Resolution of the Wave-Particle Paradox of Light using a New Approach, Part I: Theoretical Considerations*

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We are especially pleased to announce resolution of the quantum wave-particle paradox, using a new approach originated by one of us [1]. This two-part series of papers presents the most essential ideas of the new approach in qualitative terms. The discussion is, nevertheless, augmented with quantitative statements. This paper, the Part I, is concerned with the theory fundamental to the new approach. The Part II juxtaposes the results of a preliminary computer simulation with those of a comparable experiment [2]. Together, it is shown how each quantum, following a simple (but rigorously valid) modification to the classical Huygens' Principle, traces a continuous path in space. Thus, a single quantum goes through only one slit at a time. Yet, with a shower of quanta, the wave-like interference pattern necessarily emerges at the screen. The discussion in both papers is restricted to the considerations arising in the double-slit interference of light quanta; future possibilities in both classical and quantum mechanics are virtually limitless.

I. INTRODUCTION

The paradox concerning the wave-particle duality of quantum phenomena needs no introduction. Physicists have grappled with the fundamental issues raised by the paradox for a century, only to throw up their hands in exasperation; e.g. see [3, 4, 5]. Popular science literature is replete with articles and books on these intriguing phenomena; e.g. see [6, 7, 8]. Purely speculative "literature" involving "quantum" phenomena is perhaps even larger in volume, but better left out of the present discussion; e.g. see [9] together with [10].

Nobel-laureate Richard Feynman once remarked to the effect that the double-slit experiment brings out the paradox of quantum wave-particle duality in its logically simplest form; and that a satisfactory theoretical explanation of this particular experimental situation would essentially imply resolution of *all* the known paradoxes from quantum mechanics [4].

In the Proceedings of the 48th Congress of ISTAM held in 2003, one of us announced a new approach for modeling the linear second-order PDE fields [1], therein called "Helmholtzian" fields. (That is, the linear wave, diffusion and Poisson/Laplace equations taken together as a single class. Mathematical literature unfortunately does not separately define this particular class; we shall continue to call it Helmholtzian.) The aforementioned paper on Helmholtzian fields stated a new interpretation for the Laplacian operator itself, and then took the new approach in computer modeling of ideal fluid flow (i.e. potential flow). At that time, it was implicitly assumed that, in principle, the new approach would be relevant for quantum mechanics too. The reason is that Schrödinger's equation again involves the Laplacian operator, and formally is only a linear diffusion equation.

However, instead of solving for Schrödinger's equation, it is the problem of wave fields that we now address using the new approach. In the process, we note a correction to be made to a widely accepted misconception in diffraction analysis, viz. that obliquity factor is essential to the Huygens-Fresnel Principle [11].

In the context of the Helmholtzian class of equations, although the new approach algorithmically can be reduced to random walks, the conceptualization and the proof for the new approach proceeds on the basis of the ideas fundamental to the differential wave equation and geometric probability. That is to say, in the new approach, fundamentally, continuum fields are not viewed as the limiting case of random walks; instead, the latter are viewed as a special and *non-exhaustive* implication of the former. Thus, in addressing the Helmholtzian class of field problems with the new approach, it is the Huygens-Fresnel Principle which is taken as the base.

For theory, the continuum view of the Huygens' process is first presented in the next section.

II. THEORY

A. Classical (Continuum) Huygens' Process

Consider an isolated point-source of light in a possibly multiply-connected, closed, finite 3D region of arbitrary shape and size. The problem is to find the radiation field at all the points in such a region. (The extension of the theory to infinite regions only involves physical reasoning and mathematical application on the lines indicated by Sommerfeld's analysis of diffraction [12], but fundamentally no new concepts.) For the present discussion, it is sufficient to consider monochromatic radiation; the principles remain applicable to group-waves.

The Huygens' Principle is applied to the differential wave-equation field, assuming isotropy [11]. The primary emission of the Huygens wavelets may be considered to begin at point-sources; values for line- and surface-sources can then be obtained by appropriate integrals. Note that the initially prescribed value of the field variable is not necessarily equal to its final value obtained at the source point(s). In the present, simplest model, the secondary wavelets are imagined as equal-sized spheres, each having its radius equal to the wavelength, λ. (The restriction of equal-sized spheres can be relaxed but will not be pursued in this paper.)

