

## THE HOLOMORPHIC BOSONIC STRING

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#### 1. FROM CLASSICAL TO QUANTUM: ANOMALIES IN THE BV FORMALISM

BW: A rapid overview of classical BV and effective quantizations. Stress how obstructions appear, where they live, and how to compute them.

OG: I think we should articulate here the structural features of our BV package that make the arguments below more conceptual. For instance:

- Linear BV quantization is determinantal, which explains why we'll produce determinant line bundles when we do free  $\beta\gamma$  system.
- "Gauging" a theory corresponds to a stacky quotient of the original fields. Hence, obstruction to quantizing a gauged theory corresponds to descending the quantization to the quotient.
- If a classical theory makes sense on a class (=site) of manifolds, then to quantize the whole class, it suffices to check on a generating cover (typically given by disks with geometric structure) but compatibly with all automorphisms. This often explains the appearance of characteristic classes as anomalies.

- Every BV theory produces a factorization algebra. The local structure encodes the OPE algebra (and hence recovers a vertex algebra in chiral CFT situation). On compact manifolds, solutions to EoM typically form finite-dimensional space, and the global observables encode a volume form on this space. (An example is conformal blocks for the free  $bc\beta\gamma$  system.)

Please add others as you think of them!

OG: We might also add that we view the BV formalism as the analogue in field theory of derived geometry in geometry. That is, in ordinary algebraic geometry, one first builds geometry and then adds (sheaf) cohomology on top: in ordinary physics, one first builds field theories and then adds (BRST) cohomology on top. But derived geometry (respectively, BV formalism) builds the cohomological aspect into the foundations.

1.1. **OG: description of algorithm.** For us, quantization will mean that we use perturbative constructions in the setting of the BV formalism. Concretely, this means that we enforce the gauge symmetries using the homological algebra of the BV formalism and that we use Feynman diagrams and renormalization to obtain an expression for the desired, putative path integral. **OG: Be more careful about saying path integral. It's an approximation.** There are toy models for this approach where one can see very clearly how it gives asymptotic expansions for finite-dimensional integrals **OG: add references.** In particular, these toy models show that this approach need not recover the true integral but does know important information about it; a similar relationship should hold between this quantization method and the putative path integral, but in this case there is no *a priori* definition of the true integral in most cases.

This notion of quantization applies to any field theory arising from an action functional, and the algorithm one applies to obtain a quantization is the following:

- (1) Write down the integrals labeled by Feynman diagrams arising from action functional.
- (2) Identify the divergences that appear in these integrals and add “counterterms” to the original action that are designed to cancel divergences.
- (3) Repeat these steps until no more divergences appear in Feynman diagrams. We call this the “renormalized action.”
- (4) Check if the renormalized action satisfies the quantum master equation. If it does, you have a well-posed BV quantum theory, and we call the result a *quantized action*. If not, guess a way to adjust the renormalized action and begin the whole process again.

It should be clear that along the way, one makes many choices; hence if a quantization exists, it may not be unique. It is also possible that a BV quantization may not exist.

## 2. THE CLASSICAL HOLOMORPHIC BOSONIC STRING

BW: First define the holomorphic theory we will work with. Then show how it's related to more familiar models for the string, eg the Polyakov action. Level of detail depending on the space we have.

There is a basic format for a string theory, at least in the perturbative approach. One starts with a nonlinear  $\sigma$ -model, whose fields are smooth maps from a Riemann surface to a target manifold  $X$ ; in this setting we want the theory to make sense for an arbitrary Riemann surface as the source manifold. In the usual bosonic string theory, this nonlinear  $\sigma$ -model picks out the harmonic maps from a Riemannian 2-manifold to a Riemannian manifold. In our holomorphic setting, the nonlinear  $\sigma$ -model picks out holomorphic maps from a Riemann surface to a complex manifold. One then quotients the space of fields (and solutions to the equations of motion) with respect to reparametrization. OG: This description is a bit opaque. We should find a better one. In the usual bosonic string, one quotients by diffeomorphisms, which can thus change the metric on the source. In our setting, we quotient by diffeomorphisms as well, which can thus change the complex structure on the source.

In this section we begin by describing our theory in the BV formalism. We do not expect the reader to find the action functional immediately clear, so we devote some time to analyzing what it means and how it arises from concrete questions. We then turn to interpreting this classical BV theory using dg Lie algebras and derived geometry (i.e., we identify the moduli space it encodes). Finally, we conclude by sketching how our theory appears as the chiral sector of a degeneration of the usual bosonic string when the target is a complex manifold with a Hermitian metric. Our theory thus does provide insights into the usual bosonic string; moreover, it clarifies why so many aspects of the bosonic string, like the anomalies or  $B$ -fields, have holomorphic analogues.

