Introduction to Strings: Part II

Largely an open-ended story...

Debashis Ghoshal

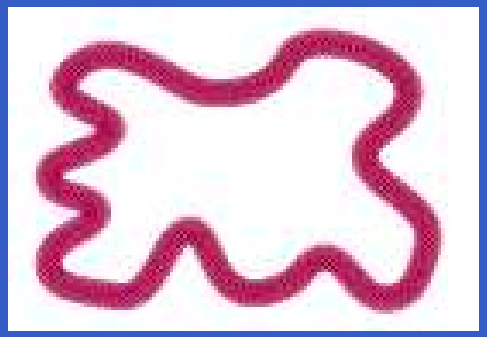
Harish-Chandra Research Institute

Allahabad

Overview

- Recap

[animated] Closed string



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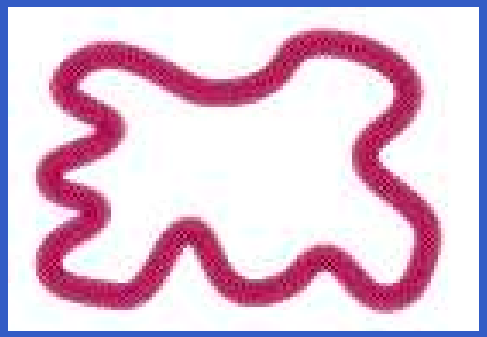

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- Recap
- Open strings . . . need boundary conditions
  - ◇ Neumann condition
  - ◇ Dirichlet condition

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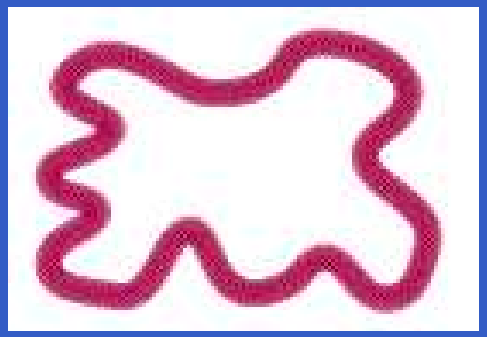

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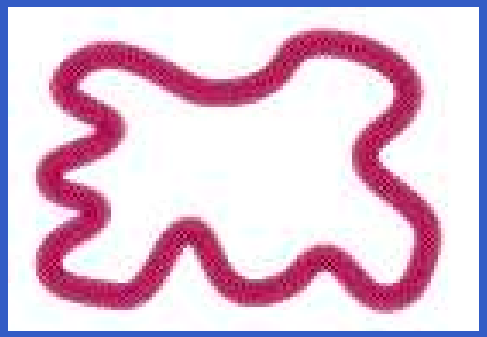

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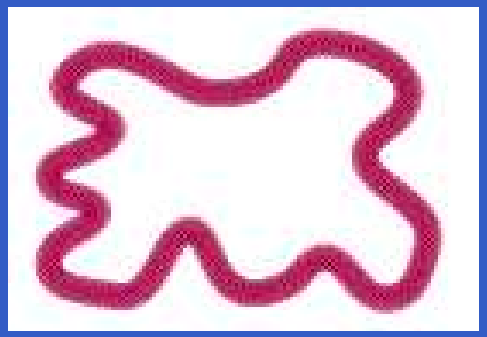

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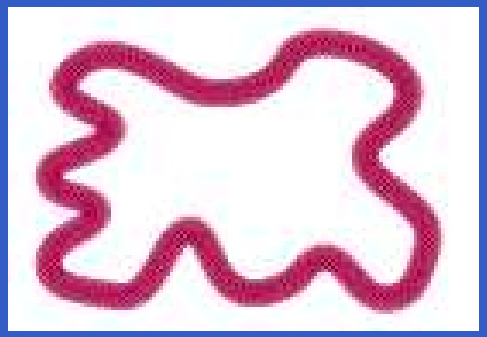

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- D-branes
- Open string interactions
- A larger picture?

Recap

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strings of size $\sim 10^{-33}$ cm.

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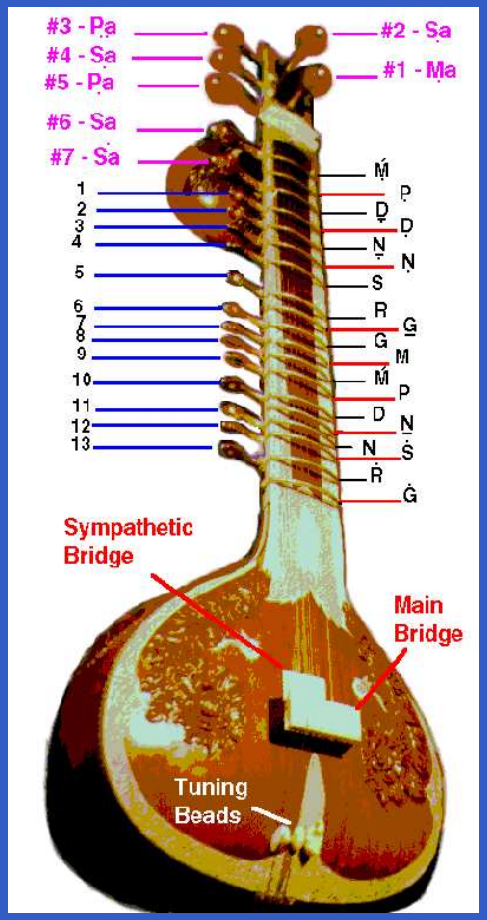

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The music of the strings!

Recap. . . (ii)

One string can split into two or two strings can join into one:

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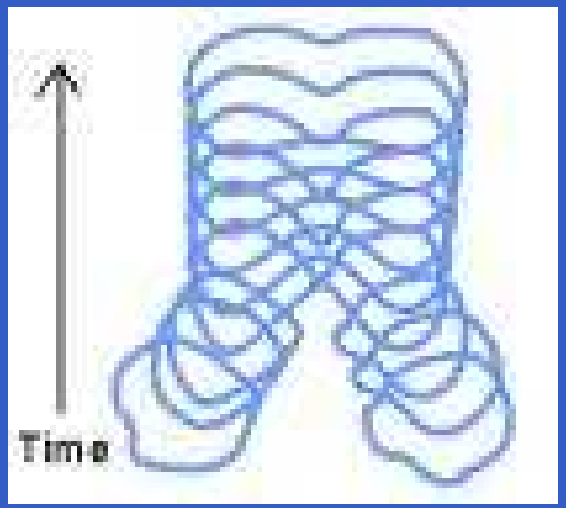

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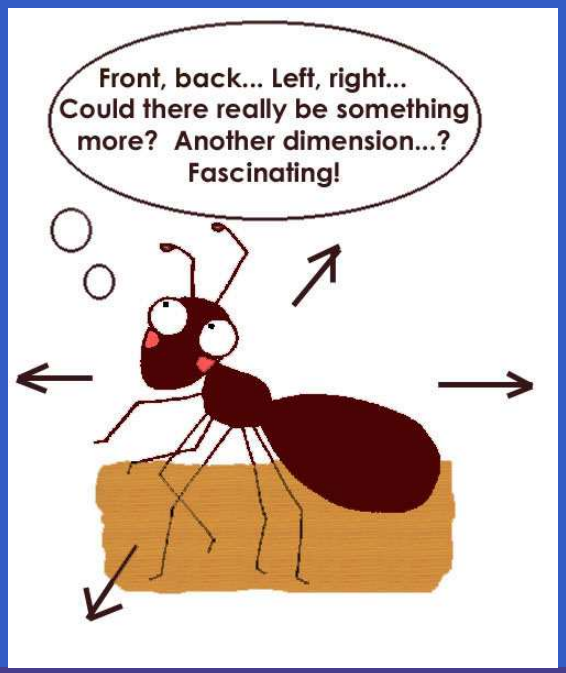

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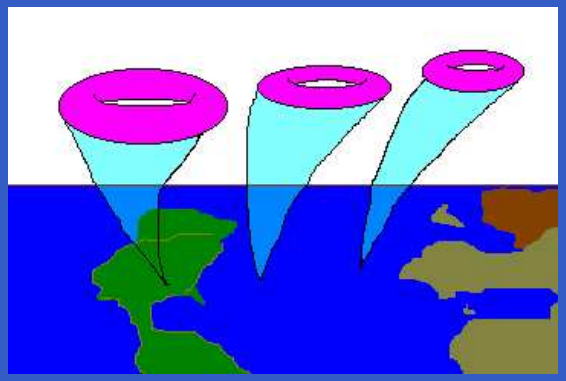

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Everyday strings

The strings that we see around us are macroscopic nonrelativistic strings.
Many of these are musical strings

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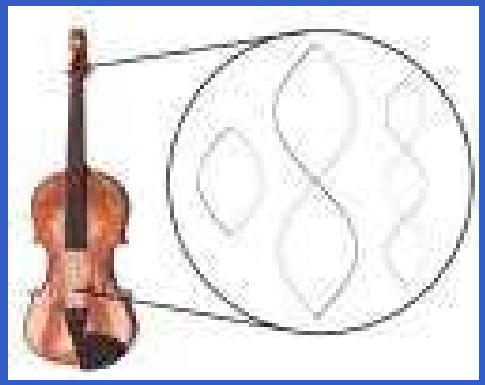

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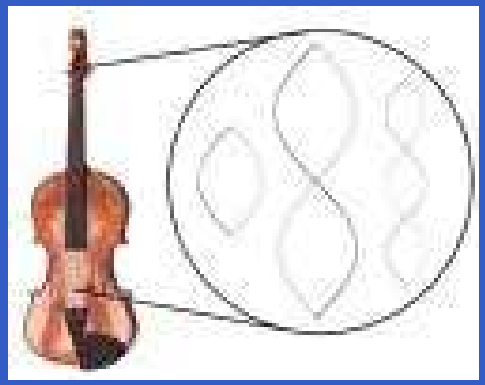

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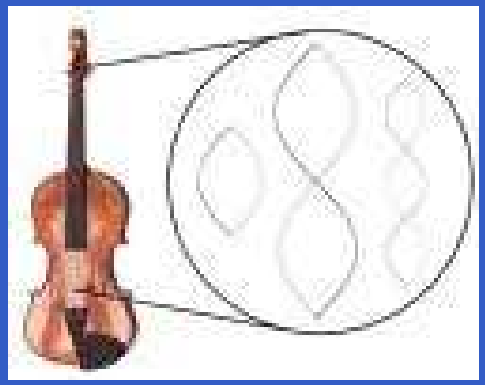

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Fundamental open strings also need boundary conditions.

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Boundary conditions are independent at each end point.

