GENERAL STATUS: SUMMARY AND OUTLOOK

MURRAY GELL-MANN*

CERN, Geneva, Switzerland**

I am honored to have been chosen for the second time to summarize one of these Conferences. On the first occasion, at Berkeley in 1966, two circumstances were more favorable than now - one, that I gave the summary at the beginning rather than at the end, so that I didn't have to be confused by the facts; the other, that I had two hours instead of one. Today, I barely have time to mention the various topics, let alone comment on them; you will have to guess the comment each time from the expression on my face: gauge theories - hope; $K_L^\circ \to \mu^+\mu^-$ - relief; etc. It will be no surprise that the summary represents a theoretician's point of view, but I shall try to concern myself with experiments as well as theory.

Let me begin with one or two experimental results that challenge earlier, paradoxical results. Last year the rate of K_L° decay into $\mu^+ + \mu^-$ was reported to be lower than allowed by unitarity unless fantastic hypotheses are concocted. Now the matter has become experimentally controversial, and we theorists can relax for a while and see what happens.

A less shocking result has also been challenged. Evidence on the decays $K \to \pi$ + leptons, from e/μ ratio, spectrum, and polarization, has tended not to agree with the "Callan-Treiman point," just outside the experimental region, and the disagreement would rule out:

the validity of the PCAC idea in the presence of other currents (so-called "strong" PCAC),

the idea that $m_\pi^2 \approx 0$ is connected with approximate invariance under $SU_2 \times SU_2$,

the related idea that the bare mass of the non-strange quarks is much lower than that of the strange one.

* John Simon Guggenheim Fellow.

** Present address: Lauritsen Laboratory of High Energy Physics, California Institute of Technology, Pasadena, California, U.S.A.

Now the experimental situation might be shifting toward agreement, although the weight of evidence is still on the other side.

What is the news about CP violation? The notion of electromagnetic violation, which stirred some excitement at one time, is not supported by any good evidence. The hypotheses of multi-strong and milli-weak violations, which were never very attractive, are fading as the upper limit on the electric dipole moment of the neutron keeps being reduced; it is now of the order of e times 10^{-23}cm. The hypothesis of a superweak $|\Delta S| = 2$ interaction that violates CP and conserves P is still in excellent agreement with all the data, despite new experimental controversies over the lifetime of K°_S and the rate of $K^\circ_L \to \pi^+ + \pi^-$. Assuming the superweak theory is right, will it lead, in our lifetimes, to new observable effects? If the $|\Delta S| = 2$, P-conserving interaction is accompanied by a $|\Delta S| = 0$, P-violating one that also breaks CP, then we could get an E1 moment for the neutron of the order of e times 10^{-26} or 10^{-27} cm, which may be detectable some day. Such an extra term might arise, for example, if we try to construct the CP violation in a quark picture by taking the square of a single neutral current. Instead of

$$(\bar{s}d)_{\text{1st class}}\ (\bar{s}d)_{\text{2nd class}} + \text{h.c.},$$

which would give the usual kind of term, we might have

$$\left[(\bar{s}d + \bar{d}s)_{\text{1st class and 2nd class, V and A}}\right]^2 ,$$

which would give both types of term.

Coming now to weak interactions, I should like to express my enthusiasm over the recently revived attempts to unify the electromagnetic and weak interactions in the framework of a renormalizable field theory. The renormalizability has recently been demonstrated for a wide class of theories, and it means not only that for each theory specific finite results are predicted in every order of perturbation theory, but also that unphysical singular behavior of cross sections at high energy is avoided. The ideas behind this class of theories are the following:

1) There is a Yang-Mills gauge theory to start with, based on a Lie group generated by the electric charge, the weak charge, its hermitian conjugate, and perhaps other charges, associated with new currents.

2) All violations of exact gauge symmetry whether for leptons, hadrons, or intermediate bosons, come from invariant couplings to a set of invariantly self-coupled scalar fields ϕ, which undergo spontaneous unsymmetrical translation, $\phi \to \Phi$ + const.

3) In particular, all masses that break gauge symmetry arise from this translation, couplings $\bar{\psi}\phi\psi$ yield bare mass terms (const.) $\bar{\psi}\psi$ after translation. Before the translation, the lepton masses show high symmetry and so do the quark bare masses (the parameters of violation of $SU_3 \times SU_3$ symmetry for hadrons). In fact all these lepton and quark masses may vanish before translation, as the intermediate boson masses certainly do. The photon mass stays zero after translation, of course.

