The Utility of Quantum Field Theory

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- Beyond Quantum Field Theory: Holography

Quantum Field Theory as Effective Theory

The past 30 years have witnessed extraordinary triumphs of quantum field theory. At the same time, we have come to view quantum field theories as *effective* theories, valid up to some energy scale. This idea is familiar in the Fermi theory, a theory which we know is valid only up to scales of order 10's of GeV, where it must be supplanted by a larger theory.

Viewing the standard model in this way, we don't require, e.g., renormalizability. However, operators which are not renormalizable will be suppressed by some scale (compare 250 GeV in the Fermi theory), Λ, where some new particles, interactions, or other phenomena must appear.

The effects of physics at scales above Λ can be absorbed into the parameters of the effective lagrangian of the low energy field theory. This low energy theory is not renormalizable; non-renormalizable operators are suppressed by powers of Λ.

This principle is a crucial part in our current understanding of the standard model. It also gives us a way to understand what sorts of physics might lie beyond the standard model. Finally, these ideas have proven a powerful way to understand basic questions which we confront in theoretical physics.

By thinking about the low energy behavior of complicated models, we have been able, during the last several years, to:

- Make significant progress in understanding field theories themselves. It has proven possible to make exact statements about a variety of field theories, even strongly interacting ones, particularly in cases where the theories are supersymmetric. There are quantum field theories where we can study phenomena such as confinement and electric-magnetic duality in *controlled* approximations.

- Make exact statements about strongly interacting limits of string theory, even though we don't have a non-perturbative setup in which to describe the microscopic theory.

The Standard Model as an Effective Field Theory

- Physics as we know it has $SU(3) \times SU(2) \times U(1)$ symmetry. There are three flavors of quarks and leptons. The unsuppressed (i.e. renormalizable) terms are exactly the gauge and Yukawa interactions of the standard model

- There are a variety of possible suppressed – non-renormalizable – interactions. The most interesting of those – those which we have the best chance of observing – are those which violate cherished symmetry principles, e.g. baryon number, such as:

  $$\mathcal{L}_{\not B} = \frac{1}{\Lambda^2} QQQL \tag{1}$$

  or lepton number:

  $$\mathcal{L}_{\not L} = \frac{1}{\Lambda} \phi L \phi L \tag{2}$$

In each case, the question is: what is Λ? If we are lucky, Λ is not so large that we can't observe the corresponding phenomenon. We have some theoretical guesses: Λ might be the Planck scale of the scale of grand unification. It might be some scale associated with supersymmetry breaking (10^{11} GeV? 10^{3} GeV?)

Neutrino masses? Expect some suppression, similar to Yukawa couplings. So, e.g., if suppressed by y^2, $y \sim m_\tau/v$,

$$m_\nu = \frac{m_\tau^2}{\Lambda} \tag{3}$$

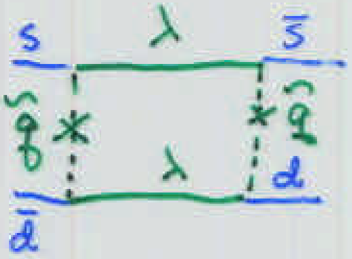
In this simple-minded view, neutrino masses suggest that there is a new scale in nature, perhaps at $10^{11} GeV$. Of course, without a theory (See Lawrence Hall's talk) y can vary over a huge range, and so can Λ. Still, neutrino masses are our first glimpse at a new scale of physics – real physics beyond the standard model.

Standard Model and CP Violation?

Suppose it turns out that $\sin(2\beta) \ll 1$.

New Physics!

Describe by operators in the low energy effective lagrangian. $\Lambda = M_{susy}$. Possibility that $\delta_{KM} \ll 1$, susy breaking origin of $K\bar{K}$ CP explored by Masiero and Murayama, Ko at at this meeting.



What might it tell us? E.g. in supersymmetric models where suppress FCNC's by flavor symmetries(Nir, Seiberg; Kagan, Leigh, M.D., Murayama et al, Kaplan, Schmaltz) susy contributions tend to saturate ϵ, spontaneous CP violation suppresses phases both in KM and in soft breakings.

The Hierarchy Problem

Thinking about field theory in this way also leads us to speculate about other physics beyond the standard model.

