String theory: challenges, successes and magic

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No NOH principle

An essential catalyst in the process of the formation of string theory was urgency, the urgency created out of the near despair to understand the amazing novel features of the hadronic interactions. String theory was revitalized by the urgency to understand together all of the four known basic interactions. Here I shall briefly review some of the motivation to study a theory of extended objects and discuss the challenges string theory faces, the successes it has had, and the magic spell it casts. We start by reviewing a hardware issue, the hard wiring of some scientific minds. Researchers using string theory are faithful followers of an ancient practice, that of ignoring the NOH principle. The NOH principle is very generic, it states that Nobody Owes Humanity neither a concise one page description of all the basic forces that govern nature nor a concise description of all the constituents of matter. Actually no reductionist type description is owed. Time and again physicists driven by their hard wiring processed the experimental data utilizing theoretical frameworks and were able to come up with explicit formulae; formulae that were able to express on less than one page the essence of a basic force. A key assumption used and vindicated was that the basic constituents of nature are point-like. The electromagnetic forces, the weak interactions and even the powerful color forces were rounded up one by one, straddled by the rules of quantum mechanics and then exposed on a fraction of a page. Using these formulae, an accomplished student abandoned on an isolated island can predict with an amazing accuracy the outcome of some very important experiments involving the basic forces. The level of accuracy ranges from a few percent in the case of some aspects of the color forces to better than 10^{-10} for some features of the electromagnetic interactions.

Why change a winning team: extended constituents are called upon to replace point like ones

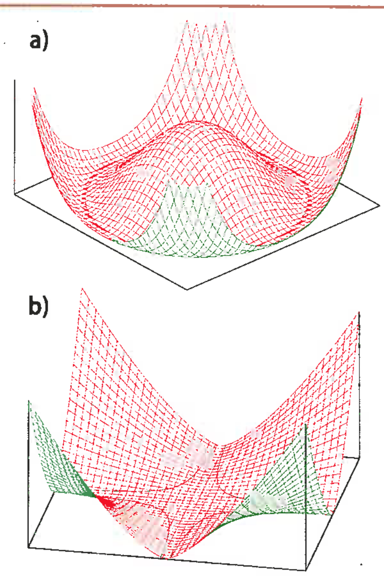
Point particles have done a tremendous job in shouldering the standard model of particle interactions. Why replace them by extended objects? The standard model does reflect the enormous progress made in the understanding of particle physics but it is not perfect, at least as seen by a critical theorist. The model is afflicted with tens of parameters as well as what are termed naturality problems. The values of some physical quantities, such as the mass of the Higgs particle, are required to be much lighter than the theory would naturally suggest. Ignoring the NOH principle, scientists find themselves once again on the path of searching for a more concise description. One effort was directed towards unifying the three interactions, thus following the conceptual unification of the electromagnetic and weak interactions, described each by a gauge theory. That direction led to possible unifications at scales not so distant from where quantum gravity effects are definitely supposed to become important. In fact, gravity, the first of the basic forces that was expressed by a mathematical formula, is the remaining unbridled known force which is considered currently as basic. Here the quantum breaking methods based on the concept of a basic point like structure have failed. Sometimes what is considered failure is also a measure of intellectual restlessness, still it made sense to search for alternatives. Actually even with no apparent failure lurking upon basic physics, a study of a theory of fundamentally extended objects is called for. After all, why should the basic constituents be just point-like? String theory is a natural extension of the idea that the basic constituents are point-like. It is an investigation into the possibility that basic constituents are ab initio extended objects, the simplest such extended objects being one-dimensional, that is strings. In a sense one may regard also point particles as extended objects dressed by their interactions. The direct consequences in this case are however totally different. It turned out that such a generalization did eventually reproduce many properties of point particle interactions and in addition enabled one to formulate what seems as a theory of gravity. This it should do, following the tradition of subjecting any new theory to the test of the correspondence principle. The theory is well defined up to several orders and perhaps to all orders in perturbation theory. The perturbations are small at the vicinity of a very small distance scale called the string scale; as small as that distance is, it is expected to be larger than the Planck length and thus is associated with lower energies than the Planck energy (it is related to the Plank scale by the string interaction coupling). Interactions among strings are, to a large extent, softer and fuzzier than those among point particles. Recall that a large number of successes of particle physics consisted of explaining and predicting the physics of the various interactions at scales at which they were weakly coupled, otherwise, a large dose of symmetry was essential. This is perhaps the most significant achievement of string theory. It is also its major source of frustration. If the string scale is indeed of the order of 10^{-32} cm or even slightly larger, it is not known today how to verify, experimentally, any prediction resulting from perturbative string theory. It is very difficult to imagine, for example, how to set up an experiment measuring the differential cross section of graviton- graviton scattering at the string scale. We will return to this extremely important issue later on and continue to follow for a while the path of the theoreticians.

