

STRING THEORY

IAN LIM

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These notes were taken for the *String Theory* course taught by R.A. Reid-Edwards at the University of Cambridge as part of the Mathematical Tripos Part III in Lent Term 2019. I live-TeXed them using Overleaf, and as such there may be typos; please send questions, comments, complaints, and corrections to itel2@cam.ac.uk.

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CONTENTS

1.	Friday, January 18, 2019	1
2.	Monday, January 21, 2019	4
3.	Wednesday, January 23, 2019	6
4.	Friday, January 25, 2019	9
5.	Monday, January 28, 2019	11
6.	Wednesday, January 30, 2019	13

Lecture 1.

Friday, January 18, 2019

Note. This is a 24 lecture course with lectures at 11 AM M/W/F. There will be PDF notes available online somehow (TBD), and also 3 + 1 problem sets plus a revision in Easter. The instructor can be reached at rar31@cam.ac.uk. Some recommended course readings¹ include “easier” texts:

- Schomerus²
- (Becker)² and Schwarz³

and “harder” texts:

- Polchinski, Vol 1.⁴
- Lüst and Teisen⁵
- Green, Schwarz, and Witten.⁶

Introduction Here are some of the major topics we’ll be covering in this course.

- Classical theory and canonical quantization
- Path integral quantization
- Conformal field theory (CFT) and BRST quantization
- Scattering amplitudes
- Advanced topics (more on this later).

¹Most of these are published by Cambridge University Press. Conspiracy– string theory was invented by CUP to sell textbooks?

²Available here for users with access to Cambridge University Press online: <https://doi.org/10.1017/9781316672631>

³Ditto: <https://doi.org/10.1017/CBO9780511816086>

⁴Here: <https://doi.org/10.1017/CBO9780511816079>

⁵Possibly available through Springer Link but not a CUP publication. <https://link.springer.com/book/10.1007/BFb0113507>

⁶Here: <https://doi.org/10.1017/CBO9781139248563>

Historically, string theory emerged from ideas in QCD, the theory of the strong force. However, it really took hold as a theory of quantum gravity in the quest to reconcile quantum mechanics with general relativity. A bit of expectation management, first. Some of the motivating ideas which string theory attempts to address are as follows:

- What sets the parameters of the Standard Model?
- What sets the cosmological constant?
- Failure of perturbative GR (problems in the UV– gravity is non-renormalizable)
- The black hole information paradox (quantum information in gravitational systems)
- How do you quantize a theory in the absence of an existing causal structure? (Most of the causal structure of spacetime is encoded in the metric. But what if it's the metric itself you're trying to quantize?)

There are alternatives to string theory– for instance, one can do QFT in curved spacetime to learn about some limit of quantum gravity. There's also loop quantum gravity and causal set theory, among others, but we won't really discuss those in this course.

What is string theory? We just don't know.

In some sense, string theory is a set of rules which, given a 10-dimensional classical spacetime vacuum, allows us to do quantum perturbation theory around this vacuum. By doing perturbation theory, we seem to arrive at a unique quantum theory (details of this to be discussed more later).

In the popular science conception of string theory, we imagine replacing particles with strings, and the harmonics of these strings correspond to different particles, including the graviton. How do we reconcile this with the idea that gravity is just a function of the curvature of space time? Answer: we assume that we are close to some well-understood solution with metric $\eta_{\mu\nu}$ and take the new metric to be a perturbation,

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x).$$

Now that we have some spacetime structure, we can start to talk about interactions. We might have a propagator for strings, and also interaction vertices with some rules. We might think that an equivalent of Feynman diagrams emerges to tell us how strings can mingle and talk to each other.

In QFT, we were given some Lagrangian and from that Lagrangian, we derived interactions and Feynman rules. But in string theory, the situation is a bit backwards. It's as though we've been given some Feynman rules which do seem to reduce to the particle interactions in some limit, but we don't in some sense know the underlying theory where these rules come from.⁷

Classical theory In quantum mechanics, we have time t as a parameter and position \hat{x} as an operator. Of course, when we started learning quantum field theory, we were motivated to take our quantum fields $\hat{\phi}(\mathbf{x}, t)$ as operators and demote \mathbf{x} to a simple label, so that (\mathbf{x}, t) are both parameters. Space and time are on equal footing. This is the “second quantization” approach.

However, this isn't the only way we could do it. We could look for a formalism in which $\hat{x}^\mu = (\hat{\mathbf{x}}, \hat{t})$ are operators.

Example 1.1. Consider the *worldline formalism*. Imagine we have a massive particle propagating on a flat spacetime with metric $\eta_{\mu\nu}$. A suitable action for this theory might be

$$S[x] = -m \int_{s_1}^{s_2} ds, \quad (1.2)$$

where we use natural units of $\hbar = c = 1$ and the m is some mass due to dimensional concerns. This has a sort of geodesic interpretation for some integration measure ds . We can parametrize the worldline (e.g. in terms of proper time) such that

$$S[x] = -m \int_{\tau_1}^{\tau_2} d\tau \sqrt{-\eta_{\mu\nu} \dot{x}^\mu \dot{x}^\nu}. \quad (1.3)$$

Here, dots indicate derivatives with respect to proper time. The conjugate momentum is then

$$P_\mu(\tau) = -\frac{m\dot{x}_\mu}{\sqrt{-\dot{x}^2}}, \quad (1.4)$$

⁷“There are many reasons to study string theory. I suppose for you lot, you've got nothing better to do between the hours of 11 to 12.” –R.A. Reid-Edwards

which obeys $P^2 + m^2 = 0$, so this is an “on-shell” formalism. We could then vary $S[x]$ with respect to trajectories $x^\mu(\tau)$ to find the equations of motion. We could imagine doing the same for an extended object and tracing out a “worldsheet” instead.