Scalar masses:

$$m_H^2 = c\Lambda^2 \tag{4}$$

This is just dimensional analysis; it also follows from looking at Feynman graphs.

$$\Delta m_H^2 = \frac{a\,\alpha_W}{4\pi}\Lambda^2$$

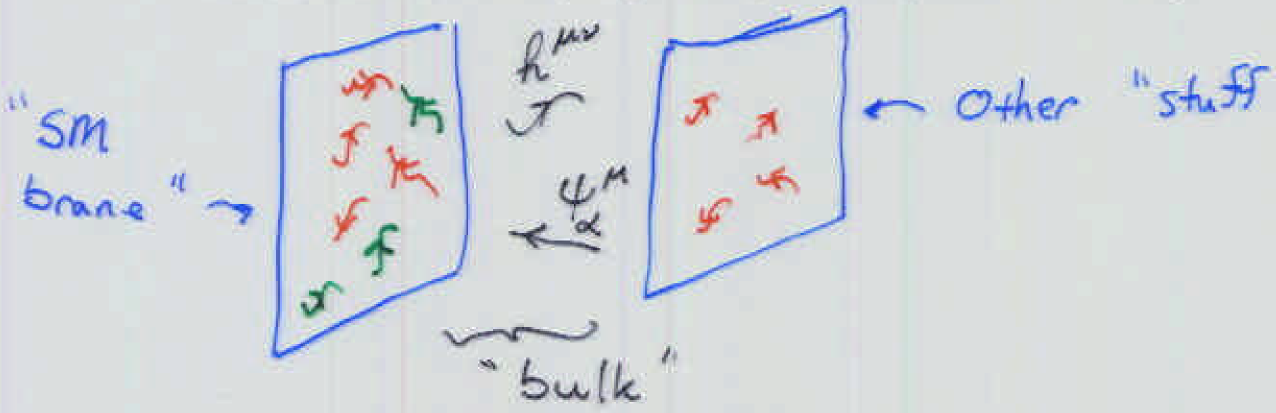
This suggests that new physics should not be too far away.

Previous guesses about this physics were:

- New Strong Interactions – Technicolor
- A New Symmetry – Supersymmetry

Of course, one of the likely possibilities is always: something we have not guessed. In the past two years, much exploration of two new possibilities:

- Large Extra Dimensions (Horava and Witten, Antoniadis et al; Lykken, Dimopoulos et al)



- Warped dimensions (Randall and Sundrum)

From precision electroweak limits, we have an interesting upper bound on the Higgs mass. But we can also ask whether something like technicolor could play a role. Bagger, Falk and Swartz have considered this question from an effective field theory point of view. Here they assume that the new physics responsible for electroweak symmetry breaking is at some high scale, and represent its effects through higher dimension operators in a theory consisting only of the standard model fields we already know. In this case, they find Λ might be as large as 3 TeV. Standard technicolor ideas have problems fitting the data, but this result suggests that there might be something there besides a weakly coupled Higgs. I'll bet on the Higgs.

Limitations of Effective Field Theory?

There appear to be problems in applying the ideas of effective theory to gravity – Cosmological Constant and Black Holes.

Cosmological constant: One of the most exciting recent developments in physics is the observation of what appears to be a non-vanishing cosmological constant. This is a quantity one would think one could compute from particle physics. However, the same sort of dimensional analysis we used before suggests that

$$\lambda = a\Lambda^4 \tag{5}$$

So even if Λ is as small as 100 GeV, we obtain an estimate 55 orders of magnitude larger than the reported observation! (Alternatively, if λ were this large, our horizon would be about 10 cm!)

Field Theory: collection of harmonic oscillators.

$$E_o = \lambda = \int^{\Lambda} \frac{d^3k}{(2\pi)^3} \frac{1}{2} (-1)^F \sqrt{k^2 + m^2} \qquad (6)$$

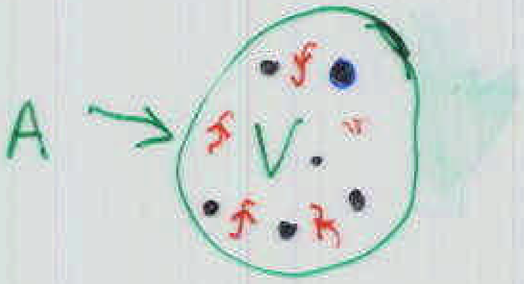
$$\propto \Lambda^4.$$

For SUSY, $\Lambda > 100$ GeV. Many other attempts have failed. It is possible that this problem represents a breakdown of our ideas about effective field theory.

