The elementary teaching of Bosonic String Theory

A. Chamani
Physics Department, Faculty of Sciences, Islamic Azad University, Bandar Abbas Branch, Iran
chamani@iauba.ac.ir , alieh_chamani@yahoo.com

Abstract. *This paper is about one of the important theories model constituting an introductory concepts designed for students acquaint some basic facts for need to beginning this theory.*

The aim of this paper is intended as preparation for the more advanced understanding on simplest aspects of string theories such as "Bosonic string theory".

Keywords. Bosonic String theory, Physics education, String theory.

1. Introduction

String theory uses a model of one-dimensional strings in place of the particles of quantum physics. These strings, the size of the Planck length (i.e. 10-35 m) vibrate at specific resonant frequencies. (NOTE: Some recent versions of string theory have predicted that the strings could have a longer length, up to nearly a millimeter in size, which would mean they're in the realm that experiments could detect them.) The formulas that result from string theory predict more than four dimensions (10 or 11 in the most common variants, though on version requires 26 dimensions), but the extra dimensions are "curled up" within the Planck length.

String theory can be formulated in terms of an action principle, either the Nambu-Goto action or the Polyakov action, which describes how strings move through space and time. In the absence of external interactions, string dynamics are governed by tension and kinetic energy, which combine to produce oscillations. The quantum mechanics of strings implies these oscillations take on discrete vibrational modes, the spectrum of the theory.

On distance scales larger than the string radius, each oscillation mode behaves as a different species of particle, with its mass, spin and charge determined by the string's dynamics. Splitting and recombination of strings correspond to particle emission and absorption, giving rise to the interactions between particles. [1]

2. What is String?

An analogy for strings' modes of vibration is a guitar string's production of multiple but distinct musical notes. In the analogy, different notes correspond to different particles. The only difference is the guitar is only 2-dimensional; you can strum it up, and down. In actuality the guitar strings would be every dimension, and the strings could vibrate in any direction, meaning that the particles could move through not only our dimension, but other dimensions as well.

String theory includes both open strings, which have two distinct end points, and closed strings making a complete loop. The two types of string behave in slightly different ways, yielding two different spectra. For example, in most string theories, one of the closed string modes is the graviton, and one of the open string modes is the photon. Because the two ends of an open string can always meet and connect, forming a closed string, there are no string theories without closed strings. [2]

Figure 1. Strings

A. Chamani (2010). The elementary teaching of Bosonic String Theory M. Kalogiannakis, D. Stavrou & P. Michaelidis (Eds.) *Proceedings of the 7th International Conference on Hands-on Science.* 25-31 July 2010, Rethymno-Crete, pp. 295 – 299
http://www.clab.edc.uoc.gr/HSci2010

2.1. String Vibrations

To get the hang of string theory, think of a guitar string that's been tuned by stretching it between the head and the bridge. Depending on how the string is plucked and how tense it is, different musical notes are created. These notes can be thought of as excitation modes of the guitar string under tension. Similarly, in string theory, the elementary particles observed in particle accelerators correspond to the notes or excitation modes of elementary strings. One mode of vibration makes the string appear as an electron, another as a photon, and so on.

In string theory, as in guitar playing, the string has to be under tension in order to become excited. A big difference is that the strings in string theory aren't tied down to anything but instead are floating in space-time. Even so, they're under tension – by an amount that depends, roughly speaking, on one over the square of the string's length. Now, if string theory is to work as a theory of quantum gravity, then the average length of a string has to be in the ballpark of the distance over which the quantization of space-time – the granularity of space and time – becomes noticeable. This outrageously tiny distance, known as the Planck length, is about 10-33 centimeters, or one billion trillion trillionth of a centimeter. So much tinier is it than anything that current or planned particle physics technology can hope to be able to see that string theorists have to look for craftier, more indirect ways to test their ideas.

3. D-branes

Another key feature of string theory is the existence of D-branes. These are membranes of different dimensionality. D-branes are defined by the fact that world-sheet boundaries are attached to them. Thus D-branes can emit and absorb closed strings; therefore they have mass (since they emit gravitons) and — in superstring theories — charge as well (since they emit closed strings which are gauge bosons).

From the point of view of open strings, D-branes are objects to which the ends of open strings are attached. The open strings attached to a D-brane are said to "live" on it, and they give rise to gauge theories "living" on it (since one of the open string modes is a gauge boson such as the photon). In the case of one D-brane there will be one type of a gauge boson and we will have an Abelian gauge theory (with the gauge boson being the photon). If there are multiple parallel D-branes there will be multiple types of gauge bosons, [3] giving rise to a non-Abelian gauge theory.

D-branes are thus gravitational sources, on which a gauge theory "lives". This gauge theory is coupled to gravity (which is said to exist in the bulk), so that normally each of these two different viewpoints is incomplete.

