String Theory and Beyond

M. Rudolph
Institut für Theoretische Physik, Univ. Leipzig
Augustusplatz 10/11, 04109 Leipzig, Germany
e-mail: michael.rudolph@itp.uni-leipzig.de

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Abstract
This is the written version of a short talk given at the University of Leipzig in December 1998. It reviews some general aspects of string theory from the viewpoint of the search for an unifying theory. Here, special emphasis lies on the motivation to consider string theory not only as the leading candidate for the unification of gravity and the other fundamental forces of nature, but also as a possible step towards a new understanding of nature and its description within the framework of physical models. Without going into details, some recent developments, including duality symmetries and the appearance of $M$–theory, are reviewed.

1 Introduction or Why Strings?

In the history of science there are only a few examples of theories and thoughts that influenced the way of physical research, mathematics and even natural philosophy to such a lasting extend like the theory of strings. But at the same time it splits the physical community into two nearly disjunct groups: one group whose representatives believe that string theory will provide a right way to the solution of the unifying problem of (theoretical) physics, and a second group whose members are convinced that string theory is nothing but another dead end in the long search for answers in physics.

As a young physicist just entering the active research in this field I do not want to choose one of this groups. In contrast I’m guided by a more diplomatic viewpoint of one of my former lecturers, a mathematician, who said that “string theory has brought many new and fascinating ideas to life and stimulated many new researches, so it cannot be completely wrong.” Thus, unanswered the question if string theory is the last answer to the open problems in theoretical physics today, it appears to be at least a small part of the truth each scientist should strive for. With this in mind it surely cannot be a failure to deal with the fascinating topics arising from it.
In what follows I want to present some arguments which justify this viewpoint. Of course it is not possible to give a detailed introduction into string theory, even at a very coarse level, within this short talk. Therefore I want to restrict to some general aspects (maybe of more philosophical nature) of string theory and its recent status. Indeed, string theory demands such a deep change of the basic principles of our physical understanding, that a more general viewpoint is necessary to experience its beauty and richness.

In that sense, let me start in a somewhat unconventional way compared to common introductionary talks to strings, namely the question about how a grand unifying theory of physics — or the Theory of Everything (TOE) [1], if you want — should look like? I guess up to now nobody knows a detailed answer to this. However, as any theoretical physicist should be able to answer the question about the fundamental forces of nature, he or she should also have at least an opinion about the question asked above.

To break any discussions, here is my coarse answer: A unifying theory should have the potential to explain the wealth of theoretical models and experimental facts within one framework using as few as possible free and unconstrained parameters. However, the unifying theory, i.e. the TOE, should in addition show that there is only a unique way in doing this, implying that there are no free parameters at all.

In the last decades one approach has been proven to be most successful in describing our physical world with its fundamental particles and interactions, the approach summarized within the magic words Quantum Field Theory (for a modern introduction see [2]). Its success is based upon (at least) two major concepts:

1. The concept of symmetry.
   On the classical level nature is described by classical mechanics, quantum mechanics (one should not worry about the word “quantum” in this context, it is merely a convention to view the first quantized quantum mechanics as a “classical” theory) as well as classical field theory (like the Maxwell theory or Einstein’s gravity). The mathematical equations of all these theories are invariant under space–time symmetries, expressing the fact that it should be unimportant when, where or in which position one performs a physical experiment. Moreover, the building blocks of field theories are classical fields which can, in addition, transform under certain global symmetry transformations mixing their internal degrees of freedom, but leaving the underlying equations also unchanged. When this global symmetries are made local, the theory in question takes the form of a gauge theory. Here new fields (gauge fields) appear acting as transmitters of the interaction between the fields which now represent particles. Over the path of second quantization one finally arrives at a quantum field theory. This way opens up the possibility to describe the electromagnetic, weak and strong interactions within a unique mathematical framework. Without doubts, the corresponding quantum field theories (basing upon the gauge symmetry groups $U(1)$, $SU(2)$ and $SU(3)$, respectively) are very successful in describing experimental results (at least in the electromagnetic sector) and deepened our understanding of nature.
2. The concept of convergence.

However, the application of certain quantum field theories to physical problems is mainly based upon one mathematical tool, namely the power expansion with respect to a small parameter. The role of this parameter is taken by the coupling constant whose meaning can be viewed in two ways. First, it describes the strength of the interaction in question. In the formal perturbation expansion the coefficients are given by sums over corresponding Feynman graphs. To be a sensible theory which gives an approximation of any desired accuracy — only this way a comparison with experiments will be possible and meaningful — this power series must converge. However, this only happens if the coupling is sufficient weak. Second, the coupling constant can be viewed as describing the strength quantum fluctuations of the fields modifying the free (classical) theory. Only if this fluctuations are sufficient small one can trust the results of calculations.

But despite the great success in describing physical processes within the framework of up-to-date quantum field theory (compare the theoretical and experimental results related to the electromagnetic force), there appear more and more rocks on the way to a deeper understanding of such phenomena, rocks which become bigger and bigger and cannot be simply thrown aside. Especially the weak–coupling requirement sets substantial limits to the calculation and treatment of physical effects. One of the most cited examples is the quantum field theory of strong interactions, quantum chromodynamics, whose treatment in the framework of perturbation theory has born only few fruits due to its large coupling. On the contrary, fundamental phenomena like confinement are addressed to non–perturbative phenomena meaning that their treatment within ordinary perturbation theory will not be possible. M.J.Duff summarized this with the words [3] “‘God does not do perturbation theory’; it is merely a technique dreamed up by poor physicists because it is the best they can do.” There is nothing more to say!

However, in addition to this principal problem — which does not automatically imply that current day quantum field theory is wrong; it only implies that up to now we do have a better way to describe nature — there is a more substantial problem, namely the occurrence of divergencies in certain diagrams of the perturbation series. The solution came early in the 1930s and 1940s when it was shown that by reshuffling and resumming different Feynman graphs in quantum electrodynamics one can cancel this infinities. This procedure, which is now known as renormalization, also works for other theories, and renormalizability now became one of the main conditions a serious quantum field theory has to fulfil. But more to this a little bit later.

