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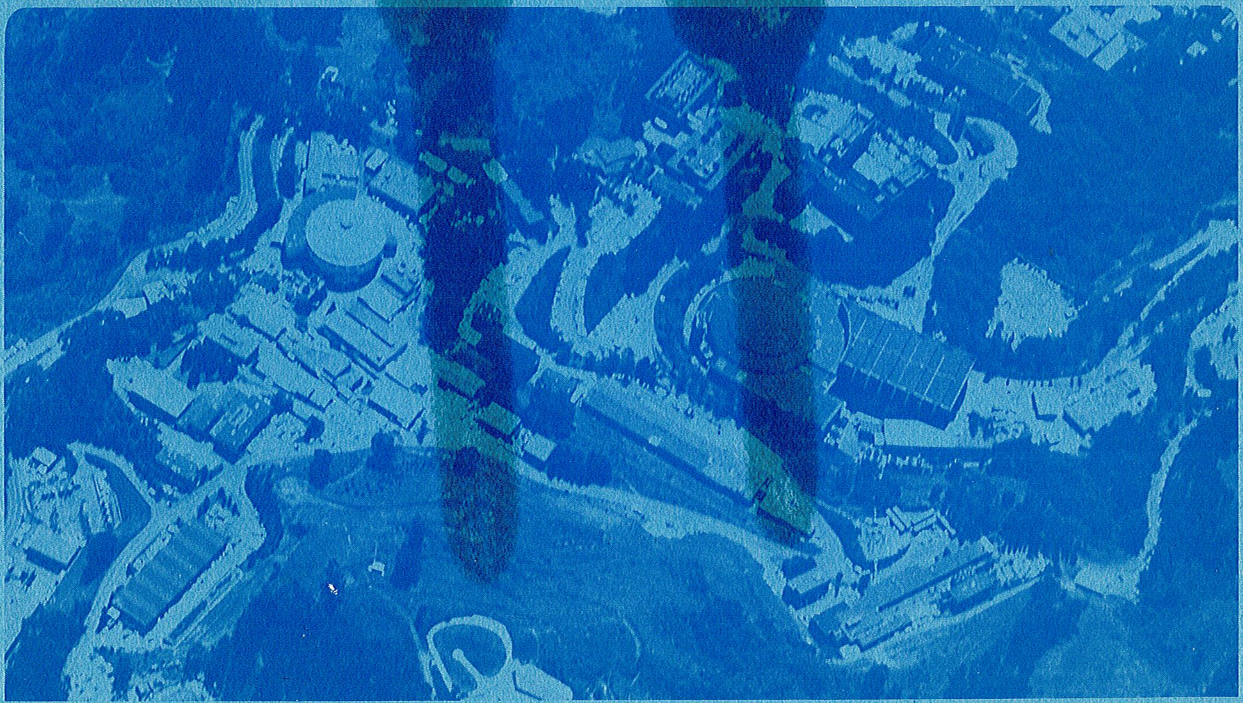

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Talk delivered at the 1981 M.I.T. Symposium to honor Francis Low on his 60th birthday.

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I. INTRODUCTION

Thirty years ago in the early fifties while at the University of Illinois I enjoyed a fruitful period of close collaboration with Francis Low, and ideas uncovered in my work with Francis started me on a lifelong quest for a theory that in the late fifties came to be described by the term "bootstrap". The general bootstrap idea is that all aspects of nature are determined by the requirement that they be consistent. No aspect is arbitrary; no aspect is "fundamental"; the combination of all aspects is self determining. Because of human limitations the bootstrap idea can never be pursued in its full sense. Compromise is unavoidable; certain assumptions must be accepted in any human contemplation of consistency, but since the early fifties the starting assumptions have shifted. At that time it was difficult to do without the Newtonian-Cartesian idea of objects moving in a space-time continuum. Quantum mechanics, even with its emphasis on the discrete, was formulated within a continuous space-time. I have come to see this assumption of an underlying continuum as the root of the celebrated paradoxes surrounding quantum mechanics. I believe that space-time--as we experience it through our classical sense of a continuous world made of real objects--should emerge from a discrete quantum world. In this view continuous space-time is an approximation--like the continuous thermodynamic notions of temperature and entropy--useful only in environments of appropriately great complexity. I shall in this talk describe an approach to the bootstrap idea in which local space-time is not a conceptual starting ingredient.

The starting idea is a notion of "elementary event", with a past and a future but not embedded in continuous space time. One does not know at the beginning the precise meaning of a physical event; bootstrap theory must generate its own physical interpretation. We shall see that a physical event is a superposition of infinitely-many patterns of correlated elementary events.

It is possible to make contact with two familiar notions by thinking of an elementary event as a collision between elementary particles or as an elementary-particle decay, both processes being "sudden"--that is to say, discrete. Mathematical meaning for the adjective "elementary" is provided by the concept of graph. The term "elementary event" is to be understood as synonymous with a graph vertex and the term "elementary particle" is to be used synonymously with a graph line. The theory must generate a meaning for physical particles as well as for physical events.

The relation between correlated elementary events is assumed to be that between the vertices of a connected graph, as in Fig. 1. The vertices can be assigned a sequential order, but there is no metric--no meaning for distance between adjacent elementary events. A discrete notion of distance between nonadjacent elementary events is nevertheless achieved by counting the minimum number of vertices along any connecting path. For large distances such a measure becomes approximately continuous, as suggested by Fig. 2.

A postulate of topological bootstrap theory is that certain clusters of correlated elementary events are not to be distinguished from single elementary events. That is, the theory considers certain graphs as equivalent by a contraction process to a graph with a smaller number of vertices and lines. Strong interactions and strongly-interacting particles (hadrons) will be distinguished from weak interactions by the contraction aspect of bootstrap theory. The rules for contraction relate to a notion of graph complexity, the idea being that contraction should not alter complexity.

I shall indicate to you how, by methods of combinatorial topology, one can associate a precise discrete measure of complexity to appropriately-embellished event graphs. There are present at the same time consistency requirements on the definition of complexity, and out of these requirements flow constraints on elementary particles. Overall consistency of complexity-carrying event graphs not only controls the spectrum of elementary particles but determines physical masses and coupling constants. I shall sketch the so-far recognized consistency requirements and show how, in meeting these demands, there arise topological embellishments whose properties allow description by such terms as "quark", "gluon", "color" and "flavor"--terms occupying niches in the phenomenology of particle physics. Within the topological bootstrap such entities are not arbitrarily postulated; they emerge together with their properties as attributes of a consistent pattern of discrete causal connections. As immediate illustration of nonarbitrariness but also to forestall misunderstanding, let me anticipate that topological quarks and gluons do not correspond to event-graph lines and thus do not emerge in the role of elementary particles; they are event-graph embellishments needed for consistency of the contraction principle.

The application of combinatorial topology to particle physics was initiated by Feynman in 1947 with his famous graphs whose lines carry energy-momentum---graphs introduced for photons and electrons but later recognized, especially by Landau,[1] as having more general significance. Feynman graphs constitute the event graphs of topological bootstrap theory even though not part of a rule for deducing the consequences of a local space-time Lagrangian; there is no Lagrangian in the topological bootstrap.

Unembellished Feynman graphs are not adequate for dealing with graph contraction, an idea which emerged in 1969 through diagrams invented independently by Harari and by Rosner.[2] Harari-Rosner diagrams when added to Feynman graphs allow a contraction rule--often characterized as "duality"--that is essential to the topological bootstrap. Harari-Rosner and Feynman diagrams are simultaneously indispensable to the theory I am describing. Also important are diagrams invented more recently by Finkelstein.