However, before we do that, let us revisit our action 1.2. In particular, we shall rewrite it as

$$S[x, e] = \frac{1}{2} \int d\tau \left(e^{-1} \eta_{\mu\nu} \dot{x}^\mu \dot{x}^\nu - em^2 \right). \quad (1.5)$$

This new action has a sensible massless limit, unlike the previous action. For our new action, the $x^\mu(\tau)$ equation of motion is then

$$\frac{d}{d\tau} (e^{-1} \dot{x}^\mu) = 0 \quad (1.6)$$

and the $e(\tau)$ equation of motion gives

$$\dot{x}^2 + e^2 m^2 = 0. \quad (1.7)$$

Now $e(\tau)$ appears algebraically, so we can substitute it back into the action to recover our previous formulation 1.2.⁸

Our theory also has some symmetry. If we shift the proper time by a function $\tau \rightarrow \tau + \zeta(\tau)$, then x and e change as

$$\begin{aligned} \delta x^\mu &= \zeta \dot{x}^\mu \\ \delta e &= \frac{d}{d\tau} (\zeta e). \end{aligned}$$

We can use the one arbitrary degree of freedom to gauge fix $e(\tau)$ to a convenient value.

There’s also a *rigid symmetry* which takes

$$x^\mu(\tau) \rightarrow \Lambda^\mu{}_\nu x^\nu(\tau) + a^\mu,$$

which we may recognize as Poincaré invariance in the background spacetime.⁹

Non-lectured aside: reparameterization invariance Here, we’ll explicitly show that the action 1.5 is invariant under the transformation

$$\tau \rightarrow \tau + \tilde{\zeta}(\tau). \quad (1.8)$$

For some reason, this is not spelled out in either David Tong’s notes or the standard textbooks I’ve consulted so far.

We make the assumption as in lecture that x and e change as

$$\begin{aligned} \delta x^\mu &= \tilde{\zeta} \dot{x}^\mu \\ \delta e &= \frac{d}{d\tau} (\tilde{\zeta} e). \end{aligned}$$

If so, then note that

$$\delta(\dot{x}^\mu) = \frac{d}{d\tau} (\delta x^\mu) = \frac{d}{d\tau} (\lambda \dot{x}^\mu) \quad (1.9)$$

and

$$\frac{1}{e + \delta(e)} \sim \frac{1}{e} - \frac{1}{e^2} \delta(e) \implies \delta(e^{-1}) = -\frac{1}{e^2} \delta(e). \quad (1.10)$$

⁸Explicitly, we see that

$$\begin{aligned} S[x, e] &= \frac{1}{2} \int d\tau (e^{-1} \dot{x}^2 - em^2) \\ &= \frac{1}{2} \int d\tau (e^{-1} (-e^2 m^2) - em^2) \\ &= \int d\tau (-em^2) \end{aligned}$$

and by setting $e = 1/m$ we recover 1.2.

⁹We can see that the action respects this symmetry, since it only depends on \dot{x}^μ and not x^μ (so translational symmetry is preserved) and $\eta_{\mu\nu} \dot{x}^\mu \dot{x}^\nu \rightarrow \eta_{\mu\nu} \Lambda^\mu{}_\sigma \dot{x}^\sigma \Lambda^\nu{}_\tau \dot{x}^\tau = \eta_{\sigma\tau} \dot{x}^\sigma \dot{x}^\tau$, so \dot{x}^2 is also preserved under Lorentz transformations as it should be.

To perform this calculation, we'll also need the equations of motion from lecture, 1.6 and 1.7, reproduced here:

$$\frac{d}{d\tau}(e^{-1}\dot{x}^\mu) = 0$$

and

$$\dot{x}^2 + e^2 m^2 = 0.$$

Let's vary the action!

$$\begin{aligned}\delta S[x, e] &= \frac{1}{2} \int d\tau \left[\delta(e^{-1}) \eta_{\mu\nu} \dot{x}^\mu \dot{x}^\nu + e^{-1} \eta_{\mu\nu} \delta(\dot{x}^\mu) \dot{x}^\nu + e^{-1} \eta_{\mu\nu} \dot{x}^\mu \delta(\dot{x}^\nu) - \delta(e) m^2 \right] \\ &= \frac{1}{2} \int d\tau \left[-\frac{1}{e^2} \delta(e) \dot{x}^2 + 2e^{-1} \eta_{\mu\nu} \frac{d}{d\tau} (\lambda \dot{x}^\mu) \dot{x}^\nu - \delta(e) m^2 \right] \\ &= \frac{1}{2} \int d\tau \left[-\frac{1}{e^2} \delta(e) (\dot{x}^2 + m^2 e^2) + 2(e^{-1} \dot{x}^\nu) \eta_{\mu\nu} \frac{d}{d\tau} (\lambda \dot{x}^\mu) \right] \\ &= \frac{1}{2} \int d\tau \frac{d}{d\tau} (\lambda e^{-1} \dot{x}^2) \\ &= 0.\end{aligned}$$

In going from the first to the second line, we have explicitly substituted the variations for e^{-1} and for \dot{x}^μ . In going from the second to the third, we simply regrouped terms into $\dot{x}^2 + m^2 e^2$, which is zero by the equations of motion, and into $e^{-1} \dot{x}^\nu$, which is constant by the other equation of motion and therefore can be moved inside the total time derivative $\frac{d}{d\tau}$.

We see that after variation, what remains is simply an integral $\int d\tau$ of a total derivative, which is zero when evaluated at the endpoints of the action integral by the boundary conditions. Therefore the action is indeed invariant under reparametrization. \square

Lecture 2.

Monday, January 21, 2019

Last time, we introduced a *worldline action* with an einbein e (auxiliary field).

$$S[x, e] = \frac{1}{2} \int d\tau \left(e^{-1} \eta_{\mu\nu} \dot{x}^\mu \dot{x}^\nu - e m^2 \right).$$

In the massless limit, this reduces to

$$S[X, e] = \frac{1}{2} \int d\tau e^{-1} g_{\mu\nu} \dot{X}^\mu \dot{X}^\nu, \quad (2.1)$$

where we have replaced the Minkowski metric with some generic metric. The classical equations of motion for $X^\mu(\tau)$ then give the geodesic equation,

$$\ddot{X}^\mu + \Gamma_{\nu\lambda}^\mu \dot{X}^\nu \dot{X}^\lambda = 0. \quad (2.2)$$

The $e(\tau)$ equations of motion would give some constraints. However, if we attempted to quantize this theory, we would find that the background metric $g_{\mu\nu}$ is not actually deformed in the solutions. Rather than being dynamic as in general relativity, it's sort of a thing that is given to us and sits in the background, unchanging, which is why for a particle this is not a theory of quantum gravity. As we'll see, this is *not* the case for strings.

