Particles vs. strings

In light of the huge amount of propaganda and confusion regarding string theory, it might be useful to consider the relative merits of the descriptions of the fundamental constituents of matter as particles or strings. (More-skeptical reviews can be found in my physics parodies. A more technical analysis can be found at "Warren Siegel's research".)

Predictability

The main problem in high energy theoretical physics today is predictions, especially for quantum gravity and confinement. An important part of *predictability* is *calculability*. There are various levels of calculations possible:

1. Existence: proofs of theorems, answers to yes/no questions
2. Qualitative: "hand-waving" results, answers to multiple choice questions
3. Order of magnitude: dimensional analysis arguments, $10^?$ (but beware hidden numbers, like powers of 4π)
4. Constants: generally low-energy results, like ground-state energies
5. Functions: complete results, like scattering probabilities in terms of energy and angle

Any but the last level eventually leads to rejection of the theory, although previous levels are acceptable at early stages, as long as progress is encouraging.

It is easy to write down the most general theory consistent with special (and for gravity, general) relativity, quantum mechanics, and field theory, but it is too general: The spectrum of particles must be specified, and more coupling constants and varieties of interaction become available as energy increases. The solutions to this problem go by various names -- "unification", "renormalizability", "finiteness", "universality", etc. -- but they are all just different ways to realize the same goal of predictability. Unfortunately, most solutions to these problems simply sweep them under the rug, solving one form of the problem and replacing it with another: For example, "renormalization", a systematic way of eliminating infinities in certain calculations, eliminates ambiguities at one stage only to have them reappear later. Other approaches look *only* at "low" energies, and thus effectively ignore most of the problem altogether. (But "low" might be ridiculously high by current standards for very weak forces, such as electromagnetism or gravity.)

Score card

topic	particles	strings
dimension	Predictive particle theories do not exist in dimension D>4, and thus effectively predict the correct result D=4 (3 space, 1 time).	Known string theories do exist in D>4. They effectively predict "critical" D=10, 11, or 26. If the observable dimensions are constrained to 4, predictive power is lost. However, useful particle models can be accomodated.
supersymmetry	The standard calculational method for particles uses an approximation method ("perturbation") that involves adding correction terms. When the infinite number of terms is summed to find an exact answer,	Known string theories have serious difficulties already at low orders of perturbation in the absence of supersymmetry, so string theory predicts supersymmetry.

	predictive power is lost in the absence of supersymmetry. Thus, particle theory predicts supersymmetry.	
graviton	Maximal supersymmetry requires (super)gravity, so the existence of the graviton (particle of gravitational force) is predicted by that particle theory. However, treating the graviton as a fundamental particle leads to a loss of predictability, even at low orders of perturbation. A possible alternative is to treat the graviton as a composite state of other particles: Such theories have been constructed, but have not yet been shown to be predictive.	The existence of the graviton is required by known string theories, and thus predicted: This is true for the superstring, which has maximal supersymmetry (although it may be hidden in some formulations). It is also true for the bosonic string; however, that string has some consistency problems. Known string theories retain their predictive power in their critical dimension at all orders of perturbation; however, summation leads to the kind of effects (hidden dimensions) that are expected to destroy predictability.
black holes	A black hole is defined by an "event horizon", which is the border of the part of space where even light must hit the singularity, which is in turn defined as the region where the theory breaks down. Thus the very existence of black holes in a theory of gravity indicates its inadequacy. (However, black hole singularities might be avoided by formulations in "Euclidean space", with imaginary time.) Black hole solutions are not expected in a composite-state theory of gravity.	Some advantages are found in the description of black holes, but the situation is unclear.
unification	Predictabilty strongly restricts the class of allowed models, but there is still a lot of freedom. Observed matter (quarks and leptons) can be unified, resulting in a unification of forces (less gravity, plus yet unseen forces), but requiring many yet unseen and un-unified "Higgs scalars" to break the symmetry. Supersymmetry introduces unseen particles as least as numerous as the known ones, and thus is not truly unifying.	String theories are essentially unique in their critical dimension, and unify all forces and particles, including gravity. But "compactification" to D=4 is far from unique, and destroys any advantages of unification.
confinement	Qualitative arguments predict confinement of quarks and gluons inside hadrons, but calculations are limited to low-energy properties of hadrons (or high-energy properties of quarks and gluons), and cannot calculate properties of any but the lightest hadrons.	Strings can describe properties of hadrons of all mass, and agree with qualitative properties of hadron scattering. But known string theories don't fit well to experiment, since they include massless hadrons.

Final tally

- Particle theory correctly predicts D=4, string theory doesn't.
- Both particle and string theory have difficulty with unification.
- Both theories predict supersymmetry. Unfortunately, it hasn't been observed yet.
- Both strings and maximally supersymmetric particles predict gravity, but neither solves the problem of predictable quantum gravity in D=4.
- The experimental facts that hadrons behave like strings, and they are bound states of quarks and gluons, which can't be confined in D>4, indicates there are D=4 string theories we're missing. Such strings would not contain gravity, since hadrons have no corresponding (massless) "strong graviton". They would be based on the particle theory of quarks and gluons. Perhaps some generalization would include both hadrons and gravitons.

Possible solution:

A composite graviton might be necessary to solve the gravity problem in particle theory. A string that is a composite of particles (as for hadrons) might be necessary to solve the D=4 problem, which may be the root of all string theory's problems. Thus particle theory and string theory would be unified, and this unification would be a requirement to solve the problems of both theories. In fact, at least one of the known strings can be expressed as a composite of particles, but this particle theory has serious problems, probably related to those of the string theory.

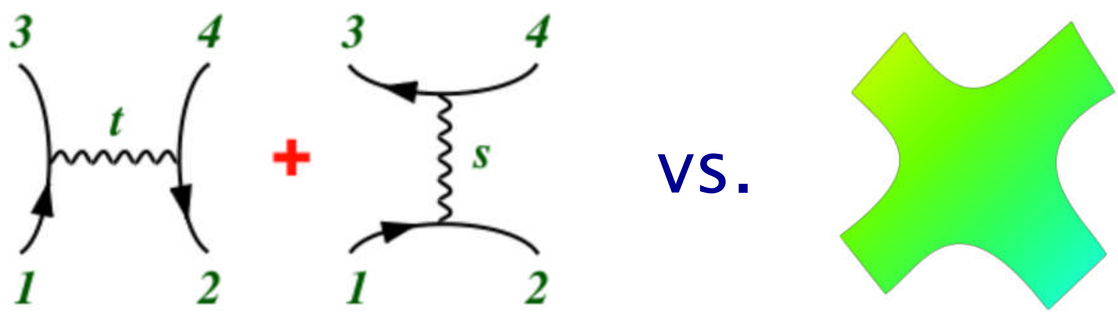
Is string theory a waste of time?

Considering that string theory has close to a monopoly on high energy theoretical physics nowadays, yet in over 40 years has failed to reach its promised goal, panic can easily set in about the future of this area of research. In response to the above question, I can think of at least 4 answers:

1. **Don't blame the product for the advertisement.** String theory has been grossly over-sold. It isn't even a "theory" yet, just a "model". It hasn't solved anything, much less everything. But just because it isn't everything doesn't mean it isn't anything. It has many interesting features, some of which have been reproduced in particle theory and proven useful, some of which haven't but would be desirable in a more realistic theory.
2. **That's what they told Columbus.** (Besides "Stop killing Indians!") Similar arguments have been leveled against the space program, but exploration often has many rewards, such as serendipity. (And theoretical research is cheaper than spacecraft.)
3. **What's "string theory"?** "String theory" is a very ambiguous term, just as "QCD" was in the 70's. Almost all of high-energy theory today is string theory, by definition. "String theory" can mean "supersymmetry", "general relativity", "differential geometry", "extra dimensions", "conformal field theory" (in either 2 or 4 dimensions), and a number of other things. Many papers on "string theory" make no use of string theory, but just use the words because their topic is related and they want to attract attention (good or bad). Many results used in papers, claimed to be features of only string theory, are in fact much more general.
4. **Compared to what?** At this point in time, there are no more-promising solutions to many of the problems of high-energy physics. Of course, alternatives exist, and you are welcome to try some (I do), but most of the complaints leveled against string theory can be applied to them even more strongly. (In particular, watch out for theories that claim to solve some problem simply because it is too difficult to even see if they have that problem.)

It is often claimed that string theory makes no testable predictions. While it is true that string theory has made no precise numerical predictions, it has made several qualitative predictions, which we mentioned above but bear repeating in more detail, that are not proven in any particle theory, but have been experimentally verified. (In fact, they were the basis of the birth of string theory, so you might complain that they were "postdictions".) These all have to do with strongly interacting particles, because the mass scale of strong interactions is smaller than those of the others (1 GeV for strong vs. 1 TeV for electroweak vs. the Planck energy for gravity), & so are accessible to present experiments:

1. The masses of the observed strongly interacting particles (hadrons) with the same properties except for mass & spin, when plotted on a graph of spin vs. mass^2, lie on parallel straight lines ("Regge trajectories").
2. These same lines, when continued to negative mass^2, describe high-energy scattering of hadrons @ small angles. Strictly speaking, this is already a property of Regge theory more generally. But string theories are the special case of Regge theories where this behavior can be described by a perturbation expansion, whose not-too-strong coupling implies the linearity of the Regge trajectories as well as the distinctively string property:
3. At lowest order in perturbation (coupling constant), the scattering amplitude can be found by summing either the contributions where particles annihilate into a single particle which then splits back into 2, or the contributions where the 2 scattering particles exchange a single particle. Either sum gives the same, total result; summing over both would be double counting. This "duality" can be pictured by viewing the scattering as the merging of particles into the "worldsheet".



Loop quantum gravity

As an example of the "Compared to what?" point, consider one alternative often mentioned, "loop quantum gravity". One way to describe this theory is as a lattice approach to gravity, replacing the spacetime continuum with a discrete set of points. But we already know a lot from lattice approaches to nonperturbative field theory, e.g., lattice quantum chromodynamics:

1. **Problems with perturbation theory are not solved by nonperturbative approaches.** The problems of "renormalizability" that appear in perturbation theory (especially for quantum gravity) return with a vengeance in nonperturbative approaches. (This has also been seen in more rigorous nonperturbative approaches to field theory, such as "constructive quantum field theory".) The lattice itself acts as a "regularization" of infinities, but the true problem of infinities is not eliminating them, but the ambiguities in eliminating them, which result in a loss of predictability. In lattice approaches, "non-universality" appears as ambiguities in the lattice description of the theory that do not disappear as one takes the limit of distances large with respect to the lattice spacing.
2. **Lattice calculations are prohibitively difficult.** So difficult that even with modern day computer power it is all one can do to calculate with a lattice that is 32 units long on a side. Thus one cannot directly even address questions such as long-distance limits. (So far, lattice approaches have been used only to calculate constants, such as masses and couplings.)
3. **Fermions are difficult to describe.** There are difficulties describing fermions, the basic constituents of matter, on lattices, already at the classical level. At the quantum level, there are further difficulties that make computations impractical. In particular, there is no known way on a lattice to describe "supersymmetry", a feature needed to solve renormalizability problems.

EXIT

Is String Theory Even Wrong?

Peter Woit

For nearly 18 years now, most advanced mathematical work in theoretical particle physics has centered on something known as string theory. This theory is built on the idea that elementary particles are not point-like objects but are the vibration modes of one-dimensional "string-like" entities. This formulation hopes to do away with certain lingering problems in fundamental particle physics and to offer the possibility of soon explaining *all* physical phenomena everything from neutrinos to black holes with a single theory. Fifteen years ago Edward Witten of the Institute for Advanced Study made the widely quoted claim that "string theory is a part of 21st-century physics that fell by chance into the 20th century," so perhaps it is now time to begin judging the success or failure of this new way of thinking about particle physics.

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The strongest scientific argument in favor of string theory is that it appears to contain a theory of gravity embedded within it and thus may provide a solution to the thorny problem of reconciling Einstein's general relativity with quantum mechanics and the rest of particle physics. There are, however, two fundamental problems, which are hard to get around.

First, string theory predicts that the world has 10 space-time dimensions, in serious disagreement with all the evidence of one's senses. Matching string theory with reality requires that one postulate six unobserved spatial dimensions of very small size wrapped up in one way or another. All the predictions of the theory depend on how you do this, but there are an infinite number of possible choices, and no one has any idea how to determine which is correct.

The second concern is that even the part of string theory that is understood is internally inconsistent. This aspect of the theory relies on a series expansion, an infinite number of terms that one is supposed to sum together to get a result. Whereas each of the terms in the series is probably finite, their sum is almost certainly infinite. String theorists actually consider this inconsistency to be a virtue, because otherwise they would have an infinite number of consistent theories of gravity on their hands (one for each way of wrapping up six dimensions), with no principle for choosing among them.

The "M" Word

These two problems have been around since the earliest work on string theory along with the hope that they would somehow cancel each other out. Perhaps some larger theory exists to which string theory is just an approximate solution obtained by series expansion, and this larger theory will explain what's going on with the six dimensions we can't see. The latest version of this vision goes under the name of "M-theory," where the "M" is said variously to stand for "Membrane," "Matrix," "Mother," "Meta," "Magic" or "Mystery" although "Mythical" may be more appropriate, given that nearly eight years of work on this idea have yet to lead to even a good conjecture about what M-theory might be.

The reigning Standard Model of particle physics, which string theory attempts to encompass, involves at its core certain geometrical concepts, namely the Dirac operator and gauge fields, which are among the deepest and most powerful ideas in modern mathematics. In string theory, the Dirac operator and gauge fields are not fundamental: They are artifacts of taking a low-energy limit. String theorists ask mathematicians to believe in the existence of some wonderful new sort of geometry that will eventually provide an explanation for M-theory. But without a serious proposal for the underlying new geometry, this argument is unconvincing.

