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QUARKS AND LEPTONS AS COMPOSITE GOLDSTONE FERMIONS

William A. Bardeen and Vladimir Višnjić
Fermi National Accelerator Laboratory
Batavia, Illinois 60510 USA

ABSTRACT

A dynamical scheme for composite quarks and leptons is proposed in which the observed fermions are Goldstone particles of spontaneously broken supersymmetry. Their residual interactions are described by a minimal effective Lagrangian which invokes a nonlinear realization of supersymmetry. Possible experimental consequences are studied and it is found that the most conspicuous signature of this scheme would be a dramatic increase in the lepton pair production in hadronic collisions, particularly in $\bar{p}p$ scattering, at high energy.

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I. INTRODUCTION

It is conceivable that the quark-lepton spectroscopy will find its ultimate explanation in terms of subquarks in a way analogous to the explanation of the hadronic spectroscopy in the framework of the quark model. The present status of this line of development is that while many subquark schemes have been proposed so far there is essentially only one potential dynamical mechanism. We feel that what is most needed in this situation is search for new candidates for realistic subquark dynamics. The most eminent problem to be solved is constructing the bound state whose spatial extent is several orders of magnitude smaller than its Compton wavelength. The only dynamical scheme proposed thus far is based on a particular realization of a Yang-Mills theory.[1] The (fermionic) subquarks in these models are assumed to carry a new kind of color and to be bound into color singlet states. The theory is supposed to confine the subquarks, but, contrary to QCD, to have the chiral symmetry realized in the Wigner mode. The characteristic mass scale of the theory is assumed to be $\gtrsim$ 1 TeV. This scheme, if realized, would have the quarks and the leptons as massless "baryons," protected by the chiral symmetry from acquiring mass. The range of the residual interaction is of order Λ^{-1} and that explains why it has not been detected at present energies. However, the precise form of the interaction is unknown and no experimental signature for the future high-energy experiments is available. The most important problem concerning this kind of models is whether they are possible: if there is a fundamental relationship between the confinement and the chiral symmetry breaking, it may prove impossible to construct a theory which combines the confinement with manifest chiral symmetry. On the phenomenological side, no particularly attractive scheme for flavor and generations has been developed in this framework. Other problems include understanding the mixing angles, GIM mechanism, and CP violation.

In another class of models[2,3] the quarks and the leptons are nearly massless bound states of a massive scalar-fermion pair held together by an unknown dynamics. Under the additional assumption that the bound states can be adequately described by means of a complete set of orthogonal wave functions, these models have several phenomenologically attractive features. The generations are understood as excitation levels. This leads to the possibility of building extremely economical models in which all quarks and leptons could be obtained from only two or three subquarks. The universality is ensured by construction. GIM mechanism is obtained automatically and the mixing angles, including the CP violating phases, are calculable.[2] The anomalous magnetic moments decouple as m/m_c, where m is the quark or lepton mass and m_c typical constituent mass. In case of the fermionic subquark being much lighter than the scalar one, there is an additional suppression factor m_F/m_S.[4] However, no dynamical scheme has been suggested which would **naturally** (i.e., without the fine-tuning of various parameters) bind massive constituents into nearly massless bound states.

The main purpose of this paper is to propose an alternative dynamical scheme which exploits supersymmetry to produce almost massless fermions as opposed to schemes which invoke the use of explicit chiral symmetry. Supersymmetry is the natural framework for a theory whose basic fields are a fermion and a scalar and the natural way for a supersymmetric theory to yield massless fermions is the Nambu-Goldstone realization[5,6]. However, on our way is an immediate apparent impasse--the impossibility of the Goldstone neutrino.

1972 Volkov and Akulov[7] constructed the nonlinear realization of supersymmetry describing the interactions of a Goldstone fermion with itself and with the other particles and proposed that this be the model for the neutrino. This idea, however, was abandoned in 1975 when Bardeen[8], de Wit, and Freedman[9] showed that the neutrino does not obey the low energy theorem which holds for the Goldstone particles. The argument is very simple: if the neutrino is a Goldstone particle it must decouple at zero momentum and that should be seen at the electron end-of-spectrum behavior in beta decay. No such effect has been observed and that seemed to be the end of the Goldstone neutrino hypothesis.