New questions

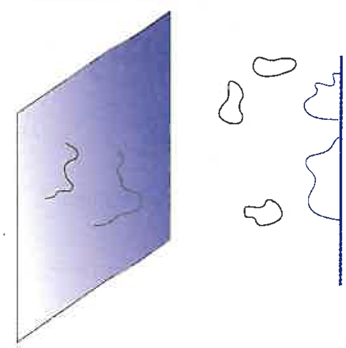
The impact of scientific progress can be tested by the type of questions it makes us aware of, as well as by the answers it eventually provides for them. By studying string theory new questions do arise. Values taken for granted are subjected to query and downgraded to being parameters. String theory suggests questioning the values of some such physical quantities and in some cases offers scientific answers to the question. A prime example is that of the number of space-time dimensions. In a point- like constituent theory there is a very large degree of theoretical freedom. As far as we know spin-zero point particles, for example, could have propagated in any number of dimensions, their interactions would have been different depending on the dimension of space-time but nevertheless they would have been allowed. Strings are much fussier than particles, like the princess sensitive to a grain of pea hidden under 17 mattresses, (super) strings can propagate quantum mechanically only in a limited number of dimensions. In fact, not only are the number of allowed possible dimensions dramatically reduced, the allowed values of the number of space- time dimensions do not include the value 4. These dimensions are usually required to be 10 or 26. (The origin of this basic number is, at this stage, disappointingly technical.) But setting that aside, one would like to detect this experimentally. As the idea of having extra dimensions was raised originally in field theory, upper bounds on the length of such dimensions were already available.

features

More recently under the security net of string theory these bounds have been revised (they have been relaxed by more than 10 orders of magnitude and brought up to the sub micron regime). In fact I am not aware of any bound on a fundamental quantity in physics that has been altered to such an extent by a theoretical idea. One should note that though, strictly speaking, the number 26 does indeed appear in string theory, it is not always possible to associate this number with the number of dimensions. Sometimes the background on which the string can propagate has no obvious geometrical description, just an algebraic one. This fact about strings illustrates the tension inherent in attempts to search for experimental verification of extremely basic but very weakly coupled phenomena. Sitting in our chairs we sometimes forget how frail gravity is. It is all of the planet earth that gravitationally pulls us towards its center, yet all this planetary effort is easily counterbalanced by the electromagnetic forces (and by the Pauli Exclusion Principle) applied by the few tiles beneath our chair. Although string theory sets constraints on the possible number of dimensions, that is not to say that point particles allow everything. The number of known restrictions is however much smaller. The interactions could be of an infinite (sometimes classifiable) variety, the color group, which happens to be SU(3), could have been for all the theory cares, SU (641), the electromagnetic force could have been absent or there could have been 17 photons. Not everything is allowed, but an infinite amount of variations could have been realized instead of what one actually sees in nature today. The same goes for many (but not all) of the properties of the space-time arena in which all the interactions are occurring, in particular effective low energy theories (and one seems to be constrained to use only such theories for a long time to come) contain many more free parameters such as masses and some of the couplings. In a string theory one may have expected that all or most of these parameters are fixed in some manner. Actually it is more complicated, for some string backgrounds, some parameters are fixed, while other parameters are not. In addition there seemed to be several string theories leading to even more possibilities.



