MASTER

QCD, UNIFICATION AND THE ROAD TO "ASYMPTOPIA"

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INTRODUCTION

In the latter sixties I coined the phrase¹ "Asymptopia" - the theoretically promised land where all asymptotic theorems came true. "Asymptopia" is reached at that energy beyond which no important new phenomena which are not predictable occur.

At the time I felt that a reasonable operational estimate of the minimum energy before we reach "Asymptopia" is that energy at which the Pomeranchuk² theorem comes true within the best experimental precision foreseeable ($\sim 0.1\%$). I used our precision $\sigma(\pi^{\pm}p)$ and real part of the forward scattering amplitude measurements³ to estimate that the Pomeranchuk theorem would not come true^{*} till E_{lab} was $> 25,000$ to $1,000,000$ GeV. These estimates of the minimum energy to reach Asymptopia were considered by many quite high at the time.

The Glashow-Salam-Weinberg⁴ model unification of E.M. and weak forces is not truly a unification but perhaps better described

* The pp and $\bar{p}p$ measurements gave an estimate consistent with that obtained from $\pi^{\pm}p$ but of course the existence of 3 forward amplitudes instead of one and a non-physical region make these predictions much less reliable.

as a mixing since the angle θ_w is an arbitrary parameter and thus there are really two coupling constants in the theory. A desire for a truly unified theory - one coupling constant - for unification of strong, E.M. and weak forces, and the inclusion of quarks and leptons in the same multiplet led theorists to the Grand unified theories^{5,6,7} which predicted 10^{12} - 10^{15} GeV (cms) for the unification energy. These led also to a Great Desert (or Grand Plateau) between 10^2 GeV and 10^{12} - 10^{15} GeV.

Pati and Salam (till recently) predicted relatively modest energies 10^4 - 10^6 GeV for Grand Unification. However Pati and Salam needed a $\sin^2 \theta_w = .28 - .30$. Recent analyses determined $\sin^2 \theta_w = 0.23 \pm .015$. Therefore Pati and Salam recently wavered and talk about partial unification at $\sim 10^4$ - 10^5 GeV.

The Great Desert advocates had selected the simplest unification groups with essentially two mass scales. One at $M_{W\pm} \sim 10^2$ GeV and the second at $M_x \sim 10^{15}$ GeV. Examples of such groups are SU(5) and SO(10). They have $\sin^2 \theta_w \sim .20$ at present energies and $\sin^2 \theta_w = 3/8$ at the unification energy. So perhaps the renormalization effects that are required to change $\sin^2 \theta_w$ to the value we observe at present energies are not understood well enough to rule out Pati-Salam.

Meanwhile a population explosion in the Higgs sector⁷ has made Grand Unification schemes based on spontaneous symmetry breaking (SSB) develop the equivalent of enormous numbers of arbitrary parameters, the calculation of which cannot be done. Therefore I think this approach should not be taken too seriously at this time.

There have been several recent attempts to reduce the huge number of Higgs bosons in SSB. These have involved dynamical symmetry breaking which use fermionic basic building blocks in $f\bar{f}$ combinations to replace the Higgs¹. One of these schemes is hypercolor (or technicolor)³ which leads to hyperquarks. Another is the preon scheme⁹ of Pati and Salam. Both represent a new structure

level which fills in the Great Desert with oases. The hypercolor oasis is at ~ 1 TeV and the Pati-Salam oasis is at ~ 100 TeV.

The scheme of Marshak and Mohapatra¹⁰ leads to neutron oscillations, and would also lead to a partial unification which would represent an oasis in the desert. This would be due to an intermediate mass scale $M_X \sim 10^4$ GeV and would be signalled by neutronless double beta decay, and neutron oscillations without proton decay.

Therefore even if one believed gauge theories are the only way to go, it is only the simplest gauge theory structures which give the great desert and there are obviously many modifications possible in the assumed hierarchy of nested gauge theories which lead to oases in the desert.

Thus perhaps the Great Desert Theory is an "Anti Mirage". An "Anti Mirage" makes a desert full of oases look like a great desert.

THE ROAD TO ASYMPTOPIA

Many great theorists have been wrong in this game of predicting the energy behavior of physics. For historical perspective let us look at the past ideas on the Road to "Asymptopia" before we proceed with the sage of the great desert.