Refer to Figure 1. Consider the sphere S1 as a primary Huygens' wavelet emitted at the source. Each point within the wavelet S1 subsequently acts as a primary source itself, and thereby re-radiates its own secondary

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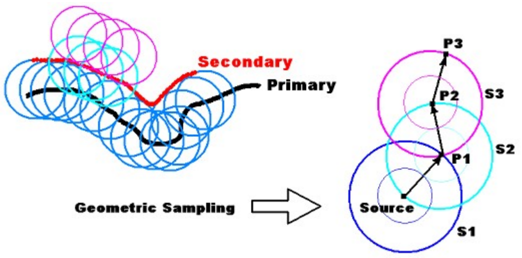

FIG. 1: Geometric sampling of the Huygens-Fresnel process. A similar figure was included during the presentation at the 48th Congress of ISTAM, but could not be included in the written paper [1] out of a lack of space.

wavelet of identical size. The frequency of the radiation remains unaffected in this process unlike in scattering. The process then repeats, progressing within the entire region, possibly with multiple internal reflections. The process stops when (at least a part of) the radiation is permanently transmitted out of the region-boundaries or absorbed at the boundaries in such a way that no re-emission again results within the enclosed region. Both the latter mechanisms of terminating the process are together called "terminal absorption" hereafter. Terminal absorption (full or partial) occurs when a wavelet-sphere comes in contact with an absorber surface. Reflection, if any, follows ordinary laws, including possible phase-reversals.

Wavelets are infinitely many even in a finite region; therefore, the field strength carried by each wavelet actually is a flux density that varies over time. The strength of the wave-field at a given point and at a given instant can be obtained by integrating over a surrounding infinitesimal sphere the flux density contributions due to all the other neighboring secondary wavelets (infinite in number) that touch it in that instant. Thus, at any given instant, the field strength at a point is given by the radiation from the local neighborhood that an imaginary, perfectly black point absorber would have accumulated there. The three assumptions of (i) integration at a point of all the field disturbances in the local neighborhood, (ii) isotropic (spherical) wavelets and (iii) infinitely many wavelets which collectively exhaust all the interior points of the region, are together sufficient to imply that the secondary wavelets interfere to produce the final, global field solution. Thus, Fresnel's hypothesis, viz. that the secondary Huygens wavelets interfere, is included in the present description of the Huygens process.

In essence, the process is spatially cascading and temporally feed-back based, involving infinitely many wavelets. However, the process still obeys the first law of thermodynamics through the mechanism of terminal absorption at boundaries. (Further, mathematically, cardinality of the region also is not an issue.) As to the second law of thermodynamics, if the inverse-square law of light intensity is to hold on the global scale, then each of the infinite Huygens' wavelets must affect its local neighborhood in an energy-conservative manner, i.e. in thermodynamic equilibrium.

Observe that the wavelets only act locally—i.e., the global field solution only evolves through the mechanisms of spatial cascades and temporal feedbacks. Thus, spatially, each point influences and is influenced by its local neighborhood alone, possibly including region boundaries; temporally, each point is influenced by the wavelets that were generated earlier in time in its local neighborhood.

Thus, the fundamental assumptions implicit here are those of causality and temporal order: Any given primary wavelet *causes* the generation of its infinite set of secondary wavelets. Further, temporally, a given primary wavelet radiates before any one of its secondary wavelets does. Such a temporal orderliness of the process is in contrast to the modern path integral-based formulations (or equivalent theories) [4, 5, 7] that remove temporal order, in principle, out of theory.

The ideas fundamental to geometric probability [13] can now be applied. However, it will help to first recast the above description, without losing a single essential feature, into a form in which probability-theoretical features can be introduced more easily.

B. Random (Yet, Continuum) Huygens' Process

First, we introduce the idea of sampling into the above description.

Using a simple model to motivate the discussion, consider the surface of the primary wavelet emitted by source S1 in Figure 1.