Spectrum of open strings

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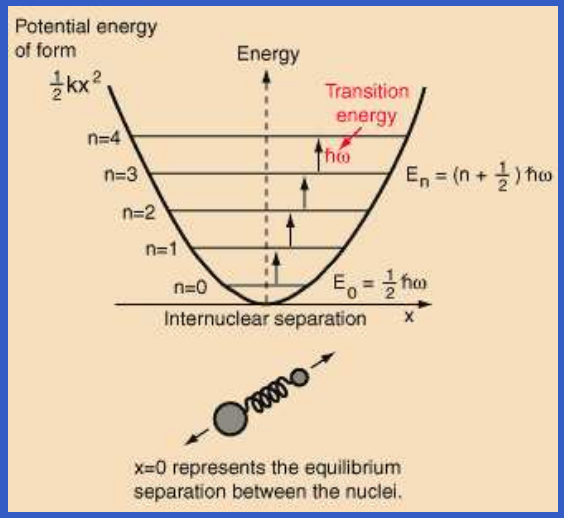

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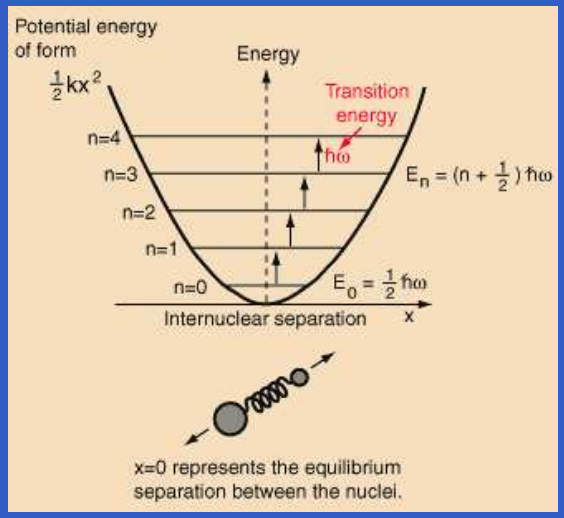

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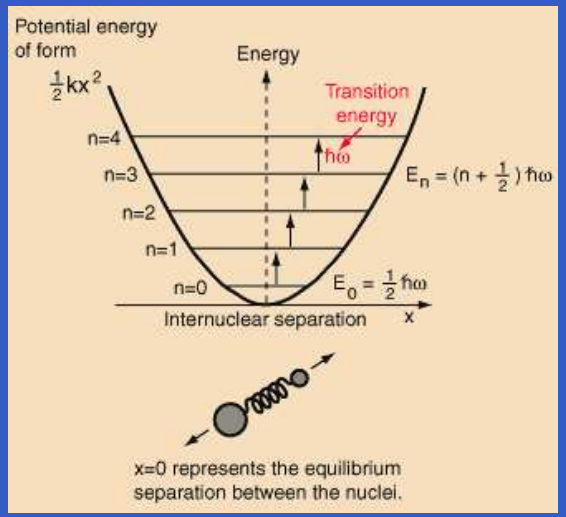

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vacuum state carrying momenta

$$|k\rangle = \prod (a^i_0)^\dagger |0\rangle$$

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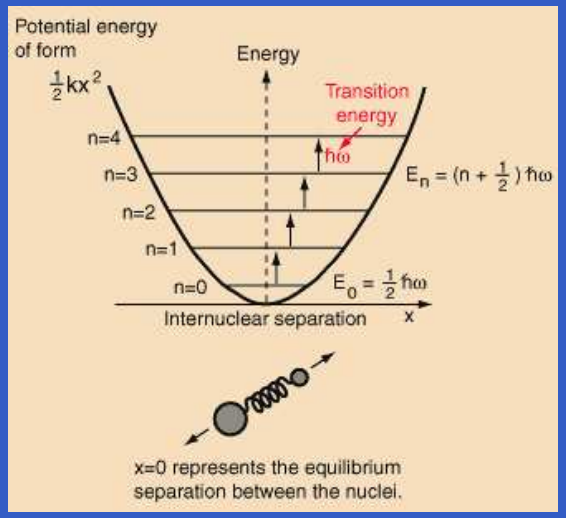

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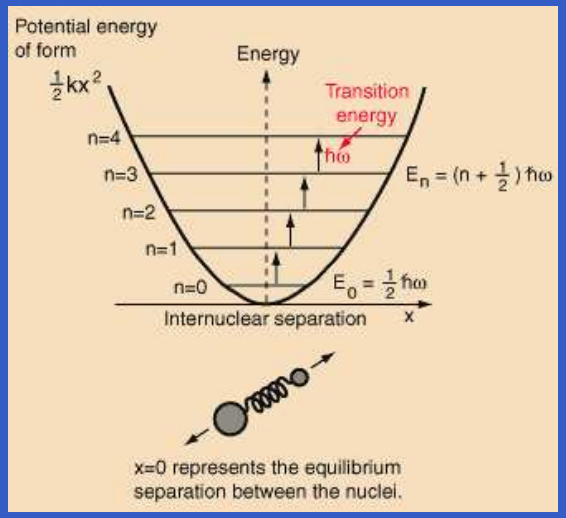

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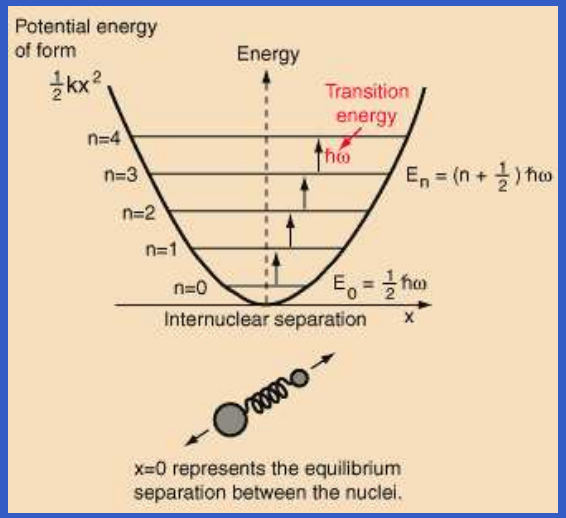

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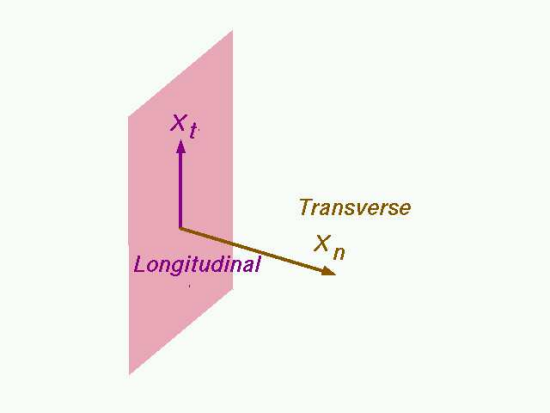
$$(a^i_1)^\dagger_{IJ}|k\rangle$$

The extra indices I, J refer to the end-points.

Spectrum of open strings... (ii)



Neumann b.c. on $X^i_{||}$

Dirichlet b.c. on $X^i_{\perp}$

String end-points are on the hyperplane

$X^i_{\perp}$ =constant

Open string can carry momentum only along the (hyper-)plane:

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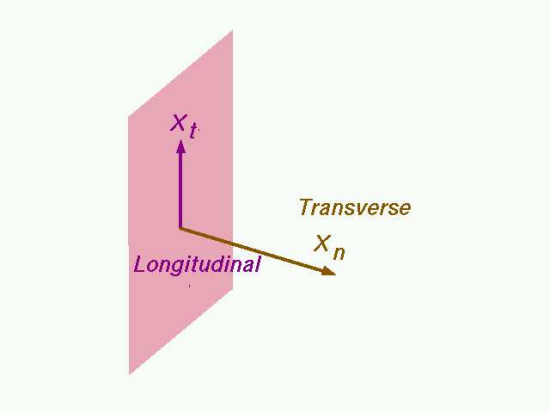

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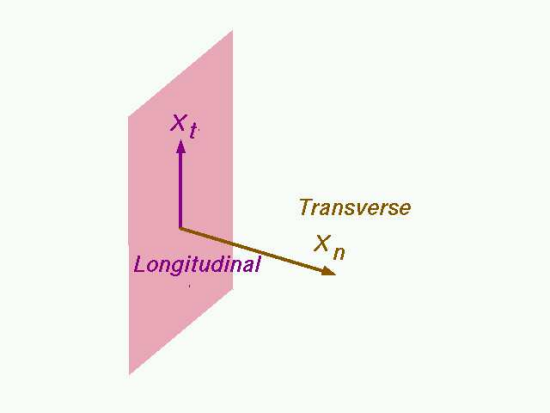

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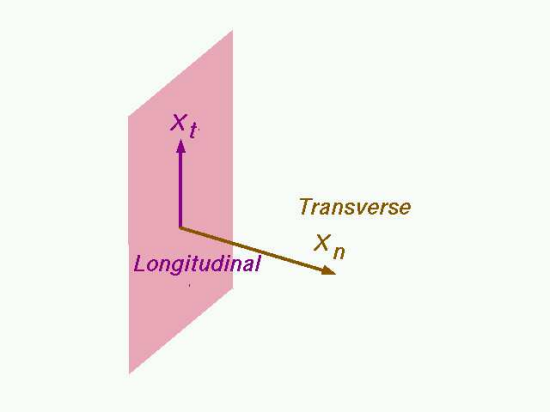

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Both live on the hyper-plane.

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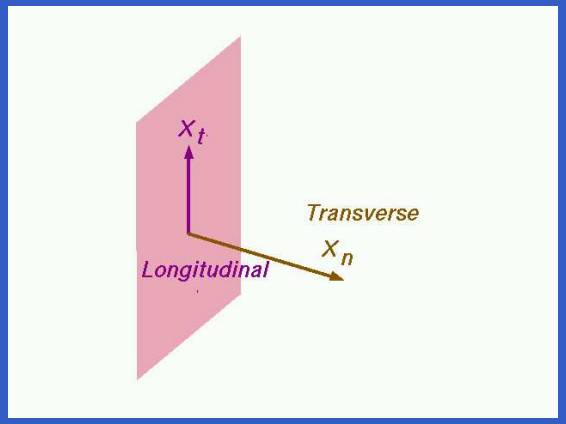

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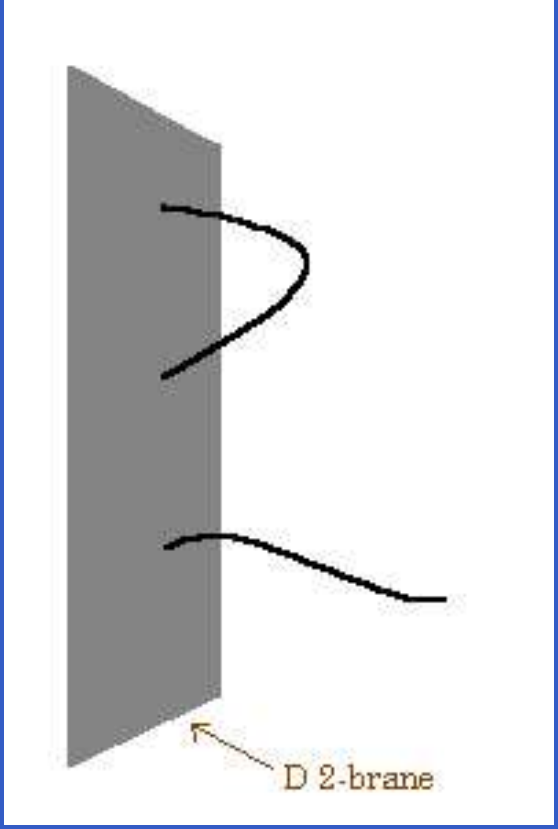
More on boundary conditions



