Concepts Introductive to String Theory[*]

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Abstract

English.

Known physics is described by a theory (the standard model), that concerns the behaviour of many fields. For coherence with quantum mechanics, the classical theory of these fields is replaced by one, that takes into account their particle nature. One puts the problems to unify the fields of the standard model, and to find a satisfactory theory of gravitation, which the standard methods have many difficulties to quantize. Seemingly, string theory solves both these problems, but it also is not free from serious complications, which are intrinsic to field quantization.

Italiano.

La fisica finora nota è descritta da una teoria (modello standard), che si occupa del comportamento di numerosi campi. Per coerenza con la meccanica quantistica, la teoria classica di questi campi viene sostituita da una, che tiene conto della loro natura corpuscolare. Si pongono i problemi di unificare i campi del modello standard, e di trovare una teoria soddisfacente della gravitazione, che i metodi usuali hanno difficoltà a quantizzare. Apparentemente, la teoria delle stringhe risolve entrambi questi problemi, ma anch'essa non è immune da serie complicazioni, intrinseche alla quantizzazione dei campi.

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[*] http://pfabbri.interfree.it/string_en.pdf

[†] http://pfabbri.interfree.it/string.pdf

Contents

1 The standard model

Till now known physics is very well represented by a theory, named the standard model [5] [1] [2] [3] [11], which describes the behaviour and the interactions of a certain number of fields: gravitational, electroweak of isospin, electroweak of hypercharge, gluonic, nine leptonic fields, nine quark fields, and one Higgs field. For the application to cosmology, one perhaps needs to add others of them, associated to inflatons and to dark matter.

Almost all of these fields possess several components, which are turned, one into the other, by some transformations which are symmetries of the theory, that is which leave it unchanged. This is analogous to the components of a vector, which are transformed one into the other, by a rotation of the reference system, which is a symmetry of all physical laws ("isotropy" of space). As space is isotropic, rotating the vector also, rather than the reference system, changes its components, but does not its properties. One cannot say the vector, oriented along a different direction, is another entity. It is always the same, observed from another point of view.

In the same way, different components, of one single field, may look like different fields, but they are the same entity. This is what happens to electric and magnetic fields in the electromagnetic one, to electromagnetic and weak fields in the electroweak ones, to fields associated to neutrinos and to their leptons in the left-handed leptonic field. One then sees that symmetries can be used to unify fields. But, in order that entities, which are in reality the same, may appear different, one needs a mechanism that "breaks" the symmetry. In the case of electric and magnetic fields it is constituted by low ordinary velocities, which hide the phenomena of electromagnetic induction. In the case of electroweak symmetry breaking, it is the fact that, when energy becomes sufficiently small, the Higgs field is forced to choose to assume, in the vacuum, one certain value. The possible values respect, on their whole, the symmetries, but when, randomly, one of them is selected, the theory is not, apparently, symmetric any more.

Symmetries also provide us with a natural way to generate interactions. Let us consider special relativity. It may be thought of as the symmetry, of physical laws, under Lorentz transformations. The latter are rotations, in space-time, by an angle that is the same everywhere. Therefore they are called "global" transformations. If we believe in the principle of relativity, limiting it to "inertial" systems seems to be insufficient. Therefore, we are induced to postulate the invariance, of physical laws, under any coordinate transformation, that is under rotations and translations, the parameters of which vary, in an arbitrary way, from a space-time point to another. Therefore they are called "local" transformations. As soon as the relativity principle, from special, becomes general, an interaction rises: gravity. In the same way, when any symmetry, from global, is promoted to local, interactions are generated. It is what happens for most of the interactions of the standard model.

The theories, that take advantage of this mechanism, are said "of gauge", because making a local symmetry transformation corresponds to change the gauge one is working in. In all these theories, as for the vector potential in electromagnetism, variables are redundant in respect of the physical situation one wishes to describe. Electromagnetism is a gauge theory too (perhaps the simplest).

