Title: Open Strings

Date: Jan 19, 2005 02:00 PM

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Abstract:

Fundamental Interactions

$3 + 1$

- Yang–Mills Theories

YM vector fields $A_\mu(x)$: electromagnetic, weak and strong interactions

$$S_{YM} = \frac{1}{g_{YM}^2} \int d^4x \, \mathrm{Tr}\, F_{\mu\nu} F^{\mu\nu}$$

$$SU(3)_C \otimes SU(2)_I \otimes U(1)_Y$$

Local Symmetries

Two distinct local symmetry principles:

- Gauge–invariance

Example: $U(1)$, or EL&M

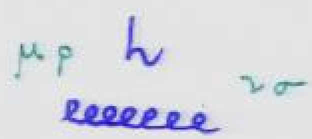
$$\delta A_\mu(x) = \partial_\mu \lambda(x)$$

Quantization gives spin one particles, the photons

- General covariance

$$\delta g_{\mu\nu} = \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$$

Quantization (of small fluctuations around a classical background) gives spin two particles, the gravitons



Clear analogies. In some sense, Gravity = $(\text{EL\&M})^2$

But there are also differences:

- EL&M field A_μ can be generalized to $U(N)$ Yang–Mills matrix field

$$A_\mu \equiv \{(A_\mu)^i_{\ j}\}\,, \quad i,j = 1,\cdots N$$

$$\delta A_\mu = \partial_\mu \lambda + [\lambda, A_\mu]$$

No such generalization for $g_{\mu\nu}$

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- Quantum theories have very different short–distance properties in perturbation theory:

Yang–Mills renormalizable, Gravity non–renormalizable

- Quantum gravity should really be about quantum geometry.

Background–independence at best obscure in this perturbative treatment.

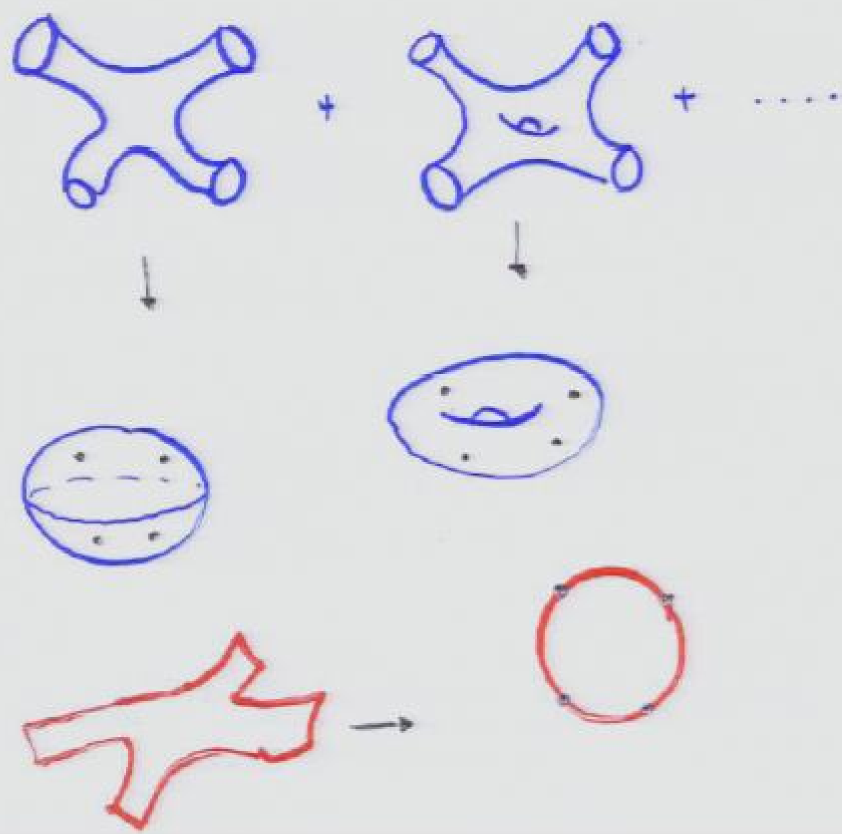
Enter String Theory

Point particles $\rightarrow$ one-dimensional strings.