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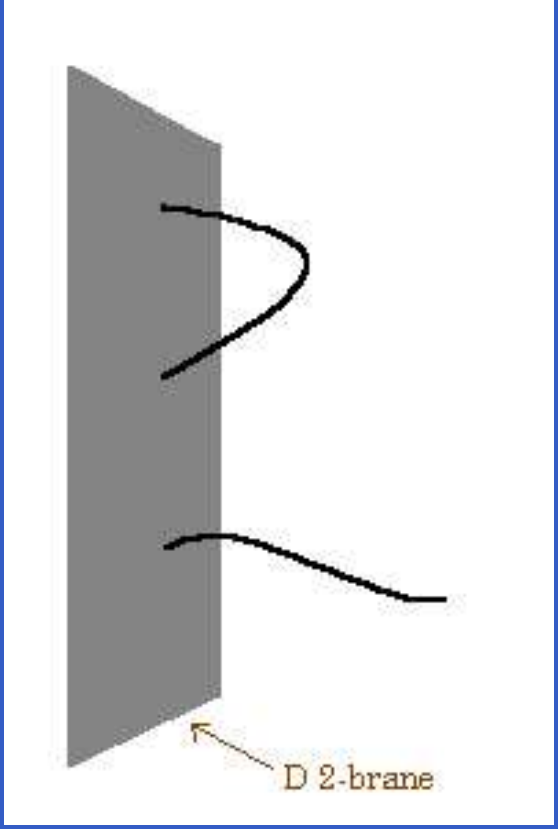

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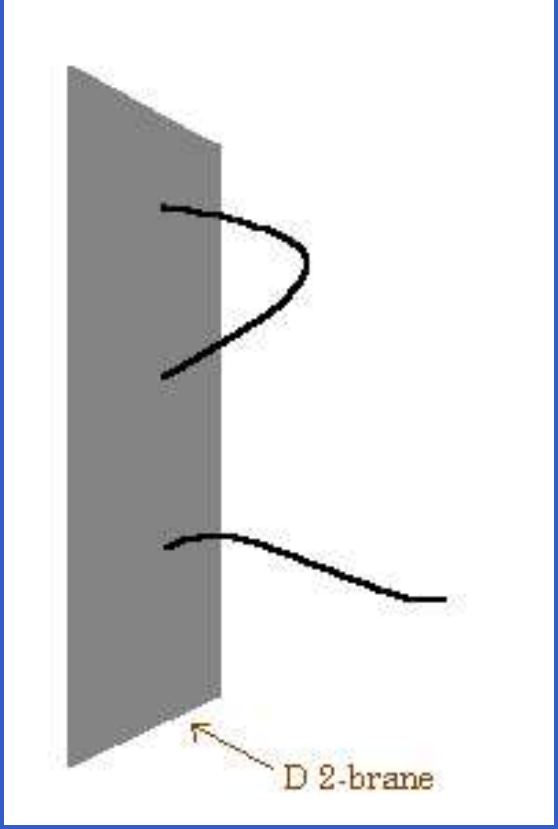

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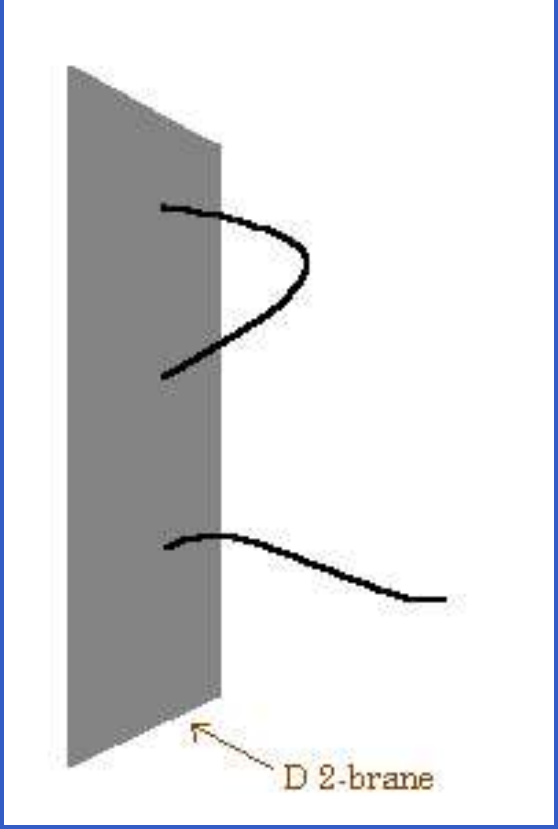

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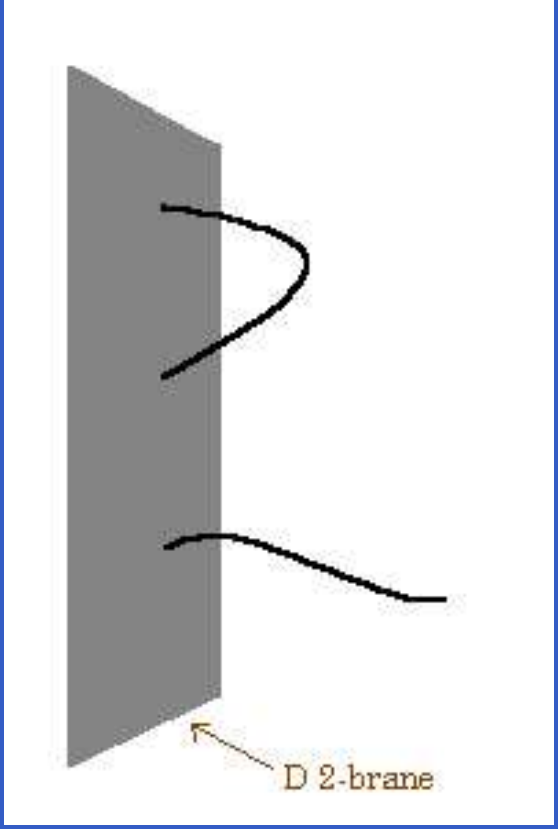

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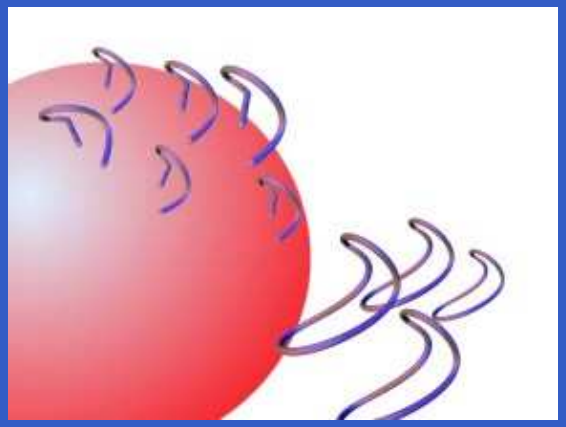

Can be any (hyper-)surface.

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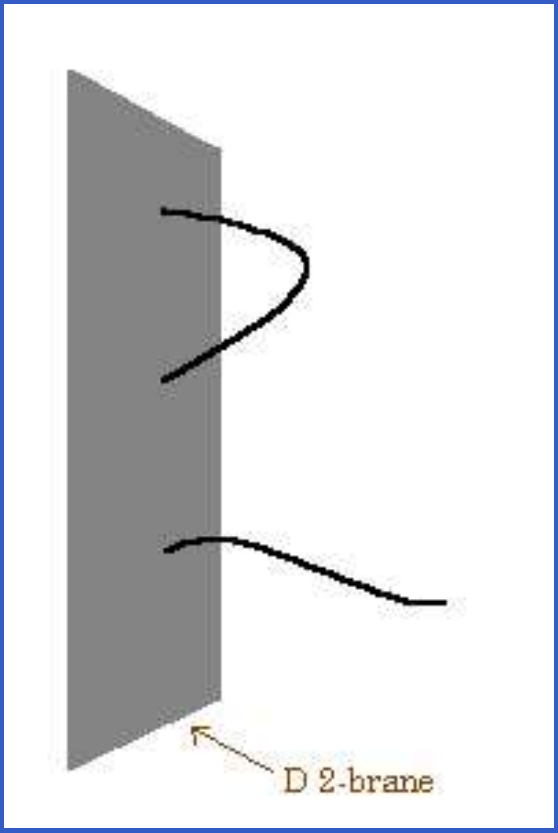

D-branes look like *defects/impurities* in space.

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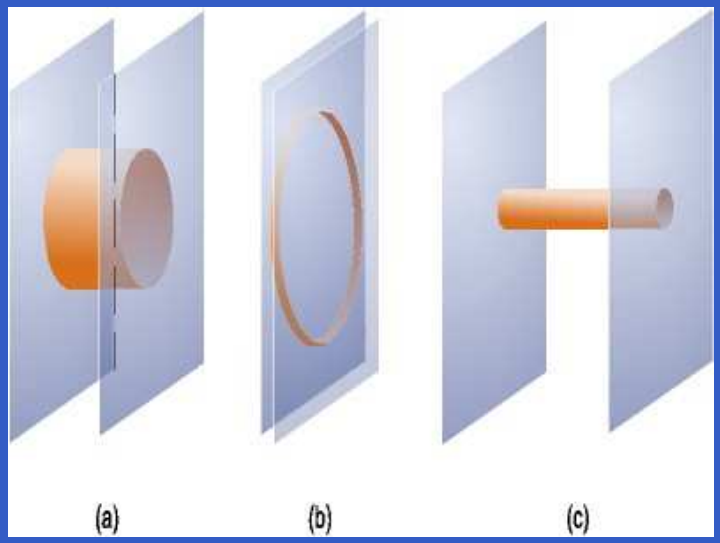

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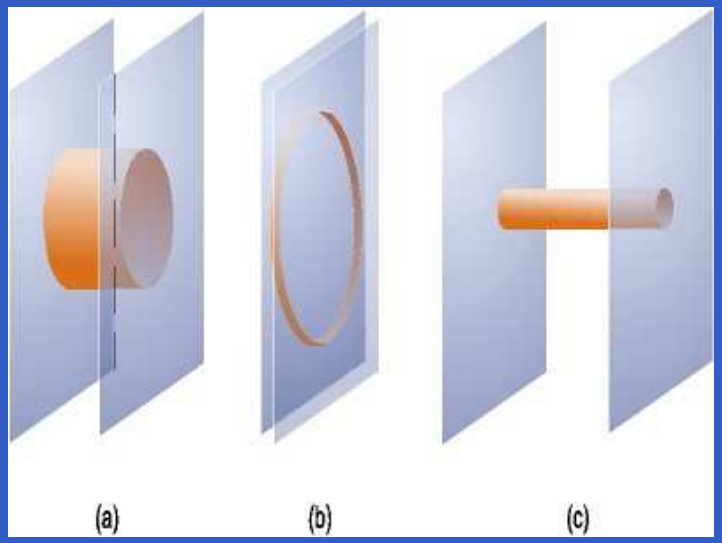