The local (or "gauge") symmetries of the standard model are: that under changes of coordinates (or "diffeomorphisms"), and three called, for technical reasons, $U(1)$, $SU(2)$, $SU(3)$. The corresponding interactions, or forces, are, respectively, the gravitational one, the hypercharge electroweak one, the isospin electroweak one, and the strong one. The fields ("gauge" fields) mediating such forces are the gravitational field, the hypercharge electroweak one, the isospin electroweak one, and the gluonic one. The leptonic fields, the quark ones and the Higgs one are also transformed by all or part of the symmetry transformations, and undergo the corresponding forces. However, in the standard sense, they are not the mediators of such forces. The Higgs field also interacts with the leptonic and the quark ones, by forces non-derivable from a symmetry principle.

For coherence with quantum mechanics, one needs to replace the classical theory of the fields (waves) we have cited, with something that takes into account their particle nature.

2 Field quantization

The classical theory of a field provides us with some partial differential equations for it ("equations of motion"). They allow us to determine its time evolution, and the eventual constraints that initial conditions must satisfy.

To quantize such a theory, the most direct idea [4] . . . [15], Appendix A of [36] is to try to derive these equations from a least action principle, with a Lagrangian functional of fields and of their time derivatives, and to deduce, from it, a Hamiltonian, functional of fields and of momenta conjugated to them. Translating fields into multiplicative operators, and momenta into functional derivatives in respect of fields, one then obtains a Hamiltonian operator, which can act on a wave functional to determine its time evolution.

In the practice, it is convenient to expand fields and their conjugated momenta into Fourier integral, and, from their commutation relations, to deduce those for Fourier coefficients. Thus, they result to be raising and lowering operators, which can be thought of as creators or destroyers of particles (quanta of the field). The corpuscular interpretation of the field, characteristic of quantum mechanics, is thus recovered. The free (or deprived of terms representing interactions) Hamiltonian is in agreement with de Broglie relation for energy, and, if one computes the quantity of motion associated to the field, it also corresponds to the other de Broglie relation.

Substituting, to fields and momenta, their Fourier expansion, in the Hamiltonian (complete of the interaction terms), one then obtains an operator built with creators and annihilators, which, acting on the state vector of the system, creates new particles, destroys some old ones, or simply changes their quantity of motion, all of this with definite probability amplitudes. The quantum evolution of the system is in this variation of the number, the type and the quantity of motion of particles.

All of this is valid in line of thought, but, putting it into practice, one must face very serious obstacles [16]:

1. In the majority of theories of practical interest, in particular in gauge theories, the Lagrangian does not contain the time derivative of some fields. This implies that momenta conjugate to such fields are zero. From one point of view, this impedes to satisfy the canonical commutation rule between such momenta and the fields conjugate to them, from the other, it makes the Hamiltonian ill-defined, because it is not possible to invert the expression of momenta, in order to extract the time derivatives of fields and to insert them into the Hamiltonian. By other ways also, one is not usually able to write a Hamiltonian, from which Hamilton equations fully coherent with the Lagrangian ones result.

2. At the moment of translating the classical Hamiltonian into a quantum operator, there is ambiguity in the choice of factor ordering in the

various terms, because it is possible that the quantum operators do not commute.

In principle, this problem is very grave [17], because any operator $F(q,p)$, with p momentum conjugate to q, can be rewritten

$$F(q,p) - \frac{i}{\hbar}(qp - qp)G(q,p), \tag{1}$$

with $G(q,p)$ arbitrary operator. Changing the factor ordering, (1) becomes

$$F(q,p) - \frac{i}{\hbar}(qp - pq)G(q,p) = F(q,p) + G(q,p), \tag{2}$$

and differs from $F(q,p)$ by an arbitrary operator. It is then possible to transform an operator into any other, only changing the factor ordering.

The requests that the term we are writing has the right symmetries, the correct classical limit and is hermitian, unitedly to the Occam razor (the philosophical principle, according to which, one must look for the simplest explanation of phenomena), permit to reduce the possibilities. However, they do not usually suffice to solve the problem.

In the "path integral" approach, this ambiguity is replaced by that on the choice of the measure of the integral itself.