Black Holes: (Hawking) Usual rules of quantum mechanics break down near black holes. Problem seems to be *locality*. String theory seems to possess some degree of non-locality, and there is growing evidence that string theory provides a consistent quantum mechanical framework in which to understand black holes.

The Holographic Principle

't Hooft and Susskind have suggested that in a theory with gravity, there are not as many degrees of freedom in a volume V as we might expect; they argue that a consistent theory of gravity must be holographic – the number of degrees of freedom is proportional to the surface area of V.



This holographic principle is in many ways mysterious, but it can sometimes be seen to hold in string theory. At low energies, for many purposes, string theory is well described by an effective field theory, but perhaps not for everything?

If these ideas are correct, some important questions in nature cannot be answered by the methods of effective field theory.

Supersymmetry and Our Understanding of Field Theory

Field theories such as real QCD are difficult to solve. In the last few years, however, it has been possible to solve, at least in part, many non-trivial field theories with supersymmetry. Supersymmetry turns out to give a great deal of mathematical control. This has allowed an attack on basic issues in quantum field theory such as duality and confinement, and on the basic problem of supersymmetry phenomenology: understanding the origin of supersymmetry breaking.

In supersymmetric theories, many of the coupling constants are complex numbers; the reason one can learn so much about these theories, is that many physical quantities are analytic functions of these numbers.

Example:

$$\tau = \frac{8\pi^2}{g^2} + i\theta \qquad g_{eff}^{-2} = f(\tau) \tag{8}$$

The low energy theory is often symmetric under:

$$\tau \to \tau + 2\pi i \tag{9}$$

This highly restricts f;

$$f = \tau + \sum_{n>0} a_n e^{-n\tau} \tag{10}$$

further considerations in some cases determine f completely.

- Exact solutions of theories with N=2 supersymmetry (Seiberg and Witten). In these theories many quantities can be computed exactly. In the strongly coupled region, monopoles condense, and cause confinement. Further progress in this area was reported at the meeting, determining the patterns of symmetry breakdown (Murayama; Yasue) and in exquisite test of these ideas (Fucito; Khoze)

- Theories with N=1 Supersymmetry might provide the solution to the hierarchy problem. Not only do they provide a way of understanding why there are not big corrections to the Higgs mass $\Lambda \ll M_p$, but they can naturally produce very large hierarchies. Further progress on such theories was reported at this conference. (Kazakov, Nitta, Tachibana)

Applied Duality

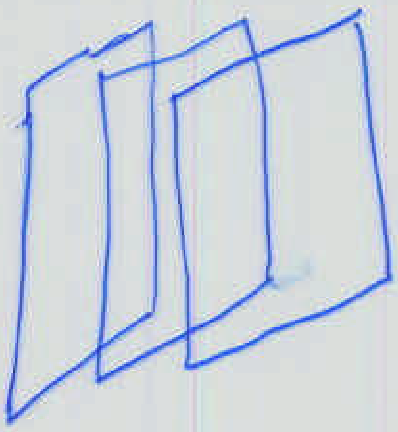
Apart from addressing fundamental questions in field theory, we can try to use these ideas to understand, e.g., how supersymmetry might be realized in nature. This is an area which has been developing for some time, but the past two years have seen some interesting new ideas:

- Models with dynamical supersymmetry breaking have been put forward in which the partners of the first generation fermions are composite and quite massive, while the partners of the third generation are light. (Cohen,Kaplan,Nelson; Kim, Choi; Grant,Luty, Terning,...) These models, first, implement both the ideas of dynamical supersymmetry breaking and quark and lepton compositeness. They are readily compatible with bounds coming from direct searches as well as processes such as $b \to s + \gamma$. They are simpler and less contrived than earlier proposals.

- Applied conformal field theories: Models in which nature is approximately conformally invariant over a range of energies have been put forward, which not only address questions of supersymmetry breaking, but also provide models of flavor. e.g. Nelson, Strassler. In these models, hierarchies arise between fields in different generations possess different anomalous dimensions. Many problems of flavor physics can be readily understood in this context.

String Theory as a Tool for the Investigation of Field Theory

Over the past several years, it has proven fruitful to consider certain problems in quantum field theory from the perspective of string theory. This is illustrated by simple configurations of D-branes.