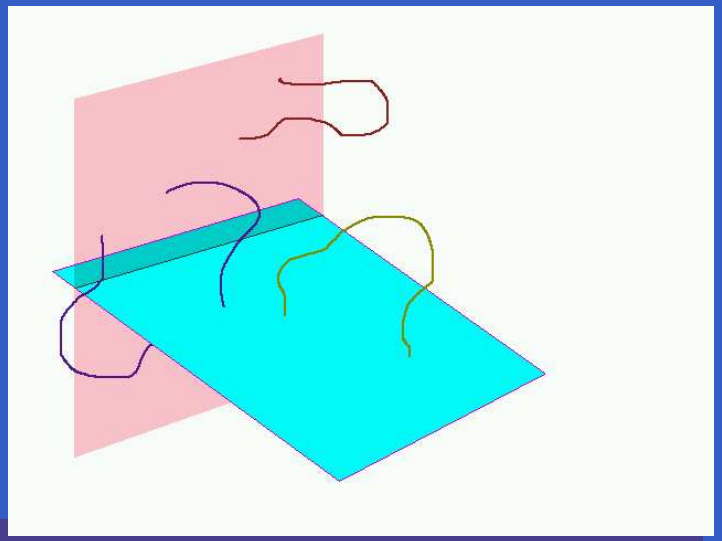

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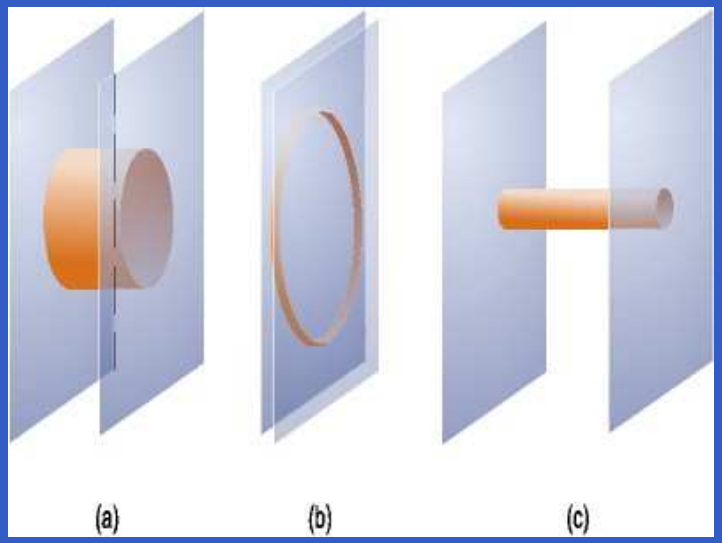

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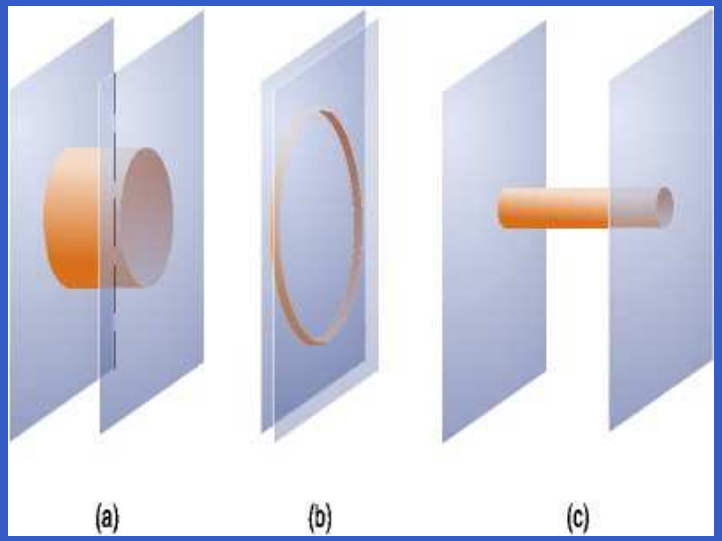
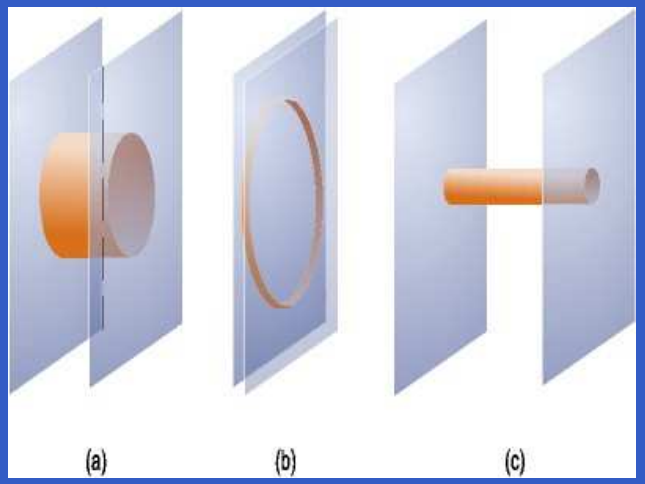


$A^i_{IJ}(\mathbf{k}) = (a^i)^\dagger_{IJ} |\mathbf{k}\rangle$
can become massless
$E^2 = |\mathbf{k}|^2$

D-branes look like *defects/impurities* in space.
There may be more than one D-brane, aligned arbitrarily — can intersect each other.
Energy of the strings between branes depend on the streching, *i.e.* on the distance between the branes.

More on boundary conditions . . . (ii)



$A^i_{II}(\mathbf{k}) = \left(a^i\right)^\dagger_{II} |\mathbf{k}\rangle$ come from excitations of a string starting and ending on the *same* D-brane.

$A^i_{IJ}(\mathbf{k}) = \left(a^i\right)^\dagger_{IJ} |\mathbf{k}\rangle$ can become massless $E^2 = |\mathbf{k}|^2$

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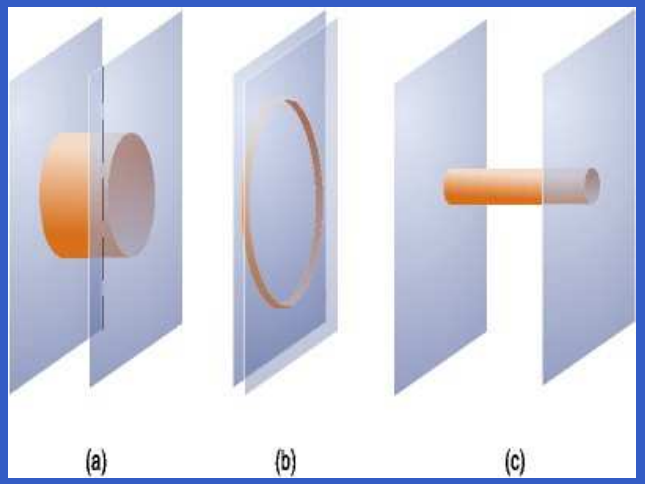

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It is always massless.

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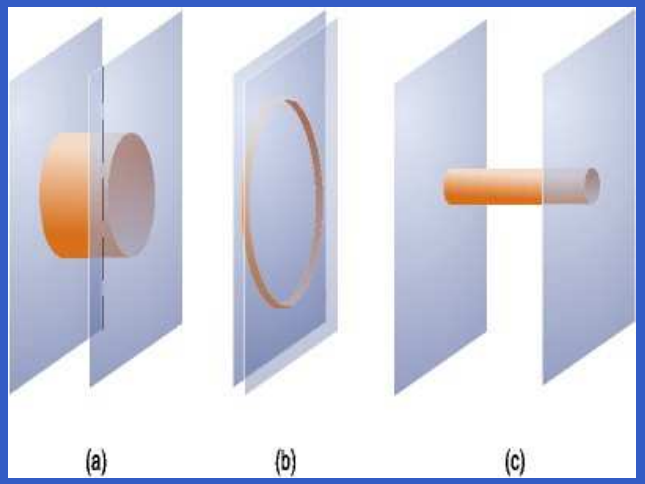

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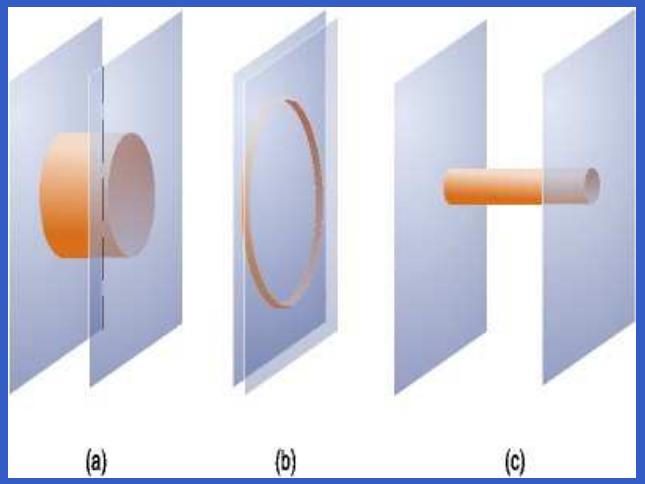
These are like photons — satisfy Maxwell eqns plus corrections.

More on boundary conditions . . . (ii)



If there are two D-branes, there are two types of photons A_{11} and A_{22}.

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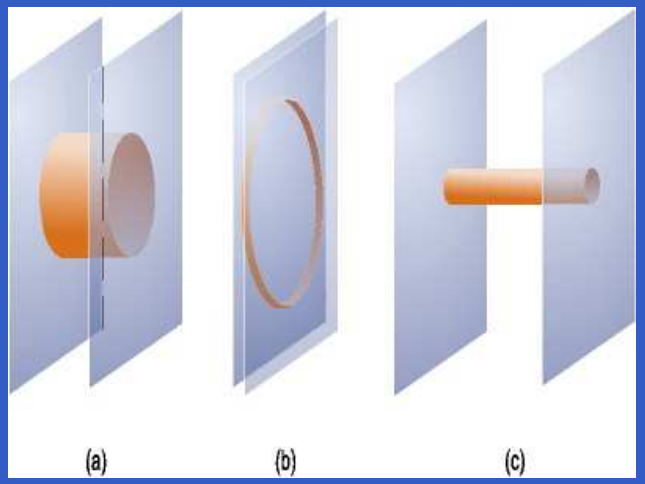

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If there are two D-branes, there are two types of photons A_{11} and A_{22}.

If they coincide, A_{12} and A_{21} also become massless.

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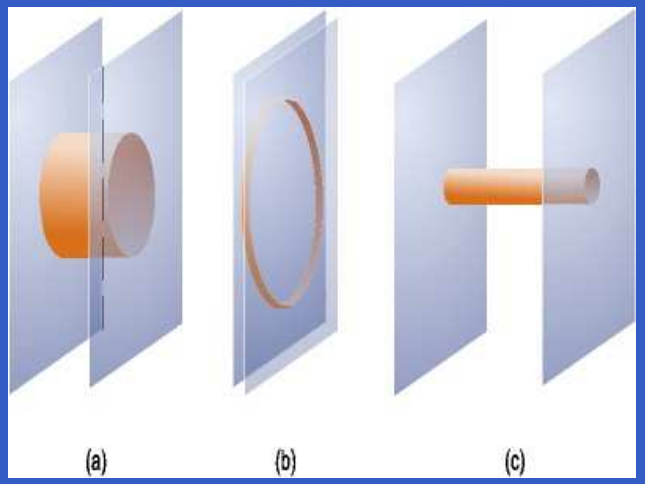

Now all *four* fields A_{11}, A_{12}, A_{21} and A_{22} are massless.

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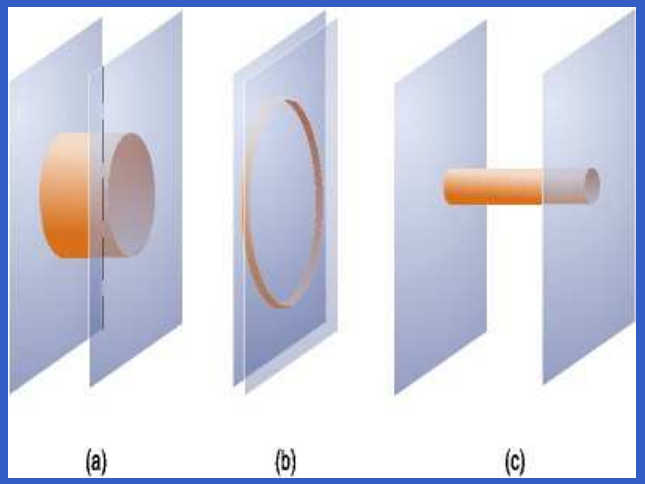

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Now all *four* fields A_{11}, A_{12}, A_{21} and A_{22} are massless.
Also massless are *transverse scalar* fields $X^\perp_{IJ}$.

