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Gauge Unification of Fundamental Forces

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Fundamental Particles, Fundamental Forces, and Gauge Unification

The Nobel lectures in physics this year are concerned with a set of ideas relevant to the gauge unification of the electromagnetic force with the weak nuclear force. These lectures nearly coincide with the 100th anniversary of the death of Maxwell, with whom the first unification of forces (electric and magnetic) matured and with whom gauge theories originated. They also nearly coincide with the 100th anniversary of the birth of Einstein—the man who gave us the vision of an ultimate unification of all forces. The ideas of today started more than 20 years ago, as gleams in several theoretical eyes. They were brought to predictive maturity more than a decade back. And they started to receive experimental confirmation some 6 years ago.

In some senses, then, our story has a fairly long background in the past. In this lecture I wish to examine some of the theoretical gleams of today and ask whether these may be the ideas to watch for maturity 20 years from now.

From time immemorial, man has desired to comprehend the complexity of nature in terms of as few elementary concepts as possible. Among his quests, in Feynman's words, has been the one for "wheels within wheels"—the task of natural philosophy being to discover the innermost wheels, if any such exist. A second quest has concerned itself with the fundamental forces which make the wheels go round and enmesh with one another. The greatness of gauge ideas—of gauge field theories—is that they reduce these two quests to one; elementary particles (described by relativistic quantum fields) are representations of certain charge operators, corresponding to gravitational mass, spin, flavor, color, electric charge, and the like, while the fundamental forces are the forces of attraction or repulsion between the same charges. A third quest is for a unification of the charges (and thus of the forces) in a single entity, of which the various charges are components in the sense that they can be transformed into one another.

But are all fundamental forces gauge forces? Can they be understood as such, in terms of charges—and their corresponding currents—only? And if they are, how many charges? What unified entity are the charges components of? What is the nature of charge? Just as Einstein comprehended the nature of gravitational charge in terms of space-time curvature, can we comprehend the nature of the other charges, of the entire unified set, as a set, in terms of something equally profound? This briefly is the dream, much reinforced by the verification of gauge theory predictions. But before I examine the new theoretical ideas on offer for the future in this particular context, I would like to give a one-man, purely subjective, perspective of the developments of the last 20 years. The point I wish to emphasize during this part of my talk was well made by G. P. Thomson in his 1937 Nobel lecture: "The goddess of learning is fabled to have sprung full grown from the brain of Zeus, but it is seldom that a scientific conception is born in its final form, or owns a single parent. More often it is the product of a series of minds, each in turn modifying the ideas of those that came before, and providing material for those that come after."

Emergence of Spontaneously Broken SU(2) × U(1) Gauge Theory

I started physics research 30 years ago as an experimental physicist in the Cavendish, experimenting with tritium-deuterium scattering. Soon I knew the craft of experimental physics was beyond me; it was the sublime quality of patience—patience in accumulating data, patience with recalcitrant equipment—which I sadly lacked. Reluctantly I turned my papers in, and started instead on quantum field theory with Nicholas Kemmer in the exciting department of P. A. M. Dirac.

The year 1949 was the culminating year of the Tomonaga-Schwinger-Feynman-Dyson reformulation of renormalized Maxwell-Dirac gauge theory and its triumphant experimental vindication. A field theory must be renormalizable and be capable of being made free of infinities—first discussed by Waller—if perturbative calculations with it are to make any sense. More, a renormalizable theory, with no dimensional parameter in its interaction term, connotes somehow that the fields represent "structureless" elementary entities. With Paul Matthews, we started on an exploration of renormalizability of meson theories. Finding that renormalizability held only for spin-zero mesons, the only mesons that empirically existed then (pseudoscalar pions, invented by Kemmer, following Yukawa), one felt euphoric that with the triplet of pions (considered as

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the carriers of the strong nuclear force between the proton-neutron doublet) one might resolve the dilemma of the origin of this particular force which is responsible for fusion and fission. By the same token, the so-called weak nuclear force—the force responsible for β-radioactivity (and described then by Fermi's nonrenormalizable theory)—had to be mediated by some unknown spin-zero mesons if it was to be renormalizable. If massive charged spin-one mesons were to mediate this interaction, the theory would be nonrenormalizable, according to the ideas then.

Now this agreeably renormalizable spin-zero theory for the pion was a field theory, but not a gauge field theory. There was no conserved charge which determined the pionic interaction. As is well known, shortly after the theory was elaborated, it was found wanting. The (3/2, 3/2) resonance Δ effectively killed it off as a fundamental theory; we were dealing with a complex dynamical system, not "structureless" in the field-theoretic sense.

For me, the trek to gauge theories as candidates for fundamental physical theories started in earnest in September 1956, when I heard Yang at the Seattle Conference expound his and Lee's ideas (*1*) on the possibility of the hitherto sacred principle of left-right symmetry being violated in the realm of the weak nuclear force. Lee and Yang had been led to consider abandoning left-right symmetry for weak nuclear interactions as a possible resolution of the (τ,θ) puzzle. I remember traveling back to London on an American Air Force transport flight. Although I had been granted, for that night, the status of a brigadier or a field marshal—I don't remember which—the plane was very uncomfortable, full of crying children of servicemen. I could not sleep. I kept reflecting on why nature should violate left-right symmetry in weak interactions. Now the hallmark of most weak interactions was the involvement in radioactivity phenomena of Pauli's neutrino. A deeply perceptive question about the neutrino, which Rudolf Peierls had asked when he was examining me for a Ph.D. a few years before, came back to me: "The photon mass is zero because of Maxwell's principle of a gauge symmetry for electromagnetism; tell me, why is the neutrino mass zero?" I had then felt somewhat uncomfortable at Peierls asking a question to which he said he did not know the answer. But during that comfortless night the answer came. The analog, for the neutrino, of the gauge symmetry for the photon existed: it had to do with the masslessness of the neutrino, with symmetry under the γ_5 transformation (*2*) (later christened chiral symmetry). The existence of this symmetry for the massless neutrino must imply a combination $(1 + \gamma_5)$ or $(1 - \gamma_5)$ for the neutrino interactions. Nature had the choice between a theory which is aesthetically satisfying but in which left-right symmetry is violated, with a neutrino which travels exactly with the velocity of light; and a theory where left-right symmetry is preserved, but the neutrino has a tiny mass—some 10,000 times smaller than the mass of the electron.

It appeared at that time clear to me what choice nature must have made. Surely, left-right symmetry must be sacrificed in all neutrino interactions. I got off the plane the next morning, naturally very elated. I rushed to the Cavendish, worked out the Michel parameter and a few other consequences of γ_5 symmetry, rushed off again to Birmingham, where Peierls lived. Peierls had asked the original question; could he approve of the answer? His reply was kind but firm; he said, "I do not believe left-right symmetry is violated in weak nuclear forces at all. I would not touch such ideas."