The experimental situation is similarly bleak. It is best described by Wolfgang Pauli's famous phrase, "It's not even wrong." String theory not only makes no predictions about physical phenomena at experimentally accessible energies, it makes no precise predictions whatsoever. Even if someone were to figure out tomorrow how to build an accelerator capable of reaching the astronomically high energies at which particles are no longer supposed to appear as points, string theorists would be able to do no better than give qualitative guesses about what such a machine might show. At the moment string theory cannot be falsified by any conceivable experimental result.

There is, however, one physical prediction that string theory does make: the value of a quantity called the cosmological constant (a measure of the energy of the vacuum). Recent observations of distant supernovae indicate that this quantity is very small but not zero. A simple argument in string theory indicates that the cosmological constant should be at least around 55 orders of magnitude larger than the observed value. This is perhaps the most incorrect experimental prediction ever made by any physical theory that anyone has taken seriously.

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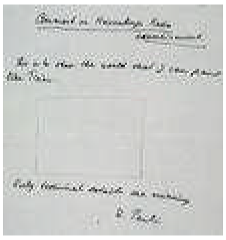


With such a dramatic lack of experimental support, string theorists often attempt to make an aesthetic argument, professing that the theory is strikingly "elegant" or "beautiful." Because there is no well-defined theory to judge, it's hard to know what to make of these assertions, and one is reminded of another quotation from Pauli. Annoyed by Werner Heisenberg's claims that, though lacking in some specifics, he had a wonderful unified theory (he didn't), Pauli sent letters to some of his physicist friends each containing a blank rectangle and the text, "This is to show the world that I can paint like Titian. Only technical details are missing." Because no one knows what "M-theory" is, its beauty is that of Pauli's painting. Even if a consistent M-theory can be found, it may very well turn out to be something of great complexity and ugliness.

What exactly *can* be said for string theory? In recent years, something called the Maldacena conjecture has led to some success in using string theory as a tool in understanding certain quantum field theories that don't include gravity. Mathematically, string theory has covered a lot of ground over the past 18 years and has led to many impressive new results. The concept of "mirror symmetry" has been very fruitful in algebraic geometry, and conformal field theory has opened up a new, fascinating and very deep area of mathematics. Unfortunately for physics, these mathematically interesting parts of string theory do little to connect it with the real world.

String theory has, however, been spectacularly successful on one front public relations. For example, it's been the subject of the best-selling popular science book of the past couple years: *The Elegant Universe* by Brian Greene, one of my colleagues at Columbia. The National Science Foundation is funding a series of *NOVA* programs based on his accessible and inspiring book. What is more, the Institute for Theoretical Physics at the University of California, Santa Barbara, organized last spring a conference to train high school teachers in string theory so that they can teach it to their students. And *The New York Times* and other popular publications regularly run articles on the latest developments in string theory.

It's easy enough to see why the general public is taken with string theory, but one wonders why so many particle theorists are committed to working on it. Sheldon Glashow, a string-theory skeptic and Nobel-laureate physicist at Harvard, describes string theory as "the only game in town." Why this is so perhaps has something to do with the sociology of physics.

During much of the 20th century there were times when theoretical particle physics was conducted quite successfully in a somewhat faddish manner. That is, there was often only one game in town. Experimentalists regularly discovered new and unexpected phenomena, each time leading to a flurry of theoretical activity (and sometimes to Nobel prizes). This pattern ended in the mid-'70s with the overwhelming experimental confirmation and widespread acceptance of the Standard Model of particle physics. Since then, particle physics has been a victim of its own success, with theoreticians looking for the next fad to pursue and finding it in string theory.

One reason that only one new theory has blossomed is that graduate students, post-docs and untenured junior faculty interested in speculative areas of mathematical physics beyond the Standard Model are under tremendous pressures. For them, the idea of starting to work on an untested new idea that may very well fail looks a lot like a quick route to professional suicide. So some people who do not believe in string theory work on it anyway. They may be intimidated by the fact that certain leading string theorists are undeniably geniuses. Another motivation is the natural desire to maintain a job, get grants, go to conferences and generally have an intellectual community in which to participate. Hence, few stray very far from the main line of inquiry.

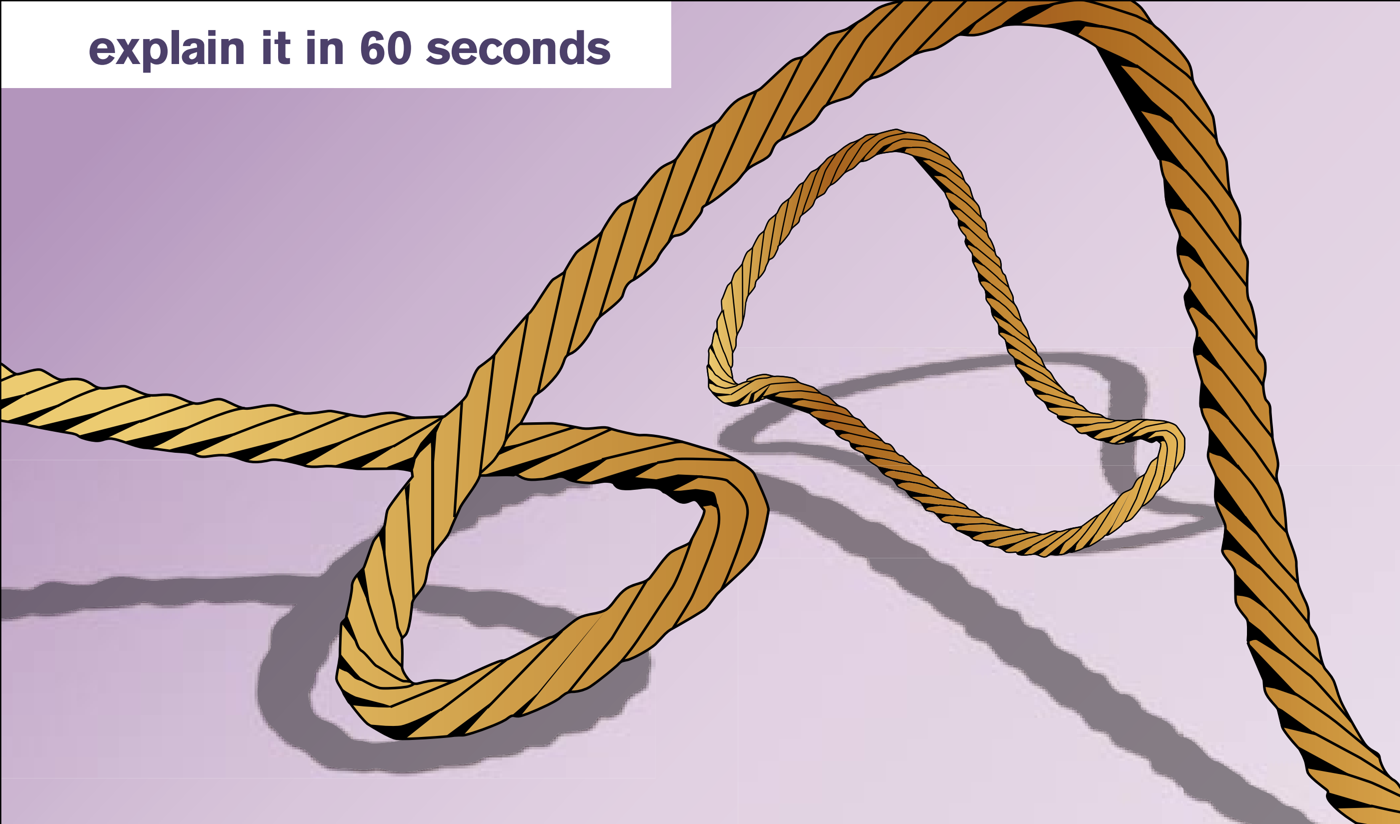
Affirmative Actions

What can be done to inject more diversity of thought into this great quest of theoretical physics? Even granting that string theory is an idea that deserves to be developed, how can people be encouraged to come up with promising alternatives? I would argue that a good first step would be for string theorists to acknowledge publicly the problems and cease their tireless efforts to sell this questionable theory to secondary school teachers, science reporters and program officers.

The development of competing approaches will require senior string theorists to consider working on less popular ideas and begin encouraging their graduate students and post-docs to do the same. Instead of trying to hire people working on the latest string-theory fad, theory groups and funding agencies could try to identify young mathematical physicists who are exploring completely different avenues. (Pushing 45, I no longer qualify.) Finding ways to support such people over the long term would give them a much-needed chance to make progress.

Although I am skeptical of science writer John Horgan's pessimistic notion that physics is reaching an end, the past 15 years of research in particle theory make depressingly clear one form such an end could take: a perpetual, well-promoted but never-successful investigation of a theory that has no connection with the physical world. If only physicists have the will to abandon a failed project and start looking for some new ideas, this sad fate can be avoided.

explain it in 60 seconds



String theory proposes that the fundamental constituents of the universe are one-dimensional "strings" rather than point-like particles. What we perceive as particles are actually vibrations in loops of string, each with its own characteristic frequency.

String theory originated as an attempt to describe the interactions of particles such as protons. It has since developed into something much more ambitious: an approach to the construction of a complete unified theory of all fundamental particles and forces.

Previous attempts to unify physics have had trouble incorporating gravity with the other forces. String theory not only embraces gravity but requires it. String theory also requires six or seven extra dimensions of space, and it contains ways of relating large extra dimensions to small ones. The study of string theory has also led to the concept of supersymmetry, which would double the number of elementary particles.

Practitioners are optimistic that string theory will eventually make predictions that can be experimentally tested. String theory has already had a big impact on pure mathematics, cosmology (the study of the universe), and the way particle physicists interpret experiments, by suggesting new approaches and possibilities to explore.

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String theory in a nutshell

Roughly one hundred years ago, at the turn of the last century, the newtonian paradigm started to collapse. Scientists who only years before had declaimed the imminent end of Physics, were now faced with empirical data for which there was no adequate theoretical explanation.

Out of this conflict emerged two scientific revolutions: Einstein's general theory of relativity, to account for the discrepancies in planetary motion; and quantum mechanics, and later quantum field theory, to explain atomic and subatomic phenomena. It took physicists the first three quarters of the twentieth century to develop these theories to the point that they can account, in principle, for most if not all of observed phenomena. Why then the need for something else?

Part of the appeal of the newtonian paradigm was its universality. Newtonian physics seemed to account for a vast range of phenomena, from the very small to the very large. As the empirical horizons widened, it became necessary to replace newtonian physics by *not* one but *two* new theories. Furthermore, these two theories happen to be incompatible. In other words, either theory loses its predictive power whenever it becomes impossible to ignore the other. Therefore besides the purely aesthetic need to have a single fundamental physical theory, there is a very real need for a theory which explains what happens at those tiny length scales at which neither quantum mechanics nor gravity can be ignored. String theory emerged in the mid-eighties as a likely candidate for such a theory.

The fundamental premise of string theory is that the basic objects in nature are not point-like, but rather string-like. Remarkably, out of this deceptively simple generalisation, one obtains a theory which does not just incorporate gauge theory, supersymmetry and gravitation in a natural and elegant way, but actually needs all three of them for its very consistency. It is precisely this fact which makes string theory such a compelling candidate

There are many links on string theory. I have tried to collect some of them here in no particular order.

The official string theory website

The elegant universe

Superstrings!

Robbert Dijkgraaf's string theory page

The second superstring revolution

Beyond string theory

What is string theory?

The symphony of everything

Warren Siegel

String theory: an evaluation

sci.physics.strings

String Theory for Undergraduates

Clifford Johnson's D-branes website

Michio Kaku's website

for a unified theory.

Two 'revolutions' punctuate the history of string theory: the first happened in 1984 as a result of the work of Green and Schwarz on anomaly cancellation, the second was sparked in 1994 by the work of Seiberg and Witten on supersymmetric gauge theories and that of Hull and Townsend on string dualities.
(The third revolution is due any day now!)

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String Theory, the ultimate theory?

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The Standard Model

In the standard model of particle physics, particles are considered to be points moving through space, tracing out a line called the 'world line'. To take into account the different interactions observed in nature, one has to provide particles with more degrees of freedom than only their position and velocity, such as mass, electric charge, colour (which is the "charge" associated with the strong interaction) or spin.

The standard model was designed within a framework known as Quantum Field Theory (QFT), which gives us the tools to build theories consistent both with quantum mechanics and the special theory of relativity. With these tools, theories were built which describe with great success three of the four known interactions in nature: Electromagnetism, and the Strong and Weak nuclear forces.

Furthermore, a very successful unification between Electromagnetism and the Weak force was achieved (Electroweak Theory) and promising ideas put forward to try to include the Strong force. But unfortunately the fourth interaction, gravity, as described by Einstein's General Relativity (GR), does not seem to fit into this scheme. Whenever one tries to apply the rules of QFT to GR, one gets results that make no sense.

The usual domains of general relativity and quantum mechanics are quite different. General relativity describes the force of gravity and hence is usually applied to the largest and most massive structures, including stars, galaxies, black holes and even, in cosmology, the universe itself. Quantum mechanics is most relevant in describing the smallest structures in the universe such as electrons and quarks.

In most ordinary physical situations, therefore, either general relativity or quantum mechanics is required for a theoretical understanding, but not both. There are, however, extreme physical circumstances that require both of these fundamental theories for a proper theoretical treatment.

Prime examples of such situations are space-time singularities such as the central point of a black hole or the state of the universe just before the big bang. These exotic physical structures involve enormous mass scales (thus requiring general relativity) and extremely small distance scales (thus requiring quantum mechanics).