In Type II string theory, this configuration describes a theory with gauge group $SU(N)$ and $N=4$ supersymmtry. More interesting models, with less supersymmetry, can be constructed along these lines. Problems which are very difficult from a field theory perspective take on quite a different character (e.g. geometric) in the string picture.

Recent new developments have been based on "AdS-CFT" correspondence.

Conformally Invariant QFT = String Theory in AdS space

But: we would like to understand QCD.

Early approaches: finite temperature in five dimensions,...

Recently, Polchinski and Strassler have exhibited cases where one can perturb the conformal theory, and where the effect on the supergravity side is completely under control (nonsingular spaces). These are theories where confinement, flux tubes, glueballs, and other interesting phenomena can be thoroughly studied in the gravity dual.

Field Theory as a Tool for Understanding M Theory

The pictures which have been described above can be viewed from a different perspective: One can hope to use one's understanding of field theory in order to understand difficult questions in string (M) theory.See esp. talk of Paul Townsend

These ideas have a long history. The easiest way to prove the finiteness of string theory is to study the effective field theory. Indeed, even though there is much that we do not understand about the fundamental structure of the theory, many questions can be addressed by considering the low energy field theory limit.

Some examples:

- Much of the understanding of duality in string theory has been obtained from the study of the low energy effective field theory.
- String theory has a host of possible vacuum states which are uncovered in various approximations. These are characterized by the number of dimensions (2-11), the amount of supersymmetry ($N = 0, \ldots 4$), the number of generations, as well as set of continuous parameters ("moduli"). The hope is that some dynamical configurations pick out one vacuum or another. From considerations of the low energy effective field theory, however, we know that all of the vacuua with some supersymmetry in $d \geq 5$ or with $N > 1$ supersymmetry in $d = 4$ are good vacua of string theory, exactly.

- We can make many exact statements about more promising vacua which, in some approximation, have $N = 1$ supersymmetry. We can often compute the ground state energy as a function of the moduli reliably using effective field theory. We can sometimes argue that couplings unify even if the theory is strongly coupled.

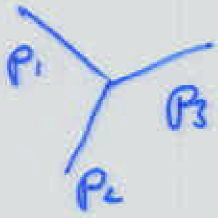
A New Type Of Field Theory

In the past year, much attention has been focused on a new type of field theory, known as "non-commutative field theory". These theories arise in some cases as the low energy limits of string theories, and seem to incorporate some of the non-locality of string theory. (Connes, Douglas, Schwarz, Seiberg and Witten ...) They exhibit bizarre connections between the infrared and the ultraviolet.

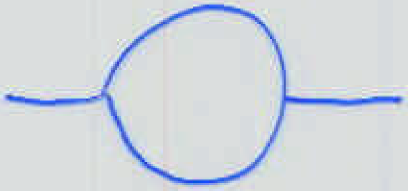
The basic feature of these theories is that space coordinates do not commute:

$$[x, y] = i\theta \tag{6}$$

This sort of relation arises in string theory in the presence of a background magnetic field. These theories can't be local. They exhibit peculiar connections between the infrared and ultraviolet – which have come to be called the infrared-ultraviolet connection.



$$\sum_{i,j} e^{i\theta_{\mu\nu} p^{\mu i} p^{\nu j}}$$



Typical Feynman graphs behave as

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} e^{i\theta p_1 k_2} \sim \frac{\theta}{p^2} \tag{7}$$

i.e. an ultraviolet divergence gets replaced by a divergence as $p^2 \to 0$.

It is fair to see that the significance of these theories is only beginning to be understood. Could there be real phenomena which might be described by such theories? Might they give some insight into the cosmological constant problem? Could these structures have relevance to other areas of physics? Time will tell.

Kuirke, Chaichian reported results on the renormalization of these theories.

Unconventional Approaches to Outstanding Problems

In the past two years, two new approaches have been put forth to the hierarchy problem. While the underlying justification for both is string or M theory, both are firmly based on pictures developed by considering the low energy field theory.

The premise of both is that the fundamental scale of physics might be close to the weak scale. This obviates the need for supersymmetry as a solution to the hierarchy problem, and, indeed, in both of these approaches, low energy supersymmetry (at least as it is conventionally discussed) is not a likely outcome.

Lawrence Hall has discussed the large dimension possibility at some length.