Scattering amplitudes of string states evaluated by summing over all possible embeddings

$$X^{\mu}(\sigma, \tau) \quad \mu = 0, \cdots D$$

in D–dimensional spacetime



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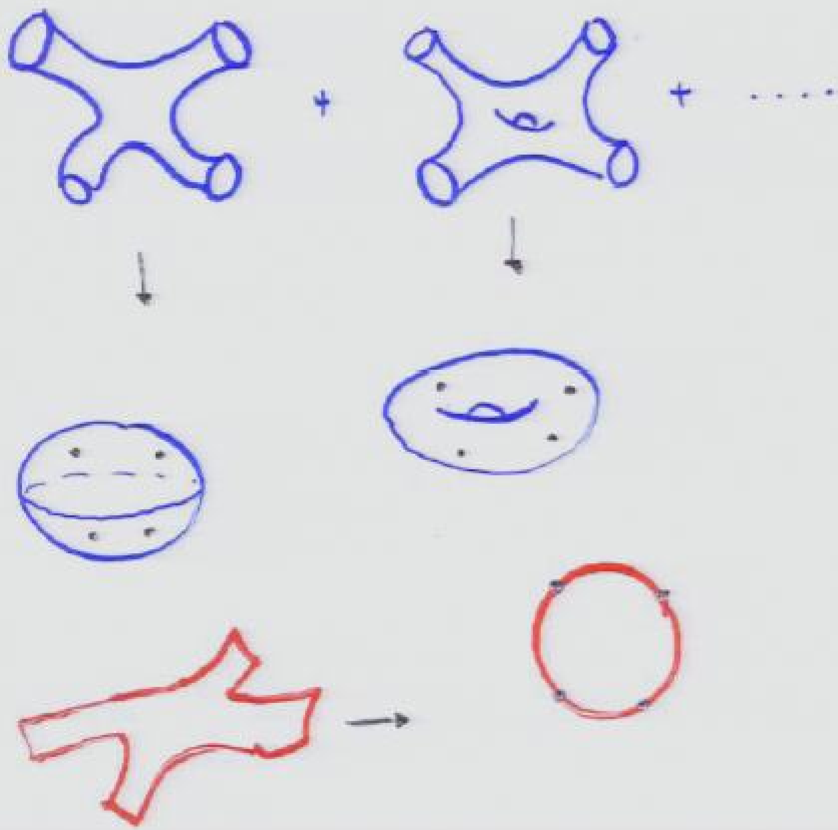

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Critical dimension $D = 26$

In spacetime, string theory gives an infinite tower of quantum fields

Negative zero point energy $\rightarrow$

lowest mode of the string has $m^2 < 0$ (open or closed tachyon)

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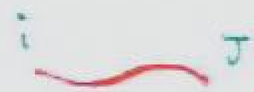
At the next level, we find (among other things)

- For an open string, a massless spin one field A_μ field (EL&M!)
- For a closed string, a massless spin two field $g_{\mu\nu}$ (gravity!)

String theory generalizes and unifies both EL&M and gravity.

• From the string viewpoint, it is now clear why EL&M, but not gravity, admits of a matrix version: we can put indices at the open string end-points



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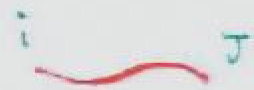
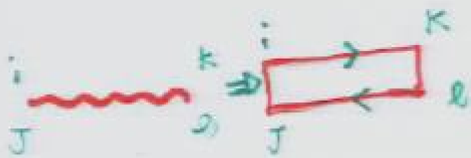


YM → open strings: just take seriously 't Hooft's double–line notation $\cdots$



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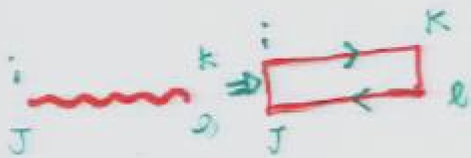
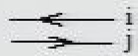
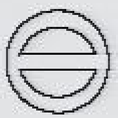