The weak and electromagnetic dimensionless coupling constants are of the same order of magnitude in these theories, and at high energies the strength of the weak interaction levels off at electromagnetic strength, rather than reaching the unitary limit. The intermediate boson masses are thus of the order of 50 - 100 GeV. (There may also be a set of additional intermediate bosons of higher mass.) In general, higher order weak corrections to amplitudes are of order α, α^2, etc., just like higher order electromagnetic ones.

We need a theory that satisfies a number of conditions, including the following:

1) If there are new neutral interactions, they must not couple $|\Delta S| = 1$ hadronic currents to known lepton pairs, since experiment sets very low upper limits on such couplings.

2) There are rules, such as the vanishing of the $K_1^\circ - K_2^\circ$ mass difference in the lowest order of the weak coupling constant, that must not be violated in the next order of α, but only by a much smaller amount.

3) "Anomalies" of the Adler type must cancel; perhaps they cancel between leptons and hadrons!

Above all, the theory should be beautiful. Those examples that have received wide publicity, although some are not altogether excluded by experiment, are not very beautiful, in my opinion. But they have revived interest in three types of possible new phenomena:

a) neutral currents of various kinds and even new charged currents;

b) new dimensions of strangeness for hadrons (e.g. "charm"); and

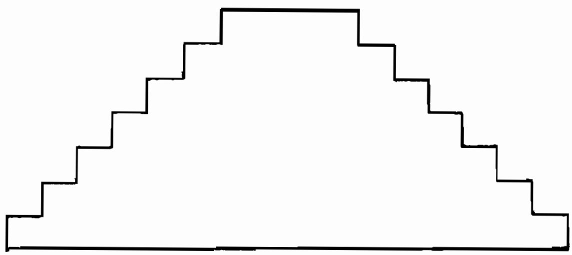
c) heavy leptons, charged and/or neutral.

Thus the proposed models are a bonanza to experimentalists as well as a thought-provoking challenge to theorists.

Possibly we will find an elegant model, in agreement with observation, that yields the pattern of lepton masses as well as the pattern of quark bare masses and even relates hadrons and leptons. This is <u>our</u> dream; touch us!

While speculation is rife about how to unite electromagnetic theory and weak interaction theory, both are healthy. Quantum electrodynamics seems in good agreement with experiment up to the huge number of decimal places allowed by the tiny errors; and lowest order weak theory remains in good agreement with data. Second class currents seemed to be a threat for a while, but the nuclear physicists have changed their minds and we don't have to worry about them, it seems. The expected weak non-leptonic parity violation has been seen in many experiments on nuclei. (Unfortunately, the effect may be too large to agree with particle theory estimates, if recently revised estimates of nuclear effects by nuclear theorists survive, or if a recent 3 standard-deviation result on the reaction $n + p \to d + \gamma$ survives.)

Next, we come to the hadrons, their strong interaction, and their weak and electromagnetic currents. Here, I should like to present Figure 1.



E - TEMEN - AN - KI

This is not a histogram, but a sketch of a model of a building; many of us saw the model at the Oriental Institute. The name is from a language much older than Middle English; the language was old even when it was used by the Babylonians to name the building - in Sumerian, "House of the Foundation of Heaven and Earth." In the Bible a tale is told of its construction, as you know. "Go to, let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name...." "Go to, let us go down, and there confound their language, that they may not understand one another's speech..." "....and they left off to build the city." If we allow the same thing to happen to us, we will have to leave off building our temple of the foundations of the universe.

If we avoid the fate of the builders of the Tower of Babel, then I see, close at hand, another marvelous dream - a unified theory of the hadrons, their strong interaction, and their currents, incorporating all the respectable ideas now being studied: constituent quarks, current quarks, the bootstrap, dual resonance methods, Regge poles and cuts, hadronic scaling, weak and electromagnetic scaling, and current algebra. These are all or nearly all compatible, if we can get our language straight.

Let me try to clarify some of these concepts and the words used to describe them, especially those connected with quarks.

Current quarks:

The electromagnetic and weak interactions of hadrons are thought to act, in many respects (algebraic properties such as equal time commutation relations, light cone singularities of commutators and products, and perhaps much deeper properties as well) as if they had the form $\bar{q}$(matrix)q for a hypothetical relativistic quark field q. We abstract these properties from a model field theory, for example one in which the quark fields are coupled universally to a neutral vector "gluon" field. Such abstracted relations are supposed to be exact to all orders of the strong interaction, and are subject, in many cases, to check by experiment. So far, the tests have not been sufficiently incisive, but they have never disproved any relation of quark current algebra.