Figure 1 shows a sketch of the Road to "Asymptopia". It starts with a series of straight solid line segments with sudden changes of direction marking either discovery of a new unforeseen domain or attainment of a theoretically predicted asymptotic energy which turned out to not truly represent "Asymptopia" even for the class of physical phenomena considered. The starting point on the road is the classical physics of Newton and Maxwell, etc. In the classical era it was generally believed that we were in "Asymptopia" since Newton's and Maxwell's theories explained what was considered the important phenomena.

Experimental surprises which showed quantization effects in electromagnetic radiation and the constancy of the velocity of

Figure 1: The Road to "Asymptopia"

light led to the new domain characterized, by Atomic Physics ($\sim \text{ev}$) Quantum Mechanics and Special Relativity (followed thereafter by general relativity). One then seemed to have perhaps again reached "Asymptopia" until the very small ($\sim 10^{-12}$ cm) nuclear domain ($E \sim \text{MeV}$) was uncovered by Lord Rutherford and subsequently found to exhibit the striking new phenomena of nuclear forces etc. The characteristics of Nuclear Forces led Yukawa to predict the pion and many physicists thought that once it was discovered the last important piece of the puzzle in the strong (and thus probably most important) interactions would have been found. After discovery of the pion Fermi was convinced that all higher energy strong interaction phenomena could be described by a simple statistical theory which he proposed. Thus the Fermi statistical theory¹¹ became the first modern Asymptotic theorem, and Fermi believed from an analysis of cosmic ray data that for $E \sim 1 \text{ GeV}$ we would be in Asymptopia and that all strong interaction phenomena were calculable by using constant matrix elements and phase space.

The discovery of pion-nucleon resonances,¹² the observation of the production of nucleon isobars and their domination of inelastic events in the GeV to few GeV region ruled out this theory.¹³

This led to the Isobar Model¹⁴ and one meson exchange models¹⁵ which were clearly non-asymptotic models. The number of elementary particles was increasing in the few GeV region and it was clear that "Asymptopia" would have to lie higher.

The second modern asymptotic theorem was proposed by Pomeranchuk² and is known as the Pomeranchuk theorem using dispersion relations and other arguments Pomeranchuk concluded $\sigma(\pi + \pi) = \sigma(\bar{\pi} + \pi)$ for high enough energies. He estimated this theorem would become true at incident lab energies of about 10 GeV.

CERN^{16a} and AGS experiments^{16b} soon demonstrated this was not the case. High precision AGS total and differential π^+p and $p\bar{p}$ and $\bar{p}p$ experiments^{17,18} performed by the speakers group later showed the Pomeranchuk theorem likely wouldn't become true till 25,000 to 1,000,000 GeV.¹

The third modern asymptotic theorem was the Regge Pole Pomeron dominance theory.¹⁸ It predicted that in the 10-20 GeV energy region a universal shrinkage of elastic scattering would be observed and thus universal logarithmic shrinkage of the scattering pattern would persist at all higher energies in a known way.

A group at the CERN PS¹⁹ produced evidence for pp shrinkage. A group at the BNL-AGS²⁰ showed that Regge shrinkage was not universal, and in fact pp shrank, n^+p did not shrink, K^+p shrank $<$ pp, K^-p did not shrink and $\bar{p}p$ expanded. This led to the multi-Regge pole model, which needed more than fifty parameters²¹ to describe the data, and this to the death of Regge Pole Theory as a viable Asymptotic theory.^{22,1} Even today at the highest energies at FNAL the observed trend points clearly toward a universal lack of (or small) shrinkage.

After the Regge pole theory the speaker felt that if asymptotic theorems were to be used to estimate the energies needed to reach asymptopia, the Pomeranchuk theorem seemed like the best bellweather theorem. It had the important added advantage that its higher energy behavior could be predicted by the unsubtracted forward dispersion relation which I felt could be used as a crystal ball to estimate where the Pomeranchuk theorem would come true. This led to the next assault on estimating on where asymptopia will lie.