Bootstrap thinking in the late fifties and early sixties already recognized particles as "interevent connections" rather than as Newtonian-Cartesian "objects". Until contraction entered the game, however, there was no recognition that a complexity hierarchy is essential to consistency. Two decades ago bootstrappers spoke of a "nuclear democracy" in which all hadrons enjoy equal status. Today's topological bootstrap has uncovered a finite set of "elementary hadrons"--associated with a base level of topological complexity that we call "zero entropy". But even though an aristocracy, zero-entropy elementary hadrons are not arbitrarily assignable; they are determined by the demands of interevent consistency, and the contraction principle implies that each is a "composite"--built from other elementary hadrons.

II. ENTROPY AND THE TOPOLOGICAL EXPANSION

In 1973 Veneziano[3] identified the notion of "topological entropy", so-called because this attribute of a complexity-carrying event graph cannot decrease when one graph is combined with another to form a new graph, as in the first step of Fig. 3. The second step of Fig. 3 illustrates how contraction represents the equivalence to a single event of certain clusters of causally-connected elementary events. Uncontrolled cluster contraction evidently undermines meaning for "distance" within an event chain, but Veneziano (following Virasoro, Sakita and others) realized that embedding the Feynman graph in an oriented 2-dimensional surface, which cyclically orders the lines incident on each vertex, allows a notion of complexity that controls contraction--as illustrated in Fig. 4 where an intermediate line remains unerasable. (Embedding graphs in manifolds of more than 2 dimensions is not useful for complexity theory.) Veneziano furthermore found that a suitably-defined complexity never decreases under graph addition followed by contraction. The intermediate line in Fig. 4, for example, cannot be removed by adding further event graphs and then contracting. When spin as well as momentum is topologically represented it turns out, as I shall explain, that certain graph vertices as well as lines are unerasable. No vertex involving a photon, for example, can ever be removed by contraction.

The discovery of topological entropy through Feynman-graph 2-dimensional "thickening" opened the door to the notion of "topological expansion" for a physical-event amplitude--a complex number which according to quantum theory gives through its absolute value squared the probability for the event to occur. If M_{fi} designates the amplitude for a physical event where a collection of i ingoing particles leads to a collection f of outgoing particles, Veneziano's topological expansion reads

$$M_{fi} = \sum_{\gamma} M_{fi}^{\gamma},$$

where each value of the index γ--associated to a particular topological object--carries an entropy g(γ). It is tacitly assumed that for some M_{fi} the expansion converges rapidly; i.e. that low entropy is more important than high entropy. Low energy emerges as essential to rapid convergence.

Where no contractions are possible, as turns out to be the case when hadrons are not involved, the idea of a topological expansion is essentially that of Feynman[4]--where the index γ refers to a Feynman diagram and the total number of graph vertices (minus 1) is an entropy index. Harari-Rosner contractions may change the number of vertices but they never alter the value of a legitimate entropy index. Finding such indices is the topological bootstrap game.

Implicit in the definition of entropy is that zero-entropy topological components cannot be built by addition from components with nonzero entropy. Most of the latter may be built from simpler (lower-entropy) components by a linear additive process, but zero-entropy components must be nonlinearly self-building. Herein lies the first bootstrap stage: The spectrum of elementary hadrons is postulated to be determined by zero-entropy consistency, and strong interactions are generally defined as those topological-expansion components generated by "connected sum" of zero-entropy components. I shall explain later how, in a second stage, electroweak components enter the bootstrap.

Veneziano's topological expansion, formalized by Rosenzweig and me,[5] is now called "classical DTU"--these initials standing for "dual topological unitarization".[6] Each value of γ corresponds to a single-vertex Feynman graph embedded in a 2-dimensional oriented bounded "classical" surface whose boundary divides into "particle pieces" dual to the external lines of the graph. A zero entropy topological component corresponds to a disk, such as illustrated in Fig. 5a. (The disk topology is usually called "planar".) "Addition" of two different components corresponds to an orientation-preserving connected sum along the boundary, those particle pieces of boundary being identified and erased that correspond to intermediate particles--as shown in Fig. 6 and Fig. 7.

In classical DTU two adjacent Feynman vertices contract to a single vertex and two "parallel" Feynman lines contract to a single line. There are two (nondecreasing) entropy indices: g_1 = genus or twice the handle number and g_2 = number of (noncontractible) closed loops

$$= b - 1 + g_1,$$

where b is the number of boundary components. As illustrated in Figs. 6 and 7 these two indices record the complexity of intermediate thickened Feynman-graph lines involved in building up a given topology starting from zero entropy ("planar" in classical DTU)--zero entropy being uniquely characterized by $g_1 = g_2 = 0$. The full (infinite) topological expansion contains components belonging to all possible values of g_1 and g_2.

The boundary of the classical surface inherits the surface orientation and constitutes a closed graph--if cut open at the Feynman-graph ends we have the globally oriented Harari-Rosner graph. (See Fig. 5b) The Harari-

Rosner graph, that is to say, is the boundary of the oriented thickened Feynman graph.

The general rules for determining a topological amplitude M_{fi}^{γ} are based on S-matrix principles such as unitarity together with the graphical Landau prescription for the singularities of S-matrix connected parts.[7] Corrections to zero-entropy turn out in many cases to be expressible through Feynman-like rules.

III. SPIN AND ELECTRIC CHARGE

In classical DTU the Feynman graph is recognized as carrying momentum-energy and the topology γ of the classical embedding surface correlates with the Riemann surface that carries the momentum singularities of the amplitude M^{γ}_{fi}.[5] But no recognition is given in classical DTU to spin. Now momentum and spin are both "direct" classical observables; both emerge from the Poincaré group and both are needed to define an S matrix in a Hilbert space of asymptotic quantum states. To make contact with experiment topological particle theory requires an S matrix. Ultimately one hopes to explain as a manifestation of high complexity the notion of "measurement" which gives meaning to asymptotically-observable momentum and spin, but presently the possibility of momentum and spin measurement is a starting assumption. Topological bootstrap theory, in exploring requirements of consistency within the S-matrix context, takes for granted both momentum and spin as particle characteristics. So where does spin reside on the classical surface?

As revealed by the work primarily of Mandelstam[8] and Stapp[9] but with clarification by Finkelstein,[10] spin flows along the classical-surface boundary; that is, the Harari-Rosner graph is the carrier of spin in the sense that the spin-dependence rules for M^{γ}_{fi} are expressible through Harari-Rosner lines. Although I shall not here state the Mandelstam-Stapp rules, they employ the notion of chirality and are unambiguously determined by the consistency demands of zero entropy. The rules depend on the classical surface containing locally-oriented patches which at zero entropy are defined by the Feynman (momentum) graph together with the boundary (Harari-Rosner) graph. Additional patch-boundary lines may be generated by mismatch of local orientations in connected sums and constitute an ingredient of complexity which blocks contraction of vertices. See Fig. 8. I shall explain later that within strong-interaction topologies these added patch lines are appropriately called "topological vector gluons"; the number of such "gluons" is an entropy index g_3 which augments the g_1 and g_2 of Veneziano. I return later to further discussion of spin in connection with the quantum-mechanical notion of "fermion" but pass now to the final classical (asymptotic) observable--electric charge--whose measurement inevitably intertwines with that of momentum and spin.