Strings As a string moves through some flat spacetime \mathcal{M} with metric $\eta_{\mu\nu}$, it sweeps out a worldsheet Σ . Assume that the string is closed, so it has a coordinate σ (along the length of the string, if you like):

$$\sigma \sim \sigma + 2n\pi, n \in \mathbb{Z}.$$

And it moves through time as parametrized by a proper time τ , so the embedding of the worldsheet is given by $X^\mu(\sigma, \tau)$. That is, σ and τ provide good coordinates for the worldsheet in \mathcal{M} .

Definition 2.3. We call these X^μ embedding fields. They are maps $X : \Sigma \rightarrow \mathcal{M}$ from the worldsheet to the background spacetime manifold.

We also say that the area of the worldsheet Σ is given by

$$\text{area} = \int d\tau d\sigma \sqrt{-\det(\eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu)} \quad (2.4)$$

where $\sigma^a = (\tau, \sigma)$ so that $\partial_a = \frac{\partial}{\partial \sigma^a}$. In fact, we shall introduce an extra factor know (for historical reasons) as α' and write

$$S[X] = -\frac{1}{2\pi\alpha'} \int d\tau d\sigma \sqrt{-\det(\eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu)}, \quad (2.5)$$

where α' is a free parameter. We often refer to the *string length*,

$$l_s \equiv 2\pi\sqrt{\alpha'} \quad (2.6)$$

or the *tension*

$$T \equiv \frac{1}{2\pi\alpha'}. \quad (2.7)$$

Definition 2.8. The object

$$G_{ab} \equiv \eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu \quad (2.9)$$

is an induced metric on Σ , and the action 2.5 is called the *Nambu-Goto action*.

Having just defined this, we won't really do anything with it for the rest of the course. Bummer. However, to make up for it, let's write down a new and improved action, the *Polyakov action*.

Definition 2.10. Consider the action

$$S[X, h] = -\frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{-h} h^{ab} \eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu. \quad (2.11)$$

This should remind us of what we did with the einbein last lecture, where we introduced e into our action.

This *Polyakov action* is classically equivalent to the Nambu-Goto action, since this auxiliary h which we have introduced will turn out to be non-dynamical.

The h_{ab} equations of motion are given by a weird variation of the action,

$$-\frac{2\pi}{\sqrt{-h}} \frac{\delta S}{\delta h^{ab}} = 0. \quad (2.12)$$

These equations of motion give the vanishing of the stress tensor, $T_{ab} = 0$, where

$$T_{ab} = -\frac{1}{\alpha'} \left(\partial_a X^\mu \partial_b X_\mu - \frac{1}{2} h_{ab} \partial_c X^\mu \partial_d X_\mu h^{cd} \right). \quad (2.13)$$

Note that in two dimensions, $T_{ab} h^{ab} = 0$, i.e. T_{ab} is traceless. This is our first indication that something is different about two dimensions.

The X^μ equations of motion are

$$\frac{1}{\sqrt{-h}} (\partial_a \sqrt{-h} h^{ab} \partial_b X^\mu) = 0, \quad \square X^\mu = 0. \quad (2.14)$$

Now we could imagine adding a cosmological constant (which would cause the trace of the stress tensor to change) or perhaps some sort of Einstein-Hilbert term to our metric h_{ab} . But we'll see why this might be more complicated than it initially seems.

Symmetries The Polyakov action 2.11 has the following symmetries:

- Rigid (global) symmetry, $X^\mu(\sigma, \tau) \rightarrow \Lambda^\mu_\nu X^\nu(\sigma, \tau) + a^\mu$ (Poincaré invariance).
- Local symmetries– the physics should be invariant under reparametrizations of the coordinates of the worldsheet, so under transformations $\sigma^a \rightarrow \sigma'^a(\sigma, \tau)$. The fields themselves transform as

$$X'^\mu(\sigma', \tau') = X^\mu(\sigma, \tau)$$

$$h_{ab}(\sigma, \tau) = \frac{\partial \sigma'^c}{\partial \sigma^a} \frac{\partial \sigma'^d}{\partial \sigma^b} h'_{cd}(\sigma', \tau').$$

Infinitesimally, this means that $\sigma^a \rightarrow \sigma^a - \xi^a(\sigma, \tau)$, which gives us the variations

$$\begin{aligned}\delta X^\mu &= \xi^a \partial_a X^\mu \\ \delta h_{ab} &= \xi^c \partial_c h_{ab} + \partial_a \xi^c h_{cb} + \partial_b \xi^c h_{ca} = \nabla_a \xi_b + \nabla_b \xi_a \\ \delta \sqrt{-h} &= \partial_a (\xi^a \sqrt{-h}).\end{aligned}$$

Note this second variation, δh_{ab} , can be written in terms of some covariant derivatives for an appropriate connection, but we won't usually bother.

- Weyl transformations– we send

$$\begin{aligned}X'^\mu(\sigma, \tau) &= X^\mu(\sigma, \tau) \\ h'_{ab}(\sigma, \tau) &= e^{2\Lambda(\sigma, \tau)} h_{ab}(\sigma, \tau).\end{aligned}$$

Thus $\delta X^\mu = 0$ and $\delta h_{ab} = 2\Lambda h_{ab}$. Under such transformations, we have three arbitrary degrees of freedom in (ξ^a, Λ) (two from the two components of ξ plus one from Λ), and we can use them to fix the three degrees of freedom in h_{ab} (there are three, since h is symmetric and 2×2).

