strings 2001

NO FEAR

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Aspen Winter Conference

Outline

- Pedagogical introduction
- Lost in moduli space
- Branes branes branes
- AdS/CFT
- Tachyon condensates
- Nylons

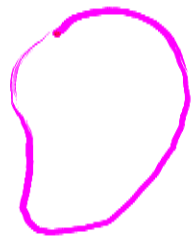
Strings: the traditional approach

A weakly self-coupled fundamental string

open:

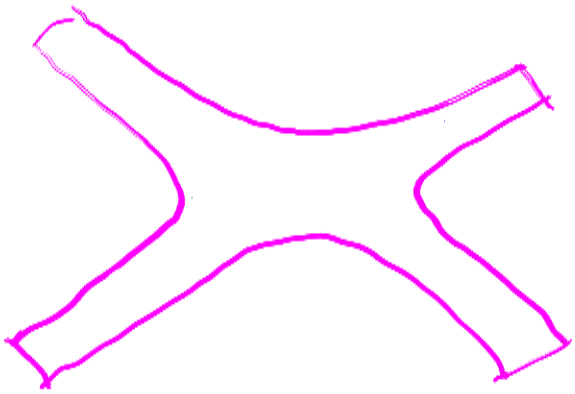
open string worldsheet

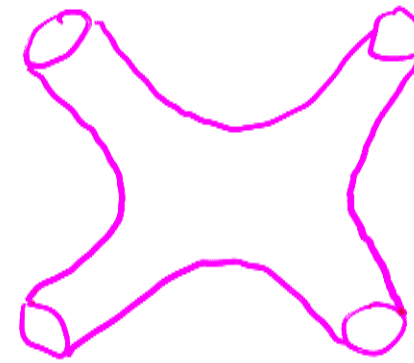
closed:



closed string worldsheet

string interactions





An obvious action principle:

$$S_{string} = \int d\sigma d\tau \, (\text{area element of worldsheet})$$

local symmetries: worldsheet reparametrization invariance

Quantize this theory!

Some immediate results are:

1. Quantum implementation of the full local symmetries requires extra spatial dimensions

   i.e. $X^\mu(\sigma,\tau)$ needs $\mu = 0,1,2..25$
   not $\mu = 0,1,2,3$

2. The quantized string has a negative zero-point energy $\Leftrightarrow$ a tachyonic instability

3. Massless modes: open string $\Rightarrow$ photon
   closed string $\Rightarrow$ graviton

Strings → Superstrings

- Add supersymmetry to get rid of the tachyonic instability
- Added bonus that with SUSY we "only" need to have a $d=10$ spacetime

Depending on how we implement SUSY (from a $d=10$ spacetime point of view) there are several different closed superstrings:

Type IIA	nonchiral maximal SUSY
Type IIB	chiral maximal SUSY
Type I	nonmaximal SUSY
heterotic	a $d=10$ / $d=26$ hybrid where the "mismatch" becomes extra gauge boson modes, either $SO(32)$ or $E_8 \times E_8$

Low energy field theory description of these 5 $d=10$ superstrings

= the 5 anomaly-free $d=10$ supergravities

They contain:

- graviton
- gauge bosons
- dilaton
- antisymmetric tensor gauge fields
- superpartners

These are all string theory in flat $d=10$ spacetime.

We can also describe these strings around compactified backgrounds, e.g.