One expects classical particle topology to contain some feature related to electric charge. An embellishment consistent with classical electromagnetism as well as with S-matrix requirements is a set of nonintersecting directed lines on the classical surface, each of which begins and ends on a different boundary subpiece without crossing a momentum line. Figure 9 provides an example by embellishing Fig. 5a with 4 charge arcs. With n charge lines the boundary then divides into 2n subpieces. Belonging to each particle is a boundary portion consisting of several subpieces while on each subpiece lies the end of exactly one charge line. Electric charge is quantized and conserved if the charge carried by each subpiece is zero when charge and boundary directions disagree and ±1 when there is agreement of direction. Charge lines are indispensable for electromagnetism, but they turn out to be needed already for strong interactions. Their principal architect has been Jerry Finkelstein, although the papers describing this embellishment have included other authors because of correlated additional topological features.[11]

IV. THE QUANTUM SURFACE

The major further feature is the quantum surface, originally proposed by me and developed in detail through a lengthy, still-continuing, collaboration with Poénaru.[12] The primary question to be answered through the quantum surface is how many boundary subpieces attach to each elementary particle. It was shown by Weissmann[13] from the zero-entropy contraction aspects of classical DTU that the conditions for zero-entropy joining of one boundary particle-piece end to the end of a different particle piece must be independent of other ends. Because a particle piece of boundary has at least 2 ends, there must be for each particle at zero entropy at least 2 subpieces[14]--each with its own attached charge line. The number of subpieces per particle may, however, be larger than 2. The ambiguity is resolved through a closed oriented "quantum" surface, transverse to the classical surface and "thickening" the boundary thereof. Thickening means that the boundary graph is embedded in the quantum surface.

The quantum surface divides into oriented particle areas, one for each ingoing or outgoing elementary particle in the event; each particle area houses the corresponding particle piece of the classical-surface boundary. Division of a particle boundary piece into subpieces corresponds to a division on the quantum surface of the particle area into subareas inside each of which there ends one charge line, and consistency conditions on particle subdivisions flow from the requirement that at zero entropy the total quantum surface closes into a sphere. Certain conserved "internal" quantum numbers are thereby implied, together with zero-entropy symmetries that become broken at higher levels of the topological expansion.

Connected sums along boundaries of classical surfaces are accompanied by quantum-surface connected sums in which corresponding particle areas are identified and erased in such fashion as to preserve surface orientation. The orientation of the classical surface boundary (the Harari-Rosner graph) is inherited from the quantum-surface orientation--the latter providing the distinction between ingoing and outgoing particles or between particles and antiparticles.

The search for a consistent pattern of zero-entropy particle areas on the quantum surface has been lengthy and laden with surprises. Numerous patterns have been proposed and subsequently discarded. The pattern now to be described, found by Poénaru and me, has been stable for more than one year and has survived many consistency tests. Although no uniqueness proof has been achieved, we are aware of no satisfactory alternative.

Our pattern divides the quantum surface into triangles of alternating orientation, each triangle being "mated" to exactly one other triangle of opposite orientation--mating being defined as a sharing of all 3 vertices. The mate of a triangle in one particle area at zero entropy always lies in another particle area. Particle areas are triangulated disks; each subpiece of the classical-surface boundary thickens into exactly one quantum triangle.

Only three forms of particle area on the quantum surface are allowed at zero entropy--those shown in Fig. 10 where two types of triangle occur. A "peripheral" triangle contributes two edges to the particle-disk perimeter while a "core" triangle contributes no edges, although all triangle vertices lie along the perimeter. Figure 11 shows how the classical-surface boundary (or "belt", for short) cuts all triangles and at zero entropy always enters and leaves particle disks at trivial vertices, which uniquely belong to peripheral triangles. Also shown in Fig. 11 are the ends of charge lines, one for each triangle. Finally, each edge along a particle perimeter is oriented, as shown in Fig. 12; these orientations must match when particle disks are fitted together on the quantum surface.

Looking at an individual fully-embellished peripheral triangle, as in Fig. 13, we see a two-fold electric charge degree of freedom and a 4-fold edge orientation degree of freedom, all of which must be matched at zero entropy by the mate of this peripheral triangle. These quantum numbers we associated with "flavor" and thus predict 8 flavors. The 4 edge flavors, usually called "generations", will be separately conserved on any orientable quantum surface with trivial vertices, although nonorientable surfaces allow generation mixing. Continuity of charge-line direction assures that electric charge is always conserved.

Each peripheral triangle not only mates with an "anti"-peripheral triangle but shares a trivial vertex therwith. The Mandelstam-Stapp rule for spin dependence at zero entropy centers on the quantum-triangulation trivial vertices that connect adjacent particle pieces on the classical-surface boundary. The rule effectively attaches spin 1/2 to each quantum triangle sharing such a trivial vertex. Since the latter are always peripheral, fermion number is the number of clockwise peripheral triangles minus the anticlockwise number.

The full collection of peripheral-triangle attributes makes "topological quark" appropriate as a descriptive name for this type of triangle. It must be remembered, however, that topological quarks do not carry momentum; they are not elementary particles, even though they carry spin, electric charge and flavor.

The quantum surface is not built entirely from topological quarks. Already at zero entropy there appear core triangles, which carry no spin or flavor but which are electrically charged and each of whose edges, correspondingly, can be said to carry one of 3 different "topological colors"--as shown in Fig. 14. Equivalently one may say 3 differently-colored sheets of the classical surface meet at a "junction line" that ends inside a core triangle.[12] The sheet colored #1 carries the Feynman graph. Color may be attributed to a quark according to the classical sheet on which it lies and each topological color is separately conserved even though topological quarks of a given flavor may change color in connected sums that increase entropy. Each exchange of color between a pair of quarks builds a link between corresponding sheets of the classical surface, the number of such links being an entropy index g_4. Topological color, unlike QCD color, admits only discrete transformation (permutations) and color #1 is evidently not symmetric with respect to colors #2, 3.

The number of clockwise core triangles minus the anticlockwise number is conserved and, for strong-interaction topologies, may be identified with the negative of baryon number B. At this stage we are able to associate the disk of Fig. 10a with "elementary meson"--quark plus antiquark with B = 0. The disk of Fig. 10b is an "elementary baryon"--3 quarks and one anticore triangle, so B = 1. The disk of Fig. 10c is an "elementary baryonium"--2 quarks, 2 antiquarks, one core triangle and one anticore triangle, so B = 0. The quantum numbers of low-mass mesons and baryons agree with topological bootstrap theory. The experimental failure to observe baryonium is discussed below.

Because all requirements for smooth joining of particle quantum disks must reside on disk perimeters (Weissmann),[13] the direction of a core charge arc is not variable. In fact zero-entropy consistency conditions require agreement between core charge and boundary (Harari-Rosner) orientations, so a clockwise (anticlockwise) hadron core triangle must have electric charge Q = + 1(-1), a point first noted by McMurray. Because topological quarks carry Q = 1, 0, the total electric charge of a hadron disk is

$$Q = N_{\text{quarks}}^{\text{charged}} - B$$

At the same time, for any hadron, (see Fig. 10)

$$B = \frac{1}{3} N_{\text{quarks}} = \frac{1}{3} (N_{\text{quarks}}^{\text{charged}} + N_{\text{quarks}}^{\text{neutral}}),$$

so

$$Q = \frac{2}{3} N_{\text{quarks}}^{\text{charged}} - \frac{1}{3} N_{\text{quarks}}^{\text{neutral}} .$$

Thus if hadron core triangles are ignored it appears that quarks carry charge $Q = \frac{2}{3}, -\frac{1}{3}$. For pure strong-interaction topologies a bookkeeping has been devised that makes no reference to core triangles--keeping track only of quarks--although this device does not work for electroweak interactions. With such bookkeeping the familiar fractional quark charges are appropriate.