The most important applications of the algebraic relations can be discussed in terms of currents on or near a single null plane, say $x_+ \equiv x_3 + x_o = 0$. (This replaces the older method in which the third component P_3 of momentum tends to infinity.) The "good" components of the currents are those that have one Lorentz index equal to +. According to quark current algebra, the integrals of these "good" components over the null plane form a Lie algebra $[U_6]_{W,\text{currents}}$ of the charges of the vector and axial vector currents on the null plane. The vector current charges are, of course, exact or approximate symmetries of the hadrons and their strong interaction, depending on the SU_3 index, but the other generators of the algebra $[U_6]_{W,\text{currents}}$ are not at all close to being symmetries. If they were, we would have zero anomalous magnetic moments for neutron and proton, and other results very far from being true, such as $-G_A/G_V = 5/3$. There is, however, another algebra, isomorphic to $[U_6]_{W,\text{currents}}$ but not identical with it; we may call it $[U_6]_{W,\text{strong}}$ and it is presumably a unitary transform of $[U_6]_{W,\text{currents}}$. The generators of $[U_6]_{W,\text{strong}}$ are approximate symmetries of the hadrons. We have now come to the next topic.

Constituent or structure quarks:

The known bound and resonant states of baryons B and mesons M act, with respect to spectrum, quantum numbers, and symmetry of vertices BBM and MMM, as if they were made up, in a sort of non-relativistic system, of qqq in the case of B and $q\bar{q}$ in the case of M. (There may also be higher states in the B and M spectra that behave like $qqqq\bar{q}$, $qqq\bar{q}$, etc.; these configurations would contain states with "exotic" quantum numbers that do not occur for qqq and $q\bar{q}$. Of course such states occur in the continuum in any case.)

The constituent quark model is inherently approximate and naive, and yet seems to work surprisingly well. The spectrum is very approximately symmetrical under the group $U_6 \times U_6 \times O_3$, where one U_6 is for quarks and one for antiquarks and O_3 describes a relative orbital angular momentum $\underset{\sim}{L}$. Collinear amplitudes, like vertices and forward scattering amplitudes, with the single direction of motion chosen to be the z-direction, are approximately symmetrical under a subgroup of $U_6 \times U_6 \times O_3$, namely $[U_6]_{W,\text{strong}} \times [O_2]_{W,\text{strong}}$, where $[O_2]_{W,\text{strong}}$ is generated by L_z and $[U_6]_{W,\text{strong}}$ is just the group we have described above as being a unitary transform of $[U_6]_{W,\text{currents}}$.

The unitary transformation is the one that we may describe as taking current quarks into constituent quarks. Whereas a baryon or meson state consists approximately of qqq or $q\bar{q}$ respectively in terms of constituent quarks, the transformation introduces an indefinitely large number of quark pairs when we express the baryon or meson in terms of current quarks. This transformation conserves J_z, $\underset{\sim}{I}$, and Y and nearly conserves the other vector current charges F_i, but changes $\underset{\sim}{J}$, P, and the axial vector current charges F_i^5 drastically.

The transformation preserves statistics, and there is some evidence from both current quarks and constituent quarks for peculiar "quark statistics." In the case of constituent quarks, the quark statistics would permit the ground state of the baryon to have a symmetrical spatial wave function (as befits a simple model) even though the spin and SU_3 wave function is also symmetrical (belonging to the famous $\underset{\sim}{56}$ representation of $[SU_6]_{W,\mathrm{strong}}$). The peculiar statistics has been used for a long time, and may be called "para-Fermi statistics of rank 3 with restriction to fermionic baryons and bosonic quarks." Recently an equivalent but simpler formulation has been employed: one imagines three indistinguishable classes of quarks (each containing the usual three varieties, of course) and one labels the classes by "color" - say red, white, and blue. Each kind of quark obeys Fermi-Dirac statistics, but physical particles are required to be singlets under the SU_3 of color, transforming for example like $\bar{q}_R q_R + \bar{q}_B q_B + \bar{q}_W q_W$ or $q_R q_B q_W + q_B q_W q_R + q_W q_R q_B - q_R q_W q_B - q_B q_R q_W - q_W q_B q_R$.

Real quarks:

Real quarks, detectable in the laboratory, are not required by theory. In this respect, they are like magnetic monopoles or the B^o particles of Lee and Wick; they may conceivably exist, but do not fill any obvious theoretical need. (This is in contrast to intermediate bosons for the weak interaction, which are really important for the construction of a sensible theory.) The search for real quarks is, of course, justified by the excitement of the chase and the chance of practical applications if they are found, but not by any real theoretical prediction.

Now the quark statistics we have described probably rules out the existence of real quarks, even if the color singlet restriction is applied only to baryons and mesons (the reason being that, if quarks were real, such a restriction would tend to violate the factorization of the S-matrix for two widely separated systems.)