▲ Fig. 1: a) The potential, familiar from the standard model, has a shape of a sombrero. In the figure, its minima lie on a circle; each point along the circle, can be a basis for a ground state. The physics around each is equivalent. In string theory and in supersymmetric systems flat potentials arise. b) The potential has two orthogonal flat directions. The landscape of the valleys is generically more elaborate. Each point along the flat directions can serve as a basis of a ground state. In many cases, the physics around each ground state is different.



◀ Fig. 2: Branes are lower dimensional solitons embedded in a higher dimensional space. They may come in all possible dimensions. On special types of solitons called D-branes, open strings may end.

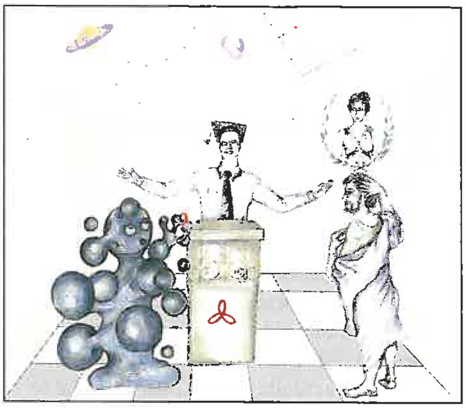
The one and only?

As we have discussed the desire to find the one and only theory encompassing all fundamental physical phenomena seems hard wired in many scientific minds. Is string theory an example of such a theory? Before addressing this question let us reflect upon the limitations of the methods used. What would in fact satisfy the purest (or extremist) of reductionists? A one-symbol equation? Be her desires, what they may be, one should recall that one is using mathematics as our tether into the unknown. This tool, which has served science so well, has its own severe limitations, even ignoring the issue of using differential equations as a tool to probe short distance, a generic problem in mathematics can't be solved. Maybe the NOH principle will eventually have its day, one will run out of interesting questions which have answers, maybe that day is today! (Although some mathematicians suggest using physicists as hound dogs that will sniff their way towards interesting and soluble problems). Having this in mind the key question is posed in the hope that it does have an answer: find the unique theory describing the fundamental forces. There have been ups and downs for the proponents of the one and only string theory. The understanding of the situation has passed several evolutionary stages. From the start it was recognized that one may need to settle for more than only one string theory. It was thought that a distinction could have been drawn between a theory of only closed strings and a theory containing both open and closed strings. A theory with only open strings was realized to be perturbatively inconsistent. Even those theories needed not only a fixed dimension but in addition an extra symmetry, supersymmetry, to keep them consistent. It was very quickly realized that actually there are an infinite varieties of backgrounds in which a string could move. For example, consider 26 dimensional spaces in which one dimension is actually a circle of radius R. It turned out that all possible values for the radius, R, of the circle are allowed. It was then realized that there is a large variety of 22 dimensional compact manifolds in the case of bosonic strings (6 dimensional compact dimensions in the case of the super symmetry), which could accompany the four dimensional Minkowski space-time one is familiar with. Each such compact manifold was called a string compactification. Next it was suggested that actually all possible compactifications are nothing but different solutions/ground states of a single string theory, each of the solutions differing from each other by the detailed values of the physical parameters it leads to. But the ground states have also many common features, such as generically the same low energy gauge group. To appreciate this consider the difference between the potential of the Higgs particles which may describe the mass generation of the carriers of the weak interactions and the effective potential leading to the ground states in string theory. For the electro-weak interaction case the potential has the form of a Mexican hat. The ground state may be described by any point in the valley (figure 1a) but all choices are equivalent, they describe exactly the same physics.

In the case at hand the valley of minima is flat and extends all the way to infinity. Any point along the valley can be chosen as a ground state as they all have the same energy and yet each describes different physics. The manifold describing the infinity of these degenerate ground states is called the moduli space when they are continuously connected (figure 1b).