$$M_4 \otimes CY$$

4d flat space

a 6d Calabi-Yau compact space

This corresponds to a different string vacuum

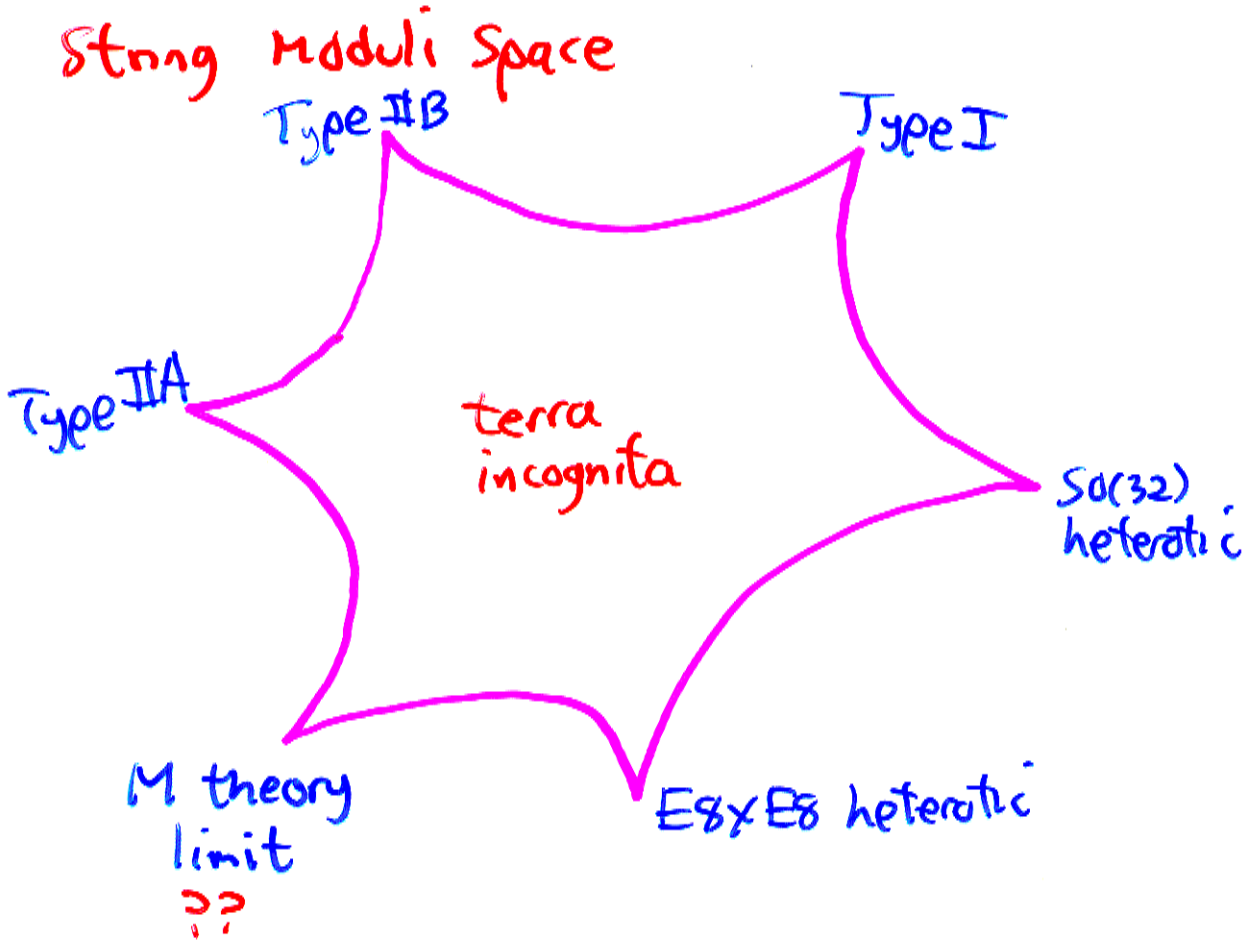
Lost in Moduli Space

- superstrings have zillions of different degenerate stable vacua.
- They are distinguished by vevs of "moduli" fields

examples of moduli vevs:

- dilaton vev $\Rightarrow$ g_s the string self-coupling
- Calabi-Yau radii

The low energy effective theory is different depending on which vacum you choose!



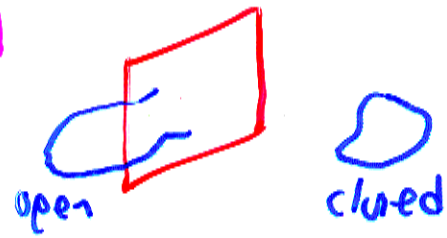
Good news: • there is only <u>one</u> string theory

Bad news:
- we don't know how to map out and explore this whole space of vacua
- we don't know what principle selects among these vacua
- we don't know which vacuum (if any) has the real world as its low energy limit!

Branes

- some of these closed string vacua also have open strings
- open strings have Dirichlet or Neumann b.c. at their ends; different choice for each of the spatial components of the string coordinate $X^\mu(\sigma)$
- if open string has p Dirichlet b.c. then its ends are attached to a p-dimensional sub-manifold

  $\equiv$ a Dp brane



An equivalent point of view:

- various string vacua contain various branes of various dimensionalities: $D\emptyset, D1, D2, D3 \ldots D9$
- these are dynamical; their fluctuations are the open string modes

$\Rightarrow$ low energy effective description of D brane physics = a $p+1$ dimensional gauge theory

Lessons of D-branes:

- fundamental strings are not fundamental!

  why?:

  - string theory has strong-weak coupling dualities such that D1 branes get interchanged with "fundamental" closed strings
  - D branes are "smaller" than fundamental strings

    ℓ_s = length scale set by string tension

    Dbrane thickness $\sim g_s \ell_s$
  - Dϕ branes of $d=10$ Type IIA string are secretly Kaluza-Klein modes of an 11th dimension

    $\hookrightarrow$ M theory limit: low energy limit is $d=11$ supergravity

    This corner of moduli space has no strings!

