The Triumph and Limitations of Quantum Field Theory

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Abstract

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1 The Triumph of Quantum Field Theory

Although the title of this session is “The Foundations of Quantum Field Theory”, I shall talk, not of the foundations of quantum field theory (QFT), but of its triumphs and limitations. I am not sure it is necessary to formulate the foundations of QFT, or even to define precisely what QFT is. QFT is what quantum field theorists do. For a practicing high energy physicist, nature is a surer guide as to what quantum field theory is as well to what might supersede it, is than the consistency of its axioms.

Quantum Field Theory (QFT) is today at a pinnacle of success. It provides the framework for the the standard model, a theory of all the observed forces of nature. This theory describes the forces of electromagnetism, the weak interaction responsible for radioactivity, and the strong nuclear force that governs the structure of nuclei, as consequences of local (gauge) symmetries. These forces act on the fundamental constituents of matter, which have been identified as pointlike quarks and leptons. The theory agrees astonishingly well with experiment to an accuracy of $10^{-6} - 10^{-10}$ for electrodynamics, of $10^{-1} - 10^{-4}$ for the weak interactions and of $1 - 10^{-2}$ for the strong interactions. It has been tested down to distances of $10^{-18}$ cm. in some cases. We can see no reason why QFT should not be adequate down to distances of order the Planck length of $10^{-33}$ cm. where gravity becomes important. If we note that classical electrodynamics and gravity are simply limiting cases of their quantum field theoretic generalizations, then quantum field theory works from the Planck length to the edge of the universe—over 60 orders of magnitude. No other theory has been so universally successful.

1.1 The Problems of the Past

It is hard for today’s generation to remember the situation 35 years ago, when field theory had been abandoned by almost all particle physicists. The exhilaration following the development of Quantum Electrodynamics (QED) was short lived when the same methods were applied to the new field of mesons and nucleons. The proliferation of elementary particles and their strong couplings, as well as the misunderstanding and discomfort with renormalization theory, gave rise to despair with field theoretic models and to the conclusion that quantum field theory itself was at fault.

Renormalization was originally a response to the ultraviolet divergences
that appeared in the calculations of radiative corrections in QED in a perturbative expansion in the fine structure constant. The basic observation was that if physical observables were expressed, not in terms of the bare parameters that entered the definition of the theory (like the bare mass of the electron) and refer to idealized measurements at infinitely small distances, but rather in terms of the physical parameters that are actually measurable at finite distances, then they would be finite, calculable functions of these. Feynman, Schwinger, Tomanaga and Dyson set forth the procedure for carrying out this renormalization to all orders in perturbation theory and proved that it yielded well-defined, finite results. Even though this program was very successful many physicists were uncomfortable with renormalization, feeling that it was merely a trick that swept the fundamental problem of ultraviolet divergences under the rug.

Furthermore, there was great concern as to the consistency of quantum field theory at short distances. Most four dimensional quantum field theories are not asymptotically free, thus their short distance behavior is governed by strong coupling and thus not easily treatable. In the fifties it was suspected, especially by Landau and his school, that the nonperturbative ultraviolet behavior of QFT meant that these theories were inherently inconsistent, since they violated unitarity (which means that the total sum of probabilities for the outcomes of measurements of some physical processes was not unity). This is probably the case for most non-asymptotically free theories, which are most likely inconsistent as complete quantum field theories. The discovery of asymptotic freedom, however, has provided us with theories whose ultraviolet behavior is totally under control.

The disillusionment with QFT as a basis for the theory of elementary particles was also premature. What one was missing were many ingredients, including the identification of the underlying gauge symmetry of the weak interactions, the concept of spontaneous symmetry breaking that could explain how this symmetry was hidden, the identification of the fundamental constituents of the nucleons as colored quarks, the discovery of asymptotic freedom which explained how the elementary colored constituents of hadrons could be seen at short distances yet evade detection through confinement, and the identification of the underlying gauge symmetry of the strong interactions. Once these were discovered, it was but a short step to the construction of the standard model, a gauge theory modeled on QED, which opened the door to the understanding of mesons and nucleons.
2 The Lessons of Quantum Field Theory

The development and successes of QFT have taught us much about nature and the language we should use to describe it. Some of the lessons we have learned may transcend QFT. Indeed they might point the way beyond QFT. The most important lessons, in my opinion, have to do with symmetry principles and with the renormalization group.