Unfortunately, general relativity and quantum mechanics are mutually incompatible. Any calculation that simultaneously uses both of these tools yields nonsensical answers. The origin of this problem can be traced to equations that become badly behaved when particles interact with each other across minute distance scales on the order of 10^{-33}cm - the Planck length.

Another problem with this model is that one has to assume the existence of distinct forces and their carriers. Einstein hoped that there would be a 'unified' theory in which all known forces would emerge out of a single one in some way. Electricity and magnetism used to be thought of as two forces, but now we know they are different aspects of the same (electro-magnetic) force. Could the same type of unification hold for the four forces that are today viewed as distinct?

String theory is currently the most promising example of a candidate unified theory. We do not yet know whether it correctly describes nature, but it seems to be a theory that broadly describes a world similar to ours and is endowed with beauty and consistency to an astonishing degree.

Strings

The physical idea is utterly simple. Instead of many types of elementary point-like particles, physicists postulate that in nature there is a single variety of string-like object. The string is not 'made up of anything', rather, it is basic and other things are made up of it. As with musical strings, this basic string can vibrate, and each vibrational mode can be viewed as a point-like elementary particle, just as the modes of a musical string are perceived as distinct notes!

String theory solves the deep problem of the incompatibility of the two fundamental theories (GR and QFT) by modifying the properties of general relativity when it is applied to scales on the order of the Planck length. Modern accelerators can only probe down to distance scales around 10^{-16}cm and hence these loops of string appear to be point objects.

However, the string theoretic hypothesis that they are actually tiny loops changes drastically the way in which these objects interact on the shortest of distance scales. This modification is what allows gravity and quantum mechanics to form a harmonious union.

There is a price to be paid for this solution, however. It turns out that the equations of string theory are self-consistent only if the universe contains, in addition to time, nine spatial dimensions. As this is in gross conflict with the perception of three spatial dimensions, it might seem that string theory must be discarded. This is, however, not true.

Multiple String Theories

There is, however, more than one string theory. These theories are classified according to whether or not the strings are required to be closed loops and whether or not the particle spectrum includes fermions (particles that makes up matter). In order to include fermions in string theory, there must be a special kind of symmetry called supersymmetry, which means for every boson (particle that transmits a force) there is a corresponding fermion. So supersymmetry relates the particles that transmit forces to the particles that make up matter.

String theories that incorporate bosons only are no longer popular as they require 26 space-time dimensions and a particle with imaginary mass known as the tachyon. There are quite a few superstring theories that make sense mathematically that only require ten dimensions. A few of the differences between them include theories with closed loops only and others with closed loops that can break into open strings.

Theories with massless fermions only spinning one way (chiral) and string theories, which are heterotic, meaning right moving and left moving strings, differ. Different combinations of the above properties leave us with 5 (mathematically) plausible theories.

M-Theory

There was a difficulty in studying these theories: physicists and mathematicians did not have tools to explore the theories over all possible values of the parameters in the theories. Each theory was like a large planet of which we only knew a small island somewhere on the planet. But over the last four years, techniques were developed to explore the theories more thoroughly, in other words, to travel around the seas in each of those planets and find new islands. And only then it was realised that those five string theories are actually islands on the same planet, not different ones! Thus there is an underlying theory of which all string theories are only different aspects. This was called M-theory.

One of the islands that was found on the M-theory planet corresponds to a theory that lives not in 10 but in 11 dimensions. This seems to be telling us that M-theory should be viewed as an 11 dimensional theory that looks 10 dimensional at some points in its space of parameters. Such a theory could have as a fundamental object a membrane, as opposed to a string. Like a drinking straw seen at a distance, the membranes would look like strings when we curl the 11th dimension into a small circle.

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String-theory calculations describe 'birth of the universe'

Dec 6, 2011 31 comments

Do new calculations describe the "birth of the universe"?

Researchers in Japan have developed what may be the first string-theory model with a natural mechanism for explaining why our universe would seem to exist in three spatial dimensions if it actually has six more. According to their model, only three of the nine dimensions started to grow at the beginning of the universe, accounting both for the universe's continuing expansion and for its apparently three-dimensional nature.

String theory is a potential "theory of everything", uniting all matter and forces in a single theoretical framework, which describes the fundamental level of the universe in terms of vibrating strings rather than particles. Although the framework can naturally incorporate gravity even on the subatomic level, it implies that the universe has some strange properties, such as nine or ten spatial dimensions. String theorists have approached this problem by finding ways to "compactify" six or seven of these dimensions, or shrink them down so that we wouldn't notice them. Unfortunately, Jun Nishimura of the High Energy Accelerator Research Organization (KEK) in Tsukuba says "There are many ways to get four-dimensional space–time, and the different ways lead to different physics." The solution is not unique enough to produce useful predictions.

These compactification schemes are studied through perturbation theory, in which all the possible ways that strings could interact are added up to describe the interaction. However, this only works if the interaction is relatively weak, with a distinct hierarchy in the likelihood of each possible interaction. If the interactions between the strings are stronger, with multiple outcomes equally likely, perturbation theory no longer works.

Matrix allows stronger interactions

Weakly interacting strings cannot describe the early universe with its high energies, densities and temperatures, so researchers have sought a way to study strings that strongly affect one another. To this end, some string theorists have tried to reformulate the theory using matrices. "The string picture emerges from matrices in the limit of infinite matrix size," says Nishimura. Five forms of string theory can be described with perturbation theory, but only one has a complete matrix form – Type IIB. Some even speculate that the matrix Type IIB actually describes M-theory, thought to be the fundamental version of string theory that unites all five known types.

The model developed by Sang-Woo Kim of Osaka University, Nishimura, and Asato Tsuchiya of Shizuoka University describes the behaviour of strongly interacting strings in nine spatial dimensions plus time, or 10 dimensions. Unlike perturbation theory, matrix models can be numerically simulated on computers, getting around some of the notorious difficulty of string-theory calculations. Although the matrices would have to be infinitely large for a perfect model, they were restricted to sizes from 8×8 to 32×32 in the simulation. The calculations using the largest matrices took more than two months on a supercomputer, says Kim.

Physical properties of the universe appear in averages taken over hundreds or thousands of matrices. The trends that emerged from increasing the matrix size allowed the team to extrapolate how the model universe would behave if the matrices were infinite. "In our work, we focus on the size of the space as a function of time," says Nishimura.

'Birth of the universe'

The limited sizes of the matrices mean that the team cannot see much beyond the beginning of the universe in their model. From what they can tell, it starts out as a symmetric, nine-dimensional space, with each dimension measuring about 10^{-33} cm. This is a fundamental unit of length known as the Planck length. After some passage of time, the string interactions cause the symmetry of the universe to spontaneously break, causing three of the nine dimensions to expand. The other six are left stunted at the Planck length. "The time when the symmetry is broken is the birth of the universe," says Nishimura.

"The paper is remarkable because it suggests that there really is a mechanism for dynamically obtaining four dimensions out of a 10-dimensional matrix model," says Harold Steinacker of the University of Vienna in Austria.

Hikaru Kawai of Kyoto University, Japan, who worked with Tsuchiya and others to propose the IIB matrix model in 1997, is also very interested in the "clear signal of four dimensional space–time". "It would be a big step towards understanding the origin of our universe," he says. Although he finds that the evolution of the model universe in time is too simple and different from the general theory of relativity, he says the new direction opened by the work is "worth investigating intensively".

Will the Standard Model emerge?

The team has yet to prove that the Standard Model of particle physics will show up in its model, at much lower energies than this initial study of the very early universe. If it leaps that hurdle, the team can use it to explore cosmology. Compared with perturbative models, Steinacker says, "this model should be much more predictive".

Nishimura hopes that by improving both the model and the simulation software, the team may soon be able to investigate the inflation of the early universe or the density distribution of matter, results which could be evaluated against the density distribution of the real universe.

The research will be described in an upcoming paper in *Physical Review Letters* and a preprint is available at arXiv:1108.1540.

About the author

Kate McAlpine is a science writer based in the UK

31 comments

Comments on this article are now closed.

1 **Cabbynum**
Dec 6, 2011 2:48 PM
I find the way that the matrix works to be very intriuging in the subject itself.

2 **andwor**
Dec 7, 2011 9:50 AM

Harmonic quintessence

Quote:
> *Originally posted by* ***Cabbynum***
> I find the way that the matrix works to be very intriuging in the subject itself.

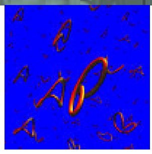
The nine dimensional component of space is elegant, but can be far more easily modelled using "harmonic quintessence". In this model there are three real dimensions and 6 vibrational dimensions at the Planck length.

It has all the unifying chracteristics of string theory but also can predict the constants of Nature.

3 **rloldershaw**
Dec 7, 2011 3:20 PM

Still No Definitive Predictions

For 44 years string/brane theory has been promising a "theory of everything", but has not come up with even a



String theory: From Newton to Einstein and beyond

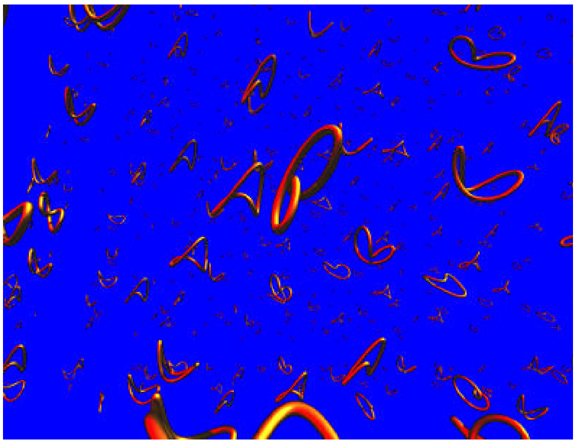
by David Berman (/content/list-by-author/David Berman)

Submitted by plusadmin on December 1, 2007

This article is part of the Researching the unknown project (http://plus.maths.org /content/researching-unknown) , a collaboration with researchers from Queen Mary, University of London (http://ph.qmul.ac.uk/) , bringing you the latest research on the forefront of physics. Click here (http://plus.maths.org/content/researching-unknown) to read more articles from the project.

Queen Mary University of London

Unifying forces



A string universe. Image © R. Dijkgraaf.

To understand the ideas and aims of string theory, it's useful to look back and see how physics has developed from Newton's (http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Newton.html) time to the present day. One crucial idea that has driven physics since Newton's time is that of *unification*: the attempt to explain seemingly different phenomena by a single overarching concept. Perhaps the first example of this came from Newton himself, who in his 1687 work *Principia Mathematicae* explained that the motion of the planets in the solar system, the motion of the Moon around the Earth, and the force that holds us to the Earth are all part of the same thing: the force of gravity. We take this for granted today, but pre-Newton the connection between a falling apple and the orbit of the Moon would have been far from obvious and quite amazing.

The next key unifying discovery was made around 180 years after Newton by the Scottish mathematician James Clerk Maxwell (http://www-groups.dcs.st-and.ac.uk/~history/Biographies /Maxwell.html) . Maxwell showed that electrostatics and magnetism, by no means similar phenomena at first sight, are just different aspects of a single thing called electromagnetism. In the process Maxwell discovered electromagnetic waves, which are in fact light — Maxwell had inadvertently explained a further seemingly different aspect of nature.

Another two hundred years on, in 1984, the Pakistani Abdus Salam (http://scienceworld.wolfram.com/biography/Salam.html) and the American Steven Weinberg (http://scienceworld.wolfram.com/biography/Weinberg.html) showed that the electromagnetic force and the weak nuclear force, which causes radioactive decay, are both just different aspects of a single force called the electroweak force.

This leaves us with three fundamental forces of nature: gravity, the electroweak force and the strong nuclear force which holds protons together.

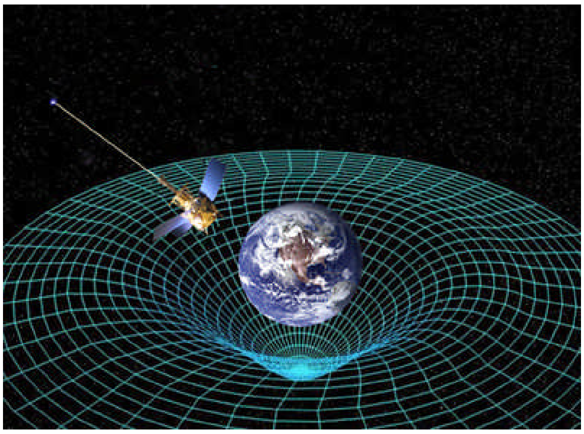
Unifying matter

That deals with the forces, but what about matter? Many ancient belief systems have postulated that matter — and reality itself — is made from a finite number of elements. Modern physics confirms this idea. Experiments performed with the particle accelerator at CERN (http://public.web.cern.ch/Public/Welcome.html) in Geneva have shown that there are just twelve basic building blocks of matter. These are known as the *elementary particles*. Everything we've ever seen in any experiment, here or in distant stars, is made of just these twelve elementary particles. (See *Plus* article The physics of elementary particles (/issue29/features/kalmus/) to find our more.)

All this is truly impressive: the entire Universe, its matter and dynamics explained by just three forces and twelve elementary objects. It's good, but we'd like to do better, and this is where string theory first enters: it is an attempt to unify further. To understand this, we have to tell another story.

Quantum gravity

There have been two great breakthroughs in the 20th century physics. Perhaps the most famous is Einstein's theory of general relativity. The other equally impressive theory is quantum mechanics.


Massive bodies warp spacetime. Image coutesy NASA (http://www.nasa.gov) .