From today's point of view, however, the idea of the Goldstone neutrino would not be considered fully satisfactory even if it had not been shown to be in the apparent contradiction with experiment. In 1972 there were two neutrinos and they were both massless. Today we have three and perhaps all of them have mass. Also, the idea of the quark-lepton unification is today generally accepted: no explanation of neutrinos would be considered satisfactory if it did not encompass the charged leptons **and** the quarks. On the contrary, in 1972 the neutrinos were grouped together with the photon and the graviton rather than with quarks.

For these reasons, we suggest that the modern version of the question "Is the neutrino a Goldstone particle?" read "Are the quarks and the leptons Goldstone particles?" We are thus led to consider the following questions: (i) Is there a way out of the Bardeen-de Wit-Freedman no-go theorem? (ii) Is there a nonlinear realization of **extended** supersymmetry **à la** Volkov-Akulov which could accomodate the charged leptons and the quarks? (iii) Can we realize composite quarks and leptons in this scheme? (iv) What are the experimental consequences of the resulting model?

We show that the answer to the first and the second question is affirmative and construct the model in which there can be an arbitrary number of Goldstone fermions. We propose that these be the quarks and the leptons which then must have a new universal interaction characterized by a single constant f, analog of the pion decay constant f_π. The model is unique, however, the parameter f (the mass scale) is arbitrary.

The paper is organized in the following way. In Section II we consider the low energy theorem and show that the contradiction with experiment can be removed. We describe the general picture of quarks and leptons as Goldstone fermions. In Section III we describe the composite models of quarks and leptons based on these ideas. In Section IV we construct the Volkov-Akulov model for the case of extended supersymmetry and in Section V consider the consequences for the quark/lepton spectroscopy and the scattering processes among quarks and leptons due to the new interaction. Section VI contains a brief summary of our work.

II. THE PROBLEM OF DECOUPLING

The low energy theorem that was responsible for abandoning the Goldstone neutrino hypothesis states that the amplitude $M(q)$ of any process of the type $A \to B + \nu$, where A and B are single- or multi-particle states involving only massive particles, vanishes as the momentum of the neutrino q goes to zero:

$$\lim_{q \to 0} M(q) = 0.$$

In assessing the phenomenological consequences of this theorem, however, it is necessary to specify the scale at which the decoupling occurs.

This can be exemplified in case of pions. The relevant mass scale is f_π, the pion decay constant. The pion-pion coupling constant is $1/f_\pi^2$ and the pion-pion scattering amplitude is proportional to s/f_π^2, t/f_π^2, and u/f_π^2. The decoupling is obvious, however, **observing it** will depend on the relative magnitude of e.g. s/f_π^2 and the strength of the other interactions involved. At very low momenta $[s/f_\pi^2 = O(e^2)]$ the electromagnetic interaction which **breaks** the chiral symmetry sets in, and the pions do not decouple further, i.e., at zero momentum the pions interact only electromagnetically.

Precisely stated, the argument of Bardeen, de Wit, and Freedman says that **if the relevant scale is that of the weak interactions**, in other words, **if the weak interactions are supersymmetric**, the neutrino cannot be the Goldstone fermion. In view of the fact that the supersymmetric models of weak interactions have not so far appeared to be phenomenologically successful, we see no particular reason in further insisting on the weak interactions being supersymmetric. If the mass scale at which the decoupling takes place is higher than M_W (say $\gtrsim$ 1 TeV) and the observed weak interactions **break** the supersymmetry, it is clear that there is no contradiction with experiment.

The general qualitative picture which we would like to propose here can be outlined in the following way. Before the strong and the electroweak interactions are turned on, the quarks and the leptons are massless Goldstone fermions whose interactions are described in terms of a universal coupling constant $1/f^2$ in a manner similar to that of the nonlinear sigma model describing the interactions among pions. At energies much smaller than $f^{1/2}$* the quarks and the leptons are essentially decoupled. Turning on the gauge interactions gives mass to the fermions and breaks the supersymmetry. The gauge interactions are then all that we see at low (i.e., $\ll f^{1/2}$) energies. Approaching the scale $f^{1/2}$ is characterized by the increasing strength of the residual interaction, i.e., increasing deviations from the behavior predicted by the gauge theories. The precise form of the residual interaction is uniquely determined by the effective Lagrangian.

*In case of Goldstone fermions the constant f has dimension mass squared.