I remark here that the complexity growth recorded by the two entropy indices g_3 and g_4 (now added to Veneziano's g_1 and g_2) can appropriately be described in quark-gluon language. One may speak of "vector gluons" emitted by topological quarks because, when a classical patch boundary line ends at a trivial vertex, the effect on quark spin is similar to that in perturbative field theory at a quark-gluon vertex. On the other hand a color switch between two topological quarks is as if a "color-carrying gluon" were exchanged. Gluons in either sense are absent at zero entropy; conversely, large values of g_3 and g_4 correspond to large numbers of topological gluons.

V. TOPOLOGICAL SUPERSYMMETRY

It was pointed out by Gauron, Nicolescu and Ouvry[15] that zero entropy (where $g_1 = g_2 = g_3 = g_4 = 0$) is characterized by a "topological supersymmetry"--all elementary mesons, baryons and baryoniums sharing a single (nonvanishing) mass m_0 even though the spin values 0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2 occur. The zero-entropy S-matrix conditions allow a complete factorization of spin, flavor, color and chirality degrees of freedom, so that only momentum remains in the nonlinear bootstrap equations representing unitarity. It is plausible that these equations admit no more than one solution and determine, among other things, a unique value for the zero-entropy 3-hadron dimensionless coupling constant g_0.[16] (The mass m_0 simply sets the energy scale for the topological expansion.)

By variety of approximations, Balazs, Finkelstein and Espinosa[17] have attempted to calculate the zero-entropy coupling constant and have found that

$$g_0 \lesssim 2e$$

The smallness of g_0 here derives from the large multiplicity f of closed elementary-hadron loops at zero entropy.[16] It turns out that $f = 32(31) \approx 10^3$ while $g_0^2/16\pi^2 \sim 1/f$. The number 32 is the total number of distinct zero-entropy topological quarks:

$$2 \text{ spins} \times 2 \text{ charges} \times 4 \text{ generations} \times 2 \text{ chiralities} = 32$$

Each closed momentum loop is accompanied by either 1 or 2 closed quark loops. Hence the net factor is $-32 + (-32)^2 = 32\ (31)$. The minus sign is that originally discovered by Feynman for any closed fermion loop and rediscovered by Stapp[9] as part of the topological spin rules. One consequence of the minus sign is that a consistent zero-entropy (hadron) spectrum cannot terminate with elementary mesons; elementary baryons and baryoniums must be included.

Gluonic (g_3, g_4) corrections to zero entropy break topological supersymmetry. A mechanism breaking spin degeneracy is qualitatively understood, calculations by Levinson being underway to see whether such observed splittings as $\pi - \rho - N - \Delta$ can be semiquantitatively achieved through leading topological components with nonvanishing g_3. A tentative color-switch (g_4) mechanism for breaking generation symmetry has also been uncovered, based on topological-color asymmetry, but so far there is no visible strong-interaction mechanism to break charge-doubling symmetry (e.g. interchange of charmed and strange quarks). We anticipate that charge symmetry is first broken by electroweak interactions.

An argument can be made that dimensionless hadron coupling constants are less affected than hadron masses by corrections to zero entropy. Finkelstein, Levinson and I[18] accordingly have calculated elementary 3-hadron physical coupling constants in the zero-entropy approximation where each is a simple multiple of g_0 and found that $SU(6)_W$ ratios emerge, as reported earlier by Mandelstam[8] on the basis of a less complete but compatible version of zero entropy. But topological supersymmetry goes further and correctly gives the measured ratios of baryon-meson to meson-meson couplings. Thus <u>all</u> measured elementary-hadron coupling constants are explained by a single assignment of g_0. This value predicts enormous baryonium coupling constants and correspondingly large widths, so the experimental failure to find narrow baryonium states is understandable.

The most accurately measured hadronic coupling constant $\left(\frac{g^2_{N\bar{N}}}{4\pi}\right) = 14.3$ implies to within a few percent that $g_0 \approx 2e$.[19] Could there be a reason why g_0 is <u>exactly</u> equal to 2e? Here we must consider how electroweak interactions enter topological particle theory.

VI. ELECTROWEAK INTERACTIONS

From a bootstrap standpoint why should there be anything beyond hadrons and strong interactions? One reason for electromagnetism relates to the high entropy limit corresponding to the classical world of real objects embedded in space-time. I shall argue later that soft photons constitute the key to such a limit--which is needed for the measurements defining an S matrix. Topological representation of photons has been achieved through the ingredients already described[11] and brings along in a natural fashion 3 other electroweak vector bosons.[10] (A quartet of scalar bosons--charge doublet plus antidoublet--is also natural.) But why leptons?

A conjectured reason is motivated by standard Lagrangian perturbation theory which, at least for photon-lepton interactions, has the same content as a topological expansion. (A source of such equivalence is the fact that electroweak bosons have attached ingredients of topological complexity that block contraction.) Now Lagrangian electroweak perturbation theory has uncovered consistency problems which require quarks and leptons to be paired--one lepton matching each distinct quark but carrying opposite electric charge. We conjecture that topological theory will encounter a similar problem: A consistent interaction between electroweak vector bosons and quarks would then require quarks to be paired with leptons.

The present leading candidate for a lepton quantum-surface area is a (nonorientable) Möbius band built from one peripheral triangle and one neutral core triangle, with two edges of the latter identified. The spin and flavor content is the same as that of a quark, since the perimeter is built from the two oriented peripheral-triangle edges. There is, however, a momentum line ending inside the lepton area so, unlike a topological quark, a lepton area corresponds to an elementary particles. Each electroweak boson corresponds to a closed quantum surface covered by 2 triangles. Vector-boson triangles are like that of Fig. 13 but without edge orientations, while scalar-boson (Higgs) triangles are like that of Fig. 14.

The topological similarity between strong and electroweak interactions, together with the close relation between Lagrangian perturbation methods and corrections to zero entropy, suggests that the connections between coupling-constants characteristic of gauge-invariant Lagrangian theories may arise in topological bootstrap theory as necessary to overall consistency. Among these connections may be $g_0 = 2e$. If indeed the bootstrap demands a single universal dimensionless coupling constant, the small but not extremely small value of the constant is seen, as I have explained, as being related to the number (32) of different quarks, this multiplicity in turn emerging from zero entropy consistency.

Strong-interaction topology has been developing for more than 10 years and electroweak topology for less than 2; the structure of the former is correspondingly more secure. So far our electroweak topologies have been guided as much by quantum electrodynamics (Q.E.D.) and the Weinberg-Salam extension thereof as by consistency considerations. It is reassuring that the full content of Q.E.D. is embeddable in topological particle theory, but we hope eventually to understand from consistency considerations not only the raison d'être for electroweak interactions but the zero photon mass together with other arbitrary aspects of Weinberg-Salam theory and eventually CP violation. It is possible that certain aspects of Weinberg-Salam theory will not be duplicated.

The breaking of CP invariance, as well as Cabibbo quark-generation mixing and proton decay, is related to nonorientable quantum and classical surfaces. We have a tentative understanding of why lepton generation mixing is weaker than Cabibbo quark mixing and why baryon-lepton transitions are extremely weak but perhaps not impossible.

