What *is* a Photon?

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ABSTRACT

The linguistic and epistemological constraints on finding and expressing an answer to the title question are reviewed. First, it is recalled that "fields" are defined in terms of their effect on "test charges" and not in terms of any, even idealistically considered, primary, native innate qualities of their own. Thus, before fields can be discussed, the theorist has to have already available a defined "test particle" and field source. Clearly, neither the test nor the engendering particles can be defined as elements of the considered field without redefining the term "field."

Further, the development of a theory as a logical structure (i.e., an internally self consistent conceptual complex) entails that the subject(s) of the theory (the primitive elements) and the rules governing their interrelationships (axioms) cannot be deduced by any logical procedure. They are always hypothesized on the basis of intuition supported by empirical experience. Given hypothesized primitive elements and axioms it is possible, in principle, to test for the 'completion' of the axiom set (i.e., any addition introduces redundancy) and for self consistency. Thus, theory building is limited to establishing the self consistency of a theory's mathematical expression and comparing that with the extremal, ontic world.

Finally, a classical model with an event-by-event simulation of an EPR-B experiment to test a Bell Inequality is described. This model leads to a violation of Bell's limit without any quantum input (no nonlocal interaction nor entanglement), thus substantiating previous critical analysis of the derivation of Bell Inequalities. On the basis of this result, it can be concluded that the electromagnetic interaction possesses no preternatural aspects, and that the usual models in terms of waves, fields and photons are all just imaginary constructs with questionable relation to a presumed reality.

Keywords: photon, fundamental electromagnetic interaction, Bell Inequalities, entanglement, theory formulation

1. INTRODUCTION

The question in the title may not have an answer. Each proposed answer may be just one more iteration in an infinite regress. On the other hand, even if this suspicion is true, the question may be posed in a sense for which there is still a reasonable response. One such possibility, for example, might be that the poser expects just to have the properties of whatever a photon might be, associated with with familiar personal experiences. This would have the utility that, in thinking about phenomena involving what are surmised to be photons, it would be possible to analyze, and predict, their behavior by analogy in terms of common experiences.

In what follows, an informal discussion of the abstract features of the overarching environment for an effort to answer the title question is presented.

Historically, questions of this sort, as best the documented record reveals, arose first in ancient Greece. Actually, at that time questions about the true or fundamental nature of the material universe were secondary to those questions associated nowadays with theology, namely, what is the purpose of life (and the consequences of death) and who or what is responsible for creating it all? Frustration with the effort to answer these "religious" questions convincingly seems to have driven thinkers in a reductionist manner to focus on understanding the simpler, necessarily inanimate, constituents of the universe. It was then hoped, apparently, that the answers to the seemingly simpler questions on the nature of the inanimate world would offer guidance to answering the more complex spiritual ones. The general enterprise of contemplating both levels of such questions was known as 'Natural Philosophy.' Through the ages the effort to examine these two aspects of ontological inquiry have come to be known as: 'Theology' and 'Physics.' In this sense, Physics is the sister of Theology, In either discipline, a fundamental challenge is to establish the intrinsic validity of whatever conclusions are drawn. Here, over the millennia, these two branches have come to falling back on radially different means, in general. Very many theologians hold that certain truths have been "revealed" by means of prophets and divinely inspired books, whereas in the physical sciences the verification method is based on repeatable, empirical evidence as obtained in a process exploiting formal logic, usually in the abstract form of mathematics, for guidance.*

However, with respect to existential questions there are impediments and constraints on the 'scientific' means of verifying the validity of whatever assertions have been made or conclusions drawn. To begin, most often comprehensible, unambiguous, empirical evidence cannot be directly obtained. This is particularly true for photons, not only for the reason it is true for all hyper-microscopic entities and phenomena, i.e., they are too small to "see," but for an additional matter of principle, namely, "photons" cannot be observed directly at any size. Photons are by definition quantized portions of electromagnetic 'fields,' which, in turn, are defined in terms of their effect on 'infinitesimal test charges.' That is, fields are not seen, rather their imputed effect on charges is observed and subsequently their character is inferred, which, therefore, removes them an extra degree of abstraction from empirical study. In addition, insofar as the closest entity to an 'infinitesimal test charge' is a finite electron, itself the source of additional electromagnetic field, the inferred properties can never be purely native. That is, whatever a photon *does* that can be observed is determined finitely (not infinitesimally) by the charge(s) employed in its detection. Consequently, insofar as electrons are countable entities, the 'quantized' aspect of their nature can be the source of the impression that fields, too, are quantized in the first place.