Let us return to the quest for an unifying theory! Despite the problems mainly concerned with our limited ability to go beyond the perturbative level, the first of the above mentioned basic concepts of QFT, namely the concept of symmetry, opened up the way to unify three of the four known fundamental forces of nature. The receipt is very simple: Find a larger gauge group which contains the gauge groups of the known
quantum field theories as subgroups, and construct a new quantum field theory using the common scheme. This receipt has been proven to be very successful, at least at a formal level. Besides the fact that this way, i.e. by enlarging the gauge group, some of the divergencies occurring in the “smaller” theories can be eliminated, the standard model (see Fig.1) of S.L.Glashow, S.Weinberg and A.Salam (for a review see [4]) became a nearly full accepted theory, although some of the main ingredients — for instance Higgs bosons — are still lacking in the laboratories of the experimentalists. Other standard model puzzles, like the fermion masses and charge quantization, are solved to more or less satisfaction within the framework of even “larger” theories, like the Grand Unified Theories (see for instance [5]), although even here new problems arise.

Nevertheless, without going further into details, one is faced with at least two subtleties on this way of unification. First of all it is strictly based upon physical experience. Of course the agreement with everyday physics is the last (or first?) “external consistency” check for a theory. But in the above mentioned cases of electroweak and grand unified models the outputs of physical experiments — namely the fact that there are electromagnetic, weak and strong forces in the nature (I will exclude gravity for the moment) — are the fundamental building blocks. What happens if some experimentalists measure effects of a very weak fifth force whose quantum field theoretical
model does not fit into the unification scheme used up to this point? There are no “internal” or theoretical arguments showing that the fundamental forces known today are the only possible or realized ones. In fact, I believe that in the framework of the common unification scheme such arguments will never be available!

This brings me straight to the second subtlety, which concerns the richness and arbitrariness of possible unifying models: The most popular choices for the “grand unified” gauge group — $SU(5)$ or $O(10)$ — are the simplest ones (hence the name “minimal models”). Much more complex structures are conceivable. Of course, in addition to the “external consistency” checks mentioned above, each of the conceivable models has to obey also “internal consistency” checks (meaning that their mathematical structure and physical interpretation should not lead to contradictions). But this is only of little help for reducing the infinite number of possible grand unified models.

With this in mind, one has to recall the question asked at the beginning in a slightly modified form: Does the way of unification described so far open up a way to a grand unifying theory? Yes, without doubts! But with emphasis lying on the words a grand unifying theory, i.e. a theory which will be only one in the huge space of all possible and allowed unifying models. Moreover, using the receipt sketched above, one does not leave the common framework of QFT. Thus, besides the just mentioned subtleties of more philosophical nature, we are again faced with all other problems of more mathematical nature appearing in the ordinary quantum field theoretical approach. This brings us to the question, whether the description of physical phenomena within the framework of formal QFT and its concrete utilization in perturbation theory provides the correct way to a deeper and more fundamental understanding of nature going beyond the current knowledge?

To make this way of thinking more clear — and to demonstrate that this can be viewed as the birthplace of string theory, at least in a “philosophical” sense — let us take some closer look at quantum field theories and their realization. As mentioned above, within the framework of perturbation theory concrete results are deviated using a formal power expansion with respect to a (hopefully small) coupling constant. The coefficients of the resulting series are sums over appropriate Feynman diagrams. Those diagrams — although very useful and illustrative — bear the first danger, namely, they are just graphs and not manifolds. With other words, at an interaction point the local topology is not $\mathbb{R}^n$. This fact has at least two significant effects. First, there is no restriction to introduce at that interaction points arbitrarily high spins because there is no correlation between the internal lines (indicating the propagation of quantum particles) and the vertices (indicating points of interaction between the quantum particles). That is, point particle theories are accompanied by the problem of an infinite degree of arbitrariness concerning the structure of possible interactions. Of course, demanding renormalizability sets strict constraints to the type of interactions, but, nevertheless, the possibility to write down an infinite number of renormalizable quantum field theories for point particles remains. The second point is, that Feynman diagrams with at least two interaction points are suffered from ultraviolet divergencies which occur if we “pinch” the diagram by shrinking an internal line to zero and, thus, deforming the
local topology of the graph. The occurring infinities can in some cases be removed by renormalization.

However, things become even worse if we try to unify gravity (which up to this point was exclude from the discussion) and quantum mechanics, i.e. if we try to build up a consistent QFT of gravity (for a recent review of present–day approaches see [6]). Here a renormalization procedure does not provide a way out of the appearing difficulties, especially the so–called “short distance problem”. The reason for this bad behavior is related to the fact that gravity couples to energy rather than charge, and that the gravitational coupling (i.e. Newton's constant) in natural units is given by \( g_N = l_P^2 = m_P^{-2} \) (where \( l_P \approx 1.6 \times 10^{-33} cm \) denotes the Planck length and \( m_P \approx 10^{-8} kg \sim 10^{19} GeV \) the Planck mass), thus having the dimension \([\text{length}]^2\) or \([\text{mass}]^{-2}\). For instance, the one–graviton correction to the original gravitational scattering amplitude of two point particles (see first picture in Fig.2(b)) is proportional to Newton’s constant and the square of the typical energy \(E\) involved in the process, \(E^2/m_P^2\). This dimensionless ratio indicates that the strength of this correction is small at long distances, i.e. low energies, but becomes large at higher energies \(E > m_P\). This way the perturbative power expansion with respect to quantum corrections due to graviton exchange becomes useless at short distances, meaning that perturbation theory breaks down.

As already mentioned above, a renormalization procedure, which eliminate unwanted infinities by an infinite redefinition of the parameters of the theory, does work very well for the known quantum field theoretic models of strong, weak and electromagnetic interactions, but cannot be applied to quantum gravity. Here we have a power expansion in a dimensional parameter \(g_N\) and, therefore, we are no longer able to reshuffle and resumme graphs at different order in the power series to cancel the occurring infinities. Thus, the ordinary (naive) renormalization theory does not work, making a quantum field theory of gravity a non–renormalizable theory.

Of course there are several other ways which may lead out of this problems. One path is given by putting calculations on a lattice. I do not want to argue this way any further. Just let me stress that, although it can be very useful, in my opinion the lattice is nothing but a tool to remove substantial difficulties occurring in a concrete calculation; principal problems of the underlying continuum theory coming from a limited understanding or the limits of the used model itself, cannot be solved this way — they can only be thrown to another place. Moreover, in the case of gravity we know that Lorentz invariance holds to a very good approximation in the low energy theory. Thus, if we go on the lattice by making the interaction in the spatial directions discreet, we have to do this at the same time as well in the time direction. This will result in the loss of causality and unitarity, two of the basic demands which a consistent theory has to fulfil.