4. World-sheet

A point-like particle's motion may be described by drawing a graph of its position against time. The resulting picture depicts the world-line of the particle in spacetime. By analogy, a similar graph depicting the progress of a string as time passes by can be obtained; the string will trace out a surface, known as the world-sheet. The different string modes (representing different particles, such as photon or graviton) are surface waves on this manifold.

A closed string looks like a small loop, so its world-sheet will look like a pipe or, more generally, a Riemann surface (a two-dimensional oriented manifold) with no boundaries (i.e. no edge). An open string looks like a short line, so its world-sheet will look like a strip.

5. Bosonic String Theory

The earliest string model, the bosonic string, incorporated only bosons. This model describes, in low enough energies, a quantum gravity theory, which also includes (if open strings are incorporated as well) gauge fields such as the photon (or, more generally, any gauge theory). However, this model has problems. Most importantly, the theory has a fundamental instability, believed to result in the decay (at least partially) of space-time itself. Additionally, as the name implies, the spectrum of particles contains only bosons, particles which, like the photon, obey particular rules of behavior. Roughly speaking, bosons are the constituents of radiation, but not of matter, which is made of fermions.

6. Supersymmetry in String Theory

Some qualitative properties of quantum strings can be understood in a fairly simple fashion. For example, quantum strings have tension, much like regular strings made of twine;

this tension is considered a fundamental parameter of the theory. The tension of a quantum string is closely related to its size. Consider a closed loop of string, left to move through space without external forces. Its tension will tend to contract it into a smaller and smaller loop. Classical intuition suggests that it might shrink to a single point, but this would violate Heisenberg's uncertainty principle. The characteristic size of the string loop will be a balance between the tension force, acting to make it small, and the uncertainty effect, which keeps it "stretched". Consequently, the minimum size of a string is related to the string tension.

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

Investigating how a string theory may include fermions in its spectrum led to the invention of supersymmetry, a mathematical relation between bosons and fermions. String theories which include fermionic vibrations are now known as superstring theories; several different kinds have been described, but all are now thought to be different limits of M-theory.

Supersymmetric partners to currently known particles have not been observed in particle experiments, but theorists believe this is because supersymmetric particles are too massive to be detected using present-day high-energy accelerators. Particle accelerators could be on the verge of finding evidence for high energy supersymmetry in the next decade. Evidence for supersymmetry at high energy would be compelling evidence that string theory was a good mathematical model for nature at the smallest distance scales.

In string theory, all of the properties of elementary particles – charge, mass, spin, etc – come from the vibration of the string. The easiest to see is mass. The more frenetic the vibration, the more energy. And since mass and energy are the same thing, higher mass comes from greater vibration.

7. Gravity and the development of string theory

How get gravity into the scheme? A clue to this emerged while researchers were working on the quantum field theory of the strong force. Along the way, they came up with a wonderfully creative explanation for the observed relationship between the mass and spin of hadrons. Called string theory, it treats particles as specific vibrations or excitations of very, very small lengths of a peculiar kind of string. In the end, quantum chromodynamics (QCD) proved to be a better theory for hadrons. Yet string theory wasn't consigned to the trashcan of ideas that had passed their sell-by date. It made one extremely interesting prediction: the existence of a particle – a certain excitation of string – with a rest mass of zero and an intrinsic spin of two units. Theorists had long known that there ought to be such a particle. It was none other than the hypothetical exchange particle of gravitation – the graviton.

With this discovery, that one of the essential vibrational modes of string corresponded to the graviton, string theorists realized they had a bigger fish to fry than trying to explain the ins and outs of hadrons. Their notions of elemental quivering threads might, it seemed, bear directly on the much sought-after quantum theory of gravity – and not just because the graviton is predicted by string theory. You can stick a graviton into quantum field theory by hand if you like, but it won't do you any good because you'll be blown away by infinities. Particle interactions happen at single points in space-time, so that the distance between interacting particles is zero. In the case of gravitons, the mathematics behaves so badly at zero distance that the answers come out as gobbledygook. String theory gets around this problem because the interacting entities aren't points but lengths, which collide over a small but finite distance. As a result, the math doesn't self-destruct and the answers make sense.

8. Varieties of string theory

String theories come in various forms. All of these assume that the basic stuff of creation are tiny wriggling strings. However, if the theory deals with only closed loops of string, like Spaghetti Hoops, then it's limited to describing bosons – the force-carrying particles – and so is called bosonic string theory. The first string theory to be developed was of this type. If open strings, like strands of ordinary spaghetti, are allowed into the theoretical picture then these provide a description of fermions, or particles of matter. But a very interesting thing happens when string theory is extended in this way to let in fermions. It demands that there must be a special kind of symmetry in the particle world, know as supersymmetry. In this expanded masterplan of things, there's a corresponding fermion for every boson. In other words, supersymmetry relates the particles that transmit forces to the particles that make up matter. A supersymmetric string theory is called, not surprisingly, a superstring theory.