VIII. SPACE-TIME

At this point of the story we are often asked about gravitons. But before that question we should first be asked about space-time and the classical world of real objects embedded in space time. Our viewpoint is that objective reality and its accompanying spacetime acquire meaning through event patterns of high complexity. Gravitation, as an aspect of space-time, will correspondingly be meaningful only in such a classical limit--where quantum effects have been smoothed away. We therefore do not anticipate significance for gravitons.

It appears that soft photon emission and absorption is the unique type of quantum event "gentle enough" to allow development of classical objectivity. Any photon event, no matter how soft, is noncontractible and contributes to growth of the chiral entropy index g_3; electromagnetism becomes recognized as the key to compatibility between the real world of classical measurement and the quantum world of elementary events. If so, "real" space-time and gravitation are meaningful only in a photon-dominated environment.

What about the "short-distance parton" concept so valuable to the phenomenology of hadron events with large transfer of momentum? Here again as the key to significance we see high complexity, although not a complexity generated by gentle photons. Quite the contrary, here events are violent and large values for the classical-DTU entropy indices g_1 and g_2 become important. We must suppose that "partons at short distance" will acquire approximate meaning for sufficiently large average values of g_1 and g_2.

Related field-theoretical ideas are those of "asymptotic freedom" and "grand unification" in violent events. I have spoken of topological unification corresponding to $g_0 = 2e$, but g_0 is a low energy parameter. Physical elementary-hadron coupling constants are big multiples of $g_0 (2^3 g_0, 2^5 g_0, 2^7 g_0, 2^9 g_0)^{18}$ because of <u>coherent</u> (same phase) addition of many different zero-entropy topological compoents. But in events with large momentum transfer, zero-entropy components are small and the more important topological components have high complexity. Phase differences there occur, and coherent addition to a large magnitude for physical amplitudes is not to be expected. Topological theory thus anticipates a weakening of strong interactions in violent events, suggestive of asymptotic freedom in field theory. So far, however, we have identified no topological parallel to the idea of strong-electroweak unification at large momentum transfer. It is possible to speak of "topological grand unification" but the meaning depends on low energy.

IX. ACCESSIBLE AND INACCESSIBLE DEGREES OF FREEDOM

Looking back over topological bootstrap theory one distinguishes 3 categories of topological features. First there are the graphs invented by Feynman, Finkelstein and Harari-Rosner that record, respectively, the flow of the direct observables: momentum, electric charge and spin. Next there are the quantum-surface orientations that distinguish different types of elementary particle and that correspond to internal quantum numbers--revealed indirectly through event selection rules. The first category of topological feature is directly accessible to experiment and the second category is indirectly accessible. Finally there is a 2-dimensional classical surface which embeds both momentum and charge graphs and which has for boundary the spin graph. It is the intergraph relation through the classical surface that generates entropy from inaccessible features of the topology.

The momentum-entropy indices g_1 and g_2 emerge from the cyclic ordering of momentum lines incident on Feynman-graph vertices, an ordering without physical significance. The chirality-entropy index g_3 stems from oriented classical-surface patches defined by the momentum and spin graphs; the patch orientations are not accessible to experiment. The color-entropy index g_4 emerges from the location of Finkelstein's charge graph on the classical surface, a location also without physical meaning.

For a given event--specified by sets i and f of initial and final particles--the topological superposition building the event amplitude

$$M_{fi} = \sum_{\gamma} M_{fi}^{\gamma}$$

runs over inaccessible degrees of freedom, all accessible topological features being fixed by i and f. One may feel uneasy about the theory's dependence on physically-unmeasureable variables, but it should be remembered that quantum mechanics, as formulated more than half a century ago, depends on an inaccessible but essential mathematical feature: the phase of a complex Hilbert-space vector. So topological bootstrap theory may be seen as an extension of quantum theory's complex numbers--to a broader domain of mathematical structures inaccessible to objective measurement but essential to overall consistency. Objective measurement promises itself eventually to emerge in a larger bootstrap as a necessary component of a consistent nature.

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FIGURE CAPTIONS

1. A connected graph representing a cluster of correlated elementary events.
2. Graphs that illustrate the meaning of discrete interevent "distance".
3. A connected sum of two single-vertex Feynman graphs that leads to a contractible 2-vertex graph.
4. A connected sum of graphs with cyclically-ordered vertices where an intermediate line remains uncontractible.
5. (a) Classical surface for a 4-meson zero-entropy event.

   (b) The corresponding Harari-Rosner diagram.
6. Connected-sum of two zero-entropy classical surfaces that leads to a zero-entropy surface ($g_1 = g_2 = 0$).
7. Connected sum of two classical surfaces that leads to a surface of nonzero entropy ($g_1 = 0$, $g_2 = 1$).
8. Example of classical surface with one unit of chiral complexity.
9. An example of charge lines on a zero-entropy classical surface.
10. The allowable zero-entropy elementary-particle areas.
11. Intersection of belt with zero-entropy particle areas. Ends of charge lines are also shown.
12. Edge orientations along perimeters of elementary-particle areas.
13. The peripheral triangle or "topological quark"; also called I-triangle.
14. The core triangle; also called Y-triangle.