2.1 Symmetry

The most important lesson that we have learned in this century is that the secret of nature is symmetry. Starting with relativity, proceeding through the development of quantum mechanics and culminating, in the standard model symmetry principles have assumed a central position in the fundamental theories of nature. Local gauge symmetries provide the basis of the standard model and of Einstein’s theory of gravitation.

Global symmetry principles express the invariance of physical laws under an actual transformation of the the physical world. Local symmetry principles express the invariance of physical phenomena under a transformation of our description of them, yet local symmetry underlies dynamics. As Yang has stated: *Symmetry dictates interaction.* The first example of a gauge theory was general relativity where diffeomorphism invariance of spacetime dictated the laws of gravity. In the standard model, non-Abelian gauge symmetry dictates the electroweak and strong forces. Today we believe that global symmetries are unnatural. They smell of action at a distance. We now suspect, that all fundamental symmetries are local gauge symmetries. Global symmetries are either broken, or approximate, or they are the remnants of spontaneously broken local symmetries. Thus, Poincaré invariance can be regarded as the residual symmetry of general relativity in the Minkowski vacuum under changes of the spacetime coordinates.

The story of symmetry does not end with gauge symmetries. In recent years we have discovered a new and extremely powerful new symmetry—supersymmetry— which might explain many mysteries of the standard model. We avidly await the experimental discovery of this symmetry. The search for even newer symmetries is at the heart of many current attempts to go beyond the standard model. String theory, for example, shows signs of containing totally new and mysterious symmetries with greater predictive power.
Another part of the lesson of symmetry is that, although the secret of nature is symmetry, much of the texture of the world is due to mechanisms of symmetry breaking. The spontaneous symmetry breaking of global and local gauge symmetries is a recurrent theme in modern theoretical physics. In quantum mechanical systems with a finite number of degrees of freedom global symmetries are realized in only one way. The laws of physics are invariant and the ground state of the theory is unique and symmetric. However, in systems with an infinite number of degrees of freedom a second realization of symmetry is possible, in which the ground state is asymmetric. This spontaneous symmetry breaking is responsible for magnetism, superconductivity, the structure of the unified electro-weak theory and more. In such a situation the symmetry of nature’s laws is hidden from us. Indeed, the search for new symmetries of nature is based on the possibility of finding mechanisms, such as spontaneous symmetry breaking or confinement, that hide the new symmetry.

There are two corollaries of the lesson of symmetry that are relevant to our understanding of QFT. First is the importance of special quantum field theories. A common strategy adopted years ago, say in constructive field theory, was to consider theories with only scalar fields. Their study, it was thought, would teach us the general principles of QFT and illuminate its foundations. This, to an extent, was achieved. But, in the absence of vector or fermionic fields one cannot construct either gauge invariant or supersymmetric theories, with all of their special and rich phenomena. Today it might be equally foolhardy to ignore quantum gravity in the further development of QFT. Indeed the fact that QFT finds it so difficult to incorporate the dynamics of spacetime suggests that we might search for more special theories.

Second, we have probably exhausted all possible symmetries of QFT. To find new ones we need a richer framework. Traditional quantum field theory is based on the principles of locality and causality, on the principles of quantum mechanics and on the principles of symmetry. It used to be thought that QFT, or even particular quantum field theories, were the unique way of realizing such principles. String theory provides us with an example of a theory that extends quantum field theory, yet embodies these same principles. It appears to contain new and strange symmetries that do not appear in QFT. If there are new organizing principles of nature, the framework of QFT may simply not be rich enough. We may need string theory, or even more radical theories, to deal with new symmetries, especially those of spacetime.
2.2 The Renormalization Group

The second important lesson we have learned is the idea of the renormalization group and effective dynamics. The decoupling of physical phenomena at different scales of energy is an essential characteristic of nature. It is this feature of nature that makes it possible to understand a limited range of physical phenomena without having to understand everything at once. The renormalization group describes the change of our description of physics as we change the scale at which we probe nature. These methods are especially powerful in QFT which asserts control over physics at all scales. Quantum field theories are most naturally formulated at short distances, where locality can be most easily imposed, in terms of some fundamental dynamical degrees of freedom (described by quantum fields). Measurement, however, always refers to physics at some finite distance. We can describe the low energy physics we are interested in by deriving an effective theory which involves only the low momentum modes of the theory. This procedure, that of integrating out the high momentum modes of the quantum fields, is the essence of the renormalization group, a transformation that describes the flow of couplings in the space of quantum field theories as we reduce the scale of energy.