Let us suppose there are no real quarks. Then the hadron theory must be such that quarks are somehow permanently contained inside hadrons. There can then be an alternative formulation of the theory that does not start with quarks at all, but introduces them at a later stage as an ansatz or an aid in defining a useful set of variables.

Thus we may well have a situation in which quark language and bootstrap or duality language bear the same kind of relation to each other as wave mechanics and matrix mechanics, namely two different frameworks for formulating the same theory.

<u>Proposed variants of the quark scheme</u>:

a) The Han-Nambu picture has three fermion triplets, with charges 1,0,0 ; 1,0,0 ; and 0,-1,-1. On the average these give + 2/3, - 1/3, - 1/3. The known baryons would thus correspond to combinations of three fermions, one from each triplet. The "color" variable that distinguishes the triplets from one another is physical in this scheme, and even coupled to electromagnetism. Baryons and mesons that are not singlets with respect to the SU_3 of "color" must be found some day if the scheme is correct. Moreover, the basic fermions themselves could well be real.

b) Glashow and Maiani have introduced a scheme for hadrons that makes it easier to include them in a unified theory of weak and electromagnetic interactions.

They add to the three usual quarks a fourth one, with charge + 2/3 and a non-zero value of a new quantum number called "charm." The new quark contributes an SU_3 singlet term to the electromagnetic current. For the scheme to be right, charmed baryons and mesons must be found. We can, if we like, use the three-valued color variable of the quark statistics in the Glashow-Maiani scheme, along with the restriction of physical states to color singlets.

Partons:

This is a general term, which seems to mean current quarks (or variants thereof) along with some kind of neutral "gluons." "Parton" ideas were used by Bjorken, Feynman, Llewellyn Smith, Landshoff and Polkinghorne, and others to give numerous results of light cone current algebra before light cone current algebra was abstracted from current quark models. There are also "parton" ideas that go beyond light cone current algebra and assume an actual quark and gluon Fock space, along with the validity of a kind of impulse approximation as certain energy variables tend simultaneously to infinity. The results of this point of view are discussed further on, in connection with mixed scaling.

Electromagnetic and weak scaling:

The SLAC-MIT experiments on deep inelastic electron-nucleon scattering suggest, although they do not prove, the following theoretical statements -

a) As $q^2 \to \infty$ and $q \cdot p \to \infty$, with $\xi \equiv -q^2/2q \cdot p$ fixed, the cross-sections are expressible in terms of the Bjorken scaling functions of ξ.

b) The ratio σ_L/σ_T of longitudinal to transverse virtual photon cross-sections tends to zero like $(p \cdot q)^{-1} f(\xi)$ in the Bjorken limit, indicating that we can abstract formal results from a field model in which the charged objects have spin 1/2 only.

c) The Bjorken limit and the Regge limit ($p \cdot q \to \infty$ for fixed q^2) can be interchanged, so that the Bjorken functions exhibit Regge behavior as $\xi \to 0$.

If these ideas are right, then we may make an ambitious abstraction from a relativistic field model with quarks and neutral (say vector) gluons, treated formally. This "light cone current algebra," a generalization of the old current algebra, gives for the Bjorken scaling functions sum rules relating ep, en, νp, and $\bar{\nu} p$ deep inelastic cross-sections; inequalities like $1/4 \leq F^{en}(\xi)/F^{ep}(\xi) \leq 4$; and other predictions. So far, it is compatible with experiment, but needs to be tested much better.

For that we need neutrino experiments, which up to now have not gone very far into the deep inelastic region. Yet scaling predictions like $\sigma^{\nu p} \propto E_{lab}$ seem to be fulfilled precociously, and the predicted relations of neutrino and electron cross sections are in qualitative agreement with the data, as discussed by Perkins.

If the ratio of $\sigma^{\nu p}$ to E_{lab} is indeed the asymptotic one, then we can conclude that only about half the momentum of the nucleon is attributable to current quarks and the rest should be ascribed to neutral glue of some kind.

The V-A interference term $\xi F_3(\xi)$ has apparently been detected in neutrino experiments and found to be large, which affords some hope of testing the Gross and Llewellyn Smith sum rule of quark light cone algebra.

Light cone algebra (if abstracted from a quark and vector gluon picture) can be generalized to include divergences of V and A currents, so that a large algebraic system of V,A,S,P, and T densities is encountered. Here the bare masses of the quarks are physical quantities, measurable in difficult experiments. (By the way, if strong PCAC is right, with $SU_2 \times SU_2$ an exact Goldstone symmetry as $m_\pi^2 \to 0$, then the ratio of the bare mass of the non-strange quarks to that of the strange quark is very small, something like 0.04. With a weak version of PCAC, the ratio could be near unity.)

