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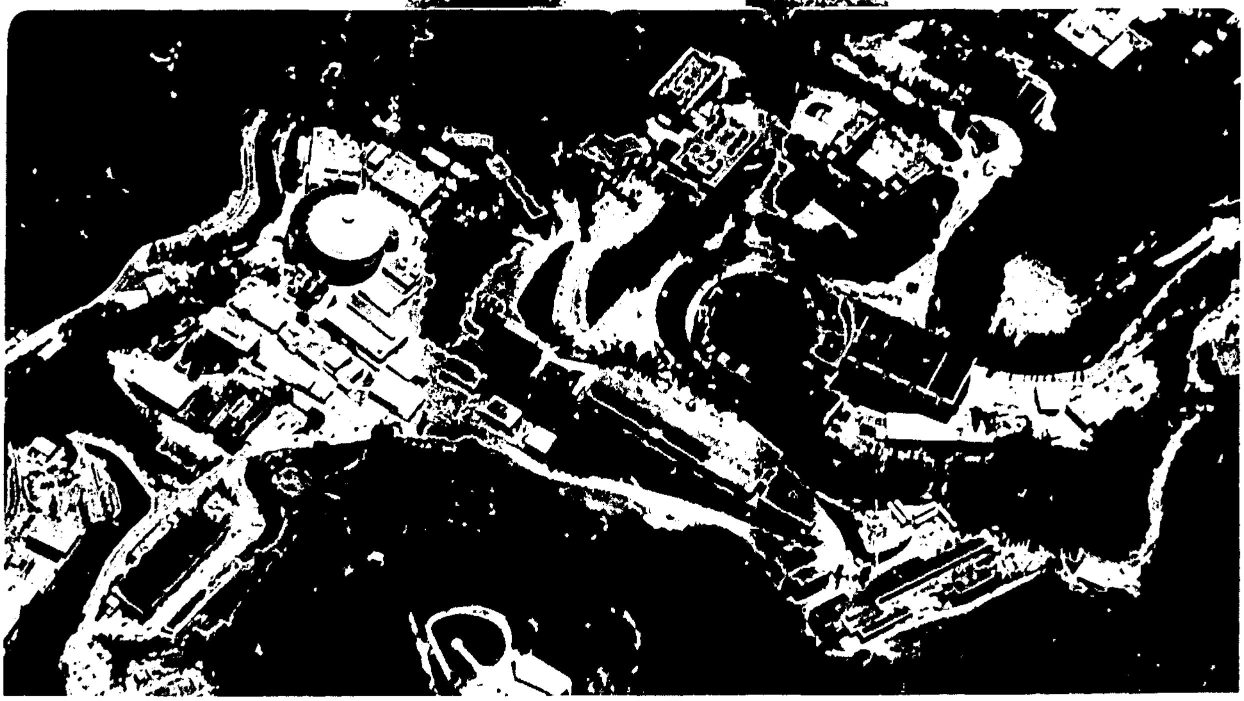
G.F. Chew

December 1985



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Bootstrapping 3 Levels of Reality in the Language of Open Graphs* ,**

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Abstract

A survey is given of topological-bootstrap-theory aspects that connect objective reality, the S matrix and elementary particles.

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I. Introduction

For purposes of this talk, "objective reality" is to be understood as meaning the Cartesian-Newtonian world of distinguishable and observable entities moving in an *a priori* continuous space-time. The "objectively-real" continuous world can be puzzling from a discrete – "quantized" – viewpoint. This talk will review relevant aspects of a discrete world picture based on graphs that has been evolving for more than a decade.(1) Principal contributors have been Dieter Issler (since 1982), Jerry Finkelstein (since 1977), Basarab Nicolescu and V. Poénaru (since 1978), and Henry Stapp (since 1974), although a dozen or so further names would be needed for a complete list. Fritjof Capra, for example, has had an influence. I am writing a book about this approach which is called Topological Bootstrap Theory (TBT). The adjective "topological" reflects the theory's dependence on graphs and surfaces that embed graphs, while the adjective "bootstrap" characterizes the attempt to avoid arbitrariness through attention to consistency. TBT seeks to avoid arbitrary ingredients through the criterion of a unique consistent pattern of "event" relationships. The word "event" in TBT starts out meaning no more than the vertex of a graph; finding a richer meaning is part of the bootstrap process.