Thus rebuffed in Birmingham, like Zuleika Dobson, I went next to CERN in Geneva, with Pauli—the father of the neutrino—nearby in Zurich. At that time CERN was located in a wooden hut just outside Geneva airport. Besides my friends, Prentki and d'Espagnat, the hut contained a gas ring on which was cooked the staple diet of CERN—entrecôte à la creme. The hut also contained Villars of the Massachusetts Institute of Technology, who was visiting Pauli the same day in Zurich. I gave him my paper. He returned the next day with a message from the Oracle; "Give my regards to my friend Salam and tell him to think of something better."

This was discouraging, but I was compensated by Pauli's excessive kindness a few months later, when experiments of Wu (*3*), Lederman (*4*), and Telegdi (*5*) were announced showing that left-right symmetry was indeed violated and ideas similar to mine about chiral symmetry were expressed independently by Landau (*6*) and Lee and Yang (*7*). I received Pauli's first somewhat apologetic letter on 24 January 1957. Thinking that Pauli's spirit should by now be suitably crushed, I sent him two short notes (*8*) I had written in the meantime. These contained suggestions to extend chiral symmetry to electrons and muons, assuming that their masses were a consequence of what has come to be known as dynamically spontaneous symmetry breaking. With chiral symmetry for electrons, muons, and neutrinos, the only mesons that could mediate weak decays of the muons would have to carry spin one. Reviving thus the notion of charged intermediate spin-one bosons, one could then postulate for these a type of gauge invariance which I called the "neutrino gauge." Pauli's reaction was swift and terrible. He wrote on 30 January 1957, then on 18 February, and later on 11, 12, and 13 March: "I am reading (along the shores of Lake Zurich) in bright sunshine quietly your paper. . . ." "I am very much startled on the title of your paper 'Universal Fermi interaction.'. . . For quite a while I have for myself the rule if a theoretician says *universal* it just means pure nonsense. This holds particularly in connection with the Fermi interaction, but otherwise too, and now you too, Brutus, my son, come with this word." Earlier, on 30 January, he had written, "There is a similarity between this type of gauge invariance and that which was published by Yang and Mills. . . . In the latter, of course, no γ_5 was used in the exponent"; and he gave me the reference to the paper of Yang and Mills (*9*). Again from his letter, "However, there are dark points in your paper regarding the vector field B_μ. If the rest mass is infinite (or very large), how can this be compatible with the gauge transformation $B_\mu \rightarrow B_\mu - \partial\mu\Lambda$?" He concluded with the remark, "Every reader will realize that you deliberately conceal here something and will ask you the same questions." Pauli had forgotten his earlier penitence; he was clearly and rightly on the warpath.

Now the fact that I was using gauge ideas similar to the Yang-Mills [non-Abelian SU(2)-invariant] gauge theory was no news to me. This was because the Yang-Mills theory, which married gauge ideas of Maxwell with the internal symmetry SU(2) of which the proton-neutron system constituted a doublet, had been independently invented by a Ph.D. pupil of mine at Cambridge, Shaw (*10*), at the same time Yang and Mills had written. Shaw's work is relatively unknown; it remains buried in his thesis. I must admit I was taken aback by Pauli's fierce prejudice against universalism—against what we would today call unification of basic forces—but I did not take this too seriously. I felt it was a legacy of the exasperation which Pauli had always felt at Einstein's somewhat formalistic attempts at unifying gravity with electromagnetism—forces which in Pauli's phrase "cannot be joined—for God hath rent them asunder." But Pauli was right in accusing me of darkness about the problem of the masses of the Yang-Mills fields; one could not obtain a mass without wantonly destroying the gauge symmetry one had started with. And this was particularly serious in this context, because Yang and Mills had conjectured the desirable renormalizability of their theory with a proof which relied heavily and exceptionally on the masslessness of their spin-one intermediate mesons. The problem was to be solved only 7 years later with the understanding of what is now known as the Higgs mechanism, which I will come back to later.

The point I wish to make from this exchange with Pauli is that already in early 1957, just after the first set of parity experiments, many ideas coming to fruition now had started to become clear. These are:

1) The idea of chiral symmetry leading to a *V-A* theory. In those early days my suggestion (*2*, *8*) of this was limited to neutrinos, electrons, and muons; shortly after that, Sudarshan and Marshak (*11*), Gell-Mann and Feynman (*12*), and Sakurai (*13*) had the courage to postulate γ_5 symmetry for baryons as well as leptons, making this into a universal principle of physics (*14*). Concomitant with the *V-A* theory was the result that if weak interactions are mediated by intermediate mesons, these mesons must carry spin one.

2) The idea of spontaneous breaking of chiral symmetry to generate electron and muon masses, although the price which Nambu and Jona-Lasinio (*15*) and Goldstone (*16*) exacted for this—the appearance of massless scalars—was not yet appreciated.

3) Finally, although the use of a Yang-Mills-Shaw (non-Abelian) gauge theory for describing spin-one intermediate charged mesons had been suggested already in 1957, the giving of masses to the intermediate bosons through spontaneous symmetry breaking, to preserve the renormalizability of the theory, was to be accomplished only during a long period of theoretical development between 1963 and 1971.

Once the Yang-Mills-Shaw ideas were accepted as relevant to the charged weak currents—to which the charged intermediate mesons were coupled in this theory—the question was raised during 1957 and 1958 of what was the third component of the SU(2) triplet, of which the charged weak currents were two members. There were the two alternatives: the electroweak unification suggestion, where the electromagnetic current was assumed to be the third component; and the rival suggestion that the third component was a neutral current unconnected with electroweak unification. With hindsight, I shall call these the Klein (1938) (*17*) and Kemmer (1937) (*18*) alternatives. The Klein suggestion, made in the context of a Kaluza-Klein five-dimensional space-time, is a real tour de force; it combined two hypothetical spin-one charged mesons with the photon in one multiplet, deducing from the compactification of the fifth dimension, a theory which looks like the Yang-Mills-Shaw one. Klein intended his charged mesons for strong interactions, but if one reads charged weak mesons for Klein's strong ones, one obtains the theory independently suggested by Schwinger (1957) (*19*), although Schwinger, unlike Klein, did not build in any non-Abelian gauge aspects. With just these non-Abelian Yang-Mills gauge aspects very much to the fore, the idea of uniting weak interactions with electromagnetism was developed by Glashow (*20*) and Ward and myself (*21*) in late 1958. The rival Kemmer suggestion of a global SU(2)-invariant triplet of weak charged and neutral currents was independently suggested by Bludman (1958) (*22*) in a gauge context, and this is how matters stood until 1960.