3. The transition amplitudes, from a state to another, computed at the perturbative order lowest in the parameters of the theory that regulate interactions ("coupling" constants), give easily interpretable results. But subsequent corrections yield, besides true amplitude corrections, corrections to effective values of parameters (electric charges, masses, ...). These latter corrections are usually infinite. To have the finite value, experimentally observed, one then needs to suppose that the true ("bare") values, of parameters, are also infinite and opposite to corrections, so as to compensate them and to leave a finite difference ("renormalization"). These differences are fixed by the experimental values.

   Unfortunately, even terms, with their infinite multiplicative constant, absent from the original Lagrangian, may rise as corrections. For them, we do not know what value the experimentally observable parameter must have. Its presence is a point the theory leaves undetermined. The greater the number of such points is, the less the predictive power of the theory itself is, and the less it is attracting as a fundamental theory (because vitiated by many arbitrary choices). In some cases, the number of parameters, that remain undetermined, can even be infinite. In this case, one, perhaps improperly, says the theory is not renormalizable.

4. The infinite values of parameters, which require renormalization, originate from integrals, over the quantities of motion of particles, which diverge in the great quantity of motion region. To effect renormalization one previously needs to make such integrals finite, cutting off their upper extreme in some way. At the ending of the process, such cut-off will be removed, giving back the original theory. The method, by which one makes these integrals finite, is called "regularization". Various possible types of regularization exist, and, seemingly, the choice of a regulator, rather than another, also influences the results of the theory.

5. There is no certainty that symmetries, present in the classical theory, are preserved passing to the quantum one, and some of them, as the Lorentz one or the gauge ones, represent physical principles in which we believe.

Problem 1 (the lack of time derivatives of some fields in the Lagrangian) is faced fixing the gauge, or realizing the constraints, present in these cases, among the dynamical variables. However, in the quantum case, these operations are not easy to understand, and, sometimes, to put into practice.

The presence of symmetries (problem 5), if they are not manifest, must be tested (with a lot of labour) on the obtained theory, and can or cannot be confirmed. If the symmetry falls, and one cannot renounce it, the theory, if it is possible, should be rejected.

The ambiguities, originating from factor ordering or from the measure of the path integral (problem 2), and from the choice of regulator (problem 4), can be absorbed into the value of the observable parameters at the moment of renormalization (problem 3).

Problem 3 is solved, if one wills that the theory is manifestly renormalizable, and if its classical limit permits to do this. In fact, the number of such theories is restricted. Varying few experimentally determinable parameters, one obtains all quantum theories consistent with the given symmetries and with the correct classical limit.

In the absence of gravity, the standard model is manifestly renormalizable. Unfortunately (or luckily) gravity is not.

If one is able to conceive a theory that does not need renormalization, ordering ambiguities often reappear.

3 Beyond the standard model

In the light of the two previous sections, one puts the problems to unify the fields that the standard model still leaves uncorrelated, and to find a satisfactory quantum theory of gravitation.

Generalizing $U(1)$, $SU(2)$ and $SU(3)$ to a symmetry that includes them as a special case, it is possible to unify the hypercharge electroweak field, the isospin electroweak one and the gluonic one [1] [18] [3]. They become components of a new, more general, gauge field, of which components absent from the standard model are also part. The leptonic fields are also unified to quark fields. The new symmetry can be of various types (some names are $SU(5)$, $SO(10)$, $E6$), and must be broken by a mechanism analogous to that for the electroweak symmetries ($U(1)$ and $SU(2)$). For this, one needs to add new Higgs fields.

This picture is named “grand unification”.

The unification of all the fields, into a single entity, is more difficult, and is named “superunification” or “theory of everything”.

Let us begin, trying to bind also gravity to the other gauge fields.

The most promising way is to make the hypothesis that it is the only really existing gauge field, but that the space-time dimensions are in greater number than the four known ones. The exceeding dimensions are not observed, because, in the directions along them, space-time is curved to form a subspace (“internal space”) of very small extension. Only along four directions, space-time extends to infinity or nearly. As an example, think of a two dimensional space, closed to form the surface of an undefined cylinder. If the circumference, base of the cylinder, has a sufficiently small radius, the cylinder appears as a line, one dimensional rather than two dimensional.