General relativity is itself a unification. Einstein realised that space and time are just different aspects of a single object he called *spacetime*. Massive bodies like planets can warp and distort spacetime, and gravity, which we experience as an attractive force, is in fact a consequence of this warping. Just as a pool ball placed on a trampoline will create a dip that a nearby marble will roll into, so does a massive body like a planet distort space, causing nearby objects to be attracted to it.

The predictions made by general relativity are remarkably accurate. In fact, most of us will have inadvertently taken part in an experiment that tests general relativity: if it were false, then global positioning systems would be wrong by about 50 metres per day. The fact that GPSs work to within five metres in ten years shows just how accurate general relativity is.

The other great breakthrough of the 20th century was quantum mechanics. One of the key ideas here is that the smaller the scale at which you look at the world, the more random things become. *Heisenberg's uncertainty principle* is perhaps the most famous example of this. The principle states that when you consider a moving particle, for example an electron orbiting the nucleus of an atom, you can never ever measure both its position and its momentum as accurately as you like. Looking at space at a minuscule scale may allow you to measure position with a lot of accuracy, but there won't be much you can say about momentum. This isn't because your measuring instruments are imprecise. There simply isn't a "true" value of momentum, but a whole range of values that the momentum can take, each with a certain probability. In short, there is randomness. This randomness appears when we look at particles at a small enough scale. The smaller one looks, the more random things become!

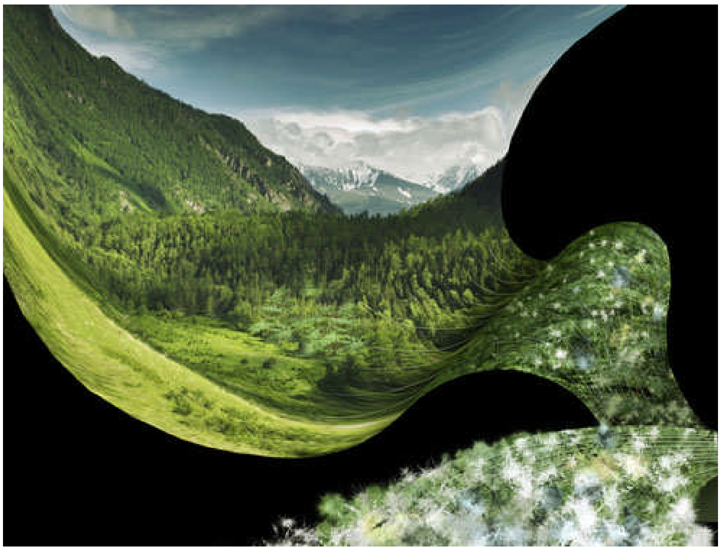
The idea that randomness is part of the very fabric of nature was revolutionary: it had previously been taken for granted that the laws of physics didn't depend on the size of things. But in quantum mechanics they do. The scale of things does matter, and the smaller the scale at which you look at nature, the more different from our everyday view of the world it becomes: randomness dominates the small scale world.

Again, this theory has performed very well in experiments. Technological gadgets that have emerged from quantum theory include the laser and the microchip that populate every computer, mobile phone and MP3 player.

But what happens if we combine quantum mechanics and relativity? According to relativity, spacetime is something that can stretch and bend. Quantum mechanics says that on small scales things get random. Putting these two ideas together implies that on very small scales spacetime itself becomes random, pulling and stretching, until it eventually pulls itself apart.

Evidently, since spacetime is here and this hasn't happened, there must be something wrong with combining relativity and quantum mechanics. But what? Both these theories are well-tested and believed to be true.

Perhaps we have made a hidden assumption?


What happens to spacetime at small scales?

It turns out that indeed we have. The assumption is that it's possible to consider smaller and smaller distances and get to the point where spacetime pulls itself apart. What has rested in the back of our minds is that the basic indivisible building blocks of nature are point-like — but this may not necessarily be true.

Strings to the rescue

This is where string theory comes to the rescue. It suggests that there is a smallest scale at which we can look at the world: we can go that small but no smaller. String theory asserts that the fundamental building blocks of nature are not like points, but like strings: they have extension, in other words they have length. And that length dictates the smallest scale at which we can see the world.

What possible advantage could this have? The answer is that strings can vibrate. In fact they can vibrate in an infinite number of different ways. This is a natural idea in music. We don't think that every single sound in a piece of music is produced by a different instrument; we know that a rich and varied set of sounds can be produced by even just a single violin. String theory is based on the same idea. The different particles and forces are just the fundamental strings vibrating in a multitude of different ways.

The mathematics behind string theory is long and complicated, but it has been worked out in detail. But has anyone ever seen such strings? The honest answer is "no". The current estimate of the size of these strings is about 10^{-34}m, far smaller than we can see today, even at CERN. Still, string theory is so far the only known way to combine gravity and quantum mechanics, and its mathematical elegance is for many scientists sufficient reason to keep pursuing it.

The theory's predictions

If string theory is indeed an accurate model of spacetime, then what else does it tell us about the world?

One of its more startling and most significant predictions is that spacetime is not four, but ten-dimensional. It is only in ten dimensions of spacetime that string theory works. So where are those six extra dimensions? The idea of hidden dimensions was in fact put forward many years before the advent of string theory by the German Theodor Kaluza (http://www-history.mcs.st-and.ac.uk/Biographies/Kaluza.html) and the Swede Oskar Klein (http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Klein_Oskar.html).

Aerial view of the CERN site just outside Geneva. The underground particle accelerators (with circumferences of 27 km and 7 km) allow scientists to look at tiny scales. Image © CERN (http://public.web.cern.ch/Public/Welcome.html).

Shortly after Einstein described the bending of space in general relativity, Kaluza and Klein considered what would happen if a spatial dimension would bend round and rejoin itself to form a circle. The size of that circle could be very small, perhaps so small that it couldn't be seen. Those dimensions could then be hidden from view. Kaluza and Klein did show that in spite of this, these dimensions could still have an effect on the world we perceive. Electromagnetism becomes a consequence of the hidden circle with motion in the hidden dimension being electric charge. Hidden dimensions are possible and they in fact can give rise to forces in the dimensions that we can see.

String theory has embraced the Kaluza-Klein idea and currently various experiments are being devised to try and observe the hidden dimensions. One hope is that the extra dimensions may have left an imprint on the *cosmic microwave background*, the left-over radiation from the Big Bang, and that a detailed study of this radiation may reveal them. Other experiments are more direct. The force of gravity depends crucially on the number of dimensions, so by studying gravitational forces at short distances one can hope to detect deviations from Newton's law and again see the presence of extra dimensions.

Mathematics and physics have always influenced each other, with new mathematics being invented to describe nature, and old mathematics turning out to lend perfect descriptions for newly-discovered physical phenomena. String theory is no different and many mathematicians work on ideas inspired by it. These include the possible geometries of the hidden dimensions, the basic ideas of geometry when there is a minimum distance, the ways in which strings can split and come together, and the question of how we can relate strings to the particles in the world that we see.

String theory gives us an exciting vision of nature as miniscule bits of vibrating string in a space with hidden curled-up dimensions. All the implications of these ideas are yet to be understood. String theory is an active area of research with hundreds of people working to see how the theory fits together and produces the world we see around us.

For a more mathematical treatment of string theory read Plus article Tying it all up (/issue21/features/strings/).

About the author

David Berman (http://www.strings.ph.qmul.ac.uk/~dsb/) is a lecturer in theoretical physics at Queen Mary, University of London. He previously spent time at the universities of Manchester, Brussels, Durham, Utrecht, Groningen, Jerusalem and Cambridge as well as a year at CERN in Geneva.

His interests outside of physics include football, music and theatre and the arts.

Comments

Brilliant article (/content/string-theory-newton-einstein-and-beyond#comment-4312)

Submitted by Anonymous on May 3, 2013.

Love the article.

I have read further that two particles pulled apart a great distance can still impact each other. I think Maxwell suggested this but Einstein disagreed.

WHY CURVATURE? (/content/string-theory-newton-einstein-and-beyond#comment-4193)

Submitted by Anonymous on March 21, 2013.

Massive bodies like planets can warp and distort spacetime, and gravity, which we experience as an attractive force, is in fact a consequence of this warping. Just as a pool ball placed on a trampoline will create a dip that a nearby marble will roll into, so does a massive body like a planet distort space, causing nearby objects to be attracted to it.

BUT THE MARBLE ROLLED ON THE CURVED TRAMPOLINE NOT BECAUSE OF ITS CURVATURE BUT GRAVITY WORKING UNDER IT.

why curvature.. (/content/string-theory-newton-einstein-and-beyond#comment-4224)

Submitted by Anonymous on April 5, 2013.

Your question is a good one and brings out the problem of using metaphors to explain phenomena.

So the bit of the story that is missing is the statement that all particles should travel in "straight lines" unless acted on by a force. Now on a curved surface we need to understand what we mean by a "straight line". Well a good definition is that a straight line is the shortest distance between two points. In flat space this corresponds to our usual idea of what straight is. But on a curved surface the shortest distance between two points is curved in a very particular way. If you want to get idea of how then look at the flight trajectories of aircraft going from point to point around the earth. (Airlines are very keen to make sure they don't fly further than necessary). So the "straight line" motion on a curved spacetime appears curved from the perspective of someone who thinks the space is flat. That trajectory is the motion of particles in a gravitational field. So in general relativity the perceived curved motion of objects due to gravity is just "straight line" motion (in the sense described above). So curvature=gravity...

David Berman

why curvature.. (/content/string-theory-newton-einstein-and-beyond#comment-4413)

Submitted by Anonymous on June 16, 2013.

Hi,

Thank you so much for such a lucid explanation of String Theory.

Re "So curvature=gravity..." its a really elegant and beautiful concept.

I'm no mathematician but have a simple appreciation without the mathematical depths of the concepts you explain.

However, I'm a bit befuzzled by the randomness described by String Theory at the quantum level with the idea of a Big Bang emanating from a single point proposed in GR.

How does String Theory account for the apparent lack of randomness in a Big Bang universe with galaxies travelling apart from one another at a fixed speed apparently from a single point back in time?

colm brazel

String theory: From Newton to Einstein and beyond (/content/string-theory-newton-einstein-and-beyond#comment-3580)

Submitted by Anonymous on September 14, 2012.

I don't belong to the field of science; but I have greatly benefitted from the subject article written by Mr.David Berman; I think he has the natural ability to express complex and complicated things to make them simple; like nature is simple and beautiful which some may describe to be complex though.

STRING THEORY: FROM NEWTON TO EINSTEIN FAR BEYOND (/content/string-theory-newton-einstein-and-beyond#comment-3455)

Submitted by Anonymous on July 4, 2012.

Thank you david for sharing such a complicated topic in an easy way.you have told a story which is really classic and excellent.try to tell us stories like these on the recent developments in quantum mechanics,the failure of classical mechanics and current inventions in the string theory.

THANK YOU.
JANANIKUMAR

Simple yet Amazing (/content/string-theory-newton-einstein-and-beyond#comment-3419)

Submitted by Anonymous on June 21, 2012.

It is so well written that the string theory got into my head at once. Finally after so much searching on this i got a site to help me understand topics like these.
Keep up your great work.

Hello (/content/string-theory-newton-einstein-and-beyond#comment-3405)

Submitted by Anonymous on June 15, 2012.

This was really interesting. Thanks for sharing!

Quantum Gravity (/content/string-theory-newton-

einstein-and-beyond#comment-2870)

Submitted by Anonymous on October 13, 2011.

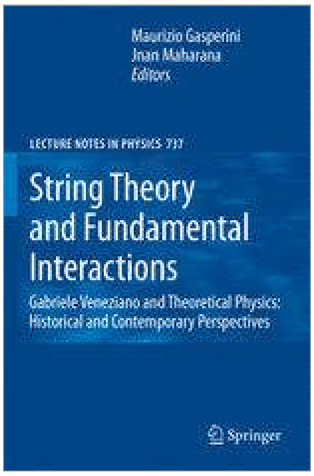
I read the section on quantum gravity and i was just amazed on how it explained everything about string theory and how enstein realised space and time are diffrent aspects

String Theory and Fundamental Interactions
Lecture Notes in Physics Volume 737, 2008, pp 59-118

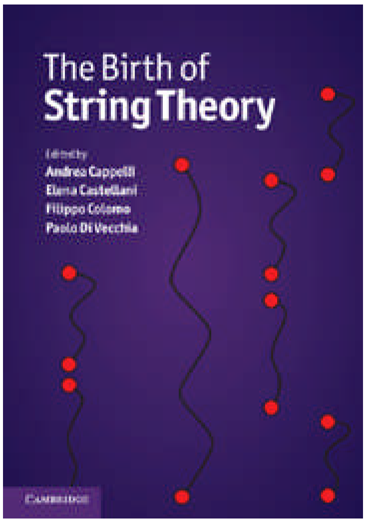
The Birth of String Theory

Abstract

In this contribution we go through the developments that in the years from 1968 to about 1974 led from the Veneziano model to the bosonic string theory. They include the construction of the *N*-point amplitude for scalar particles, its factorization through the introduction of an infinite number of oscillators and the proof that the physical subspace was a positive-definite Hilbert space. We also discuss the zero slope limit and the calculation of loop diagrams. Lastly, we describe how it finally was recognized that a quantum-relativistic string theory was the theory underlying the Veneziano model.



The Birth of String Theory



Edited by Andrea Cappelli
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Book Description | Table of Contents

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The Birth of String Theory

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and Nordita, Stockholm

Contents

Preface

In May 2007 we organized a workshop on the origin and early developments of string theory at the Galileo Galilei Institute for Theoretical Physics in Arcetri (Florence). A fair number of researchers who had contributed to the birth of the theory participated and described, according to their personal recollections, the intriguing way in which the theory developed from hadron phenomenology into an independent field of research. It was the first occasion in which they were all brought together again since the 1975 conference in Durham, which represented the last meeting on string theory as applied to hadronic physics.