**2.1. The theory we study.** Let  $V$  denote a complex vector space (the target), and let  $\langle -, - \rangle_V$  denote the evaluation pairing between  $V$  and its linear dual  $V^\vee$ . Let  $\Sigma$  denote a Riemann surface (the source). Let  $T_\Sigma^{1,0}$  denote the holomorphic tangent bundle on  $\Sigma$ , let  $\langle -, - \rangle_T$  denote the evaluation pairing between  $T_\Sigma^{1,0}$  and its vector bundle dual  $T_\Sigma^{1,0*}$ . OG: Correct terminology? These are the key geometric inputs.

In a BV theory, the fields are  $\mathbb{Z}$ -graded; we call this the *cohomological grading*. We have four kinds of fields:

field	-1	0	1	2
$\gamma$		$\Omega^{0,0}(\Sigma) \otimes V$	$\Omega^{0,1}(\Sigma) \otimes V$	
$\beta$		$\Omega^{1,0}(\Sigma) \otimes V^\vee$	$\Omega^{1,1}(\Sigma) \otimes V^\vee$	
$c$	$\Omega^{0,0}(\Sigma, T_\Sigma^{1,0})$	$\Omega^{0,1}(\Sigma, T_\Sigma^{1,0})$		
$b$			$\Omega^{1,0}(\Sigma, T_\Sigma^{1,0*})$	$\Omega^{1,1}(\Sigma, T_\Sigma^{1,0*})$

More accurately, we have eight different kinds of fields, but we view each row as constituting a single type since each given row consists of the Dolbeault forms of a holomorphic vector bundle. For instance, the field  $\gamma$  is a  $(0, *)$ -form with values in the trivial bundle with fiber  $V$ , and the field  $b$  is a  $(0, *)$ -form with values in the bundle  $T_\Sigma^{1,0*} \otimes T_\Sigma^{1,0*}$ .

To orient oneself it is helpful to start by examining the fields of cohomological degree zero, since these typically have a manifest physical meaning. For instance, the degree zero  $\gamma$  field is a smooth  $V$ -valued function and hence the natural field for the nonlinear  $\sigma$ -model into  $V$ . The degree zero  $c$  field is a smooth  $(0,1)$ -form with values in vector field “in the holomorphic direction,” and hence encodes an infinitesimal change of complex structure of  $\Sigma$ . They thus constitute the obvious fields to introduce for a holomorphic version of the bosonic string. The fields  $a\beta$  and  $b$  are less obvious but appear as “partners” (or antifields) whose role is clearest once we have the action functional and hence equations of motion.

The action functional is

$$(1) \quad S(\gamma, \beta, c, b) = \int_{\Sigma} \langle \beta, \bar{\partial}\gamma \rangle_V + \int_{\Sigma} \langle b, \bar{\partial}c \rangle_T + \int_{\Sigma} \langle \beta, [c, \gamma] \rangle_V + \int_{\Sigma} \langle b, [c, c] \rangle_T.$$

(We discuss below how to think about fields with nonzero cohomological degrees as inputs.) The equations of motion are thus

$$\begin{aligned} 0 &= \bar{\partial}\gamma + [c, \gamma] & 0 &= \bar{\partial}\beta + [c, \beta] \\ 0 &= \bar{\partial}c + \frac{1}{2}[c, c] & 0 &= \bar{\partial}b + [c, b] \end{aligned}$$

Note that these equations are familiar in complex geometry. For instance, the equation purely for  $c$  encodes a deformation of complex structure on  $\Sigma$ ; concretely, it modifies the  $\bar{\partial}$  operator to  $\bar{\partial} + c$ . The other equations then amount to solving for holomorphic sections (of the relevant bundle) with respect to this deformed complex structure. For instance, the equation in  $\gamma$  picks out holomorphic maps from  $\Sigma$ , with the  $c$ -deformed complex structure, to  $V$ .

OG: Add something about how to understand the degrees. E.g., does  $b$  ever appear?

OG: Add explanation of writing BV theory from ordinary action.

*Remark 2.1.* Just looking at this action functional, one might notice that if one drops the last two terms, which are cubic in the fields, then one obtains a free theory

$$(2) \quad S_{\text{free}}(\gamma, \beta, c, b) = \int_{\Sigma} \langle \beta, \bar{\partial}\gamma \rangle_V + \int_{\Sigma} \langle b, \bar{\partial}c \rangle_T,$$

which is known as the *free  $bc\beta\gamma$  system*. Thus, one may view the holomorphic bosonic string as a deformation of this free theory by “turning on” those interaction terms. We will repeatedly try a construction first with this free theory before tackling the string itself, as it often captures important information with minimal work. For instance, we will examine the vertex algebra for the free theory before seeing how the interaction affects the operator products. Similarly, one can identify the anomaly already at the level of the free theory.