More on boundary conditions . . . (ii)

This is a U(2) non-abelian gauge theory.

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N coincident D-branes give U(N) non-abelian gauge theory.

U(N) $\sim$ U(1)$\times$SU(N)

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For superstrings one has supersymmetric non-abelian U(N) gauge theory.

The world of the end

The *dynamics* of open strings come from the end-points.

The world of the end

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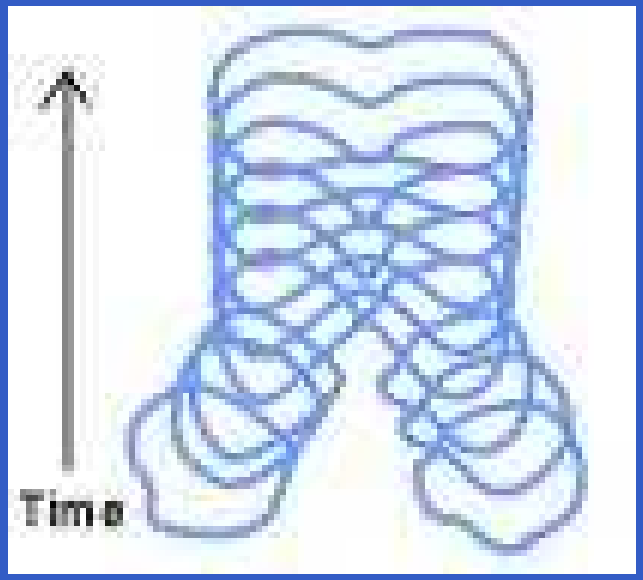
The *dynamics* of open strings come from the end-points.
This may be how we look to the big green giants living in higher dimensions!

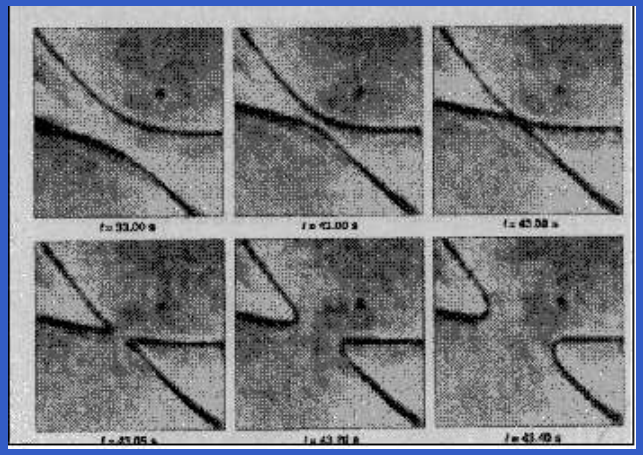
String interactions



String scattering

Closed strings interact by splitting and joining.

String interactions



Interation of strings in nematic liquid crystal

Closed strings interact by splitting and joining.

String interactions

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In a typical process:

2 strings $\stackrel{\text{join}}{\longrightarrow}$ 1 string

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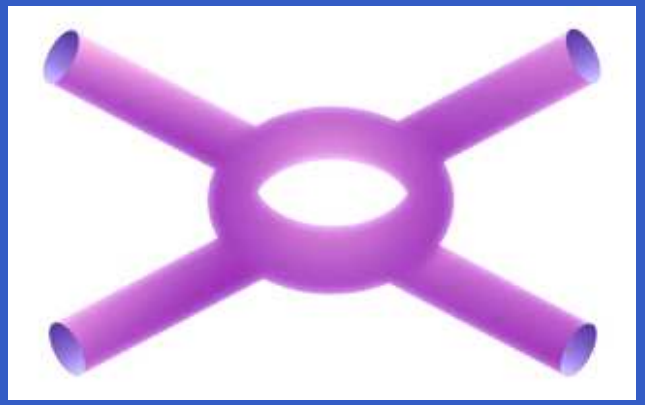

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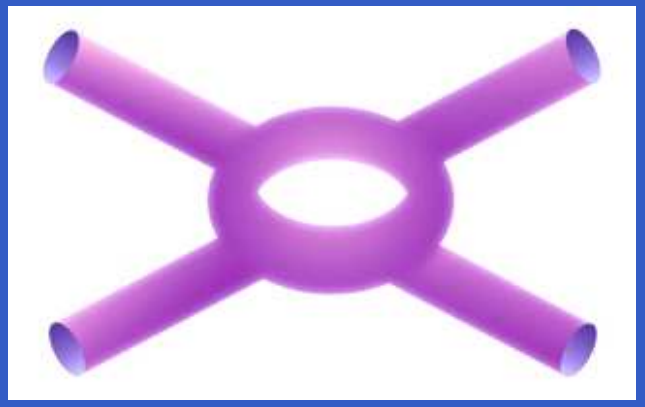

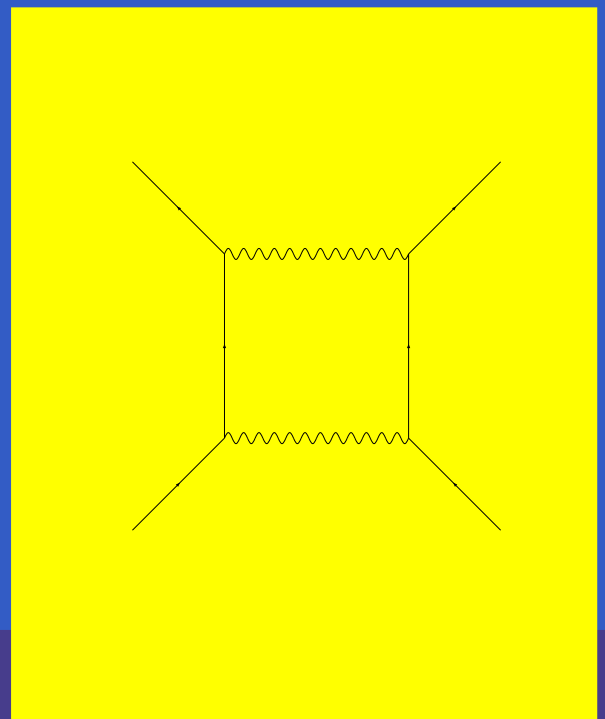

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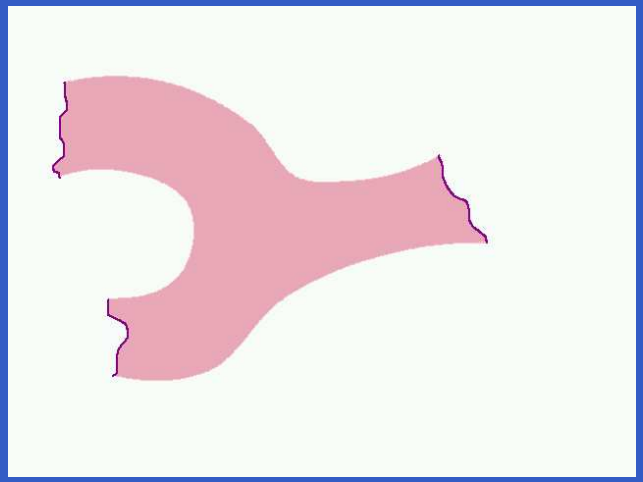
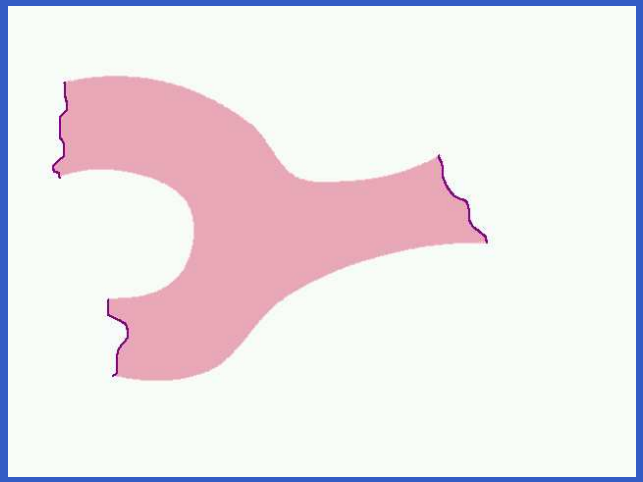
Small string tension $(\alpha' \to 0)$ limit.

Open string interactions



Open strings interact by splitting and joining at the end points.

Open string interactions



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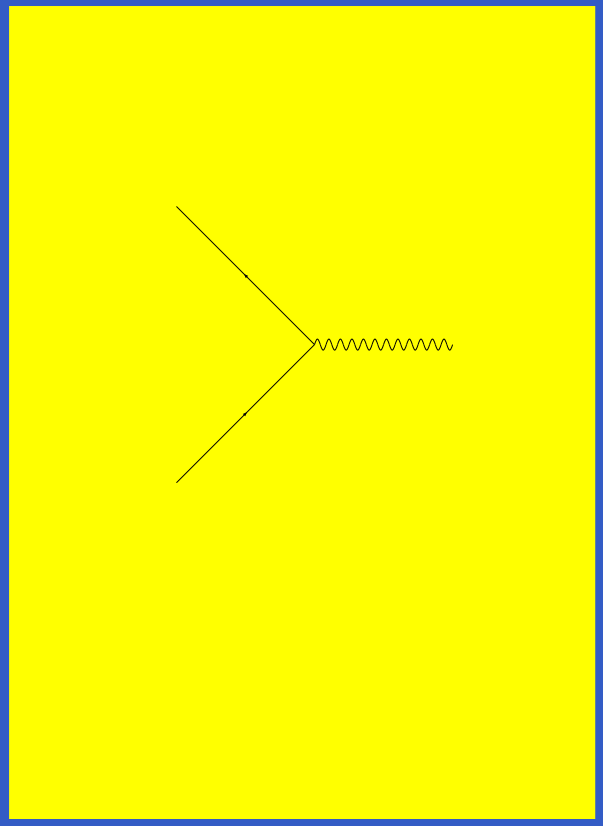

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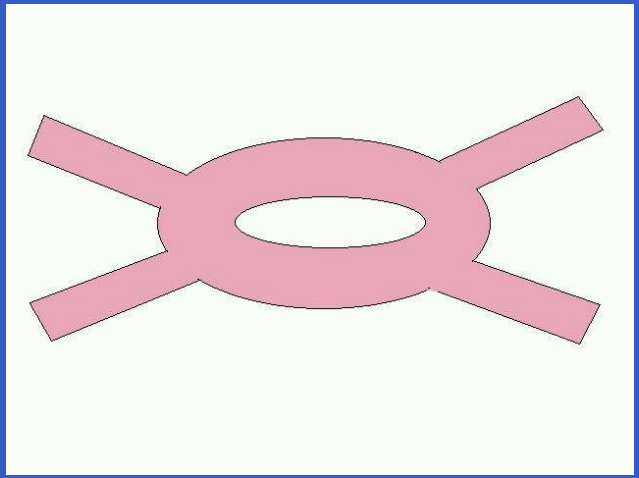

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A typical 2 strings $\longrightarrow$ 2 strings process.