A second path is given by supersymmetry whose study began in the 1970s as the only possible extension of the known space–time symmetries of particle physics (for a short introduction with emphasis on some modern aspects see [7]) and which may lead to a unifying theory beyond the standard model. As remarked above, an enhancement
Figure 2: New physics appearing when one goes to some higher energy scale. Figure (a) shows how divergencies occurring in the leptonic weak interaction of four–Fermi theory can be removed by resolving the contact interaction at short distances (i.e. high energies) into the exchange of a corresponding $W$ boson. Similar, the potential infinities appearing at high energies due to the exchange of a graviton between two point particles shown in figure (b) can be resolved by replacing the point particles with one–dimensional objects (strings). This provides a natural cut–off scale and, thus, removes automatically all ultraviolet divergencies.

of symmetries by introducing larger gauge groups in a gauge field theory can cancel a large class of divergencies due to Ward–Takahashi identities. Despite the fact that the supersymmetric partners of the known particles are still waiting for their observational discovery, this way it is possible to construct quantum theories of gravity that are finite to every order in the coupling constant. Such models are called supergravity theories.

However, popular models in four dimensions (such as the $O(8)$ or $Osp(N/4)$ model) are either too small to accommodate the minimal $SU(3) \times SU(2) \times U(1)$ grand unified model or too small to eliminate all occurring divergencies.

However, a third and maybe the most “natural” path — at least from the viewpoint of a string theorist — is to interpret the point particle quantum field theories as valid only up to some energy scale beyond which one is faced with new physics [8]. One way to look at this new physics is that it should have the effect of smearing out the interaction in space–time. Thus, by providing a natural ultraviolet cut–off scale, this will soften out the high energy behavior of the theory in question. However, the number of possible ways on which this could be achieved is very limited because the combined constraints of Lorentz invariance and causality set profound restrictions.

Let me make this viewpoint more clear by considering the following simple example. In the four–Fermi theory the leptonic weak interaction (see Fig.2(a)) leads to divergencies which can be removed in the context of Weinberg–Salam theory by resolving the contact interaction at short distances — and thus high energies — into the exchange of a corresponding $W$ gauge boson of weak interaction. Due to internal consistency reasons, this is the only way to solve the short–distance problem of weak interaction. In a similar way (see Fig.2(b)), the exchange of gravitons between two elementary particles, which also leads to potential infinities at high energies due to the short–distance problem when described within the framework of usual QFT (see above), can be resolved by “smearing out” the point particle, for instance by replacing
the point particles with one–dimensional objects — *strings*. The Feynman graphs get replaced by a smooth two–dimensional genuine manifold (called world–sheet) which one cannot shrink to zero without changing the whole topology of the corresponding diagram. Thus, one obtains a “natural” cut–off preventing ultraviolet divergencies; one cannot “pinch” the world–sheet of a string to obtain an ultraviolet divergence due to topological reasons.

This way we are faced for the first time — although in a very naive way — with the concept of strings. But the replacement of point particles by one–dimensional objects has even more consequences as the simple resolution of ultraviolet divergencies. Some of these will be the topic of the next section. Moreover, there we will recall the original question whether this new viewpoint provides an acceptable and maybe deeper answer to the unifying problem of physics bringing us beyond the usual approaches.

### 2 String Basics or *What are Strings?*

Curiously, the original approach to string theory was addressed neither to the solution of the short–distance problem of quantum gravity or the corresponding ultraviolet divergencies, nor the search for a unifying theory. It was discovered more unexpectedly in the late 1960s when Y.Nambu, H.B.Nielsen and L.Susskind made the remarkable observation that the Veneziano model, constructed to explain the abundance of hadronic resonances in experiments, describes the scattering of one–dimensional objects, strings. Up to the mid 1970s this new theory was studied as a possible theory of strong interaction. However, a closer look revealed a lot of unwanted features because Lorentz invariance sets high constraints to make it a consistent theory. So it contained besides tachyons with negative mass–squared a mysterious massless spin–two particle. Despite this, the most striking fact was that the model could seemingly only be consistent in specific dimensions, called “critical dimensions”, which were found to be 26 for the Veneziano model and 10 for the later invented Ramond–Neveu–Schwarz model incorporating in addition to bosons also fermions.

Thus, the idea of string–like particles was dropped out of the physicists minds and forgotten for about one decade. But after the first euphoric successes of ordinary QFT it became more and more clear, that even here one is faced with many new and difficult problems. One of these was the observation that it seemed to be impossible to treat the last of the four fundamental forces, gravity, within a quantum theoretical framework. Each attempt to construct a quantum gravity led to a dead–end. But some physicists remembered a formerly unwanted feature of the forgotten string theory, namely that it provides from the very beginning a massless spin–two particle which could be viewed as the graviton — the transmitter of gravitational force. Every consistent string theory predicts gravity, i.e. every string theory includes “automatically” a quantum theory of general relativity! Moreover, further calculations showed that the quantum corrections to amplitudes are ultraviolet finite to all orders. So 1984, among others, M.B.Green and J.Schwarz continued to study string theory, this time as a leading candidate for a
Figure 3: The point particle of ordinary quantum field theory (a) sweeping out an one–dimensional world–line gets replaced in string theory by one–dimensional objects of Planck–length (b) sweeping out a two–dimensional world–sheet in a higher dimensional target–space.

unification of QFT and gravity.

Then, in the second half of 1984, happens what now is called the first superstring revolution: M.B.Green and J.Schwarz showed that a special type of string theories, called type $I$ string theory, is free from anomalies if the ten–dimensional gauge group is uniquely $SO(32)$. D.Gross, J.Harvey, E.Martinec and R.Rohm discovered a new consistent kind of heterotic (hybrid) string theory based on just two groups: $E_8 \times E_8$ and $SO(32)$. Last but not least, P.Candelas, G.Horowitz, A.Strominger and E.Witten showed that these heterotic theories admit a Kaluza–Klein compactification from ten to four dimensions leading to the known grand unifying model of strong, weak and electromagnetic forces. A great success which showed that string theory is much more than just an exotic idea of some theorists!