*Remark 2.2.* It is easy to modify this action functional to allow a curved target, i.e., one can replace the complex vector space  $V$  with an arbitrary complex manifold  $X$ . The fields  $b, c$  remain the same. The degree 0 field  $\gamma$  still encodes smooth maps into  $X$ , but now the degree 1 field is a section of  $\Omega^{0,1}(\Sigma, \gamma^* T_X^{1,0})$ . Similarly,  $\beta$  is now a section of  $\Omega^{1,*}(\Sigma, \gamma^* T_X^{1,0*})$ . The action is then

$$(3) \quad S(\gamma, \beta, c, b) = \int_{\Sigma} \langle \beta, \bar{\partial}\gamma \rangle_{T_X} + \int_{\Sigma} \langle b, \bar{\partial}c \rangle_{T_{\Sigma}} + \int_{\Sigma} \langle \beta, [c, \gamma] \rangle_{T_X} + \int_{\Sigma} \langle b, [c, c] \rangle_{T_{\Sigma}}.$$

In Section 8 we will indicate how the results with linear target generalize to this situation.

**2.2. From the perspective of derived geometry.** We would like to explain what this theory is about in more conceptual terms, rather than simply by formulas and equations. Thankfully this theory is amenable to such a description. We will be informal in this section and not specify a particular geometric context (e.g., derived analytic stacks), except when we specialize to the deformation-theoretic situation (i.e., perturbative setting) that is our main arena.

Let  $\mathcal{M}$  denote the moduli space of Riemann surfaces, so that a surface  $\Sigma$  determines a point in  $\mathcal{M}$ . Let  $\text{Maps}_{\bar{\partial}}(\Sigma, V)$  denote the space of holomorphic maps from  $\Sigma$  to  $V$ , and hence a bundle  $\text{Maps}_{\bar{\partial}}(-, V)$  over  $\mathcal{M}$  by varying  $\Sigma$ . For our equations of motion, the  $\gamma$  and  $c$  fields of a solution determine a point in this bundle  $\text{Maps}_{\bar{\partial}}(-, V)$ .

This construction makes sense on noncompact Riemann surfaces as well. Let  $\mathcal{RS}$  denote the category whose objects are Riemann surfaces and whose morphisms are holomorphic embeddings. There is a natural site structure: a cover is a collection of maps  $\{S_i \rightarrow \Sigma\}_i$  such that the union of the images is all of  $\Sigma$ . Then  $\text{Maps}_{\bar{\partial}}(-, V)$  defines a sheaf of spaces over  $\mathcal{RS}$ . The observables for the classical theory is, in essence, the cosheaf of commutative algebras  $\mathcal{O}(\text{Maps}_{\bar{\partial}}(-, V))$ , and hence provides a factorization algebra.

In fact, it is better to work with the derived version of these spaces. One important feature of derived geometry is that the appropriate version of a tangent space at a point is, in fact, a cochain complex. In our setting, a point  $(c, \gamma)$  in  $\text{Maps}_{\bar{\partial}}(-, V)$  determines a complex structure  $\bar{\partial} + c$  on  $\Sigma$ —we denote this Riemann surface by  $\Sigma_c$ —and  $\gamma$  a  $V$ -valued holomorphic function on  $\Sigma_c$ . The tangent complex of  $\text{Maps}_{\bar{\partial}}(-, V)$  at  $(c, \gamma)$  is precisely

$$\Omega^{0,*}(\Sigma_c, T^{1,0})[1] \oplus \Omega^{0,*}(\Sigma_c, V).$$

The first summand is the usual answer from the theory of the moduli of surfaces (recall, for example, that the ordinary tangent space is the sheaf cohomology  $H^1(\Sigma, \mathcal{T}_{\Sigma})$  of the holomorphic tangent sheaf), and the second is usual elliptic complex encoding holomorphic maps.

*Remark 2.3.* It is useful to bear in mind that the degree zero cohomology of the tangent complex will recover the “naive” tangent space. In our case, we have

$$H^1(\Sigma_c, \mathcal{T}_{\Sigma_c}) \oplus H^0(\Sigma_c, V),$$

which encodes deformations of complex structure and holomorphic maps. Negative degree cohomology of the tangent complex detects infinitesimal automorphisms (and automorphisms of automorphisms, etc) of the space. For instance, here we see  $H^0(\Sigma_c, \mathcal{T}_{\Sigma_c})$  appear in degree -1, since a holomorphic vector field is an infinitesimal automorphism of a complex curve. These negative directions are called “ghosts” (or ghosts for ghosts, etc) in physics. The positive degree cohomology detects infinitesimal relations (and relations of relations, etc). For instance, here we see  $H^1(\Sigma_c, V)$ , the cokernel of  $\bar{\partial} + c$ . **OG: ???**

Note that the underlying graded spaces of this tangent complex are the  $c$  and  $\gamma$  fields from the BV theory described above. We emphasize that the tangent complex is only specified up to quasi-isomorphism, but it is compelling that a natural representative is the BV theory produced by the usual physical arguments. This behavior, however, is typical of the relationship between derived

geometry and BV theories: when physicists write down a classical BV theory, the underlying free theory is essentially always the tangent complex of a nice derived stack.