III. SUPERSYMMETRIC COMPOSITE MODELS OF QUARKS AND LEPTONS

The possibility of the quarks and the leptons being Goldstone fermions suggests a new kind of dynamics for composite models. The dynamics that we propose for the composite Goldstone fermions is very different from that of the models based on the unbroken chiral symmetry. The chief mechanism for forming massless bound states is supposed to be the **dynamical breaking of supersymmetry.** The starting point is assumed to be a massless supersymmetric theory containing a scalar and a fermion field. The dynamical breaking of supersymmetry is expected to give the quark/lepton constituents mass, while keeping the bound states massless. This is similar to the way the Nambu-Jona-Lasimio model[6] gives the nucleons mass while keeping the nucleon-antinucleon bound state (pion) massless. According to this scheme, the quarks and the leptons could be considered to be effectively "tightly bound" states of heavy constituents.

The residual interaction decouples as powers of $1/f^2$. It is very important for phenomenological purposes that the form of the interaction is uniquely determined, as we elaborate in Section IV, thus leading to well-defined experimental signatures. We emphasize that the effect of the residual interaction is suppressed by the **fourth** power of the mass scale in the amplitude. Consequently, f need not be very large in order to account for the present bound on residual interactions from current observations. On the other hand, the onset of the interaction at high enough energy is rather dramatic, due to the fourth power of momentum in the amplitudes. Also, the anomalous magnetic moment of the quarks and the leptons decouples like a power of $m/f^{1/2}$, where m is the quark/lepton mass. The absence of low-lying spin 3/2 quarks and leptons is ensured in this scheme: they are not Goldstone particles and therefore their masses are expected to be of the order $f^{1/2}$.

A very important question is the one of incorporating the flavor quantum numbers, in particular the generations into the scheme. A real step toward simplification would be reducing the generation number to a dynamical quantum number, i.e., excitation of certain kind. In this case we would have an understanding of the GIM scheme and the prescription for computing the mixing angles. On the other hand, the success of the excitation scheme would necessarily imply that the bound states must be adequately describable by means of the wave functions which are orthogonal and complete to a very high degree. Within the context of the Goldstone mechanism it appears difficult to incorporate this explanation of generation structure.

In general, incorporating flavor in the supersymmetric composite models outlined here will be related to the possible current algebras one can construct. We do not expect their number to be large in the usually rather restrictive form of supersymmetric theories. The question of current algebra is of crucial importance in all models in which the quarks and the leptons are Goldstone fermions. This is due to the fact that it is the current algebra, rather then details of the dynamics, that dictates the low-energy phenomenology. We have not yet studied this question in detail and do not consider it further in this paper.

Since the subquarks in our scheme are massive they do not have necessarily to be confined, contrary to the models with massless subquarks. It is indeed a rather exciting possibility that they may start getting liberated in future high energy accelerators.

There are several open questions which will have to be answered before a realistic model along these lines could emerge. First is, of course, to construct a working example of dynamical supersymmetry breaking. Several models are presently under investigation and the results will be reported in a forthcoming publication. In the rest of the paper we assume that the mechanism can be made to work and study the effective Lagrangian and the phenomenology of Goldstone fermions.

IV. NONLINEAR REALIZATION OF EXTENDED SUPERSYMMETRY

The nonlinear realization of supersymmetry first constructed by Volkov and Akulov[7] describes interaction of a Goldstone fermion with itself and with other particles. Since we want the quarks and the leptons to be Goldstone fermions, we have to incorporate internal degrees of freedom in the Volkov-Akulov model, i.e., to construct the nonlinear realization of **extended** supersymmetry.

The Volkov-Akulov Lagrangian reads

$$\mathscr{L} = f^2 \det W. \tag{4.1}$$

Here f is a parameter of dimension $(\text{mass})^2$ and

$$W_{\mu\nu} = \delta_{\mu\nu} + \frac{1}{f^2} T_{\mu\nu} \tag{4.2}$$

where

$$T_{\mu\nu} = \frac{1}{2i} (\bar{\psi}\gamma_\mu \partial_\nu \psi - \partial_\nu \bar{\psi}\gamma_\mu \psi). \tag{4.3}$$

$\psi(x)$ is the Goldstone spinor transforming nonlinearly and inhomogeneously according to

$$\delta\psi = \varepsilon + \frac{i}{2f^2} \partial_\mu \psi(\bar{\varepsilon}\gamma_\mu \psi - \bar{\psi}\gamma_\mu \varepsilon). \tag{4.4}$$

(Note that we use Dirac spinors. This and all the other formulae in this section look simpler with Majorana spinors. However, since we wish to identify these spinors with the physical leptons and quarks, we prefer to work with slightly more cumbersome Dirac spinors which allow for a well defined concept of fermion number and a distinction between particles and antiparticles.)