A bootstrap theory is inherently circular and without unalterable "fundamental" principles. The "rightness" of a framework and rules for connecting with our awareness of "reality" can be justified only a posteriori. No bootstrap concepts need be "exact" but merely should be meaningful to an accuracy sufficient for consistency of the whole picture. The present TBT framework has evolved by trial and error out of the notion, generated in the late fifties, of bootstrapping hadrons through an analytic S matrix that requires a priori meaning for momentum but not for microscopic space-time. Studies of conditions satisfied by a consistent S matrix focussed attention on graphs, which gradually became seen as providing language that might describe not only the S matrix but other "levels of reality".

II. S Matrix and Objective Reality

I shall here be speaking of 3 different but circularly-connected "levels of reality". At each level graphs are relevant, although interpretation of a graph depends on the level. The best-understood graphical regime is that of the S matrix, where a graph line corresponds to a stable (or almost stable) particle that can be individually given meaning by the experimental apparatus of atomic, nuclear and high-energy physics. Each line of an S-matrix graph carries a discrete spin and a continuous 4-vector momentum P_μ of a definite Lorentz length – $P_\mu P^\mu = m_i^2$ – where m_i is the particle mass. Each graph represents a singularity in the complex-momentum space of an analytic S-matrix element – characterizing location, nature (e.g., pole or branch point) and strength of the singularity – through rules associated with the names of Landau and Cutkosky.(2)

Built into the S-matrix notion, however, is a paradox: Although graphs have discrete structure, the experimental meaning of momentum requires the continuous objective (macroscopic) reality of Newton and Descartes; such a reality does not immediately attach to elements of the S matrix. TBT assumes massless spin-1 photons, coupled to a conserved electric charge, to underlie this paradox. The attempt to describe low-momentum ("soft") photons through the S matrix requires changing basis to asymptotic coherent states where the number of photons is not well defined, corresponding in some sense to a classical electromagnetic field. The precise sense is not understood – the meaning of "S matrix" becoming blurred by soft photons; at the same time it appears true that any apparatus capable of measuring momentum depends on macroscopic classical electromagnetism. I shall expand later on how soft-photon coherence clouds an S-matrix meaning that is clear when only massive particles are involved, while providing significance for momentum.

Let me note in passing that the miracle of objective reality – which implies "reproducible observability of isolated systems" – requires "screening", the tendency for "clumps of matter" to be electrically neutral. Screening of electromagnetism, which stems from unit photon spin, is essential to allowing experimental configurations where the S matrix has approximate significance. Gravitational forces cannot be screened and fail to be a disabling impediment for the S matrix only because they are so much weaker than electromagnetic forces.

The familiar level of objective reality provides the underpinning of "hard science" with its localized and reproducible measurements. Stapp has suggested the term "classical event" to characterize a "measurement" approximately localized in a continuous macroscopic space time. (Ignoring possible finiteness of the universe and assuming no limit to the space-time separation between "localized" measurements, imprecision of individual localization can be made arbitrarily unimportant.)

Any "classical event" needs involvement of a large number of particles to yield the extraordinary accuracy of objective reality, but individual particles may be "observed" through interaction with a large collection of other particles. Such "semiclassical events" provide the Copenhagen bridge between S-matrix and objective reality – giving hard science capacity to "measure" connected parts of the S matrix, such as designated by the diagram of Fig. 1, where there are N external lines. Here each s_i designates a "semiclassical event" that (approximately) locates particle i in the (macroscopic) space-time of objective reality and measures its momentum. A complex number called a "scattering amplitude", belonging to each set of momenta $P_1, P_2 \cdots$ in Fig. 1, is an analytic function of P_i apart from isolated singularities associated with graphs such as that of Fig. 2. One sees here that S-matrix-graph ends associate with "semiclassical events". It has been shown that any S-matrix internal vertex is meaningfully characterizable as an "unobserved intermediate event" involving those particles whose lines impinge on the vertex. (Momentum is conserved at each internal vertex.) In the sense that an analytic function is constructable from its singularities, the scattering amplitude corresponding to Fig. 1 is built from all patterns of unobserved intermediate events that can connect the specified collection $[s_i]$ of semiclassical events. Fig. 2 is one such pattern.