The reader has probably noticed that, yet again, we have postponed discussing the  $\beta$  and  $b$  fields. From a derived perspective, the full BV theory describes the shifted cotangent bundle  $\mathbb{T}^*[-1]\text{Maps}_{\bar{\mathcal{D}}}(-, V)$ . At the level of a tangent complex, the shifted cotangent direction contributes

$$\Omega^{1,*}(\Sigma_c, T^{1,0*})[-1] \oplus \Omega^{1,*}(\Sigma_c, V^\vee),$$

whose underlying graded spaces are the  $\beta$  and  $b$  fields. These “antifields” are added so that the overall space of fields has a 1-shifted symplectic structure when  $\Sigma$  is closed, and a shifted Poisson structure when  $\Sigma$  is open.

**2.3. Relationship to the Polyakov action functional.** This holomorphic bosonic string has a natural relationship with the usual bosonic string. We sketch it briefly, only considering a linear target.

We begin with a bosonic string theory where the source is a 2-dimensional smooth oriented manifold  $\Sigma$  and the target is a Hermitian vector space  $(V, h)$ . The “naive” action functional is

$$S_{Poly}^{naive}(\varphi, g) = \int_{\Sigma} h(\varphi, \Delta_g \varphi) \, \text{dvol}_g$$

where the field  $g$  is a Riemannian metric on  $\Sigma$  and the field  $\varphi$  is a smooth map from  $\Sigma$  to  $V$ . The notation  $\Delta_g$  denotes the Laplace-Beltrami operator on  $\Sigma$ .

Note that  $S_{Poly}^{naive}$  is invariant under the diffeomorphism group  $\text{Diff}(\Sigma)$  and under rescalings of the metric (i.e., the theory is classically conformal). Typically we express rescaling as  $g \mapsto e^f g$  with  $f \in C^\infty(\Sigma)$ . As we are interested in a string theory, we want to gauge these symmetries. In geometric language, we want to think about the quotient stack obtained by taking solutions to the equations of motion and quotienting by these symmetry groups.

**OG: It might be better to explain the first-order description of sigma model before entering into the perturbative & BV discussion.**

Our focus is perturbative, so that we want to study the behavior of this action near a fixed solution to the equations of motion (e.g., the Taylor expansion of the true action near some solution). **OG: Might be good here to leverage the derived discussion earlier: it’s easy to see what the tangent complex looks like ... which leads to fields we work with.** Hence, we fix a metric  $g_0$  on  $\Sigma$  and substitute for the field  $g$ , the term  $g_0 + \alpha$  where  $\alpha \in \Gamma(\Sigma, \text{Sym}^2(T_\Sigma))$ . That is, we simply consider deformations of  $g_0$ . As  $\varphi$  is linear, we just consider expanding around the zero map. Thus our initial fields are  $\varphi \in C^\infty(\Sigma, V)$  and  $\alpha \in \Gamma(\Sigma, \text{Sym}^2(T_\Sigma))$ .

There are also ghost fields associated to the symmetries we gauge. First, there are infinitesimal diffeomorphisms, which are described by vector fields on  $\Sigma$ . We denote this ghost field by  $X \in \Gamma(\Sigma, T_\Sigma)$ . It acts on the initial fields by the transformation

$$(\varphi, \alpha) \mapsto (\varphi + X \cdot \varphi, \alpha + L_X \alpha),$$

where  $L_X$  denotes the Lie derivative on tensors. Second, there are infinitesimal rescalings such as  $\alpha \mapsto \alpha + f\alpha$ , with ghost field  $f \in C^\infty(\Sigma)$ . The rescaling does not affect  $\varphi$ . The two symmetries are compatible: given  $f$  and  $X$ , then  $L_X(f\alpha) = X(f)\alpha + fL_X\alpha$  for any  $\alpha \in \text{Sym}^2(T_\Sigma)$ .