So, what is string theory? At this time it was “nothing but” the quantum theory of one–dimensional extended objects, with a length of about $10^{-33} \text{cm}$ — thus far away to be resolved by present day experiments — and only one free parameter, namely the energy per unit length (string tension). These strings move in a higher–dimensional target space and sweep out two dimensional surfaces called world–sheets, see Fig.3. One distinguishes between open and closed strings, leading in the target space to a long strip of finite width or a long tube, respectively. This way string theory can be considered as a conformal field theory (a two–dimensional quantum field theory) where the spatial direction labeling the coordinate on the string is finite. With that in mind, conformal field theories, formerly studied merely as simple toy models, now become the mathematical framework for a realistic theory of unification.

Particles in the target space — and, thus, the particles moving in space–time — are identified with the various eigenmodes of the string. That is, they are nothing but excitations of one fundamental string, just like the vibration modes of a violin string produce various sounds. To be more concrete, the massless modes, which correspond to the lowest excitation, lead to the particles contained in the standard model (i.e. gauge bosons, leptons, quarks), whereas the higher excitations produce an infinite tower of heavy particles with masses of order of the Planck mass (i.e. $10^{19} \text{GeV}$) which, for that reason, will be unobservable in current–day experiments.

However, conformal invariance, modular invariance and cancellation of anomalies in addition to the already mentioned Lorentz invariance puts substantial restrictions on the number of space–time dimensions of the target space as well as the possible
space–time particle spectrum. As in the case of the old Veneziano model, a consistent formulation of string theory including bosonic and fermionic excitations (superstrings) is only possible in a ten–dimensional target space. But despite this drawback it turns out, that in this “critical dimension” there are only five consistent superstring theories — type IIA, type IIB, type I, type \( SO(32) \) heterotic and type \( E_8 \times E_8 \) heterotic string theory — differing in properties like the type of the involved strings (open or closed, oriented or non–oriented), the field content of the world–sheet theory, the number of supersymmetry generators or the ten–dimensional gauge group. The following table and list summarize some of that properties (for much more information there exists a plenty of good literature about strings and related fields; here I want to mention only the standard book about strings — *Superstring Theory* by M.B.Green, J.Schwarz and E.Witten \[9\] — and the latest book — *String Theory* by J.Polchinski \[10\] — which contains some of the most recent developments).

|          | IIA                  | IIB                  | I                    | \( SO(32) \) heterotic string | \( E_8 \times E_8 \) heterotic string |
|----------|----------------------|----------------------|----------------------|---------------------------------|--------------------------------------|
| stringtype | closed oriented      | closed oriented      | non–oriented          | closed oriented                  | closed oriented                      |
| ten–dim. SUSY | \( N = 2 \) non–chiral | \( N = 2 \) chiral   | \( N = 1 \)            | \( N = 1 \)                      | \( N = 1 \)                          |
| ten–dim. gauge group | none                  | none                  | \( SO(32) \)          | \( SO(32) \) \( (Spin(32)/\mathbb{Z}_2) \) | \( E_8 \times E_8 \)                |

1. **type IIA string theory:**
   - *field content of the world–sheet theory:* world–sheet theory is a free field theory containing 8 scalar fields (representing the 8 transverse coordinates of a string moving in nine spatial directions) and 8 Majorana fermions (regarded as 16 Majorana–Weyl fermions, 8 of them having left–handed chirality and the other 8 having right–handed chirality)
   - *massless bosonic spectrum:*
     - \( NS – NS \)–sector: metric, antisymmetric tensor, dilaton
     - \( R – R \)–sector: vector potential, rank three antisymmetric tensor
   - *remarks:*
     - the 8 scalar fields satisfy periodic boundary conditions; the fermions are chosen to obey either periodic (Ramond, \( R \)) or anti–periodic (Neveu–Schwarz, \( NS \)) boundary conditions
     - type IIA string theory seems to be non–realistic in the sense that no realistic QFT in lower dimensions can be deduced from it

2. **type IIB string theory:**
   - *field content of the world–sheet theory:* world–sheet theory is a free field theory containing 8 scalar fields and 8 Majorana fermions (see type IIA string theory)
   - *massless bosonic spectrum:*
• \( NS−NS \)–sector: metric, antisymmetric tensor, dilaton
• \( R−R \)–sector: rank four antisymmetric tensor gauge field satisfying the constraint that its field strength is self–dual, rank two antisymmetric tensor field, scalar

\textit{remarks:}

• as in type \( IIA \) string theory the 8 scalar fields satisfy periodic boundary conditions, whereas the fermions can have Ramond or Neveu–Schwarz boundary conditions
• seems to be non–realistic due to the same reasons as type \( IIA \) string theory

3. \textbf{heterotic} \( E_8 \times E_8 \) \textit{string theory}:

\textit{field content of the world–sheet theory:} world–sheet theory consists of 8 scalar fields, 8 right–moving Majorana–Weyl fermions and 32 left–moving Majorana–Weyl fermions; NS and R boundary conditions for the right–moving fermions

\textit{massless bosonic spectrum:} metric, antisymmetric tensor field, dilaton, set of 496 gauge fields in the adjoint of \( E_8 \times E_8 \)

\textit{remarks:} leads to four–dimensional theories which resemble quasi–realistic grand unified theories with chiral representations for quarks and leptons

4. \textbf{heterotic} \( SO(32) \) \((\text{Spin}(32)/\mathbb{Z}_2)\) \textit{string theory}:

\textit{field content of the world–sheet theory:} world–sheet theory consists of 8 scalar fields, 8 right–moving Majorana–Weyl fermions and 32 left–moving Majorana–Weyl fermions; NS and R boundary conditions for the right–moving fermions

\textit{massless bosonic spectrum:} metric, antisymmetric tensor field, dilaton, set of 496 gauge fields in the adjoint of \( SO(32) \)

\textit{remarks:} leads also to four–dimensional quasi–realistic grand unified theories with chiral representations for quarks and leptons

5. \textbf{type I} \textit{string theory}:

\textit{field content of the world–sheet theory:} world–sheet theory is a free field theory containing 8 scalar fields and 8 Majorana fermions

\textit{massless bosonic spectrum:}

• \( NS−NS \)–sector: metric, dilaton
• \( R−R \)–sector: rank 2 antisymmetric tensor field
• open string sector: set of 496 gauge fields in the adjoint of \( SO(32) \)

\textit{remarks:}

• \( SO(32) \) Chan–Paton factors coupling to the ends of the open string
• looks realistic as a unified theory in the sense that it incorporates internal symmetry groups containing the \( SU(3) \times SU(2) \times U(1) \) of the common grand unified model