The foregoing "pure S-matrix" notions make sense to the extent that S-matrix graphs lack lines corresponding to photons of momentum vanishingly small on the scale of charged-particle masses and mass differences. Such lines couple two different levels of reality. TBT supposes that multitudes of "soft"-photon lines cohere to give meaning to "semiclassical events" – "gently connecting" each end of an S-matrix graph to some large assembly of charged particles that collectively constitute a "classical object". Some small "effect" on the classical object "induced" by this soft-electromagnetic connection to the S-matrix external-line i constitutes "measurement" of the position and momentum of particle i. (Quotation marks here identify words that are especially ill-defined.)

In what sense can a large assembly of charged-particle graph lines behave as a "classical object"? Is it possible, in principle, to explain objectivity through superposition of graph-associated complex numbers? Answers to these questions are not known, but examples abound in the literature of quantum mechanics where amplitude superposition leads to near cancellation except for extremely special event patterns close to those allowed by the usual understanding of objective reality. A TBT conjecture is that systems of large baryon and lepton number, because of phase factors associated with soft electromagnetic interparticle linkage, can behave as classical objects. Fig. 3 associates this conjecture with a graph, where wiggly lines denote "semi-soft photons" – of momentum small compared to masses but not necessarily to mass differences. Solid lines in Fig. 3 are massive particles, whose continuity provides a continuing "identity" for the object. (Contrast with Fig. 2, where there is no continuing identity.)

Another TBT idea, motivated by the infrared-graphical analysis of Stapp,(3) is that the meaning of a single (universal) macroscopic space-time interlocks with soft electromagnetism. The internal vertices of a connected S-matrix graph like Fig. 2 (without soft-photon lines) can be given macroscopic space-time labels x_j interpretable as the approximate location of corresponding events. "Macroscopic" means these x_j labels become asymptotically meaningful as distances between vertices become "large" on distance scales associated with (inverse) particle masses and mass differences. Space-time vertex labels on a connected S-matrix graph are defined, however, only up to an arbitrary Poincaré transformation plus an arbitrary expansion of space-time scale. What ties together the space-times belonging to different, disconnected graphs (thereby allowing the notion of a "single universe")?

Roughly speaking, one might say that all disconnected S-matrix graphs are connected by soft photons. Stapp shows that soft-photon lines attached to the "interior" of any S-matrix graph, such as that of Fig. 2, collectively correspond to a classical electromagnetic field whose sources are approximately localized at the vertex x_j's. This classical field, carrying a single space-time label x, is coherently generated by all event patterns (throughout the "universe").

I have in fact both overstated and misstated Stapp's result in an effort to simplify and persuade. More study is needed to make precise the meaning of what has here been called a "classical field". A better statement would be that I personally find in Stapp's result a compelling suggestion that (discrete) graphical superposition, when zero-mass photons are included as well as massive particles, implies objective reality in (continuous) macroscopic space-time. It seems to me unnecessary to postulate (continuous) objective reality independently of (discrete) "quantum mechanics".

The foregoing scenario requires both massive and massless particles. A feature of objective reality is the presence of length scales that allow classical objects to have a "size". Let me also remark that passage from P_i line-labels to x_j vertex-labels on S-matrix graphs involves a linear superposition with coefficients $e^{iP_ix_j}$ – fourier transformation – and rules for how to circumvent singularities in momentum space. These rules ensure "macroscopic causality", another aspect of objective reality. I stress that, from the TBT viewpoint, x_j vertex labels, introduced by fourier transformation, acquire significance (as "event locations" and "sources of electromagnetism") from their place in a bootstrap mosaic which employs soft photons together with massive charged particles to generate "classical objects" and both classical and semiclassical events. TBT supposes the meaning of continuous macroscopic space-time to emerge from the bootstrap hand in hand with the meaning of continuous classical electromagnetism. Approximate continuity stems from the "gentleness" of any graph vertex where a massive charged particle emits or absorbs a soft photon. Multitudes of discrete "gentle events" are supposed to create (approximately) continuous objective reality.

