirical support for a universal light-speed postulate for experimental procedures measuring light-speed from moving sources, employment of the same model in a process of theory construction, offers additional possibilities. Beyond the wave-front model being consistent with properties of quantum entanglement and the extinction theorem, inclusion of the memoryless Markov property for wave-front propagation can claim to offer a simple, and intuitive explanation for the *appearance* of an independent light-speed constancy, and this without invoking counter-intuitive notions, or any reappraisal of classical understandings of time and space. In practical terms it is essentially the relative velocity of a source frame of reference that is lost when radiation is intercepted for assessment in a laboratory frame. On this view, a length dimension would not be thought to contract due to relative motion, but rather, local information about the dimension would be seen as distorted due to a loss in velocity information incurred in the interception and measurement process. Equally, an interval of time applicable to a system in relative motion, would also falsely appear in laboratory measurement as having been dilated. Consequently, the Lorentz transformations might then be seen to quantify only the degree of information distortion expected when attempting measurement of spatial and temporal dimensions in relative motion, and where electromagnetic radiation is the chosen information carrier. Of equal importance, no upper constraint on attainable speeds of motion or propagation would be implied, and a classical Galilean conception of the relativity principle would require no modification. Such a revision of theoretical understanding might recommend itself as the ‘conceptual renewal’ sought by Bell and the fundamental modification required by Maudlin.

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