The characteristic behavior of the solutions of the renormalization group equations is that they approach a finite dimensional sub-manifold in the infinite dimensional space of all theories. This defines an effective low energy theory, which is formulated in terms of a finite number of degrees of freedom and parameters and is largely independent of the high energy starting point. This effective low energy theory might be formulated in terms of totally different quantum fields, but it is equally fundamental to the original high energy formulation, insofar as our only concern is low energy physics.

Thus, for example, QCD is the theory of quarks whose interactions are mediated by gluons. This is the appropriate description at energies of billions of electron volts. However, if we wish to describe the properties of ordinary nuclei, at energies of millions of electron volts we employ instead an effective theory of nucleons, composites of the quarks, whose interactions are mediated by other quark composites—mesons. Similarly, in order to discuss the properties of ordinary matter made of atoms at energies of a few electron volts we can treat the nuclei as pointlike particles, ignore their internal structure and take into account only the electromagnetic interactions of the
charged nuclei and electrons. The renormalization group influences the way we think about QFT itself. One implication is that there may be more than one, equally fundamental, formulation of a particular QFT; each appropriate for describing physics at a different scale of energy. Thus, the formulation of QCD as a theory of quarks and gluons is appropriate at high energies where, due to asymptotic freedom, these degrees of freedom are weakly coupled. At low energies it is quite possible, although not yet realized in practice, that the theory is equivalent to a theory of strings—describing mesons as tubes of confined chromodynamic flux. Both formulations might be equivalent and complete, each appropriate to a different energy regime. Indeed, as this example suggests, a quantum field theory might be equivalent to a totally different kind of theory, such as a string theory. The renormalization group has had a profound influence on how we think about renormalizability. Renormalizability was often regarded a selection principle for QFT. Many quantum field theories, those whose couplings had dimensions of powers of an inverse mass (such as the Fermi theory of weak interactions), were not renormalizable. This meant that, once such interactions were introduced, it was necessary to specify an infinite number of additional interactions with an infinite number of free parameters in order to ensure the finiteness of physical observables. This seemed physically nonsensical, since such a theory has no predictive power and was taken to be the reason why theories of nature, such as QED, were described by renormalizable quantum field theories.

Our present view of things is quite different. The renormalization group philosophy can be applied to the standard model itself. Imagine that we have a unified theory whose characteristic energy scale, $\Lambda$, is very large or whose characteristic distance scale, $\hbar c/\Lambda$, is very small (say the Planck length of $10^{33}$ cm.). Assume further that just below this scale the theory can be expressed in terms of local field variables. As to what happens at the unification scale itself we assume nothing, except that just below this scale the theory can be described by a local quantum field theory. (String theory does provide us with an example of such a unified theory, which includes gravity and can be expressed by local field theory at distances much larger than the Planck length.) Even in the absence of knowledge regarding the unified theory, we can determine the most general quantum field theory. In absence of knowledge as to the principles of unification this theory has an infinite number of arbitrary parameters describing all possible fields and all possible interactions. We also assume that all the dimensionless couplings that char-
acterize the theory at energy $\Lambda$ are of order one (what else could they be?). Such a theory is useless to describe the physics at high energy, however, at low energies, of order $E$, the effective dynamics, the effective Lagrangian that describes physics up to corrections of order $E/\Lambda$, will be parameterized by a finite number of couplings. The renormalization group describes how the various couplings run with energy. We start at $\Lambda$ with whatever the final unified theory and then one can show that the low energy physics will be described by the most general renormalizable field theory consistent with the assumed couplings plus non-renormalizable interactions that are suppressed by powers of the energy relative to the cutoff. If we demand further that the theory at the scale $\Lambda$ contain the local gauge symmetry that we observe in nature, then the effective low energy theory will be described by the standard model up to terms that are negligible by inverse powers of the large scale compared to the energy that we observe. The extra interactions will give rise to weak effects, such as gravity or baryon decay. But these are very small and unobservable at low energy.