Light Cone Algebra in the Vacuum:

A further abstraction from quark-gluon field theory models permits us to apply light cone algebra to processes without hadron targets. The ratio $\sigma(e^+ + e^- \to \text{hadrons})/\sigma(e^+ + e^- \to \mu^+ + \mu^-)$ to order e^2 would then approach a definite number at high energy. This number would be:

2 for quarks with quark statistics, or else for three triplets of quarks;

2/3 for quarks with Fermi-Dirac statistics;

4 for the Han-Nambu scheme, but only at very high energies where the Han-Nambu degrees of freedom are excited;

10/3 for quarks with charm and quark statistics, but only at sufficiently high energies for charmed hadrons to be created.

Experimentally, the situation is not yet clear. Data are available up to about 4 GeV total, and it is not certain that any asymptotic value is being approached yet. In so far as the data suggest an asymptotic ratio, it is more like 3 or 4 than 2, but the uncertainties are still considerable. Here is a case in which increased energy and especially increased accuracy will really help us to learn something fundamental.

If light cone algebra is right, then in the PCAC approximation we can calculate the amplitude for the decay $\pi^0 \to 2\gamma$ using the same assumptions as in the case of e^+e^- annihilation. The amplitude comes out correct in sign and magnitude, within the errors of observation, for the case of quarks with quark statistics (with or without charm) or for the Han-Nambu scheme. For quarks with Fermi-Dirac statistics, the amplitude is too small by a factor of 3.

Unless PCAC can be shown to be drastically wrong for this problem or some serious flaw is found in vacuum light cone algebra, the $\pi^0 \to 2\gamma$ decay can be taken as evidence that the quark scheme with Fermi-Dirac statistics is not the one to use. (Let me re-emphasize that quarks have usually been assigned quark statistics or its equivalent in order to make the constituent quark picture simpler; there is no reason to label quarks with Fermi-Dirac statistics by the names of Gell-Mann and Zweig, as some speakers have done!)

Hadronic Scaling:

We have discussed weak and electromagnetic scaling, considering the four-momentum q of a current and the four-momentum p of a target hadron and taking the Bjorken limit, in which $q^2 \to \infty$ and $p \cdot q \to \infty$ with $q^2/p \cdot q$ fixed. Now in purely hadronic processes, another type of scaling has been proposed (for example, by Feynman and by Yang et al.). Here there is no q, only hadronic p's, and every p^2 is fixed, since the hadrons are on the mass shell. We consider the inclusive cross-section for two hadrons, with four-momentum p_1 and p_2, giving a final hadron, with four-momentum p, plus anything.

There is a forward fragmentation region, in which $p \cdot p_1 \to \infty$, $p_1 \cdot p_2 \to \infty$, the ratio is fixed, and $p \cdot p_2$ is finite. There is also a backward fragmentation region, with p_1 and p_2 interchanged. There is also the central or pionization region, where, for example, $p \cdot p_1$ and $p \cdot p_2$ both go to infinity like $\sqrt{p_1 \cdot p_2}$.

The suggestion is that in all these regions, at superhigh energies, the inclusive cross-sections should be given in terms of energy-independent functions of the scaling variable and of the other finite variable. Experiments ranging from Brookhaven to ISR energies tend to support hadronic scaling in the fragmentation region, and scaling in the central region appears to set in at ISR energies, according to recent experiments; the slower onset in the central region is quite compatible with theory.

A CERN-Columbia-Rockefeller inclusive pion production experiment at the ISR for high s, in the central region, for very large $p_{transverse}$, was reported at this Conference. It gives a much higher cross-section than would be expected on the basis of exponential extrapolation in p_T and the kind of scaling observed at lower values of p_T. This experiment may or may not indicate a failure of scaling; it is certainly very encouraging for data rates at large p_T.

A word or two will be said further on about the theory of hadronic scaling.

Mixed Scaling:

It has also been proposed that scaling may occur in various mixed processes, involving a current with four-momentum q and at least two hadrons, with four-momenta p and p^1. The scaling limit is one in which, for example, $p \cdot p^1 \to \infty$ and $q^2 \to \infty$ with fixed ratio. One kind of example is provided by the reaction $p + p \to \mu^+ + \mu^-$ + anything. The reaction $\gamma_{virtual} + p \to \pi$ + anything provides another sort of example, in the so-called current fragmentation region.

The theoretical study of the systematics of mixed scaling should throw light on the relation that it bears to hadronic and to weak and electromagnetic scaling and also on the relation that these bear to one another, which is not really understood.