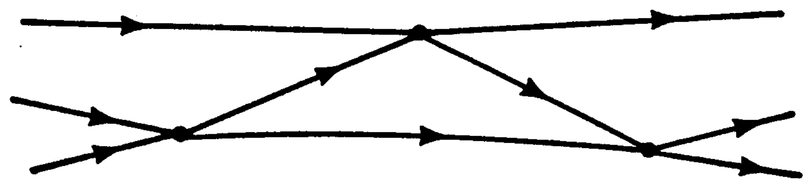

Figure 1

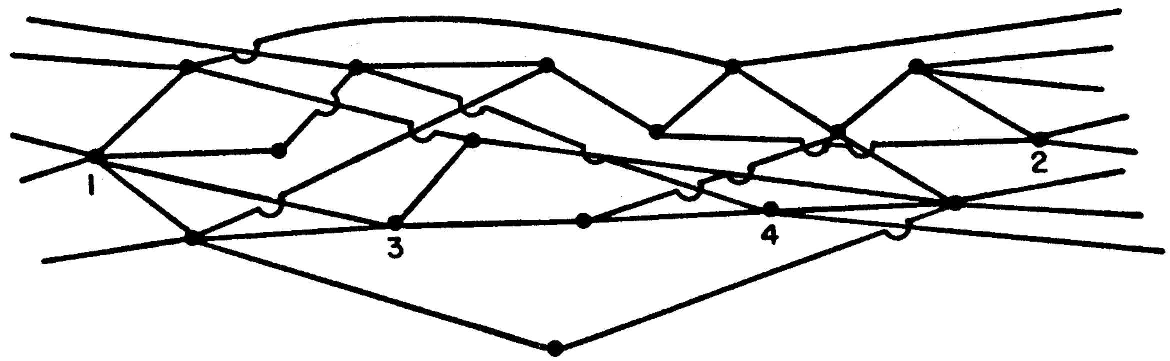

Figure 2

XBL8112-12091

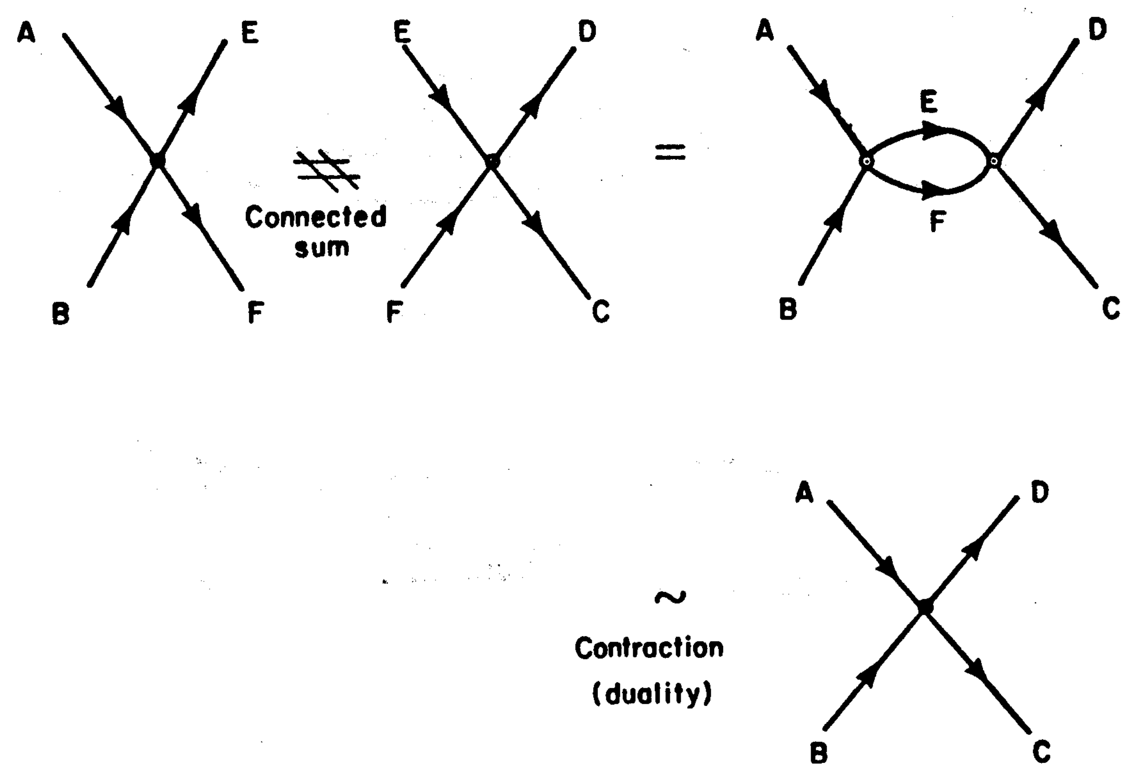

FIGURE 3

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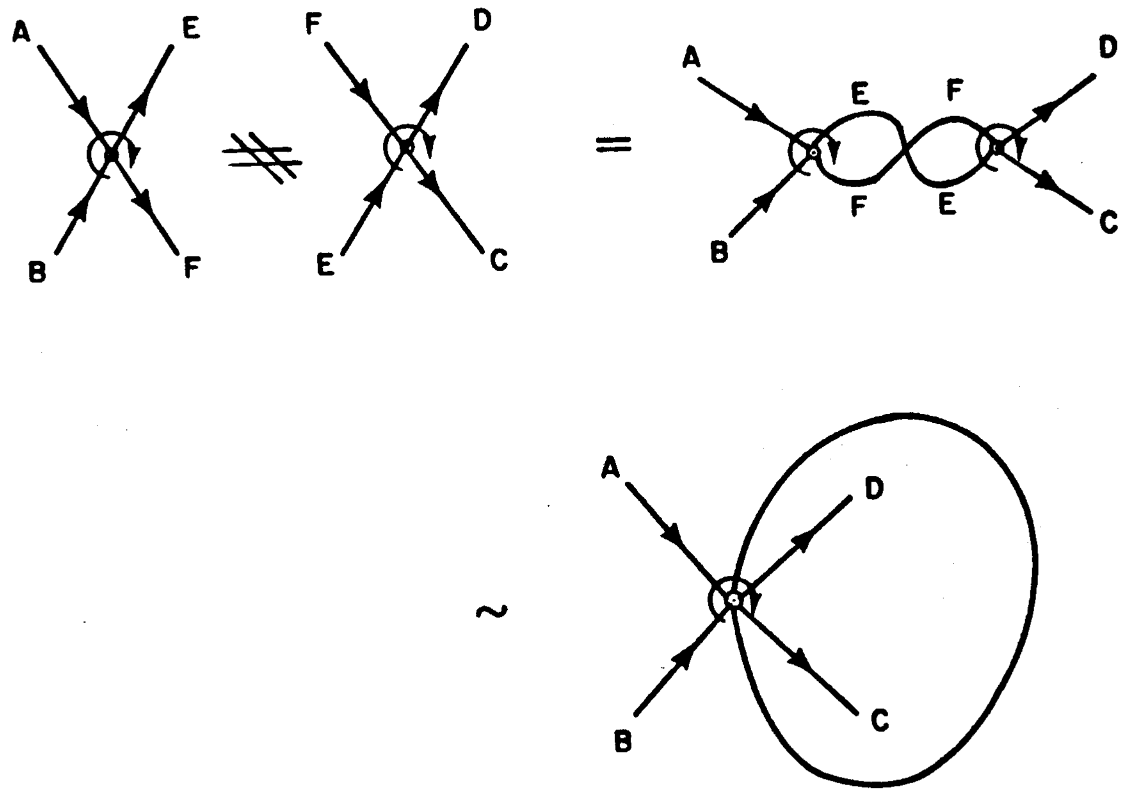

FIGURE 4

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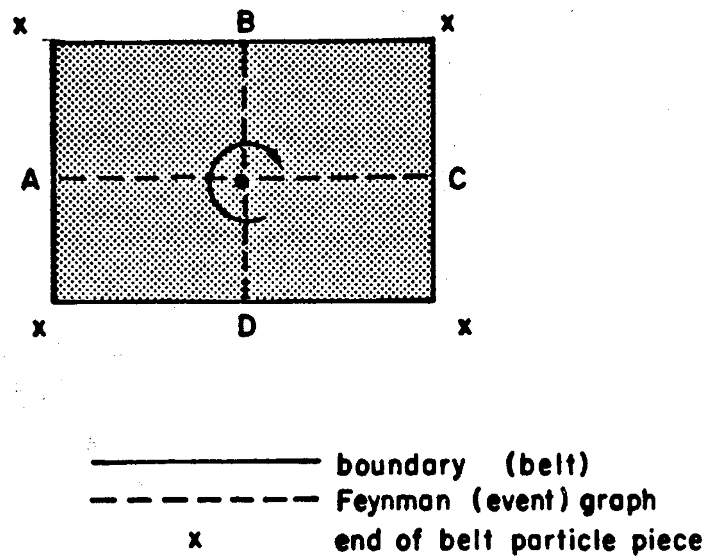


