

# Derived Geometric Satake Notes

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### Preface

There will be some gaps in explanation, either due to the lecturer's admission or my own lack of understanding. In particular, many "proofs" are sketches of proofs. Gaps due to my own misunderstanding will be indicated by three red question marks: **???**. More generally, my own questions about the material will also be in red. Things like "**Question**" will be questions posed by the lecturer. Feel free to reach out to me with explanations.

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# 1 Mar 25

## 1.1 Geometric Satake

We let  $\mathcal{K} = \mathbb{C}((t))$  and  $\mathcal{O} = \mathbb{C}[[t]]$ . Let  $G$  be a complex reductive group. We have groups  $G(\mathcal{K})$  and  $G(\mathcal{O})$ , and their quotient is the **affine Grassmannian**  $Gr_G = Gr = G(\mathcal{K})/G(\mathcal{O})$ . This is an analogue of the partial flag manifold for  $G$ . There is a clear action of  $G(\mathcal{O})$  on  $Gr$  by left translation. There is a  $\mathbb{C}^\times$ -action called **loop rotation** induced by  $(z \cdot f)(t) = f(zt)$  on  $\mathcal{K}$ . If we think of an element of  $G(\mathcal{K})$  as a loop  $\gamma$  in  $G$ , i.e. we take  $t = \exp(i\theta)$ , and we take  $z = \exp(i\alpha)$ , then  $(z \cdot \gamma)(t) = \gamma(\exp(i + \alpha))$ , which explains the name loop rotation.

One of the main objects of Geometric Satake is  $D_{\mathbb{C}^\times \ltimes G(\mathcal{O})}(Gr)$ , the  $\mathbb{C}^\times \ltimes G(\mathcal{O})$ -equivariant constructible derived category. In terms of stacks, we may write this as  $D_{\mathbb{C}^\times}(G(\mathcal{O}) \backslash G(\mathcal{K})/G(\mathcal{O}))$ . When written in this form, it is evident that, just as with biinvariant functions, there is a monoidal (convolution) structure  $\star$  on this category.

**Theorem 1.1** (Derived Satake). *There is a monoidal equivalence of triangulated categories between  $(D_{\mathbb{C}^\times}(G(\mathcal{O}) \backslash G(\mathcal{K})/G(\mathcal{O})), \star)$  and the derived category of Harish-Chandra  $\mathcal{U}_h(\mathfrak{g})$ -bimodules (with the tensor product as the monoidal operation).*

Here,  $\mathcal{U}_h(\mathfrak{g})$  is the Rees algebra of the enveloping algebra of the Langlands dual Lie algebra  $\mathfrak{g}$ .  $\hbar$  corresponds to loop rotation. If we set  $\hbar = 0$ , we get the quasi-classical specialization, which is a monoidal equivalence between  $(D(G(\mathcal{O}) \backslash G(\mathcal{K})/G(\mathcal{O})), \star)$  and the derived category of  $\check{G}$ -equivariant  $\text{Sym} \mathfrak{g}$ -modules. More geometrically, this module category is the derived category of  $QCoh^{\check{G}}(\mathfrak{g}^*)$ .

**Abelian Satake** is a restriction of the above quasi-classical equivalence. Namely, it is a monoidal equivalence between the category of  $G(\mathcal{O})$ -equivariant perverse sheaves on  $Gr$  (still with  $\star$ ) and the category of quasi-coherent sheaves of the form  $\mathcal{O}_{\mathfrak{g}^*} \otimes_{\mathbb{C}} V$ , where  $V$  is a finite dimensional representation of  $\check{G}$ . This can be further simplified to the category of finite dimensional representations of  $\check{G}$ , but on the derived level one needs this description of the quasi-coherent sheaves.

*Remark.* 1.  $G(\mathcal{O})$ -equivariance of a perverse sheaf is a property, not additional data.

2. Abelian Satake is used in the construction of the derived equivalences, but the statements of the derived equivalences make no mention of perverse sheaves.
3. Derived Satake is related to the representation theory of  $\mathfrak{g}$ . In particular, there are connections to Verma modules, the Grothendieck-Springer resolution, and the universal centralizer for  $\check{G}$ .

4. There is no  $\infty$ -categorical analogue of the derived Satake equivalence with loop rotation (at least, one involving quantization); the monoidal structure does not lift.

The **classical Satake** theorem is “secretly” taking complexification of the Grothendieck groups on both sides of the quasi-classical derived equivalence. However, one deals with  $\mathcal{K}$  being a local field. The equivalence looks like  $C_c(G(\mathcal{O}) \backslash G(\mathcal{K}) / G(\mathcal{O})) \cong \mathbb{C}[\check{G}]^{\text{Ad} \check{G}}$ .

## 1.2 Equivariant Stuff

Let  $G$  be either a compact Lie group over  $\mathbb{R}$ , or a linear algebraic group over  $\mathbb{C}$ . According to these cases, let  $X$  be a “reasonable” topological space, namely a smooth manifold or an algebraic variety over  $\mathbb{C}$ . For us, nonreduced structure plays no role. We want  $G$  to act on  $X$  in either a smooth or algebraic manner, again according to our two cases. We want to define  $D_G(X)$  so that we can associate to the objects  $\mathcal{F}$  some “equivariant cohomology”  $H_G^\bullet(\mathcal{F})$ .

**Theorem 1.2.** *Let  $G$  be connected complex reductive. Let  $T$  be a maximal torus of  $G$  with Weyl group  $W$ . Then for  $mcF \in D_G(X)$ , we have  $H_G^\bullet(\mathcal{F}) = H_T^\bullet(\mathcal{F})^W$ .*

**Theorem 1.3** (Localization). *There is a correspondence(???) between  $H_T^\bullet(\mathcal{F})$  and  $H^\bullet(\mathcal{F}|_{X^T})$ .*

There is a “refined” version of this theorem called GKM (Goresky-Kottwitz-MacPherson). Another important result is (Braden’s) hyperbolic localization. There is also a result that gives equivariant Ext groups between IC sheaves.

Now, we want to discuss how  $D_G(X)$  is defined. If we use stacks, then it is “simple”:  $D_G(X) = D(X/G)$ . However, this is useless for more refined questions, e.g. formality (degeneration of spectral sequences) and IC sheaves. We instead look at a classical approach based on classifying spaces.

**Definition 1.1.** A **universal  $G$ -bundle** is a principal  $G$ -bundle  $EG \rightarrow BG$  such that  $EG$  is weakly contractible, i.e. (for us)  $\mathbb{Q} \otimes \pi_i(EG) = 0$  for all  $i$ .

The spaces  $EG, BG$  are infinite dimensional, but we can write them as direct limits of spaces  $E_n G, B_n G$ , where we have a principal  $G$ -bundle  $E_n G \rightarrow B_n G$  for each  $n$ , subject to the following conditions:

1.  $\mathbb{Q} \otimes \pi_i(E_n G) = 0$  for  $i \leq n$
2. For fixed  $k \geq 0$ , the maps  $\cdots \rightarrow H_k(B_n G) \rightarrow H_k(B_{n+1} G) \rightarrow \cdots$  stabilize.
3. If  $G$  is a compact Lie group, then the  $E_n G, B_n G$  are smooth manifolds and  $B_n G$  are compact. If  $G$  is linear algebraic over  $\mathbb{C}$ , then  $E_n G, B_n G$  are smooth algebraic varieties, and  $B_n G$  are projective.

There are many constructions that satisfy these criteria. We will follow one particular construction.

**Example 1.1.** Let  $G = \mathbb{C}^\times$ . Then  $E_n G = \mathbb{C}^n - \{0\}$  with obvious dilation  $G$ -action. Thus  $B_n G = \mathbb{P}^{n-1}$ . We call  $BG = \varinjlim_n \mathbb{P}^{n-1}$  by  $\mathbb{P}^\infty$ . We have  $H^*(\mathbb{P}^{n-1}) = \mathbb{C}[u]/(u^n)$ , so  $H^*(\mathbb{P}^\infty) = \varprojlim_n \mathbb{C}[u]/(u^n) = \mathbb{C}[u]$ . Here  $u$  is a degree 2 element.

**Example 1.2.**  $G = T$  is a torus, which is an  $r$ -fold product of  $\mathbb{C}^\times$ . Then  $BT$  is the  $r$ -fold product of  $\mathbb{P}^\infty$ , and the cohomology ring  $H^*(BT)$  is  $\mathbb{C}[u_1, \dots, u_r] = \mathbb{C}[\mathfrak{t}]$  for  $\mathfrak{t} = \text{Lie}T$ .

**Example 1.3.** Let  $G = GL_N$  over  $\mathbb{C}$ . Let  $E_n G = M_{N \times n}^{reg}$  be the space of full rank  $N \times n$  matrices. For  $n$  large,  $B_n G = Gr_N(\mathbb{C}^n)$ . In particular,  $BG = Gr_N(\mathbb{C}^\infty)$ .

If  $H$  is a closed subgroup of  $G$ , then  $(EG)/H$  is a model for  $BH$ . The map  $BH = (EG)/H \rightarrow (EG)/G = BG$  is a fibration with fiber  $G/H$ . We get maps  $H^*(BG) \rightarrow H^*(BH)$ .

**Example 1.4.** Let  $G$  be a linear algebraic group over  $\mathbb{C}$ . Pick a closed embedding  $G \hookrightarrow GL_N$ . Then we take  $BG = \varinjlim_n (M_{N \times n}^{reg}/G)$ .

*Remark.* 1. If  $G$  is unipotent, then it is isomorphic to an affine space, i.e. it is contractible. Then  $BG$  and  $EG$  are also contractible, so the equivariant theory for unipotent groups is trivial.