Classical solutions Let us now use reparametrization invariance to fix

$$h_{ab} = e^{2\phi} \eta_{ab}, \quad \eta_{ab} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}. \quad (2.15)$$

The Polyakov action then becomes

$$S[X] = -\frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma (-\dot{X}^2 + X'^2), \quad (2.16)$$

where

$$\dot{X}^\mu \equiv \frac{\partial X^\mu}{\partial \tau}, \quad X'^\mu \equiv \frac{\partial X^\mu}{\partial \sigma} \quad (2.17)$$

and squares are taken by contracting with the metric η_{ab} . In that case, the $X^\mu(\sigma, \tau)$ equation of motion becomes the wave equation in 2D, so solutions are of the form

$$X^\mu(\sigma, \tau) = X_R^\mu(\tau - \sigma) + X_L^\mu(\tau + \sigma). \quad (2.18)$$

Moreover, since we have a wave equation it is useful to introduce modes $(\alpha_n^\mu, \bar{\alpha}_n^\mu)$ where

$$X_R^\mu(\tau - \sigma) = \frac{1}{2}x^\mu + \frac{\alpha'}{2}p^\mu(\tau - \sigma) + i\sqrt{\frac{\alpha'}{2}} \sum_{n \neq 0} \frac{1}{n} \alpha_n^\mu e^{-in(\tau - \sigma)}, \quad (2.19)$$

where x^μ, p^μ are some constants in (τ, σ) and similarly the left-going modes are

$$X_L^\mu(\tau + \sigma) = \frac{1}{2}x^\mu + \frac{\alpha'}{2}p^\mu(\tau + \sigma) + i\sqrt{\frac{\alpha'}{2}} \sum_{n \neq 0} \frac{1}{n} \bar{\alpha}_n^\mu e^{-in(\tau + \sigma)}. \quad (2.20)$$

It's sometimes useful to define a zero-mode,

$$\alpha_0^\mu = \bar{\alpha}_0^\mu = \sqrt{\frac{\alpha'}{2}} p^\mu. \quad (2.21)$$

Lecture 3.

Wednesday, January 23, 2019

Two announcements. First, the official course notes will be released this weekend (I'll link them here soon). Second, today's colloquium is being given by Johanna Erdmenger, a Part III alumna working on AdS/CFT (gauge-gravity duality). The ideas in AdS/CFT were motivated by stringy concepts, and so should be relevant to our course.

Last time, we introduced the Polyakov action,

$$S[X, h] = -\frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{-h} h^{ab} \eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu. \quad (3.1)$$

Note that $h = \det(h_{ab})$ with h_{ab} considered as a 2×2 matrix. The equations of motion for h_{ab} gave the requirement that the stress tensor vanishes, $T_{ab} = 0$, with

$$T_{ab} = \partial_a X^\mu \partial_b X_\mu - \frac{1}{2} h_{ab} \partial^c X^\mu \partial_c X_\mu. \quad (3.2)$$

Here, a, b indices are raised and lowered with the appropriate metric h_{ab} and μ, ν indices are raised and lowered with $\eta_{\mu\nu}$.

Now, how does the Polyakov action relate to the Nambu-Goto action? Let us define the quantity

$$G_{ab} \equiv \partial_a X^\mu \partial_b X_\mu. \quad (3.3)$$

If $T_{ab} = 0$, then by 3.2,

$$G_{ab} = \frac{1}{2} h_{ab} (h^{cd} G_{cd}). \quad (3.4)$$

Taking determinants of both sides yields

$$\det(G_{ab}) = \left(\frac{1}{2} h^{cd} G_{cd} \right)^2 \det(h_{ab}) = \frac{1}{4} (h^{cd} G_{cd})^2 h. \quad (3.5)$$

Therefore

$$2\sqrt{-\det(G_{ab})} = (h^{ab} G_{ab}) \sqrt{-h} = \sqrt{-h} h^{ab} \partial_a X^\mu \partial_b X_\mu. \quad (3.6)$$

Substituting this back into the Polyakov action now gives us

$$S[X] = -\frac{1}{2\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{-\det G_{ab}},$$

the Nambu-Goto action. However, the Polyakov action is nicer to work with since it does not involve square roots of the coordinates X .

The stress tensor Recall that the conjugate momentum to X^μ is

$$P_\mu = \frac{1}{2\pi\alpha'} \dot{X}_\mu, \quad (3.7)$$

where a dot is a derivative with respect to proper time τ . We can define a Hamiltonian density \mathcal{H} as

$$\mathcal{H} = P_\mu \dot{X}^\mu - \mathcal{L} = \frac{1}{4\pi\alpha'} (\dot{X}^2 + X'^2). \quad (3.8)$$

Definition 3.9. For our Hamiltonian formalism, we'll also need some *Poisson brackets* which we denote $\{, \}_{PB}$ (to contrast with another use of brackets later in the quantum theory). Given F, G defined on the phase space, we have

$$\{F, G\}_{PB} \equiv \int_0^{2\pi} d\sigma \left(\frac{\delta F}{\delta X^\mu(\sigma)} \frac{\delta G}{\delta P_\mu(\sigma)} - \frac{\delta F}{\delta P_\mu(\sigma)} \frac{\delta G}{\delta X^\mu(\sigma)} \right). \quad (3.10)$$

In particular, $\{X^\mu(\tau, \sigma), P_\nu(\tau, \sigma')\}_{PB} = \delta^\mu_\nu \delta(\sigma - \sigma')$.

Last time, we introduced a mode expansion

$$X^\mu(\sigma, \tau) = X_R^\mu(\tau - \sigma) + X_L^\mu(\tau + \sigma), \quad (3.11)$$

writing e.g. the right-going mode in terms of modes α_n^μ ,

$$X_R^\mu(\tau - \sigma) = \frac{1}{2} x^\mu + \frac{\alpha'}{2} p^\mu(\tau - \sigma) + i\sqrt{\frac{\alpha'}{2}} \sum_{n \neq 0} \frac{1}{n} \alpha_n^\mu e^{-in(\tau - \sigma)}, \quad (3.12)$$

and something similar holds for X_L^μ using the modes $\bar{\alpha}_n^\mu$.

Let's try to work in terms of modes rather than the embedding fields X^μ . We assert that the Poisson brackets acting on the modes $\alpha_n^\mu, \bar{\alpha}_n^\mu$ are

$$\{\alpha_m^\mu, \alpha_n^\nu\}_{PB} = -im\delta_{m, -n}\eta^{\mu\nu} \quad (3.13)$$

$$\{\alpha_m^\mu, \bar{\alpha}_n^\nu\}_{PB} = 0 \quad (3.14)$$

$$\{\bar{\alpha}_m^\mu, \bar{\alpha}_n^\nu\}_{PB} = -im\delta_{m, -n}\eta^{\mu\nu} \quad (3.15)$$

for $n \neq 0, m \neq 0$. If we define $\alpha_0^\mu = \bar{\alpha}_0^\nu = \sqrt{\frac{\alpha'}{2}} p^\mu$, we see that $\{x^\mu, p_\nu\}_{PB} = \delta_\nu^\mu$.

