COHOMOLOGY OF GKM FIBER BUNDLES

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Abstract. The equivariant cohomology ring of a GKM manifold is isomorphic to the cohomology ring of its GKM graph. In this paper we explore the implications of this fact for equivariant fiber bundles for which the total space and the base space are both GKM and derive a graph theoretical version of the Leray-Serre theorem. Then we apply this result to the equivariant cohomology theory of flag varieties.

Keywords: Equivariant fiber bundle, equivariant cohomology, GKM space, flag manifold

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1. Introduction

Let $T$ be an $n$–dimensional torus, and $M$ a compact, connected $T$–manifold. The equivariant cohomology ring of $M$, $H^*_T(M; \mathbb{R})$, is an $\mathbb{S}(t^*)$–module, where $\mathbb{S}(t^*) = H^*_T(\text{point})$ is the symmetric algebra on $t^*$, the dual of the Lie algebra of $T$. If $H^*_T(M)$ is torsion-free, the restriction map

$$i^*: H^*_T(M) \to H^*_T(M^T)$$

is injective and hence computing $H^*_T(M)$ reduces to computing the image of $H^*_T(M^T)$ in $H^*_T(M^T)$. If $M^T$ is finite, then

$$H^*_T(M^T) = \bigoplus_{p \in M^T} \mathbb{S}(t^*) ,$$

with one copy of $\mathbb{S}(t^*)$ for each $p \in M^T$. Determining where $H^*_T(M)$ sits inside this sum is a challenging problem. However, one class of torsion-free spaces for which this problem has a simple and elegant solution is the one introduced by Goresky-Kottwitz-MacPherson in their seminal paper [GKM]. These are now known as GKM spaces: an equivariantly formal space $M$ is a GKM space if $M^T$ is finite and for every codimension one subtorus $T^i \subset T$, the connected components of $M^T/M^i$ are either points or 2-spheres.

To each GKM space $M$ we attach a graph $\Gamma = \Gamma_M$ by decreeing that the points of $M^T$ are the vertices of $\Gamma$ and the oriented edges, $E_\Gamma$, of $\Gamma$ are these two-spheres with pre-assigned orientations; such orientations may be induced, for example, by pre-assigned complex structures, identifying the two-spheres with copies of $\mathbb{CP}^1$. It is easy to check that if $S$ is one of the edge two-spheres, then $S^T$ consists of exactly two $T$–fixed points, $p$ and $q$ (the “North” and “South” poles of $S$) and one defines $S$ to be the oriented edge of $\Gamma$ joining $q$ to $p$. These data determine a map

$$\alpha: E_\Gamma \to \mathbb{Z}_T^*$$

of oriented edges of $\Gamma$ into the weight lattice of $T$. This map assigns to the edge 2-sphere $S$ with North pole $p$ the weight of the isotropy representation of $T$ on the tangent space to $S$ at $p$. The map $\alpha$ is called the axial function of the graph $\Gamma$. We use it to define a subring $H^*_\alpha(\Gamma_M)$ of $H^*_T(M^T)$ as follows. Let $c$ be an element of $H^*_T(M^T)$, i.e. a function which assigns to each $p \in M^T$ an element $c(p)$ of $H^*_T(\text{point}) = \mathbb{S}(t^*)$. Then $c$ is in $H^*_\alpha(\Gamma_M)$ if and only if for each edge $e$ of $\Gamma_M$ with vertices $p$ and $q$ as end points, $c(p) \in \mathbb{S}(t^*)$ and $c(q) \in \mathbb{S}(t^*)$ have the same image in $\mathbb{S}(t^*)/\alpha e \mathbb{S}(t^*)$. A consequence of a Chang-Skjelbred result ([CS]) is that $H^*_\alpha(\Gamma_M)$ is the image of $i^*$, and therefore there is an isomorphism of rings

$$H^*_T(M) \simeq H^*_\alpha(\Gamma_M) . \quad (1.1)$$

In a companion paper [GSZ] we proved a fiber bundle generalization of this result. Let $M$ and $B$ be $T$–manifolds and $\pi: M \to B$ be a $T$–equivariant fiber bundle. If $H^*_T(M)$ is torsion free, then the restriction map

$$i^*: H^*_T(M) \to H^*_T(\pi^{-1}(B^T))$$

is injective, and if, in addition, $B$ is GKM, then $H^*_T(\pi^{-1}(B^T))$ is isomorphic to

$$\bigoplus_{p \in B^T} H^*_T(F_p) \quad (1.2)$$
with $F_p = \pi^{-1}(p)$. We show in [GSZ] that the image of $H^*_T(M)$ in (1.2) can be computed by a generalized version of (1.1). Moreover, if the fiber bundle is balanced (as defined in [GSZ]), there is a holonomy action of the groupoid of paths in $\Gamma$ on the sum (1.2) and the elements which are invariant under this action form an interesting subring of $H^*_T(M)$.