Non-renormalizable theories were once rejected since, if they had couplings of order one at low energies, then their high energy behavior was uncontrollable unless one specified an infinite number of arbitrary parameters. This is now turned around. If all couplings are moderate at high energies, then non-renormalizable interactions are unobservable at low energies. Furthermore, the standard model is the inevitable consequence of any unified theory, any form of the final theory, as long as it is local at the very high energy scale and contains the observed low energy symmetries. In some sense this is pleasing, we understand why the standard model emerges at low energy. But from the point of view of the unified theory that surely awaits us at very high energy it is disappointing, since our low energy theory tells us little about what the final theory can be. Indeed, the high energy theory need not be a QFT at all.
3 QCD As A Perfect QFT

For those who ever felt uncomfortable with ultraviolet divergences, renormalization theory or the arbitrary parameters of quantum field theory, QCD offers the example of a perfect quantum field theory. By this I mean:

- This theory has no ultraviolet divergences at all. The local (bare) coupling vanishes, and the only infinities that appear are due to the fact that one sometimes expresses observables measured at finite distances in terms of those measured at infinitely small distances.

- The theory has no free, adjustable parameters (neglecting the irrelevant quark masses), and dimensional observables are calculable in terms of the dynamically produced mass scale of the theory \( m = \Lambda \exp[-1/g_0^2] \), where \( g_0 \) is the bare coupling that characterizes the theory at high energies of order \( \Lambda \).

- The theory shows no diseases when extrapolated to infinitely high energies. To the contrary, asymptotic freedom means that at high energies QCD becomes simple and perturbation theory is a better and better approximation.

Thus, QCD provides the first example of a complete theory with no adjustable parameters and with no indication within the theory of a distance scale at which it must break down.

There is a price to be paid for these wonderful features. The absence of adjustable parameters means that there are no small parameters in the theory. The generation of a dynamical mass scale means that perturbative methods cannot suffice for most questions. The flip side of asymptotic freedom is infra-red slavery, so that the large distance properties of the theory, including the phenomenon of confinement, the dynamics of chiral symmetry breaking and the structure of hadrons are issues of strong coupling. What are the limitations of such a QFT? In traditional terms there are none. Yet, even if we knew not of the electroweak and gravitational interactions, we might suspect that the theory is incomplete. Not in the sense that it is inconsistent, but rather that there are questions that can be asked which it is powerless to answer; such as why is the gauge group \( SU(3) \) or what dictates the dynamics of spacetime?
4 The Limitations of QFT

Quantum field theory is a mature subject; the frontier of fundamental physics lies elsewhere. Nonetheless there are many open problems in quantum field theory that should and will be addressed in the next decades.

First there are problems having to do with QCD, our most complete field theory. Much is understood, but much remains to be understood. These problems include the proof of the existence of QCD and of confinement; the development of analytic methods to control QCD in the infrared; and the development of numerical algorithms for Minkowski space and scattering amplitudes. The second class of problems are more general than QCD, but would help in solving it as well. These include the development of large N methods; the formulation of a non-perturbative continuum regularization; the rigorous formulation of renormalization flow in the space of Hamiltonians; a first quantized path integral representation of gauge mesons and the graviton; the exploration of the phase structure of particular theories, particularly supersymmetric gauge theories; the complete classification and understanding of two-dimensional conformal field theories and integrable models; and the discovery and solution of special integrable quantum field theories.

You will have noticed that the big problems of high energy physics are not on the above list. These include: the unification of forces, the mass hierarchy problem (namely why is the scale of the electroweak symmetry breaking and the mass scale of the strong interactions smaller than the Planck or unification scale by 14 to 18 orders of magnitude), the origin of lepton-quark families, the explanation of the parameters of the standard model, quantum gravity, the smallness or vanishing of the cosmological constant, the early history of the universe . . . .