This was a indeed great surprise! The infinity of consistent point particle theories in four dimensions on one side faces only five consistent string theories in ten dimensions
Figure 4: From point–particle scattering to string-string scattering. Figure (a) shows the scattering of two particles in ordinary QFT. The shaded region denotes the infinite number of Feynman graphs one has to sum up. One problem arising within this approach is that the number of Feynman graphs increases very rapidly with increasing order, making the calculation of higher order corrections more and more difficult. The picture changes in string theory, figure (b). Here there is only one diagram per order, where the latter is given by the topological genus of the corresponding Riemannian surface. Finally, using the conformal properties of string theory, the calculation of the two particle scattering amplitude can be mapped to the sum over compact Riemannian manifolds labelled by their topological genus, where the incoming and outgoing particles are represented by appropriate vertex operators inserted at the surfaces, see figure (c).

on the other side. What a big step towards a unification! However, at least two points were still open in the mid 1980s and determined significantly the further way of string theory. First, there was the question how to step down from ten dimensions to the real four dimensional world. The second open problem concerned the application of string theory, i.e. the question how to get experimental verifiable results, or at least results which can be compared with ordinary quantum field theory.

The latter is handled within the framework of string perturbation theory, where the far–reaching and well understood topics of Riemannian geometry come into play. This perturbative approach to string theory is mainly based upon the thoughts of ordinary path integral methods — maybe because this is just a first try or due to the lack of any better way. To be more concrete, the string scattering amplitudes are defined as path integrals over the two–dimensional quantum field theory on the world–sheet, with insertions of suitable vertex operators representing the particles being scattered (see Fig.4). This corresponds to the calculation of correlation functions of vertex operators in two–dimensional conformal field theories. That recipe takes automatically into account the infinite number of massless and massive modes which can be exchanged in the scattering process. Thus, whereas in the calculation of a corresponding scattering amplitude within the framework of ordinary point particle QFT all different Feynman graphs has to be taken into account (whose number become very large in higher orders), in string perturbation theory there is only one diagram per order.
Here the order is given simply by the genus of the corresponding Riemannian surface. Potential problems arise because the topological sum is augmented by integrals over conformally equivalent shapes that the Riemannian surface at a given order can have. Indeed, the “correct” integration variables are only those describing conformally inequivalent surfaces which are mathematically hard to describe. This fact makes calculations beyond the one–loop level very difficult. Nevertheless, the genuine absence of ultraviolet divergencies to all orders of the perturbation series was such a strong motivation to overlook this difficulties.

The second and much more potential drawback arose from the question, how to descend from the giddy highs of ten dimensions to the real four–dimensional world or, with other words, how to construct low energy “effective” theories. The magic word which comes into play is compactification: Dismantle the ten–dimensional target space into a four–dimensional “large” piece building up our real world, and some compact six–dimensional manifold “small” enough to vanish at low energies from our view. The good news are, that indeed such compactification schemes exists which lead at low energies to theories exactly of the type wanted, namely the grand unifying model of strong, weak and electromagnetic forces. However, the bad news are, that there are possibly an infinite number of ways to compactify the ten–dimensional string theories, leading to a plenty of different lower–dimensional theories and, thus, predictions for a “real world”. This substantial difficulties are now summarized as the vacuum–degeneracy problem: the parameters or moduli which determine the shape and properties of the compact manifold correspond “physically” to vacuum expectation values of scalar fields in the string theory. During the compactification procedure they enter the obtained effective field theories in lower dimensions as free parameters which are not constrained by any obvious fundamental principles. In contrast, they build up what is called moduli space or vacuum. This way, their values are only determined by choosing — merely “by hand” — a special vacuum or point in this moduli space. On the other hand, these parameters are related to the physical observables of the effective field theories, like mass parameters, coupling strengths of the interactions and so on. With other words, most of the properties of the low energy theory are not determined by the microscopic theory itself, i.e. the terms entering in the Lagrangian, but by the choice of the vacuum structure — and, unfortunately, there are infinitely many ways in doing this. The main problem is that there is no dynamical mechanism that would single out a particular vacuum.

But recall the question asked at the beginning, namely the question about the nature of a unifying theory, and let us summarize what we have learned so far. There are only five consistent string theories in ten dimensions with only one free parameter, the string tension. Moreover, internal consistency dramatically reduces the number of possible low energy spectra and independent couplings — at least compared to ordinary quantum field theories. Despite many difficulties it was shown that three of this five string theories contain the standard model of strong, weak and electromagnetic forces, describing our real world, as a subtheory. Thus, string theory has at least the potential to explain the things that happen in the laboratories of the experimentators, making it
without doubts a unifying theory. However, besides others, the vacuum–degeneracy problem is one of the huge rocks blocking the way to make string theory much more like this, namely the unifying theory going beyond the current understanding of nature. Even this fact has led — for the second time — to the retreat of string theory from an active field of research at the end of the 1980s. Moreover, it splits the physical community into two nearly disjunct groups — one group whose members think that those huge rocks could never be thrown out of the way, and a second group of unshakeable enthusiasts who believed and still believe in the potential strength of string theory.

3 The Future of Strings or Quo Vadis?

The faith of those string enthusiasts became more and more substantial by one fundamental consideration: There are five consistent superstring theories in ten dimensions. Indeed, this number is much lower than the number of consistent point particle quantum field theories in four dimensions, but still too large for the one and only unifying theory. But before choosing one of the string theories to be the “most fundamental” one and asking the question about the meaning of the others, one should spend some time to think about the question in which sense these five string theories are different. A possible answer comes immediately! The formulation of the five superstring theories is based upon the tools of up–to–date QFT, which is only successfully accessible in the framework of perturbation theory. Thus the question arises, if the five different but consistent string theories are merely a result of their perturbative formulation, i.e. the standard way calculations are carried out in QFT, rather than a result of a “deeper” lying and not yet understood principle which says that there has to be five fundamental theories?