One set of results which have emerged from this work are new ideas for the mediation of supersymmetry breaking. These start from the idea of two separated walls, with the standard model on one wall, supersymmetry-breaking on another.

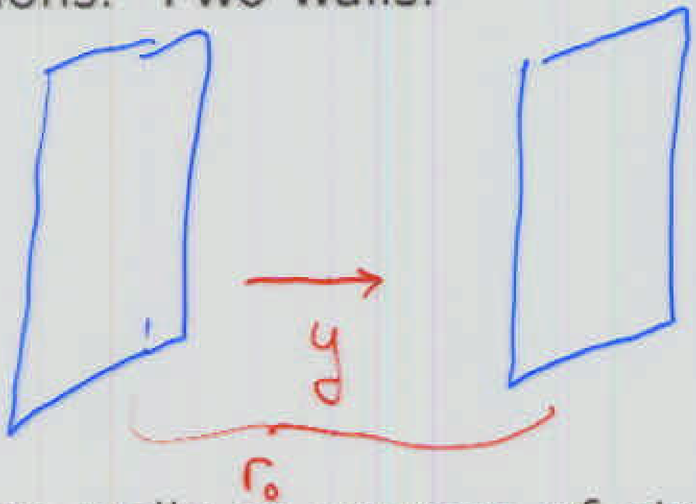
- Anomaly Mediation (Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi)

- Gaugino Mediation (Kaplan, Kribs, Schmaltz; Chacko, Luty, Nelson; Schmaltz, Skiba)

These ideas lead to predictions for the low energy soft breakings.

Warped extra dimensions:
The Randall-Sundrum Model(s)

Several versions. Simplest to describe: Five dimensions. Two walls.



With the walls as sources of stress-energy, if one tunes parameters, Einstein's equations admit a solution:

$$ds^2 = e^{-2kr_o|y|}dx^\mu dx_\mu + r_o^2 dy^2 \qquad (11)$$

The first term is the infamous "warp factor."

In the effective theory in four dimensions, Newton's constant:

$$G_N = \frac{k}{M^3}\frac{1}{1-e^{-kr_o\pi}} \qquad (12)$$

while the typical scales on our brane are of order

$$m_H^2 = M^2 e^{-2kr_o} \qquad (13)$$

So the hierarchy is due to the warping of space, and it is large because it is the exponential of a rather modest number(compare technicolor, susy approaches).

New solutions of this type were reported at this meeting by Ichinose

Phenomenology discussed by Hewett.

What fixes the separation of the walls which determines the exponential? Goldberger and Wise have shown that it can arise from plausible scalar field dynamics in the low energy theory.

There are a number of versions of these ideas currently being explored. These include the possibility that the extra dimensions are in infinite, with gravity localized on a brane, or that, viewed from far enough away, the extra dimension is simply flat ("quasilocalization."– Gregoriev, Rubakov) Surprisingly, these ideas are not easily ruled out (Randall, Sundrum, Lykken), and if correct, these lead to distinctive phenomenologies, with some features in common with the large dimension picture.

It should be noted that this structure, unlike the large dimensions structure, has not been derived from string theory, though there is much effort along these lines.

An Effective Field Theory Critique

The large dimension and warped dimension ideas are exciting, and are plausible alternatives to supersymmetry as solutions to the hierarchy problem. Experiment might produce a smoking gun for one of them.

On the theoretical side, there are many questions which must be settled. All of these are problems of the effective field theory:

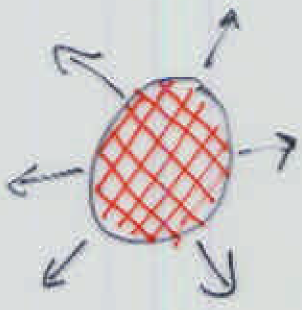
- Proton decay, $\mu \to e + \gamma$, etc.
- Flavor changing neutral currents.
- High precision electroweak experiments.

The last typically puts a limit on the fundamental scale in the TeV range. This is perhaps troubling for hierarchies, and is perhaps reminiscent of some of the problems of technicolor. Solutions have been proposed for the others (Arkani-Hamed, Dimopoulos, Dvali, March-Russell)

Is Low Energy Supersymmetry A Prediction of String Theory?

It is often said that low energy supersymmetry is a prediction of string theory. But Randall Sundrum, large dimension ideas: need not exhibit the states (squarks, sleptons, neutralinos...) expected there.