These connected regions of valleys trace out very elaborate geography and describe different possible solutions of string theory. All known stable ones share in common the property of describing a supersymmetric theory. In such theories each bosonic particle has a fermionic particle companion. It then turned out that there actually are several different types of string theories, each having its own infinite set of degenerate ground states. What made the string theories different were details, most of which are rather technical , which seemed to affect the particle content and gauge symmetries of the low energy physics. There was a stage, in the eighties of the last century, at which some researchers imagined they were on the verge of being able to perform reliable perturbative calculations of a realistic theory containing all the aspects of the standard model. That turned out not to be the case. However, in the process, the geography of many interesting ground states was surveyed. Next, a large amount of circumstantial evidence started to accumulate hinting that all these theories are after all not that distinct and may actually be mapped into each other by a web of surprising dualities. This led once again to the conjecture that there is but one string theory. This time the theory that was supposed to encompass all string theories and bind them was given a special name, M theory. Even in this framework all string theories brought as dowries their infinite moduli space. M theory still had an infinite number of connected different degenerate supersymmetric ground states; these were elaborated and greatly enriched by what are called brane configurations. Branes are a special type of solitons that appear in string theory. They come in various forms and span different dimensions (figure 2). What is common to several of them , is that open strings may end on them.

Thus what was thought to be a theory of only closed strings contains open strings excitations in each of its sectors that contain branes. Moreover, every allowed brane configuration leads to its own low energy physics. In fact there are suggestions that our four dimensional experience results from us living on one or several branes all embedded in a larger brane configuration placed in a higher dimensional space-time. How does that fit with the expectations to have the One and Only string theory? Well, in this framework there is one theory but an infinite amount of possible ground states. Are we owed only one such state? There are those who hope that the vacua degeneracy will be lifted by some yet to be discovered mechanism leaving the one unique ground state. Others are losing their patience and claiming that the NOH principle takes over at this stage, that the theory will retain its large number of ground states (figure 3).



▲ Fig. 3: A match made in heaven? A Democritus is offered in a shot-gun marriage the continuum plus discretum Hydra of universes. Will this Democritus give up his dream of the one and only? Does Hydra think he is good enough for her?

Moreover a crucial ingredient of string theory at present is super symmetry, a beautiful symmetry not yet detected in nature, and even if detected, it seems at this stage to play only a role of a broken symmetry. It is not easy to obtain even remotely realistic models of string theory in which supersymmetry is broken(that is the symmetry between fermions and bosons is broken), a nearly vanishing cosmological constant and light particles whose mass values are amendable to a calculation within 'a reliable approximation'. Candidates for such ground states have been suggested recently; these particular candidates consist of very many isolated solutions living off the shore of the supersymmetric connected valleys. Many of these solutions actually have different values for the vacuum energy and perhaps may thus decay from one to the other. In particular bubbles may form within one configuration, bubbles that contain in them a lower energy configuration. Some researchers would like to see the universe itself, or the bubbles that form in it, as eternal tourists who will end up visiting many of these metastable states. Some suspect that many of these metastable states are stable. Some would encourage brave sailors to take to sea again, as they did in the 80s, and chart this unknown geography, some are trying to make this endeavor quantitative by counting vacua which have a given property, such as a given cosmological constant. This subject is still in its infancy. Many hopes and opinions are currently being expressed, but it would be nice if this issue would turn out to fall within the realm of soluble problems. In that case abstracts of papers in the near future could look something like:

I am reporting that the calculation of the mass ratio between the tau lepton and the electron to be 3417±8. This calculation was done in the sole ground state of M theory. This vacuum was identified after all non perturbative effects were carefully considered and shown to remove all other candidate vacua.

or:

We have shown that the probability of finding a universe, in which the muon to electron mass ratio is 203±2 and the mass ratio of the Z and W particles is 1.13385±0.00026, is 0.05±0.01%. Do you feel lucky today?