Some mixed scaling ideas can be understood by combining the hypothesis of hadronic scaling with light cone current algebra. Others seem to require the impulse approximation invoked by the "parton" theorists, who have provided most of the impetus for the study of mixed scaling.

Experiments on mixed scaling will obviously be of considerable value. So far there is insufficient evidence at high enough energies to provide real tests.

So much for the electromagnetic and weak currents of hadrons. The rest of this talk is devoted to the strong interactions. First, let us consider the spectra of meson and baryon bound and resonant states.

The baryon states, as revealed by experiment and elaborate phenomenological analysis, were discussed by Lovelace, in a remarkable talk in which he exhibited simultaneously his talents as a physicist and as an entertainer. The constituent quark model seems to work better than ever for baryons, with the $\underset{\sim}{56}$, $L = 0^+$ and $\underset{\sim}{70}$, $L = 1^-$ supermultiplets showing up very nicely, along with families of higher L. There is one good candidate for an exotic resonance, a Z^* with $I = 0$; if the quark picture is to hold up, this state must go away or else be accompanied by a huge number of cousins in a $qqqq\bar{q}$ family or else represent some totally new phenomenon, such as the occurrence of unstable charmed hadrons. Evidently the search for resonance families that include exotics needs to be carried further, for both baryons and mesons. At the moment, there are no candidates in exotic meson resonances.

Meson states were discussed by Diebold, and he made clear that while the constituent quark model is probably all right for mesons, it is undergoing some renovation from the experimental point of view, as far as the P states of $q\bar{q}$ are concerned. We may consider the $I = 1$ mesons, for example; there should be ${}^3P_2$, ${}^3P_1$, ${}^3P_0$, and ${}^1P_0$ configurations, that is, mesons with $J^P = 2^+$, 1^+, 0^+, and $1^{+'}$ (with opposite charge conjugation). The ${}^3P_2$ and ${}^1P_0$ examples are there without any doubt, at around 1310 and 1235 MeV respectively. The ${}^3P_1$, referred to experimentally as A_1, has come under a cloud, since in the reaction where it showed up most strikingly, a large part of the bump can be accounted for by kinematic enhancement. Clearly more research is needed, especially on other reactions where such a meson could be found. The ${}^3P_0$, identified with a scalar meson around 980 MeV decaying into $\pi + \eta$, was not discussed in the review talk; it is apparently covered by Diebold's law of meson decay, which states that a meson decays out of the tables if it has not been detected lately.

As in the case of baryons, there is scattered evidence for meson families with higher L. The ρ' meson, which seems to show up in e^+e^- annihilation and elsewhere as a resonance, decaying mainly into $\rho+\pi+\pi$, could be thought of either as a radial excitation of the ρ or else as a $^3D_1$ configuration of $q\bar{q}$.

One type of excitation of higher and higher J, for both mesons and baryons, can be described without explicit reference to the quark model. As far as we know, all the bound and resonant states of baryons and mesons belong to Regge sequences, lying on Regge trajectories; all quantum numbers except J are constant and the physical values of J are spaced 2 apart. For baryons, spins as high as 11/2 are known and others are conjectured as high as 21/2. For mesons, only much lower spins are verified so far, but the sequences are assumed to go on and on as they do for baryons. For all known trajectories, the real part of J seems to be nearly linear in M^2, and the slopes are always close to the universal value of about one unit per $(\text{GeV})^2$. This striking pattern may persist up to very high energies, where it would have remarkable consequences, since equal spacing in M^2 means closer and closer spacing in M, and ultimately implies fascinating restrictions on decays because of angular momentum barriers.

As experiments have gotten more difficult and expensive and harder to interpret and to corroborate, it has been easy to become discouraged about the search for resonances, but the task of verifying and further exploring the "horizontal" patterns of the constituent quark model and the "vertical" patterns of Regge trajectories is so important that it is worth a great deal of further effort.

The meson trajectories are very crudely "exchange degenerate," with odd and even parity trajectories nearly superposed. This can be explained by the fact that in the crossed channel for meson-meson scattering "exotic" mesons are lacking, at least at low energies.

For baryon trajectories, there is a special problem arising from the approximate linearity of J with M^2. The scattering amplitude formulae possess the MacDowell symmetry that connects change of parity with a change of sign in the mass M. Thus it would be natural to have degenerate trajectories of opposite parity, with all other quantum numbers equal, and to have resonances accompanied by degenerate resonances of opposite parity, unless these are somehow suppressed. But observations have never revealed any parity degeneracy, so the suppression is essential. At least two schemes have been proposed to account for the suppression - one involves a zero canceling each resonance pole of the wrong parity and the other is based on the Carlitz-Kislinger cuts. Which is right, if either?