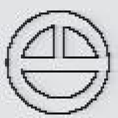
General Large N Analysis

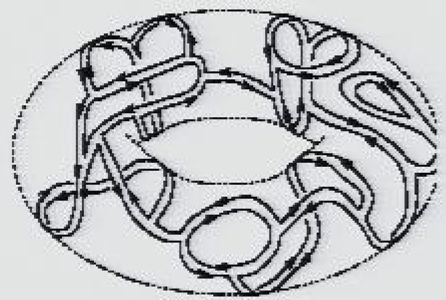
$$L = \frac{1}{g^2} Tr[(\partial M)^2 + M^2 + M^3 + \cdots] = \frac{1}{g^2} Tr[(\partial M)^2 + V$$

Propagator M^i_j 

Vertices 

 $N^3(g^2) \sim N^2(g^2 N)$

 $N^4(g^2)^2 \sim N^2(g^2 N)^2$



$$N^{\#\text{faces} - \#\text{edges} + \#\text{vertices}} (g^2 N)^{\#\text{faces}} = N^{2 - 2\,\text{genus}} (g^2 N$$

• From the string v

admits of a matrix

YM → open string

• Amplitudes pertu

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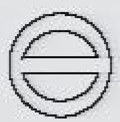
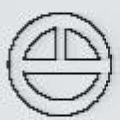
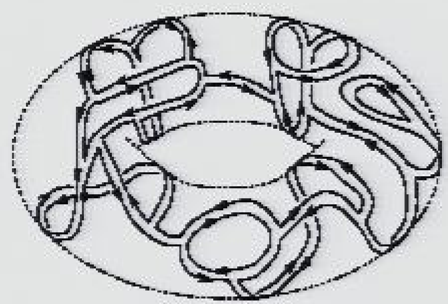
 $N^3(g^2) \sim N^2(g^2N)$

 $N^4(g^2)^2 \sim N^2(g^2N)^2$

 $\sim N^0(g^2N)^{\#\text{faces}}$

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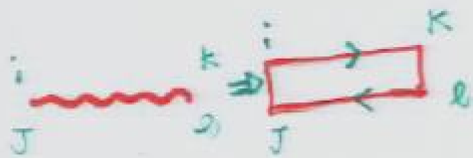

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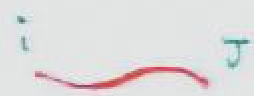

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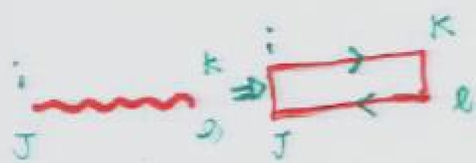


• Amplitudes perturbatively finite for both open *and* closed strings

Unification of YM and gravity in string theory goes much further.

At the quantum level, open and closed strings need each other

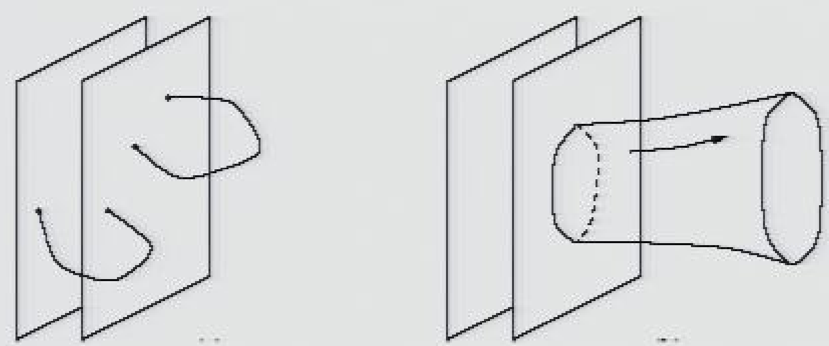
- Open → Closed $\qquad g_{closed} = (g_{open})^2$

"Gravity = $(\text{YM})^2$", insight used to simplify calculation KLT

Dp brane:

Neumann b.c. $\partial_\sigma X^\mu(\sigma = 0, \pi) \equiv 0$ for $\mu = 0, \cdots p$