To give the flavor of the year 1960, I quote from a paper written that year by Ward and myself (*23*): "Our basic postulate is that it should be possible to generate strong, weak and electromagnetic interaction terms with all their correct symmetry properties (as well as with clues regarding their relative strengths) by making local gauge transformations on the kinetic energy terms in the free Lagrangian for all particles. This is the statement of an ideal which, in this paper at least, is only very partially realized." I am not claiming that we were the only ones who were saying this, I just wish to convey the temper of the physics of 20 years ago—qualitatively no different from that of today. But what a quantitative difference the next 20 years made, first with new and far-reaching developments in theory, and then—thanks to CERN, Fermilab, Brookhaven, Argonne, Serpukhov, and SLAC—in testing it.

It was the 7 years between 1961 and 1967 that were crucial for quantitative comprehension of the phenomenon of spontaneous symmetry breaking and the emergence of the SU(2) × U(1) theory in a form capable of being tested. The story is well known and Steve Weinberg has already spoken about it. I will give the barest outline. First, there was the realization that the two alternatives mentioned above—a pure electromagnetic versus a pure neutral current (Klein-Schwinger versus Kemmer-Bludman)—were not alternatives; they were complementary. As noted by Glashow (*24*) and independently by Ward and myself (*25*), both types of currents and the corresponding gauge particles (W^+, Z^0, and γ) were needed to build a theory that could simultaneously accommodate parity violation for weak and parity conservation for electromagnetic phenomena. Second, there was the influential paper in which Goldstone (*26*), utilizing a nongauge self-interaction between scalar particles, showed that the price of spontaneous breaking of a continuous internal symmetry was the appearance of zero-mass scalars—a result foreshadowed by Nambu. In giving a proof of this theorem (*27*) with Goldstone I collaborated with Weinberg, who spent a year at Imperial College in London. I will not dwell on the now well-known contributions of Anderson (*28*), Higgs (*29*), Englert, Brout, and Thiry (*30*), and Guralnik, Hagen, and Kibble (*31*), which showed how spontaneous symmetry breaking with spin-zero fields could generate vector meson masses, defeating Goldstone at the same time. This is the so-called Higgs mechanism.

The final steps toward the electroweak theory were taken during 1967 by Weinberg (*32*) and myself (*33*) (with Kibble at Imperial College tutoring me about the Higgs phenomena). We were able to complete the present formulation of the spontaneously broken SU(2) × U(1) theory so far as leptonic weak interactions were concerned—with one parameter $\sin^2\theta$ describing all weak and electromagnetic phenomena and with one isodoublet Higgs multiplet (*32*). As is well known, we did not then, and still do not, have a prediction for the scalar Higgs mass.

Both Weinberg and I suspected that this theory was likely to be renormalizable (*34*). Regarding spontaneously broken Yang-Mills-Shaw theories in general, this had earlier been suggested by Englert, Brout, and Thiry (*30*). But this subject was not pursued seriously except at Utrecht, where the actual proof of renormalizability was given by 't Hooft (*35*) in 1971. This was elaborated further by the late Benjamin Lee working with Zinn-Justin (*36*) and by 't Hooft and Veltman (*37*). This followed on the earlier basic advances in Yang-Mills calculational technology by Feynman (*38*), DeWitt (*39*), Faddeev and Popov (*40*), Mandelstam (*41*), Fradkin and Tyutin (*42*), Boulware (*43*), Taylor (*44*), Slavnov (*45*), and Salam and Strathdee (*46*). In Coleman's eloquent phrase "'t Hooft's work turned the Weinberg-Salam frog into an enchanted prince." Just before had

Table 1. Families of elementary particles.

	$SU_c(3)$ triplets		
Family I	Quarks $\left\{ \begin{matrix} u_R, u_Y, u_B \\ d_R, d_Y, d_B \end{matrix} \right\}$	Leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	SU(2) doublets
Family II	Quarks $\left\{ \begin{matrix} c_R, c_Y, c_B \\ s_R, s_Y, s_B \end{matrix} \right\}$	Leptons $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	SU(2) doublets
Family III	Quarks $\left\{ \begin{matrix} t_R, t_Y, t_B \\ b_R, b_Y, b_B \end{matrix} \right\}$	Leptons $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$	SU(2) doublets

come the Glashow, Iliopoulos, and Maiani (GIM) mechanism (*47*), emphasizing that the existence of the fourth charmed quark (postulated earlier by several authors) was essential to the natural resolution of the dilemma posed by the absence of strangeness-violating currents. This tied in naturally with the understanding of the Steinberger-Schwinger-Rosenberg-Bell-Jackiw-Adler anaomaly (*48*) and its removal for SU(2) × U(1) by the parallelism of four quarks and four leptons, pointed out by Bouchiat, Iliopoulos, and Meyer and independently by Gross and Jackiw (*49*).

If one has kept a count, I have so far mentioned around 50 theoreticians. As a failed experimenter, I have always felt envious of the ambience of large experimental teams and it gives me the greatest pleasure to acknowledge the direct or indirect contributions of the "series of minds" to the spontaneously broken SU(2) × U(1) gauge theory. My profoundest personal appreciation goes to my collaborators at Imperial College, Cambridge and the Trieste Centre, Paul Matthews, John Ward, Jogesh Pati, John Strathdee, Tom Kibble, and to Nicholas Kemmer.

In retrospect, what strikes me most about the early part of this story is how uninformed all of us were, not only of each other's work, but also of work done earlier. For example, only in 1972 did I learn of Kemmer's paper written at Imperial College in 1937. Kemmer's argument essentially was that Fermi's weak theory was not globally SU(2) invariant and should be made so—not for its own sake, but as a prototype for strong interactions. Then this year I learned that in 1936 Kemmer's Ph.D. supervisor, Wentzel (*50*), had introduced (the yet undiscovered) analogs of lepto-quarks, whose mediation could give rise to neutral currents after a Fierz reshuffle. And only this summer, Cecilia Jarlskog at Bergen rescued Oscar Klein's paper from the anonymity of the Proceedings of the International Institute of Intellectual Cooperation of Paris, and we learned of his anticipation of a theory similar to the Yang-Mills-Shaw theory long before these authors. The interesting point is that Klein was using his triplet, of two charged mesons plus the photon, not to describe the weak interaction, but for strong nuclear force unification with the electromagnetic—something our generation started on only in 1972. Even here I am sure I have inadvertently left out some of those who have in some way contributed to SU(2) × U(1). Perhaps the moral is that not unless there is the prospect of quantitative verification, does a qualitative idea make its impress in physics.