To summarize, we have the following fields:

-1	0	1	2
	$\Omega^0(\Sigma) \otimes V$	$\Omega^2(\Sigma) \otimes V$	
$\text{Vect}(\Sigma) \oplus C^\infty(\Sigma)$	$\text{Sym}^2(T_\Sigma)$	$\Omega^2(\Sigma; \text{Sym}^2(T_\Sigma^*))$	$\Omega^2(\Sigma; T_\Sigma^*) \oplus \Omega^2(\Sigma)$ .

The BV action functional is then

$$S_{Poly}(\phi, \alpha, X, f) = \int_\Sigma h(\varphi, \Delta_{g_0 + \alpha} \varphi) \, \text{dvol}_{g_0 + \alpha} + \text{MORE STUFF}$$

**OG: Finish writing action** This situation is quite a bit more complicated than our holomorphic bosonic string, but it admits a succinct description in geometric terms **OG: add statement about quotient of mapping stack**

\*\*\*\*\*

In this section we start with a description of the classical Polyakov model for the bosonic string as a classical BV theory. This is the ordinary  $\sigma$ -model of maps  $\Sigma \rightarrow V$  coupled to a metric on  $\Sigma$ . More precisely, this is a perturbative model for the Polyakov string, since we only look at deformations of the fixed metric  $g_0$ . We will show that after a reparametrization of the space of fields that it makes sense to take a certain “infinite volume limit” as  $h \rightarrow \infty$ . In this limit we will show that the Polyakov model splits into a certain holomorphic theory plus its complex conjugate. The holomorphic theory is what we call the *holomorphic bosonic string*.

*Remark 2.4.* A similar analysis has appeared in [?] where one does not consider deformations of the metric: the infinite volume limit of the bare  $\sigma$ -model of maps  $\Sigma \rightarrow V$  splits into the free  $\beta\gamma$  system plus its complex conjugate. In the case of the string we find an interacting theory that can be thought of as a deformation of a  $\beta\gamma$  system.

**OG: Give explanation of what this section will be about: writing down a holomorphic theory that appears as the chiral part of a large volume limit of the usual bosonic string. We should advertise that we start with conventional ways of writing a theory and explain the algorithm by which one extracts a BV action.**

We recall the most familiar form of the classical Polyakov string and show how to write it down in terms of a classical BV theory. The fields of the Polyakov model consist of a  $C^\infty$  function  $\varphi : \Sigma \rightarrow V$  and a metric  $g$  on  $\Sigma$ . Since we are doing perturbation theory, we assume that  $g$  is infinitesimally close to the fixed metric  $g_0$  in the space of all metrics on  $\Sigma$ . There is an identification of the tangent space of the space of all metrics  $T_{[g_0]} \text{Met}(\Sigma) \cong \text{Sym}^2(T_\Sigma)$ . Thus, we can take the metric  $g$  to be of the form  $g = g_0 + \alpha$  where  $\alpha \in \text{Sym}^2(T_\Sigma)$ . **OG: Should we include comments about “formal (derived) spaces”?** In the definition of a classical BV theory we must prescribe the data of a  $(-1)$ -shifted symplectic pairing on the BRST complex together with an interaction which is

a local functional on the complex. The pairing can be described as follows. If  $\varphi \in \Omega^0(\Sigma; V)$  and  $\psi \in \Omega^2(\Sigma; V)$  then

$$\langle \varphi, \psi \rangle = \int h(\varphi, \psi).$$

The fields  $(X, f) \in W_n(\Sigma) \oplus C^\infty(\Sigma)$  pair with the conjugate fields  $(X', f') \in \Omega^2(\Sigma; T_\Sigma^*) \oplus \Omega^2(\Sigma)$  via

$$\langle (X, f), (X', f') \rangle = \int \text{ev}(X, X') + \int f f'$$

where  $\text{ev}$  denotes the evaluation pairing between the tangent and cotangent bundles.

BW: Start with Polyakov action and explain how the chiral theory emerges in the infinite volume limit. There should also be an explanation for the theory we write down as a twist of 2d supergravity (in the same way that CDO's are a twist of a  $(0, 2)$  theory), not sure if you want to get into that. OG: I don't know anything about the supergravity thing you mention. It sounds interesting.

### 3. DEFORMATIONS OF THE THEORY AND STRING BACKGROUNDS

OG: Maybe the Gelfand-Fuk discussion can be anticipated in Section 1? I think versions of it are easy to motivate: "We want to study Lagrangian densities, which are functions on jets of fields. Hence the simplest case is to consider functions on jets at a point, which we recognize as a version of Gelfand-Fuks ..." Then we invoke that discussion to work with formal vector fields and simply quote GF.

OG: We should observe that we see the deformations of the action, such as  $B$ -fields and dilatons. Observe we've rediscovered "string backgrounds."

BW: Might be good to hint at the curved sigma model here.