$X^\mu(\sigma = 0, \pi) \equiv x^\mu$ for $\mu = p + 1, \cdots 26$



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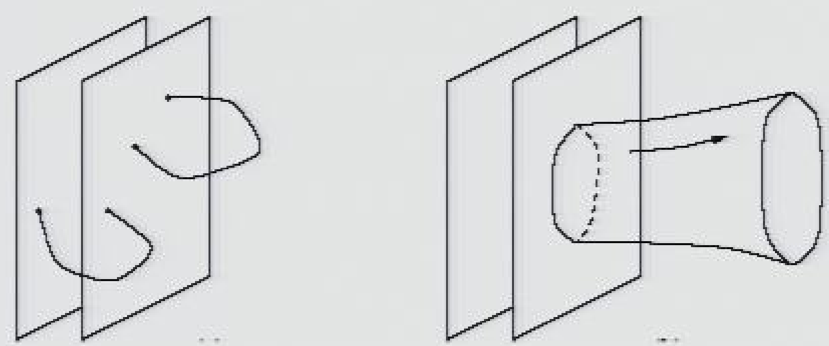


As we turn on interactions, D-branes become dynamical objects:
sources for closed strings $\rightarrow$ backreaction

D-brane tension $\sim 1/g_c \rightarrow$ non–perturbative objects.
Necessary for the consistency of the closed string theory.

- Hence a purely closed (perturbative) string theory has also open strings at the non–perturbative level.

We can always think of open strings as the degrees of freedom on the worldvolume of some appropriate D-branes.

String Field Theory

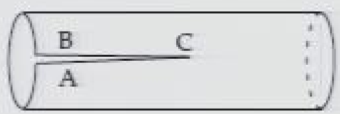
So far, a "first quantized" viewpoint.
Can we write a spacetime action for string theory, a string field theory?

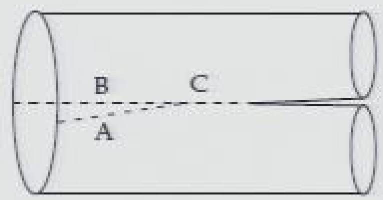
A priori, introduce an open string field $\Psi[X^\mu(\sigma)]$
and a closed string field $\Phi[X^\mu(\sigma)]$,

$$\mathcal{S}[\Psi, \Phi] .$$

This is what is done in light-cone quantization
or in Zwiebach's covariant open/closed SFT.

$$\mathcal{V}_{lightcone} = \mathcal{V}_3^{closed} + \mathcal{V}_3^{open} + \mathcal{V}_4^{open} + \mathcal{V}_{1,1}^{open/closed} + \mathcal{V}_{2,1}^{open/closed}$$



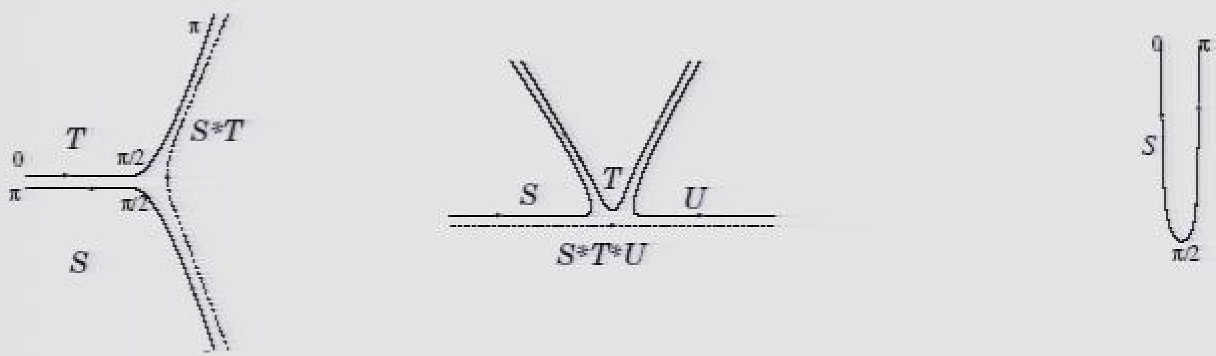


However, a more beautiful alternative is Witten's Open SFT.