The answer to the title question is generally expected to be at least part of an encompassing physics theory. So, what is a physics theory—why are such theories sought to begin with? Without too much adventuresome speculation, it can be said that the sought positive quality is that possessed by formal logical structures, the prototype of which is Euclidean Geometry, specifically: internal self consistency. A correctly constituted logical structure does not contain a contradiction within itself.

Logical structures consist of three levels. The first level, in the priority of the means to specify such a structure, is the selection of 'primitive elements.' For Euclidean Geometry, these are: point, line, plane, etc. In fact, their choice is a matter of intuition. For a physics theory, Einstein observed that primitive elements are deduced from common experience by intuitive, but otherwise unrestrained mental activity.[1] Another way of saying this is, there is no logical process to use to identify potential primitive elements for either a formal (mathematical) logical structure or a physics theory. The next level is the identification of certain relationships among the primitive elements; for Geometry these constitute the axiom set. Again, there is no logical procedure enabling one to "turn the crank" to deduce or otherwise arrive at this set. There are, however, some formal constraints on their choice, e.g., 'completion,' which is satisfied when the addition of one more candidate axiom introduces a redundancy. Another constrain at this level is self consistency.

The third and final level is that of additional syllogisms (known as 'theorems' for a mathematical logical structure, and in some sense as 'experiments' in a physics theory). Manipulations at this final level can determine the consistency of the axiom set. Since any contradiction within the axiom set enables the proof of any theorem whatsoever, true or false, the test for self consistency of the axiom set then is to find a theorem that cannot be proven true. In general, the disproof of a proposition (theorem) is accomplished when the offending contradiction is ultimately exposed by reducing it to an easily recognized form. Similar steps are taken to formulate and verify a physics theory.

In view of all above, the formulation now of a physics theory answering the title question is faced with the following obstacles or challenges:

1. The determination of appropriate primitive elements through the ages has proceeded from "fire, water, air and earth" through "flagiston, *elan vita*l and aether" to, *inter alia*, "Higgs-Bosons and Photon-Fermions." Hopefully this represents actual progress; although, the accepted modern "elementary particles" are of little

*Actually, some theologians too, e.g., Thomas Aquinas, have argued that the only means God has given mankind to preclude self-deception or to identify false prophesy is logical reasoning; and, motivated by this realization he authored an extensive treatise, *Summa Theologica*, in which he purports to have "logically" confirmed Christian doctrine—whether successfully so is beside the current issue.

use for interpreting physical phenomena of any sort in terms of common, macroscopic experience. Nowadays elementary entities most often are chosen to correspond with symbols found in elaborate mathematical structures.

2. In Physics, items corresponding to an axiom set would be fundamental theories. Although there are many proposed candidates, it is generally taken that their mutual incompatibility foreclosing unification is a symptom of some yet unidentified basic error or incomplete feature. In sum, arguably, the true fundamental theories are just unknown, although currently accepted variants with their empirical base certainly will come to occupy at least a niche in future theories.

3. The third level of structure for physics theories is populated with many islands consisting of chains of experiments, most of which have somewhat arbitrary starting points, usually substantially disjoint from those for other islands, but mostly near macroscopic phenomena. Many of these chains sort of appear to be converging on a common theory at a fundamental level, but there is great uncertainty.

Thus it can be said that, Physics, as a social enterprise has, as a strategy, what is essentially the reverse of that employed in Mathematics.†

Where a mathematician starts by supposing the existence of primitive elements using simple intuition, a physicist must intuit both possible primitive elements and a candidate theory on the basis of experiments the results of which could be deduced 'logically' were the fundamental particles and theories (axioms) known in the first place. In the end, moreover, while any given physics theory may be an axiom in a self consistent logical structure, in which sense it is an absolute truth, it is still just true in the sense of *self*-consistency, not necessarily consistency with respect to any exterior ontological world. Thus, while this may be the best that can be done, there still will be no guarantee that it answers those questions posed in ancient Greece. In other words, there is no logical (in the technical sense) proof that the so identified fundamental entities are anything more than fictitious characters in some kind of legend.