    2d membranes wrap the $d=11$ circle instead.

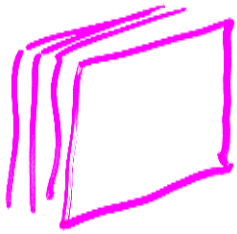
Lessons of D branes:

- Since D branes have gauge theories living on them, maybe the Standard model lives on some collection of branes

"The braneworld hypothesis"

Are there string vacua where this really happens?
Try the simplest thing:

A flat 10-dimensional Type IIB string vacuum with a stack of n D3 branes in it:



What gauge theory lives on these branes?

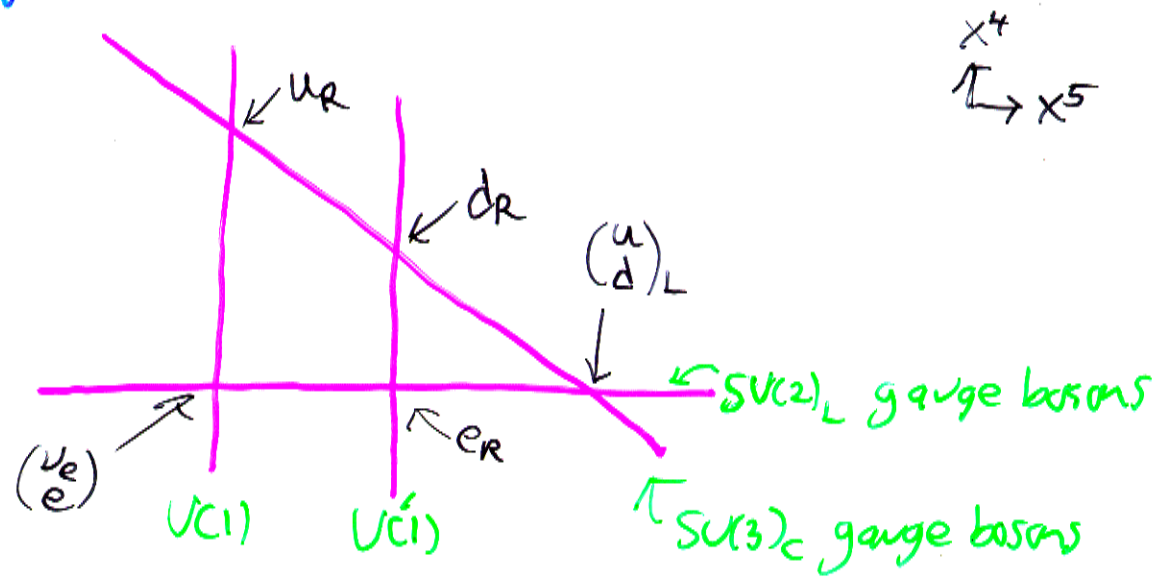
answer:

4-dimensional $U(n)$ Yang-Mills with maximally extended $(N=4)$ supersymmetry

Recent progress: "Intersecting Brane Worlds"

(Aldazabal, Franco, Ibáñez, Rabadán, Uranga)
hep-ph/0011132

Use D4 branes intersecting at angles in some of the compact extra dimensions:



- SM chiral fermions live at brane intersections
- three generations is due to multiple intersections
- supersymmetry is broken, but string scale can be low.

Prediction at colliders: "gonions"

= vectorlike 4th generation quarks + leptons which are actually massive string excitations

$$(\text{Mass})^2 \propto \alpha_{\text{inter}} (M_{\text{string}})^2$$

Lessons of D branes:

- Sometimes gauge theories describe the same physics as string theory in a special vacuum state.

☆ AdS/CFT conjecture of Maldacena ☆

Go back to our stack of n D3 branes in 10 dim. Type IIB string theory

- We said the low energy D brane physics is a 4 dim. $U(n)$ $N=4$ super-Yang-Mills gauge theory

- considered as solitons in Type IIB 10 dim supergravity the D branes are <u>black hole like</u> distortions of the 10 dim flat space

$\Rightarrow$ near the "horizon" the string d.o.f. (including gravity) are red-shifted and provide another low energy description

$$\underset{\substack{\uparrow \\ \text{4d CFT gauge theory!}}}{\text{4dim } U(n)\ N=4\ \text{SYM}} \equiv \underset{\substack{\uparrow \\ \text{10d strings!}}}{\text{Type IIB string}} \text{ on } \underset{\substack{\uparrow \\ \text{"near horizon" geometry}}}{AdS_5 \times S_5}$$

Recent Progress: Randall–Sundrum theory

(see e.g. Arkani-Hamed, Porrati, Randall hep-ph/0012148)

warped AdS_5 geometries of various types with extra branes (see Lisa's talk)

$\Rightarrow$ generalize the AdS/CFT duality

↳ lots of phenomenology here!