A series of high precision experiments^{3,17} on n^+p and pp and $\bar{p}p$ total cross sections were performed by the speakers group at the AGS. These were accompanied by high precision measurements of the differential elastic scattering down into the Coulomb region to observe the coulomb-nuclear interference and thus extract the real part as well as the imaginary part of the forward scattering amplitude.

A critical experimental proof of the validity of the forward dispersion relations was accomplished for the first time. Their use in conjunction with the behavior of the total cross sections led to the "at the time" startling prediction by the speaker that the

minimum energy for the Pomeranchuk theorem to come true was 25,000 to 1,000,000 GeV. Thus Asymptopia was pushed decisively beyond our reach at the time. Hence I have had the sobering experience of personally contributing decisively to the contradiction of the first three modern asymptotic theorems.

Meanwhile the continued enormous proliferation of so-called elementary particles had led to their classification under the groups $SU(3)$ ^{23,24} and $SU(6)$.²⁵ This led to the standard three quark model,²⁴ then to the need for 3 colors and then to quantum chromodynamics.²⁶ It was the unification of QCD with the previously established electro-weak unification which produced the great desert.

UNIFICATIONS

Glashow, Salam and Weinberg⁴ using gauge theory had unified EM and weak interactions using $SU(2)_L \times U(1)$. This was not a true unification in that even though there was one arbitrary coupling constant, the Weinberg angle was arbitrary and thus there were effectively two coupling constants. Hence it was really more of a mixing than a unification.

Motivated by a desire of a truly unified theory with one coupling constant, several theorists^{5,6} realized that if one included the strong interactions in a gauge theory approach one could achieve a so-called grand unification which unifies EM, weak and strong interactions with one coupling constant, and a predicted Weinberg angle. The first path followed was to use simple groups* such as $SU(5)$, $SO(10)$ and E_6 which spontaneously break to $SU(2)_L \times U(1) \times SU(3)_C$. This gave a unification mass energy of $\sim 10^{15}$ GeV which in recent calculation could be $\sim 10^{12}$ GeV. The Weinberg angle corresponding to these groups was $\sin^2 \theta_w \approx 0.20$.

* E_7 is ruled out by much too large a Weinberg angle.

Pati and Salam⁵ believed the world is described by gauge groups; but asked the important question is the great desert necessary? They used semi-simple groups and started from $[SU(4)]^4 = [SU(4)_L \times SU(4)_R]_{\text{flavor}} \times [SU(4)_L \times SU(4)_R]_{\text{color}}$, which spontaneously breaks to $SU(2)_L \times SU(2)_R \times U_L^1(1) \times U_R^1(1) \times [SU(3)_L \times SU(3)_R]^1$. This approach gave a unification mass energy $\sim 10^4 - 10^6$ GeV which is approximately ten orders of magnitude less than the $\sim 10^{15}$ GeV originally found for the great desert.

What is the difference due to? Pati and Salam have used left-right symmetry, but the real origin of the difference is the dichotomy between flavor and color descents. This leads in the unifying symmetric limit to $g_2 = g_G/\sqrt{2}$ but $g_S^c = g_G$.

This tiny factor $1/\sqrt{2}$ when squared = 1/2. When the calculation is done properly, the result is a factor $\sim 1/2.7$ to 1/3. This factor multiplies in M/u which is in the denominator of g_S^c and thus reduces M_x from 10^{15} to about $10^4 - 10^6$ GeV.

Pati and Salam had gauged chiral color. $SU(3)_L^1 \times SU(3)_R^1$ was a good low or intermediate energy symmetry. They obtained two sets of solutions. The first had the familiar octet of neutral massless vector colored gluons with fractionally charged colored quarks, with color confined. The second solution had unconfined, unstable integer charged quarks with $(mq) \sim \text{few} - 10$ GeV and an unstable massive octet of vector gluons four of which are neutral and four charged with charges ± 1 and $m(\text{gluon})_{\text{out}} \sim \text{few to } 10 \text{ GeV}$.¹¹

The conventional gauge theory world is left-handed but the PS world has complete left-right symmetry at high enough energy. $V - A$ is accompanied by $V + A$. However, $m_{W_R} \neq m_{W_L}$ so as to preserve the obvious left-handed situation observed at present energies.

At high enough energies parity violation would disappear. Perhaps at high enough energies all symmetry violations P, C, CP, I, SU(2), SU(3) etc. would also disappear if these are not intrinsic to the equations of motion but due to SSB.