2. If  $G/H$  is weakly contractible, then  $BG$  is (weakly?) homotopic to  $BH$ , so the equivariant theories are the same. For instance, the equivariant theory for a reductive group  $G$  is the same as that of its maximal compact subgroup  $G_c$ . As a concrete example, if  $G = \mathbb{C}^\times$  and  $G_c = S^1$ , we get  $S^\infty/S^1 = \mathbb{P}^\infty$ .

## 2 Mar 27

Let  $X$  be a  $G$ -space. We have two maps  $G \times X \rightarrow X$ , namely the action  $a$  and the projection  $\text{pr}$ . An **equivariant structure** on a sheaf  $\mathcal{F}$  of vector spaces on  $X$  is an isomorphism  $\alpha : a^* \mathcal{F} \xrightarrow{\sim} \text{pr}^* \mathcal{F}$  such that  $\alpha|_{1_G \times X} = \text{id}$  and a certain cocycle condition is satisfied (condition omitted by lecturer).

**Example 2.1.** A constant sheaf  $C_X$  has a natural equivariant structure via the isomorphisms  $C_{G \times X} \rightarrow \text{pr}^* C_X$  and  $C_{G \times X} \rightarrow a^* C_X$ .

We denote by  $Sh(Y)$  the abelian category of sheaves on any space  $Y$ . We denote by  $Sh_G(X)$  the abelian category of  $G$ -equivariant sheaves on a  $G$ -space  $X$ .

**Lemma 2.1.** Let  $q : \tilde{Y} \rightarrow Y$  be a  $G$ -bundle. Then  $q^* : Sh(Y) \rightarrow Sh_G(\tilde{Y})$  is an equivalence with inverse given by  $\tilde{\mathcal{F}} \mapsto (q_* \mathcal{F})^G$  (taking  $G$ -invariants stalk-wise).

Now let  $X$  be a  $G$ -space and  $E \rightarrow B$  a  $G$ -bundle. Let  $E \times^G X = (E \times X)/G$ . We have a diagram

$$\begin{array}{ccccc} X & \xleftarrow{p} & E \times X & \xrightarrow{q} & E \times^G X \\ & & \downarrow & & \downarrow \pi \\ & & B \times X & \longrightarrow & B \end{array}$$

where  $q$  is a  $G$ -bundle and  $\pi$  is a locally trivial fibration on  $B$  with fiber  $X$ . Let  $\mathcal{F}_X \in Sh_G(X)$ . Then  $p^* \mathcal{F}_X$  is  $G$ -equivariant. By Lemma 2.1, we can uniquely (up to iso) write  $p^* \mathcal{F}_X \cong q^* \tilde{\mathcal{F}}$  for  $\tilde{\mathcal{F}} \in Sh(E \times^G X)$ . Then for any fiber  $\pi^{-1}(b)$ , which is non-canonically isomorphic to  $X$ , we have  $\tilde{\mathcal{F}}|_{\pi^{-1}(b)}$  is non-canonically isomorphic to  $\mathcal{F}_X$ .

We apply the above to the bundle being  $EG \rightarrow BG$ . Let  $X_G = EG \times^G X$ . Let  $H_G^\bullet(X) = H^\bullet(X_G)$ . Here is a picture relating our setup, on the left, to stacks, on the right, where  $\sim$  denotes weak homotopy equivalence:

$$\begin{array}{ccc} EG \times X & \sim & X \\ \downarrow q & & \downarrow \\ X_G & \sim & X/G \\ \downarrow & & \downarrow \\ BG & \sim & pt/G \end{array}$$

We have  $H_G^\bullet(pt) = H^\bullet(BG)$ , which acts as our “base ring”, and this comes with a map to  $H_G^\bullet(X) = H^\bullet(X_G)$ .

Now consider the diagram above in our universal bundle setting:

$$\begin{array}{ccccc} X & \xleftarrow{p} & EG \times X & \xrightarrow{q} & X \\ & & \downarrow & & \downarrow \pi \\ & & BG \times X & \longrightarrow & BG \end{array}$$

For any space  $Y$ , we write  $D(Y)$  for the ordinary derived category of  $Sh(Y)$ . We “define” (this definition is not technically correct, and will be remedied later) the equivariant derived category  $D_G(X)$  to have objects given by a triple  $\mathcal{F} = (\mathcal{F}_X, \mathcal{F}_{X_G}, \alpha)$ , where  $\mathcal{F}_X \in D(X)$ ,  $\mathcal{F}_{X_G} \in D(X_G)$ , and  $\alpha : p^* \mathcal{F}_X \xrightarrow{\sim} q^* \mathcal{F}_{X_G}$  is an isomorphism in  $D(EG \times X)$ . We define  $H_G^\bullet(\mathcal{F}) = H^\bullet(\mathcal{F}_{X_G})$ . Morphisms in  $D_G(X)$  are given by a pair of morphisms between the relevant objects of the non-equivariant derived categories (we will often call these sheaves) that satisfy a natural compatibility diagram. This is a triangulated category, where the distinguished triangles are pairs of distinguished triangles with compatibility condition. We have a forgetful functor  $D_G(X) \rightarrow D(X)$  which sends a triple to its first element. We have a functor  $Sh_G(X) \rightarrow D_G(X)$  defined by  $\mathcal{F}_X \mapsto (\mathcal{F}_X, \tilde{\mathcal{F}}, \alpha)$  for some naturally defined  $\alpha$ . This extends to a functor  $D(Sh_G(X)) \rightarrow D_G(X)$ , which is almost never an equivalence.

$D_G(X)$  has a notion of a constant sheaf, namely  $(C_X, C_{X_G}, \text{id}_{C_{EG \times X}})$ . Its sheaf cohomology recovers  $H_G^\bullet(X)$ .

We now retroactively impose the condition “constructible” everywhere. Because of this, we have to assume that  $G$  has finitely many connected components. This assumption implies  $\pi_1(BG)$  is finite, and if  $G$  is connected, then  $BG$  is simply connected. This follows by a homotopy sequence  $\pi_1(EG) \rightarrow \pi_1(BG) \rightarrow \pi_0(G)$  and  $\pi_1(EG) = 1$ .

We note that anytime we write sheaf functors, particularly pushforward, we mean their derived versions, unless otherwise specified. As in the abelian case,  $\mathcal{F}_{X_G}$  restricted to a fiber of  $\pi$  is isomorphic to  $\mathcal{F}_X$ . If we take the stalk at  $b \in BG$  of  $\mathcal{H}^k(\pi_* \mathcal{F}_{X_G})$ , we get  $H^k(\mathcal{F}_X)$ . Thus  $\mathcal{H}^k(\pi_* \mathcal{F}_{X_G})$  is a locally constant sheaf on  $BG$ . In particular, if  $G$  is connected, then this cohomology sheaf is constant.

We have a Leray spectral sequence  $E_2^{p,q} = H^p(BG, \mathcal{H}^q(\pi_* \mathcal{F}_X))$ , which converges to  $H_G^\bullet(\mathcal{F}_X)$ . If  $G$  is connected, then  $E_2^{p,q} = H^p(BG) \otimes H^q(\mathcal{F}_X)$ . In particular, if  $\mathcal{F}_X$  is constant,  $E_2^{p,q} = H^p(BG) \otimes H^q(X)$ , and this converges to  $H_G^\bullet(X)$ .

Let  $C \in D_G(X)$  be constant. Then  $\text{Ext}_{D_G(X)}^k(C, \mathcal{F}) = \text{Hom}_{D_G(X)}(C, \mathcal{F}[k]) = H_G^k(\mathcal{F})$ .

**Example 2.2.** Let  $X$  be a point, and let  $G$  be connected. Then  $Sh_G(pt)$  is  $\text{Vect}$ , the category of vector spaces. Thus  $D(Sh_G(pt)) = D(\text{Vect})$ . We have  $\text{Ext}_D^k(C, C) = \mathbb{C}$  if  $k = 0$ , and 0 otherwise. On the other hand,  $\text{Ext}_{D_G(pt)}^k(C, C) = H_G^k(C) = H_G^k(pt) = H^k(BG)$ . If  $G = \mathbb{C}^\times$ , then  $H^k(BG) \neq 0$  for all positive even integers  $k$ . It follows that  $D(Sh_G(pt))$  is very different from  $D_G(pt)$ .

We now take care of the issue of  $EG, BG$  being infinite dimensional and correct the definition of  $D_G(X)$ . Recall  $EG = \varinjlim_n E_n G$ ,  $BG = \varinjlim_n B_n G$ , with  $G$ -bundles  $E_n G \rightarrow B_n G$ . Let  $i_n : E_n G \rightarrow E_{n+1} G$ . We have a commutative

diagram

$$\begin{array}{ccccc}
& E_n G \times X & \xrightarrow{q_n} & X_{n,G} & \\
p_n \swarrow & \downarrow i_n \times \text{id} & & \downarrow \overline{i_n} & \\
X & & & & \\
p_{n+1} \swarrow & \downarrow & E_{n+1} G \times X & \xrightarrow{q_{n+1}} & X_{n+1,G}
\end{array}$$

An object  $\mathcal{F}$  of  $D_G^b(X)$  is a collection consisting of  $\mathcal{F}_X \in D^b(X)$ ,  $\mathcal{F}_n \in D^b(X_{n,G})$  for each  $n$ ,  $\alpha_n : p_n^* \mathcal{F}_X \xrightarrow{\sim} q_n^* \mathcal{F}_n$  for each  $n$ , and  $\nu_n : \mathcal{F}_n \xrightarrow{\sim} \overline{i_n}^* \mathcal{F}_{n+1}$  for all  $n$ , satisfying the following compatibility diagrams for all  $n$ :

$$\begin{array}{ccc}
p_n^* \mathcal{F}_X & \xrightarrow{\text{id}} & (i_n \times \text{id})^* p_{n+1}^* \mathcal{F}_X \\
\alpha_n \downarrow & & \downarrow (i_n \times \text{id})^* (\alpha_{n+1}) \\
q_n^* \mathcal{F}_n & \xrightarrow{q_n^* (\nu_n)} q_n^* \overline{i_n}^* \mathcal{F}_{n+1} \xrightarrow{\text{id}} & (i_n \times \text{id})^* q_{n+1}^* \mathcal{F}_{n+1}
\end{array}$$

**Example 2.3.** Let  $X$  be an algebraic variety. We define  $IC_G(X) \in D_G^b(X)$  by  $(\mathcal{F}_X = IC(X), \mathcal{F}_n = IC(X_{n,G})[-\dim B_n G])$  with natural compatibility maps. For any Zariski open  $U \subset X$ , we have  $IC_G(X)|_U = C_U[\dim X]$ .