In the passage to the described configuration (“compactification” or “dimensional reduction”), some of the components of the gravitational field distinguish themselves from it and form gauge fields of another type, the symmetries of which depend on the symmetries of the internal space. If it is a circumference, the symmetry is $U(1)$ and can, for example, account for electromagnetism, which has the same symmetry of the hypercharge electroweak field. The components of the gravitational field, that distinguish themselves, are those with one index corresponding to the internal space directions. From the four dimensional point of view, they appear as vectors. In the process, the components, with both indices along the internal directions, also distinguish themselves. They appear as scalars, and can originate Higgs fields, inflatonic ones, or other ones.

The compactification may be regarded as a symmetry breaking.

It may seem unlikely that the universe has assumed the form of such a long and thin filament. But, if, by random fluctuation, a small size filament had formed at the origin of the universe, known four dimensional physical laws would have been valid in it. Therefore it would have expanded to the present dimensions in the way we know.

Temporarily, the only variable of the described mechanism (said "of Kaluza-Klein") [19] [20] [34] is the form of the internal space. It can already originate various possibilities, but, in the theory we are introducing, other entities ("branes", "fluxes") are also added. Thus, the number of possible results is enormous, and, in practice, any four dimensional theory can be obtained. As the standard model has some properties, very unlikely at first sight, and needful for the existence of life, one thinks a great number of universe-bubbles has formed, and continues to form, by random fluctuation. Each has its apparent physical laws, and we inhabit one of the few compatible with life ("anthropic principle") [21] [22] [23] [24]. The continuous bubble formation, and their successive expansion, from regions of microscopic dimensions to enormous ones, which appear as distinct universes, is in accordance with physical laws and with the theory of "inflation" [25] [26], which seems confirmed by some experiments [25].

It remains to unify leptonic and quark fields to the gravitational one. Particles, corresponding to them, are fermions, while gauge and scalar fields are associated to bosons. One completes the unification, introducing a symmetry ("supersymmetry") [27] [28] [18], Appendix B of [36] that transforms fermions to bosons and vice versa. When it is made local, one discovers it forms a single symmetry with diffeomorphisms (it cannot exist by itself). Therefore, the gravity field is a component of its gauge field. The latter has a fermionic component too, the particles of which are said "gravitinos". It is a remarkable fact, that supersymmetry does not introduce a new gauge field, which one does not know how to unify to gravity, but embraces it in a natural way.

Local supersymmetry is called "supergravity" [18] [29] [30], and the particle associated to its gauge field, with all its components, "supergraviton".

When one compactifies supergravity, besides the already cited bosonic fields, fermionic fields, which can account for fermions of the standard model, also originate owing to the presence of gravitinos.

Supersymmetry must also be broken, and there are various mechanisms to do this, without adding any new fields.

Grand unification and superunification produce new effects at the high (or very high) energies, while the standard model is valid at the low ones.

A seeming weakness, of this picture, is that the number of dimensions of space-time is an arbitrary parameter of the theory (even if some arguments would suggest 11 as the maximum number, and 11 also seems to be the minimum number to be able to realize the standard model [31]). Moreover, supergravity is not manifestly renormalizable too.

To face the problem of renormalizability, we observe that a point object, charged in respect of a certain field, produces, around itself, a configuration of the field, which is rapidly reduced as one goes away from the charge, while, approaching it, it grows, to usually create a singularity in correspondence of the charge itself. In the case of gravity, such configuration is a black hole. It exists even if there is no material charge (mass) to create it, provided the field singularity is present. Moreover, it has all the properties of a massive body: it attracts the other bodies by a force corresponding to the mass associated to its field, and moves by uniform straight motion until it is not attracted by other masses in its turn. Elementary particles (quanta of fields) are point objects. It then appears, that, if they have mass, they can be regarded as black holes.