Let's see why this might be reasonable. We will set $\tau = 0$ so that

$$X^\mu(\sigma) = x^\mu + i\sqrt{\frac{\alpha'}{2}} \sum_{n \neq 0} \frac{1}{n} \left(\alpha_n^\mu e^{in\sigma} + \bar{\alpha}_n^\mu e^{-in\sigma} \right),$$

$$P^\nu(\sigma') = \frac{p^\nu}{2\pi} + \frac{1}{2\pi} \sqrt{\frac{1}{2\alpha'}} \sum_{m \neq 0} \left(\alpha_m^\nu e^{im\sigma'} + \bar{\alpha}_m^\nu e^{-im\sigma'} \right).$$

Recall that we get P^ν by deriving $X^\mu(\tau, \sigma)$ with respect to τ and dividing by a factor of 2π . (Check this expression for $P^\nu(\sigma, \tau = 0)$!)

Now we can compute the Poisson bracket: it is

$$\{X^\mu(\sigma), P_\nu(\sigma')\}_{PB} = \frac{1}{2\pi} \{x^\mu, p^\nu\} - \frac{1}{4\pi} \sum_{n, m \neq 0} \frac{1}{2m} \left(\{\alpha_m^\mu, \alpha_n^\nu\} e^{i(m\sigma + n\sigma')} + \{\bar{\alpha}_m^\mu, \bar{\alpha}_n^\nu\} e^{-i(m\sigma + n\sigma')} \right). \quad (3.16)$$

Using the Poisson bracket relations on the modes and the “periodic delta function”

$$\delta(\sigma - \sigma') = \frac{1}{2\pi} \sum_{m=-\infty}^{\infty} e^{im(\sigma - \sigma')}, \quad (3.17)$$

one can show that

$$\{X^\mu(0, \tau), P^\nu(0, \sigma')\}_{PB} = \eta^{\mu\nu} \delta(\sigma - \sigma'). \quad (3.18)$$

The Wit algebra We'll quickly introduce the following concept. On our worldsheet, it will be useful to use light-cone (null) coordinates

$$\sigma^\pm = \tau \pm \sigma. \quad (3.19)$$

Thus the metric becomes

$$ds^2 = -d\tau^2 + d\sigma^2 = (d\sigma^+, d\sigma^-) \begin{pmatrix} 0 & -\frac{1}{2} \\ -\frac{1}{2} & 0 \end{pmatrix} \begin{pmatrix} d\sigma^+ \\ d\sigma^- \end{pmatrix}. \quad (3.20)$$

Derivatives become

$$\partial_\pm \equiv \frac{\partial}{\partial \sigma^\pm} = \frac{1}{2} (\partial_\tau \pm \partial_\sigma). \quad (3.21)$$

In these new coordinates, the action and equations of motion become

$$S[X] = -\frac{1}{2\pi\alpha'} \int_\Sigma d\sigma^+ d\sigma^- \partial_+ X^\mu \partial_- X_\mu, \quad \partial_+ \partial_- X^\mu = 0. \quad (3.22)$$

The stress tensor becomes

$$T_{++} = -\frac{1}{\alpha'} \partial_+ X^\mu \partial_+ X_\mu, \quad T_{--} = -\frac{1}{\alpha'} \partial_- X^\mu \partial_- X_\mu, \quad (3.23)$$

with $T_{+-} = 0$ since this is nothing more than the trace of T_{ab} .

We can introduce modes l_m, \bar{l}_m for the stress tensor, writing

$$l_n = -\frac{1}{2\pi} \int_0^{2\pi} d\sigma T_{--} e^{-in\sigma}$$

$$\bar{l}_n = -\frac{1}{2\pi} \int_0^{2\pi} d\sigma T_{++} e^{+in\sigma}.$$

Again, our goal is to work with modes rather than the entire solutions.

For instance,

$$\partial_- X^\mu = \sqrt{\frac{\alpha'}{2}} \sum_n \alpha_n^\mu e^{-in\sigma}, \quad \text{where } \alpha_0^\mu = \sqrt{\frac{\alpha'}{2}} p^\mu.$$

Lecture 4.

Friday, January 25, 2019

Last time we introduced the light cone coordinates on Σ , defined as $\sigma^\pm = \tau \pm \sigma$. Recall also that we want to work with modes rather than embedding fields, and for $\tau = 0$, the modes are given by

$$l_n = -\frac{1}{2\pi} \int_0^{2\pi} d\sigma T_{--}(\sigma) e^{-in\sigma}$$

$$\bar{l}_n = -\frac{1}{2\pi} \int_0^{2\pi} d\sigma T_{++}(\sigma) e^{+in\sigma},$$

with $T_{+-} = 0$.

We shall see that l_m, \bar{l}_m are conserved quantities on the space $T_{ab} = 0$. Using

$$\partial_- X^\mu(\sigma) = \sqrt{\frac{\alpha'}{2}} \sum_n \alpha_n^\mu e^{-in\sigma}, \text{ where } \alpha_0^\mu = \sqrt{\frac{\alpha'}{2}} p^\mu,$$

we would like to get expressions for the stress tensor modes l_n in terms of the string modes α_m^μ . We postulated some Poisson brackets on the modes, which will hopefully help us out in this calculation.

For instance,

$$\begin{aligned} l_n &= \frac{1}{2\pi\alpha'} \int_0^{2\pi} d\sigma \partial_- X \cdot \partial_- X e^{in\sigma} \\ &= \frac{1}{4\pi} \sum_{m,p} \alpha_m \cdot \alpha_p \int_0^{2\pi} d\sigma e^{i(m+p-n)\sigma} \\ &= \frac{1}{4\pi} \sum_{m,p} \alpha_m \cdot \alpha_p (2\pi \delta_{m+p,n}) \\ \implies l_n &= \frac{1}{2} \sum \alpha_{n-m} \cdot \alpha_m, \quad \bar{l}_n = \frac{1}{2} \sum \bar{\alpha}_{n-m} \cdot \bar{\alpha}_m. \end{aligned}$$

Using these expressions and the PB relations for the α s, one can (and should) show that the l_n satisfy the following Poisson brackets:

$$\begin{aligned} \{l_m, l_n\}_{PB} &= (m-n) l_{m+n} \\ \{\bar{l}_m, \bar{l}_n\}_{PB} &= (m-n) \bar{l}_{m+n} \\ \{l_m, \bar{l}_n\}_{PB} &= 0. \end{aligned}$$

This is often called the *Wit algebra*, and it is related to the Virasoro algebra in the quantum theory. n.b. the stress tensor modes $l_0, l_{\pm 1}, \bar{l}_0, \bar{l}_{\pm 1}$ generate the Lie algebra of $SL(2, \mathbb{C})$.