We now need to rigorously define  $H_G^\bullet(\mathcal{F})$ . We have maps  $\pi_n : X_{n,G} \rightarrow B_n G$  which are locally trivial fibrations with fiber  $X$ . We have as before  $H^\bullet(\mathcal{F}_n) = H^\bullet((\pi_n)_* \mathcal{F}_n)$  and a spectral sequence  $E_2^{p,q} = H^p(\mathcal{H}^q((\pi_n)_* \mathcal{F}_n))$  converging to it. Recall that the maps in cohomology between the  $B_n G$  stabilize. Then we get maps between spectral sequences that also stabilize, whence the sheaf cohomologies stabilize.



### 3 Apr 1

Let  $K \leq G$  be a subgroup. Let  $X$  be a  $K$ -space. Then we can form the *induced* space  $G \times^K X = (G \times X)/K$ . We have an *induction functor*  $\text{Ind}_K^G : D_K(X) \rightarrow D_G(G \times^K X)$  defined via the isomorphism  $X_K = EG \times^K X \xrightarrow{\sim} EG \times^G (G \times^K X)$ . This functor is an equivalence. Note that we have chosen  $EG$  as a model for  $EK$ . We have  $H_G(\text{Ind}_K^G \mathcal{F}) \cong H_K(\mathcal{F})$ .

If  $X$  is a  $G$ -space, then we have a *restriction functor*  $\text{Res}_K^G : D_G(X) \rightarrow D_K(X)$  given by pullback along the map  $p : X_K \rightarrow X_G$ . Equivalently, you can pullback along the action map  $G \times^K X \rightarrow X$  and then use the inverse to induction:  $D_G(X) \rightarrow D_G(G \times^K X) \rightarrow D_K(X)$ .

Let  $G$  be connected, and either a compact Lie group or a complex reductive algebraic group. Let  $V \in \text{Rep}(G)$ . Consider the vector bundle  $V_{BG}$  with fiber  $V$  given by  $EG \times^G V \rightarrow BG$ . Its Chern classes are certain classes  $c_i(V_{BG}) \in H^{2i}(BG)$ . The Chern character is  $ch(V_{BG}) = \sum_{i \geq 0} \frac{1}{i!} c_i(V_{BG})$ . We will use this only when  $G = T$  is a torus. Let  $\mathfrak{t} = \text{Lie} T$ . Let  $X^*(T) = \text{Hom}(T, \mathbb{C}^\times)$  be the character lattice. We have (after complexifying)  $\mathfrak{t}^* = \mathbb{C} \otimes_{\mathbb{Z}} X^*(T)$ . Recall  $BT \simeq (\mathbb{P}^\infty)^r$  for  $r = \dim T$ . For  $\lambda \in X^*(T)$  we have a line bundle  $ET \times^T \mathbb{C}_\lambda = \mathbb{C}_{ET, \lambda} \rightarrow BT$ . Since it is a line bundle, it only has a  $c_1$ . The map  $\lambda \mapsto c_1(\mathbb{C}_{ET, \lambda})$  gives a group homomorphism  $X^*(T) \rightarrow H^2(BT)$ , which extends to a  $\mathbb{C}$ -linear  $\mathfrak{t}^* \rightarrow H^2(BT, \mathbb{C})$ . This further extends to an algebra homomorphism  $\mathbb{C}[\mathfrak{t}] = \text{Sym} \mathfrak{t}^* \rightarrow H^*(BT, \mathbb{C})$  (which doubles the degrees).


Return to the case of  $G$  as in the previous paragraph, and let  $T$  be a maximal torus with Weyl group  $W$ . Via the construction above, we have the following commutative diagram with  $p : BT \rightarrow BG$ :

$$\begin{array}{ccccc}
 & \text{Rep} T & \xrightarrow{ch} & \mathbb{C}[[\mathfrak{t}]] = \prod_{i \geq 0} H^{2i}(BT) & \\
 \text{Res}_T^G \nearrow & & & & \nwarrow p^* \\
 \text{Rep} G & & & & \\
 \searrow char & & & & \\
 & \mathbb{C}[G]^G & \xrightarrow{\exp^*} & \mathbb{C}[[\mathfrak{g}]]^G & \xrightarrow{ch} \prod_{i \geq 0} H^{2i}(BG)
 \end{array}$$


Now we want to generalize this to sheaves. Let  $X$  be a  $G$ -space. We have maps  $X_T \xrightarrow{p} X_{N(T)} \xrightarrow{q} X_G$ , where  $p$  is a  $W$ -bundle and  $q$  is a  $G/N(T)$  bundle. Let  $\mathcal{F} = \mathcal{F}_{X_G}$  be the  $D(X_G)$ -component of an element in  $D_G(X)$  (we will often treat elements of the derived category in this way). Then  $p^* q^* \mathcal{F} \in D(X_T)$ , so  $p^* q^* : D_G(X) \rightarrow D_T(X)$ .

**Theorem 3.1.**  $H_G(\mathcal{F}) = H(X_G, \mathcal{F}_{X_G}) \rightarrow H_T(\mathcal{F}) = H(X_T, p^* q^* \mathcal{F}_{X_G})$  is an isomorphism onto  $H(X_T, p^* q^* \mathcal{F}_{X_G})^W$ .


**Lemma 3.1.**  $H^i(G/N(T), \mathbb{C}) = \mathbb{C}$  if  $i = 0$  and 0 otherwise.

*Proof.* Suppose  $f : \tilde{Y} \rightarrow Y$  is a Galois covering with finite Galois group  $W$ . For  $\mathcal{E} \in D(Y)$ , we have  $H(\tilde{Y}, f^*\mathcal{E}) = H(Y, f_*f^*\mathcal{E})$ .  $W$  acts on the RHS, and the projection formula gives  $H(Y, \mathcal{E}) = H(Y, f_*f^*\mathcal{E})^W$ . We apply this to the map  $G/T \rightarrow G/N(T)$ . Then  $H(G/N(T), \mathbb{C}) = H(G/T, \mathbb{C})^W$ . We conclude via the following Theorem of Borel. 

**Theorem 3.2** (Borel).  $W \curvearrowright H^\bullet(G/T)$  is the regular representation.


*Proof of Theorem 3.1.*  $H(X_{N(T)}, q^*\mathcal{F}) = H(X_G, q_*q^*\mathcal{F})$ . The Leray spectral sequence gives  $E_2^{i,j} = H^i(X_G, \mathcal{H}^j q_*q^*\mathcal{F})$  converging to  $H(X_G, q_*q^*\mathcal{F})$ . By equivariance,  $\mathcal{H}^j q_*q^*\mathcal{F}$  restricted to a fiber of  $q$ , which is  $G/N(T)$ , is constant. Then, by Lemma 3.1, the stalks of  $\mathcal{H}^j q_*q^*\mathcal{F}$  are  $\mathbb{C}$  for  $j = 0$  and 0 otherwise. Then the spectral sequence gives us  $H(X_G, \mathcal{F}) \cong H(X_{N(T)}, q^*\mathcal{F})$ , and then this is  $H(X_T, p^*q^*\mathcal{F})^W$  using the fact that  $p$  is a Galois covering. 

**Corollary 3.1.**  $H(BG) \cong H(BT)^W \cong \mathbb{C}[\mathfrak{t}]^W \cong \mathbb{C}[\mathfrak{g}]^G$ , where the last isomorphism is due to Chevalley. In particular,  $H^{2i+1}(BG) = 0$ .


*Proof.* Apply the Theorem in the case of a constant sheaf. 

**Definition 3.1.**  $\mathcal{F} \in D_G(X)$  is called **equivariantly formal** if  $\pi_*\mathcal{F} \cong \bigoplus_i \mathcal{H}^i \pi_*\mathcal{F}$  in  $D(BG)$ , where  $\pi : X_G \rightarrow BG$ .

**Corollary 3.2.** If  $\mathcal{F}$  is equivariantly formal, then  $H_G(\mathcal{F}) \cong H(BG) \otimes H(X, \mathcal{F}_X)$ .

*Proof.* Since we are still assuming  $G$  is connected, we have  $BG$  is simply connected. This implies that  $\mathcal{H}^i(\pi_*\mathcal{F})$  is a constant sheaf with stalk  $H^i(X, \mathcal{F}_X)$ . Formality gives  $H(\pi_*\mathcal{F}) \cong \bigoplus_{i,j} H^i(BG, \mathcal{H}^j \pi_*\mathcal{F}) = \bigoplus_{i,j} H^i(BG) \otimes H^j(X, \mathcal{F}_X)$ . 