The reason I have not listed these is that I believe that their resolution does not originate in quantum field theory at all. To solve these we will have to go beyond quantum field theory to the next stage, for example to string theory. In this sense QFT has reached true maturity. Not only do we marvel at its success but we are aware of its boundaries. To truly understand a physical theory it is necessary to have the perspective of the next stage of physics that supersedes it. Thus we understand classical mechanics much better in the light of quantum mechanics, electrodynamics much better after QED. Perhaps the true understanding of QFT will only transpire after we find its successor.
The search for a replacement for QFT has been ongoing ever since its invention. Every conceptual and technical difficulty that was encountered was taken as evidence for a fundamental length at which QFT breaks down. With the success of QFT as embodied in the standard model the search for a fundamental length has been pushed down to the Planck length. There almost everyone believes that a new framework will be required, since many of the basic concepts of QFT are unclear once space-time fluctuates violently. The longstanding problem of quantizing gravity is probably impossible within the framework of quantum field theory. Einstein’s theory of gravity appears to be an effective theory, whose dimensional coupling, Newton’s constant $G_N$, arises from the scale of unification which might be close to the Planck mass $M_p$, i.e., $G_N \propto 1/M_p^2$. General relativity is then simply an incredibly weak force that survives at low energies and is only observable since it couples coherently, via long range forces, to mass, so that we can observe its effects on large objects. QFT has proved useless in incorporating quantum gravity into a consistent theory at the Planck scale. We need to go beyond QFT, to a theory of strings or to something else, to describe quantum gravity.

There are other indications of the limitations of QFT. The very success of QFT in providing us with an extremely successful theory of all the non-gravitational forces of nature has made it clear that this framework cannot explain many of the features and parameters of the standard model which cry out for explanation. In the days before the standard model it was possible to believe that the requirement of renormalizability or symmetry would be sufficient to yield total predictive power (as in QCD). But today’s understanding makes it clear that these principles are not sufficient. Thus, the limitations of QFT are not those of consistency or incompleteness in its own terms, but rather of insufficiency and incompleteness in broader terms. If we restrict ourselves to effective field theories, or the use of QFT in dealing with nonrelativistic many body systems, or fundamental theories of limited domain (such as QCD), then QFT is in fine shape. But if we are to come to grips with the quantization of the dynamics of spacetime then QFT is, I believe, inadequate. I also believe that we will learn much about QFT itself from its successor. For example, there are certain features of special quantum field theories (such as the recently developed duality symmetries) whose deeper understanding might require the embedding of field theory within string theory.
5 Beyond QFT—String Theory

We have one strong candidate for an extension of physics beyond QFT that does claim to be able to answer the questions that QFT cannot and more—string theory. String theory is a radically conservative extension of the principles of physics, in which one introduces fundamental degrees of freedom that are not pointlike, but rather have the structure of extended one-dimensional objects—strings, while leaving untouched (at least in the beginning) the other principles of causality, relativistic invariance and quantum mechanics. The structure of this theory, which appears to be rather unique and free of any non-dynamical parameters, is quite remarkable. It yields a consistent theory of quantum gravity, at least in the perturbative, weak field domain, providing us with an existence proof that gravity and quantum mechanics are mutually consistent. In addition, it appears to possess all the ingredients that would be necessary to reproduce and explain the standard model. Most important, it is definitely an extension of the conceptual framework of physics beyond QFT.

There have been two major revolutions completed in this century: relativity, special and general, and quantum mechanics. These were associated with two of the three dimensional parameters of physics: \( \hbar \), Planck’s quantum of action, and \( c \), the velocity of light. Both involved major conceptual changes in the framework of physics, but reduced to classical non-relativistic physics when \( \hbar \) or \( 1/c \) could be regarded as small. The last dimensional parameter we need in order to establish a set of fundamental dimensional units of nature, is Newton’s gravitational constant, which sets the fundamental (Planck) scale of length or energy. Many of us believe that string theory is the revolution associated with this last of the dimensional parameters of nature. At large distances, compared to the string scale of approximately \( 10^{-33} \text{cm.} \), string theory goes over into field theory. At shorter distances it is bound to be very different, indeed it calls into question what we mean by distance or spacetime itself.

The reason we are unable to construct predictive models based on string theory is our lack of understanding of the nonperturbative dynamics of string theory. Our present understanding of string theory is very primitive. It appears to be a totally consistent theory, that does away with pointlike structures and hints at a fundamental revision of the notions of space and time at short distances while at the same time reducing to field theory at large...
distances. It introduces a fundamental length in a way that had not been envisaged—not by, for example, discretizing space and time—but rather by replacing the fundamental point-like constituents of matter with extended, non-local strings. The constituents are non-local but they interact locally; this is sufficient to preserve the usual consequences of locality—causality as expressed in the analyticity of scattering amplitudes.