The challenges to string theory on the experimental side have been to reproduce the standard model. This has not been done to this day. Many new ideas and insights have been added. Bounds have been shifted several times, one has felt being very near to obtaining the desired model, each new approach seemed to bring one nearer to that goal, but obtaining one completely worked-out example, which is the standard model, remains a challenge for string theorists. Another important issue is that of the value of the cosmological constant. It is usually stated that the small value of the cosmological constant is a major problem. These arguments are centered around some version of a low-energy effective-field theory. That theory could be valid below a few tens of electron volt thus describing only aspects of electromagnetism or it could be at a Tev scale describing both the electroweak interactions. The argument goes on to say that the vacuum energy of such an effective theory should be, on dimensional arguments grounds, proportional to the scale of the cutoff, (the cutoff is set at that energy beyond which the ingredients of the physics start to change) that is evs or Tevs in the above examples. In either case, the value of this vacuum energy, which is the source of the cosmological constant, is larger by an astonishing number than the known bounds on the value of the cosmological constant. The argument is not correct as stated, it is not only the cutoff that contributes to the cosmological constant, all scales do actually contribute to the vacuum energy and if a cutoff should be invoked, it is the highest one, such as the Planck scale, that should be chosen. Moreover, this argument does not take into account the possibility that the fundamental theory has a certain symmetry which could be the guardian of a vanishingly small value of the cosmological constant. Such a symmetry exists, it is called scale invariance, and it has shown to be a guardian in several settings. Scale invariance is associated with the absence of a scale in the theory. There are many classical systems which have this symmetry and there are also quantum systems which retain it. In a finite, scale-invariant theory not only does the vacuum energy get contributions from all scales, they actually add up to give rise to a vanishing vacuum energy. This remains the case even when the symmetry is spontaneously broken. Being a consequence of a symmetry, the vacuum energy contribution to the cosmological constant vanishes also in the appropriate effective theory. What does string theory have to say about that? String theory could well be a finite theory; it is not scale invariant, as it contains a string scale, but if that scale would be spontaneously generated perhaps one would be nearer to understanding the value of the cosmological constant. If that scale is indeed not elementary, one would be searching for the stuff the strings themselves are made off. Such searches originating from other motivations are underway, some go by the name of Matrix Model. Particle physics as we know it is described by the standard model evolving in an expanding universe. The methods used to study string theory are best developed for supersymmetric strings, and for strings propagating on a time-independent background; nature is explicitly neither. What then are the successes of string theory?

Successes: Black Holes, Holography and all that...