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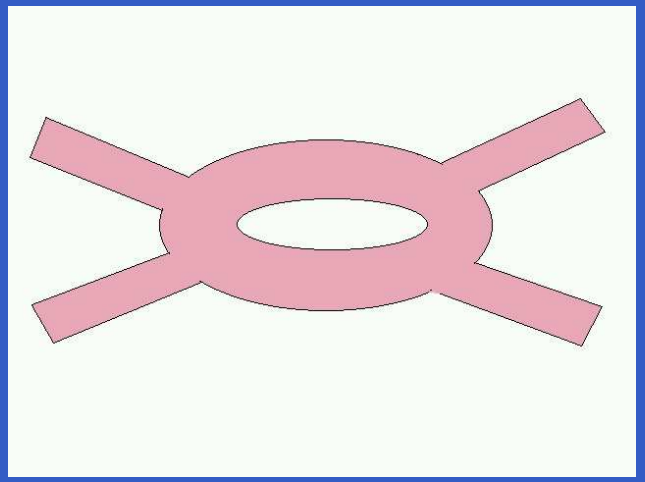

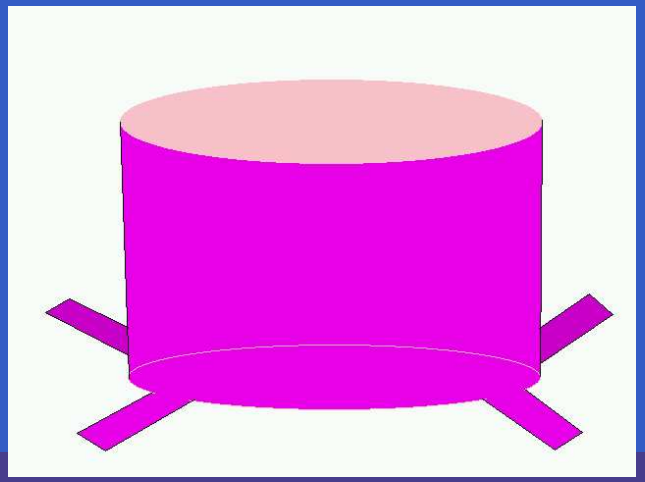

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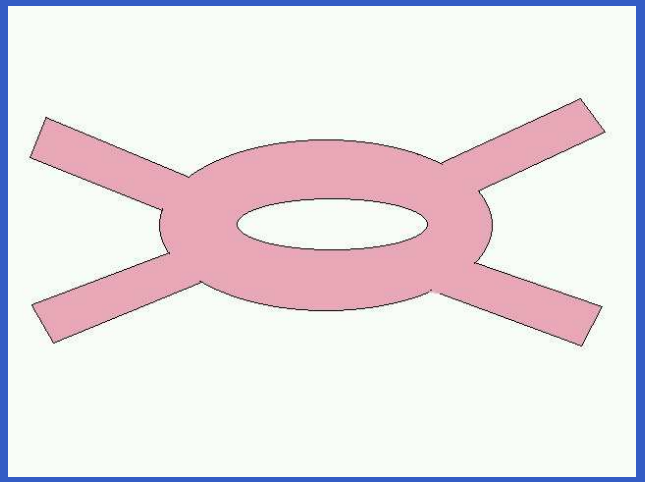

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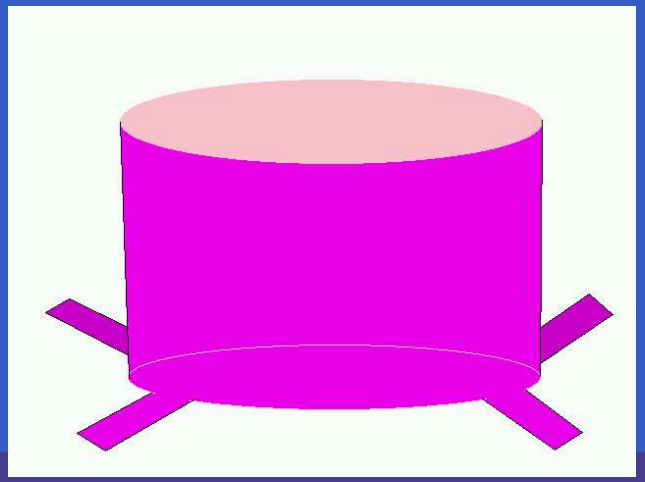


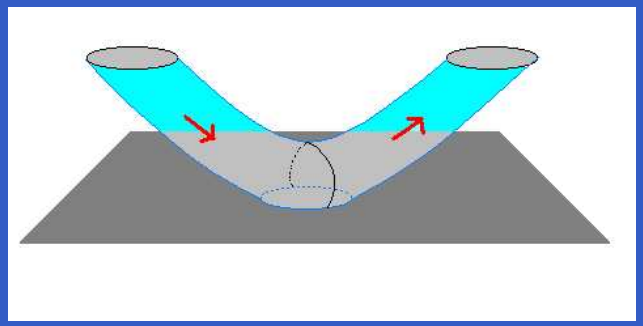
Now there is another way to see this:

4 open strings $\longrightarrow$ 1 closed string

Open string interactions . . . (ii)

End points of an open strings can join to form a closed string.

Open string interactions . . . (ii)



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A closed $\rightarrow$ open $\rightarrow$ closed process involving a D-brane.

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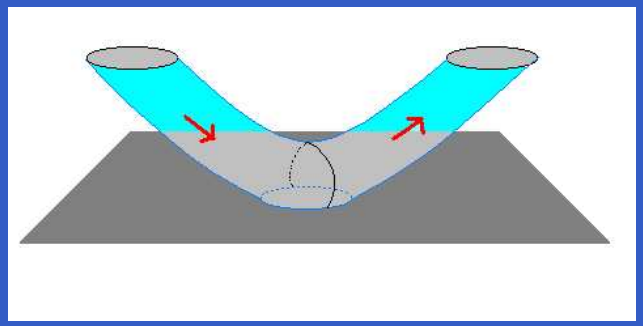

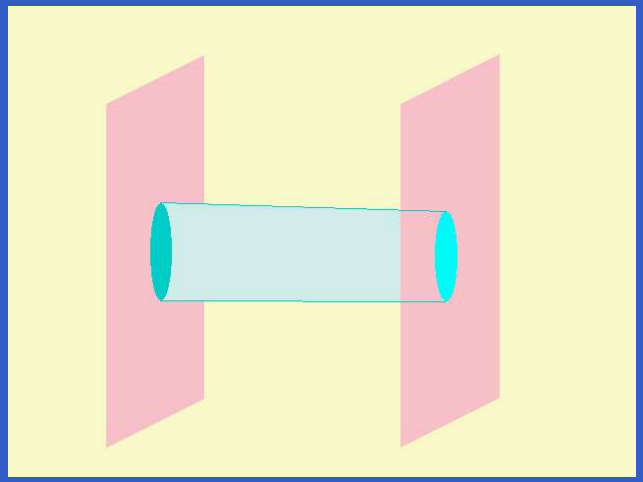

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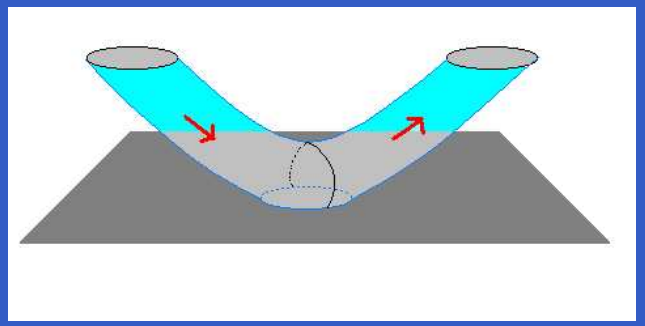

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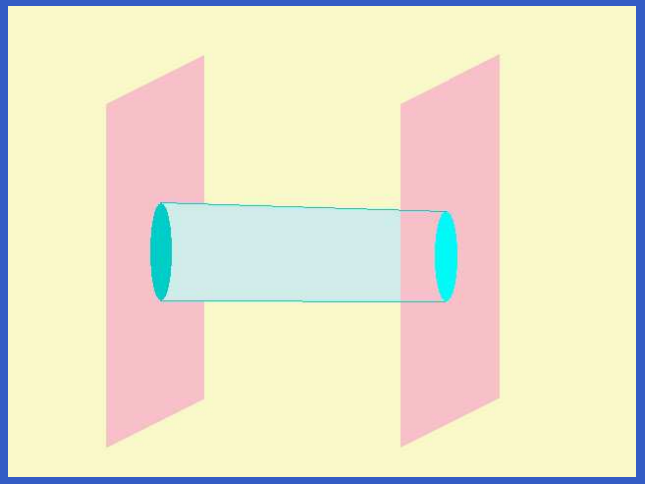

D-branes can *exchange* closed strings.

D-branes interact gravitationally.

Dynamical branes

D-branes have gravitational interaction

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Tension = mass/(hyper-)volume

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How does the D-brane tension compare with the excitation of the string?

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Tension of D-1-brane = D-string is:

$$T_{D1} = \frac{1}{2\pi\alpha' g_s}$$

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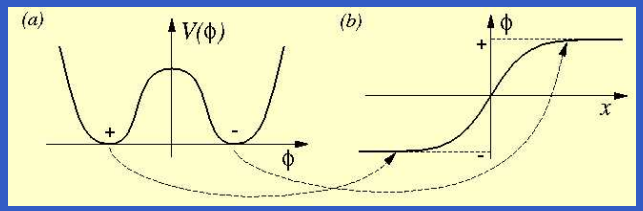
D-branes are *not* rigid defects in spacetime.

D-branes & closed strings

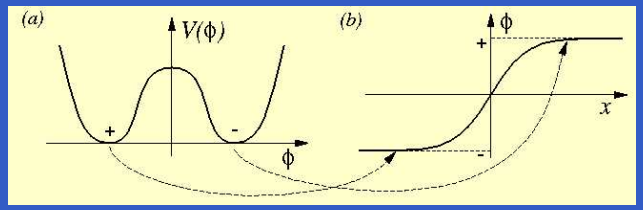
D-branes are black hole -like solutions

D-branes & closed strings



D-branes are black hole -like solutions of *closed string* equations of motion.