To be more specific, string theory is constructed to date by the method of \textit{first quantization}. Feynman’s approach to QFT, wherein scattering amplitudes are constructed by summing over the trajectories of particles, with each history weighted by the exponential of \((i \times)\) the classical action given by the proper length of the of the path, is generalized to strings by replacing the length of the particle trajectory with the area swept out by the string as it moves in spacetime. This yields a perturbative expansion of the amplitudes in powers of the string coupling, which is analogous to the Feynman diagram expansion of QFT. However, string theory exhibits profound differences from QFT. First, there is no longer any ambiguity, or freedom, in specifying the string interactions, since there is no longer an invariant way of specifying when and where the interaction took place. Consequently, the string coupling itself becomes a dynamical variable, whose value should ultimately be determined (in ways we do not yet understand). Furthermore, there are only a few, perhaps only one, consistent string theory. Finally, the issue of ultraviolet divergences is automatically solved, the smoothing out of world-lines to world-tubes renders the interactions extremely soft and ensures that string amplitudes are totally finite.

At low energies string theory goes over into field theory. That means that we can describe the scattering amplitudes by an effective field theory describing the light particles to any degree of approximation in powers of the momenta \(p/M_{\text{planck}}\). However string theory is not just a complicated field theory. It exhibits features at short distances or high energies that are profoundly different than QFT; for example the Gaussian falloff of scattering amplitudes at large momenta. At the moment we are still groping towards an understanding of its properties for strong coupling and for short distances. In our eventual understanding of string theory we might have to undergo a discontinuous conceptual change in the way we look at the world similar to that which occurred in the development of relativity and quantum mechanics. I think that we are in some sense in a situation analogous to where physics was in the the beginning of the development of quantum mechanics, where
one had a semiclassical approximation to quantum mechanics, that was not yet part of a consistent, coherent framework. There was an enormous amount of confusion until quantum mechanics was finally discovered.

What will this revolution lead to? Which of our concepts will have to be modified? There are many hints that our concepts of spacetime, which are so fundamental to our understanding of nature, will have to be altered. The first hint is based on a stringy analysis of the measurement of position, following Heisenberg’s famous analysis in the quantum mechanics. Already in ordinary quantum mechanics space becomes somewhat fuzzy. The very act of measurement of the position of a particle can change its position. In order to perform a measurement of position \( x \), with a small uncertainty of order \( \Delta x \), we require probes of very high energy \( E \). That is why we employ microscopes with high frequency (energy) rays or particle accelerators to explore short distances. The precise relation is that

\[
\Delta x \approx \frac{\hbar c}{E},
\]

where \( \hbar \) is Planck’s quantum of action and \( c \) is the velocity of light. In string theory, however, the probes themselves are not pointlike, but rather extended objects, and thus there is another limitation as to how precisely we can measure short distances. As energy is pumped into the string it expands and thus there is an additional uncertainty proportional to the energy. All together

\[
\Delta x \approx \frac{\hbar c}{E} + \frac{GE}{c^5}.
\]

Consequently it appears impossible to measure distances shorter than the Planck length.

The second hint is based on a symmetry of string theory known as duality. Imagine a string that lives in a world in which one of the spatial dimensions is a little circle of radius \( R \). Such situations are common in string theory and indeed necessary if we are to reconcile the fact that the string theories are naturally formulated in nine spatial dimensions so, that if they are to look like the real world, six dimensions must be curled up, compactified, into a small space. Such perturbative solutions of realistic string theories have been found and are the basis for phenomenological string models. Returning to the simple example of a circle, duality states that the theory is identical in all of its physical properties to one that is compactified on a circle of
radius $\bar{R} = L_p^2/R$, where $L_p$ is the ubiquitous Planck length of $10^{-33}$ cm. Thus if we try to make the extent of one of the dimensions of space very small, by curling up one dimension into a circle of very small radius $R$, we would instead interpret this as a world in which the circle had a very large radius $\bar{R}$. The minimal size of the circle is of order $L_p$. This property is inherently stringy. It arises from the existence of stringy states that wind around the spatial circle and again suggests that spatial dimensions less than the Planck length have no meaning.