Experiments to decide this and other questions about trajectories include the study of high energy amplitudes with two particles in and two particles (or sprays) out, in which the Regge poles, along with associated cuts, are <u>exchanged</u>. Despite a great deal of adverse propaganda, the Regge pole and cut picture of non-diffraction scattering is quite successful. At high values of s, with t or u near zero, the leading power law in s for each exchange gives a value $\alpha(0)$ that lies right on the relevant straight line trajectory, to within the errors.

Low-lying poles are obscured by Reggeon-Reggeon cuts. Even in the case of the pion trajectory, such cuts may give important competition.

Still more important are "Reggeon-Pomeron" cuts arising out of interference between a non-diffraction Regge pole and the singularity responsible for diffraction. Near t = 0 or u = 0, these should be suppressed by a factor of ln s compared to the corresponding Regge pole, but for larger values of -t or -u they are expected to dominate at sufficiently high energies. At present accelerator energies, however, there are cases where the Reggeon-Pomeron cut contributions are not very large, and the pole contributions can be detected over a broad range of t or u. This happens particularly for the imaginary part of amplitudes in which there is a helicity change of one unit; presumably absorption corrections do not greatly alter the form of such amplitudes at moderate energies. The Regge trajectories can then be followed into the negative t or u region, and they remain close to the straight lines extrapolated from positive values of the variable.

The exchange of the Pomeron or diffraction singularity is more mysterious than that of the normal Regge poles. We are not sure that the leading diffraction singularity is a pole, nor that it is a moving singularity; even if it is a moving pole, it probably does not have the usual slope and it may not have any particles lying on it. Whatever the leading Pomeranchuk singularity is like, moreover, it has to be accompanied by other singularities only slightly less strong. The exchange of the whole complex of these singularities gives rise not only to elastic diffraction scattering, but also to a host of diffraction excitation and dissociation processes.

These diffraction amplitudes are related by unitarity to bilinear sums over themselves and over the non-diffractive amplitudes involving the exchange of Reggeons and associated cuts. Any given non-diffractive contribution to such a sum has too low an energy dependence to compete with the diffractive contribution; but the sum of all the non-diffractive contributions may be able to compete, since the number of processes keeps increasing with energy.

The asymptotic behavior of total cross-sections tells us about the nature of the diffraction singularity at $t = 0$. We now have data on several cross-sections up to Serpukhov energies and on the p-p cross-sections at ISR energies. The total cross-sections appear to be constant or gently rising; if rising, they might still level off at even higher energies or else continue to increase as $\ln s$ or $\ln^2 s$. If the leading diffraction singularity is a fixed or moving pole with $\alpha(0) = 1$, the cross-section should be asymptotically constant (except perhaps for electromagnetic corrections); a logarithmic increase would mean a leading branch point or pair of branch points at $J = 1$.

The t-dependence of p-p elastic scattering exhibits some shrinking of the diffraction peak as the energy increases, but this shrinking is not very pronounced at the highest energies available.

If the leading singularity at $t = 0$ is a moving pole with $\alpha(0) = 1$, then its contribution would continue to exhibit shrinking as s increases, but the associated cuts should gradually take over at $t \neq 0$ and give less and less shrinking.

If the leading singularity is a fixed pole at $J = 1$, then its contribution to the scattering gives a constant cross-section and a fixed t-dependence for the diffraction peak, as in classical theory. However, relativistic quantum mechanics, including unitarity in the crossed channel, requires an accompanying singularity called the shielding cut, with a branch point that reaches $J = 1$ at $t = 4\, m_\pi^2$, the lowest threshold in the crossed channel. The branch point may be quite close to $J = 1$ at $t = 0$ and could give a significant, though decreasing contribution to the s- and t-dependence at ISR energies.

Leading branch points at $J = 1$ can give a logarithmically increasing cross-section, going asymptotically like $\ln s$ or $\ln^2 s$. Theorists have considered such pictures, particularly with a pair of complex conjugate branch points, for two reasons:

1) An asymptotic $\ln^2 s$ dependence saturates the Froissart bound, and thus corresponds to maximally strong interactions.

2) In such pictures, the diffractive amplitudes give a contribution to the unitarity sum that reproduces the leading energy dependence of the diffractive amplitudes themselves. The non-diffractive contribution may be comparable (as in a model with $\sigma \sim \ln^2 s$) or smaller (as in a model with $\sigma \sim \ln s$).

A branch point picture may or may not lead to shrinking of the diffraction peak at very high energies, depending on the details of the picture.