Even here the answer became quickly clear at the beginning of the 1990s: Duality. This concept was not new to the physical community. Already in 1931 P.Dirac pointed out the invariance of Maxwell’s equations under the exchange of the electric and magnetic field strength after the introduction of magnetic sources. Over 40 years later, in 1977, C.Montonen and D.Olive showed that this electric/magnetic (or strong/weak) duality is indeed an exact symmetry of the whole QFT. However, although very simple, the idea of duality existed merely as a more hidden playground for mathematical physicists; up to the late 1980s when first indications arose within the context of string theory that duality is much more than just a really nice looking but more or less useless symmetry of the considered field theories. The more light were thrown into the dark, the more it became clear that this special concept of symmetry may be one of the leading principles of nature (especially from a unifying viewpoint), just like its “big” or “little” — depending from the viewpoint — brothers, the gauge symmetries of quantum field theories. It induced what after the inspiration of J.Schwarz [11] now is called the second superstring revolution.

In the last years the investigation of dualities in string theory became one of the main research fields. It turned out that there are three fundamental types of duality
symmetries which are called \(S\)-duality, \(T\)-duality and \(U\)-duality (for further information see \([8, 12]\) and references therein):

- **\(S\)-duality**
  
  This duality describes the quantum equivalence of two theories \(A\) and \(B\) which are perturbatively distinct. Its central idea is, that the strong coupling limit of string theory \(A\) is equivalent to the weak coupling limit of string theory \(B\) and vice versa, see Fig. 5(a). Thus, perturbative excitations of \(A\) are mapped to non-perturbative excitations of the dual theory \(B\) and vice versa, making \(S\)-duality a non-perturbative symmetry. If the theories \(A\) and \(B\) are the same, one has \(S\)-self–duality, see Fig. 5(b). Examples of this type of duality are the equivalence of type \(I\) string theory and \(SO(32)\) heterotic string theory, and the self–duality of type \(IIA\) string theory.

- **\(T\)-duality**
  
  This type of duality relates the weak coupling limit of theory \(A\) compactified on a space with large volume to the weak coupling limit of another theory \(B\) or \(A\) itself (self–duality) compactified on a space with small volume and vice versa. Hence \(T\)-duality is a perturbatively verifiable symmetry (see Fig. 5). Examples are the duality between type \(IIA\) string theory compactified on a sphere \(S^1\) of radius \(R\) and the type \(IIB\) string theory compactified on \(S^1\) with radius \(R^{-1}\), as well as the self–duality of each of the heterotic string theories when compactified on \(S^1\) with radius \(R\) and compactified on \(S^1\) with the inverse radius \(R^{-1}\).

- **\(U\)-duality**
  
  This third type of duality symmetries combines \(S\)- and \(T\)-duality, making theory \(A\) compactified on a space with large (small) volume is dual to the strong (weak) coupling limit of another theory \(B\). Thus, \(U\)-duality is also a non–perturbative duality.

However, a closer look also reveals one of the current main problems with this very powerful tool of duality symmetries, namely the question how to perform tests of duality conjectures. Because its historical appearance, up to date we do not have an
independent description of string theories at strong couplings. Thus, an exact proof of
dualities, especially of $S$– and $U$–duality conjectures, is still lacking. The only way to
test it is by working out various consequences using certain constraints and symme-
tries of string theory. Up to now there are two main streams which one follows. The
first is the analysis of the low energy effective action, obtained from a perturbatively
formulated string theory by restricting to the lowest lying (massless) excitations. Most
of the duality conjectures are tested this way by comparing the effective actions of two
string theories compactified on some manifold. However, although very simple, this
method provides only a very crude test of duality.

Much more exact are tests involving the spectrum of the corresponding string the-
tories. Here the attention lies on a very special part of the spectrum in superstring the-
ories, namely the so–called BPS–saturated states — or, shorter, BPS states — named
after Bogomol'nyi, Prasad and Sommerfeld. Such states are invariant under parts of the
underlying supersymmetry transformation and characterized by two important proper-
ties: First, the mass of a BPS state is completely determined by its charge as a con-
sequence of the supersymmetry algebra. Hence the properties of such states are not
modified by quantum corrections, independent how strong they are. Second, the de-
generacy of a BPS multiplet is independent of the point chosen in the moduli space.
With other words, the degeneracy at any value of the string coupling is the same as that
at weak coupling, making it possible to compare perturbative and non–perturbative
formulations. This provides a non–trivial test of the corresponding non–perturbative
duality conjectures. However, the detailed mathematical realization of such tests is
often very difficult — but we are just at the beginning on the way to an understanding
of non–perturbative phenomena.

Nevertheless, despite the lack of rigorous proofs of duality conjectures, the “old”
picture of string theory at the end of its first revolution changed dramatically when du-
ality pushes some rocks out of the way to a deeper insight into the underlying structures
of string theory. It became clear that the five perturbatively distinct superstring the-
ories are connected by a whole net of duality symmetries, whose higher–dimensional
part is depicted in Fig. 7. With other words, it was shown that by compactifying any
one of the five perturbatively distinct superstring theories on a suitable manifold and

Figure 6: $T$–duality. Inside the shaded regions the coupling is weak and perturbation theory is valid.
Figure (a) shows how $T$–duality relates the weak coupling regime of theory $A$ (compactified on a space
with large volume) to the weak coupling regime of another theory $B$ (compactified of a space with small
volume). If both theories coincide one speaks of $T$–self–duality, see figure (b).
Figure 7: The net of string dualities in higher dimensions. As it is shown, the perturbatively different string theories in ten dimensions are connected by duality transformations using certain compactifications. Moreover, in eleven dimensions a new theory arises, which is called $M$–theory and whose compactification on the circle $S^1$ or the finite line interval $I$ gives rise to type $IIA$ and $E_8 \times E_8$ heterotic string theory, respectively.

then de–compactifying it in another manner, one can reach any other of the five theories in a “continuous” way. The supposition arose that the five superstring theories in ten dimensions are just different limits of one unique and, thus, more fundamental theory. This theory was called by A.Sen $U$–theory, where the “$U$” stands for “Unified” or “Unknown” [13].