FIGURE 5A

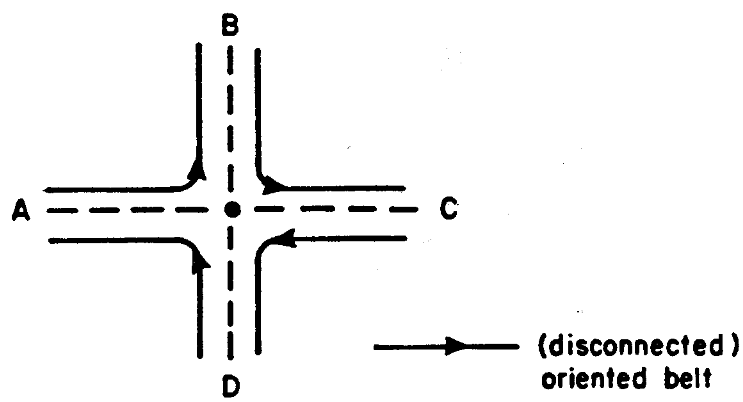


FIGURE 5B

XBL8112-12093

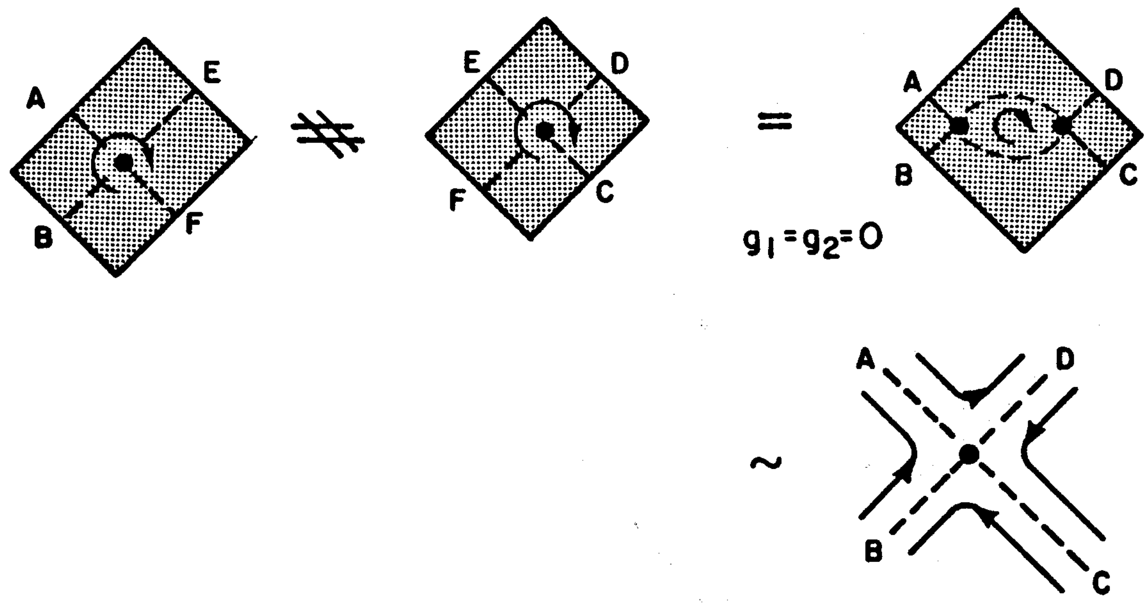


FIGURE 6

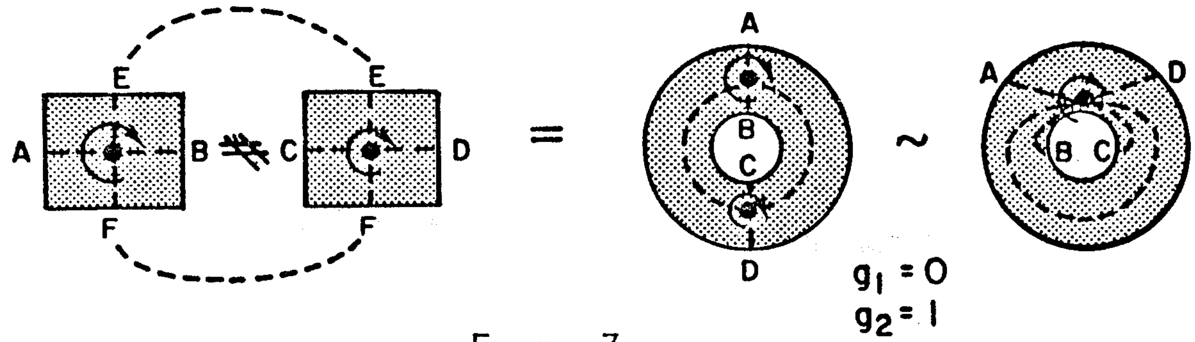


FIGURE 7

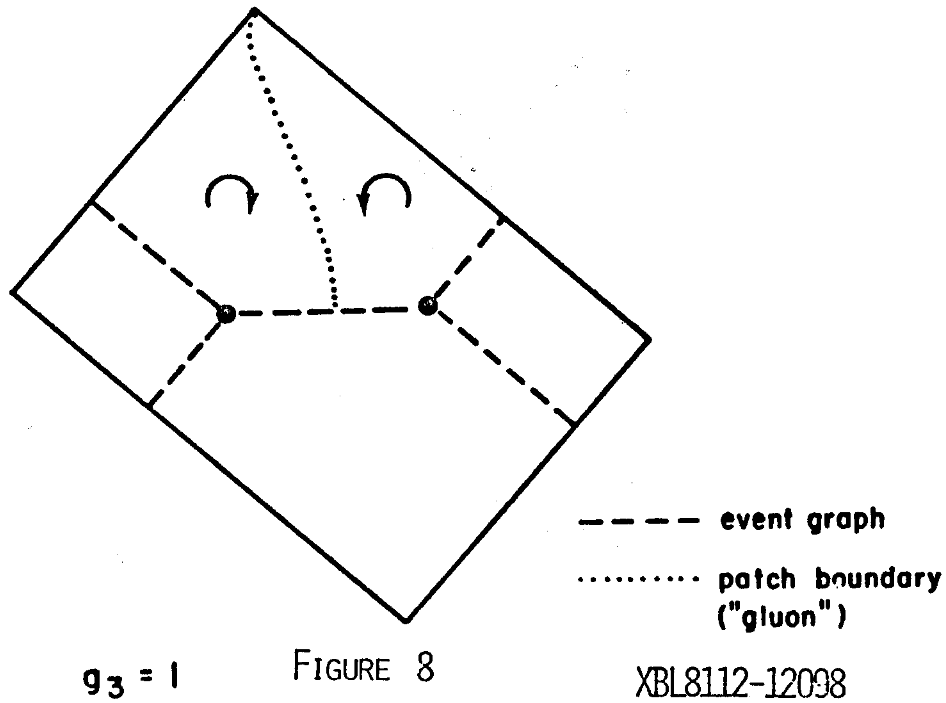
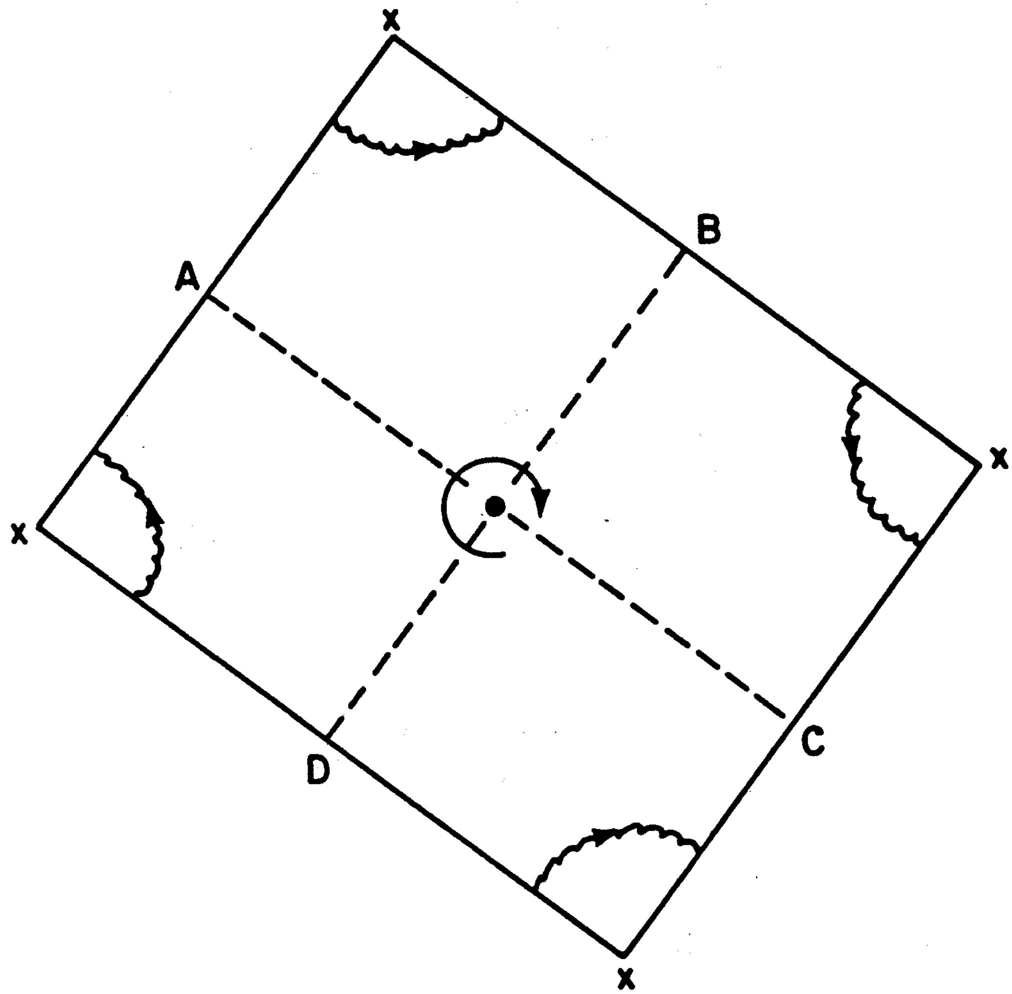