Recent Progress: perturbed AdS/CFT

(Polchinski and Strassler hep-th/0003136)

add mass terms so that

$N=4$ super-YM $\longrightarrow$ $N=1$ confining gauge theories "QCD-like"

The QCD-like gauge theories have QCD-like gluonic flux tubes between confined quarks

In the dual picture these "QCD strings" are "fundamental" strings bound to branes!

Lessons of D branes:

- D branes are a handle on lots of <u>nonperturbative</u> behavior in string theory

Recent Progress: "Tachyon condensation"

(papers by Sen, talks by Sen and Zwiebach at Strings 2001, etc)

- we saw that nonsupersymmetric strings have tachyons
- superstrings have regions of moduli space where SUSY is completely broken and tachyons also appear.

e.g. 10 dim. Type IIA string with a D9 brane

what happens?

Sen:
- tachyon condenses to its true (stable) vacuum
- D9 brane evaporates
- in the true vacuum all of the perturbative open string states are gone

Recent work
- nonperturbative "lumps" describe lower-dim D branes
- need <u>open string field theory</u> to describe this!

Are Elementary Particles Really Nylons?

L. Susskind, ...

- Suppose we consider particle collisions at superPlanckian energies. Here "Planck" is the effective Planck scale M_*, which could be just a few TeV.
- Roughly speaking, if the impact parameter b is smaller than or of the order of

$$b \sim \sqrt{s}/M_*^2$$

then a black hole will form. Thus a high energy point particle becomes an object with finite transverse "size" b.

- The Compton wavelength *decreases* with increasing energy, while the transverse "size" *increases* with increasing energy.
- Energy growing with size sounds like strings or branes.

Maximal Weirdness

- It now appears in string theory that there are examples where "particles" acquire a transverse size at high energies:
- E.g. "Attack of the giant gravitons from Anti de Sitter space" (J. McGreevy, L. Susskind, N. Toumbas).
- E.g. Wrapped branes in warped compactifications of M theory or string theory (E. Silverstein).

In the second case, we compactify 11 dim Horava-Witten theory on a K3 surface, and wrap a 2-brane on a cycle of the K3 with some area A_0. The geometry is warped along the 11th dimension (call this coordinate y).

- The wrapped brane should look almost like a point particle to us, with some fuzziness in its size of order the UV cutoff l_{11}. Taking into account the warping, it has energy

$$E = y^{1/2} \frac{A_0}{l_{11}^3}$$

Taking into account the warping, its transverse size is

$$R = y^{1/6} l_{11}$$

So this object has a brane-like energy/size relation:

$$E \propto R^3$$

- In fact, this object is neither a point particle nor a brane, rather it is something in between.

- You can see this by counting states. Compute the KK modes (with respect to the warped direction y) of the wrapped 2-brane. The scalar KK modes are the solutions of a 1 dim Schrodinger eqn with a potential which is approximately quadratic. The KK modes are discrete with

$$E^4 \propto (n + 1/2)$$

- The number of these KK states increases like E^4, compared to $n \propto E$ for a point particle! On the other hand, for a brane (or any extended object), the number of states increase exponentially with energy.

- These new objects are called elastic states (nylons).

Phenomenology

- Could there be accessible regimes where what you thought were point particles turn into nylons?
- Linear colliders are a good way to look for this!
- Note this is not like the usual quark/lepton compositeness, since there (presumably) aren't any bound pointlike constituents. You don't necessarily generate the 4-fermion terms of Eichten-Lane-Peskin, just form factors:

$$\frac{d\sigma}{dQ^2} = \left(\frac{d\sigma}{dQ^2}\right)_{SM} \cdot F_e^2(Q^2) \cdot F_f^2(Q^2),$$

where

$$F(Q^2) = 1 + \frac{1}{6} Q^2 R^2$$

The current best limits on this "electron radius" appear to be from LEP (D. Bourilkov):

$$R_e < 2.8 \cdot 10^{-17} \mathrm{cm}$$

Conclusions

- string theory is telling us a lot about real stuff: gauge theories, gravity, black holes, etc

- The "predictions" of string theory for experiment will be stranger than we can presently imagine