2. ELECTROMAGNETIC INTERACTION

Electromagnetic interaction from the time of its discovery was found mysterious. This results, evidently, from the fact that it works at a distance whereas all force exercised by biological creatures involves the experience of contact. In fact, however, contact forces, it is known nowadays, are entirely illusory. That is, when one picks up an object, no electron in the outer layer of the object "contacts" an electron of an atom in the outer layer of the actor's skin. On a nanoscopic level there is no *contact.* Thus, it is fundamentally misleading when one tries to gain precise understanding of electromagnetic interactions intuitively from common experience. Nevertheless, theorizing on the title question has involved imaginary agents of contact, which have connection with ballistic experience, namely: fields, waves and photons. For each there are multiple reasons to strongly doubt they possess any sort of ontological character, i.e., they are simply imaginary constructs corresponding to symbols appearing in mathematical formulations.

Fields, for example, are not mathematically invariant, their form depends on the observers conditions, suggesting that they are immaterial. Moreover, in formulations for the simplest possible electrodynamic problem, namely in a toy universe consisting of only two charged, structureless interacting particles, they are redundant. Specifically, if particle A is taken as a source current for which its fields at the location of particle B are found with Maxwell's equations, and then B's response found using the Lorentz Force Law, and *visa versa,* the full set of coupled (with delay) equations will have an excessive number of variables. Eliminating the offending excess variables banishes the *field variables.* The remaining equations involve only the coordinates of the world lines

†The assured existence of a logical structure is still a long way from realizing it. Mathematicians, in spite of their enviable structural proximity to logical certitude, disagree sharply among themselves regarding the solidity of much, perhaps most, of known mathematics. The situation can be only more challenging for physicists.[2]

Actually the situation is still more challenging than portrayed herein. Kurt Goedel is credited with having shown that there are valid theorems in number theory for which proof requires an infinite set of axioms.[3] In other words, the axiom set for number theory cannot be made complete by mortals. Arguably, a theory for the real, ontic world must be at least as complex as that for number theory.

for both particles, which are obviously invariant, observable, ontological entities.[4,5] Thus, self consistency alone relegates fields to the status of just abstract, mathematical aids.

Waves, in turn, in all other uses of this term, are collective motions of particles constituting a medium. Although electromagnetic waves are taken be an exception, i.e., there is no medium, the empirically known features of the electromagnetic interaction do not imply, in fact preclude, the existence of any aether or medium similar in any way to material substance. What the empirical base does support is Gauss's Law which holds between every charge and every other charge in the universe eternally. Insofar as there are two genders of charge, assemblies of charges can appear to a 'test charge' involved in an observation to be anything from intense sources of interaction, with structure (monopole, dipole, quadrapole, etc.), to neutral bodies by means of mutual shading or cancelation. Temporal variability of such structures is describable with the current wave theory of electromagnetic interaction as an appropriate approximation but not verification of ontological substance.

Photons, too, as ontological entities comprising quantized (nonexistent) fields are suspect from the start. Evidence for the existence of photons comes virtually exclusively in the optical region of the spectrum where detection is based on the photoelectric effect. As a consequence of the fact that photoelectrons are countable entities, the inference that whatever elicited them or lifted them into the conduction band of a detector circuit is also countable (quantized), is natural but not sufficient.

Thus, the state knowledge of the nature of the electromagnetic interaction between charged particles is just that it is quantitatively described by Gauss's Law with delay. Large quantities of charges, in various arrangements, on the other hand, can exhibit complex multi-body phenomena for which the most incisive approximate description can be in other terms, such as fields, waves or photons. In some circumstances, these concepts are misleading, however. In sum, there exist no fields, waves or photons as material entities; they are imaginary constructs useful as approximations for the description of limited aspects of the interaction of charged particles.