**Corollary 3.3.** If  $\mathcal{F}$  is equivariantly formal, then  $H_T(\mathcal{F}) = H(BT) \otimes_{H(BG)} H_G(\mathcal{F})$ .

*Proof.* Take  $W$  invariants on both sides of  $H_G(\mathcal{F}) \cong H(BG) \otimes H(X, \mathcal{F}_X)$ . 

In general, proving that something is equivariantly formal is difficult. However, there are some situations where we are lucky.

One such case is for a projective algebraic  $G$ -variety  $X$ ; then  $IC(X)$  is equivariantly formal. Indeed, we recall that  $IC(X)$  is defined to be the “limit” of  $IC(X_{G,n})$  for varying  $n$ . We have maps  $\pi_n : X_{G,n} \rightarrow BG_n$  whose fibers are  $X$ . Since  $X$  is projective and  $BG_n$  is projective, the map  $\pi_n$  is projective. Thus equivariant formality holds by the *BBD decomposition theorem*.

Another case is if  $H^{2i+1}(X, \mathcal{F}_X) = 0$ . This follows by an argument with the Leray spectral sequence. Namely, by Corollary 3.1, the spectral sequence collapses since there are no odd degree terms. Namely,  $H_G(\mathcal{F}) = H(BG) \otimes H(\mathcal{F}_X)$ . Lecturer is actually a little unsure on how to get the full statement of formality from here.

## 4 Apr 3

### 4.1 Strategy for Derived Geometric Satake Proof (Without Loop Rotation)

Let  $G$  be connected complex reductive with maximal torus  $T$ . Let  $\mathfrak{g} = \text{Lie}G$  and  $\mathfrak{t} = \text{Lie}T$ . We have the Langlands dual group and algebras  $\check{G}, \check{\mathfrak{g}}, \check{\mathfrak{t}}$ . There is a canonical identification  $(\check{\mathfrak{t}})^* \cong \mathfrak{t}$ . The Weyl groups of both groups are also the same,  $W$ . The important computation is  $\mathbb{C}[\mathfrak{t}]^W \cong (\text{Sym}^*)^W \cong (\text{Sym}\check{\mathfrak{t}})^W \cong (\text{Sym}\check{\mathfrak{g}})^{\check{G}}$ , where the last isomorphism is due to Chevalley.

Let  $A$  be a graded (or dg) algebra. Let a reductive group  $K$  act on  $A$  by graded algebra automorphisms. In the lecturer's course last quarter, a category  $HC_{A,K}$  of Harish-Chandra modules was defined. Namely, each object  $M \in HC_{A,K}$  is simultaneously a graded  $A$ -module and a  $K$ -representation, with the compatibility  $k(am) = k(a)k(m)$ . We assume from here on out that  $A$  is commutative (this is where the strategy breaks for loop rotation). Then  $HC_{A,K}$  becomes a monoidal category with  $\otimes_A$ .

We will apply the above formalism to  $A = \text{Sym}\check{\mathfrak{g}}$  and  $K = \check{G}$  acting on  $A$  via adjoint action. Derived Satake is a monoidal equivalence  $\Phi : D_{G(\mathcal{O})}(Gr) \xrightarrow{\sim} D(HC_{\text{Sym}\check{\mathfrak{g}}, \check{G}})$ .

Consider  $A = \mathbb{C}$  with trivial  $K$ -action. Then  $HC_{A,K} = \text{Rep}K$ . We have two functors  $\text{Rep}K \rightarrow \text{Vect}$ , namely invariants  $M \mapsto M^K$  and forgetful  $M \mapsto \underline{M}$ . The regular representation  $R = \mathbb{C}[K]$  decomposes as  $\bigoplus_{V \in \text{Irr}(K)} V \otimes V^* \in \text{Ind}(\text{Rep}K)$ . For any  $M \in \text{Rep}K$ , we have  $R \otimes M \cong R \boxtimes M$  as  $K \times K$ -modules. On  $R \otimes M$ , the first copy of  $K$  acts diagonally, while the second copy of  $K$  acts only on  $R$ , and on the right. On  $R \boxtimes M$ , the first copy of  $K$  acts only on  $R$  and the second copy acts only on  $M$ . Thus, in  $\text{Rep}K$ , where we only take the first copy of  $K$ , there is no  $K$ -action on  $M$  in  $R \boxtimes M$ . We have  $(R \otimes M)^K = R^K \boxtimes M = M$  and  $R \otimes R \cong R \boxtimes R$ .

$G$  is a  $G$ -torsor under right action. If  $X$  is an affine  $G$ -torsor then we have a coaction map  $\mathbb{C}[X] \rightarrow \mathbb{C}[X \times G]$ . Note  $\mathbb{C}[X \times G] \cong \mathbb{C}[X] \otimes \mathbb{C}[G]$ . The isomorphism  $R \otimes R \cong R \boxtimes R$  corresponds to  $\mathbb{C}[X] \otimes \mathbb{C}[X] \cong \mathbb{C}[X] \otimes \mathbb{C}[G]$ . (???)

We use  $\text{triv}$  to denote the trivial 1-dimensional representation in  $\text{Rep}K$ . It is the monoidal unit of  $\text{Rep}K$ . We have  $M^K = \text{Hom}_K(\text{triv}, M)$ .

We can also take  $K$ -invariants on  $HC_{A,K}$  to get an element of  $A^K\text{-mod}$ . We have that  $A$  is the monoidal unit of  $HC_{A,K}$ , and  $M^K = \text{Hom}_{HC}(A, M)$ .

Let  $R_A = R \otimes A$ . We have  $\text{Hom}_{HC}(A, R_A \otimes_A M) \cong (R_A \otimes_A M)^K \cong ((R \otimes A) \otimes_A M)^K \cong (R \otimes M)^K \cong \underline{M}$ , giving an internal way to take the forgetful functor.

**Example 4.1.** Let  $A = \text{Sym}\check{\mathfrak{g}}$ ,  $K = \check{G}$ . Then  $R_A = R \otimes A = \mathbb{C}[\check{G}] \otimes \text{Sym}\check{\mathfrak{g}} = \mathbb{C}[\check{G}] \otimes \mathbb{C}[(\check{\mathfrak{g}})^*] = \mathbb{C}[\check{G} \times (\check{\mathfrak{g}})^*] = \mathbb{C}[T^*\check{G}]$ .

Let  $\Lambda \subset X^*(\check{T}) \subset \check{\mathfrak{t}}^*$  be the dominant Weyl chamber. For  $\lambda \in \Lambda$  we have the finite dimensional  $V_\lambda \in \text{Irr}(\check{G})$  with highest weight  $\lambda$ . Then  $R = \mathbb{C}[\check{G}] = \bigoplus_{\lambda \in \Lambda} V_\lambda \otimes V_\lambda^*$ . Abelian Satake is a monoidal functor  $\Psi : (\text{Rep}(\check{G}), \otimes) \rightarrow (D_{G(\mathcal{O})}(Gr), \star)$  sending  $V_\lambda$  to  $IC_\lambda$ . Let  $\mathcal{R} = \psi(R)$ ; it decomposes as  $\bigoplus_{\lambda \in \Lambda} IC_\lambda \otimes V_\lambda^*$ . We get a map  $G \rightarrow \text{Aut}(\mathcal{R})$  via the action on  $V_\lambda^*$ . The monoidal unit of  $\star$  is  $IC_0$ .

We will treat  $\mathcal{R}$  as  $R_A$ , thus giving us a candidate for  $\Phi$ :  $R\text{Hom}_{D_{G(\mathcal{O})}(Gr)}(IC_0, \mathcal{R} \star (-)) = \bigoplus_{\lambda \in \Lambda} V_\lambda^* \otimes R\text{Hom}(IC_0, IC_\lambda \star (-))$ . This would mean that  $A$  is  $R\text{Hom}(IC_0, \mathcal{R})$ .

Let us see how to give it an algebra structure.  $R = \mathbb{C}[\check{G}]$  has a multiplication  $m$ , which gives a map  $\mu : \mathcal{R} \star \mathcal{R} \rightarrow \mathcal{R}$ . For  $\alpha, \beta \in \text{Hom}(IC_0, \mathcal{R})$ , we can form  $\alpha \star \beta : IC_0 \star IC_0 \rightarrow \mathcal{R} \star \mathcal{R}$ . Then precomposing with  $IC_0 \cong IC_0 \star IC_0$  and postcomposing with  $\mu$  gives us a map  $IC_0 \rightarrow \mathcal{R}$ , which we call  $\alpha \circ \beta$ . Adding in appropriate shifts shows that this works on  $R\text{Hom}$  as well. We can also modify this to work for  $\beta \in R\text{Hom}(IC_0, \Psi(M))$ , giving  $A$ -module structures to the image of  $\Psi$ .

For any space  $X$  and  $\mathcal{F} \in D(X)$ , we have  $C_X \otimes \mathcal{F} \cong \mathcal{F}$  where  $C_X \otimes \mathcal{F} = \Delta^*(C_X \boxtimes \mathcal{F})$  for  $\Delta : X \hookrightarrow X \times X$ . This induces a map  $H(C_X) \otimes H(\mathcal{F}) \rightarrow H(\mathcal{F})$ , i.e.  $H(\mathcal{F})$  becomes a module over  $H(C_X) = H(X)$ . This works equally well in the equivariant setting. In particular,  $H_{G(\mathcal{O})}(IC_\lambda)$  is a graded  $H_{G(\mathcal{O})}(Gr)$ -module.