In fact, the apparently different string theories and their compactifications can be viewed as just different limits in the parameter space (moduli space) of this central theory where the coupling is weak, as shown in Fig.8. Here, the shaded regions correspond to weakly coupling limits in the moduli space, giving rise to the perturbatively different string theories. Moreover we see, that most of the regions in the moduli space of $U$–theory are not perturbatively accessible. One special limit, namely the limit where the coupling goes to infinity, is now known as $M$–theory. Here, to speak with the words of E.Witten, “‘$M$’ stands for ‘Magical’, ‘Mystery’ or ‘Membrane’, according to taste’” — or “Mother” (A.Sen). It was first introduced by E.Witten on a talk given at the University of Southern California in February 1995.[4] Its discovery during the investigation of the strong coupling limit of type $IIA$ strings was a real sur-

\footnote{At this point I want to note that $M$–theory is often identified with $U$–theory. However, here we shall keep in mind the distinction between the two: $M$–theory is a certain limit in the moduli space of the more fundamental $U$–theory, which also inherits the known weakly coupled string theories as certain limits.}
Figure 8: The moduli space of $U$–theory, the unified string theory. Here, the shaded regions denote the weak coupling limits in this moduli space and, thus, refer to the five perturbatively distinct string theories. In the other regions such a description in terms of a weakly coupled theory — where perturbation theory is allowed — is not possible. One of this corners is the limit where the coupling goes to infinity, which now is called $M$–theory.

It turned out that in this limit certain non–perturbative objects, now called $D0$–branes, appear, forming a continuous spectrum and effectively generate an extra eleventh dimension. This way, the type $IIA$ string theory at ultra–strong coupling gains eleven–dimensional Lorentz invariance.

However, at present not very much is known about $M$–theory. As shown in Fig. 7, it arises in certain compactifications of type $E_8 \times E_8$ heterotic and type $IIA$ string theory. Moreover, the low energy limit of $M$–theory is given by the well–known eleven–dimensional $N = 1$ supergravity, which in some sense can be viewed as the unique (although non–renormalizable) “mother” of all theories. But due to the fact that $M$–theory is defined as that limit in the moduli space where the coupling reaches infinity — therefore it does not possess any longer a coupling constant or another free parameter — up to now one does not have an appropriate mathematical description or, at least, a deeper physical understanding of this theory beyond the perturbative level given in the framework of its low–energy supergravity limit. First attempts to overcome this lack are stimulated by the observation that $M$–theory in a certain frame, namely the infinite momentum frame, is equivalent to a quantum mechanical system in the sense that scattering amplitudes in $M$–theory correspond to correlation functions in this quantum mechanical system. The fundamental degrees of freedom of this quantum mechanical system are given by $N \times N$ matrices, and its Hamiltonian is that of a certain supersymmetric quantum mechanics, where at the end of the calculation one has to take the limit $N \to \infty$ (see [3] or [15] for a short introduction).

Although not fully understood, the main power of $M$–theory lies in its non–per-
Figure 9: The net of string dualities in higher dimensions manifests also in lower dimensions after suitable compactifications. Due to the plenty of possible compactifications, the resulting moduli space takes a much more complicated structure. In general, each region of the four–dimensional moduli space can be reached in several “dual” ways via compactification of the higher dimensional theories. Moreover, non–perturbatively all these vacua turn out to be connected (for instance by extremal transitions) and, this way, form a continuous web.

turbative description. Maybe no physicist doubts that perturbation theory is only and can only be a small step towards a more fundamental understanding of nature. \( M \)–theory itself is necessarily (by definition) a non–perturbative and, thus, an exact theory without any free parameters from which by duality transformations different regions in the moduli space of \( U \)–theory are accessible. This moduli space, which describes the higher dimensional theories, is just a small piece of a much more extended moduli space obtained by compactifying the higher–dimensional theories on certain manifolds. Due to the huge amount of allowed ways to compactify down to lower dimensions, the resulting moduli space is significantly more complicated, as it is schematically depicted in Fig.9 [16].

However, even in lower dimensions one is faced with the lack of an exact mathematical description of string dualities, especially of non–perturbative symmetries. But one very important viewpoint also applies here: All theories in lower dimensions — which can be obtained via compactification from the five ten–dimensional superstring theories — seem to be connected by duality symmetries, either by continuous transformations, extremal transitions or the detour over higher dimensions. With other words, instead having to choose between many four–dimensional string theories (each one equipped with its own moduli space) — which, among many others, also contain the standard model of strong, weak and electromagnetic forces as a possible solution — we really have just one theory with, nevertheless, very many facets. Although this is
only of little help to solve the vacuum degeneracy problem mentioned above (because it does not restrict the ways how to compactify), it gives for the first time in the history of physics (even the whole science) a hint how a “realistic” unifying theory should look like: Each of the existing mathematical and physical models describing different aspects of our nature (and, thus, bearing some truth in it) can be viewed as just different aspects — different realizations, if you want — of one and only one underlying theory. This is similar to the concept of effective theories which can be obtained from a more fundamental exact theory. All those different effective models are adapted to describe distinct aspects within their limits. But instead of trying to unify the small number of realized or used effective theories, one can look for the underlying exact theory, which in the case of strings is given by the parameter–free $M$–theory. This indeed is a great discovery, not just from the viewpoint of the search for a real unifying theory (or TOE). The concept of duality symmetries opens up a complete new way of thinking about strings, unifying theories and the physical description of the nature as a whole.

But this new way of looking at physical theories (namely string theories in various dimensions) in some sense as just different realizations of one and the same exact theory (adapted to the physical phenomena they intended to describe and only valid within certain limits) is only one part of the story. The concept of duality and the search for proofs of duality conjectures has led to completely new developments also in another sense: Some formerly rather sharp separated and more or less independent investigated aspects of (mathematical) physics — like classical and quantum properties of field theories, solitonic solutions of classical field equations and the fundamental degrees of freedom of quantum theories, singular classical objects (for instance black holes) and new types of topological defects, namely $D$–branes and $p$–branes — are now starting to appear in a new and unexpected unifying light.

For instance, as mentioned above, duality often relates a weakly coupled (string) theory to a strongly coupled (string) theory. This way a perturbative expansion in one theory contains information about non–perturbative effects in the dual theory and vice versa, making duality a property of the full quantum theory and not just of its classical limit. However, because quantum objects in one theory get mapped via the duality transformation to rather classical solutions, like solitons, the distinction between classical and quantum objects loses its significance. At the same time, under a certain duality map, an elementary particle in one theory can be transformed into a composite particle in the dual theory and vice versa, making the strict classification of particles into fundamental and composite ones less meaningful.