Now, the Hamiltonian may be written as

$$H = \frac{1}{2\pi\alpha'} \int_0^{2\pi} d\sigma \left((\partial_+ X)^2 + (\partial_- X)^2 \right) \quad (4.1)$$

$$= \frac{1}{2} \sum_n (\alpha_{-n} \cdot \alpha_n + \bar{\alpha}_{-n} \cdot \bar{\alpha}_n) \quad (4.2)$$

$$= l_0 + \bar{l}_0. \quad (4.3)$$

Anticipating the quantum case, we will call these l modes *Virasoro generators*.

On the constraint surface $l_n \approx 0$, one can show that $\{H, l_n\} \approx 0$, since

$$\frac{dl_n}{d\tau} = \{H, l_n\}_{PB} = -nl_n. \quad (4.4)$$

Canonical quantization We have been working entirely with the classical string so far, and our main approach will be the path integral formalism. However, it may be enlightening for us to consider how to canonically quantize the string.

In the classical theory, we have $\{X^\mu, P_\nu\}_{PB}$ the Poisson bracket, with $T_{ab} = 0$. In going to a quantum theory, we could *impose* $T_{ab} = 0$ and promote variables to operators, $\{q^\mu, \pi_\nu\}_{PB}$, and then promote the

Poisson bracket to a commutator of quantum operators, $i[q^\mu, \pi_\nu]$. That is, we first constrain the phase space and then quantize. This gives us a Hilbert space $\mathcal{H}_{l.c.}$ on the light cone.

On the other hand, our approach will be a little different. We can quantize first, $\{\cdot, \cdot\}_{PB} \rightarrow i[\cdot, \cdot]$, giving us commutators $[X^\mu, P_\nu]$, and then impose $T_{ab} = 0$, where T_{ab} is now an operator and the constraint is $T_{ab}|\psi\rangle = 0\forall|\psi\rangle$. This will yield another Hilbert space \mathcal{H}_Q , which we hope (and could prove, although it is non-trivial) is equivalent to the light cone Hilbert space.

Thus in our approach, we start by replacing *fundamental* Poisson bracket relations with canonical commutation relations,

$$\{X^\mu, P_\nu\} \rightarrow -i[X^\mu, P_\nu], \quad (4.5)$$

and can do something equivalent for the $\alpha_n^\mu, \bar{\alpha}_n^\mu$ modes.

We now introduce the *Virasoro operators*

$$L_n = \frac{1}{2} \sum_m \alpha_{n-m} \cdot \alpha_m, n \neq 0, \quad (4.6)$$

where we distinguish the L_n s from the classical l_n since the quantum L s do not quite satisfy the Wit algebra. \bar{L}_n is defined equivalently.

We also introduce a vacuum state $|0\rangle$, which we will define as the state annihilated by all α modes,

$$\alpha_n^\mu |0\rangle = 0 \text{ for } n \geq 0. \quad (4.7)$$

We think of $\alpha_n^\mu, n > 0$ as annihilation operators analogous to those of the harmonic oscillator, and $n < 0$ as creation operators.¹⁰ What are these operators creating and annihilating? Harmonics of the string, essentially.

We now notice an ambiguity in the definition of L_0 and \bar{L}_0 . We have

$$L_0 = \frac{1}{2} \alpha_0^2 + \sum_{n>0} \alpha_{-n} \cdot \alpha_n, \quad (4.8)$$

but note that the $\alpha_{-n} \cdot \alpha_n$ terms have an ordering ambiguity.

To resolve this, we define normal ordering (denoted by $::$) in the usual way, moving all creation operators to the left and all annihilation operators to the right. We then define composite operators using this ordering, e.g.

$$T_{--}(\sigma^-) = -\frac{1}{\alpha'} : \partial_- X^\mu \partial_- X_\mu :. \quad (4.9)$$

Physical state conditions We define the number operators N_n, \bar{N}_n by

$$nN_n = \alpha_{-n} \cdot \alpha_n, \quad n\bar{N}_n = \bar{\alpha}_{-n} \cdot \bar{\alpha}_n, \quad (4.10)$$

and the total number operators as

$$N = \sum_n nN_n, \quad \bar{N} = \sum_n n\bar{N}_n. \quad (4.11)$$

The L_0, \bar{L}_0 may be written as

$$L_0 = \frac{\alpha'}{4} p^2 + N, \quad \bar{L}_0 = \frac{\alpha'}{4} p^2 + \bar{N}. \quad (4.12)$$

Next time, we will impose the conditions

$$L_n |\phi\rangle = 0, n > 0 \text{ and } (L_0 - a) |\phi\rangle = 0 \quad (4.13)$$

for $|\phi\rangle$ to be a physical state, with $a \in \mathbb{R}$.

¹⁰ α_0 is a little special and has to do with the center of mass of the string, though it does annihilate the vacuum.

Lecture 5.

Monday, January 28, 2019

Last time, we began discussing the quantization of the string. We said that our approach would be to quantize the unconstrained first and then apply the quantum-ized constraint $T_{ab} = 0$ on all physical states in the Hilbert space. We do this by imposing the conditions

$$L_n |\phi\rangle = 0, \quad n > 0 \quad (5.1)$$

for $|\phi\rangle$ to be physical. Note that $\bar{L}_n |\phi\rangle = 0$ as well— for most of our theory, we'll get an exact copy of the behavior of the right-handed modes L_n in the left-handed modes \bar{L}_n .

We also observed that our definition of L_0 was ambiguous in the quantum theory. In the other operators, we always had products of modes α_n with different harmonics n , but for L_0 there is an ordering ambiguity. We therefor impose the physical condition that

$$(L_0 - a) |\phi\rangle = 0, \quad (\bar{L}_0 - a) |\phi\rangle = 0 \quad (5.2)$$

where $a \in \mathbb{R}$ quantifies this ordering ambiguity. We will see later (cf. BRST invariance) that the theory is consistent only if $D = 26, a = 1$. From now on we shall assume $a = 1$.