The PS framework can have fractionally charged confined quarks and confined color. Alternately there can be integrally charged quarks and color can only be partially confined thus free quarks and gluons can exist at high enough energies.

There are predictions different from those of conventional gauge theory which are not testable with presently available data. If $M_X = 10^4$ GeV perhaps experiments at PETRA, PEP, pp and $\bar{p}p$ colliders can tell the difference.¹¹ If $M_X = 10^6$ GeV we have to wait.

TO ME THE IMPORTANT POINT IS that a different theoretical viewpoint changes the grand unification energy from 10^{15} - 10^{16} GeV down to 10^4 - 10^6 GeV.

Although neither may be correct the existence of both demonstrates how uncertain the original estimates are. Remember they both take non-abelian gauge theory as the gospel.

So far the only gauge boson that I know of whose existence has been demonstrated is the photon - which is an abelian gauge boson. Secondly the non-abelian gauge boson theories of the SSB type depend on 'huge numbers of Higgs'. It is in my opinion premature to believe that the universe is described by a hierarchy of nested gauge groups. The establishment of QCD as the non-abelian gauge group describing strong interactions has not yet been accomplished. The gauge bosons of the low energy electroweak group are yet to be discovered. One must also demonstrate that they are truly the gauge bosons one assumes they are.

Possible Surprises

One must also allow for the large possibility of unforeseen experimental surprises somewhere between here and 10^{15} GeV.

For example just like the nucleon and nucleus lost their point-like status, quarks may have a structure and characteristic size.

F.D. Lee¹² thinks the quark has size.

Sam Ting¹³ has shown that the size of the e, μ and τ is $< 1 \times 10^{-16}$ cm, but he is still looking.

N. Zichichi³⁰ clearly believes in lots of experimental surprises and doesn't believe in great deserts either.

We may find:

Several sets of IVB($W^\pm$, Z^0).

New generations of a baffling nature.

That the proton is stable beyond lifetimes predicted by these various CUTS. A fundamental length may arise at a high enough energy where micro-causality and analyticity break down.

Other conservation laws like E, P, J etc. may even break down somewhere on the road to asymptopia.

Surprises may well originate from cosmic ray events.³¹ One such present candidate is the centauro events at $E \sim 500$ TeV. These events contain an anomalously small fraction of their energy in the π^0 component compared to what is presumed to be the $\pi^\pm$ and nucleon components. The π^0 content is $\sim$ one percent. Cosmic ray air showers may probe up to millions of TeV. It is likely that the surprises not even mentioned or thought of may be the most important.

Problems with Pati-Salam Theory

[SU(4)]⁴ gives too large a Weinberg angle (i.e. $\sin^2 \theta_w \sim .28-.30$). However, one can question whether the uncertainties introduced by a hierarchy of gauge groups in the determination of $\sin^2 \theta_w$ at present energies from the value (3/4) at the unification mass, and the uncertainties in the measurements are small enough to rule out Pati-Salam.

Nevertheless the PS approach can give a reasonable value for the Weinberg angle and yield instead of a full unification, a partial unification at $\sim 10^5$ GeV.

This would provide an oasis in the desert at 10^5 GeV.

In order to reduce the huge number of Higgs they have postulated more basic elements which make up the quarks which they call preons, but about 15 of these arbitrary new basic building blocks are required.

Population Explosion of Higgs in SSB

The number of Higgs required for various models^{7,8} are:

$W - S$	$4 - 3 = 1$
$C - G[SU(5)]$	$124 - 15 = 109$
E_7	~ 950

Hypercolor or Technicolor

Beg⁸ and others have used a dynamical symmetry breaking scheme to construct the Higgs systems from more basic fermionic elements. They have introduced hyperquarks, fermions with hypercolor. Gauging hypercolor leads to QC'D which is a scaled up version of QCD. This gives a new series of meson and baryon mass spectra at a much higher energy. They estimate the natural mass scale for QC'D gives:

$$m(\rho') \cong m(\omega') \cong 1 \text{ TeV}$$

$$B_B = 1.8 (N_c'/N_f)^{1/2} \text{ TeV.}$$

Thus the meson and baryon spectroscopies we know at a mass scale ~ 1 GeV would appear again at a mass scale ~ 1 TeV. There would be new islands of stability such as hypernucleons and hypernuclei. One problem with this scheme is where are the hypernuclei? Hypercolor scheme of course has other problems.