In order to compute  $R\text{Hom}(IC_0, \mathcal{R})$ , we need to compute  $\text{Ext}(IC_0, IC_\lambda)$ . Taking equivariant cohomology gives us a map  $\text{Ext}^i(IC_0, IC_\lambda) \rightarrow \text{Hom}_{H_{G(\mathcal{O})}(Gr)}(H_{G(\mathcal{O})}^\bullet(IC_0), H_{G(\mathcal{O})}^{i+\bullet}(IC_\lambda))$ .

**Theorem 4.1.**  $\text{Ext}(IC_\mu, IC_\lambda) \xrightarrow{\sim} \text{Hom}_{H_{G(\mathcal{O})}(Gr)}(H_{G(\mathcal{O})}(IC_\mu), H_{G(\mathcal{O})}(IC_\lambda))$ .

We have  $H_{G(\mathcal{O})}(Gr) = \mathbb{C}[T^*(\mathfrak{t}^*/W)] = \mathbb{C}[T^*\mathfrak{c}] = \text{SymLie}\check{\mathcal{J}}$ , universal centralizer (explained last quarter). We also have  $\text{Hom}(H(IC_0), H(\mathcal{R})) \cong \mathbb{C}[\check{\mathfrak{t}} \times \check{G}] \cong \mathbb{C}[T_\psi^*(\check{G}/\check{U})]$  (notation also explained last quarter).

## 5 Apr 8

Cohomology of affine Grassmannian.

## 6 Apr 10

$G$  connected reductive,  $L = G(\mathcal{O})$ ,  $Gr = G(\mathcal{K})/L$ .  $\pi_0(Gr) \simeq \pi_1(G)$ . For any two connected components  $X, X'$  of  $Gr$ , there is some  $g(t) \in G(\mathcal{K})$  such that the map  $x \mapsto g(t)x$  is an isomorphism  $X \xrightarrow{\sim} X'$ . The components are  $\mathbb{G}_m \times L$ -stable. We fix a component  $X$ . We will prove that  $X$  is a disjoint union of spaces  $X_0, X_1, \dots$  such that

- Each  $X_d$  is  $\mathbb{G}_m \times L$ -stable.
- Each  $X_{\leq d} = X_0 \cup \dots \cup X_d$  is a projective variety.
- Each  $X_d$  is a disjoint union of affine spaces (cells).
- For all  $i \geq 0$ , there is  $d(i) \gg 0$  such that  $X_d$  has no cells of dimension  $\leq i$  for  $d > d(i)$ .

As a consequence, the embeddings  $X_{\leq d} \hookrightarrow X_{\leq d+1}$  don't add cells of "low" dimension. In particular, for  $d > d(i)$ , we have isomorphisms  $H_i(X_{\leq d}) \xrightarrow{\sim} H_i(X_{\leq d+1})$  and  $H^i(X_{\leq d+1}) \xrightarrow{\sim} H^i(X_{\leq d})$ . (It follows that?)  $X_d$  is equivariantly formal and  $H_{\mathbb{G}_m \times L}^i(X_{\leq d+1}) \xrightarrow{\sim} H_{\mathbb{G}_m \times L}^i(X_{\leq d})$ . We then define  $H^i(Gr)$  to be the stable limit of  $H^i(X_{\leq d})$ , and similarly for the equivariant cohomology. The odd degree cohomologies vanish and  $Gr$  is equivariantly formal.

Let  $M = \{g(t) \in L \mid g(0) = 1\}$ . There is a SES  $1 \rightarrow M \rightarrow L \rightarrow G \rightarrow 1$ , where the map  $L \rightarrow G$  sends  $g(t)$  to  $g(0)$ .  $M$  is pro-unipotent and there is a group contraction  $M \times [0, 1] \rightarrow M$  defined by  $(g(t), c) \mapsto g(ct)$ . It follows that in all of our equivariant cohomologies, we can replace  $L$  by  $L/M = G$ .

We now address a point from last time and avoid the use of stacks. Let  $\widetilde{Gr} = G(\mathcal{K})/M$ . This has an evident map to  $Gr$  which has the structure of a principal  $G$ -bundle (since  $L/M = G$ ). In particular,  $\widetilde{Gr}$  has a left and right action by  $G$ . We have  $H_{\mathbb{G}_m \times G \times G}(\widetilde{Gr}) \cong H_{\mathbb{G}_m \times G}(Gr)$ .

Let  $\mathfrak{g} = \text{Lie}G$  have Cartan  $\mathfrak{t}$  and Weyl group  $W$ . Let  $Z = \mathbb{C}[\mathfrak{t}]^W = \mathbb{C}[\mathfrak{t}/W] = H_G(pt)$ . We have  $(Z \otimes Z)[\hbar] = H_{\mathbb{G}_m \times G \times G}(pt)$ . Let  $\zeta : (Z \otimes Z)[\hbar] \rightarrow H_{\mathbb{G}_m \times G}(Gr)$  be the map induced by  $\widetilde{Gr} \rightarrow pt$ , rewritten with the preceding identifications. Let  $\mathcal{A}$  be the subalgebra of  $(Z \otimes Z)[\hbar, \hbar^{-1}]$  generated by  $(Z \otimes Z)[\hbar]$  and  $(z \otimes 1 - 1 \otimes z)\hbar^{-1}$  for  $z \in Z$ .

**Theorem 6.1.** *Let  $X \subset Gr$  be the connected component of  $1 \cdot L/L$ . Then the map  $\zeta$  is injective and extends uniquely to a degree doubling algebra isomorphism  $\mathcal{A} \rightarrow H_{\mathbb{G}_m \times G}(Gr)$ .*

*Proof Strategy.* By Chevalley,  $Z = \mathbb{C}[p_1, \dots, p_r]$  for homogeneous polynomials  $p_i$  of degree  $d_i$ . Then  $Z \otimes Z = \mathbb{C}[p_i \otimes 1, 1 \otimes p_i]$ . Let  $\xi_i = (p_i \otimes 1 - 1 \otimes p_i)\hbar^{-1}$ . Then  $\mathcal{A} = \mathbb{C}[\hbar, p_i \otimes 1, \xi_i]$ . Note that  $\deg(\xi_i) = d_i - 1$ . If  $\pi_1(G) = 1$ , then  $d_i \geq 2$  (for reasons related to tori), so  $\mathcal{A}$  is non-negatively graded and  $\mathcal{A}_0 = \mathbb{C}$ . It is

free over  $(Z \otimes 1)[\hbar]$ ; the basis is given by the  $\xi_i$ . By formality,  $H_{\mathbb{G}_m \times G}(Gr)$  is also free over  $(Z \otimes 1)[\hbar]$ ; it is generated by the non-equivariant cohomology of  $Gr$ .

Now we “forget about loop rotation”:  $\zeta|_{\hbar=0} : Z \otimes Z \rightarrow H_{\mathbb{G}_m \times G}(Gr)/(\hbar)$ . By formality, the codomain is  $H_G(Gr)$ . We will show that this map sends  $z \otimes 1 - 1 \otimes z$  to 0. This will imply, by flatness, that  $\zeta$  extends to  $\tilde{\zeta} \mathcal{A} \rightarrow H_{\mathbb{G}_m \times G}(Gr)$ . We can again restrict this map to  $\hbar = 0$ . We recall  $\mathcal{A}/\hbar \mathcal{A} = \mathbb{C}[T(\mathfrak{t}/W)]$ . So  $\tilde{\zeta}$  gives a map  $\mathbb{C}[T(\mathfrak{t}/W)] \rightarrow H_G(Gr)$ . As a side note, the generators  $\xi$  in  $\mathcal{A}$  give rise to partial derivatives in  $\mathcal{A}/\hbar \mathcal{A}$ .

Let  $\mathcal{J} \subset Z$  be the augmentation ideal. If we mod out by  $\mathcal{J}$  on both sides, we get a map  $\mathbb{C}[\xi_i] \rightarrow H(Gr)$ . We will prove that this map is an isomorphism. To do so, we will show that it is injective and that Poincare polynomials agree. Once we show this, we will have  $\zeta$  is an isomorphism by flatness and Nakayama. 🇧🇷

We will now change notation; denote  $G_{\mathbb{C}}$  by the complex reductive group and  $G$  by a maximal compact subgroup.  $G_{\mathbb{C}}$  contracts to  $G$  so there is no topological information lost. We can choose a Borel  $B$  and maximal complex torus  $T_{\mathbb{C}}$  such that  $T = G \cap B$  is a maximal torus in  $G$ . There is an anti-holomorphic anti-involution  $G_{\mathbb{C}} \rightarrow G_{\mathbb{C}}$ ,  $g \mapsto g^*$ , such that  $G = \{g \in G_{\mathbb{C}} \mid g^* = g^{-1}\}$ . The Iwasawa decomposition states  $G_{\mathbb{C}} = GB$ . The embedding  $G \hookrightarrow G_{\mathbb{C}}$  induces an isomorphism  $G/T \xrightarrow{\sim} G_{\mathbb{C}}/B$ , i.e. the flag manifold and flag variety can be identified.

We want an Iwasawa decomposition analogue for loop groups. Fix an embedding  $G_{\mathbb{C}} \hookrightarrow GL_n(\mathbb{C})$  such that  $G = G_{\mathbb{C}} \cap U_n$ . Let  $LG = G[z^{\pm 1}]$ , which we can think of as algebraic maps  $S^1 \rightarrow G$ .