Only open string field Ψ as dynamical variable. "Chern–Simons" form

$$\mathcal{S}_W = \frac{1}{g_o^2}\left(\int \Psi * Q_B \Psi + \int \Psi * \Psi * \Psi\right)$$

Associative $*$ product



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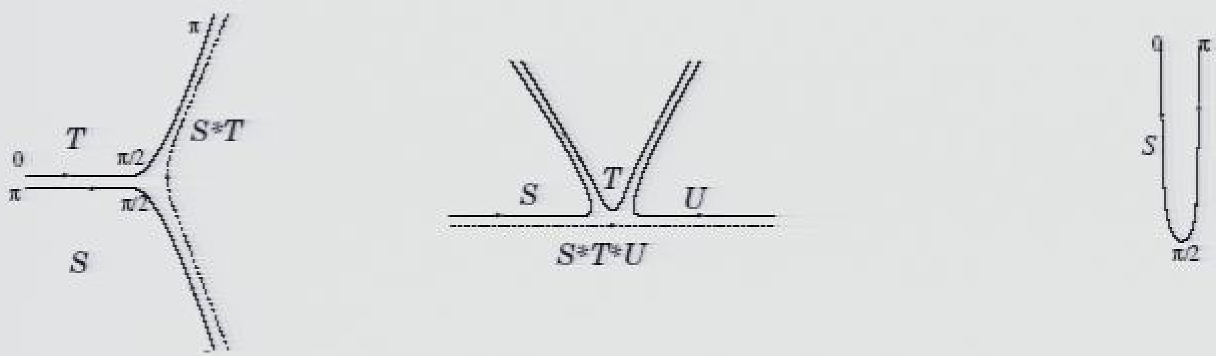
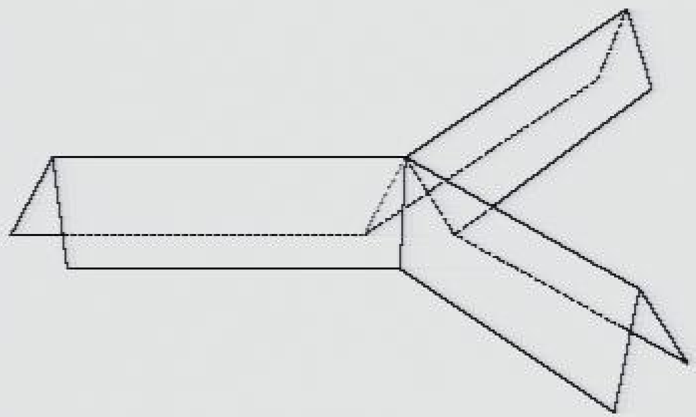


Infinite dimensional generalization of massless gauge–invariance

$$\delta\Psi = Q_B\Lambda + \Lambda * \Psi - \Psi * \Lambda$$



Theorem: Penner, Strebel

Feynman rules of cubic OSFT give a triangulation of moduli space of all Riemann surfaces (with at least one boundary).

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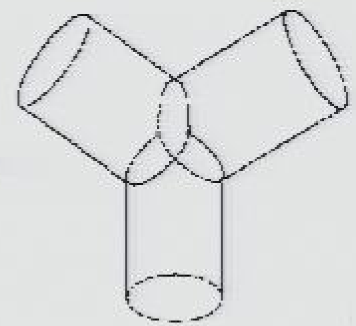

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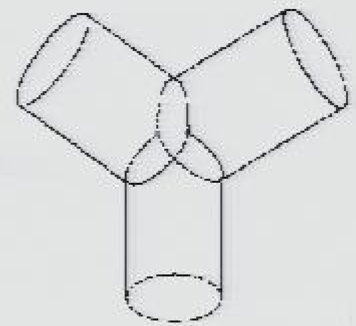

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gauge–invariant observables, certain singular open–string functionals.