This brings me to experiment, and the year of the Gargamelle (*51*). I remember Paul Matthews and I getting off the train at Aix-en-Provence for the 1973 European Conference and foolishly deciding to walk with our heavy luggage to the student hostel where we were billeted. A car drove from behind us, stopped, and the driver leaned out. This was Musset, whom I did not know well then. He peered out of the window and said, "Are you Salam?" I said, "Yes." He said, "Get into the car. I have news for you. We have found neutral currents." I will not say whether I was more relieved to be given a lift because of our heavy luggage or for the discovery of neutral currents. At the Aix-en-Provence meeting that great and modest man, Lagarrigue, was also present and the atmosphere was that of a carnival. At least this is how it appeared to me. Weinberg gave the rapporteur's talk with T. D. Lee as the chairman. T.D. was kind enough to ask me to comment after Weinberg finished. That summer Jogesh Pati and I had predicted proton decay within the context of what is now called grand unification, and in the flush of this excitement I am afraid I ignored weak neutral currents as a subject which had already come to a successful conclusion, and concentrated on speaking of the possible decays of the proton. I understand now that proton decay experiments are being planned in the United States by the Brookhaven, Irvine, Michigan, and Wisconsin-Harvard groups and also by a European collaboration to be mounted in the Mont Blanc Tunnel Garage No. 17. The later quantitative work on neutral currents at CERN, Fermilab, Brookhaven, Argonne, and Serpukhov is, of course, history, but a special tribute is warranted to the beautiful SLAC-Yale-CERN experiment (*52*) of 1978, which exhibited the effective Z^0-photon interference in accordance with the predictions of the theory. This was foreshadowed by experiments of Barkov *et al.* (*53*) at Novosibirsk in their exploration of parity violation in the atomic potential for bismuth. There is an apocryphal story about Einstein, who was asked what he would have thought if experiment had not confirmed the light deflection he predicted. Einstein is supposed to have said, "Madam, I would have thought the Lord has missed a most marvellous opportunity." I believe, however, that the following quotation from Einstein's Herbert Spencer lecture of 1933 expresses his, my colleagues, and my own views more accurately: "Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it." This is exactly how I feel about the Gargamelle-SLAC experience.

The Present and Its Problems

Thus far I have reviewed the last 20 years and the emergence of SU(2) × U(1), with the twin developments of a gauge theory of basic interactions, linked with internal symmetries, and of the spontaneous breaking of these symmetries. I shall first summarize the situation now and the immediate problems, and then turn to the future.

1) To the level of energies explored, we believe that the sets of particles listed in Table 1 are "structureless" (in a field-theoretic sense) and, at least to the level of energies explored hitherto, constitute the elementary entities of which all other objects are made. Together with their antiparticles, each family consists of 15 or 16 two-component fermions (15 or 16 depending on whether the neutrino is massless or not). The third family is still conjectural, since the top quark (t_R, t_Y, t_B) has not yet been discovered. Does this family really follow the pattern of the other two? Are there more families? Does the fact that the families are replicas of each other imply that nature has discovered a dynamical stability about a system of 15 (or 16) objects, and that by this token there is a more basic layer of structure underneath (*54*)?

2) Quarks come in three colors: red (R), yellow (Y), and blue (B). Parallel with the electroweak SU(2) × U(1), a gauge field (*55*) theory, $SU_c(3)$, of strong

Table 2. Examples of grand unifying groups.

Type	Multiplet	Exotic gauge particles	Proton decay
Semisimple groups* With left-right symmetry Example $[SU(6)_F \times SU(6)_c]_{L \to R}$	$G_L \to \begin{pmatrix} q \\ \ell \end{pmatrix}_L, G_R \to \begin{pmatrix} q \\ \ell \end{pmatrix}_R$ $G = G_L \times G_R$	Lepto-quarks → $(\bar{q}\ell)$ Unifying mass ≈ 10^6 MeV	Lepto-quarks → W + (Higgs) or Proton = qqq → $\ell\ell\ell$
Simple groups Examples Family groups → SU(5), SO(10) ↓ ↓ Tribal groups → SU(11), SO(22)	$G \to \begin{pmatrix} q \\ \ell \\ \bar{q} \\ \bar{\ell} \end{pmatrix}_L$	Diquarks → (qq) Dileptons → $(\ell\ell)$ Lepto-quarks → $(\bar{q}\ell)$, $(q\ell)$ Unifying mass ≈ 10^{13} to 10^{15} GeV	qq → $\bar{q}\ell$ Proton P = qqq → $\bar{\ell}$ Also possible, P → ℓ, P → $3\bar{\ell}$, P → 3ℓ

*Grouping quarks (q) and leptons (ℓ) together implies treating lepton number as the fourth color; that is, $SU_c(3)$ extends to $SU_c(4)$ (*106*). A tribal group, by definition, contains all known families in its basic representation. Favored representations of tribal SU(11) (*107*) and tribal SO(22) (*108*) contain 561 and 2048 fermions.

(quark) interactions—quantum chromodynamics (QCD) (*56*)—has emerged which gauges the three colors. The indirect discovery of the (eight) gauge bosons associated with QCD (gluons), has already been surmised by the groups at DESY (*57*).

3) All known baryons and mesons are singlets of color $SU_c(3)$. This has led to a hypothesis that color is always confined. One of the major unsolved problems of field theory is to determine if QCD—treated nonperturbatively—is capable of confining quarks and gluons.

4) In respect of the electroweak SU(2) × U(1), all known experiments on weak and electromagnetic phenomena below 100 GeV carried out to date agree with the theory which contains one theoretically undetermined parameter $\sin^2\theta = 0.230 \pm 0.009$ (*58*). The predicted values of the associated gauge boson ($W^{\pm}$ and Z^0) masses are $m_W \approx 77$ to 84 GeV and $m_Z \approx 89$ to 95 GeV, for $0.25 \geqslant \sin^2\theta \geqslant 0.21$.

5) Perhaps the most remarkable measurement in electroweak physics is that of the parameter $\rho = (m_W/m_Z \cos\theta)^2$. Currently this has been determined from the ratio of neutral to charged current cross sections. The predicted value $\rho = 1$ for weak isodoublet Higgs is to be compared with the experimental (*59*) $\rho = 1.00 \pm 0.02$.

6) Why does nature favor the simplest suggestion in SU(2) × U(1) theory of the Higgs scalars being isodoublet (*60*)? Is there just one physical Higgs? Of what mass? At present the Higgs interactions with leptons and quarks as well as their self-interactions are nongauge interactions. For a three-family (six-quark) model, 21 of the 26 parameters needed are attributable to the Higgs interactions. Is there a basic principle, as compelling and as economical as the gauge principle, which embraces the Higgs sector? Alternatively, could the Higgs phenomenon itself be a manifestation of a dynamical breakdown of the gauge symmetry (*60*)?