The supersymmetry algebra is

$$[\delta', \delta]\psi = \frac{i}{f^2}\,\partial_\mu\psi\left(\bar{\varepsilon}\gamma_\mu\varepsilon' - \bar{\varepsilon}'\gamma_\mu\varepsilon\right). \tag{4.5}$$

The extended (N>1) supersymmetry transformation is

$$\delta\psi^i = \varepsilon^i + \frac{i}{2f^2}\,\partial_\mu\psi^i\left(\bar{\varepsilon}^j\gamma_\mu\psi^j - \bar{\psi}^j\gamma_\mu\varepsilon^j\right), \tag{4.6}$$

where i,j = 1,...,N denote the internal degree of freedom. By performing two successive infinitesimal transformations (4.6) characterized by the parameters ε and ε' we obtain the algebra

$$[\delta', \delta]\psi^i = \frac{i}{f^2}\,\partial_\mu\psi^i\left(\bar{\varepsilon}^j\gamma_\mu\varepsilon'^j - \bar{\varepsilon}'^j\gamma_\mu\varepsilon^j\right). \tag{4.7}$$

which is same as in the N=1 case, Eq. (4.5). Note that the model does not realize a central charge. The Lagrangian (4.1), where now

$$T_{\mu\nu} = \frac{1}{2i}\left(\bar{\psi}^i\gamma_\mu\partial_\nu\psi^i - \partial_\nu\bar{\psi}^i\gamma_\mu\psi^i\right), \tag{4.8}$$

is invariant under the extended supersymmetry transformation (4.6). In fact, it is the unique effective Lagrangian which provides a minimal realization of this current algebra.

In order to show the invariance of the Lagrangian under (4.6) we make use of the formula

$$\delta(\det W) = \det W \; \mathrm{Tr}(W^{-1}\delta W). \tag{4.9}$$

The infinitesimal change of $W_{\mu\nu}$ can be cast in the form

$$\delta W_{\mu\nu} = \xi_\lambda \partial_\lambda W_{\mu\nu} + W_{\lambda\nu}\partial_\mu \xi_\lambda,$$

where ξ_λ stands for $\frac{i}{2f^2}\left(\bar{\varepsilon}^j \gamma_\lambda \psi^j - \bar{\psi}^j \gamma_\lambda \varepsilon^j\right)$. The trace in Eq. (4.9) is thus

$$\mathrm{Tr}(W^{-1}\delta W) = W^{-1}_{\nu\mu}\left(\xi^\lambda \partial_\lambda W_{\mu\nu} + W_{\lambda\nu}\partial_\mu \xi^\lambda\right).$$

Since

$$W^{-1}_{\nu\mu}\partial_\lambda W_{\mu\nu} = (\det W)^{-1} \; \partial_\lambda \det W$$

and

$$W^{-1}_{\nu\mu} W_{\lambda\nu}\partial_\mu \xi^\lambda = \partial_\mu \xi^\mu,$$

the variation of the Lagrangian is total divergence

$$\delta\mathscr{L} = f^2 \partial_\mu(\xi^\mu \det W).$$

Therefore, the action is invariant under the transformation (4.6).

Expanding the Lagrangian (4.1) in powers of $1/f^2$ yields (neglecting the constant term equal to f^2)

$$\mathscr{L} = i\bar{\psi}^i \not{\partial}\psi^i - \frac{1}{8f^2}\Big\{(\bar{\psi}^i \not{\partial}\psi^i)^2 + (\partial_\mu\bar{\psi}^i \gamma_\mu \psi^i)^2 - 2(\bar{\psi}^i \not{\partial}\psi^i)(\partial_\mu \bar{\psi}^j \gamma_\mu \psi^j) +$$

$$+ (\bar{\psi}^i \gamma_\mu \partial_\nu \psi^i)(\bar{\psi}^j \gamma_\nu \partial_\mu \psi^j) + (\partial_\nu \bar{\psi}^i \gamma_\mu \psi^i)(\partial_\mu \bar{\psi}^j \gamma_\nu \psi^j) - \qquad (4.10)$$

$$- 2(\bar{\psi}^i \gamma_\mu \partial_\nu \psi^i)(\partial_\mu \bar{\psi}^j \gamma_\nu \psi^j)\Big\} + O\left(\frac{1}{f^4}\right) + O\left(\frac{1}{f^6}\right).$$

Unlike the case of the nonlinear σ model, the series terminates. The two-body scattering is governed by the $O(1/f^2)$ term. The four-fermion interaction contains a derivative which makes it a dimension eight operator so that f has dimension of mass squared.