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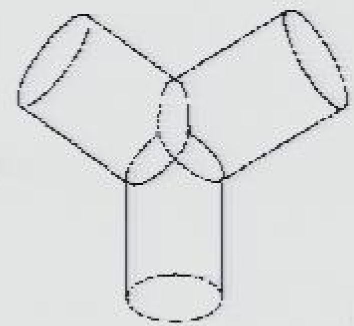

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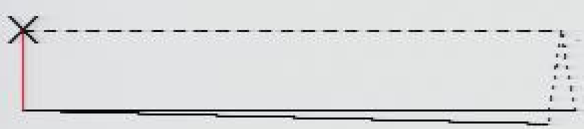

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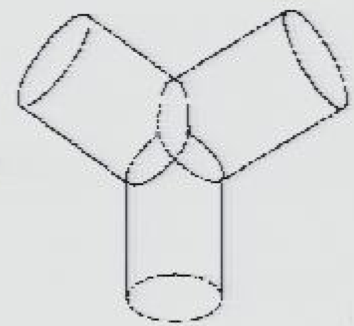

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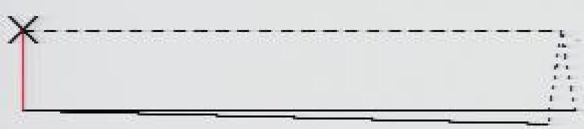

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Including by hand a dynamical closed string field Φ would amount to overcounting.

In Open SFT, D-branes are classical solitons.

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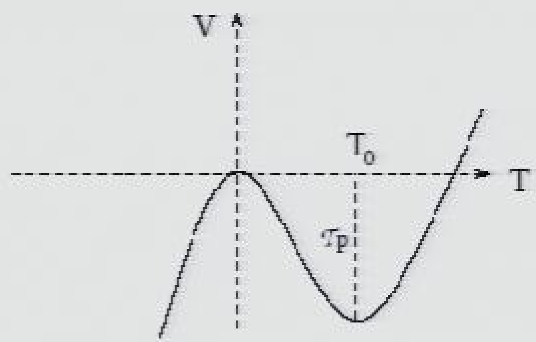
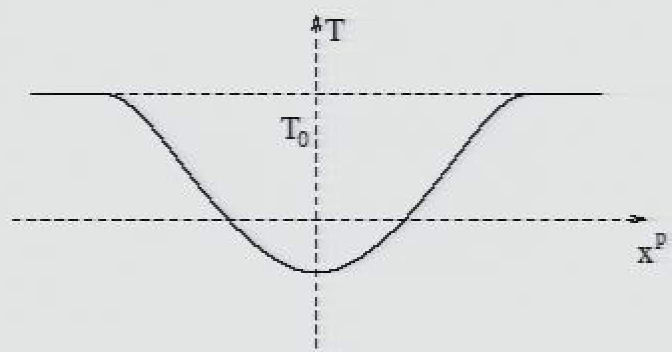
Bosonic open string tachyon ≡ instability of the D-brane Sen

Tachyon potential



Tachyon condensation makes the brane (and hence the open strings!) disappear

Lower-dimensional D-branes are lumps



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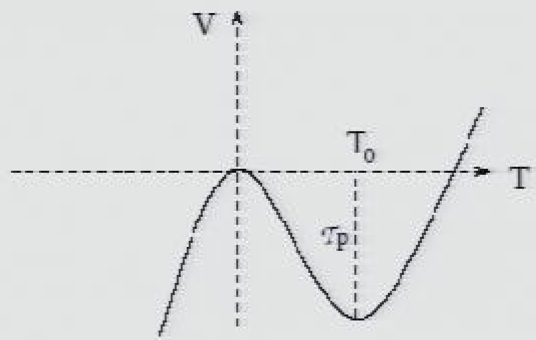