Evidently we need more theoretical work as well as careful experiments at very high energies if we are ever to pin down the elusive diffraction singularity.

The asymptotic total cross-sections σ_{ab} for hadron a on hadron b should factorize into p(a)p(b) if the Pomeron is a moving pole. This creates some curious problems in the case of nucleon-nucleus and nucleus-nucleus cross-sections, which would have to go like F(A)F(A'), where A is the baryon number. We might expect $F(A) \propto A$ because the nucleons become huge and transparent at high energies; in that case, the known cross-sections going like $A^{2/3}$ or $(A^{1/3} + A'^{1/3})^2$ would be very different from the asymptotic ones, and nuclear cross-sections would increase steadily even at energies where nucleon-nucleon cross-sections had become constant. If $F(A) \propto A^{2/3}$, the situation is even more peculiar.

If the leading singularity is a fixed pole or a branch point or pair of branch points, then there is no need to have this type of factorization. These days a more general type of factorization is considered by those who treat the Pomeron as a moving pole (and sometimes even by those who don't!). Generalized factorization leads to factorization of inclusive cross-sections in the fragmentation regions, a result that is compatible with experiment so far. There is a theoretical result that generalized factorization is actually incompatible with a leading pole that has $\alpha(0) = 1$; however, it may be that a pole together with its associated cuts can evade the conditions of the theorem.

Some theorists working with a moving pole for the Pomeron have avoided the claimed inconsistency by having $\alpha(0)$ very slightly less than one. That must ultimately give a decreasing total cross-section, but one can try to arrange for the decrease to set in at energies higher than those available now. Others have suggested that perhaps no fully consistent picture can be worked out without including electromagnetic and/or other effects.

On the whole, it is simpler to try to evade the theorem, or else to drop the moving pole or generalized factorization or both. Even if it is not a rigorous property of high energy cross-sections, generalized factorization might still hold in a useful approximation.

The ingenious techniques of Mueller can be applied to studying hadronic scaling in inclusive reactions. If the Pomeron is a fixed or moving pole with $\alpha(0) = 1$, then hadronic scaling seems to follow, in the fragmentation regions and also in the pionization region. If the Pomeron is a pair of branch points and the asymptotic total cross-section rises logarithmically, we can divide the inclusive cross-sections by the total and ask if the ratio scales. Such scaling may work in the fragmentation regions, but it is harder to see how to get it in the pionization region.

Data are becoming available not only on total cross-sections, elastic angular distributions, and inclusive cross-sections but also on details of products of very high energy collisions, especially multiplicities and momentum distributions. Here general principles must be supplemented by detailed theoretical statements if an understanding of the results is to be achieved. Considerable insight has been provided by "multiperipheral" models, as described in earlier talks.

I have left until last a brief description of some of the most exciting theoretical work on the strong interaction, namely the attempt to construct a dual resonance theory of hadrons. The approach is very close to a "bootstrap" approach, except that one apparently free coupling parameter is introduced. The hadrons are all restricted to their mass shells, and initially they are introduced as an infinite spectrum of discrete states, with a pattern of n-particle couplings that is crossing-invariant, is suitably analytic, and possesses Regge pole asymptotic behavior with straight, parallel Regge trajectories. This initial scheme is not unitary, and an infinite sequence of "dual loops" is usually introduced to make the complete theory unitary. The discrete states then couple to a normal continuum, and a kind of diffraction singularity appears.

All existing versions of dual theory are marred by certain defects, especially the difficulty of including fermions, the presence of massless vector mesons, and the failure of the dual loop expansion to look reasonable except in an unphysical number of dimensions.

It is hoped that when one has correctly introduced into dual theory the sort of spin and SU_3 variables ascribed to quarks in the quark picture, the difficulties can be overcome. A fascinating question is whether the approximate discrete spectrum of resonances with linearly rising trajectories will then be introduced into all parts of hadron Hilbert space, including arbitrarily exotic configurations; at the moment it looks that way.

The early stages of a simple dual scheme can be imitated by a multilocal field theory that corresponds to the relativistic quantum mechanics of a string. It remains to be seen whether this amusing point of view can be applied to a complete dual theory.

In any case, the dual theorists are making a serious effort to construct an explicit theory of hadrons and the strong interaction, and there is no reason to believe that their approach necessarily conflicts with other points of view that have thrown light on the hadrons.

In closing, let me express my indebtedness to a group of colleagues at CERN who in a series of interesting discussions helped to prepare me for the task of summarizing this Conference. And, most important, let me, on behalf of all of us, express our thanks to the Conference organizers at NAL and Chicago and to the speakers.