3. PHOTON NONLOCALITY

In recent times certain theorizing undertaken to plumb the fundamental nature of Quantum Mechanics seemingly has invested photons with capacity that is arguably of preternatural character, namely "entanglement" and some kind of instantaneous (nonlocal) communication. The story behind this development is long, complicated and obtuse; but, it has been discussed extensively elsewhere. In the end it all comes down to a crucial assertion, nowadays known as "Bell's Theorem," and several experimental realizations intended to test this so-called theorem.‡

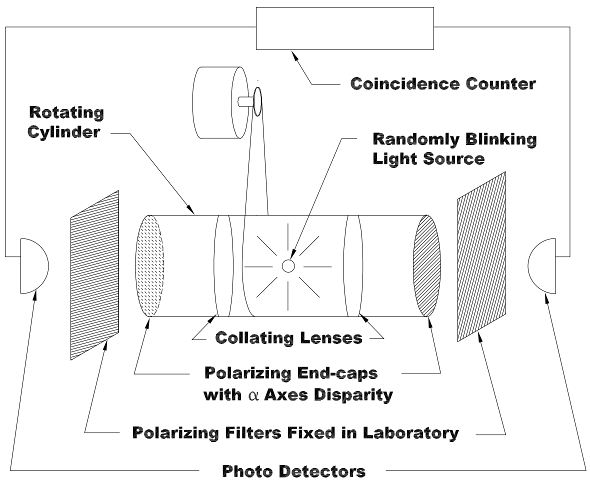

Figure 1. Schematic of a fully classical setup to produce pulses correlated in polarization but with a random bias angle. This setup is parallel to the envisioned EPR-B setup.

Bell's Theorem (the term 'theorem' in this use does not conform with conventional use) is not a verified proof, but a loose derivation of an unconventional statistic which is held to admit empirical testing capable of deciding between classical and quantum ontology. Essentially it says that, if a certain inequality is violated, then the ontic universe is ineluctably nonlocal (i.e., there exists some

‡The author's own odyssey through the mostly quite simple technological features but obscure and contorted sociological history of the origin and institutional ensconcement of Bell's ideas can be found on the web-page: www.nonloco-physics.0catch.com.

kind of superluminal communication or interaction) or nonrealistic (in the technical sense, namely that, material entities come into existence only with the collaboration of 'observers'—whether human seems undecided).

A reformulation of the common version of this statement is: 'Quantum Mechanics cannot be extended with additional variables (thus far "hidden") to get a local, realistic covering or meta theory.' Another oft seen reformulation is: 'a fully local and realistic explanation of the empirical violation of a Bell inequality cannot be found in principle.' Thus, from the last version, exhibiting a simulation based on classical physics (itself never considered nonlocal or nonrealistic) and yielding a violation of a Bell Inequality constitutes valid disproof of the general proposition unless the relevance of the classical input into the simulation can be rejected as inappropriate.

Nowadays the most common experiment proposed to test Bell's Assertion is based on a modification of the famous EPR (Einstein, Podolski and Rosen) *Gedanken* experiment. The modification consists of replacing the variables 'position' and 'momentum' as used by EPR, with the two states of polarization of electromagnetic emissions.[§] In certain experimental setups, pairs of (anti)correlated in polarization pulses are analyzed separately with polarizers set to certain combinations of angles calculated to violate a Bell Inequality.