It will be useful to define

$$L_0^\pm = L_0 \pm \bar{L}_0, \quad (5.3)$$

so that we have

$$(L_0^+ - 2) |\psi\rangle = 0, \quad L_0^- |\psi\rangle = 0, \quad L_n |\psi\rangle = \bar{L}_n |\psi\rangle = 0, n > 0. \quad (5.4)$$

These three conditions characterize physical states. Recall that $L_0 = \frac{\alpha'}{4} p^2 + N$, $\bar{L}_0 = \frac{\alpha'}{4} p^2 + \bar{N}$.

The spectrum We'll start by looking at the lowest-lying modes of the theory. We haven't yet discussed the creation or destruction of strings, so the following discussion will, if you like, be centered on free propagators.

We begin by remarking that in our version of the theory, there are problems in the infrared which have to do with *tachyons*. These problems can be addressed in superstring theory, which is beyond the scope of this course.

The simplest state we can write down is the momentum eigenstate,

$$|k\rangle = e^{ik \cdot x} |0\rangle, \quad (5.5)$$

with k_μ some four-vector of our choice and x the center of mass coordinate for the string (i.e. the x such that $X^\mu(\sigma, \tau) = x^\mu + p^\mu \tau + \text{oscillations}$). The action of the center of mass momentum p_μ is then

$$p_\mu |k\rangle = k_\mu |k\rangle. \quad (5.6)$$

We could define a general state by a weighted sum of these momentum eigenstates,

$$|T\rangle = \int d^D k T(k) |k\rangle, \quad (5.7)$$

where $T(k)$ is a function of our choosing and we are working in D dimensions. Now the $L_0^- |\phi\rangle = 0$ condition imposes $N = \bar{N}$. This is called the “level-matching” condition. It turns out to be the only condition that relates the left-going and right-going modes— otherwise, they are totally uncoupled.

If we look at L_0^+ , we get the condition

$$(L_0^+ - 2) T(k) |k\rangle = \left(\frac{\alpha'}{2} p^2 + N + \bar{N} - 2 \right) T(k) |k\rangle = 0, \quad (5.8)$$

which tells us that $N = \bar{N} = 0$. Therefore

$$(L_0^+ - 2) T(k) |k\rangle = \left(\frac{\alpha'}{2} p^2 - 2 \right) T(k) |k\rangle = 0, \quad (5.9)$$

which we can rewrite as a mass-shell condition on the momentum space field $T(k)$:

$$(k^2 + M^2) T(k) = 0 \quad \text{where } M^2 = -\frac{4}{\alpha'}. \quad (5.10)$$

We notice that the field $T(k)$ is tachyonic, i.e. its mass squared is negative. (We use the mostly + sign convention for the Minkowski metric.) Note that

$$L_n |T\rangle = 0 = \bar{L}_n |T\rangle \text{ for } n > 0 \quad (5.11)$$

is satisfied trivially. A priori, tachyons need not sink our theory. It could be that we're just working relative to the wrong vacuum. This is an open question, though there are other reasons the bosonic string might not be quite the right model for our universe's physics. Having declared that superstring theory does provide some solution to this problem, we will pay it no more thought and move on.

Massless states Next, we consider states of the form

$$|\epsilon\rangle = \epsilon_{\mu\nu}(k) \alpha_{-1}^\mu \bar{\alpha}_{-1}^\nu |k\rangle, \quad (5.12)$$

where we have included both α and $\bar{\alpha}$ to satisfy level-matching, and we have thrown in an ϵ in order to kill the free indices.

The condition $(L_0^+ - 2) |\epsilon\rangle = 0$ gives $M^2 = 0$ since $N = \bar{N} = 1$. Note that $L_n |\epsilon\rangle = 0$ is satisfied trivially for $n > 1$ (and so is $\bar{L}_n |\epsilon\rangle = 0$).

What about $L_1 |\epsilon\rangle = 0$? We have

$$\begin{aligned} L_a |\epsilon\rangle &= \frac{1}{2} \sum_n \alpha_{1-n} \cdot \alpha_n \epsilon_{\mu\nu} \alpha_{-1}^\mu \bar{\alpha}_{-1}^\nu |k\rangle \\ &= \epsilon_{\mu\nu}(k) \alpha_0 \cdot \alpha_1 \alpha_{-1}^\mu \bar{\alpha}_{-1}^\nu |k\rangle \\ &= \sqrt{\frac{2}{\alpha'}} \epsilon_{\mu\nu}(k) k_\lambda \alpha_1^\lambda \alpha_{-1}^\mu \bar{\alpha}_{-1}^\nu |k\rangle \\ &= \sqrt{\frac{2}{\alpha'}} \epsilon_{\mu\nu}(k) k_\lambda \left([\alpha_1^\lambda, \alpha_{-1}^\lambda] + \alpha_{-1}^\mu \alpha_1^\lambda \right) \bar{\alpha}_{-1}^\nu |k\rangle. \end{aligned}$$

We conclude that

$$\epsilon_{\mu\nu}(k) k^\mu = 0, \quad (5.13)$$

so two states related by

$$\epsilon_{\mu\nu}(k) \rightarrow \epsilon_{\mu\nu}(k) + k_\mu \xi_\nu \quad (5.14)$$

are physically equivalent since $k^2 = 0$, with ξ arbitrary. Similarly,

$$\bar{L}_1 |\epsilon\rangle = 0 \implies k^\nu \epsilon_{\mu\nu}(k) = 0. \quad (5.15)$$

It is useful to decompose $\epsilon_{\mu\nu}(k)$ as follows:

$$\epsilon_{\mu\nu}(k) = \tilde{g}_{\mu\nu}(k) + \tilde{B}_{\mu\nu}(k) + \eta_{\mu\nu} \tilde{\phi}(k), \quad (5.16)$$

where $\tilde{g}_{\mu\nu}$ is traceless symmetric and $\tilde{B}_{\mu\nu}$ is antisymmetric. Now $\tilde{g}_{\mu\nu}(k)$ has the interpretation of a momentum space metric perturbation,

$$\tilde{g}_{\mu\nu}(k) \sim \tilde{g}_{\mu\nu}(k) + k_\mu \xi_\nu + \xi_\mu k_\nu, \quad (5.17)$$

which is simply (linearized) diffeomorphism invariance. What about this antisymmetric guy? We get a “B-field” which corresponds to a momentum spacetime field $\tilde{B}_{\mu\nu} = -\tilde{B}_{\nu\mu}$, where

$$\tilde{B}_{\mu\nu}(k) \sim \tilde{B}_{\mu\nu}(k) + k_\mu \lambda_\nu - k_\nu \lambda_\mu. \quad (5.18)$$

In spacetime this is a gauge invariance, where $B_{\mu\nu} \sim B_{\mu\nu} + \partial_\mu \lambda_\nu - \partial_\nu \lambda_\mu$. Some older textbooks call this the notoph (which is nearly “photon” backwards).