I have said nothing yet in this introduction about "fully-classical events" – where one classical object "makes a measurement" upon another. A graphical representation of such "interobject awareness" would employ a number of soft-photon lines that is large and yet much smaller than the number of "semisoft" lines internal to the "individual" objects. See Fig. 4. To the extent that most of the massive charged-particle lines are not directly involved in the "event", a classical object remains almost undisturbed when a measurement is made upon it. It is at present only a conjecture that superposition of contributions from (graph-associated) singularities of complex amplitudes is consistent with the Fig. 4 graphical representation of classical objects and classical events. The best I can do is to plead ignorance of any argument for inconsistency.

III. Elementary Particles

A third level of reality I shall call "elementary particles", although such a name can be misleading because most TBT elementary particles are "bound states" built of indefinite numbers of other elementary particles. The elementary-particle level is represented by single-vertex "embellished graphs" – or "topologies" – that associate with topological amplitudes, together with multivertex embellished graphs that associate with singularities of these amplitudes. I shall below explain the significance of the adjective "embellished". Superposition of a denumerable but indefinitely-large collection of topological amplitudes – called the "topological expansion" – is assumed by TBT to generate singularities in (complex) momentum that correspond to the lines of an S-matrix graph – i.e., to "physical" particles.

Graphical singularity generation is a familiar feature of perturbative Lagrangian field theory, but two features distinguish TBT therefrom:

A) Discrete labels – "quantum numbers" – on elementary-particle lines are not arbitrarily assignable but derive from 1 and 2-dimensional oriented manifolds that consistently "embellish" the momentum-carrying graphs – endowing each graph with a definite topological complexity or "entropy". I shall explain how the current version of TBT associates electric charge to orientation of a (1-dimensional) line and spin to orientation of a (2-dimensional) surface; all other discrete TBT particle properties similarly stem from line and surface orientations.

B) Any collection of embellished TBT elementary-particle amplitude topologies related to each other by smooth entropy-preserving displacement of lines and vertices are equivalent – i.e., all equivalent topologies associate with a single amplitude. Roughly speaking, such equivalence means that a cluster of elementary particles may be indistinguishable from a single elementary particle.

A TBT elementary-particle momentum graph is embedded in an oriented and bounded two-dimensional surface, with graph ends on the boundary. The TBT surface boundary is a one-dimensional manifold that bears some resemblance to the "string" concept employed in a currently popular form of Lagrangian theory. But the TBT "string" does not move in space-time; it simply is the boundary of an abstract surface that embeds the momentum graph. Because the surface is 2-dimensional, the boundary is 1-dimensional.

The essential function of the 2-dimensional surface that embeds the momentum graph is to provide precise characterization of topological entropy, which controls topology equivalence. TBT assigns to each embellished graph a set of nonegative integers that characterize the topology complexity. These integers are called entropy indices because they can only increase when topologies are sewn together (building larger event-clusters from smaller event-clusters). Some momentum graphs, for example, are embedded in (bounded) surfaces of zero genus – spheres minus disks – while other graphs require a toroidal surface. The surface genus is an entropy index; e.g., the sphere has genus zero and the torus genus 2.