Actually, fully classical analogues of the so-called quantum inspired experiments have been proposed and simulated with success. (See Fig. 1.)[6])[¶] That is, under similar circumstances, they too violate Bell Inequalities, thus constituting sufficient proof that there must be an error in the reasoning leading to Bell's conclusion.

```
Distribution of detections among detector pairs: N  =     2506.    2534.    2462.    2498.

*****************
Raw detections  (channels x angle choice), D:

    814.    804.    836.    414.
    417.    424.    388.    857.
    415.    426.    386.    839.
    860.    880.    852.    388.

*****************
Bell Index for this distribution of detections: S  = 2.7884935

*****************
Theoretical maximum violation: S0  = 2.8284271



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Figure 2. Typical output from the Scilab simulation depicted in the appendix. The deduced Bell Limit, S, varies about the theoretical maximum. This results from the fact that the simulation includes no provision for taking account of inefficient detectors or arrival time variability of photoelectrons in those detectors.

Nevertheless, the generally held opinion is still in favor of the validity of the Bell-type argumentation and all of the consequent conceptions. The reasons for this situation are many but surely include the fact that it has proven difficult to simulate classical models of EPR experiments at the event-by-event level. The difficulty

[§]This modification can be criticized on the grounds that, whereas EPR proposed an experiment described by mechanics in *phase space*, The Bohm Modification is to be described in polarization space. The former can be, and is, quantized, the later is not, and cannot be. That is, logically, quantum phenomena cannot be fathomed in a venue in which they cannot exist.

[¶]This model was used by Mizrahi & Moussa to simulate EPR-B experiments and show that classical analysis leads unambiguously and directly to a violation of Bell Inequalities. However, they did not report an event-by-event simulation.
There are least a dozen similar models to be found in the literature, e.g., one by Barut in which he shows that a statistical analysis of spins also leads to an classical understanding of what usually is regarded as a quantum phenomenon.[7]

just at this point arises, apparently, from the way in which signal intensity has to be treated in order that a simulation mock the imagined quantum processes involved in experiments. In the experiments, it is imagined that, the processes are at the one-photon intensity level. At this level relative intensities are determined only in terms of the relative populations of detections and not directly measured as current intensity for each event.

Additionally, the definition of a correlation coefficient requires the data to be both normalized and zero-mean. Normalized detection counts span the interval $[0, 1]$ but are not offset to the interval $[-1/2, +1/2]$, and therefore are not qualified in this form for calculating correlation coefficients.

In any case, with this understanding in mind, classical event-by-event simulations of the model of the processes involved in generating the data from an EPR-B set-up (The EPR variant proposed by Bohm employing light polarization states in place of phase space variables) are straightforward. For example, see the Appendix, which presents a Scilab (Matlab clone) routine to simulate the model described by Fig. 1. Fig. 2 presents typical results.

This demonstration leaves one point still open, however. It is the following:

The full mathematical definition of the correlation coefficient is:

$$\kappa(a,b) = \frac{< I(a)I(b) > - < I(a) >< I(b) >}{[(< (I(a))^2 > - < (I(a)) >^2)\,(< (I(b))^2 > - < (I(b)) >^2)]^{1/2}}, \tag{1}$$

where $I(\bullet)$ is a data point as a measured current intensity or a detection count. The $< \bullet >$ indicate normalized variables for which the correlation is sought; the terms $- < (I(\bullet)) >^2$ shift the normalized variables making them zero-mean. When the raw data is normalized and shifted (or is intrinsically zero-mean), then this formula reduces to:

$$\kappa(a,b) = \frac{D'_{++} + D'_{--} - D'_{+-} - D'_{-+}}{D'_{++} + D'_{--} + D'_{+-} + D'_{-+}}, \tag{2}$$

where the D' are adjusted counts. The adjustment is given by:

$$D' = \frac{D'' - < D'' >}{< D'' >}, \tag{3}$$

where D'' are the normalized data for which the mean equals $1/2$.[‖] Thus, the fully adjusted data is given by $D' = 2D'' - 1$. When inserted in Eq. (2), the final result takes the form:

$$\kappa(a,b) = \frac{2(D_{++} + D_{--} - D_{+-} - D_{-+})}{D_{++} + D_{--} + D_{+-} + D_{-+}}, \tag{4}$$

where the D's are *unadjusted* counts, i.e., neither shifted nor normalized.

All this leads to the following observation: Experimenters report calculating κ with Eq. (2) using unadjusted data from EPR-B setups. They also claim that, even with such counts they obtain a violation of a Bell Inequality. The manipulations above, however, show that, such data cannot violate a Bell Inequality without the factor of two (derived from the shift to zero-mean in the numerator of Eq. (4)); but, their reports do not discuss or display this factor.[**] In the quantum calculation the offset factor is built in as the normalization for the singlet state.

[‖]In addition, these data result from an application of Malus' Law, proportional to $\cos^2(\theta)$ for which the mean is $1/2$. This cannot be validated in detail from experimental data because the random bias angle is unknowable. Likewise, it cannot be excluded.

[**]Many experimenters report labeling some channels "+" and others "−" and then seem to indicate doing calculations with these labels. This may offer a means of doing the offset to zero-mean under artificial premises.

It has been suggested that, "Unuploaded experiments (including explicit data analysis) have no results."[8] Perhaps this principle should be extended to 'unuploaded simulation routines.'

4. CONCLUSIONS

Based on the considerations presented herein, it can be argued that "photons" are much more likely to *be* mental conceptions than to *be* ontic entities. Their primary utility seems to be as imaginary agents for ballistically transmitting contact from one charged ontic entity to another charged ontic entity. Apparently, mortals find it less difficult to imagine "contact forces," even though it is utterly clear that such are not ever in play—electrons cannot "contact" each other without infinite energy expenditure.

Moreover, it is certainly contestable that the electromagnetic interaction, at any level, exhibits mystical properties, e.g., 'entanglement,' 'non-locality' or 'irreality.' these features of current theories are more easily taken as symptoms of fundamental errors in reasoning or the application of probability theory.

On the whole, theorization may be incapable of answering the question: "what is a photon?" or, what is any ontic entity with assurance that any given candidate answer is 'certain knowledge.' The best that appears to be achievable is the proof of self consistency for a logical structure based on hypothetical entities. Thus, only if the *surmised* primitive elements are in fact very similar to ontic entities, is a degree of confidence in the theory justifiable.

This is not to claim that theorizing on the ontic nature of the primitive elements is pointless, only that it cannot be taken to lead to certain knowledge. It seems obvious that, analyzing macroscopic situations with very large sums of Gaussian interactions (with or without delay) would be very inefficient, if doable at all. In such circumstances a continuous Maxwell field rendition, as an approximation, may be the only practical means available. Likewise, a photon picture has proven useful, virtually essential, in many circumstances, even while it cannot be taken as guidance for fundamental ontological determinations.

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5. APPENDIX