Lecture 6.

Wednesday, January 30, 2019

Last time, we discovered the mildly disturbing fact that our bosonic string theory has tachyons. Having made note of this, we decided to take it on faith that superstring theory has a reasonable solution to this problem, and proceeded to define massless modes of the string by

$$|g\rangle = h_{\mu\nu} \alpha_{-1}^{(\mu} \tilde{\alpha}_{-1}^{\nu)} |k\rangle \quad (6.1)$$

$$|B\rangle = B_{\mu\nu} \alpha_{-1}^{[\mu} \tilde{\alpha}_{-1}^{\nu]} |k\rangle \quad (6.2)$$

$$|\phi\rangle = \phi \alpha_{-1}^{\mu} \tilde{\alpha}_{-1\mu} |k\rangle. \quad (6.3)$$

These correspond sort of to a graviton ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$), a B -field (since $B_{\mu\nu} = -B_{\nu\mu}$), and a so-called dilaton ϕ (scalar field). One can show that these fields arise as a linear approximation to the theory described by the following spacetime action:

$$S = -\frac{1}{2K^2} \int d^D x \sqrt{-g} e^{-2\phi} \left(R - 4\partial_\mu \phi \partial^\mu \phi + \frac{1}{12} H_{\mu\nu\lambda} H^{\mu\nu\lambda} \right), \quad (6.4)$$

where $H_{\mu\nu\lambda} = \partial_{[\mu} B_{\nu\lambda]}$ and K is a coupling constant which will be related to Newton's gravitational constant in D dimensions.

This suggests to us that the fields and modes on our worldsheet have in fact told us something about how to deform the background (until now Minkowski) metric, so we could consider the more general starting point

$$S_1[X, h] = -\frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{-h} h^{ab} \partial_a X^\mu \partial_b X^\nu g_{\mu\nu}(X). \quad (6.5)$$

Moreover, it turns out that the quantum theory has Weyl symmetry if $g_{\mu\nu}(x)$ satisfies

$$R_{\mu\nu} = 0$$

to first order in α' (the only parameter in our theory, really), which are simply the Einstein equations in vacuum. That is, imposing the symmetry of the quantum theory on the worldsheet results in a condition on the background metric in all of spacetime. Higher orders will give corrections to this result – to next order in α' ,

$$R_{\mu\nu} + \frac{\alpha'}{2} R_{\mu\rho\lambda\sigma} R_\nu^{\rho\lambda\sigma} = 0. \quad (6.6)$$

Our theory therefore suggests that there are higher order corrections to the Einstein equations.

We could also add a term like

$$S_2 = -\frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{-h} \epsilon^{ab} \partial_a X^\mu \partial_b X^\nu B_{\mu\nu}, \quad (6.7)$$

with ϵ^{ab} the completely antisymmetric rank two tensor. This links the action to the stress-energy tensor of our B -field.

Finally, we could add a coupling to the dilaton,

$$S_3 = \frac{1}{4\pi} \int_\Sigma d^2\sigma \sqrt{-h} \phi(X) R_\Sigma, \quad (6.8)$$

with R_Σ the worldsheet Ricci scalar.

The condition that the action

$$S = S_1 + S_2 + S_3$$

gives a Weyl-invariant quantum theory results in what we might call equations of motion in spacetime for $g_{\mu\nu}$, $B_{\mu\nu}$, and ϕ . To leading order in α' , these equations of motion may be derived from the action

$$S = -\frac{1}{2K^2} \int d^D x \sqrt{-g} e^{-2\phi} \left(R - 4\partial_\mu \phi \partial^\mu \phi + \frac{1}{12} H_{\mu\nu\lambda} H^{\mu\nu\lambda} \right) + O(\alpha').$$

If you like, the worldsheet theory couples to the metric of the background spacetime. Now, we could have just written down this action to start with. But deriving it from the worldsheet allows us to argue that any higher order terms are suppressed by the length scale of α' .

What happens if spacetime has some weird topology? Consider a theory where spacetime has the topology of $\mathbb{R}^2 \times S^1$. Then a string can move around the spacetime just like a particle, but it can also wrap around the compact S^1 direction and probe the topology of the spacetime. Therefore something else interesting is happening which the modes we've currently defined seem totally insensitive to.

Path integral quantization Some of the details of path integral quantization are covered in *Advanced Quantum Field Theory*, and also in Polchinski (appendix in vol. 1), as well as in Ryder on QFT and Feynman and Hibbs (though this last one is broadly maligned for having errors in other sections).

Path integrals give us a conceptually different way to think about calculating amplitudes in QM and more generally in QFT. Morally speaking, a path integral is a weighted sum of paths satisfying some boundary conditions,

$$\langle x_f, t_f | x_i, t_i \rangle = \int_{x(t_i)}^{x(t_f)} \mathcal{D}x e^{iS[x]} \quad (6.9)$$

for some action $S[x] = \int_{t_i}^{t_f} dt L(x, \dot{x})$. We will be interested in the path integral quantization of the Polyakov action.

That is, given some initial and final string states $\Psi_{i,f}$, the path integral is

$$\langle \Psi_f | \Psi_i \rangle = \int_i^f \mathcal{D}x \mathcal{D}h e^{iS[h,x]}, \quad (6.10)$$

with $S[h, x]$ the Polyakov action. But now by analogy with QFT we will have to deal with strings splitting and merging in our path integral. There will be new complications when we try to compute the path integral.