7) Finally there is the problem of the families; Is there a distinct SU(2) for the first, another for the second, as well as a third SU(2), with spontaneous symmetry breaking such that the SU(2) apprehended by present experiment is a diagonal sum of these "family" SU(2)'s? To state this in another way, how far in energy does the e-μ universality (for example) extend? Are there more (*61*) Z^0's than one, effectively differentially coupled to the e and μ systems? (Their existence would require minimodifications of the theory, but not a drastic revolution of its basic ideas.)

In the next section I turn to a direct extrapolation of the ideas which went into the electroweak unification, so as to include strong interactions as well. Later I shall consider the more drastic alternatives which may be needed for the unification of all forces (including gravity)—ideas which have the promise of providing a deeper understanding of the charge concept. Regretfully, I must also become more technical and obscure for the nonspecialist. I apologize for this. The nonspecialist may sample the flavor of the arguments with the next section, ignoring Table 2 and the Appendix, and then go on to the section after that, which is perhaps less technical.

Direct Extrapolation from Electroweak to Electronuclear

The three ideas. The three main ideas which have gone into the electronuclear—also called grand—unification of the electroweak with the strong nuclear force (and which date back to the period 1972 to 1974) are the following:

1) The psychological break (for us) of grouping quarks and leptons in the same multiplet of a unifying group G, suggested by Pati and myself in 1972 (*62*). The group G must contain SU(2) × U(1) × $SU_c(3)$ and must be non-Abelian if all quantum numbers (flavor, color, lepton, quark, and family numbers) are to be automatically quantized and the resulting gauge theory asymptotically free.

2) An extension, proposed by Georgi and Glashow (*63*), which places not only (left-handed) quarks and leptons but also their antiparticles in the same multiplet of the unifying group. Table 2 gives some examples of the unifying groups presently considered.

Now a gauge theory based on a "simple" (or with discrete symmetries, a "semisimple") group G contains one basic gauge constant. This constant would manifest itself physically above the "grand unification mass" M, exceeding all particle masses in the theory—these themselves being generated (if possible) hierarchically through a suitable spontaneous symmetry-breaking mechanism.

3) The development by Georgi, Quinn, and Weinberg (*64*), who showed how, using renormalization group ideas, one could relate the observed low-energy couplings $\alpha(\mu)$, $\alpha_s(\mu)$ ($\mu \sim 100$ GeV) to the magnitude of the grand unifying mass M and the observed value of $\sin^2\theta(\mu)$ [$\tan\theta$ is the ratio of the U(1) to the SU(2) couplings].

If one extrapolates with Jowett (*65*) that nothing essentially new can possibly be discovered—that is, assumes that there are no new features, no new forces, or no new "types" of particles to be discovered until we go beyond the grand unifying energy M—then the Georgi, Quinn, Weinberg method leads to a startling result: this featureless "plateau" with no "new physics" heights to be scaled stretches to fantastically high energies. More precisely, if $\sin^2\theta(\mu)$ is as large as 0.23, then M cannot be smaller than 1.3×10^{13} GeV (*66*). [Compare with the Planck mass $m_P \approx 1.2 \times 10^{19}$ GeV related to Newton's constant, where gravity must come in (*67*).] The result follows from the formula (*66, 68*):

$$\frac{11\alpha}{3\pi} \ln \frac{M}{\mu} = \frac{\sin^2\theta(M) - \sin^2\theta(\mu)}{\cos^2\theta(M)} \quad (1)$$

if it is assumed that $\sin^2\theta(M)$—the magnitude of $\sin^2\theta$ for energies of the order of M—equals 3/8 (see Appendix).

This startling result will be examined more closely in the Appendix. It is very much a consequence of the assumption that the $SU(2) \times U(1)$ symmetry survives intact from the low regime energies μ up to the grand unifying mass M. There is already some experimental indication that this assumption is too strong and that there may be peaks of new physics at energies of 10 TeV upward.

Tests of electronuclear grand unification. The most characteristic prediction from the existence of the electronuclear force is proton decay, first discussed in the context of grand unification at the Aix-en-Provence conference (*69*). For semisimple unifying groups with multiplets containing quarks and leptons, but no antiquarks or antileptons, the lepto-quark composites have masses (determined by renormalization group arguments), of the order of $\approx 10^5$ to 10^6 GeV (*70*). For such theories the characteristic proton decays (proceeding through exchanges of three lepto-quarks) conserve quark number and lepton number; that is, $P = qqq \rightarrow \ell\ell\ell$, $\tau_P \sim 10^{29}$ to 10^{34} years. On the contrary, for the simple unifying family groups like SU(5) (*63*) or SO(10) (*71*), with multiplets containing antiquarks and antileptons, proton decay proceeds through an exchange of one lepto-quark into an antilepton (plus pions and so on) ($P \rightarrow \bar{\ell}$).

An intriguing possibility in this context is that investigated recently for the maximal unifying group SU(16)—the largest group to contain a 16-fold fermionic family (q, ℓ, $\bar{q}$, $\bar{\ell}$). This can permit four types of decay modes: $P \rightarrow 3\ell$ as well as $P \rightarrow \bar{\ell}$, $P \rightarrow \ell$ (for example, $P \rightarrow \ell^- + \pi^+ + \pi^+$), and $P \rightarrow 3\ell$ (for example, $N \rightarrow 3\nu + \pi^0$, $P \rightarrow 2\nu + e^+ + \pi^0$), whose relative magnitudes are model-dependent on how precisely SU(16) breaks down to $SU(3) \times SU(2) \times U(1)$. Clearly, it is the central fact of the existence of proton decay for which the present generation of experiments must be designed, rather than for any specific type of decay modes.

Finally, grand unifying theories predict mass relations like (*72*)

$$\frac{m_d}{m_e} \approx \frac{m_b}{m_\mu} \approx \frac{m_b}{m_\tau} \approx 2.8$$

for six (or at most eight) flavors below the unification mass. The important remark for proton decay and for mass relations of the above type, as well as for an understanding of baryon excess (*73*) in the universe (*74*), is that for the present these are essentially characteristic of the fact of grand unification—rather than of specific models.

"Yet each man kills the thing he loves," sang Oscar Wilde in his famous Ballad of Reading Gaol. Like generations of physicists before us, some in our generation also—through a direct extrapolation of the electroweak gauge methodology to the electronuclear, and with faith in the assumption of no new physics, which leads to a grand unifying mass $\sim 10^{13}$ GeV—are beginning to believe that the end of the problems of elementarity as well as of fundamental forces is nigh. They may be right, but before we are carried away by this prospect, it is perhaps worth stressing that, even for the simplest grand unifying model [Georgi and Glashow's SU(5) with just two Higgs (a 5 and a 24)], the number of presently ad hoc parameters needed by the model is still unwholesomely large—22, compared with 26 for the six-quark model based on the humble $SU(2) \times U(1) \times SU_c(3)$. We cannot feel proud.