The boundary of the TBT graph-embedding surface is not necessarily connected, but any boundary component containing momentum-graph ends exhaustively divides into connected pieces each associated with an elementary particle. I give as an immediate example in Fig. 5 a closed piece of TBT surface boundary which corresponds to a gauge boson (such as a photon). The mark x locates the end of the gauge-boson momentum line while the second mark locates the ends of electric-charge carrying lines, embedded in the surface carrying the momentum graph, that were introduced into TBT by Jerry Finkelstein. The sense in which a Finkelstein line controls electric charge through its orientation will be explained. Also to be explained is how each of the two "boundary units" that build the gauge boson of Fig. 1 may be described as "fermionic" – carrying a 2-valued degree of freedom that couples to momentum like spin 1/2. (The unit spin of a TBT vector gauge boson arises from its two constituent spin-1/2 units.) Although a gauge boson corresponds to a circular portion of surface boundary, most TBT elementary particles correspond to open boundary portions such as the 4-unit portion shown in Fig. 6, which has been called an "elementary meson". The two boundary units here touching the momentum graph are fermionic, like the units of Fig. 5, while the two units that fail to touch the momentum graph emerge as "bosonic" – carrying no spin but another 2-valued attribute, this one corresponding to an "internal" quantum number uncoupled to momentum.

Fig. 7 shows a cubic-vertex embellished momentum graph coupling a photon to an elementary pair of singly-charged mesons. The surface here is a cylinder (sphere minus 2 disks), divided into 5 patches by Finkelstein and momentum lines. The entire surface is (globally) oriented, as shown by the circular arrow, and although not indicated in Fig. 7, each patch is (locally) oriented. The 3 momentum lines and 3 Finkelstein lines also are each independently oriented, although Fig. 7 shows only Finkelstein orientations.

A Finkelstein orientation is designated $c(n)$ if it agrees (disagrees) with global surface orientation (see Fig. 7). Because Finkelstein orientation is continuously preserved together with global surface orientation when embellished graphs are sewn together, the (c, n) index corresponds to a pair of conserved quantum numbers. In particular the head (tail) of a c Finkelstein line corresponds to $+1(-1)$ unit of electric charge carried by the elementary particle within whose boundary portion the Finkelstein line ends, whereas both ends of an n Finkelstein line bestow zero electric charge. Each elementary meson in Fig. 7 contains one c and one n Finkelstein-line end; these mesons correspondingly each carry one unit of electric charge. The photon, containing 1 c Finkelstein head and 1 c tail, itself has zero electric charge; nevertheless the photon is seen to couple to electric charge by virtue of its own c^+c^- content.

The 2-valued (c, n) index corresponds to an "internal" degree of freedom that particle physicists call weak isospin; Finkelstein lines are often called "isospin lines". Isospin symmetry corresponds to a topological amplitude remaining unchanged in value when a (local) Finkelstein orientation is reversed. All other TBT symmetries have an analogous basis. (In Fig. 7, if one c Finkelstein line is reversed in orientation – becoming n – the photon changes to a W boson while one of the charged mesons becomes neutral.)

Ordinary spin, which can couple to momentum, resides in orientations of fermionic surface patches – that touch momentum-carrying lines. In Fig. 7 each fermionic patch (densely shaded) includes exactly two particle units (of the full-surface boundary) along the patch boundary. Any such fermionic boundary unit, when isolated, touches a momentum-carrying line at one end and an isospin line at the other – as shown in Fig. 8. If a $U(D)$ label is attached to a boundary unit according to whether the local patch orientation agrees (disagrees) with global surface orientation, two boundary units belonging to the same fermionic patch necessarily agree in (U, D) label. The TBT surface thus couples (U, D) content of different elementary particles; Fig. 7 couples photon fermionic (U, D) content to that of mesons.

The fermionic (U, D) degree of freedom becomes identifiable as spin because of its relation to momentum. TBT rules for sewing together embellished graphs(1) lead to structures such as the meson-meson topology of Fig. 9, which should be compared to Fig. 7. The hole in the middle of Fig. 9 does not correspond to a gauge boson but rather to a momentum factor that appears in the associated amplitude. The four components of momentum correspond to the 4 pairs of labels, (U, U), (U, D), (D, U), (U, U) that attach to the two fermionic boundary units that surround the hole. Here the TBT surface is coupling meson spin to meson momentum. Because of the parallelism illustrated by Figs. 7 and 9, which generally allows interchange of gauge bosons with factors of momentum, the hole in Fig. 9 is called a "gauge hole". It is hoped that, at the elementary-particle level of reality, gauge-hole, gauge-boson parallelism – the TBT analogue of gauge invariance in field theory – will lead at the S-matrix level to massless spin-1 photons coupled to a conserved electric charge and thereby to the macroscopic objective reality that allows physical meaning for momentum and closes a bootstrap cycle.