The workshop in Arcetri was a success: the atmosphere was enthusiastic and the participants showed a true pleasure in discussing the lines of thought developed during the years from the late Sixties to the beginning of the Eighties, mutually checking their own reminiscences. This encouraged us to go on with the project, we had been thinking of for some time, of providing an historical account of the early stages of string theory by gathering the recollections of its main exponents. We were fortunate enough to have on board practically all the physicists who developed the theory. While some of the contributions to the Volume originated from the talks presented at the meeting, most of them have been written expressly for this book.

In starting this project we were moved by the observation that the history of the beginnings and early phases of string theory is not well accounted for: apart from the original papers, the available literature is rather limited and fragmentary. A book specifically devoted to the historical reconstruction of these developments – the formulation of a consistent and beautiful theory starting from hadron phenomenology, its failure as a theory of strong interactions, and, finally, its renaissance as a unified theory of all fundamental interactions – was not available. This Volume aims at filling the gap, by offering a collection of reminiscences and overviews, each one contributing from the Author's own perspective to the general historical account. The collection is complemented with an extended editorial apparatus (Introductions, Appendices and Editors' Chapters) according to intents and criteria that are explained below.

Beside the historical record, this book could be of interest for several reasons. First, by showing the dynamics of ideas, concepts and methods involved, it offers a precious background information for a better understanding of the present status of string theory, which has recently been at the centre of a widespread debate. Second, it provides an illustration of the fruitfulness of the field, both from a physical and a mathematical perspective: a number of ideas that are central to contemporary theoretical physics of fundamental interactions, such as supersymmetry and extra spacetime dimensions, originated in this context; furthermore, some theoretical methods, as e.g. two-dimensional conformal symmetry, found important physical applications in various directions outside the original domain. Finally, from a philosophical point of view, early string theory represents a particularly interesting case study for reflections on the construction and evaluation of physical theories in modern physics.

In the following, we illustrate the structure of the book and offer some guidelines to the reader. The Volume is organized into seven Parts: the first one provides an overview of the whole book; the others correspond to significant stages in evolution of string theory from 1968 to 1984 and are accompanied by specific introductory Chapters.

In Part I, the Introduction summarizes the main developments and contains a temporal synopsis with a list of key results and publications. The following two Chapters, by Veneziano and by Schwarz, offer a rather broad overview on the early (1968-1973) and later (1974-1984) periods of the string history, respectively. They introduce all the themes of the book that are then addressed in detail in the following Parts. The last Chapter of Part I by Castellani presents some elements for the philosophical discussion on the early evolution of the theory and the scientific methodology employed in it.

The Introductions to the other Parts and the Appendices are meant to fit the needs of undergraduate/early graduate students in theoretical physics, as well as of philosophers, who have a background on quantum mechanics and quantum field theory, but need the specific vocabulary to fully appreciate Authors' contributions. The Introductions and Appendices, taken together with the final Chapter can also be used as an entry-level course in string theory, presenting the main physical ideas with a minimum of technique.

The detailed content of the Editors' Chapters is reported below for better reference.

For a broader audience, we suggest to begin with the first, non-technical paragraph in each Introduction, and then approach the Authors that are less technical and more comprehensive, whose Chapters are located first of every Part. The final Chapter of the book by Cappelli and Colomo provides a non-technical overview of string theory from 1984 till the present times, that complement the historical and scientific perspective. Furthermore, the rich material presented in the Authors' Chapters, together with the original literature, can be the starting point of in-depth historical studies of the many events that took place in the development of string theory.

We hope that the book could be read at different levels, and, as such, be useful for both scientific, historical and philosophical approaches to this fascinating, but complex, subject.

The book has associated the web page:

http:/theory.fi.infn.it/colomo/string-book/

that gives access to the original talks of the 2007 GGI workshop and to additional material already provided by some Authors or to be collected in the future.

We are very grateful to all those who have helped us in preparing this Volume. First and foremost, our thanks go to all the Authors who have accepted to contribute their reminiscences to the book. Many thanks also to all those who gave us precious comments and suggestions during the preparation of the Volume; in particular, Leonardo Castellani, Camillo Imbimbo, Yuri Makeenko, Raffaele Marotta, Igor Pesando, Giulio Peruzzi, Franco Pezzella, Augusto Sagnotti, John H. Schwarz, Domenico Seminara, Gabriele Veneziano, Guillermo R. Zemba and Hans v. Zur-Mühlen. We are indebted to the Galileo Galilei Institute for hosting the 2007 workshop. We also wish to thank the staff of Cambridge University Press for assistance and S. De Sanctis for helping with the bibliography. Finally, we are grateful to our collaborators and to our families for their patience and support.

Contents of Editors' Chapters

1

Introduction and synopsis

String theory describes one-dimensional systems, like thin rubber bands, that move in spacetime in accordance with relativity theory. These objects supersede the point-like particles as the elementary entities supporting the microscopic phenomena and the fundamental forces at high energy.

This simple idea has originated a wealth of other concepts and techniques, concerning symmetries, geometry, spacetimes and matter, that still continue to astonish and puzzle the experts in the field. The question 'What is string theory?' is still open today: indeed, the developments in the last fifteen years have shown that the theory also describes higher-dimensional extended objects like membranes, and, in some limits, it is equivalent to quantum field theory, the theory of point particles.

Another much debated question, also outside the circle of experts, is: 'What is string theory good for?'. In its original formulation, the theory could not completely fit strong nuclear interactions; later, it was reproposed as a unified theory of all fundamental interactions including gravity, but still needs experimental confirmation.

This book will not directly address such kind of question: its aim is to document what the theory *was* in the beginning, about forty years ago, and follow the threads connecting its developments from 1968 to 1984. Over this period of time, the theory grew out of a set of phenomenological rules into a consistent quantum mechanical theory, while the concepts, physical pictures and goals considerably evolved and changed.

The development of the theory is described by the direct narration of thirty-five physicists who worked in the field at the time. From this choral ensemble, an interesting 'scientific saga' emerges, with its ups and downs, successes and frustrations, debates, striking ideas and preconceptions.

String theory started from general properties of scattering amplitudes and some experimental inputs; it then developed as an independent theory, by progressive generalization, and through the exploitation of symmetries and consistency conditions. It required plenty of imagination and hard work in abstract formalisms, and was very appealing to young researchers in the early Seventies. They collectively undertook the enterprise of understanding the Dual Resonance Model, as string theory was originally called, attracted by its novelty, beauty and deep intricacy. They were helped by some mentors, senior theorists who supported them, often against the general opinion. Among them, let us mention: D. Amati (CERN), S. Fubini (MIT and CERN), M. Gell-Mann (Caltech), S. Mandelstam (Berkeley) and Y. Nambu (Chicago).

The evolution of physical ideas in this field is fascinating. Let us just underline that in early string theory we can find the seeds of many new concepts and mathematical methods of contemporary theoretical physics, such as supersymmetry, conformal symmetry and extra spacetime dimensions. The mathematical methods helped to refine the tools and scopes of quantum field theory and were also applied to condensed matter physics and statistical mechanics. The new concepts of supersymmetry and extra dimensions have been introduced in the theories of fundamental interactions beyond the Standard Model, that are awaiting experimental test by the Large Hadron Collider now operating at CERN, Geneva.

A brief overview of early string history and the book

The book is divided into seven Parts that correspond to major steps in the development of the theory, arranged in logical/chronological order. The first Chapter in each Part is an Editors' Introduction to the main topics discussed in there, that helps the reader to understand the Authors' Chapters and follow the line of ideas.

Part I provides an introduction to the whole book: the present Chapter includes a synopsis of early string history and points to the essential references. Chapter 2 and 3, by Veneziano and Schwarz respectively, introduce the first (1968-1973) and second (1974-1984) periods into which the evolution of early string theory can be divided. They are followed by the Chapter by Castellani, devoted to highlight some main aspects of philosophical interest in the developments narrated in the Volume.

Part II, 'The prehistory: the analytic S-matrix', discusses the panorama of theoretical physics in the Sixties from which the Veneziano amplitude, the very beginning of string theory, originated. The first steps of the theory were made in close connection with the phenomenology of strong interactions: experiments showed a wealth of particles, the hadrons, that could not be all considered elementary and had large couplings among themselves. The methods of perturbative quantum field theory, developed in earlier studies of the electromagnetic force, could not be used since they relied on the existence of only a few, weakly-interacting, elementary particles.

The dominant approach was the S-matrix (scattering matrix) theory, that only involved first-principle quantum mechanics and empirical data, as originally advocated by Heisenberg. Approximated solutions to the scattering matrix were searched for by first assuming some phenomenological input on particle exchanges and asymptotic behaviour, and then solving self-consistently the general requirements of relativistic quantum mechanics. A simplified form of these conditions, called Dolen-Horn-Schmid duality, allowed for the closed-form solution of the famous Veneziano four-meson scattering amplitude in 1968.

The impact of Veneziano's result was enormous, because it provided a simple, yet rich and elegant solution after many earlier attempts. It was immediately clear that a new structure had been found, involving infinite towers of particles organized in linearly rising Regge trajectories.

Part III, 'The Dual Resonance Model', describes the intense activity taking place in the period 1969-1973: the Veneziano model was generalized to the scattering of any number of mesons and the structure of the underlying quantum theory was understood, separating the physical states from the unphysical ones. The operator formalism was introduced and first loop corrections were computed in open and closed string theories, at the time called Dual Resonance Model (DRM) and Shapiro-Virasoro Model (SVM), respectively. Some theoretical methods were imported from the study of Quantum Electrodynamics, while others were completely new. It is surprising how far the theory was developed before reaching a clear understanding of the underlying string dynamics, i.e. before the quantization of the string action.

The consistency conditions in the quantum theory of the DRM brought to striking results. First, the linear Regge trajectories were uniquely fixed, leading to the presence of tachyons (unphysical particles with negative mass squared) with spin zero and of massless particles with spin one and two in the open and closed string, respectively. Second, unitarity of the theory required $d = 26$ spacetime dimensions, in particular for loop corrections, as observed by Lovelace in 1971. On the one hand, these results showed the beauty of the theory, stemming from its high degree of consistency and symmetry; on the other hand, they were in contradiction with hadron phenomenology, requiring $d = 4$ dimensions and at most massless spin-zero particles.

Part IV, 'The string', illustrates how the DRM was eventually shown to correspond to the quantum theory of a relativistic string. The analogy of the DRM spectrum with the harmonics of a vibrating string was soon noticed in 1969, independently by Nambu, Nielsen and Susskind. The string action, proportional to the area of the string world-sheet, was also introduced by Nambu and then by Goto in analogy with the action of the relativistic point particle, proportional to the length of the trajectory.

Although the string action was introduced rather early, its quantization was not straightforward. Goddard, Goldstone, Rebbi and Thorn eventually worked it out in 1973, upon using the so-called light-cone gauge, involving the $(d-2)$ transverse string coordinates; after quantization, they showed that Lorentz invariance was maintained only in $d = 26$ spacetime dimensions, where the DRM spectrum of physical states was recovered.

Part V, 'Beyond the bosonic string', collects the contributions describing the addition of extra degrees of freedom to the DRM in the quest for a better agreement with hadron phenomenology. The addition of fermions, i.e. half-integer spin hadrons, was achieved by Ramond, while a new dual model for pions was developed by Neveu and Schwarz. These models were recognized as the two sectors of the Ramond-Neveu-Schwarz (RNS) fermionic string. This theory had a rich spectrum of states, including both bosons and fermions, and required $d = 10$ spacetime dimensions.

The RNS theory was the starting point for many modern developments. Gervais and Sakita observed a symmetry of the theory corresponding to transformations mapping fermionic and bosonic degrees of freedom among themselves: this was the beginning of supersymmetry. Moreover, the introduction of additional symmetries allowed for non-Abelian gauge symmetries in the massless spectrum and extended current-algebra invariances.

Part VI, 'The superstring', describes the transformation of string theory into its modern formulation. Around 1974, the application to hadron physics was definitely abandoned in favour of the successful description provided by Quantum Chromodynamics (QCD), a non-Abelian gauge field theory. At the same time, it was understood by Scherk, Neveu, Schwarz and Yoneya that the presence of the massless spin one/two states in the open/closed string spectrum meant that the theory could reproduce gauge theories and Einstein gravity in the low-energy limit, where all other states in the Regge trajectories become infinitely massive and decouple. Therefore, string theory was an extension of field theory rather than an alternative to it, as originally thought.

This result led Scherk and Schwarz to propose in 1974 the unification within string theory of all four fundamental interactions: the electromagnetic, weak and strong forces, described by gauge theories, together gravity, described by Einstein's general relativity theory. This remarkable idea was much ahead of time and could not be immediately appreciated: most of the theoretical physics community was busy developing the gauge theories that form the so-called Standard Model. Other ingredients of modern string theory, such as the Kaluza-Klein compactification of the extra dimensions and a mechanism for supersymmetry breaking, were also introduced by Scherk and Schwarz.

In the meanwhile, supersymmetry was formulated by Wess and Zumino in quantum field theory, independently of strings, as a spacetime symmetry relating particle spectra in four dimensions. Furthermore, the Ramond-Neveu-Schwarz string was proved to be spacetime supersymmetric by Gliozzi, Scherk and Olive in 1976, upon performing a projection of its spectrum that also eliminated the unwanted tachyon. To sum up, by 1976 open superstring theory was fully developed in its modern formulation of a unifying theory. However, it was left aside in favour of gauge theories, seemingly more economical and concrete.