FIGURE 8

XBL8112-12098



Finkelstein charge arc

x end of belt particle piece

FIGURE 9 XBL 8112-12095

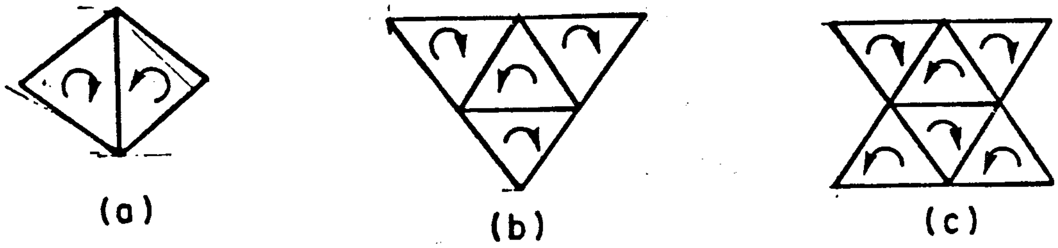


FIGURE 10

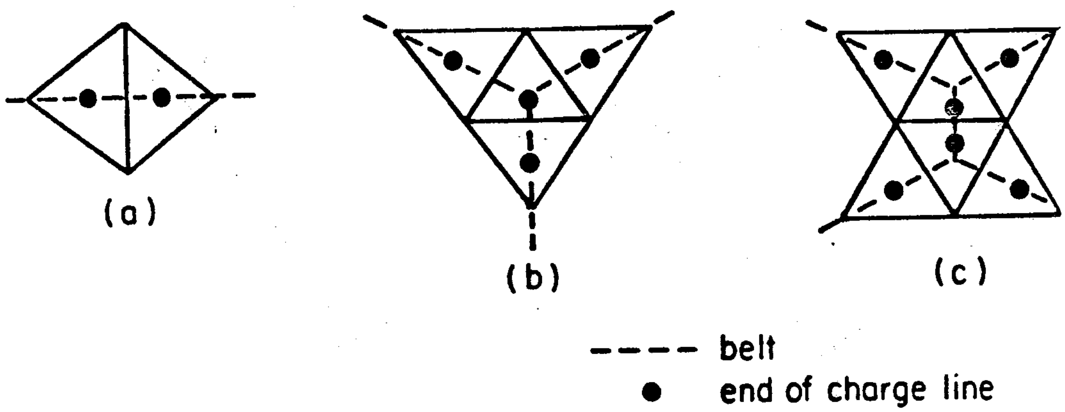
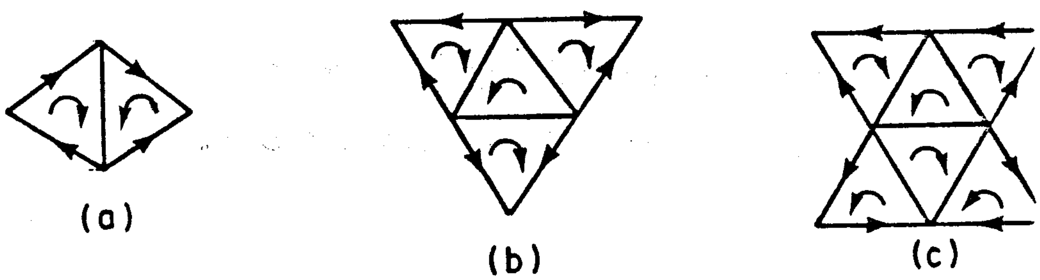
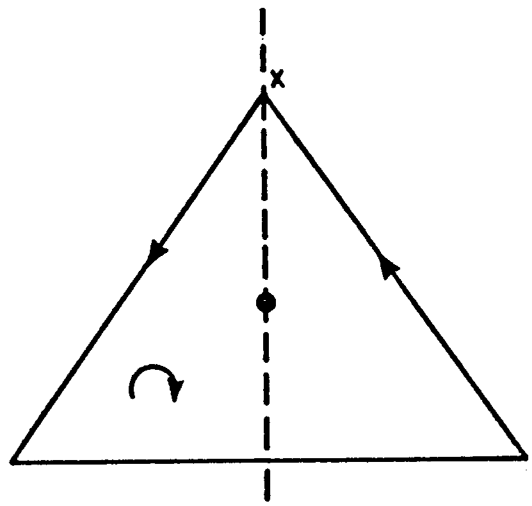


FIGURE 11



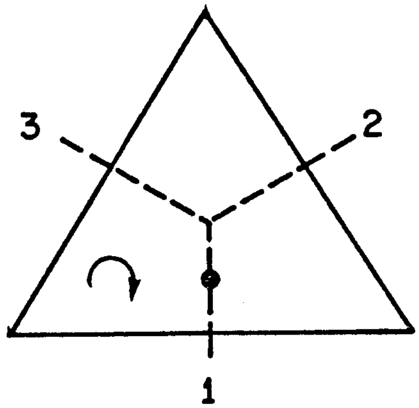
XBL8112-12096

FIGURE 12



---- belt
● end of charge line
x trivial vertex (spin 1/2)
—— edge flavor (generation)

FIGURE 13



---- belt
● end of charge line

XBL8112-12097

FIGURE 14