```
//Scilab routine to simulate EPR-B experiments;  exec("Bell_EPR-B_sim.sl")

clearglobal(); clear();                                        // Clean kernel
a1=0; a2=%pi/4; b1=%pi/8; b2= -%pi/8;                          // Set polarizer angles
D=zeros(4,4); N=zeros(1,4); K=zeros(1,4);                      // Initialize variables
S0=2*sqrt(2);
E=10000;                                                       // Set No. total pairs

for i=1:E;
        if rand()<0.5 then p=0; else, p=1; end;                // Generate orthogonal
        Pl = round(rand(1)*35)*1*%pi/36;                       // signals with random bias
        Pr = Pl + (-1)^(p)*%pi/2;
        if rand()<0.5 then Dl=a1; a=1; else, Dl=a2; a=2; end;  // Select detector angles
        if rand()<0.5 then Dr=b1; b=1; else, Dr=b2; b=3; end;

        c=a*b;
        select c                                               // Set key "k"
                case 1 then k=1;
                case 3 then k=2;
                case 2 then k=3;
                case 6 then k=4;
        end,

        N(k)=N(k)+1;                                            // Count pairs/angles
        if rand()<I*cos(1*(Dl-Pl))^2 then; e=1; else, e=2; end;  // Register detections
        if rand()<I*sin(1*(Dr-Pr))^2 then; f=1; else, f=3; end;  // (Malus Law)

g=e*f;
        select g                                                //Count coincidences/pairs
                case 1 then, D(1,k)=D(1,k)+1;
                case 3 then, D(2,k)=D(2,k)+1;
                case 2 then, D(3,k)=D(3,k)+1;
                case 6 then, D(4,k)=D(4,k)+1;
        end;
end;

for k=1:4;
        K(k)=2*(D(1,k) + D(4,k) - D(2,k) - D(3,k))/N(k);       // Coincidence Coefficients
end;
S= K(1) + K(2) + K(3) - K(4);                                  // "Bell Index ( ? <2 ? )"

printf('Distribution of detections among detector pairs:'), N, write(%io(2),'************'),
printf('Raw detections  channels x angle choice:'), D, write(%io(2),'************'),
printf('Bell Index for this distribution of detections:'), S, write(%io(2),'************'),
printf('Theoretcial maximum violation:'), S0,
```

Appendix This is a Scilab routine that simulates the processes envisioned in the setup depicted in Fig. 1. It yields a violation of Bell Inequalities if the data is normalized shifted to be zero-mean in accord with the formal definition of a correlation coefficient.