Elementarity: Unification with Gravity and Nature of Charge

In some of the rest of this lecture I will be questioning two of the notions that have gone into the direct extrapolation of the preceding section: First, do quarks and leptons represent the correct elementary (*75*) fields, which should appear in the matter Lagrangian and which are structureless for renormalizability? Second, could some of the presently considered gauge fields themselves be composite? This part of the lecture relies heavily on an address I gave at the European Physical Society meeting in Geneva in 1979 (*68*).

The quest for elementarity, prequarks (preons and pre-preons). While the rather large number (15) of elementary fields for the family group SU(5) already makes one feel somewhat uneasy, the number 561, for example, proposed in the context of the three-family tribal group SU(11) or 2048 for SO(22) (see Appendix), of which presumably $3 \times 15 = 45$ objects are of low and the rest of Planckian mass, is positively baroque.

The numbers by themselves would perhaps not matter so much. After all, Einstein in his description of gravity (*76*), chose to work with ten fields [$g_{\mu\nu}(x)$] rather than with just one (scalar field) as Nördstrom (*77*) had done before him. Einstein was not perturbed by the multiplicity he chose to introduce, since he relied on the sheet anchor of a fundamental principle—the equivalence principle—which permitted him to relate the ten fields for gravity $g_{\mu\nu}$ with the ten components of the physically relevant quantity, the tensor $T_{\mu\nu}$ of energy and momentum. Einstein knew that nature was not economical of structures, only of principles of fundamental applicability. The question we must ask ourselves is this: Have we yet discovered such principles in our question for elementarity, to justify having fields with such large numbers of components as elementary?

Recall that quarks carry at least three charges (color, flavor, and a family number). Should one not, by now, entertain the notions of quarks (and possibly of leptons) as being composites of some more basic entities (*78*) (prequarks or preons), which each carry but one basic charge (*54*)? These ideas have been expressed before, but they have become more compulsive now, with the growing multiplicity of quarks and leptons. Recall that it was similar ideas which led from the eightfold of baryons to a triplet of (Sakatons and) quarks in the first place.

The preon notion is now new. In 1975 Pati, Salam, and Strathdee (*54*), among others, introduced four chromons (the fourth color corresponding to the lepton number) and four flavons, the basic group being SU(8)—of which the family group $SU_F(4) \times SU_c(4)$ was but a subgroup. As an extension of these ideas, we now believe these preons carry magnetic charges and are bound together by very strong short-range forces, with quarks and leptons as their magnetically neutral composites (*79*). The important remark in this context is that in a theory containing both electric and magnetic generalized charges, the analog of the well-known Dirac quantization condition (*80*) gives relations like $eg/4\pi = n/2$ for the strength of the two types of charges. Clearly, magnetic monopoles (*81*) ($g = 4\pi n/2e$, $e^2/4\pi = 1/137$) of opposite polarity are likely to bind much more tightly than electric charges, yielding composites whose nonelementary nature will reveal itself only for very high energies. This appears to be the situation at least for leptons if they are composites.

In another form, the preon idea has been revived this year by Curtright and Freund (*54*) who, motivated by ideas of extended supergravity, reintroduce an SU(8) of three chromons (R, Y, B), two flavons, and three familons (horrible names). The family group SU(5) could be a subgroup of this SU(8). In the Curtright-Freund scheme, the $3 \times 15 = 45$ fermions of SU(5) (*63*) can be found

Table 3. Past experience and prediction for the next decade.

	1950 to 1960	1960 to 1970	1970 to 1980	1980→
Discovery in early part of the decade	The strange particles	The eightfold way, Ω^-	Confirmation of neutral currents	W, Z, proton decay
Expectation for the rest of the decade		SU(3) resonances		Grand unification, tribal groups
Actual discovery		Hit the next level of elementarity with quarks		May hit the preon level, and composite structure of quarks

among the 8 + 28 + 56 of SU(8), or alternatively the 3 × 16 = 48 of SO(10) among the vectorial 56 fermions of SU(8). [The next succession after the preon level may be the pre-preon level. It was suggested at the Geneva Conference (*68*) that with certain developments in field theory of composite fields it could be that just two pre-preons may suffice. But at this stage this is pure speculation.]

Before I conclude this section, I would like to make a prediction regarding the course of physics in the next decade, extrapolating from our past experience of the decades gone by. This is shown in Table 3.

Post-Planck physics, supergravity, and Einstein's dreams. I now turn to the problem of a deeper comprehension of the charge concept (the basis of gauging)—which, in my humble view, is the real quest of particle physics. Einstein, in the last 35 years of his life, lived with two dreams. One was to unite gravity with matter (the photon)—he wished to see the "base wood" (as he put it) which makes up the stress tensor $T_{\mu\nu}$ on the right-hand side of his equation $R_{\mu\nu} - 1/2\, g_{\mu\nu}R = -T_{\mu\nu}$ transmuted through this union, into the "marble" of gravity on the left-hand side. The second (and complementary) dream was to use this unification to comprehend the nature of electric charge in terms of space-time geometry in the same manner as he had successfully comprehended the nature of gravitational charge in terms of space-time curvature.

In case someone imagines (*82*) that such deeper comprehension is irrelevant to quantitative physics, let me adduce the tests of Einstein's theory versus the proposed modifications to it [Brans-Dicke (*83*), for example]. Recently, the strong equivalence principle—the proposition that gravitational forces contribute equally to the inertial and gravitational masses—was tested to 1 part in 10^{12} [the same accuracy as achieved in particle physics for $(g - 2)_e$] through lunar laser-ranging measurements (*84, 85*). These measurements determined departures from Kepler equilibrium distances of the moon, the earth, and the sun to better than ± 30 centimeters and triumphantly vindicated Einstein.

There have been four major developments in realizing Einstein's dreams:

1) The Kaluza-Klein (*86*) miracle: An Einstein Lagrangian (scalar curvature) in five-dimensional space-time (where the fifth dimension is compactified in the sense of all fields being explicitly independent of the fifth coordinate) precisely reproduces the Einstein-Maxwell theory in four dimensions, the $g_{\mu 5}$ (μ = 0, 1, 2, 3) components of the metric in five dimensions being identified with the Maxwell field A_μ. From this point of view, Maxwell's field is associated with the extra components of curvature implied by the (conceptual) existence of the fifth dimension.

2) The recent realization by Cremmer, Scherk, Englert, Brout, Minkowski, and others that the compactification of the extra dimensions (*87*)—their curling up to sizes perhaps smaller than Planck length $\lesssim 10^{-33}$ cm and the very high curvature associated with them—might arise through a spontaneous symmetry breaking (in the first 10^{-43} second) which reduced the higher dimensional space-time effectively to the four dimensions that we apprehend directly.