Another way of development is given by the explicit occurrence of higher dimensional objects within the framework of string theory. A special type of solutions of the string field equations are $p$–dimensional objects, called $p$–branes, whose quantum dynamics can be described by a $(p + 1)$–dimensional QFT. Here a $p$–brane denotes a static configuration which extends along $p$ spatial directions (tangential directions) and is localized in all other spatial directions (transverse directions). Thus, a 0–brane is a point–like object (particle) which sweeps out a one–dimensional world line. Analo-
A special type of $p$–branes, namely topological defects on which the ends of a string can be trapped, are called Dirichlet $p$–branes or, simply, $D$–branes (see for instance [17]). They were first discovered in the study of perturbative dualities of string theories and manifest itself as extended solitonic objects. In the presence of these solitons there can be open string states whose ends lie on these extended objects, see Fig. 10. This way, the open string dynamics can describe the internal dynamics of the $D$–brane to which it is attached, yielding a quantum field theory of higher dimensional objects. Such field theories were formerly considered to be inconsistent and suffered from deep anomalies. Indeed, it is now known that in addition to the fundamental strings, non–perturbative string theory must contain a rich spectrum of branes in order to be consistent. Thus, also the strings lose their significance as the fundamental objects of string theory; one has to describe the underlying theory using in addition a plenty of other objects. This is without doubts a further step towards a real unification! String theory was just our entrance to that new and fascinating description of nature where different aspects magically get unified.

This unifying concept of formerly nearly unrelated fields of theoretical physics becomes most obvious in the case of the black holes of general relativity and the solution of the black hole information paradox within the framework of string theory. Black holes are long known as singular solutions of the classical field equations of gravity. In the early 1970s it was found that black holes also obey laws analogous to the laws of thermodynamics. This opened up the way to a “quantum theory” of black holes, which was initiated by the famous discovery of the Hawking radiation in 1975: Black holes radiate as black bodies at the corresponding temperature. In addition, the entropy of a black hole was found to be given by the Bekenstein–Hawking formula. However, until recently there was no known way to count the states of a black hole to give a
Figure 11: A state of many $D0$–branes with strings attached. When the coupling becomes strong, the $D0$–branes get modified by gravitational self–interactions in such a way that a classical black hole space–time becomes the right description.

A microscopic interpretation of this entropy (as it is known from conventional statistical mechanics). Moreover, due to the absence of such a microscopic description in the case of thermal radiation from a black hole, one is faced with the so–called black hole information paradox: A black hole of a definite mass and charge can be formed in a very large number of ways. The final state after its evaporation is given by black body radiation and does not depend on how the black hole was formed. That is, many initial states evolve into a single final state. But this violates the known laws of quantum mechanics and thermodynamics!

A lot of solutions to this problem were proposed (for a short summary see \cite{5}), but only recently a solution was presented which does not lead to a change of the basic laws of physics (such as the laws of quantum mechanics or the locality principle in QFT) and to the introduction of mystical states remaining after the evaporation of the black hole. This solution comes within the framework of string theory: For a special type of charged black holes, so–called extremal black holes, the counting of microscopic states, namely BPS states, were carried out. It was shown that this black holes have a perturbative description in terms of a collection of $D$–branes at weak coupling. When the coupling becomes strong and, thus, this perturbative description breaks down, the $D$–branes become modified by gravitational self–interactions in such a way that a classical black hole space–time appears. At weak coupling one uses perturbation theory to count the number of quantum states of the strings propagating along the “surfaces” of the $D$–branes. Due to the fact that the degeneracy of BPS states does not change when going to strong couplings, that number must also be valid for strong coupling, i.e. the black hole space–time. As a surprise it turned out that the answer one finds corresponds exactly to the Bekenstein–Hawking entropy of the black hole! Thus, string theory provides a “natural” microscopic explanation of the black hole entropy without giving up too much fundamental concepts of physics. Moreover,
one can compute the rate of Hawking radiation from these black holes due to quantum scattering processes inside the hole. Even here this rate agrees with the Hawking radiation.

Although the calculations are carried out only for the specific type of extremal black holes one hopes that this arguments can also be applied to the general case. No matter how the results will look like, this very concrete application of string theory shows that it is more than just an idea thought up by some “crazy” theorists. String theory opens up the possibility to understand up–to–now unsolved problems in theoretical physics, and without doubts it sheds more light into the darkness surrounding the way towards a more fundamental understanding of nature.

4 Resume or What have we learned so far?

This brings me straight to the question of what the conclusion of all this might be. Of course, currently no one can give a satisfying answer to this question because the analysis of that new and amazing discovery called string theory just started. But some general aspects and concepts became already clear:

• String theory, originally regarded as an ultraviolet finite way to unify classical gravity with quantum mechanics, now became a — or the (at least from the viewpoint of a string theorist) — leading candidate for an unifying theory of the known fundamental forces of nature. Within its framework, the concept of duality symmetries arose to one of the main physical principles (not only of string theory, but of nature at all), showing that the five perturbatively different superstring theories in ten dimensions (which are the result of the first superstring revolution in the 1980s) can be unified and are just different facets of one unique underlying theory, called \( U \)–theory.

• In the moduli space of \( U \)–theory there appears in the limit of infinite coupling a new eleven–dimensional theory, called \( M \)–theory, with no free parameters or couplings. In the mathematical and physical understanding of this exact theory, whose description can only be achieved non–perturbatively, might lie the key to the TOE.

• Duality symmetries are not restricted to higher dimensions but also appear after compactification in lower dimensions, even in the real four–dimensional space–time. They lead to remarkable symmetries between formerly unrelated physical theories and models. As in the case of string theories in higher dimensions, duality shows that lower–dimensional effective theories are just different limits in the moduli space of a unique theory, adapted to describe certain physical aspects of nature.

• The investigation of dualities opened up completely new ways between formerly rather unrelated or strictly distinguished aspects of theoretical physics (classical
and quantum, composite and elementary, smooth and singular, strings and $p$–branes).

- Non–perturbative dualities take us beyond string theory and the perturbative description of nature.

To summarize, string theory has proven to be a unifying theory allowing a deeper understanding of the leading physical principles of nature. Moreover, the developments of the last years have shown that it provides powerful tools whose application will bring us beyond the current description of our world within the framework of physical theories. Thus, without doubts, string theory opens up a possible new way towards one of the great goals of theoretical physics, namely the formulation of the unifying theory — or TOE. Even if that hope will never come true in the future, string theory has shed and will shed light into many formerly dark areas of theoretical physics. So, it cannot be completely wrong!

String theory is — at least compared with the ordinary quantum field theoretical researches — a very young development; we all (especially those who do not believe in that “crazy” string theory) should give it some time to prove itself useful . . .

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