A major success described above was to obtain a theory of gravity well defined to several orders in perturbation theory; in addition, no obvious danger signals were detected as far as the higher orders in perturbation theory are concerned, non- perturbative effects being yet to be definitely understood. This issue involves the short distance structure of string theory. String theory is supposed to be a consistent completion of General Relativity(GR). General Relativity suffers from several problems at low energies. String theory, which according to a correspondence principle, is supposed to reproduce GR in some long distance limit, will thus have inherited all the debts and problems of GR in this merger. If it does solve them it will need to do it with a "twist" offering a different point of view. That perspective could have been adopted in GR but was not. This has occurred in several circumstances. One outstanding problem in GR is to deal with the singularities that classical gravity is known to have. These include black holes, big bangs and big crunches as well as other types of singularities. String theory can offer a new perspective on several of these issues. Let us start with black holes. The first mystery of black holes is that they seem to possess thermodynamical properties such as temperature and entropy. This is true for charged black holes as well as for uncharged Schwarzchild ones. In the presence and under the protection of a very large degree of supersymmetry, string theory tools have enabled one to provide a detailed microscopical accounting of the entropy of some black holes. More precisely it was shown in these special cases that the number of states of a black hole is identical to the number of states of essentially a gauge theory. It was possible to count the microscopic number in the gauge theory case and the resulting number of states was exactly that predicted for black holes! These are mostly higher dimensional very cold black holes This has not yet been fully accomplished for uncharged black holes. Black holes have several more non-conventional properties. The above mentioned entropy of a mass M black hole is much smaller, for many types of black holes, than that of a non gravitating system of particles which have the same energy, M. In fact one may suspect that such black holes dominate by far the high energy spectrum of any gravitating system. The Schwarzchild radius of these black holes actually increases with their mass. In general one associates large energies with short distances; in the case of black holes large energies are related also to large distances. A meticulous separation of long and short distances is a corner stone of the renormalization group approach. This is not evident in the case of gravity. One possible implication of this behavior is that in gravitational systems the amount of information stored in a spatial volume is proportional to the boundary's surface area rather then to the bulk volume. String theory provides explicit and concrete realizations of this amazing behaviour. A system of strings moving in particular ten dimensional space-times (of the anti-deSitter type) are equivalent to special highly symmetric supersymmetric non-abelian gauge theories living in four dimensions and experiencing no gravitational forces. Moreover modifying the backgrounds on which the strings propagate by adding defects to them, one finds that strings propagating on certain backgrounds are equivalent to gauge theories in which color is confined. String theory methods are used to perform difficult calculations in hadronic physics. String theory, which was born out of hadronic physics, has returned to pay back its original debt! In addition, remarkable structures have been uncovered in supersymmetric gauge theories using string theory methods. Attempts have been made to confront strings with other singularities. Why should strings respond to singularities in any other way than particles do? A Talmudic story helps explain the manner in which extended objects modify problems associated with point particles. During a seminar, the following question came up: Assume a pigeon (a very valuable animal at the time) is found somewhere, to whom does it belong? The rule is, finders-keepers, as long as the pigeon is found further away, than some determined distance, from the entrance to an owned pigeon-hole. A student raised his hand and asked: "The pigeon is, after all, an extended object, what if one of its legs is nearer than the prescribed distance to the pigeon-hole but the other leg is further away?" The student was ejected from his place of study for raising the question! Strings definitely turn out to soften some harsh singularities which are time independent (called time-like singularities). Strings are also found to punch through singularities which form at particular times such as a big crunch. The analysis of such systems is still at very early stages. However, I would like to note a very interesting, common feature up to the present of all attempts to study, using string theory methods, universes that are spatially closed. In these cases the compact universe is found to be immersed in one way or another in a non-compact universe. The study of strings near these singularities could well be essential to appreciate their properties at short distances. A key ingredient driving some researchers is a new panoramic vista opening up to them. For some it is the precise calculations of experimentally measurable quantities, for others it is the Magic.

Magic

The universe as viewed with string probes is full of magic ambiguities and symmetries unheard of before. In fact most mathematical concepts used to describe the universe are veiled under symmetry.

There are cases for which each of the following concepts becomes ambiguous: distance, the number of dimensions, topology, singularity structure , the property of being commutative or not being commutative. Let us somewhat elaborate on the magic.

- Distance- The simplest example is that of a universe in which one of the dimensions is extended along a circle of radius R. It turns out that an experimentalist using strings as her probes will not be able to determine if the universe is indeed best described by one of its dimensions being a circle of radius R (in the appropriate string scale) or by being a circle of radius 1/R. For point particles moving on a circle of radius R, the energy spectrum has large gaps when R is small, and very small gaps when the value of R is large. For strings, which are extended objects, the spectrum consists of an additional part, that of the strings wrapping around the circle. A point particle can't wrap around the circle. This part of the spectrum is narrowly gapped for small values of R and widely gapped for large values of R; this is because the energy required to wrap a string, which has its tension, around the circle, is proportional to the length of the wrapped string. For an experimentalist, who can use point particles as probes, the distinction is clear, but not so for one using string probes. This is but the tip of the iceberg of an infinite set of ambiguities. Some geometries, judged to be different by point probes, are thus identified by extended probes.