Part VII, 'Preparing the string renaissance', describes the 'dark age' of string theory, between 1977 and 1983, when only a handful of people continued to work at it. They nevertheless obtained further results that were instrumental for its comeback in 1984. Towards the end of the Seventies, the main theoretical and experimental features of the Standard Model were being settled, and the issue of further unification was brought up with strength in the theoretical physics community. Unification of electro-weak and strong interactions above the Standard Model energy scale, and unification with gravity, were addressed in the context of supersymmetric field theories and supergravities, respectively. Supergravity theories were the supersymmetric generalization of Einstein's general relativity, offering higher consistency and extra dimensions. Although low-energy limits of superstring theories, they were developed and analyzed independently.

The abrupt change of attitude that brought back superstring theories on focus is then described. The type I superstring was more appropriate and sound than the supergravity theories considered so far: it could describe the Standard Model spectrum of particle, requiring chiral fermions in four dimensions as well as the cancellation of the associated chiral anomalies, as remarkably shown by Green and Schwarz. Moreover, it provided a consistent quantum theory of gravity. On the other hand, supergravity theories, in particular the most fundamental one in eleven dimensions, could not provide a finite quantum theory of gravity.

These developments led to a new booming period of string theory from 1984 onwards, that continued with highs and lows till the present time. Recent findings show that string theory contains further degrees of freedom besides strings, i.e. membranes and D-branes, and that the five consistent superstring theories unify in a single theory called 'M-theory'. Furthermore, a novel relation between string and gauge theories has brought new insight into the hadronic string picture. A summary of these contemporary developments is presented in the last Chapter of Part VII.

Finally, the Volume contains five Appendices that provide more technical presentations of some key features of string theory: the S-matrix approach of the Sixties, the features of the Veneziano amplitude, the full quantization of the bosonic string action, supersymmetry and the field-theory limit.

Here below we list the main books and review articles on early string theory. The Introductions to the Parts also provide general references on the topics discussed therein.

References

[Fra86] Frampton, P.H. ([1974] 1986). *Dual Resonance Models and Superstrings* (World Scientific Publishing, Singapore).

[GSW87] Green, M.B., Schwarz, J.H. and Witten, E. (1987). *Superstring theory*, in two volumes (Cambridge University Press, Cambridge).

[Jac74] Jacob, M. ed. (1974). *Dual Theory*, Physics Reports Reprints Book Series Vol. 1 (North Holland, Amsterdam).

[Sch75] Scherk, J. (1975). An introduction to the theory of dual models and strings, *Rev. Mod. Phys.* **47**, 123–163.

[Sch85] Schwarz, J.H. ed. (1985). *Superstrings: the first 15 years of superstring theory*, in two volumes (World Scientific Publishing, Singapore).

Synopsis: 1968-1984

In the following we list the main developments in the early history of string theory, organized according to the Parts of the book in which they are described. Each topic is associated with some key references that are just a sample of the relevant literature. Complete lists of references can be found at the end of each Author's Chapter; a comprehensive guide to the bibliography on early string theory is given at the end of the textbook by Green, Schwarz and Witten.

Part II - The prehistory: the analytic S-matrix

Developments till 1968

- The S-matrix approach to strong interactions is pursued [Che61] [ELOP66].

- Dolen, Horn and Schmid introduce an hypothesis on the structure of scattering amplitudes [DHS67], the so-called DHS duality, later called planar duality [Fre68] [Ros69] [Har69]; this is implemented in the superconvergence sum rules [ARVV68].
- Veneziano proposes a scattering amplitude obeying DHS duality: this is the beginning of the Dual Resonance Model [Ven68].

Other developments in theoretical physics

- The theory of weak nuclear interactions is developed.
- The spontaneous breaking of a symmetry is recognized as being a general phenomenon in many-body systems and quantum field theory.

References

[ARVV68] Ademollo, M., Rubinstein, H.R., Veneziano, G. and Virasoro, M.A. (1968). Bootstrap of meson trajectories from superconvergence, *Phys. Rev.* **176**, 1904–1925.

[Che61] Chew, G.F. (1961). *S-Matrix Theory of Strong Interactions* (Benjamin, W.A. Inc., New York).

[DHS67] Dolen, R., Horn, D. and Schmid, C. (1967). Prediction of Regge parameters of ρ poles from low-energy $\pi - N$ data, *Phys. Rev. Lett.* **19**, 402–407.

[ELOP66] Eden, R.J., Landshoff, P.V., Olive, D.I. and Polkinghorne, J.C. (1966). *The Analytic S Matrix* (Cambridge University Press, Cambridge).

[Fre68] Freund, P.G.O. (1968). Finite-energy sum rules and bootstraps, *Phys. Rev. Lett.* **20**, 235–237.

[Har69] Harari, H. (1969). Duality diagrams, *Phys. Rev. Lett.* **22**, 562–565.

[Ros69] Rosner, J.L. (1969). Graphical form of duality, *Phys. Rev. Lett.* **22**, 689–692.

[Ven68] Veneziano, G. (1968). Construction of a crossing-symmetric, Reggeon behaved amplitude for linearly rising trajectories, *Nuovo Cim.* **A57**, 190–197.

Part III - The Dual Resonance Model

Developments during 1969-73

- The Veneziano amplitude is generalized to the scattering of N particles [GS69] [Cha69] [CT69]; in particular, the string world-sheet first appears in Koba-Nielsen's work [KN69].
- Shapiro and Virasoro extend the Veneziano formula and obtain the first amplitudes of closed string theory [Vir69] [Sha70].
- The residues of the poles of the N-point amplitude are shown to be given by a sum of factorized terms and their number is shown to increase exponentially with the mass [BM69] [FV69].

- Fubini, Gordon and Veneziano introduce an operator formalism of harmonic oscillators that allows for the analysis of the theory spectrum [FGV69] [FV70]; additional decoupling conditions are obtained if the intercept of the Regge trajectory is $\alpha_0 = 1$ [Vir70]; in this case the lowest state of the spectrum is a tachyon. Fubini and Veneziano obtain the algebra of the Virasoro operators and Weis finds its central extension [FV71].
- The equations characterizing the on-shell physical states are derived [DD70] and an infinite set of physical states, called DDF states after Del Giudice, Di Vecchia, and Fubini, is found [DDF72]; the Dual Resonance Model has no ghosts if $d \leq 26$ [Bro72] [GT72]; for $d = 26$ the DDF states span the whole physical subspace.
- One-loop diagrams are constructed for restoring perturbative unitarity [KSV69] [BHS69] [ABG69]; Lovelace shows that the nonplanar loop diagram complies with unitarity only for 26 spacetime dimensions [Lov71].
- The 3-Reggeon vertex is constructed [Sci69] [CSV69] and is generalized to N external particles [Lov70a]; the N-Reggeon vertex is used for computing multiloop diagrams [Lov70b] [Ale71] [AA71] [KY70].
- Vertex operators for excited states of the string are constructed [CFNS71] [CR71].
- Brink and Olive construct the physical state projection operator and clearly show that only $(d-2)$ transverse oscillators contribute to one-loop diagrams [BO73].

Other developments in theoretical physics

- The non-Abelian gauge theory describing weak and electromagnetic interactions is formulated; this is the first step towards the Standard Model of particle physics.
- The experiment of deep inelastic scattering shows the existence of point-like constituents inside hadrons.

References

[Ale71] Alessandrini, V. (1971). A general approach to dual multiloop amplitudes, *Nuovo Cimento* **2A**, 321–352.

[AA71] Alessandrini, V. and Amati, D. (1971). Properties of dual multiloop amplitudes, *Nuovo Cimento* **4A** , 793–844.

[ABG69] Amati, D., Bouchiat, C. and Gervais, J.L. (1969). On the building of dual diagrams from unitarity, *Nuovo Cimento Lett.* **2S1**, 399–406.

[BHS69] Bardakci, K., Halpern, M.B. and Shapiro, J.A. (1969). Unitary closed loops in Reggeized Feynman theory, *Phys. Rev.* **185**, 1910–1917.

[BM69] Bardakci, K. and Mandelstam, S. (1969). Analytic solution of the linear-trajectory bootstrap, *Phys. Rev.* **184**, 1640–1644.

[BO73] Brink, L. and Olive, D. I. (1973). The physical state projection operator in dual resonance models for the critical dimension of the spacetime, *Nucl. Phys.* **B 56**, 253–265.

[Bro72] Brower, R.C. (1972). Spectrum-generating algebra and no-ghost theorem in the dual model, *Phys. Rev.* **D6**, 1655–1662.

[CFNS71] Campagna, P., Fubini, S., Napolitano, E. and Sciuto, S. (1971). Amplitude for n nonspurious excited particles in dual resonance models, *Nuovo Cimento* **A2**, 911–928.

[CSV69] Caneschi, L., Schwimmer, A. and Veneziano, G. (1970). Twisted propagator in the operatorial duality formalism, *Phys. Lett.* **30B**, 351–356.

[Cha69] Chan, H.M. (1969). A generalized Veneziano model for the N-point function, *Phys. Lett.* **22B**, 425–428.

[CT69] Chan, H.M. and Tsou, S.T. (1969). Explicit construction of the N-point function in the generalized Veneziano model, *Phys. Lett.* **28B**, 485–488.

[CR71] Clavelli, L. and Ramond, P. (1971) Group-theoretical construction of dual amplitudes, *Phys. Rev.* **D3**, 988–990.

[DD70] Del Giudice, E. and Di Vecchia, P. (1970). Characterization of the physical states in dual-resonance models, *Nuovo Cim.* **A70**, 579–591.

[DDF72] Del Giudice, E., Di Vecchia, P. and Fubini, S. (1972). General properties of the dual resonance model, *Ann. Phys.* **70**, 378–398.

[FGV69] Fubini, S., Gordon, D. and Veneziano, G. (1969). A general treatment of factorization in dual resonance models, *Phys. Lett.* **B29**, 679–682.

[FV69] Fubini, S. and Veneziano, G. (1969). Level structure of dual-resonance models, *Nuovo Cimento* **64 A**, 811–840.

[FV70] Fubini, S. and Veneziano, G. (1970). Duality in operator formalism, *Nuovo Cim.* **A67**, 29–47.

[FV71] Fubini, S. and Veneziano, G. (1971). Algebraic treatment of subsidiary conditions in dual resonance model, *Annals of Physics* **63**, 12–27.

[GT72] Goddard, P. and Thorn, C.B. (1972). Compatibility of the pomeron with unitarity and the absence of ghosts in the dual resonance model, *Phys. Lett.* **B40**, 235–238.

[GS69] Goebel, C.J. and Sakita B. (1969). Extension of the Veneziano form to N-particle amplitude, *Phys. Rev. Lett.* **22**, 257–260.

[KY70] Kaku, M. and Yu, L. (1970). The general multiloop Veneziano amplitude, *Phys. Lett.* **B 33**, 166–170.

[KSV69] Kikkawa, K., Sakita, B. and Virasoro, M. (1969). Feynman-like diagrams compatible with duality. I. Planar diagrams, *Phys. Rev.* **184**, 1701–1713.

[KN69] Koba, Z. and Nielsen, H.B. (1969). Manifestly crossing invariant parameterization of n meson amplitude, *Nucl. Phys.* **B12**, 517–536.

[Lov70a] Lovelace, C. (1970). Simple n-reggeon vertex, *Phys. Lett.* **B 32**, 490–494.

[Lov70b] Lovelace, C. (1970). M-loop generalized Veneziano formula, *Phys. Lett.* **B 52**, 703–708.

[Lov71] Lovelace, C. (1971). Pomeron form factors and dual Regge cuts, *Phys. Lett.* **B34**, 500–506.

[Sci69] Sciuto, S. (1969). The general vertex function in generalized dual resonance models, *Nuovo Cimento Lett.* **2**, 411–418.

[Sha70] Shapiro, J.A. (1970). Electrostatic analogue for the Virasoro model, *Phys. Lett.* **B33**, 361–362.

[Vir69] Virasoro, M. (1969). Alternative constructions of crossing-symmetric amplitudes with Regge behavior, *Phys. Rev.* **177**, 2309–2311.
[Vir70] Virasoro, M. (1970). Subsidiary conditions and ghosts in dual-resonance models, *Phys. Rev.* **D1**, 2933–2936.

Part IV - The string

Developments during 1970-73

- Nambu, Nielsen and Susskind independently suggest that the dynamics underlying the dual model is that of a relativistic string [Nam70a] [Nam70b] [Nie69] [Nie70] [Sus69] [Sus70].
- Nambu and then Goto write the string action [Nam70b] [Got71].
- The analogue model, proposed by Fairlie and Nielsen and related to the string picture, is used for computing dual amplitudes [FN70] [FS70].
- The string action is quantized in the light-cone gauge and the spectrum is found to be in complete agreement with that of the Dual Resonance Model for $d = 26$ [GGRT73]; apart from the tachyon, string theory is now a consistent quantum-relativistic system.
- The computation by Brink and Nielsen [BN73] of the zero-point energy of the string gives a relation between the dimension of spacetime and the mass of the lowest string state.
- The interaction among strings is introduced within the light-cone path-integral formalism [Man73a], and within the operator approach by letting the string interact with external fields [ADDN74]; the coupling between three arbitrary physical string states is computed both in the path-integral [Man73a] [CG74] and operator [ADDF74] formalisms, finding agreement.