**Lemma 6.1.**  $LG = \{g(z) \in G_{\mathbb{C}}[z^{\pm 1}] \mid g(z)^* = g(z^{-1})\}$ .

**Example 6.1.**  $G_{\mathbb{C}} = C^{\times}$ ,  $G = S^1$ . Note that  $G_{\mathbb{C}}[z^{\pm 1}] \cong \mathbb{C}^{\times} \times \mathbb{Z}$ , and  $\mathbb{Z} \cong \pi_1(G_{\mathbb{C}})$ . The  $g(z) = cz^n$  that are in  $LG$  must satisfy  $|c| = 1$ . More generally, if  $G_{\mathbb{C}} = T_{\mathbb{C}}$  is a torus, then  $G = T$  is a torus,  $T_{\mathbb{C}}[z^{\pm 1}] \cong T_{\mathbb{C}} \times X_*(T_{\mathbb{C}})$ ,  $T[z^{\pm 1}] \cong T \times X_*(T)$ , where  $X_*$  denotes the cocharacter lattice, and  $X_*(T) = \pi_1(T)$ .

We can now state Iwasawa decomposition for loop groups.

- $G_{\mathbb{C}}(\mathcal{K}) = LG \cdot G_{\mathbb{C}}(\mathcal{O})$ .
- $LG \cap G_{\mathbb{C}}(\mathcal{O}) = G$ , which we interpret as constant maps  $S^1 \rightarrow G$ .

This is equivalent to  $LG/G \xrightarrow{\sim} G_{\mathbb{C}}(\mathcal{K})/G_{\mathbb{C}}(\mathcal{O}) = Gr$ . The form  $LG/G$  is how topologists think of the affine Grassmannian.

## 7 Apr 15

### 7.1 Cohomology of Loop Groups

#### 7.1.1 Based Loop Groups

Let  $G$  be a compact connected Lie group. Recall  $LG$  consists of the polynomial maps  $S^1 \rightarrow G$ . Inside this we have  $\Omega G$ , the loops based at the identity (i.e. identity is sent to identity). There is a clear isomorphism  $\Omega G \times G \xrightarrow{\sim} LG$  given by translation. We can also think of this as embedding  $G \hookrightarrow LG$  via constant loops, and then  $LG/G \cong \Omega G$ .  $G$  still has an action on  $\Omega G$ , namely by conjugation. This can be seen as coming from the left  $G$ -action on  $LG$  after the right-action has been killed.

Let  $T$  be a maximal torus (say rank  $r$ ) in  $G$ . From last time we have  $LT = X_*(T) \times T$ , so we see  $\Omega T = X_*(T) = \text{Hom}(S^1, T) \cong \mathbb{Z}^r$ . We have embeddings  $LT \hookrightarrow LG$ ,  $\Omega T \hookrightarrow \Omega G$ , and in fact  $(LG)^T = LT$  and  $(\Omega G)^T = \Omega T$ . For a cocharacter  $\lambda$ , we write  $z^\lambda$  for the corresponding loop (or its image of a point  $z \in S^1$ ).

$S^1$  acts on  $LG$  by loop rotation, and we ask what happens on  $\Omega G$ . Note that  $(LG)^{S^1} = G$ , the constant loops. If  $\gamma \in \Omega G$  and  $z_0 \in S^1$ , then as free loops,  $(z_0 \gamma)(z) = \gamma(z z_0)$ . This evidently sends  $z = 1$  to  $\gamma(z_0)$ . So loop rotation on  $\Omega G$  sends  $\gamma$  to the map  $z \mapsto \gamma(z z_0) \gamma(z_0)^{-1}$ . Then we see  $(\Omega G)^{S^1} = \text{Hom}(S^1, G)$ . Note that for all  $\gamma \in \text{Hom}(S^1, G)$ , there is  $g \in G$  and  $\lambda \in X_*(T)$  such that  $\gamma(z) = \text{Ad}_g(z^\lambda)$ . Now let  $W$  be the Weyl group and let  $X_+$  be the dominant Weyl chamber in  $X_*(T)$ . Then

$$\text{Hom}(S^1, G) = \bigsqcup_{\lambda \in X_+} G/\text{Stab}(\lambda).$$

Furthermore, for each  $\lambda \in X_+$ , there is a parabolic subgroup  $P_\lambda$  of the corresponding complex group  $G_{\mathbb{C}}$  such that  $G/\text{Stab}(\lambda) \cong G_{\mathbb{C}}/P_\lambda$ .

#### 7.1.2 Algebraic Topology Review

Let  $X$  be either a finite connected  $CW$  complex or a smooth manifold. Fix a basepoint  $x_0 \in X$ . In the first case of  $X$ , let  $\Omega^c X$  be the space of continuous loops in  $X$  based at  $x_0$ . In the second case, let  $\Omega^\infty X$  be the space of smooth loops in  $X$  based at  $x_0$ . If  $X$  is simply connected, then in either case,  $\Omega^c X$  or  $\Omega^\infty X$  is homotopic to a  $CW$ -complex with finitely many cells of each dimension. We note that  $\Omega G$  is homotopic to such a space, as well as being homotopic to  $\Omega^c G$  and  $\Omega^\infty G$  (assuming  $G$  is simply connected, which the lecturer says is the reasonable thing to do). In the future we will just write  $\Omega X$  instead of  $\Omega^c X$  or  $\Omega^\infty X$ .

The based path space  $PX$  consists of continuous maps  $[0, 1] \rightarrow X$ , where 0 is sent to the basepoint  $x_0$ . It is contractible and there is a fibration  $PX \rightarrow X$



with fiber  $\Omega X$  given by sending a map to its image at 1.

Concatenation of loops makes  $\Omega X$  into an  $H$ -space, which is kind of like a group. The above fibration  $PX \rightarrow X$  can be thought of as a “principal  $\Omega X$ -bundle”. Since  $PX$  is contractible, we see that  $X$  is behaving like the classifying space, i.e.  $B\Omega X = X$ . We also have  $\pi_i(\Omega X) \cong \pi_{i+1}(X)$ . We have that  $\mathbb{C} \otimes \pi_\bullet(\Omega X) = \bigoplus_i \mathbb{C} \otimes \pi_i(\Omega X)$  has the structure of a graded Lie superalgebra (with the Whitehead/Samelson bracket). On the other hand, concatenation makes  $H_\bullet(\Omega X)$  into a graded associative algebra with the Pontryagin product. In fact, the diagonal map gives a coproduct  $\Delta$  that upgrades  $H_\bullet(\Omega X)$  to the structure of a graded Hopf algebra. The Hurewicz homomorphism  $\mathbb{C} \otimes \pi_i(\Omega X) \rightarrow H_i(\Omega X)$  sends the Whitehead/Samelson bracket to the commutator bracket.

*Note.* The lecturer will generally complexify the homotopy groups as we did above, but it may be omitted from the notation for convenience or on accident.

An element  $a \in H_\bullet(\Omega X)$  is called primitive if  $\Delta a = a \otimes 1 + 1 \otimes a$ . Let  $Prim$  be the set of primitive elements. They form a Lie subalgebra. They are the images of the Hurewicz maps. A result of Milnor-Moore says that  $H_\bullet(\Omega X) \cong \mathcal{U}(Prim)$ .

### 7.1.3 Return to Groups

We want to apply the above ideas to  $X = G$ , still a compact connected Lie group. We have that  $\Omega G$  has a group structure given by pointwise multiplication. By comparing this to the  $H$ -space structure given by concatenation, and in particular the induced structures on homology, the Eckmann-Hilton argument gives us that  $H_\bullet(\Omega G)$  is a commutative algebra. By again using the diagonal map, we get that  $H_\bullet(\Omega G)$  is a commutative and cocommutative Hopf algebra. Then the Milnor-Moore result can be refined to  $H_\bullet(\Omega G) \cong \text{Sym}(Prim_0) \otimes \bigwedge(Prim_1)$ , where  $Prim_0$  and  $Prim_1$  are the even and odd parts of  $Prim$ . A similar decomposition holds for cohomology

Note that the bundles  $PG \xrightarrow{\Omega G} G$  and  $EG \xrightarrow{G} BG$  give  $\pi_i(\Omega G) \cong \pi_{i+1}(G) \cong \pi_{i+2}(BG)$ . Using the fact that cohomology of  $BG$  only exists in even degrees, we find the same is true of  $\Omega G$ . In particular, there is no odd part coming from the Milnor-Moore result; it is the symmetric algebra of something. But we know  $H^{2\bullet}(BG) = \mathbb{C}^\bullet[t]^W = \mathbb{C}[p_1, \dots, p_r]$  with  $\deg p_i = d_i$ . The shift in degrees tells us  $H^{2\bullet}(\Omega G) = \mathbb{C}^\bullet[\xi_1, \dots, \xi_r]$  with  $\deg \xi_i = d_i - 1$  (multiply this by 2 to get the shift by 2 in degree). This is a complete description of the cohomology of  $\Omega G$ . We now look into how the  $\xi_i$  are related to the  $p_i$ .

There is a “transgression” map which sends  $p_i$  as above to some  $\eta_i \in H_{2d_i-1}(G)$  (The lecturer wrote this as homology, but I suspect it should be cohomology).

This map comes from the Leray spectral sequence for the map  $EG \xrightarrow{G} BG$ . There is also an evaluation map  $\text{ev} : S^1 \times \Omega G \rightarrow G$ . Pullback gives a map  $H^\bullet(G) \rightarrow H^\bullet(S^1) \otimes H^\bullet(\Omega G)$ . By integrating the image over  $S^1$ , we get a map  $H^\bullet(G) \rightarrow H^{\bullet-1}(\Omega G)$ . This map sends  $\eta_j$  as above to  $\xi_j$ .