Besides field configurations, corresponding to point objects, there also exist configurations corresponding to extended objects: one dimensional, that is filaments, two dimensional, that is surfaces, etc.. As a two dimensional object can be called "membrane", these entities are said "branes", or "p-branes", where p is the number of dimensions of the object. Thus, a point is a 0-brane, a filament ("string") is a 1-brane, a membrane is a 2-brane, etc.. p can assume any value minor or equal to the dimensions of space.

The centre of mass of a brane will also move by uniform straight motion, until interactions do not intervene, and, if it is small enough to appear point-like, it can, in its turn, be regarded as a particle. While the only degree of freedom of a point is its position, an extended object can change form. On the ground of it, and of the relative velocities of its parts, it can then present itself in different states, which will behave as different particles.

Supergravity also foresees solutions, that describe branes of the various dimensions. It is then possible that the supergraviton is to be looked for among the states of a brane of these.

We have said that the infinities, which are to be renormalized, originate from integrals, that diverge in the region of the quantities of motion tending to infinity, that is of the wave lengths tending to zero. If particles are, in reality, extended objects, their characteristic length can provide us with a lower bound, that is a cut-off, for such wave lengths. In fact, the particle, distributed, so to say, over the characteristic length (l_s), will feel all the effects mediated over such length. The fields, of wave length much less than l_s, will oscillate very rapidly, cancelling themselves in the mean. Then, in reality, the theory might be "finite", that is devoid of divergences.

One then puts the problem to study the various branes, in order to determine their states and their interactions, and to check if it is possible to recover the supergraviton, and if the theory is really finite.

The first case it suits to engage in is that of the string, because it is much simpler, to study, than the branes with a major number of dimensions.

The branes of supergravity can be of a particular type, said "$\frac{1}{2}$ BPS" [32] [33], which has special properties of symmetry and stability.

Choosing the string among all the branes, and choosing, among strings, the $\frac{1}{2}$ BPS ones, one discovers the following facts:

1. The supergraviton is part of the spectrum of states of the string.
2. So far as one has been able to make computations, the theory does not exhibit divergences.
3. The theory is consistent only in a space-time with 10 dimensions.

It then seems that the theory of $\frac{1}{2}$ BPS strings [34] . . . [39] solves whether the problem of the appearing non-renormalizability of supergravity, or the one of the arbitrariness in the choice of the number of dimensions of space-time. It must not discourage the fact that, 10 being less than 11, the theory seems insufficient to contain the standard model. In fact, string theory has new elements in respect of standard supergravity.

One arbitrariness seems to remain, in the fact, that at least 5 different string theories in 10 dimensions, corresponding to as many, different, supergravities, can be formulated. But, according to certain arguments, they all would be different descriptions of one single theory.

The number of $\frac{1}{2}$ BPS branes is contained. There are attempts to study such branes [40] [41], which seem to indicate, that, besides strings in 10 dimensions, only the membrane in 11 dimensions possesses supergravitons in its spectrum. According to the already cited arguments, the membrane in 11 dimensions also belongs to another, different, description of the same string theory.

A complete analysis would also require to study non-$\frac{1}{2}$ BPS branes and space-times with a number of time dimensions different from 1.

4 Cautions

The study of the string is done, applying the methods of quantum field theory to the Lagrangian describing its motion.

I do not intend to dissuade the reader from studying this subject, but I warn him that the difficulties listed in section 2 (together with some others) make, to prove the consensually accepted results are right, all but simple. I have even doubted that known principles are sufficient to do this, and, at present, I prefer to be content with the possibility to compute transition amplitudes, at the lowest perturbative order, in the (perhaps 11 dimensional) supergravity. This corresponds to processes with an energy that is not too elevated, and it is already a notable goal, in the waiting that, in line of thought, experiments fix the other infinite number of parameters necessary to complete the theory. In reality, this will, probably, never happen, given the very high energies that are needed.

It is just to remember, that, besides string theory, there exist other approaches, which are also non-free from difficulties, to quantization of gravity. Among them, "loop" quantum gravity [42] and "precanonical" quantization [43] [44] [45] are those that are known to me.

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