Another threat to our conventional view of spacetime is the discovery that in string theory the very topology of space-time can continuously be altered. In perturbative string theory there are families of solutions labeled by various parameters. In some cases these solutions can be pictured as describing strings propagating on a certain curved spatial manifold. As one varies the parameters the shape and geometry of the background manifold varies. It turns out that by varying these parameters one can continuously deform the theory so that the essential geometry of the background manifold changes. Thus one can go smoothly from a string moving in one geometry to a string moving in another; although in between there is no simple spacetime description. This phenomenon cannot be explained by ordinary quantum field theories.

Finally, during this last year, new developments have been made in the understanding of the structure of string theory. A remarkable set of conjectures have been formulated and tested that relate quite different string theories to each other (S,T,U dualities) for different values of their parameters and for different background spacetime manifolds. Until now the methods we have employed to construct string theories have been quite conservative. To calculate string scattering amplitudes one used the method of “first quantization”, in which the amplitudes are constructed by summing over path histories of propagating strings, with each path weighted by the exponential of the classical action (the area of the world sheet swept out by the string as it moves in spacetime. This approach, originally developed by Feynman for QED, is quite adequate for perturbative calculations. It was envisaged that to do better one would, as in QFT, develop a string field theory. However, these new developments suggest that in addition to stringlike objects, “string theory” contains other extended objects of higher internal dimension, that cannot be treated by the same first quantized methods and for which this approach is inadequate. Even stranger, some of the duality symmetries
of string theory connect theories whose couplings ($g_1$ and $g_2$) are inversely related $g_1 = 1/g_2$. This is a generalization of electrodynamic duality, wherein the electric and magnetic fields and their charges ($e$ and $g$, related by the Dirac quantization condition $eg = 2\pi\hbar$) are interchanged.

These developments hint that the ultimate formulation of string theory will be quite different than originally envisaged. It might be one in which strings do not play a fundamental role and it might be a theory that cannot be constructed as the quantization of a classical theory. Thus it appears that we are headed for a real theoretical crisis in the development of string theory. A welcome crisis, in my opinion, one that could force us to radically new ideas.

5.1 Lessons for QFT

What can we learn from string theory about quantum field theory? There are a few lessons that we can already extract, and I expect that many more will emerge in the future.

- First this theory, used simply as an example of a unified theory at a very high energy scale, provides us with a vindication of the modern philosophy of the renormalization group and the effective Lagrangian that I discussed previously. Using string theory as the theory at the cutoff we can verify that at energies low compared to the cutoff (the Planck mass) all observables can be reproduced by an effective local quantum field theory and, most importantly, all dimensionless couplings in this effective, high-energy theory, are of the same order of magnitude. Thus, we have an example of a theory, which as far as we can see, is consistent at arbitrarily high energies and reduces at low energy to quantum field theory. String theory could explain the emergence of quantum field theory in the low energy limit, much as quantum mechanics explains classical mechanics, whose equations can be understood as determining the saddlepoints of the quantum path integral in the limit of small $\hbar$.

- We also learn that the very same quantum field theories that play a special role in nature are those that emerge from the string. These include general relativity, non-Abelian gauge theories and (perhaps) supersymmetric quantum field theories. Thus, string theory could explain the distinguished role of these theories. From a practical point of view
string theory can be used to motivate the construction of novel field theoretic models that include less familiar interactions as well as new kinds of particles, such as axions or dilatons, that are ubiquitous features of low energy string physics.

- Finally, it appears that some of the new and mysterious dualities of supersymmetric field theories have their natural explanation in the framework of string theory. To truly understand these features of QFT it may be necessary to consider a field theory as part of a string theory and use the latter to understand the former.

6 Conclusions:

I believe that we are living in revolutionary times, where many of the basic principles of physics are being challenged by the need to go beyond QFT and in which many of our basic concepts will require fundamental revision. Will the exploration of the foundations or the philosophical meaning of QFT help us in these tasks? I admit that my prejudice is that the answer is no. The issues that face us now have little to do with those that were confronted in the struggle to make sense of QFT. Rather, it is the surprises that we unearth in the experimental exploration of nature as well as the those that emerge in the theoretical exploration of our emerging theories that will force us to radical modifications of our basic preconceptions.