But from studies of low energy field theory limit of strings, some evidence that non-supersymm states have problems. (Fabinger and Horava) have shown that many non supersymmetric states of string theory undergo catastrophic decay:



If generic, perhaps low energy supersymmetry is a prediction of string theory.

Other Anomalies?

New Ideas About the Cosmological Constant

Can field theory in four dimensions resolve the cosmological constant problem?

Old Ideas:

- Dynamics of a light particle cancels the cosmological constant? No-Go Theorems (Weinberg)

- Interesting gravitational dynamics (wormholes,...) – can't resolve without a theory of gravity.

10	1	10	10	1
2	9	2	2	1
7	9	8	10	8
3	8	3	3	1
2	8	3	3	1

Score would change if, e.g.
large or warped dimensions solved
cosmological constant problem

<u>or</u>

A discovery!

Scorecard

	Exist.?	Hierarchy	FCNC	Precision EW
MSM				
TC				
SUSY				
Large d				
Warped d				

New Ideas:

- Search for string theories (without supersymmetry) in which cosmological constant cancels (Kachru, Silverstein). Search motivated by developments related to the AdS/CFT correspondence. Models with low order cancellations. But higher orders? Realistic spectra?

- Holography: suggestive. But no precise formulation. De Sitter horizon today:

  $$d \approx 10^{10} \text{ light years} \tag{14}$$

  but $d \times (100\text{GeV}) \sim 10^{36}$ and this is not enough! (need about 10^{55}). Some ideas have been discussed by Cohen, Kaplan and Nelson.)

- Warped geometries: several suggestions that equations seem to permit solutions with vanishing four dimensional cosmological constant. (Kachru, Silverstein, Schulz; Arkani-Hamed, Dimopoulos, Kaloper, Sundrum; Kakusadze, Wasserman; at this meeting, Guendelman; earlier: Rubakov, Shaposhnikov) But troubling singularities appear, and it is not yet clear whether these solutions make sense. It has been argued that these singularities are just a rephrasing of the fine-tuning problems. (Gubser; Polchinski, Strassler; Forst, Lalak, Lavignac, Nilles) Under intense investigation.

Weinberg:

A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you're against it, some people will think you're a little too interested.

More Embarassing Proposals

What are we trying to explain?

If recent observations of a cosmological constant are correct, then the value of the constant is just such that the cosmological constant is becoming important in the present epoch of cosmic history,

$$\Omega_\Lambda \approx 0.7\ \Omega_{crit} \tag{15}$$

The following piece of numerology is often invoked:

$$\lambda \approx \frac{(\mathrm{TeV})^8}{M^4}. \tag{16}$$

Here M is the reduced Planck mass, $M \approx 10^{18}$.

But we would like to explain a close coincidence. If we change TeV to 2.7 TeV, for example, in this formula

$$\Omega_\Lambda \approx 10^3 \Omega_{crit} \tag{17}$$

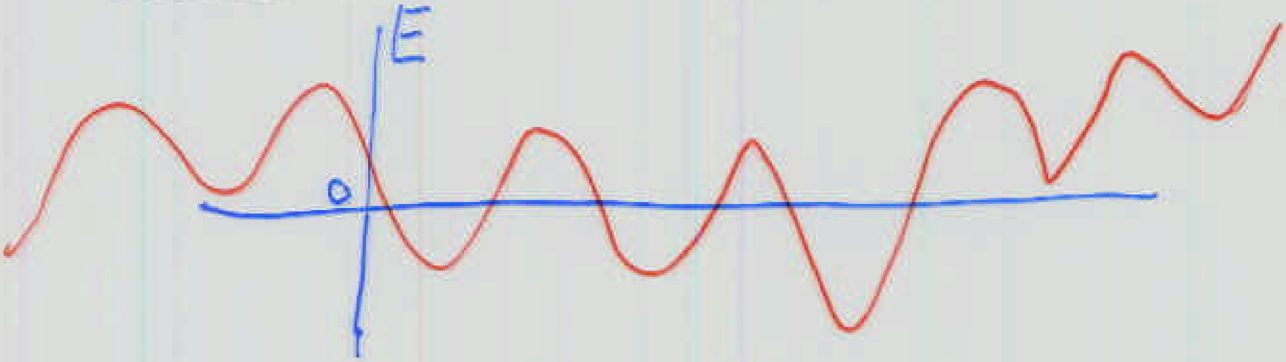
The Anthropic Principle Rears Its Ugly Head

These remarks are suggestive of an anthropic explanation.