TBT practitioners nevertheless cannot be content with the continuous status of momentum that goes along with the idea of an indefinitely-large and flat macroscopic space-time. Consideration of gravitation and cosmology – a fourth level of reality – promises to make momentum discrete (perhaps cosmological reality is representable through closed graphs). Conversely put, if TBT can achieve an entirely discrete representation for all levels of reality, a finite cosmology is a natural expectation.

Acknowledgments

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Figure Captions

Fig. 1: S-matrix connected part coupling "semiclassical events".

Fig. 2: Landau graph representing an S-matrix singularity in complex momentum.

Fig. 3: Classical object.

Fig. 4: Classical event.

Fig. 5: Gauge-boson boundary portion (2 units).

Fig. 6: Elementary-meson boundary portion (4 units).

Fig. 7: Embellished momentum graph for interaction of photon with pair of charged mesons.

Fig. 8: Fermionic boundary unit.

Fig. 9: Gauge hole in meson propagation.

References

1. A recent paper containing a complete list of TBT references is "Single-Surface Basis for Topological Particle Theory" by G.F. Chew and V. Poénaru, Phys. Rev. D32, 2683 (1985).
2. The Analytic S-matrix, R. Eden, P. Landshoff, D. Olive and J. Polkinghorne, Cambridge Univ. Press (1964).
3. H.P. Stapp, Phys. Rev. D28, 1386 (1983).