- Dimensions- One could at least expect that the value describing the number of space-time dimensions to be unique. It turns out not to be the case. Ambiguities in calling the "correct" number of space-time dimensions come in several varieties. In string theory there are examples of a string moving in certain ten dimensional space-times which measures exactly the same physics as that measured by a certain point-particle gauge theory in four dimensions. Each system is made out of totally different elementary constituents, one system is defined to exist in ten dimensions, the other in four and yet both reproduce the same observables, the same physics. Another example consists of a strongly coupled string theory in ten dimensions whose low energy physics is reproduced by an eleven-dimensional supergravity theory. This is true for large systems. For small, string scale, systems, more magic is manifested. A string in some cases can't distinguish if it is moving on a three dimensional sphere or a one dimensional circle. So much for non-ambiguous dimensions.

- Topology- Objects that can be deformed into each other without using excessive violence (such as tearing) are considered to have the same topology. The surface of a perfect sphere is the same, topologically, as that of the surface of a squashed sphere, but different, topologically, from that of a bagel/torus. Well, once again that is always true only as far as point-particle probes are concerned. In string theory there are examples in which the string probes can describe the same set of possible observations as reflecting motions on objects with different topologies. In addition in string theory there are cases were one may smoothly connect two objects of different topology in defiance of the definition given above for different topologies. Topology can thus be ambiguous.

- Singularities- A crucial problem of General Relativity is the existence of singularities. Bohr has shown how such singularities are resolved in electrodynamics by quantum mechanics. In GR one is familiar with singularities which are stationary (time-like) such as the singularity of a charged black hole and those which form or disappear at a given instant such as the big bang and the big crunch(space-like). What happens in string theory to black holes, big crunches or big bangs? A good question. Consider first the motion of a particle on a circle of some radius and the motion of the string on a segment of some length. The circle is smooth, the segment has edges. For a point-particle probe the first is smooth and the second is singular. In some cases, viewed by stringy probes, both are actually equivalent, i.e. both are smooth. The string resolves the singularity. Moreover there are black holes for which a string probe cannot distinguish between the black hole's horizon and its singularity. There are many other cases in string theory where time-like singularities are resolved. The situation in the case of space-like singularities is more involved and is currently under study. Some singularities are in the eyes of the beholder.

- Commutativity- The laws of quantum mechanics can be enforced by declaring that coordinates do not commute with their conjugate momenta. It is however taken for granted that the different spatial coordinates do commute with each other and thus in particular can be measured simultaneously. The validity of this assumption is actually also subject to experimental verification. A geometry can be defined even when coordinates do not all commute with each other. This is called non-commutative geometry. There are cases when strings moving on a commutative manifold would report the same observations as strings moving on a non-commutative manifold.

It seems many certainties can become ambiguities, when observed by string probes. Stated differently, string theory has an incredible amount of symmetry. This may indicate that the space-time that one is familiar with is in some sense suited only for a "low" energy description. At this stage each of these pieces of magic seems to originate from a different source. The hard-wired mind seeks a unified picture for all this tapestry. This review may reflect ambiguous feelings; challenges, success and magic each have their share. All in all, string theory has been an amazingly exciting field, vibrating with new results and ideas, as bits and pieces of the fabric of space time are uncovered and our idea of what they really are shifts.