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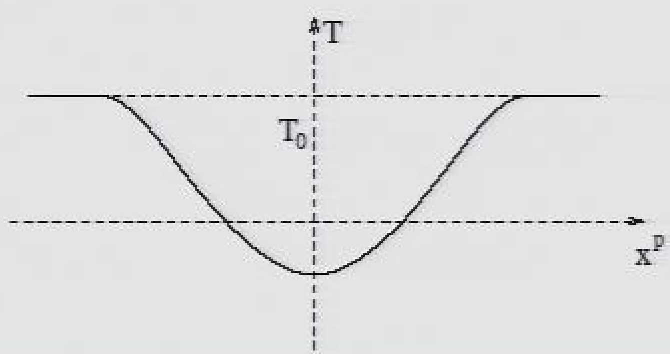
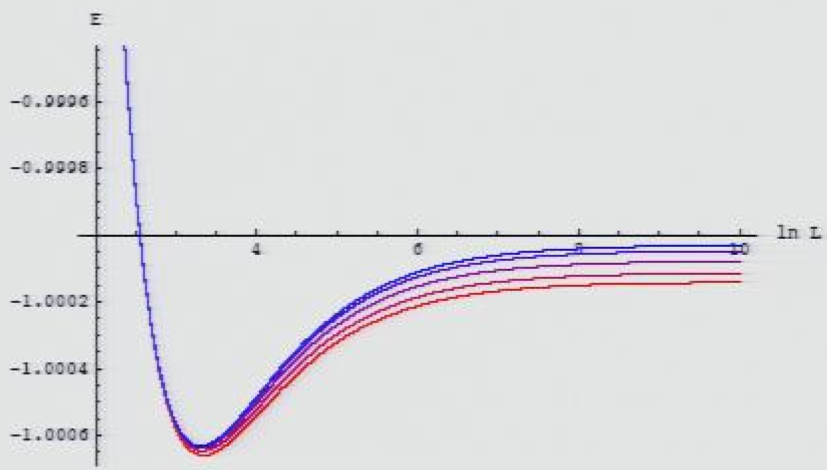


Many tests of Sen's conjectures in Open SFT

L	$E_{(L,3L)}$	$E_{(L,2L)}$
2	-0.9593766	-0.9485534
4	-0.9878218	-0.9864034
6	-0.9951771	-0.9947727
8	-0.9979302	-0.9977795
10	-0.9991825	-0.9991161
12	-0.9998223	-0.9997907
14	-1.0001737	-1.0001580
16	-1.0003754	-1.0003678
18	-1.0004937	-1.00049



The Long Arm of the Open String Field

Fix once and for all the closed moduli (= geometry).
Consider the "open string landscape" , i.e. the possible open string b.c. (=D-branes)

Classical OSFT gives a global picture of this landscape:
D-branes in $1-1$ correspondence with classical solutions of OSFT.

"Background–independence" for the open moduli (though not *manifestly* so).

Open String Completeness

Conjecture: Sen
open SFT (with only open string variables) on a given configuration of N D-branes is by itself a consistent quantum theory.
In general, it describes a proper subsector of the full Hilbert space of the string theory.
In some cases, the full Hilbert space is recovered as $N \to \infty$.

Rolling Tachyon

A case study: decay of an unstable D-brane in real time.

Two equivalent descriptions:

- Open: Worldvolume dynamics (Open SFT).

Using boundary CFT techniques, compute large time behavior of spacetime stress-tensor $T_{\mu\nu}$

$$T_{00} = \delta(x_\perp)\,\mathcal{E}$$

$$T_{ij} = \delta(x_\perp)\,p(t)\,\delta_{ij} \to 0 \quad \text{for } t \to \infty$$

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• Closed: decay into closed string modes.
Dominated by very massive modes with $m \sim 1/g_c$.
For large time, non–relativistic pressureless dust of massive closed strings localized at $x_\perp = 0$.

Sen, Lambert Liu Maldacena, Gaiotto Itzhaki L.R.

Nice agreement.

Two–Dimensional String Theory

Very explicit tests of these ideas in two–dimensional string theory.

McGreevy Verlinde, Klebanov Maldacena Seiberg

Exact duality between the closed string theory and the matrix model (=Open SFT on $N \to \infty$ localized D-branes).

Decay of an unstable D-brane:

- Open (=matrix QM) description:

a single fermion rolling down the inverted harmonic potential

- Closed description:

closed tachyon field Φ obtained by bosonizing the second–quantized fermion field Ψ

Exact open/closed duality given by bosonization!

Absolutely clear that the two descriptions are dual to each other.

Open description is less singular.

Closing Holes, Blowing Up Punctures

In favorable cases, we can use open/closed duality to compute purely closed amplitudes from purely open amplitudes on N D-branes.

Intuition: each boundary state (upon integration over the length of the boundary) can be replaced by an effective closed string insertion.

As we vary over the possible open string b.c., and send $N \to \infty$, we may be able to span the entire closed string Hilbert space.

Inverting this relation, we are "blowing–up" each closed puncture to a boundary with appropriate b.c.