There is a more direct way to obtain the mapping  $p_i \mapsto \xi_i$ . There is a so-called clutching construction which produces a  $G$ -bundle  $E_\gamma \rightarrow S^2$  from a (based?) loop  $\gamma : S^1 \rightarrow G$ . In particular, one glues trivial bundles on two hemispheres via  $\gamma$  on the equator. By collecting all of these  $E_\gamma$  we get a  $G$ -bundle  $E \rightarrow S^2 \times \Omega G$ . Using the universality of  $EG \rightarrow BG$ , there is a map  $f : S^2 \times \Omega G \rightarrow BG$  such that  $E \rightarrow S^2 \times \Omega G$  is the pullback of  $EG \rightarrow BG$ . Composing the pullback along  $f$  and integration along  $S^2$  gives a map  $H^\bullet(BG) \rightarrow H^{\bullet-2}(\Omega G)$ , and this map sends  $p_i$  to  $\xi_i$ .

## 8 Apr 17

We begin with a discussion of equivariant cohomology of  $S^2$ . Consider the standard embedding of  $S^2 \hookrightarrow \mathbb{R}^3$ , and let  $S^1$  act on  $S^2$  by rotation around the  $z$ -axis. If we think of  $S^2$  as  $\mathbb{CP}^1$ , then the two fixed points are 0 and  $\infty$ . Restriction to the fixed points gives a map  $\iota^* : H_{S^1}(S^2) \rightarrow H_{S^1}(0) \oplus H_{S^1}(\infty) = \mathbb{C}[\hbar] \oplus \mathbb{C}[\hbar]$ . Here  $\hbar$  has degree 2. Integration over  $S^2$  gives a map  $H_{S^1}^\bullet(S^2) \rightarrow H_{S^1}^{\bullet-2}(pt) = \mathbb{C}^{\bullet-2}[\hbar]$ .

**Proposition 8.1.** (1)  $\iota^*$  is injective.

(2)  $\text{im}(\iota^*) = \{(f_1, f_2) \mid f_1(0) = f_2(0)\}$ .

(3)  $\int_{S^2}(f_1, f_2) = (f_1 - f_2)/\hbar$ .

Let  $T$  be a maximal torus in  $G$ , and let  $\lambda$  be a cocharacter of  $T$ , which we think of as a based loop in  $T$ . Using the clutching construction and this loop, we get a  $T$ -bundle  $E_\lambda$  on  $S^2$ . Since  $T$  is abelian, the fiber product  $E_\lambda \times_T ET$  has a well-defined free  $T$ -action by acting on the first factor. We have the following diagram:

$$\begin{array}{ccc} & E_\lambda \times_T ET & \\ \swarrow & & \searrow \\ S^2 = E_\lambda/T & & BT \end{array}$$

We have  $H_T(E_\lambda \times_T ET) = H_{T \times T}(E_\lambda) = H(S^2) \otimes H_T(pt)$ . This admits a map from  $H_T(BT) = H_T(pt) \otimes H_T(pt)$ , via pullback along the right arrow in the above diagram. We can include the  $S^1$  action on  $S^2$  everywhere to get  $\eta : H_T(pt) \otimes H_T(pt) \otimes H_{S^1}(pt) \rightarrow H_{S^1}(S^2) \otimes H_T(pt)$ . The domain can be rewritten as  $\mathbb{C}[\mathfrak{t}] \otimes \mathbb{C}[\mathfrak{t}] \otimes \mathbb{C}[\hbar]$ , and the codomain can be rewritten as  $\{(f_1, f_2) \in \mathbb{C}[\hbar] \oplus \mathbb{C}[\hbar] \mid f_1(0) = f_2(0)\} \otimes \mathbb{C}[\mathfrak{t}]$ .

The  $S^1 \times T \times T$  action on  $E_\lambda$  is given by  $(z_0, t_1, t_2) \cdot x = \lambda(z_0)t_1t_2^{-1}x$  (here  $x$  is thought of as an element of  $T$ , i.e. the action is fiberwise). In particular, the subgroup  $\{t_2 = \lambda(z_0)t_1\}$  is the stabilizer. By looking at the Lie algebra of the stabilizer, we deduce that  $H_{S^1}(S^2) \otimes \mathbb{C}[\mathfrak{t}] \cong (\mathbb{C}[\mathfrak{t}] \otimes \mathbb{C}[\mathfrak{t}][\hbar]/(f(x + \hbar\lambda) \otimes 1 - 1 \otimes f(x) \mid f \in \mathbb{C}[\mathfrak{t}]))$ . Note that we are treating  $\lambda$  as an element of  $\mathfrak{t}$  by embedding  $X_*(T)$  as a lattice in  $\mathfrak{t}$ .

Let  $W$  be the Weyl group. We always have  $H_G(-) = H_T(-)^W$ . In particular,  $H_G(pt) = \mathbb{C}[\mathfrak{t}]^W$ , which we denote by  $Z$ . Recall we have  $\zeta : Z \otimes Z \otimes \mathbb{C}[\hbar] \rightarrow H_{S^1 \times G}(Gr) = H_{S^1 \times G}(\Omega G)$ . We also (will?) construct  $\zeta_T : \mathbb{C}[\mathfrak{t}] \otimes Z \otimes \mathbb{C}[\hbar] \rightarrow H_{S^1 \times T}(Gr) = H_{S^1 \times T}(\Omega G)$ .

Recall the  $G$ -bundle  $E \rightarrow S^2 \times \Omega G$  constructed last time. By repeating what we have done today, we have  $Z \otimes Z \otimes \mathbb{C}[\hbar] = H_{G \times G \times S^1}(E) \cong H_{G \times S^1}(E/G) = H_{G \times S^1}(S^2 \times \Omega G) \xrightarrow{\int_{S^2}} H_{G \times S^1}(\Omega G)$ . This is the map  $\zeta$  above. We can similarly

obtain  $\zeta_T$ , and then  $\zeta$  is obtained by taking  $W$ -invariants. The cohomology  $H_{G \times S^1}(S^2 \times \Omega G)$  is similar to what we had before; it is  $\{(f_1, f_2) \in \mathbb{C}[\mathfrak{t} \times \mathbb{A}^1]^2 \mid f_1(x, 0) = f_2(x, 0)\}$ . Integration sends  $(f_1, f_2)$  to  $(f_1 - f_2)/\hbar$  (here  $\hbar$  is the coordinate on  $\mathbb{A}^1$ ). Recall  $\mathcal{A}$  is the subalgebra of  $(Z \otimes Z)[\hbar, \hbar^{-1}]$  generated by  $(Z \otimes Z)[\hbar]$  and elements  $(f \otimes 1 - 1 \otimes f)\hbar^{-1}$ . The map  $\zeta$  extends to  $\mathcal{A} \rightarrow H_{S^1 \times G}(\Omega G)$ . We know  $\mathcal{A}^{2\bullet}/\hbar\mathcal{A} \cong \mathbb{C}^\bullet[p_1, \dots, p_r, \xi_1, \dots, \xi_r]$  with  $\deg p_i = d_i = 1 + \deg \xi_i$ , and  $H_G(\Omega G)$  has the exact same description.

Recall  $\mathcal{A}/\hbar\mathcal{A} = \mathbb{C}[T(\mathfrak{t}/W)]$ . Recall  $\check{\mathfrak{t}} \cong \mathfrak{t}^*$  as  $W$ -representations, and that  $\mathfrak{t}/W \cong \check{\mathfrak{t}}^*/W \cong \check{\mathfrak{g}}^*/\check{G} = \mathfrak{c}$ . Let  $\check{\mathfrak{g}}_{reg}^*$  be the regular locus, i.e. consisting of those  $\phi$  with  $\dim \text{Stab}_{\check{G}}(\phi) = r$ , the rank of  $\check{\mathfrak{g}}$ . The adjoint quotient map restricted to the regular locus,  $\pi : \check{\mathfrak{g}}_{reg}^* \rightarrow \mathfrak{c}$ , is a smooth morphism, and the fibers are  $\check{G}$ -orbits. Then  $\mathbb{C}[\mathfrak{c}] = \mathbb{C}[\check{\mathfrak{g}}]^{\check{G}}$ . For  $p \in \mathbb{C}[\mathfrak{c}]$  we can take its differential at a point  $c \in \mathfrak{c}$  to get  $d_cp \in T_c^*\mathfrak{c}$ . If  $x \in \check{\mathfrak{g}}_{reg}^*$  and  $\pi(x) = c$ , then  $d\pi^*$  sends  $d_cp$  to  $d_x(\pi^*p) \in T_x^*(\check{\mathfrak{g}}^*) = \check{\mathfrak{g}}$ .


Let  $Z_{reg} = \{(x, g) \mid x \in \check{\mathfrak{g}}^*, \text{Ad}_g(x) = x\}$ . Let  $\mathcal{J} = Z_{reg}/\check{G}$ . It is a smooth group scheme over  $\mathfrak{c}$ .  $\text{Lie } \mathcal{J} \rightarrow \mathfrak{c}$  is a vector bundle of rank  $r$ . The fiber of this bundle over  $c$  is the Lie algebra of the stabilizer of some  $x \in \pi^{-1}(c)$ . We can make identifications of this with  $\check{\mathfrak{g}}_x = \{d_x\pi^*p \mid p \in \mathbb{C}[\mathfrak{c}]\} = T_c^*\mathfrak{c}$ . The first equality here is due to Kostant (or using the Kostant slice?).

## 9 Apr 22

Consider the usual Langlands dual setup. For  $x \in \check{\mathfrak{g}}^*$  we let  $Z_x = \text{Stab}_{\check{G}}(x)$  and  $\mathfrak{z}_x = \text{Lie} Z_x$ . We say  $x$  is regular if  $\dim Z_x = \dim \mathfrak{t}$ . If this holds, then  $Z_x$  is abelian. We have that  $Z = \{(x, g) \mid x \in \check{\mathfrak{g}}_{reg}^*, g \in Z_x\}$  is a smooth group scheme over  $\check{\mathfrak{g}}_{reg}^*$ , and the fiber over any  $x$  is  $Z_x$ . The Lie algebra  $\mathfrak{z} = \text{Lie} Z$  is a vector subbundle of  $T^*(\check{\mathfrak{g}}_{reg}^*)$ .