References

[ADDN74] Ademollo, M., D Adda, A., D Auria, R., Napolitano, E., Sciuto, S., Di Vecchia, P., Gliozzi, F., Musto, R., Nicodemi, F. (1974). Theory of an interacting string and dual-resonance model, *Nuovo Cimento* **21 A**, 77–145.
[ADDF74] Ademollo, M., Del Giudice, E., Di Vecchia, P. and Fubini, S. (1974). Couplings of three excited particles in dual-resonance model, *Nuovo Cimento* **19 A**, 181–203.
[BN73] Brink, L. and Nielsen, H.B. (1973). A simple physical interpretation of the critical dimension of the spacetime in dual models, *Phys. Lett.* **45B**, 332–336.
[CG74] Cremmer, E. and Gervais, J.L. (1974). Combining and splitting relativistic strings, *Nucl. Phys.* **B 76**, 209–230.
[FN70] Fairlie, D.B. and Nielsen, H.B. (1970). An analog model for ksv theory, *Nucl. Phys.* **B20**, 637–651.

[FS70] Frye, G. and Susskind, L. (1970). Non-planar dual symmetric loop graphs and pomeron, *Phys. Lett.* **B31**, 589–591.

[GGRT73] Goddard, P., Goldstone, J., Rebbi, C. and Thorn, C.B. (1973). Quantum dynamics of a massless relativistic string, *Nucl. Phys.* **B56**, 109–135.

[Got71] Goto, T. (1971). Relativistic quantum mechanics of one dimensional mechanical continuum and subsidiary condition of the dual resonance model, *Prog. Theor. Phys.* **46**, 1560–1569.

[Man73a] Mandelstam, S. (1973). Interacting string picture of dual-resonance models, *Nucl. Phys.* **B 64**, 205–235.

[Nam70a] Nambu, Y. (1970). Quark model and the factorization of the Veneziano amplitude, in *Proceedings of the International Conference on Symmetries and Quark Models, Wayne State University, June 18–20, 1969*, ed. R. Chand (Gordon and Breach, New York, 1970), 269–277, reprinted in *Broken Symmetry, Selected Papers of Y. Nambu*, ed. Eguchi, T. and Nishijima, K. (World Scientific, Singapore, 1995), 258–277.

[Nam70b] Nambu, Y. (1970). *Duality and Hadrodynamics*, lecture notes prepared for Copenhagen summer school, 1970, reproduced in *Broken Symmetry, selected papers of Y. Nambu*, ed. Eguchi, T. and Nishijima, K. (World Scientific, Singapore, 1995), 280.

[Nie69] Nielsen, H.B. (1969). A physical interpretation of the n-point Veneziano model, (Nordita preprint, 1969).

[Nie70] Nielsen, H.B. (1970). An almost physical interpretation of the integrand of the n-point Veneziano model, (paper presented at the 15th International Conference on High Energy Physics, Kiev, 26 August to 4 September, 1970) - (Nordita preprint, 1969).

[Sus69] Susskind, L. (1969). Harmonic-oscillator analogy for the Veneziano model, *Phys. Rev. Lett.* **23**, 545–547.

[Sus70] Susskind, L. (1970). Structure of hadrons implied by duality, *Phys. Rev.* **D1**, 1182–1186.

Part V - Beyond the bosonic string

Developments during 1970-74

- The Dual Resonance Model is generalized to spacetime fermions by Ramond [Ram71]; an extension of the Dual Resonance Model for pions is constructed by Neveu and Schwarz [NS71]; the two models are recognized as the two sectors of the Ramond-Neveu-Schwarz model [Tho71].
- The fermion emission vertex is constructed by Corrigan and Olive [CO72]; the scattering amplitude involving four fermions is computed within the light-cone path-integral [Man73b], and operator [SW73] [CGOS73] formalisms.
- The one-loop [GW71] and multiloop [Mon74] amplitudes of the Ramond-Neveu-Schwarz model are computed.
- The RNS model is found to possess a symmetry relating bosons to fermions, the world-sheet supersymmetry [GS71].

- Further extensions of the bosonic string involve the introduction of internal symmetry groups [CP69], current-algebra symmetries [BH71], and extended supersymmetries [ABDD76].

Other developments in theoretical physics

- The gauge theory of quarks and gluons, Quantum Chromodynamics, is proposed for strong interactions.
- The proof of renormalization of non-Abelian gauge theories is completed.
- The renormalization group is understood as a general method to relate the physics at different energy scales in quantum field theory.

References

[ABDD76] Ademollo, M., Brink L., D'Adda, A., D'Auria, R., Napolitano, E., Sciuto, S., Del Giudice, E., Di Vecchia, P., Ferrara, S., Gliozzi, F., Musto, R. and Pettorino R. (1976). Supersymmetric strings and color confinement, *Phys. Lett.* **B62**, 105–110.

[BH71] Bardakci, K. and Halpern, M.B. (1971). New dual quark models, *Phys. Rev.* **D3**, 2493–2506.

[CP69] Chan, H.M. and Paton, J.E. (1969). Generalized Veneziano model with isospin, *Nucl. Phys.* **B10**, 516–520.

[CGOS73] Corrigan, E.F., Goddard, P., Smith, R.A. and Olive, D.I. (1973). Evaluation of the scattering amplitude for four dual fermions, *Nucl. Phys.* **477–491**.

[CO72] Corrigan, E.F. and Olive, D.I.(1972). Fermion-meson vertices in dual theories, *Nuovo Cimento* **11A**, 749.

[GS71] Gervais, J.L. and Sakita, B. (1971). Field theory interpretation of supergauges in dual models, *Nucl. Phys.* **B34**, 632–639.

[GW71] Goddard, P. and Waltz, R.E. (1971). One-loop amplitudes in the model of Neveu and Schwarz, *Nucl. Phys.* **B 34**, 99–108.

[Man73b] Mandelstam, S. (1973). Manifestly dual formulation of the Ramond model, *Phys. Lett.* **46B**, 447–451.

[Mon74] Montonen, C. (1974). Multiloop amplitudes in additive dual resonance models, *Nuovo Cimento* **19A**, 69–89.

[NS71] Neveu, A. and Schwarz, J.H. (1971). Factorizable dual model of pions, *Nucl. Phys.* **B31**, 86–112.

[Ram71] Ramond, P. (1971). Dual theory for free fermions, *Phys. Rev.* **D3**, 2415–2418.

[SW73] Schwarz, J. H. and Wu, C. C. (1973). Evaluation of dual fermion amplitudes, *Phys. Lett.* **B47** 453–456.

[Tho71] Thorn, C. (1971). Embryonic dual model for pions and fermions, *Phys. Rev.* **D 4** 1112–1116.

Part VI - The superstring

Developments during 1974-77

- In the limit of infinite string tension, string theory reduces to quantum field theory [Sch71]: the open string leads to non-Abelian gauge theories [NS72] [Yon74] and the closed string to gravity [SS74] [Yon73]; therefore, string theory provides a framework for unifying all fundamental interactions [SS74] [SS75].
- Extending the world-sheet supersymmetry of the Ramond-Neveu-Schwarz model to four-dimensional field theory, the Wess-Zumino model is constructed [WZ74]; supersymmetric extensions of all known quantum field theories are found.
- By performing a projection of states in the Ramond-Neveu-Schwarz model, Gliozzi, Scherk and Olive construct the first string theory that is supersymmetric in spacetime [GSO76]; this theory is free of tachyons and unifies gauge theories and gravity: modern superstring theory is born.
- To cope with experiments, the six extra dimensions can be compactified by using the Kaluza-Klein reduction [CS76], that also provides a mechanism for supersymmetry breaking [SS79].
- Supergravity, the supersymmetric extension of Einstein's field theory of gravitation is formulated [FNF76] [DZ76a].
- The supersymmetric action for the Ramond-Neveu-Schwarz string is obtained [BDH76] [DZ76b].

Other developments in theoretical physics

- Quantum Chromodynamics is shown to be weakly interacting at high energy (asymptotic freedom); it is widely recognized as the correct theory of strong interactions.
- The Standard Model of electro-weak and strong interactions is completed and receives experimental verification.
- Attempts are made to unify electroweak and strong interactions beyond the Standard Model; the Grand Unified Theory is formulated.

References

[BDH76] Brink, L., Di Vecchia, P. and Howe, P.S. (1976). A locally supersymmetric and reparameterization invariant action for the spinning string, *Phys. Lett.* **B65**, 471–474.

[CS76] Cremmer, E. and Scherk, J. (1976). Dual models in four dimensions with internal symmetries, *Nucl. Phys.* **B103**, 399–425.

[DZ76a] Deser, S. and Zumino, B. (1976). Consistent supergravity, *Phys. Lett.* **B62**, 335–337.
[DZ76b] Deser, S. and Zumino, B. (1976). A complete action for the spinning string, *Phys. Lett.* **B65**, 369–373.
[FNF76] Freedman, D.Z., van Nieuwenhuizen, P. and Ferrara, S. (1976). Progress toward a theory of supergravity, *Phys. Rev.* **D13**, 3214–3218.
[GSO76] Gliozzi, F., Scherk, J. and Olive, D. (1976). Supergravity and the spinor dual model, *Phys. Lett.* **B65**, 282–286.
[NS72] Neveu, A. and Scherk, J. (1972). Connection between Yang-Mills fields and dual models, *Nucl. Phys.* **B36**, 155–161.
[Sch71] Scherk, J. (1971). Zero-slope limit of the dual resonance model, *Nucl. Phys.* **B31**, 222–234.
[SS74] Scherk, J. and Schwarz, J.H. (1974). Dual models for nonhadrons, *Nucl. Phys.* **B81**, 118–144.
[SS75] Scherk, J. and Schwarz, J.H. (1975). Dual field theory of quarks and gluons, *Phys. Lett.* **B57**, 463–466.
[SS79] Scherk, J. and Schwarz, J.H. (1979). Spontaneous breaking of supersymmetry through dimensional reduction, *Phys. Lett.* **B82**, 60–64.
[WZ74] Wess, J. and Zumino, B. (1974). Supergauge transformations in four dimensions, *Nucl. Phys.* **B70**, 39–50.
[Yon73] Yoneya, T. (1973). Quantum gravity and the zero slope limit of the generalized Virasoro model, *Lett. Nuovo Cim.* **8**, 951–955.
[Yon74] Yoneya, T. (1974). Connection of dual models to electrodynamics and gravitodynamics, *Prog. Theor. Phys.* **51**, 1907–1920.

Part VII - Preparing the string renaissance

Developments during 1978-1984

- Using techniques developed in non-Abelian gauge theories, Polyakov quantizes the string by covariant path-integral methods, opening the way to modern treatments of string theories [Pol81a] [Pol81b]; the Polyakov approach is further developed [Fri82] [Alv83] [DOP82] [Fuj82].
- The unique and most symmetric supergravity in eleven dimensions is constructed [CJS78].
- Green and Schwarz introduce a new light-cone formalism where the fermionic coordinate is a $SO(8)$ spinor [GS81] [GS82a] [GS82b]; they construct type IIA and IIB closed string theories [GS82c] and write the covariant spacetime supersymmetric action for the superstring [GS84a].
- The contribution of chiral fields to the gauge and gravitational anomalies is computed and shown to vanish in type IIB supergravity [AW84].
- Type I superstring and supergravity with gauge group $SO(32)$ are shown to be free from gauge and gravitational anomalies [GS84b] [GS85].

- Two other anomaly-free superstring theories are constructed, the Heterotic strings with $E_8 \times E_8$ and $SO(32)$ groups [GHMR85].
- Calabi-Yau compactifications of the $E_8 \times E_8$ Heterotic string give supersymmetric four-dimensional gauge theories with realistic features for the description of the Standard Model and gravity [CHSW85].

Other developments in theoretical physics 1976-84

- The Standard Model of electro-weak and strong interactions is fully confirmed by experiments.
- Attempts aiming at the unification of all interactions including gravity are based on supergravity theories, which are extensively studied.
- Phenomenological consequences of supersymmetry are investigated; the Minimal Supersymmetric Standard Model is formulated.
- This is the 'golden era' of modern quantum field theory, with several results in gauge theories: nonperturbative methods, numerical simulations, the study of anomalies and the interplay with mathematical physics.

References

[Alv83] Alvarez, O. (1983). Theory of strings with boundaries: Fluctuations, topology and quantum geometry, *Nucl. Phys.* **B 216**, 125–184.

[AW84] Alvarez-Gaumé, L. and Witten, E. (1984). Gravitational anomalies, *Nucl. Phys.* **B234**, 269–330.

[CHSW85] Candelas, P., Horowitz, G., Strominger, A. and Witten, E. (1985). Vacuum Configurations for Superstrings, *Nucl. Phys.* **B258** 46–74.

[CJS78] Cremmer, E., Julia, B. and Scherk, J. (1978). Supergravity theory in 11 dimensions, *Phys. Lett.* **B76**, 409–412.

[DOP82] Durhuus, B., Olesen, P. and Petersen, J.L. (1982). Polyakov's quantized string with boundary terms, *Nucl. Phys.* **198**, 157–188.

[Fri82] Friedan, D. (1982). Introduction to Polyakov's string theory, in *Recent advances in Field Theory and Statistical Mechanics, proc. of 1982 Les Houches Summer School*, Eds J.B. Zuber and R. Stora, (Elsevier).

[Fuj82] Fujikawa, K. (1982). Path integrals of relativistic strings, *Phys. Rev.* **D25**, 2584–2592.

[GS81] Green, M.B. and Schwarz, J.H. (1981). Supersymmetric dual string theory, *Nucl. Phys.* **B181**, 502–530.

[GS82a] Green, M.B. and Schwarz, J.H. (1982). Supersymmetric dual string theory. 2. Vertices and trees, *Nucl. Phys.* **B198**, 252–268.

[GS82b] Green, M.B. and Schwarz, J.H. (1982). Supersymmetric dual string theory. 3. Loops and renormalization, *Nucl. Phys.* **B198**, 441–460.

[GS82c] Green, M.B. and Schwarz,J.H. (1982). Supersymmetrical string theories, *Phys. Lett.* **B 109**, 444–448.