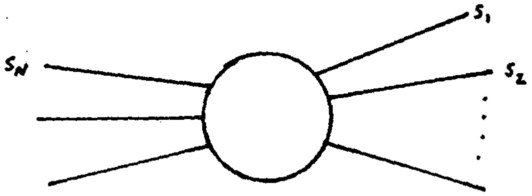

Figure 1

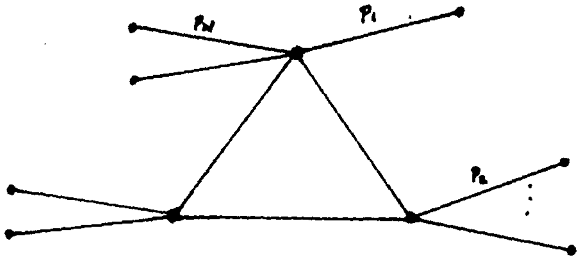

Figure 2

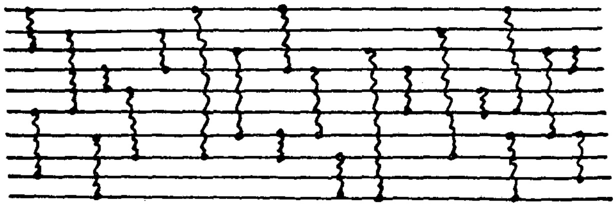

Figure 3

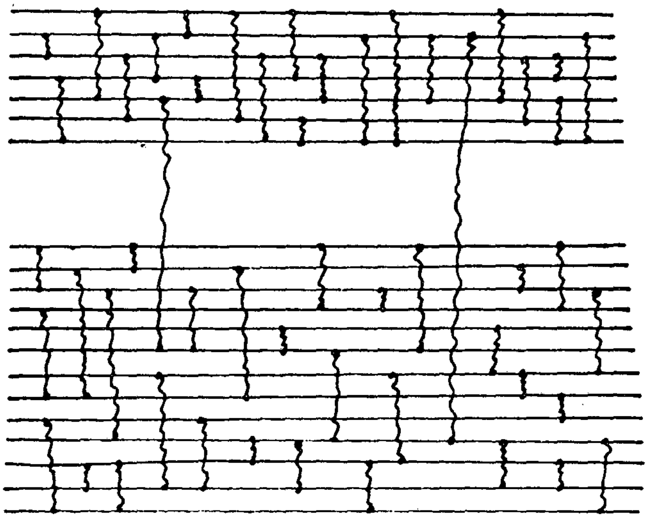

Figure 4

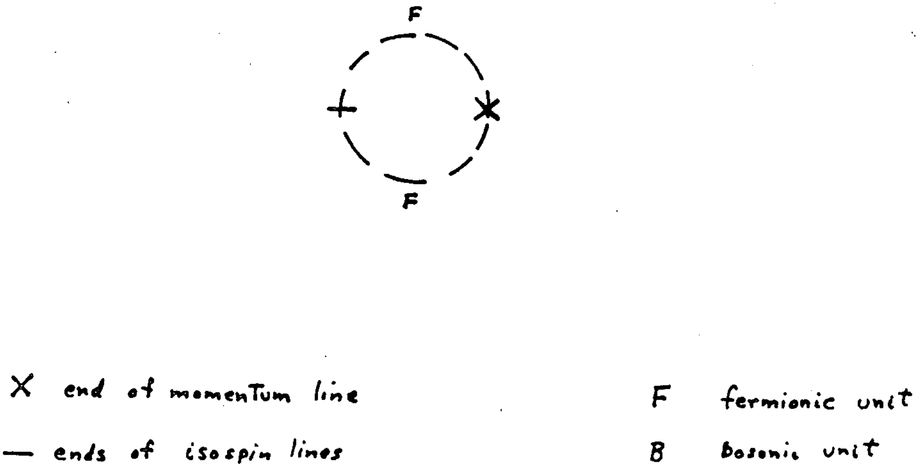

Figure 5

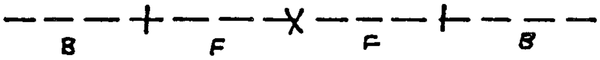

Figure 6

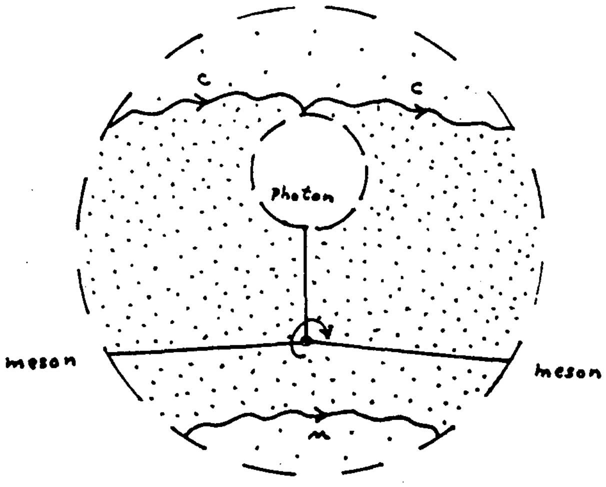

Figure 7

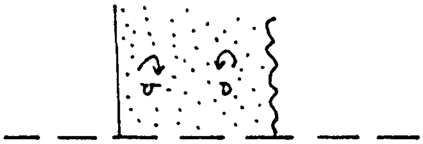

Figure 8

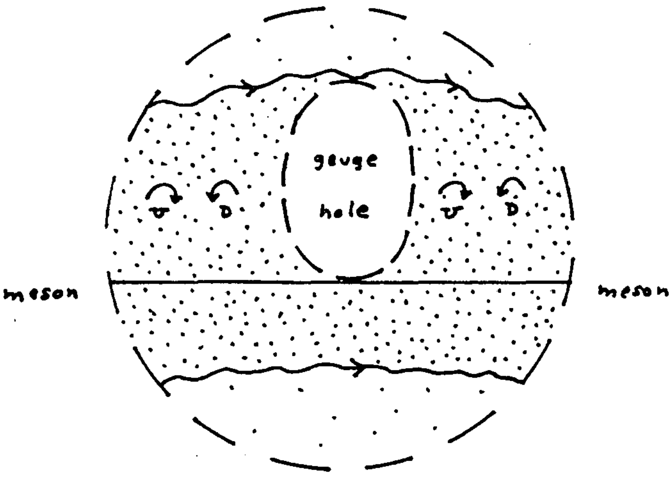

Figure 9

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