### 4. QUANTIZING THE HOLOMORPHIC BOSONIC STRING ON A DISK

BW: Gauge fixing condition. The theory is finite, no counterterms. Review Gelfand-Fuksy stuff. Local local deformation complex calculation. Do the anomaly calculation to obtain  $\dim_{\mathbb{C}} = 13$ . Argue why this produces a quantization on any source Riemann surface.

OG: I'm not sure what is the optimal order: diagrams then cohomology group, or other way? If we do the concrete Feynman diagrams and show that something vanishes exactly when you'd expect from the literature, then people might feel assured. However, it's not clear where this anomaly lives until you do the obstruction-deformation computation. Perhaps we just indicate how the reader can pick her preferred order.

We will apply the algorithm described in Section 1.1 in the case of  $\Sigma = \mathbb{C}$  (or any open subset of the plane). For this theory we are lucky, however: the integrals that appear from the Feynman diagrams do not have divergences, so that renormalized action is easy to compute. This aspect is the subject of the first part of this section. Moreover, it is easy to check whether the quantum master equation is satisfied, and the answer is simple. This aspect is the subject of the second part. The results can be summarized as follows.



**Proposition 4.1.** *The holomorphic bosonic string with source  $\mathbb{C}$  and target  $\mathbb{C}^d$  admits a BV quantization if  $d = 13$ . This quantized action only has terms of order  $\hbar^0$  and  $\hbar$  (i.e., it quantizes at one loop).*

**4.1. The Feynman diagrams.** Let us describe the combinatorics of the Feynman diagrams that appear here before we describe the associated integrals.

4.1.1. The procedure constructs graphs out of a prescribed type of vertices and edges; we must consider all graphs with such local structure. The classical action functional determines the allowed kinds of vertices and edges. The quadratic terms of the action tell us the edges; each quadratic term yields an edge whose boundary is labeled by the two fields appearing in the term. For us there are thus two types of edges: an edge that flows from  $c$  to  $b$ , and an edge that flows from  $\gamma$  to  $\beta$ . **OG: Add picture.** The nonquadratic terms tell us the vertices: each  $n$ -ary term yields a vertex with  $n$  legs, and the legs are labeled by the  $n$  types of fields appearing in the term. For us there are thus two types of trivalent vertices: a vertex with two  $c$  legs and a  $b$  leg, and a vertex with a  $c$  leg, a  $\gamma$  leg, and a  $\beta$  leg. It helpful to picture these legs as directed, so that  $c$  and  $\gamma$  legs flow into a vertex and  $b$  and  $\beta$  legs flow out. **OG: Add picture.**

The kinds of graphs one can build with such vertices and edges are limited. We focus on connected graphs. A tree (i.e., a connected graph with no loops) must have at most one outgoing leg, which can be either a  $b$  or a  $\beta$ ; the other legs are incoming, so each must be labeled by a  $c$  or a  $\gamma$ . **OG: Add picture.** A 1-loop graph will consist of a wheel (i.e., a sequence of edges that form an overall loop) with trees attached. **OG: Add pictures.** Every edge along a wheel will have the same type. It is not possible to build a connected graph with more than one loop. This combinatorics is the essential reason that we can quantize at one loop.

4.1.2. These graphs describe linear maps associated to the field. More precisely, a graph with  $k$  legs describes a linear functional on the  $k$ -fold tensor product of the space of fields. One builds this linear functional out of the data of the action functional.

For instance, a  $k$ -valent vertex corresponds to a  $k$ -ary term in the action, which manifestly takes in  $k$  copies of the fields and outputs a number. Thus, the vertex labels an element of a (continuous) linear dual of the  $k$ -fold tensor product of fields. An edge corresponds an element of the 2-fold tensor product of the space of fields, often called a *propagator*. More precisely, the edge should correspond to the Green's function for the linear differential operator appearing in the associated quadratic term of the action; hence the propagator is an element of the *distributional completion* of the 2-fold tensor product. For us the  $\beta\gamma$  leg should be labeled by  $\bar{\partial}^{-1} \otimes \text{id}_V$ , where  $\bar{\partial}^{-1}$  denotes an inverse to the Dolbeault operator on functions. The  $bc$  leg should be labeled by  $\bar{\partial}_T^{-1}$ , the inverse of the Dolbeault operator on the bundle  $T^{1,0}$ .

Given a graph, one should contract the tensors associated to the vertices and edges. In most situations this contraction is ill-defined, since the vertices label distributional sections of some vector bundle, the edges are likewise distributional, and one cannot (usually) pair distributions. Thus, in practice one labels the edges by a smooth replacement of the Green's functions. (Imagine replacing a delta function  $\delta_0$  by a bump function.) Since one can pair smooth functions and

distributions, each graph yields a linear functional on fields using these mollified edges. But now this linear functional depends on the choice of mollifications. Hence the challenge is to show that if one picks a sequence of smooth replacements that approaches the Green's function, there is a well-defined limit of the linear functionals.