Now, geometrically sample the surface S1 following some scheme of sampling that uniformly exhausts all the points of that surface. The defining application of such a sampling scheme yields a single point on S1 around which the infinitesimal surface element was located during the sampling. (In probability theory terms, the surface S1 is the sample space for the random variable that maps the surface S1 to the set of the sampled points.) Let us call the sampled point P1.

The point P1 will then re-radiate another wavelet, i.e. another sphere S2 of the same radius, λ, as shown in Figure 1. Draw a displacement vector from the center of S1 to the sampled point P1.

Now, applying the Huygens' Principle, consider *P1* as the new source, and erect a sphere S2 of radius λ surrounding it as *its* secondary wavelet. Again, geometrically sample S2 to yield another point P2 lying on the surface of S2, and draw the displacement vector from P1 to P2.

The Huygens process will further continue indefinitely so long as the wavelet does not intersect a terminally absorbing surface.

The complete field solution requires sampling *all* the points on the surfaces of *all* the infinitely many secondary wavelets that together proceed to occupy every internal part of the region. Thus, in terms of paths, the process means exhausting all the infinite possibilities of paths that can establish inter-connections within the region, with the step-size equal to radiation wavelength in this simple model. (A treatment involving Huygens' wavelets of fractional wavelengths is possible, but out of scope.)

Note that despite having introduced *sampling*, the above description remains in complete correspondence with the original continuum wave-field as described in the paragraph II A above. The *only* difference is that the Huygens process II A has now been recast into a potentially stochastic form.

The description so far is only potentially stochastic in the sense that the sampling considered so far in this section can very well be taken to be systematic or orderly without affecting the final field solution.

Now, introduce *randomness* into the sampling process via the uniform, continuous probability distribution. As a necessary implication of probability theory [14, 15] and calculus, the so-changed process necessarily maintains *complete equivalence to the original continuum wavefield.*

To fix ideas, consider a single wavelet and denote as Æ the set of all the points obtained via some unspecified sampling scheme operated on its surface. (The notation Æ is a mnemonic for all: absorption, emission, and aether. The physical reasons for introducing aether into theory are given in the Part II.)

The abovementioned equivalence, when translated into this notation means that the resulting set Æ remains the same whether the sampling is random or systematic. In both cases, the set Æ carries the same elements, remains an infinite set, and carries the same cardinality as that of the continuum surface S from which it was derived during sampling. The only change introduced by randomness pertains to the order in which individual points may be admitted into the set Æ during the sampling process—not the content of the set Æ itself. Thus, the changed description still remains fully equivalent to the continuum Huygens' process, *despite the introduction of the element of chance or probability.*

Due to this equivalence, chance introduced into theory *in such a manner* does *not* imply: (a) non-causality, (b) loss of temporal order (taken in a certain sense, as limited to the progression along a path from one wavelet to its subsequent secondary wavelet), or (c) complete loss of predictability for the final field solution. The conclusion (c) arises because in all the cases—continuum or sampled (and whether the sampling is random or systematic)—the sampling is exhaustive, with *identical* cardinality.

In the present approach, randomness is taken as the absence of a certain specific form of order (temporal, spatial, or of any other form) but not as the absolute lack of all orderliness. Thus, randomness is taken as the absence of only that kind of order which is not essential to the model definition. In other words, randomness is not being suggested as a fundamental feature of reality. As simple examples as to how a particular form of order may or may not be essential to a particular system definition, consider Moiré fringes as being brought about by an order that is essential to the system definition; in contrast, in the classical kinetic theory of gases, the heat-motion of gas molecules follows an order that is inessential to that system definition.

There are further, deeper, philosophical issues here that are best left for discussions in the appropriate forums. Thus, merely introducing an element of randomness in a system description does not necessarily destroy the causality of the system.

Finally, note that since the modified Huygens process, despite now carrying randomness, is fully equivalent to the *continuum* description, it may be applied to model continuum phenomena such as sound waves in material fluids or solids.