3) So far we have considered Einstein's second dream, the unification of electromagnetism (and presumably of other gauge forces) with gravity, giving a space-time significance to gauge charges as corresponding to extended curvature in extra bosonic dimensions. A full realization of the first dream (unification of spinor matter with gravity and with other gauge fields) had to await the development of supergravity (*88, 89*)—and an extension to extra fermionic dimensions of superspace (*90*) (with extended torsion being brought into play in addition to curvature). I discuss this development later.

4) The alternative suggestion (*91*) that electric charge may be associated with space-time topology—with wormholes, with space-time Gruyère-cheesiness. This idea has recently been developed by Hawking (*92*) and his collaborators (*93*).

Extended supergravity, SU(8) preons, and composite gauge fields. Thus far I have reviewed the developments related to Einstein's dreams as reported at the Stockholm conference held in 1978. A remarkable new development was reported during 1979 by Julia and Cremmer (*94*) which started with an attempt to use the ideas of Kaluza and Klein to formulate extended supergravity theory in a higher (compactified) space-time—more precisely in 11 dimensions. This development links up, as we shall see, with preons and composite Fermi fields—and even more important, possibly with the notion of composite gauge fields.

Recall that simple supergravity (*88*) is the gauge theory of supersymmetry (*95*)—the gauge particles being the (helicity ± 2) gravitons and (helicity ± 3/2) gravitinos (*96*). Extended supergravity gauges supersymmetry combined with SO(*N*) internal symmetry. For *N* = 8, the (tribal) supergravity multiplet consists of the following SO(8) families (*88, 94*): helicity ± 2, 1; ± 3/2, 8; ± 1, 28; ± 1/2, 56; and 0, 70. As is well known, SO(8) is too small to contain SU(2) × U(1) × $SU_c(3)$. Thus this tribe has no place for $W^\pm$ (though Z^0 and γ are contained) and no places for μ or τ or the t quark.

This was the situation last year. This year, Cremmer and Julia (*94*) attempted to write down the *N* = 8 supergravity Lagrangian explicitly, using an extension of the Kaluza-Klein *ansatz* which states that extended supergravity, with SO(8) internal symmetry, has the same Lagrangian in four space-time dimensions as simple supergravity in (compactified) 11 dimensions. This formal and rather formidable *ansatz* when carried through yielded a most agreeable bonus. The supergravity Lagrangian possesses an unsuspected SU(8) "local" internal symmetry, although one started with an internal SO(8) only.

The tantalizing questions which now arise are the following:

1) Could this internal SU(8) be the symmetry group of the eight preons (three chromons, two flavons, three familons) introduced earlier?

2) When SU(8) is gauged, there should be 63 spin-one fields. The supergravity tribe contains only 28 spin-one

fundamental objects which are not minimally coupled. Are the 63 fields of SU(8) to be identified with composite gauge fields made up of the 70 spin-zero objects of the form $V^{-1} \partial_\mu V$? Do these composites propagate, in analogy with the well-known recent result in CP^{n-1} theories (*97*), where a composite gauge field of this form propagates as a consequence of quantum effects (quantum completion)?

The entire development I have described—the unsuspected extension of SO(8) to SU(8) when extra compactified space-time dimensions are used and the possible existence and quantum propagation of composite gauge fields—is of such crucial importance for the future prospects of gauge theories that one begins to wonder how much of the extrapolation which took $SU(2) \times U(1) \times SU_c(3)$ into the electronuclear grand unified theories is likely to remain unaffected by these new ideas.

But where in all this is the possibility to appeal directly to experiment? For grand unified theories, it was the proton decay. What is the analog for supergravity? Perhaps the spin 3/2 massive gravitino, picking its mass from a super-Higgs effect (*98*) provides the answer. Fayet (*99*) has showed that for a spontaneously broken globally supersymmetric weak theory the introduction of a local gravitational interaction leads to a super-Higgs effect. Assuming that supersymmetry breakdown is at mass scale m_W, the gravitino acquires a mass and an effective interaction, but of conventional weak rather than of gravitational strength—an enhancement by a factor of 10^{34}. One may thus search for the gravitino among the neutral decay modes of J/ψ—the predicted rate being 10^{-3} to 10^{-5} times smaller than the observed rate for $J/\psi \rightarrow e^+e^-$. This will surely tax all the ingenuity of the great men and women at SLAC and DESY. Another effect suggested by Scherk (*100*) is antigravity—a cancellation of the attractive gravitational force with the force produced by spin-one gravi-photons which exist in all extended supergravity theories. Scherk shows that the Compton wavelength of the gravi-photon is either smaller than 5 cm or between 10 and 850 meters in order that there be no conflict with what is presently known about the strength of the gravitational force.

To summarize, it is conceivable that there is indeed a grand plateau—extending even to Planck energies. If so, the only eventual laboratory for particle physics will be the early universe, where we will have to seek for the answers to the questions on the nature of charge. There may, however, be indications of a next level of structure around 10 TeV; there are also beautiful ideas (for example, of electric and magnetic monopole duality) which may be manifest at energies of the order of $\alpha^{-1} m_W$ (= 10 TeV). Whether even this level of structure will give us the final clues to the nature of charge, one cannot predict. But I am continually being amazed at the depth revealed at each successive level we explore. I would like to conclude with a prediction which J. R. Oppenheimer (*101*) made more than 25 years ago and which has been fulfilled today in a manner he did not live to see. More than anything else, it expresses the faith in the future with which this greatest of decades in particle physics ends: "Physics will change even more. . . . If it is radical and unfamiliar . . . we think that the future will be only more radical and not less, only more strange and not more familiar, and that it will have its own new insights for the inquiring human spirit."

Appendix

The following went into the derivation of Eq. 1 in the text.

1) The assumption that $SU_L(2) \times U_{L,R}(1)$ survives intact as the electron weak symmetry group from energies of $\approx \mu$ up to M. This intact survival implies that one eschews, for example, all suggestions that (i) low-energy $SU_L(2)$ may be the diagonal sum of $SU_L^{I}(2)$, $SU_L^{II}(2)$, $SU_L^{III}(2)$, where I, II, III refer to the (three ?) known families; (ii) that the $U_{L,R}(1)$ is a sum of pieces, where $U_R(1)$ may have differentially descended from a $(V + A)$-symmetric $SU_R(2)$ contained in G; or (iii) that U(1) contains a piece from a four-color symmetry $SU_c(4)$ (with lepton number as the fourth color) and with $SU_c(4)$ breaking at an intermediate mass scale to $SU_c(3) \times U_c(1)$.