4.1.3. We will now sketch one method well-suited to complex geometry that allows us to see that no divergences appear for the holomorphic bosonic string.

Our primary interest in this section is  $\Sigma = \mathbb{C}$ . For this Riemann surface, a standard choice of Green's function for  $\bar{\partial}$  is

$$P(z, w) = \frac{1}{2\pi i} \frac{dz + dw}{z - w}.$$

It is a distributional one-form on  $\mathbb{C}^2$  that satisfies  $\bar{\partial} \otimes 1(P) = \delta_\Delta$ , where  $\delta_\Delta$  is the delta-current supported along the diagonal  $\Delta : \mathbb{C} \hookrightarrow \mathbb{C}^2$  and providing the integral kernel for the identity. In terms of our discussion above, we view this one-form as a distributional section of the fields  $\gamma$  and  $\beta$ : for example, for fixed  $w$ , the one-form  $dz/(z-w)$  is a  $\beta$  field in the  $z$ -variable as it is a  $(1, 0)$ -form.

We fix a Hermitian metric on  $\Sigma$ , which then associates provides an adjoint  $\bar{\partial}^*$  to the Dolbeault operator  $\bar{\partial}$ . In physics one calls a choice of  $\bar{\partial}^*$  a *gauge-fix* as it **OG: not sure how to end this sentence for noncompact manifolds ...** The commutator  $[\bar{\partial}, \bar{\partial}^*]$  is the Laplace-Beltrami operator  $D$  for this metric **OG: correct?**. We can thus call upon Hodge theory and many nice results about finding partial inverses to the Laplacian.

**OG: I'm not sure how much to say here.**

$$P_\ell^L = \bar{\partial}^* \int_\ell^L e^{-tD} dt$$

$$\bar{\partial} P_\ell^L = D \int_\ell^L e^{-tD} dt = e^{-LD} - e^{-\ell D}$$

If  $f$  is an eigenfunction of  $D$  so that  $Df = \lambda f$ , **OG: with our conventions, is  $\lambda$  positive or negative?** then

$$(\bar{\partial} P_\ell^L) f = (e^{-L\lambda} - e^{-\ell\lambda}) f,$$

which gets arbitrarily close to  $f$  as  $L \rightarrow \infty$  and  $\ell \rightarrow 0$ . Thus  $P_\ell^L$  is almost an inverse to  $\bar{\partial}$ ; moreover, it is a smooth function on  $\Sigma \times \Sigma$ . **OG: Should I say why?**

## 4.2. The quantum master equation.

## 5. OPE AND THE STRING VERTEX ALGEBRA

**BW: Write down vertex algebra from quantization above. Possibly state the relationship to semi-infinite cohomology**

**Proposition 5.1.** *Let  $\text{Obs}^q$  be the factorization algebra on  $\Sigma = \mathbb{C}$  of the holomorphic bosonic string. The factorization product of open disks  $D \subset \mathbb{C}$  determines the structure of a vertex algebra (see Proposition ?? below) on the cohomology of the factorization algebra on an open disk  $H^*(\text{Obs}^q(D))$ , that we denote  $\text{Vert}(\text{Obs}^q)$ . Moreover, there is an isomorphism of vertex algebras*

$$\Phi : V^{\text{string}} \xrightarrow{\cong} \text{Vert}(\text{Obs}^q).$$

OG: I believe these vertex algebras are cohomologically graded, unless we're lucky and the cohomology all sits in degree zero. In which case, we should point out this miracle. Perhaps better would be to extract the dg vertex algebra.

OG: Do you know a citation where the string vertex algebra is already written down? Of course it's almost explicit in any discussion of the "modern"/BRST quantization of the bosonic string, where they write down  $Q$ , which ought to be the differential of the dg vertex algebra using our construction.

BW: How deformations discussed in Section 3 gives explicit deformations of the the vertex algebra.

## 6. QUANTIZATION ON ARBITRARY RIEMANN SURFACES

### 6.1. Global sections of the factorization algebra. BW: Discuss relationship to conformal blocks

We wish to write the global observables of the holomorphic string in terms of the cohomology of natural holomorphic vector bundles on the Riemann surface.