D-branes & closed strings



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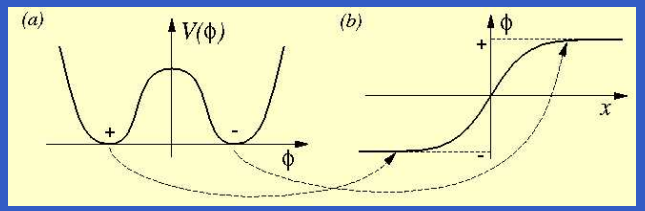
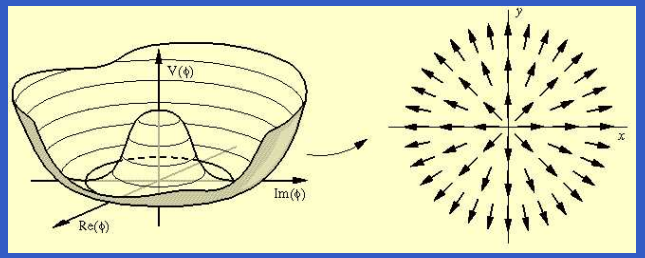
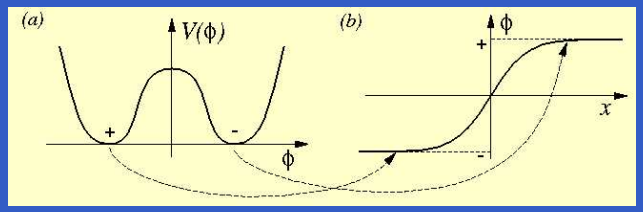
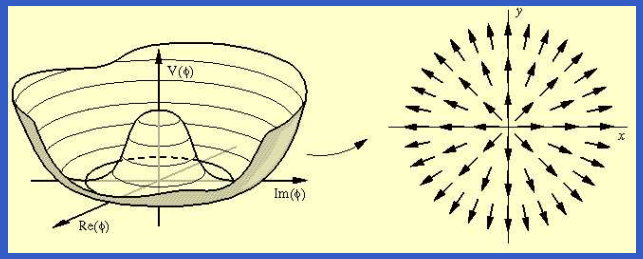




D-branes are black hole -like solutions of *closed string* equations of motion.
They carry mass and sometimes charge.

D-branes & closed strings





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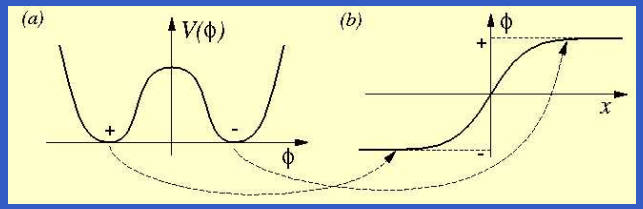
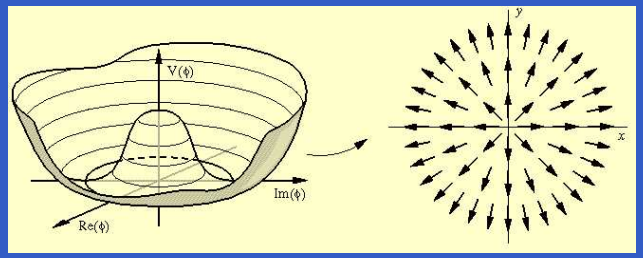
D-branes & closed strings





D-branes are black hole -like solutions of *closed string* equations of motion.

They carry mass and sometimes charge.

If a D-brane carries a conserved charge, it is stable, else it is unstable.

D-brane stability

A D-branes carrying *positive* charge is stable.

D-brane stability

Another one with *negative* charge is also stable — an anti-D-brane.

D-brane stability

But . . . the two together:

a brane-antibrane pair is *unstable*.

D-brane stability

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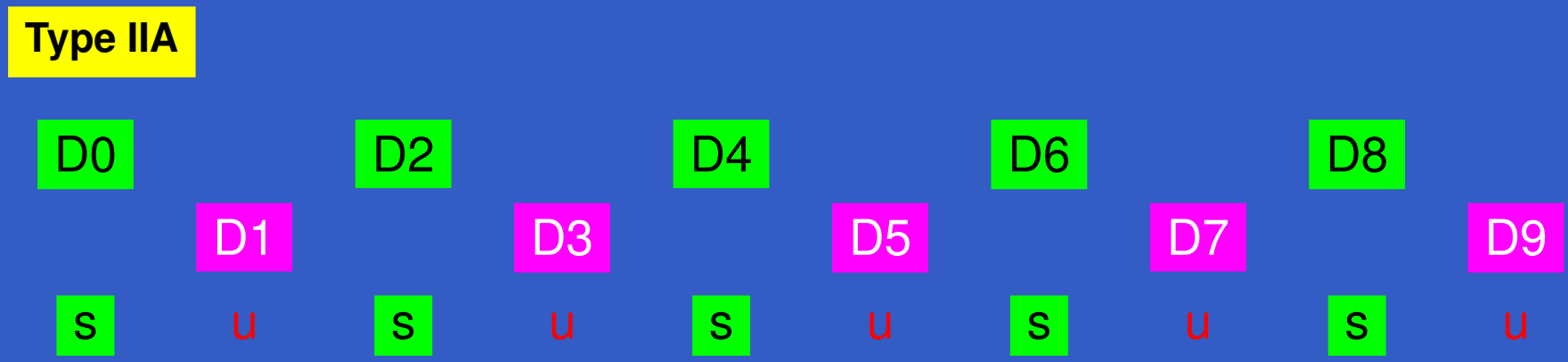
A tachyonic instability.

No net force between two stable D-branes — gravitational and Coulomb force cancel.

D-brane spectrum

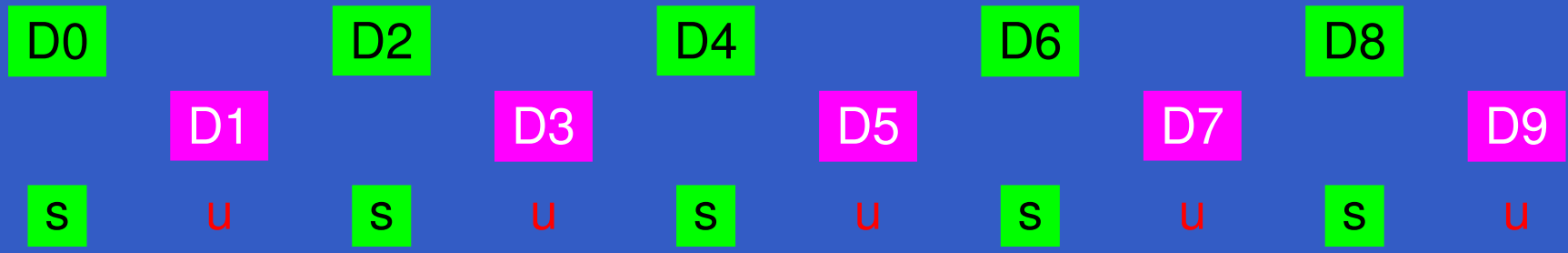
Type IIA

D-brane spectrum



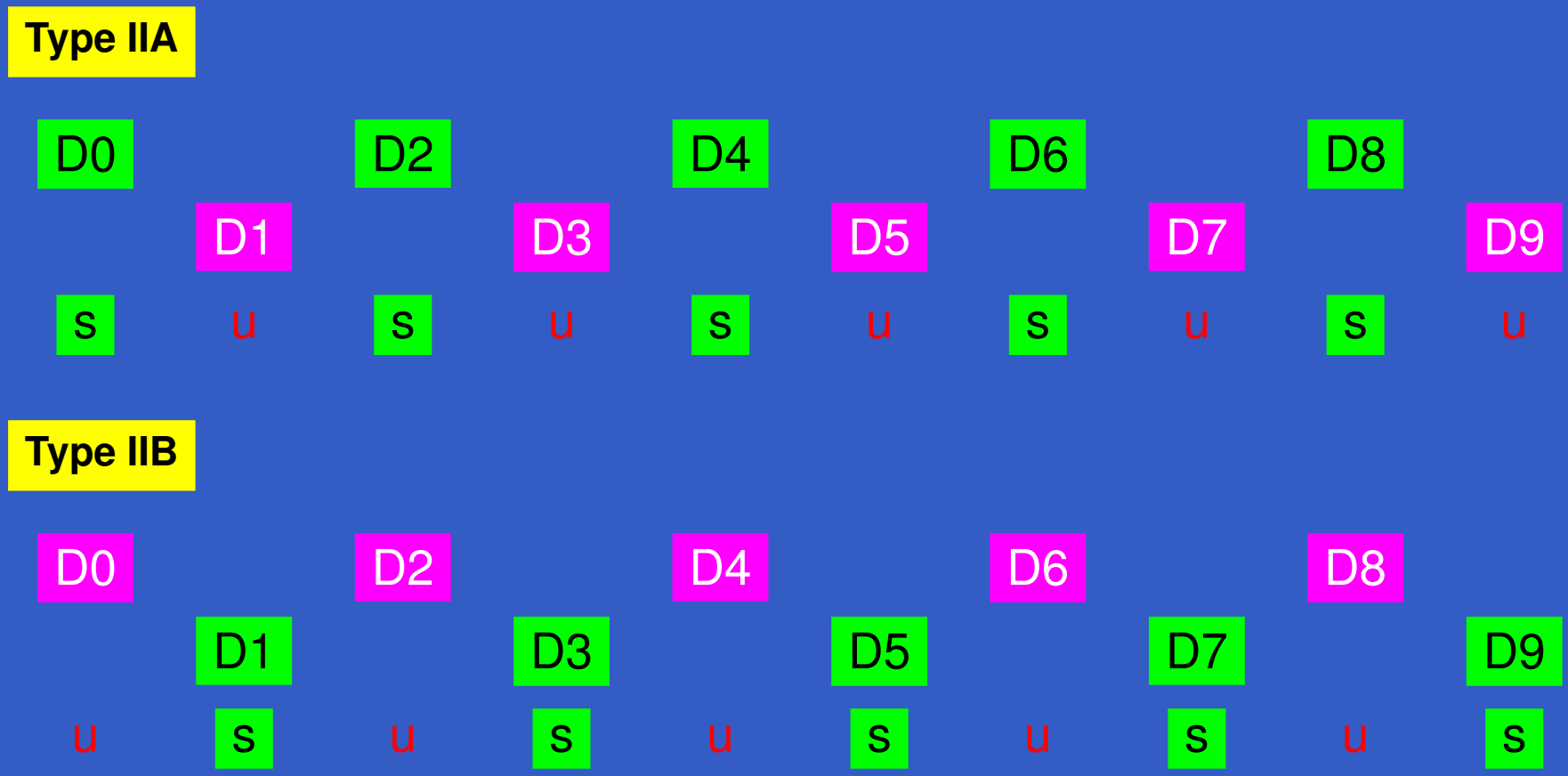
D-brane spectrum

Type IIA



Type IIB

D-brane spectrum



D-branes & T-duality

Recall from closed strings

Momenta $\overset{\text{T-duality}}{\longleftrightarrow}$ Winding

D-branes & T-duality

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For open strings:

Neumann b.c. $\overset{\text{T-duality}}{\longleftrightarrow}$ Dirichlet b.c.

D-branes & T-duality

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For open strings:

Neumann b.c. $\overset{\text{T-duality}}{\longleftrightarrow}$ Dirichlet b.c.

$$\text{D-}m\text{-brane} = \begin{cases} \text{D-}(m-1)\text{-brane} \\ \text{D-}(m+1)\text{-brane} \end{cases}$$

More symmetries

T-duality relates

Type IIA string $\overset{\text{T-duality}}{\longleftrightarrow}$ Type IIB string

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$T_{D1} = 1/2\pi\alpha' g_s$

More symmetries

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There are other relations. . .

At large values of g_s, D-branes become light $T_{D1} = 1/2\pi\alpha' g_s$ and fundamental strings $(T_{F1} = 1/2\pi\alpha')$ become heavy.

More symmetries

T-duality relates

Type IIA string $\overset{\text{T-duality}}{\leftrightarrow}$ Type IIB string

There are other relations. . .

At large values of g_s, D-branes become light $T_{D1} = 1/2\pi\alpha' g_s$ and fundamental strings $(T_{F1} = 1/2\pi\alpha')$ become heavy.