What would this mean?

The Weak Anthropic Principle (Weinberg)

Suppose a theory has many metastable ground states.



The universe in its history may sample all of these states. Only some may develop in a way which can allow for even rudimentary forms of life; some might collapse, for example, long before structure can form.

Weinberg originally argued that this was not good enough to explain the cosmological constant; $\Omega_\Lambda \approx 10^2 \Omega_{crit}$ the application of anthropic considerations was not scientifically defensible. Villenkin has argued that a more refined argument gives the right order of magnitude.

For this to make sense, the underlying theory must have lots and lots (10^{120} = zillions and zillions of reasonably stable ground states. We live in one with a small cosmological constant because that's the only place intelligent beings can evolve.

Such a theory might be able to explain the observed facts.

Do we have any theories with these properties? Recent proposal: Bousso and Polchinski – possible existence of a vast array of such states in string theory. Analysis is based on considerations of effective field theory, and in particular of certain gauge fields with three indices, $A^{[i]}_{\mu\nu\rho}$, whose flux is quantized (compare monopoles.)

$$F^{[i]}_{\mu\nu\rho\sigma} = q^{[i]} n^{[i]} \epsilon_{\mu\nu\rho\sigma} \tag{18}$$

$$E = \sum_{i}^{N} n^{[i]\ 2} q^{[i]} - \Lambda_o \tag{19}$$

If $i = 1, \ldots 120$, then may have a sufficient number of states.

It is plausible, but far from established, that there could be such a huge number of metastable states. In some versions, everything in this suggestion becomes anthropic. In others, it is only the cosmological constant. Determining whether such a vast set of states truly exists is a problem which cannot be settled in effective field theory. (Banks, Motl and M.D.)

Progress in Field Theory

Quantum field theory is an old topic, but the past few years have witnessed an enormous growth in our understanding. There are now situations where we understand exact behaviors of these theories.

Some of this progress has come in areas that are very useful for understanding experiment, and in particular in perturbative calculations of strong interaction amplitudes. Motivated originally by the observation that perturbative calculations in string theory involve far fewer Feynman diagrams than in conventional field theory, Bern, Kosower and Dixon developed methods to compute scattering amplitudes involving several gluons. These methods, in some sense, have now come full circle, and Bern at this meeting reported on the use of these methods to perform calculations in theories of gravity.

Progress continues to be made in other areas.

- Light cone methods continue to serve as a powerful tool to understand QCD. Srivastava reported further progress in this area.
- Other progress in QCD was reported by Sterman,who described methods to determine power corrections in short distance cross sections.
- Other non-perturbative issues in QCD were reported by Kondo, who discussed alternative methods to deal with large distance QCD, and Kneur who discussed variational methods.

- Field theory at finite temperature remains an important topic, from several perspectives: it provides insight into quantum field theories; it is important for understanding early universe cosmology; it is important for understanding the physics of RHIC. Brandt reported on technical progress in this challenging topic. Statistical techniques figured in other developments described here Yuasa and Turko.

Other developments reported at this meeting included

- A new class of analytic monopole solutions, due to Rosy Teh
- An alternative quantization scheme, by K. Fujikawa useful to understanding a number of difficult problems in gauge theory (Gribov copies, more speculatively generation of gauge fields?
- The role of topological terms in non-linear sigma models was discussed by Chakraborty.
- Symmetry breaking in non-simply connected spacetimes was considered by Sakamoto.

A Much Milder Use of the Anthropic Principle?

A milder application of the anthropic principle might resolve the question: why don't we live in one of the unpalatable states of string theory described earlier?

It could be that in most of them, one can not develop even the most minimal structures one would imagine are necessary to develop life, and in fact that many of them would be subject to gravitational collapse.

We are a long way from being able to answer this question completely, but partial (positive) answers can already be given, using methods of effective field theory..

CONCLUSIONS

Field theory continues to enjoy an extraordinary level of utility. It gives the standard model, as well as its limitations. It suggests broad ranges of new phenomena. It is a crucial tool in our study of candidates for a fundamental theory.

Yet field theory also has limitations. We probably need to go beyond quantum field theory if we are to understand:

- The problems of Black Holes
- The Cosmological Constant Problem
- The principles which determine the ground states of M theory, and what selects among them.