We introduce a simpler theory defined for any (graded) holomorphic vector bundle  $\mathcal{V}$  on  $\Sigma$ . First, consider the elliptic complex

$$\Omega^{0,*}(\Sigma; \mathcal{V})$$

of  $(0, *)$ -forms with values in  $\mathcal{V}$ . The differential is simply the  $\bar{\partial}$  operator. We consider its shift  $\Omega^{0,*}(\Sigma; \mathcal{V})[-1]$  as an abelian local dg Lie algebra. In this way, the associated cotangent theory of the elliptic complex is defined as

$$T^*[-1](\Omega^{0,*}(\Sigma; \mathcal{V})) = \Omega^{0,*}(\Sigma; \mathcal{V}) \oplus \Omega^{1,*}(\Sigma; \mathcal{V}^\vee).$$

We write the fields as  $\gamma \in \Omega^{0,*}(\Sigma; \mathcal{V})$  for the base direction and  $\beta \in \Omega^{1,*}(\Sigma; \mathcal{V}^\vee)$  for the fiber direction. With this notation, the action functional is defined as

$$S(\beta, \gamma) = \int_{\Sigma} \langle \beta, \bar{\partial} \gamma \rangle_{\mathcal{V}}$$

where  $\langle -, - \rangle_{\mathcal{V}}$  denotes the evaluation pairing between  $\mathcal{V}$  and its dual. This theory is called the  $\beta\gamma$  (or sometimes  $\beta\gamma - bc$  OG: what are the  $bc$  fields?) system with values in  $\mathcal{V}$ . This is a free field theory and hence has a natural quantization. We will denote the factorization algebra of quantum observables on  $\Sigma$  by  $\text{Obs}_{\mathcal{V}}^q$ .

**Lemma 6.1.** *The cohomology of the global observables of the  $\beta\gamma$  system with values in  $\mathcal{V}$  is given by*

$$H^*(\text{Obs}_{\mathcal{V}}^q(\Sigma)) \cong \det(H^*(\Sigma; \mathcal{V})) [d(\mathcal{V})]$$

where  $d(\mathcal{V}) = \dots$

OG: It would be good here to point out the GRR argument for identifying the first Chern class of this determinant line bundle. We can then point out that it resonates with our computation on the formal disk and give a reminder that this is a manifestation of “Virasoro uniformization.” This then leads into the string case: the holomorphic vector fields (rather the free  $bc$  system) also contribute a determinant line (we should include that computation) and we can ask when those determinant lines tensor to a trivial line. Note that deforming the action from free  $bc\beta\gamma$  system to holomorphic bosonic string doesn’t affect the line bundles, since those are continuous parameters and Chern classes are discrete.

Now, consider the global observables of the bosonic string  $\text{Obs}^q(\Sigma)$ . There is a spectral sequence converging to the cohomology of the global observables  $H^*\text{Obs}^q(\Sigma)$  with  $E_2$  page given by the cohomology of the global observables of the  $\beta\gamma$  system with values in the holomorphic vector bundle  $\mathcal{V} = \mathcal{T}_\Sigma[1] \oplus \mathbb{C}^{13}$ . By Lemma 6.1 this  $E_2$  page is concentrated in a single degree and is given by

$$\begin{aligned} E_2 &\cong \det(H^*(\Sigma; \mathcal{T}_\Sigma[1])) \otimes \det(H^*(\Sigma; \mathcal{O}_\Sigma)^{\oplus 13}) \\ &\cong \det(H^1(\Sigma; \mathcal{T}_\Sigma)) \otimes \det(H^0(\Sigma; \mathcal{T}_\Sigma))^{-1} \otimes \det(H^0(\Sigma; K_\Sigma))^{-13} \end{aligned}$$

where we have used the fact that  $H^0(\Sigma; \mathcal{O}) \cong \mathbb{C}$  for any  $\Sigma$ .

Let  $\Sigma_g$  be a surface of genus  $g$ . Then for  $g = 1$  the above simplifies to

$$\det(H^1(\Sigma_1; \mathcal{T}_{\Sigma_1})) \otimes \det(H^0(\Sigma_1; K))^{-14}.$$

If  $g \geq 2$  one has

$$\det(H^1(\Sigma_1; \mathcal{T}_{\Sigma_1})) \otimes \det(H^0(\Sigma_1; K))^{-13}.$$

It is clear that the spectral sequence degenerates at this page. Thus the above expressions give the global observables for the holomorphic string for genus  $g = 1$  and  $g \geq 2$ , respectively.

## 7. THE STRING PARTITION FUNCTION ON AN ELLIPTIC CURVE

BW: Sketch how to see the mumford form

OG: If possible, it would be cool to explain how one can extract the differential equations (=flat connection) governing the partition function from our construction. This might be too hard right now ...

## 8. LOOKING AHEAD: CURVED TARGETS

OG: I think here we can mention our CDO work and assert that it’s compatible with the discussion here. Then we state the corresponding theorems.

BW: State the quantization condition for curved target.