2) The assumption that there are no unexpected heavy fundamental fermions, which might make $\sin^2\theta(M)$ differ from 3/8—its value for the low-mass fermions presently known to exist (*102, 103*).

3) If these assumptions are relaxed, for example, for the three family-group $G = [SU_F(6) \times SU_c(6)]_{L \rightarrow R}$, where $\sin^2\theta(M) = 9/28$, we find the grand unifying mass M tumbles down to 10^6 GeV.

4) The introduction of intermediate mass scales [for example, those connoting the breakdown of family universality, or of left-right symmetry, or from color $SU_c(4)$ to $SU_c(3) \times U_c(1)$] will as a rule push the magnitude of M upward (*104*). To secure a proton decay life, consonant with present empirical lower limit ($\sim 10^{30}$ years) (*105*), this is desirable anyway (τ_{proton} for $M \sim 10^{13}$ GeV is unacceptably low, $\sim 6 \times 10^{23}$ years, unless there are 15 Higgs). There is from this point of view an indication in particle physics of one or several intermediate mass scales which can be shown to start from around 10^4 GeV upward. This is the end result which I wished this appendix to lead up to.

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    "I come first, My name is Jowett
    I am the Master of this College,
    Everything that is, I know it
    If I don't, it isn't knowledge"
    —The Balliol Masque

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74. The calculation of baryon excess in the universe—arising from a combination of *CP* and baryon number violations—has recently been claimed to provide teleological arguments for grand unification. For example, D. V. Nanopoulos [CERN preprint TH2737 (September 1979)] suggested that the "existence of human beings to measure the ratio n_B/n_γ (where n_B is the number of baryons and n_γ the number of photons in the universe) necessarily imposes severe bounds on this quantity: i.e., $10^{-11} \approx (m_e/m_p)^{1/2} \lesssim n_B/n_\gamma \lesssim 10^{-4}$ $(\approx O(\alpha^2))$." Of importance in deriving these constraints are the upper (and lower) bounds on the numbers of flavors (≈ 6) deduced from (i) the mass relations above, (ii) cosmological arguments which seek to limit the numbers of massless neutrinos, (iii) asymptotic freedom, and (iv) numerous (one-loop) radiative calculations. It is clear that lack of accelerators as we move up in energy scale will force particle physics to reliance on teleology and cosmology (which, in Landau's famous phrase, is "often wrong, but never in doubt").
75. I would like to quote Feynman in a recent interview in *Omni* magazine: "As long as it looks like the way things are built with wheels within wheels, then you are looking for the innermost wheel—but it might not be that way, in which case you are looking for whatever the hell it is you find!" In the same interview he remarks, "a few years ago I was very skeptical about the gauge theories . . . I was expecting mist, and now it looks like ridges and valleys after all."
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82. The following quotation from Einstein is relevant here: "We now realize, with special clarity, how much in error are those theorists who believe theory comes inductively from experience. Even the great Newton could not free himself from this error (*Hypotheses non fingo*)." This is complementary to the quotation from Einstein at the end of the second section in the text.
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$$\sin^2\theta(M) = \frac{\Sigma T_{3L}^2}{\Sigma Q^2}\left(= \frac{9\,N_q + 3\,N_l}{20\,N_q + 12\,N_l}\right)$$
Here N_q and N_l are the numbers of fundamental quark and lepton SU(2) doublets (assuming these are the only multiplets that exist). If we make the further assumption that $N_q = N_l$ (from the requirement of anomaly cancellation between quarks and leptons) we obtain $\sin^2\theta(M) = 3/8$. This assumption, however, is not compulsive; for example, anomalies also cancel if (heavy) mirror fermions exist (*106*). This is the case for $[SU(6)]^4$, for which $\sin^2\theta(M) = 9/28$.
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Territorial Strategies in Ants

Bert Hölldobler and Charles J. Lumsden

Summary. Several features in social insects, particularly in ants, make the behavioral organization of territoriality considerably more complex than that of solitary animals. The establishment and maintenance of territories are based on a division of labor and a complex communication system. The analyses of territorial strategies in ants comprise the study of the design and spatiotemporal structure of the territory, as well as the social mechanisms through which the insect society pursues its territorial strategy. The geometric and behavioral organization of the absolute territories of the African weaver ants (*Oecophylla longinoda*) and harvester ants (*Pogonomyrmex*), and of the "spatiotemporal territories" of honey ants (*Myrmecocystus mimicus*) are described, and simple cost-benefit models are developed to illustrate the economic defensibility of each type of territory.

In studies of community biology, a territory is generally defined as an area that the animal or the animal society occupies exclusively and defends—using overt aggression, aggressive displays, and "keep-out signals" either alone or in combination—against intraspecific, and sometimes interspecific, intruders. Nonoverlapping territories produce relatively evenly dispersed spacing and usually indicate competition for some resource in limiting supply (*1*).

Territorial strategies are especially elaborate in animal species that live in well-organized societies. In social insects, the establishment and maintenance of territories are based on a division of labor and a complex communication system. Although it has been known for a long time that many ant species defend territories around their nests (*2*), only recently have biologists begun to analyze the diversity of their territorial strategies and the underlying communication mechanisms.

Theories of territoriality and space utilization have been based on results obtained from research with solitary animals (*1*, *3*). But in social insects, and particularly in ant societies, there are several unique features that often make the behavioral and spatiotemporal organization of territoriality considerably more complex.

Most ant societies are stationary; like barnacles or terrestrial plants they spend their entire adult lives fixed in one spot and produce winged reproductive forms to disperse away from the nests as the functional analogs of larvae and seeds. Foraging workers comb the surrounding terrain, where they gather information, energy, and matter and retrieve these resources to the nest. Thus, space around the nest of an ant colony is a precious commodity and frequently has to be defended against competitors.

The territories of ant societies are defended cooperatively by the usually sterile worker castes. Whereas a solitary animal can at any moment be in only one place and can be doing only one thing, a colony of social insects can be in many places by deploying its workers and can be doing many different things because of the size of the worker cohorts and their division of labor. Thus the insect society achieves its optimal territorial strategy by the allocation of specific worker task forces to specific places at specific times.

Because of the division of labor between reproductive individuals and sterile worker castes, fatalities caused by territorial defense have a different qualitative significance for social insects as compared to solitary animals. The death of worker ants represents an energy and labor debit, rather than a destruction of a reproductive agent. Worker death might more than offset its costs by bringing or maintaining resources and colony security. Death can thus become a positive element in the colony's adaptive repertory.

Natural selection theory suggests that an animal should only establish and maintain a territory whose size and design make it economically defensible. In other words, the territorial defense should gain more energy than it expends (*3*). To this end, the territory can be ei-

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