V. PHENOMENOLOGY OF THE MODEL

In distinction to other theoretical schemes which might produce massless fermions, the Goldstone mechanism has a well defined low-energy phenomenology which is determined solely by the current algebra and not by the detailed dynamics of the theory. This is clearly illustrated by the non-linear realization of supersymmetry and plays an important role in the study of the fermion-fermion scattering processes. Moreover, the Goldstone mechanism is expected to be useful in the quark/lepton spectroscopy: the quarks and the leptons in the real world are not strictly massless and therefore cannot be the true Goldstone fermions. Rather, we expect them to be pseudo-Goldstone particles acquiring mass from the interactions that break the supersymmetry. The supersymmetric interaction is supposed to be symmetric under the group G containing $SU(3)_c \otimes SU(2) \otimes U(1)$ ($\otimes$, possibly, a "horizontal" group). The limit of exact supersymmetry should be understood as the one where the supersymmetry current conservation is related to the vanishing of the quark and lepton mass according to the Goldstone mechanism. The total effective Hamiltonian for the quarks and leptons can be written as

$$H = H_0 + \varepsilon H_1 \tag{5.1}$$

where H_0 is supersymmetric and G-invariant and εH_1 is such that, when $\varepsilon \to 0$, the quarks and the leptons become massless. In this framework the group G generated by the charges $Q_i (i = 1,\ldots,n,n$ = dimension of G) can be considered as an approximate symmetry group and thus we can calculate the corrections proportional to $\dot{Q} = i\varepsilon[H_1, Q]$.

We expect that the quark and lepton masses should be computable in a way analogous to the computation of the electromagnetic mass difference of pions. For example the electron mass would be calculated from

$$m_e = -\frac{1}{2}\frac{i}{(2\pi)^4}\int d^4q D^{ab}_{\mu\nu}(q) M^{ab}_{\mu\nu}(q,p), \tag{5.2}$$

where $D^{ab}_{\mu\nu}(q)$ is a gauge boson propagator and $M^{ab}_{\mu\nu}(q,p)$ forward amplitude for virtual Compton scattering:

$$M^{ab}_{\mu\nu}(q,p) = i\int d^4x e^{iqx} \left\{\langle e|T[j^a_\mu \; (x) \; j^b_\nu \; (0)]|e\rangle\right\}. \tag{5.3}$$

The computation of $M^{ab}_{\mu\nu}(q,p)$ would require the construction of the supersymmetric analog of Weinberg spectral function sum rules.[10] Of course, only those gauge interactions which explicitly break the supersymmetry would contribute to the mass as calculated in Eq. (5.2). We intend to consider this problem in more detail in a future paper.

Concerning the scattering processes among quarks and leptons, the main feature of our model is the appearance of a new interaction characterized by the coupling constant $1/f^2$ with the dimension m^{-4}. The precise form of the interaction will, of course, depend on the current algebra, i.e., on the way flavor and the generations are incorporated in the scheme, but the essential features are certain to be present in all variants of the models. Here we compute in the $N > 1$ nonlinear model several amplitudes for the fermion-fermion scattering which is governed by the $O(1/f^2)$ term of the Lagrangian (4.10).

Consider first the particle-particle scattering $a+b \to c+d$ where a,b,c, and d are the internal indices (Fig. 1). The independent helicity amplitudes are

$$\langle ++|T|++\rangle = -\frac{1}{(2\pi)^6}\frac{s^2}{f^2}\left(\cos^2\frac{\theta}{2}\,\delta_{ac}\delta_{bd} + \sin^2\frac{\Theta}{2}\,\delta_{ad}\delta_{bc}\right),$$

$$\langle +-|T|+-\rangle = -\frac{1}{(2\pi^6)}\frac{s^2}{f^2}\cos^2\frac{\theta}{2}\,\delta_{ac}\delta_{bd}, \qquad (5.4)$$