This picture can be made precise in some simple models (topological strings, strings in low-dimension). Gopakumar Vafa, Kontsevich, Gaiotto L.R., Aganagic et al.

Powerful computational tool: open side really much simpler

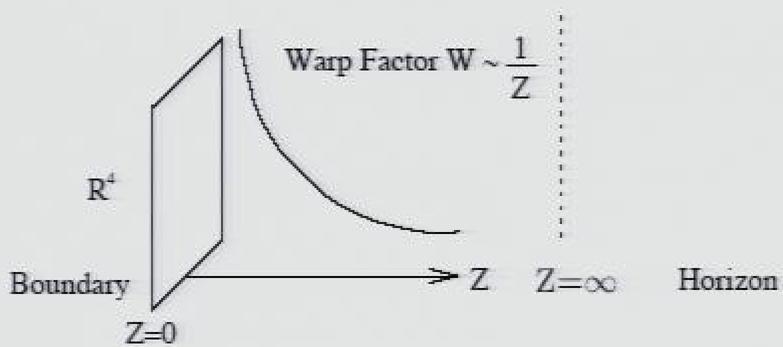
Gauge/String Correspondene

Most famous incarnation of open/closed duality: AdS/CFT

Exact equivalence:

- (open side) $d = 4$ $\mathcal{N} = 4$ super YM theory with gauge group $U(N)$
- (closed side) IIB on $AdS_5 \times S^5$ with N units of 5-form flux

$$ds^2 = R^2 \frac{dx^2 + dz^2}{z^2}$$



Precise incarnation of ‘t Hooft’s large N ideas,
and of Polyakov’s “Liouville” direction ideas

Usually motivated by taking the low-energy limit of the full OSFT on N D3 branes. Maldacena

Speculation: it should be possible to intepret $\mathcal{N} = 4$ SYM as the full OSFT on some appropriate D-branes

Thoughts on background–independence and Open SFT

For concrete calculations, open string field Ψ must be defined around a given (closed + open) background

$$\Psi(x) = \sum_i \psi_i(x) V_i$$

where $\{V_i\}$ is a complete basis of open string vertex operators: background–dependent notion.

In principle, one could attempt a completely algebraic definition of Open SFT, in terms of operation on abstract open functionals Ψ. Choosing a representation of the $*$-algebra amounts to choosing a background.

Maybe this is the way to go. It should work for open moduli. Not so clear for closed moduli.

Conclusions

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In some cases, exact reformulation of gauge theories as theories of quantum gravity (and closed strings).
This is how humans will one day solve Quantum Chromodynamics.

Open string description often simpler, perhaps more fundamental.
Open SFT on $N \to \infty$ D-branes:
best guess for a full non–perturbative definition of string theory.

Thoughts on background–independence and Open SFT

For concrete calculations, open string field Ψ must be defined around a given (closed + open) background

$$\Psi(x) = \sum_i \psi_i(x)\, V_i$$

where $\{V_i\}$ is a complete basis of open string vertex operators: background–dependent notion.

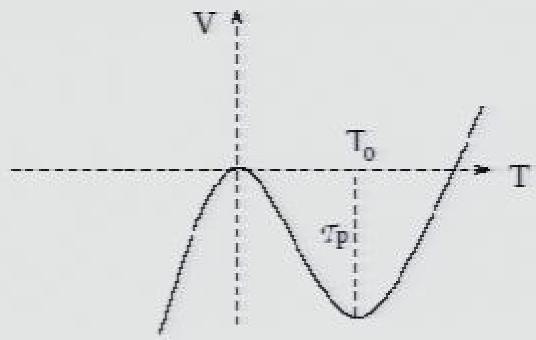
In principle, one could attempt a completely algebraic definition of Open SFT, in terms of operation on abstract open functionals Ψ. Choosing a representation of the $*$-algebra amounts to choosing a background.

Maybe this is the way to go. It should work for open moduli. Not so clear for closed moduli.

In Open SFT, D-branes are classical solitons.

Bosonic open string tachyon ≡ instability of the D-brane Sen

Tachyon potential



Tachyon condensation makes the brane (and hence the open strings!) disappear

Lower-dimensional D-branes are lumps