C. Finitely-Sampled Random Huygens' Process

The next revision to the Huygens' process makes it applicable to quantum phenomena. To see how, just introduce the element of *finite* sampling, *that's all!*

In other words, we are here asserting that the finitude of sampling constitutes the necessary and sufficient modification that, when effected to the process II B above, is able to satisfactorily explain the currently available empirical evidence regarding the *quantum* propagation of light.

This being the case let us consider the premise more carefully. The premise asks that the geometric sampling scheme must carry the following two essential attributes: (i) *finite* set Æ; (ii) *uniform* probability distribution; and one further attribute: (iii) *random* sampling. Finite geometric sampling means that the set Æ will not exhaust the set S—infinitely many points would still be left on S after taking out the set Æ from it. Uniform sampling implies that if the points of the set Æ are plotted on the surface S, their local density will be uniform over any unit surface element selected over the continuum S. Randomness requires that either prescription or observation of a form of order in the enumeration of the set Æ elements, if essential to the physical system under consideration, will automatically disqualify that particular sampling scheme.

A few remarks about the finitely-sampled random process are relevant.

(i) Randomness was introduced even earlier, in the process II B, wherein it did not destroy causality and the other implied attributes. Randomness is introduced in the present theory only because the currently available observations are insufficient.

(ii) Uniformity of sampling implies that the information necessary for the final field distribution is neither distorted nor lost; only that the solutions become not necessarily repeatable and "rarified" (to use an inexact term) compared to the continuum solution. Thus, the final field distribution remains conforming to what the isotropic identical wavelets, arranged in a certain way in the region together give rise to, whether the sampling is finite or not. Here, observe that finite sampling maps onto the indefinitely divisible Real numbers space.

As a result, in overall terms, randomness is a non-essential feature of the current process description. Causality is not lost, not even in the finitely-sampled Huygens' process, and therefore, as further discussion in Part II shows, even in the quantum description of physical reality.

One final remark: the wave-particle duality cannot be described as deterministic versus probabilistic. *Both* the wave- and particle-viewpoints are deterministic. In general, in the context of the physical world, causality necessarily implies determinism. Further, causality is retained despite introducing randomness. Therefore, a proper way to characterize the duality is: continuum versus quantum.

On the above basis, in theory it is a trivial matter that as the number of points in the set Æ increases, the field solution obtained via finite-sampling corresponds better and still better with the corresponding continuum wavefield description. (The conclusion crucially depends on the *uniformity* and *isotropy* assumptions.)

For the two descriptions to become *fully equivalent*, however, even if the set Æ were hypothetically taken to be infinite in size the *cardinality* of its infinity would also have to match that of the set S. (The set Æ would be infinite if a differential form of Planck's law were to be accommodated in theory—which is not an assumption being made presently.) This statement of equivalence for the first time establishes the precise nature of the correspondence between the continuum and quantum views.

Two consequences of the correspondence are noteworthy:

(i) A basis is provided in theory to explain why the quantum interference builds up in a *gradual* manner.

(ii) The fundamental manner in which the quantum propagation process may be distinguished from the "classical" i.e. continuum process has been identified.

Many other interesting theoretical details are out of the scope of this paper. These notably include a comprehensive explanation of the physics referred to by the so-called "Uncertainty" principle, and applying Schrödinger's equation in computer modeling.

Yet, sufficient clues have already been given both qualitatively *and* quantitatively, albeit without using equations. (Appropriate notations are oftentimes found lacking in the mathematical literature.)

Another issue of some importance left out of this paper concerns a quantitative account of the phases of the wavefield. In this regard, right from the beginning, the present research has perhaps had a simpler interpretation than the one implied by, e.g. [16, 17]. The issue of phases in the context of the finitely- and uniformly-sampled (probabilistic) Huygens process will be addressed later on.