$$\langle +-|T|=+\rangle = \frac{1}{(2\pi^6)}\frac{s^2}{f^2}\sin^2\frac{\theta}{2}\,\delta_{ad}\delta_{bc},$$

where θ is the scattering angle in CMS, $|i\rangle = |\mu_a\mu_b\rangle$ and $|f\rangle = |\mu_c\mu_d\rangle$ the initial and the final two-body helicity states and $\langle f|T|i\rangle$ are properly normalized T matrix elements. All spin-flip amplitudes are, of course, zero: the theory is by construction chirally invariant. The existence of the residual interaction among quarks and leptons of the form (4.10) would thus cause a dramatic rise of all lepton-lepton, quark-lepton and quark-quark elastic scattering cross sections at (presently undetermined) energy $f^{1/2}$.

Similarly, the particle-antiparticle scattering amplitudes (Fig. 2) are

$$\langle ++|T|++\rangle = \frac{1}{4(2\pi)^6}\frac{s^2}{f^2}\left(\sin^2\theta\ \delta_{ab}\delta_{cd} - 2(1+\cos\theta)\ \delta_{ac}\delta_{bd}\right),$$

$$\langle +-|T|+-\rangle = \frac{1}{(2\pi)^6}\frac{s^2}{f^2}\cos^2\frac{\theta}{2}\ \delta_{ac}\delta_{bd}, \qquad (5.5)$$

$$\langle ++|T|--\rangle = -\frac{1}{4(2\pi)^6}\frac{s^2}{f^2}\sin^2\theta\ \delta_{ab}\delta_{cd}.$$

General experimental consequence here, as in the previous case, is an increase in all cross sections for the processes like $e^+e^- \rightarrow \ell^+\ell^-$ or $q\bar{q}$. Of particular interest is the process $q\bar{q} \rightarrow \ell^+\ell^-$ which has a very clear signature in hadronic collisions. We have mentioned earlier that, since the amplitudes are proportional to the inverse fourth power of the mass scale $f^{1/2}$, the mass scale itself does not necessarily have to be very high. Actually, it may lie within the reach of the next generation accelerators. An anomalous yield of lepton pairs produced in the new $p\bar{p}$ machines could thus be an early sign of the quark/lepton substructure.

VI. SUMMARY

We have formulated the hypothesis that the quarks and the leptons are composite Goldstone fermions of spontaneously broken supersymmetry. The main feature of this scheme is the existence of a new (nonrenormalizable) effective interaction among quarks and leptons characterized by a single phenomenological coupling constant $1/f^2$. The new interaction should in principle be observable through its interference with the gauge interactions (electroweak, strong) and should become increasingly important at higher energies. An early sign of this interaction could be an anomalous increase in lepton-pair production in $\bar{p}p$ collisions.

An attractive feature of our scheme is that the entire well developed machinery of current algebras may turn out to be useful in obtaining physically interesting results like sum rules, low-energy theorems, etc. We propose a program for computing the quark and lepton mass analogous to the computation of the electromagnetic mass splittings of pions.

In view of the possible composite structure of quarks and leptons, we propose a new class of composite models in which spontaneously broken supersymmetry, instead of unbroken chiral symmetry, assures masslessness of the bound states.

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FIGURE CAPTIONS

Fig. 1. Fermion-fermion scattering amplitude introduced by the supersymmetric Lagrangian, Eq. (4.10).

Fig. 2. Fermion-antifermion scattering amplitdue introduced by the supersymmetric Lagrangian, Eq. (4.10).

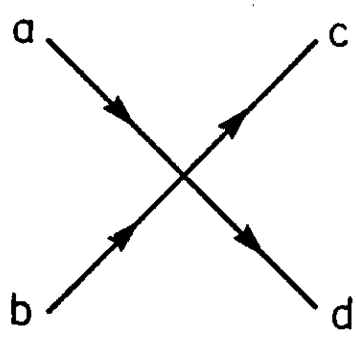

Fig. 1

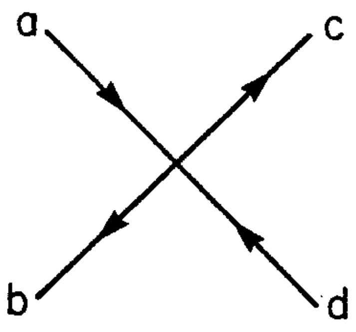

Fig. 2