The human effort and closing remarks

One may estimate that about 10,000 human years have been dedicated up to now to the study of string theory. This is a global effort. It tells an amazing story of scientific research. In the mid eighties a regime/leadership change occurred. The scientific leaders who had nursed the standard model, have been replaced by a younger generation of string theorists. Some of those leaders complained that the field had been kidnapped from them. Mathematical methods of a new type were both applied and invented, many pieces of a vast puzzle were uncovered and a large number of consistency checks were used to put parts of the puzzle together tentatively. As in any human endeavor alternative paths are suggested and criticism is offered. I have incorporated in this article some of the serious challenges string theory faces. There are additional complaints, complaints that the new style leaves too many gaps in what is actually rigorously proven, complaints that a clean field-theory description is needed and lacking. Research has been democratized and globalized to a quite unprecedented extent. This has mainly been achieved by making research results available simultaneously to most of the researchers by posting them on the web daily. There are some drawbacks inherent in this evolution. Research attitudes have been largely standardized and the ranges of different points of view have been significantly focused/narrowed. The outside pressures to quantify scientific production better have found an easily accessible statistical database. In particular, it is leading to the assignation of a somewhat excessive weight to the citation count in a variety of science policy decisions. The impact of this is yet to stabilize. All that said, one should notice that phenomenologists and experimentalists do turn to string theory and its spin-offs in search of a stimulus for ideas on how to detect possible deviations from the standard model. The problems string theory faces are difficult; one approach is to accept this and to plunge time and again into the dark regions of ignorance using string theory as an available guide, hoping that it will be more resourceful than its practitioners are. Another approach is to break away from the comfort of physics as we formulate it today and replace some of its working axioms by new ones, such as holography, the anthropic principle or eventually perhaps something else. It seems that the question of the exact nature of the basic constituents of matter will remain with us for still quite some time. My favorite picture is that it will turn out that asking if the basic constituents are point-like, or are one-, two- or three-dimensional branes, is like asking whether matter is made of earth or air. A theory including the symmetries of gravity will have different phases, some best described by stringy excitations, some by point particles, some by the various branes, and perhaps the most symmetrical phase will be much simpler. Several of these will offer the conventional space-time picture, others will offer something new. String theory, either as a source of inspiration, or as a very dynamic research effort that attracts criticism, leaves few people indifferent.

Acknowledgement

I wish to thank S. Elitzur and D. Friedan for many valuable comments on the manuscript.

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Further reading

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Particle physics from the Earth and from the sky: Part II

Daniel Treille, CERN, Geneva, Switzerland

This second part deals mostly with the results and prospects of non-accelerator physics [1], although several of the themes have a counterpart at accelerators. We will underline recent developments and give a concise report on ongoing projects, their main goals and their present status.

Neutrinos

All reviews of neutrino physics [2] recognize that in this domain the time is truly revolutionary. The proof that neutrinos have non-zero masses has been given by the observation and measurement of oscillations* between neutrino species. This effect provides the differences between masses squared, Δm^2. Other processes and techniques are needed to measure their absolute values.

Let us recall that Nature is flooding us with huge fluxes of solar electron neutrinos: this amount to ~$6 10^{10}/cm^2/s$, mostly in the 0-0.42 MeV energy range corresponding to the p-p solar process, but with a tiny fraction, in particular from the ^8B process, extending up to 15 MeV. Nature also provides us with atmospheric neutrinos: these are secondaries from cosmic interactions, giving about twice as many muon neutrinos as electron neutrinos, with useful energies between ~hundred MeV and several GeV. Neutrinos coming from the Earth's radioactivity (roughly equivalent to 10000 GigaW) are about 6 millions /s/cm², but are usually drowned in the flux coming from local reactors. We are immersed in a bath of fossil neutrinos (~$300/cm^3$), at a temperature of ~1.95°K, undetectable directly. Finally we receive neutrinos in the MeV range that originate from Supernova explosions and possible other cosmic sources.

Concerning man-made sources, electron antineutrinos of energies around 4 MeV are produced isotropically from nuclear

* Neutrino oscillations are a quantun mechanical effect. One can identify a particle by the way it is produced or interacts. For instance the positive-pion decay results in a positive muon and a muon neutrino. But one also knows its identity from the knowledge of its mass. Usually these two identifications are the same for each particle. However we already saw in Part 1 that the quarks are "a bit confused about their identity". For neutrinos the situation is more dramatic : the state that we call for instance muon neutrino is not the same as the particle mass state. The muon neutrino should actually be considered as composed of two states of slightly different masses. These states may be thought of as waves which, for a given energy, have different periodicities and oscillate in and out of phase with each other as they travel along. In one phase the pair interacts as a muon neutrino; but when shifted by 90 degrees it makes a tau neutrino. In between, one would see some fraction of each kind.

One can compare neutrino oscillations to the beats of two neighbouring musical notes. Another analogy would be with the rotation of the plane of polarization of light when passing through some optically active materials. The light is composed of right-hand circular and left-hand circular polarized photons, who travel at slightly different speeds in such media. For neutrinos, however, the oscillations happen even when they travel in empty space.