1. The replication of generations leads to unwanted global symmetries and Goldstone bosons.
2. No direct Yukawa coupling of H 's (Higgs doublets) to fermions sans hypercolor leads to no lepton mass and no current quark mass.
3. It is quite arbitrary and has no evidence for it yet, but clearly is more aesthetically appealing than the SSB schemes.

Preons

Pati and Salam⁵ have tried to handle the population explosion by introducing a new more basic set of fields carrying fundamental attributes. They are called preons and consist of n_f flavors

(carrying the n flavors) plus n'_c chromons (carrying the n' colors). If both flavons and chromons carry spin they also need spinons which carry spin $1/2$. The best they can do without inventing further new force interactions is about twenty-five preons. Clearly this is a quite arbitrary approach.

EVALUATION OF UNIFICATION AND CONCLUSIONS

The various schemes for grand or partial unification have a number of important predictions which can be checked.^{5,6,7} The most striking of these is the prediction of a finite lifetime for the protons. There are also some predictions which can be checked if the electro-weak group is left-right symmetric including neutrino and neutron oscillations.¹⁰

Assuming that laws of the universe are derived from a hierarchy of nested gauge groups seems at first to be an elegant simplification. However, unfortunately this apparently simple beautiful scheme loses its beauty when enormous numbers of Higgs' have to be introduced in spontaneous symmetry breaking versions.

The dynamical symmetry breaking attempts which were proposed to avoid this proliferation of Higgs are arbitrary guesses and have their own problems. As yet there is no evidence for them.

Therefore I cannot help but conclude the assumption that we have a world ruled by a hierarchy of nested gauge groups is quite premature. Even a successful prediction of the proton lifetime would not convince me that the world is completely described by nested gauge group theories since it has often happened that a particular prediction of a theory is quite accurate but the theory is still only a part of the story.*

* In a lecture following mine, Lipkin (see Proceedings) also expressed his doubts about too easily embracing newly proposed gauge theories of the world.

Figure 2 illustrates the existence of presently postulated oases in the Great Desert. The gauge theories which have led to the great desert are still very speculative and very far from being established. Even so it is only the most simple of these gauge theory structures which lead to the so-called Great Desert.

Other more complicated gauge theory hierarchies lead to oases populating the desert. The only gauge boson that has been established is the photon, a non-abelian unconfined gauge boson. It is of utmost importance to establish whether gluons, the gauge bosons of $SU(3)_c$ exist. Due to confinement and asymptotic freedom this probably can best be done via discovery of glueballs.²⁷ The discovery of $W^\pm$ and Z^0 , determining whether there are more than one set, and whether indeed they are the gauge bosons we think they are is of great importance.

It's a long way to infinity and I would not jump to a conclusion too hastily. As indicated earlier in the lecture, the road to "asymptopia" is strewn with the wrong predictions of many great theorists contradicted by the discovery of important unexpected oases.

My advice is to keep building next step accelerators, and doing all reasonable experiments at existing accelerators until it gets either too boring or - which is what I believe will happen - very exciting.

My overall conclusion is that it is likely there are many mini-deserts followed by important oases, all the way to the planck length.* Each of these oases has a good chance of having as drastic an impact on our thinking as past turns in the road to asymptopia (Fig. 1).

* I would hesitate to even consider speculating what happens at or beyond the planck length since these energies would correspond to those in the original big bang which created our universe.

Figure 2 The Great Desert and Some Possible Oases in it.

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32. Chiral $SU(3)'_L \times SU(3)'_R$ color may break to vectorial color $SU(3)'_{L+R}$ either by a relatively heavy mass scale ($m_{WR} \gg m_{WL}$) or by a relatively light mass scale $\sim m_{WL}$. Accordingly there will be an octet of effectively heavy or light axial gluons supplementing the familiar light or massless vector octet.

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33. If the electro-weak group is larger than $SU(2)_L \times U(1)$ - for example left-right symmetric - various experiments at some of the accelerators listed could indicate this.
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