[GS84a] Green, M.B. and Schwarz, J.H. (1984). Covariant description of superstrings, *Phys. Lett.* **B 136**, 367–370.

[GS84b] Green, M.B. and Schwarz, J.H. (1984). Anomaly cancellation in supersymmetric d=10 gauge theory and superstring theory, *Phys. Lett.* **B149**, 117–122.

[GS85] Green, M.B. and Schwarz, J.H. (1985). The hexagon gauge anomaly in type I superstring theory, *Nucl. Phys.* **B 255**, 93–114.

[GHMR85] Gross, D.J., Harvey, J.A., Martinec, E.J. and Rohm, R. (1985). Heterotic string, *Phys. Rev. Lett.* **54**, 502–505.

[Pol81a] Polyakov, A.M. (1981). Quantum geometry of bosonic strings, *Phys. Lett.* **B103**, 207–210.

[Pol81b] Polyakov, A.M. (1981). Quantum geometry of fermionic strings, *Phys. Lett.* **B103**, 211–213.

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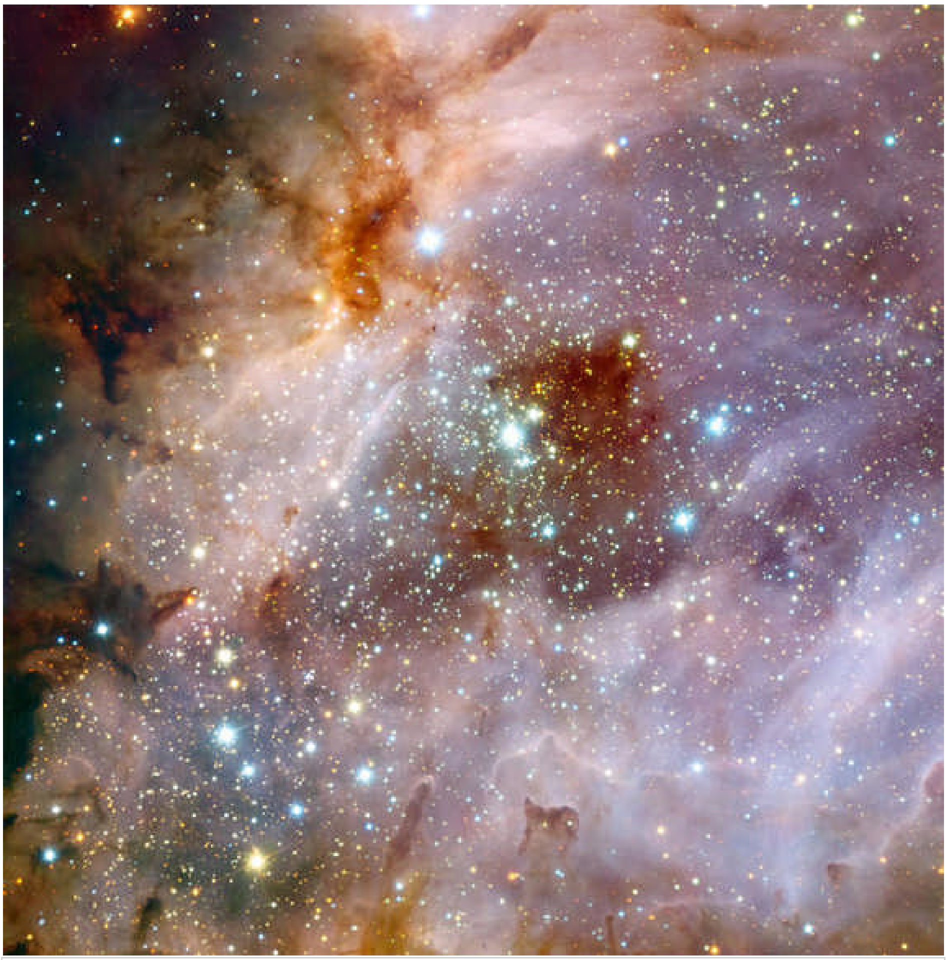
Theory of Everything: Holy Grail or Fruitless Pursuit?

Clara Moskowitz, LiveScience Senior Writer | March 08, 2011 03:30pm ET

NEW YORK – Einstein died before completing his dream of creating a unified theory of everything. Since



Astronomers using data from ESO's Very Large Telescope created this composite photo of the nebula Messier 17, also known as the Omega Nebula or the Swan Nebula. The image shows vast clouds of gas and dust illuminated by the intense radiation from young stars.

Credit: ESO/R. Chini

Pin it

then, physicists have carried on his torch, continuing the quest for one theory to rule them all.

But will they ever get there? That was the topic of debate when seven leading physicists gathered here at the American Museum of Natural History for the 11th annual Isaac Asimov Memorial Debate.

The quest for a theory of everything arises because two of the most celebrated, successful theories in physics are contradictory.

The theory that describes very big things – general relativity – and the theory that describes very small things – quantum mechanics – each work amazingly well in their own realms, but when combined, break down. They can't both be right.

And we can't just sweep that fact under the rug and continue to use them each as they are, because there are some cases in which both theories apply – such as a black hole.

"Its size is small in terms of length; its size is large in terms of mass. So you need both," explained Brian Greene, professor of physics and mathematics at Columbia University.

Scientists hope that a unified theory would resolve this incompatibility, and describe anything and everything in the universe in one fell swoop.

Vibrating strings

Many physicists say our best hope for a theory of everything is superstring theory, based on the idea that subatomic particles are actually teensy tiny loops of vibrating string. When filtered through the lens of string theory, general relativity and quantum mechanics can be made to get along.

For that reason, string theory has inspired many physicists to devote their careers to developing it since the idea was first proposed in the 1980s.

"There's been an enormous amount of progress in string theory," said Greene, a proponent of string theory whose 2000 book "The Elegant Universe" described the theory in layman's terms. "There have been issues developed and resolved that I never thought, frankly, we would be able to resolve. The progress over the last 10 years has only solidified my confidence that this is a worthwhile direction to pursue."

But other experts are getting weary of string theory, which has yet to produce concrete, testable predictions. Perhaps string theory, and the whole idea that a single theory can explain the universe, is misguided, they say.

Neil deGrasse Tyson, director of the museum's Hayden Planetarium, suggested that string theory seems to have stalled, and contrasted the lack of progress of "legions" of string theorists with the seemingly short 10 years it took one man – Einstein – to transition from special relativity to general relativity.

"Are you chasing a ghost or is the collection of you just too stupid to figure this out?" deGrasse Tyson teased, beginning a friendly banter that would continue throughout the night.

Greene admitted that string theorists have not produced testable predictions that experiments can confirm, bu said it wasn't time to give up.

"As long as progress is carrying forward, you keep going," he said. "To say there's no progress, come on man, that's just not right!"

The theory is so complex, he charged, and deals with such fantastically small scales that are inaccessible to experimental data, that no wonder it's taking a while to crack.

"Nowhere is it written that we "have to solve problems in one human lifetime," agreed Janna Levin, a physicist at Barnard College in New York. I don't see why we should be shocked that solving incredibly challenging problems may take more than one human life span."

Hidden dimensions

One aspect of string theory that riles many is that many versions of it require the universe to contain more than the three dimensions of space and one of time that we are familiar with.

The most popular version of string theory, in fact, calls for 11 total dimensions.

"Why don't we see them?" Levin said. "It might be that they're very, very small. Or it might be that we are somehow confined to a three-dimensional kind of membrane. Or it might be that they're not there. But these are very interesting ideas that have some very compelling consequences."

Yet such a bizarre notion is disquieting to many.

"I'm a higher dimensional refusnik," said physicist Jim Gates of the University of Maryland-College Park, who argued that sometimes it seems like physicists invoke higher dimensions when they can't make their theory work as it is.

"It is not at all that we can't solve a problem so we pull extra dimensions out of a hat," Greene said.

"I'm just saying it looks that way," deGrasse Tyson said, carrying on the friendly debate.

Testing string theory

Luckily, the question of higher dimensions isn't entirely restricted to the theoretical domain. There is some hope that experiments such as the Large Hadron Collider – the world's most powerful particle accelerator in Geneva, Switzerland – will be able to provide experimental evidence of hidden dimensions in the universe.

The evidence may be in the absence of certain particles, or missing energy, that might result when a particle leaves our normal dimensions and enters one of the hidden ones.

"What we have to do is go to the highest energies at accelerators and send something off into the extra dimensions," said Katherine Freese, a physicist at the University of Michigan.

Another possible test for string theory will be analyzing the detailed observations of the light left over from the Big Bang, called the cosmic microwave background radiation, which permeates space. This radiation is thought to preserve an imprint of the tiny fluctuations in density that would have been present in the early universe, and might reveal evidence for some of string theory's predictions.

"If we're lucky we can actually use this to test some of the ideas of string theory by looking at imprints in the cosmic microwave background," Freese said.

Should we even be searching?

Ultimately, some physicists say the search for a theory of everything will be a fruitless chase.

"To me the problem of a notion of a theory of everything is that it implies we will eventually know everything there is to know," said Marcelo Gleiser, a physicist at Dartmouth College in New Hampshire. "For me physics is a work in progress."

As our knowledge of physics grows like an island, he said, so too will the "shores of ignorance increase." Thus there will always be more to know, bigger questions, greater areas of uncertainty.

"I have a disquiet with the dream of a search for the final theory," said Lee Smolin, a theoretical physicist at Perimeter Institute for Theoretical Physics in Ontario, Canada. He said the quest was incompatible with the modern way of physics, which has outpaced the scientific methods of Newton, in which scientists do experiments over and over, varying the initial conditions, to isolate the generalities, or laws, that apply.

Now, Smolin said, "we no longer can do experiments over and over again. There's one experiment, which is the universe as a whole."

We can't run other universes in test scenarios to understand cosmology, he said.

"No longer can we separate out the laws from the initial conditions. We are left with the question not just what are the laws, but why these laws? Why these initial conditions rather than other initial conditions? The method that Newton gave us no longer tells us how to go ahead. We have to change the methodology by which we try to understand the universe."

You can follow LiveScience senior writer Clara Moskowitz on Twitter @ClaraMoskowitz.

Editor's Recommendations

- 8 Shocking Things We Learned From Stephen Hawking's Book
- Black Strings: Black Holes With Extra Dimensions
- Twisted Physics: 7 Mind-Blowing Findings

CapitalistImperialistPig

Necessity is the plea for every infringement of human freedom. It is the argument of tyrants; it is the creed of slaves. - William Pitt

MONDAY, JULY 31, 2006

Peter Woit on Susskind on Woit & Smolin

Peter Woit and Lee Smolin have each written books allegedly critical of string theory. I haven't seen them yet because they aren't published here yet. Leonard Susskind, one of the founders of string theory, was interviewed on KQED. He had a defense of string theory and some bad things to say about a couple of unnamed physicists who have got to be Woit and Smolin. This provoked a rather impressive slapdown from Peter at Not even Wrong which includes:

> *Near the end of the interview, when asked to cite some experimental evidence in favor of string theory he said that yes there was a lot of evidence including:*
>
> *1. The existence of gravity.*
>
> *2. The existence of particles.*
>
> *3. The laws of the universe.*
>
> *Quite remarkably he then went on to announce that QCD is a string theory and take credit for it, saying that string theory was "invented by Nambu and myself as a theory of protons and neutrons, an extremely successful theory of protons and neutrons". According to Susskind, string theory provides "the whole explanation of protons and neutrons and nuclear physics" and that "heavy ion collisions are best described in terms of string theory".*

Recent Comments

Lee
>> I say also the 100 dollar bill and maybe the 50. Like Wolfgang, I think you're probably half joking. If not, you're taking a fictional TV program way too seriously. If you really want to do...
CapitalistImperialistPig : Drugs and Money · 1 hour ago

wolfgang
>> our largely imaginary remaining privacy and one more thing. you think you are smart about this, but in my opinion you are giving away your privacy for nothing, while companies measure the value...
CapitalistImperialistPig : Drugs and Money · 7 hours ago

wolfgang
>> what can you buy with just cash now books, medicine, movies, laptops, software, ...
how long do you want the list to be?
CapitalistImperialistPig : Drugs and Money · 8 hours ago

CIPig
The 1 cent piece and the Nickel should surely go. I say also the 100 dollar bill and maybe the 50.
CapitalistImperialistPig : Drugs and Money · 8 hours ago

CIPig
Yes, cashless would mean giving up some of our largely imaginary remaining privacy, but what can you buy with just cash now and no sacrifice of privacy? Not land, nor a house, nor a car, nor a...
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wolfgang
CIP, >> cash is not needed I am not sure if you are serious or just joking around. Well, I for one like to purchase stuff with cash because I don't like the idea that somebody keeps track of what I...

It's really pretty pitiful if the best Susskind can do is petty ad hominem stuff about Peter like:

> *Well, for example, there's one fellow who failed as a physicist, never made it as a physicist, became a computer programmer, has been angry all of his life that he never became a physicist and that physicists ignore him, so he's now taking out his revenge by writing diatribes and polemics against string theory.*

Smolin gets no less snarky a dismissal:

> *There's another fellow who has his own theory, I won't tell you who his name is or what his theory is, but he writes lots and lots of theories and his theories go glub, glub, glub to the bottom of the sea before he even gets a chance to put them out there. Physicists don't take him seriously, he's angry and so he's also writing a book complaining…*

As Peter says:

> *...pathetic.*

UPDATE: Having now heard all of the Susskind interview, I have to say that apart from the cheap shots at the start, and the strange claims at the end, it was pretty good. The most interesting part for me was how he had been a plumber for five years before going to college. He went to school to study engineering, but turned out to have no talent for mechanical drawing (in those pre-computer days).

Posted by CapitalistImperialistPig at 7/31/2006 08:42:00 PM
0 Comments
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