Sometimes Fundamental string $\overset{g_s \to 1/g_s}{\leftrightarrow}$ D-string

More symmetries

T-duality relates

Type IIA string $\overset{\text{T-duality}}{\leftrightarrow}$ Type IIB string

There are other relations. . .

At large values of g_s, D-branes become light $T_{D1} = 1/2\pi\alpha' g_s$ and fundamental strings $(T_{F1} = 1/2\pi\alpha')$ become heavy.

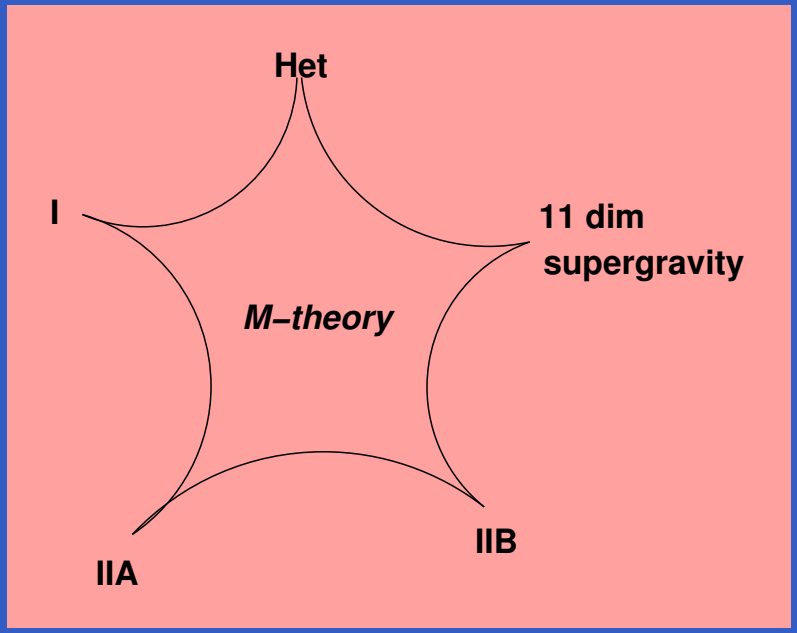
Sometimes Fundamental string $\overset{g_s \to 1/g_s}{\leftrightarrow}$ D-string

Sometimes Graviton $\overset{g_s \to 1/g_s}{\leftrightarrow}$ D-brane

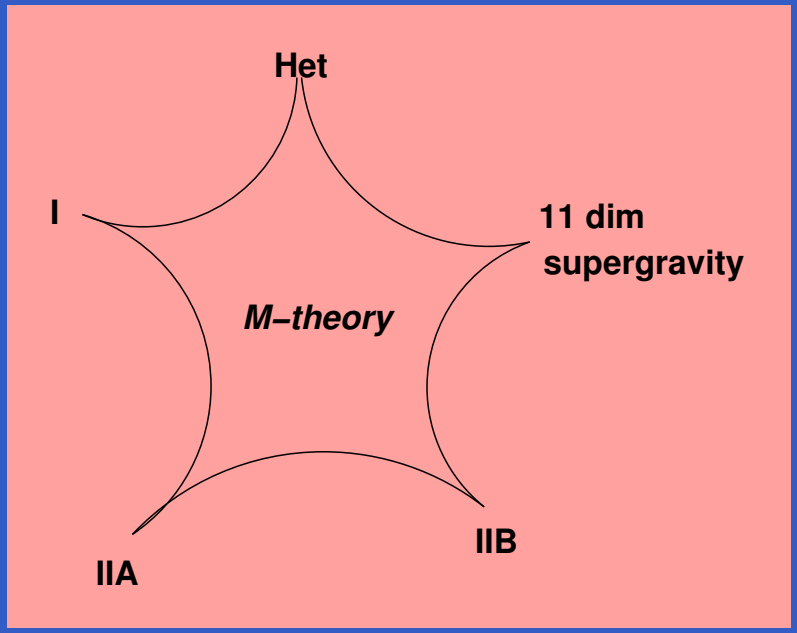
Towards a complete story...

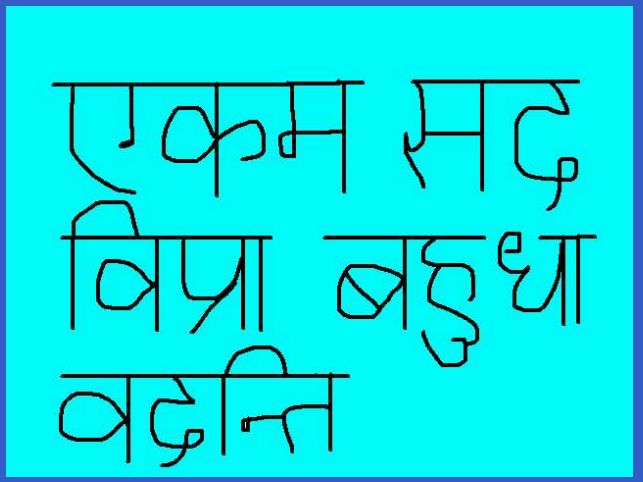
All these symmetries hint at a web of relations

Towards a complete story...

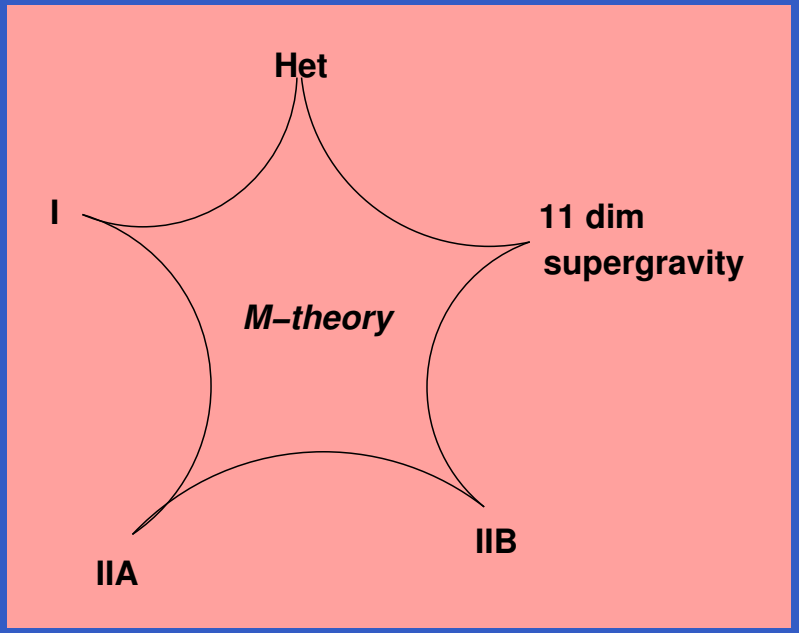


Towards a complete story...

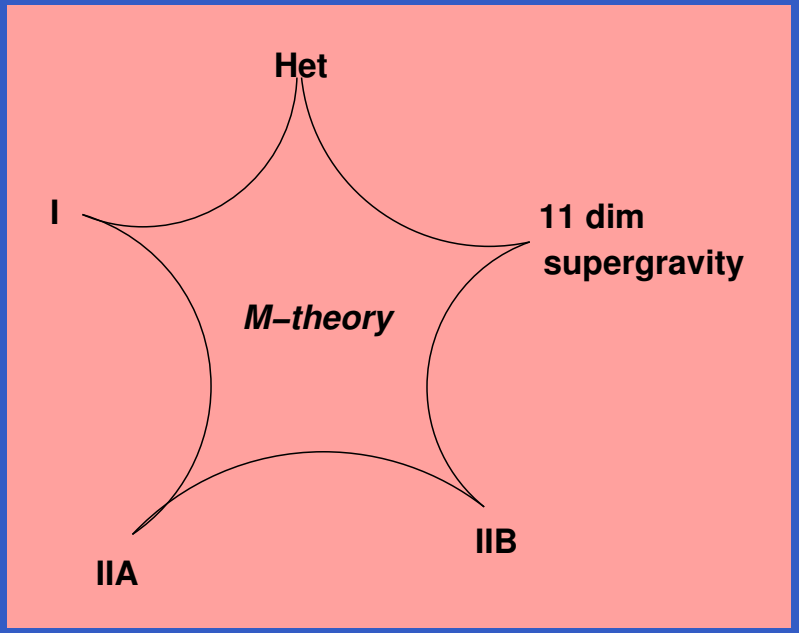




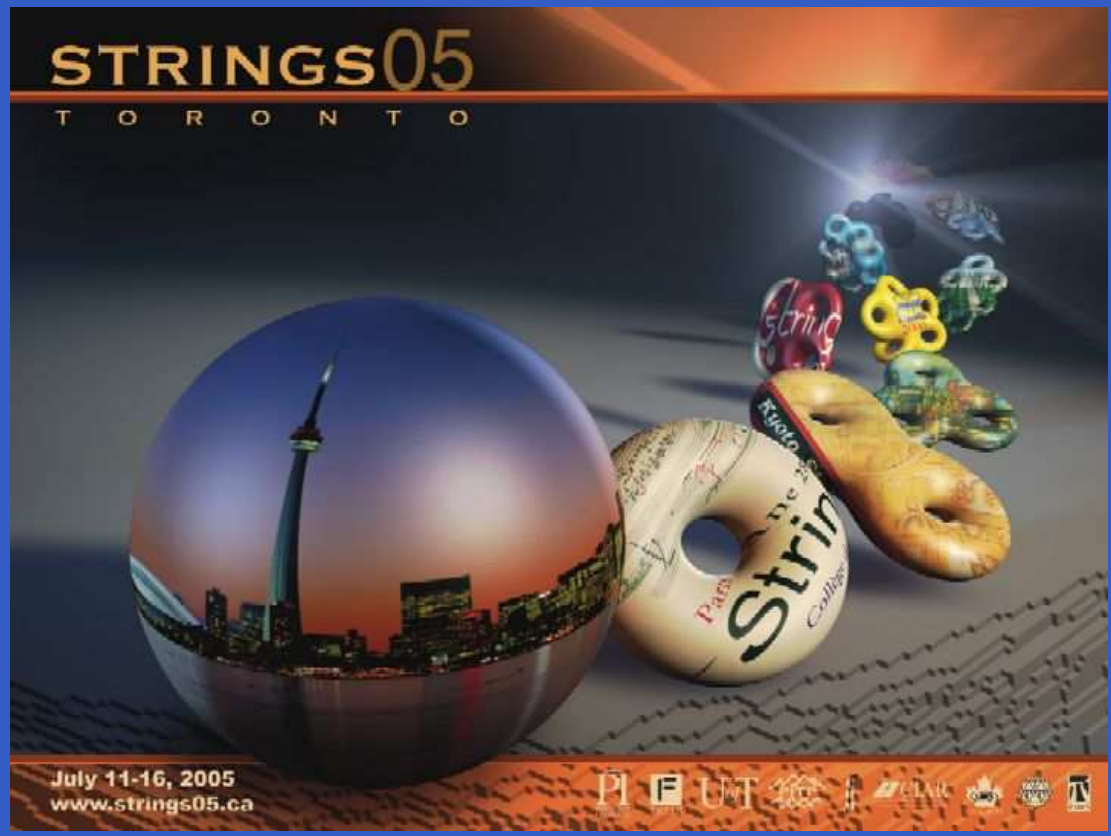
Towards a complete story...



Towards a complete story...



Strings and poster art



Strings and poster art

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