Recall  $\mathfrak{c} = \mathfrak{t}^*/W = \mathfrak{t}/W \cong \check{\mathfrak{g}}^*/\check{G}$ . Let  $\chi$  be the restricted quotient map  $\check{\mathfrak{g}}_{reg}^* \rightarrow \mathfrak{c}$ . Then there is a smooth group scheme called the universal centralizer  $\mathcal{J} \rightarrow \mathfrak{c}$  such that  $\chi^* \mathcal{J}$  is isomorphic to  $Z$ , and this isomorphism is compatible with maps to  $\check{\mathfrak{g}}_{reg}^*$ . It follows that  $\mathfrak{z} \cong \chi^*(\text{Lie} \mathcal{J})$ .

**Lemma 9.1.** *Let  $x \in \check{\mathfrak{g}}_{reg}^*$  and let  $c = \chi(x)$ . Then  $T_c^* \mathfrak{c} \cong \mathfrak{z}_x$ , and in particular,  $\text{Lie} \mathcal{J}$  is isomorphic to  $T^* \mathfrak{c}$  as vector bundles.*

*Proof.* We have  $d_x \chi : \check{\mathfrak{g}}^* \rightarrow T_c^* \mathfrak{c}$  and  $d_x \chi^* : T_c^* \mathfrak{c} \rightarrow \check{\mathfrak{g}}$ . The image of  $d_x \chi^*$  consists of those  $\varphi \in \check{\mathfrak{g}}$  such that  $\langle \varphi, T_x(\check{G}x) \rangle = 0$ . We have  $T_x(\check{G}x) = \text{ad}_{\check{g}} x$ . Now, use the Killing form  $(-, -)$  to identify  $\check{\mathfrak{g}}$  and its linear dual. Then  $x \in \check{\mathfrak{g}}$  and  $T_x(\check{G}x) = [\check{\mathfrak{g}}, x]$ . Then the image of  $d_x \chi^*$  is those  $\varphi \in \check{\mathfrak{g}}$  with  $(\varphi, [y, x]) = 0$  for all  $y \in \check{\mathfrak{g}}$ . But  $(\varphi, [y, x]) = \pm(y, [\varphi, x])$ , so this condition is equivalent to  $\varphi \in \mathfrak{z}_x$ . need some geometry to show that  $d_x \chi^*$  is injective 

Here is another approach. Let  $p \in \mathbb{C}[\mathfrak{c}]$ . Then  $\chi^* p \in \mathbb{C}[\check{\mathfrak{g}}^*]^{\check{G}}$ . The collection of  $d_x p$  over all  $p$  is  $T_c^* \mathfrak{c}$ . Now,  $d_x(\chi^* p) \in (\check{\mathfrak{g}}^*)^* = \check{\mathfrak{g}}$ . The whole differential  $d(\chi^* p) \in (\mathbb{C}[\check{\mathfrak{g}}_{reg}^*] \otimes \check{\mathfrak{g}})^{\check{G}}$ . Since we have the  $\check{G}$  invariance, we actually have  $d_x(\chi^* p) \in \mathfrak{z}_x$ .

We have  $\mathbb{C}[\mathfrak{c}] = \mathbb{C}[p_1, \dots, p_r]$ . Then  $T^* \mathfrak{c}$  has a basis of sections given by  $\xi_i = dp_i$ . Then  $\mathbb{C}[T^* \mathfrak{c}] = \mathbb{C}[p_i, \xi_i]$ . Now  $H = \mathbb{C}[T \mathfrak{c}] \cong \text{Sym}(T^* \mathfrak{c}) \cong \text{Sym}(\text{Lie} \mathcal{J}) \cong \mathcal{U}(\text{Lie} \mathcal{J})$ .  $H$  has a coproduct  $\Delta : H \rightarrow H \otimes_{\mathbb{C}[\mathfrak{c}]} H$  such that, for  $\xi \in \text{Lie} \mathcal{J}$ , we have  $\Delta(\xi) = \xi \otimes 1 + 1 \otimes \xi$ . Note that  $\text{Lie} \mathcal{J}$  consists of the primitive elements. The  $\xi_i$  are primitive and a basis.

Recall  $\Omega$  consists of the based-at-identity polynomial loops in compact Lie group  $G$ . We have  $H_{S^1 \times G}(\Omega) \cong \mathcal{A} \subset \mathbb{C}[\mathfrak{c} \times \mathfrak{c}][\hbar^{\pm 1}]$  and  $H_G(\Omega) \cong \mathcal{A}/\hbar \mathcal{A} \cong \mathbb{C}[T \mathfrak{c}] \cong \text{Sym}(\text{Lie} \mathcal{J})$ , or what we just called  $H$  above. Let  $m : \Omega \times \Omega \rightarrow \Omega$  be pointwise multiplication. Then  $\Delta = m^*$  sends  $H_G(\Omega)$  to  $H_G(\Omega \times \Omega) \cong H_G(\Omega) \otimes_{H_G(pt)} H_G(\Omega) \cong \text{Sym} \mathcal{J} \otimes_{\mathbb{C}[\mathfrak{c}]} \text{Sym} \mathcal{J}$ . After identifying  $H_G(\Omega) \cong \text{Sym} \mathcal{J}$ , this is the same as the coproduct of  $H$  mentioned above.

Fix  $T$  and consider  $X_*(T) = \Omega^T$ . For  $\lambda \in X_*(T)$ , let  $i_\lambda : \{\lambda\} \hookrightarrow \Omega$ . Then  $i_\lambda^* : H_T(\Omega) \rightarrow H_T(pt) = \mathbb{C}[\mathfrak{t}]$ . Recall that  $H_G(\Omega) = H_T(\Omega)^W$ , so we can look at  $i_\lambda^*$  on  $H_G(\Omega) \cong \mathbb{C}[T \mathfrak{c}] = \mathbb{C}[p_i, \xi_i]$ . We have that  $p_i \mapsto p_i$  and  $\xi_i \mapsto \langle \xi_i, \lambda \rangle$ . The pairing is due to the fact that  $\xi_i \in (\mathbb{C}[\mathfrak{t}] \otimes \mathfrak{t}^*)^W$  and  $\lambda$  can be identified with a point in  $\mathfrak{t}$ , so we can pair them to get an element of  $\mathbb{C}[\mathfrak{t}]$ . The fact that  $i_\lambda^*(\xi_i)$  is

linear in  $\lambda$  is very important, and we now discuss its importance.

If  $\lambda, \mu \in X_*(T) = \Omega^T$ , then the multiplication map  $m : \Omega \times \Omega \rightarrow \Omega$  sends  $(\lambda, \mu)$  to  $\lambda + \mu$ . We have the following commutative diagram:

$$\begin{array}{ccc} H_G(\Omega) & \xrightarrow{i_{\lambda+\mu}^*} & H_G(\lambda + \mu) \\ m^* \downarrow & & \downarrow \\ H_G(\Omega) \otimes_{H_G(pt)} H_G(\Omega) & \xrightarrow{i_\lambda^* \otimes i_\mu^*} & H_G(\lambda) \otimes_{H_G(pt)} H_G(\mu) \end{array}$$

The second vertical map is also a “stupid” pullback. If we start with  $\xi_i$  in the top-left corner, then we get

$$\begin{array}{ccc} \xi_i & \xrightarrow{\quad} & i_{\lambda+\mu}^* \xi_i \\ \downarrow & & \\ \xi_i \otimes 1 + 1 \otimes \xi_i & \longrightarrow & i_\lambda^* \xi_i \otimes 1 + 1 \otimes i_\mu^* \xi_i \end{array}$$

(Yes, the second vertical arrow is missing. I'm not sure what the natural description of its image would be.) The commutativity of the diagram is equivalent to  $\lambda \mapsto i_\lambda^* \xi_i$  being linear, and without this,  $\xi_i$  would not be primitive. (???)

Now we look at what happens with loop rotation. There are two embeddings  $\mathbb{C}[\mathfrak{c}] \hookrightarrow \mathcal{A}$ , namely  $p \mapsto p \otimes 1$  and  $1 \otimes p$ . The difference between these maps is related to the differential. We have that  $\mathfrak{c} \leftarrow \text{Spec } \mathcal{A} \rightarrow \mathfrak{c}$  is a commutative Hopf algebroid, namely tensor products need to be taken over  $\mathbb{C}[\mathfrak{c}][\hbar]$ . We have  $\mathcal{A} = \mathbb{C}[p_i, \xi_i, \hbar]$  where  $\xi_i = (p_i \otimes 1 - 1 \otimes p_i) \hbar^{-1}$  in  $(\mathbb{C}[\mathfrak{c}] \otimes \mathbb{C}[\mathfrak{c}])[\hbar^{\pm 1}]$ . Note however that  $p_i \otimes 1 = 1 \otimes p_i$  in  $\mathcal{A} \otimes_{\mathbb{C}[\mathfrak{c}][\hbar]} \mathcal{A}$ , or when  $\hbar = 0$ . The coproduct sends  $p_i \otimes 1$  to  $p_i \otimes 1 \otimes 1$ , sends  $1 \otimes p_i$  to  $1 \otimes 1 \otimes p_i$ , sends  $\xi_i$  to  $\xi_i \otimes 1 + 1 \otimes \xi_i$ , and sends  $\hbar$  to  $\hbar$ .