Theorists uncovered three different string theories that were mathematically consistent and therefore made good sense. Two of these were bosonic, the other of the superstring ilk. But in order to make any of them work, they had to resort to a strategy first employed by Kaluza and Klein in the days when Einstein first started wandering down his blind unification alley: they had to call upon higher dimensions, rolled up so small that they're way below the threshold of detection. The bosonic string theories needed an awesome 26 dimensions (25 of space plus one of time) in order to work properly, which seemed a bit of a stretch even for scientists who enjoyed some wayout sci-fi in their off-hours. Compared with this, the mere ten dimensions of space-time required by superstring theory seemed positively modest. Six of the ten would have to be curled up, or "compactified," to leave visible the four normal spacetime dimensions (three of space plus one of time). But these compactified dimensions, far from being an embarrassment to be swept under the cosmic carpet and forgotten about, come in very handy if string theory is to aspire to become a theory of everything: motion in them can be used to explain the values taken by important constants in nature, such as the charge on the electron.

Combining the best features of bosonic and superstring theory has led to two other consistent schemes known as heterotic string theories. So, there are five viable string theories in all [4], which, if we're hoping to arrive at the one true TOE, is a tad too many. Fortunately, it's beginning to look as if the quintet of finalists for the Miss Universe Theory competition is really the same contestant dressed up in five different costumes. This supersymmetric mistress of disguise has been given the rather enigmatic name M-theory.

Some say that the M is for Mother of All Theories. Others that it stands for Magic or Mystery. But, although no one seems to know for sure, there may be a more prosaic reason for this particular choice of initial.

Before string theory rose to scientific superstardom, the most popular unified theory in town was supergravity, which was basically supersymmetry plus gravity without the string. Like any respectable quantum gravity candidate it boasted a surfeit of spacetime dimensions – in this case, eleven (the compactified ones all wrapped up neatly on an itty-bitty 7-dimensional sphere). Unfortunately, it had to be abandoned because of the problems mentioned earlier involving point particles and string.

But along came M-theory. Still under development, it carries the hopes of many that it will combine the various flavors of string theory soup into one single, satisfying broth. The cost of this in conceptual terms is the addition of a single dimension: M-theory is 11-dimensional but with the unusual trait that it can appear 10-dimensional at some points in its space of parameters. Supergravity rides again – but this time with strings attached.

And the M in M-theory? We omitted to say earlier that while strings, with their one-dimensional extension, are the fundamental objects in string theory, they're not the only objects allowed. String theory can accommodate multidimensional entities, called branes, with anywhere from zero (points) to nine spatial dimensions. A brane with an unspecified number, p, of dimensions is called a p-brane. In M-theory, with its extra dimension, the fundamental object is an M-brane [4], which resembles a sheet or membrane. Like a drinking straw seen at a distance, the membranes would look like strings since the eleventh dimension is compactified into a small circle. Membranes, M-branes, M-theory.

Table 1. String theories

String theories		
Type	**Space-time dimensions**	**Details**
Bosonic	26	Only bosons, no fermions, meaning only forces, no matter, with both open and closed strings; major flaw: a

		particle with imaginary mass, called the tachyon, representing an instability in the theory.
I	10	Supersymmetry between forces and matter, with both open and closed strings; no tachyon tachyon; group symmetry is SO(32) Supersymmetry
IIA	10	between forces and matter, with only closed strings bound to D-brane; no tachyon; massless fermions are non-chiral
IIB	10	Supersymmetry between forces and matter, with only closed strings bound to D-branes; no tachyon; massless fermions are chairal
HO	10	Supersymmetry between forces and matter, with closed strings only; no tachyon;hetrotic, meaning right moving and left moving strings differ; group symmetry is SO(32)
HE	10	Supersymmetry between forces and matter, with closed strings only; no tachyon; hetrotic, meaning right moving and left moving strings differ; group symmetry is $E_8 \times E_8$

8. Acknowledgements

I would like to thank Fatemeh Ahmadi for her suggestions on the manuscript. This work is supported by Islamic Azad University, Bandar Abbas Branch.

9. References

[1] Polchinski J. String Theory. Cambridge University Press; 1998.
[2] Polchinski J. What is String Theory?, Les Houches Summer School, Session 62.
[3] Bachas C. D-Brane Dynamics. Phys. Lett. B 1996; 374-411.
[4] Dai J, Leigh R.G, Polchinski J. New Connections Between String Theories. Mod. Phys. Lett. 1989; A4: 2073.