III. THE QUANTUM NATURE OF LIGHT, AND THE NECESSITY OF AETHER

Physically, the assumption of the finitude of set Æ perhaps may be taken to correspond with Planck's hypothesis that emission and absorption of occurs with finite magnitudes of energy; that the energy of the emitted disturbance cannot be made infinitesimally small. Here, note that the framework of the present approach is general enough to accommodate a *differential* form of law in place of Planck's quantum hypothesis. No principle (not even a *quantitative* one) would thereby be violated. Leaving aside complicated considerations: If a wave-like propagated quantity must be taken as finite in energy *and* spatially discrete, then the finitely-sampled Huygens' process would be required to explain it. Further, primarily, it is with the empirical evidence of the single-quantum double-slit experiments (but not out of Planck's hypothesis) that a quantum is taken to be a spatially discrete pattern.

All the modified Huygens processes involving sampling (whether the sampling be finite or not, random or not) retain a fundamental and necessary connection with the corresponding "classical" or continuum description. The connection is not merely mathematical. We do not have either empirical evidence or theoretical grounds to formulate a principle whereby we may disallow certain points of the region from at all possessing a field value. Physically, light can spread anywhere, to the best of what we know today. There has never been an observation of a systematic kind of "sieving out" effect for light propagation in a material-free space. Since we cannot restrict any single point of the region from possibly being a part of the field distribution, by implication, we also cannot arbitrarily subtract any single point from the infinite set consisting of *all the sample spaces* of all the infinite wavelets. As a necessary consequence, some or the other physical form of continuum is in principle implied even for the *finitely*-sampled Huygens' process.

This now leads to the question regarding the *physical* interpretation of the continuum, but in the context of the finitely-sampled Huygens' process. In answer: If the Huygens' process, even if finitely-sampled, requires a continuum, and if in reality the corresponding physical process (quantum propagation) does result in momentum transfer, then the physical process must occur either in a material medium, or in its absence, in a non-material (non-inertial) but physically existing aether.

Contrary to the 20th century-established idea, the *finitely*-sampled process makes the case stronger for a physical description involving aether, *not* weaker. Why so? In answer: If the set Æ is *finite* (even more so than when it can indefinitely be made large in size), to preserve *isotropy* of Huygens' wavelets, there has to be a *physical* mechanism which connects a given field point to its local surrounding points.

Observe that in any lumped or discrete physical system (i.e. one that is disconnected from its neighboring points, may be except for geometrical point-contacts), in the *general* case, isotropy is *physically unrealizable* whenever any exchange of forces or momenta occurs. As a simple but representative example of this kind of a discrete system, consider a single solid column loaded beyond its critical loading—its horizontal displacement cannot be isotropic. The finitely-sampled Huygens' process, if random as in quantum propagation, necessarily involves transport of momentum via local and transient random fluctuations. Yet, the crucial elements of such a process—viz. the Huygens' wavelet—must remain locally isotropic if the global wave-like patterns are to *quantitatively* remain in correspondence with the experimental evidence. The only way to permit long-run local isotropy at a point is to allow each point within the region to interact with its entire local neighborhood.

In analytic theory, local neighborhood of a point is defined as some unspecified extent of the region lying just outside a surrounding infinitesimal sphere. For the Huygens processes II A through II C, the finite local neighborhood can be specified not to exceed beyond a single wavelet of unit wavelength. Both definitions denote infinite connectivity.

For physics of quantum propagation of electromagnetic radiation through regions that are empty of material objects, the requirement of *infinite* connectivity, in turn, simply implies a physical aether.

Thus, in the final analysis, it is the *physical* considerations that imply that, in theory, a physical (but non-material) aether must be assumed. Mathematics can only admit the possibility of aether but due to its nature, cannot at all settle the question. To conclude, the premise of aether is at the base of quantum theory—neither outside of the theory's scope, nor a replacement for it.

IV. CONCLUSIONS (PART I)

This paper covered the fundamentals of the new approach, especially with regard to the quantum nature of light. The discussion systematically progressed from the continuum Huygens process (section II A) to the modification necessary to make it applicable to explain quantum phenomena (section II C). The fundamental nature of the relation of the continuum- and quantum-views has been precisely identified. Several clarifications regarding the probabilistic nature of the process have been noted. The discussion has been mainly qualitative in nature. However, important quantitative relations, including those for flux densities, surface integrals, characteristics of sampling schemes, sizes of infinite sets, etc. have also been noted wherever necessary.

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