In this paper we will take the analysis of $H^*_T(M)$ one step further by assuming that $M$ is also GKM. By interpreting this assumption combinatorially one is led to a combinatorial notion which is a central topic of this paper, the notion of a “fiber bundle of a GKM graph $(\Gamma_1, \alpha_1)$ over a GKM graph $(\Gamma_2, \alpha_2)$,” and, associated with this, the notion of a “holonomy action” of the groupoid of paths in $\Gamma_2$ on the ring $H_{\alpha_1}(\Gamma_1)$. We will explore below the properties of such fiber bundles and apply these results to fiber bundles between generalized flag varieties; i.e. fiber bundles of the form

$$\pi: G/P_1 \to G/P_2$$

(1.3)

where $G$ is a semi-simple Lie group and $P_1$ and $P_2$ are parabolic subgroups. In particular we will examine in detail the fiber bundle

$$\pi: Fl(C^n) \to Gr_k(C^n),$$

(1.4)

of complete flags in $C^n$ over the Grassmannian of $k$–dimensional subspaces of $C^n$ and the analogue of this fibration for the classical groups of type $B_n$, $C_n$, and $D_n$. For each of these examples we will compute the subring of invariant classes in $H^*_T(M)$ (those elements which are fixed by the holonomy action of the paths in $\Gamma_2$) and show how the generators of this ring are related to the usual basis of $H^*_T(M)$, given by equivariant Schubert classes. These results were inspired by and are related to the results of Sabatini and Tolman in [ST] where they explore the equivariant cohomology of fiber bundles where the total space and the base space are more general symplectic manifolds with Hamiltonian actions.

What follows is a brief table of contents for this paper: In Section 2.1 we will describe some of the salient features of the fiber bundle (1.4). In Sections 2.2-2.4 we will define abstract versions of fibrations and fiber bundles between GKM graphs which incorporate these features, and in Sections 3.1-3.3 we will show how to compute the cohomology ring of such graphs. The main ingredient in this computation is a holonomy action of the group of based loops in the base on the cohomology of the fiber graph.

In Section 4 we apply this theory to generalized flag manifolds, which have been extensively studied in the combinatorics literature, but not from the perspective of this paper. Let $G$ be a semisimple Lie group, $B$ a Borel subgroup of $G$ and $P_1 \subset P_2$ parabolic subgroups containing $B$. In Section 4.1 we describe the GKM graph associated with the space $P_2/P_1$. In Sections 4.2-4.4 we discuss the fibration of GKM graphs associated with the fibration of $T$–manifolds (1.3) and compute the group of holonomy automorphisms associated with this fibration. In Section 5 we specialize to the case where $G$ is one of the four classical simple Lie group types, $A_n$, $B_n$, $C_n$, or $D_n$, and, using iterations of fiber bundles, give explicit construction for invariant classes.

In Section 6 we construct a second explicit basis of $H^*_T(G/B)$ consisting of classes that are $W$–invariant. These invariant classes are obtained from the equivariant Schubert classes by averaging over the action of the Weyl group. We will obtain
explicit combinatorial formulas for the transition matrix between the basis of invariant classes consisting of symmetrized Schubert classes and the basis of invariant classes obtained through the iterated fiber bundle construction. In addition we obtain an explicit formula for the decomposition of an invariant class in the basis of equivariant Schubert classes.

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2. GKM Fiber Bundles

2.1. Motivating example. Let $T^n = (S^1)^n$ be the compact torus of dimension $n$, with Lie algebra $t_n = \mathbb{R}^n$, and let $\{x_1, \ldots, x_n\}$ be the basis of $t_n^* \cong \mathbb{R}^n$ dual to the canonical basis of $\mathbb{R}^n$. Let $\{e_1, \ldots, e_n\}$ be the canonical basis of $\mathbb{C}^n$. The torus $T^n$ acts componentwise on $\mathbb{C}^n$ by

$$(t_1, \ldots, t_n) \cdot (z_1, \ldots, z_n) = (t_1z_1, \ldots, t_nz_n).$$

This action induces a $T^n$-action on both $M = Fl(\mathbb{C}^n)$, the manifold of complete flags in $\mathbb{C}^n$, and $B = Gr_k(\mathbb{C}^n)$, the Grassmannian manifold of $k$-dimensional subspaces of $\mathbb{C}^n$. Let $C = \{(t, \ldots, t) \mid t \in S^1\}$ be the diagonal circle in $T^n$ and let $T = T^n/C$. Then $T$ is isomorphic, though not through the natural projection, to the $(n-1)$-dimensional subtorus

$$\{(t_1, \ldots, t_n) \in T^n \mid t_1 \cdots t_n = 1\} = \exp(x_1 + \cdots + x_n).$$

Then $C$ acts trivially on the flag manifold and on Grassmannians, and the induced actions of $T$ on $Fl(\mathbb{C}^n)$ and on $Gr_k(\mathbb{C}^n)$ are effective. Let

$$\pi : Fl(\mathbb{C}^n) \to Gr_k(\mathbb{C}^n),$$

be the map that sends each complete flag $V_\bullet = (V_1, \ldots, V_n)$ to its $k$-dimensional component. Then $(M, B, \pi)$ is a $T$-equivariant fiber bundle.

Since flag manifolds and Grassmannians are GKM spaces, their $T$-equivariant cohomology rings are determined by fixed point data. These data can be nicely organized using the corresponding GKM graphs, as follows. For a general GKM space $M$ the fixed point set $M^T$ is finite and is the vertex set of the GKM graph $\Gamma$. If $T' \subset T$ is a codimension one subtorus of $T$, then the connected components of the set $M^{T'}$ of $T'$-fixed points are either $T$-fixed points or copies of $\mathbb{C}P^1$ joining two $T$-fixed points. The edges of the graph $\Gamma$ correspond to these $\mathbb{C}P^1$'s, for all codimension one subtori $T' \subset T$. An edge $e$ corresponding to a connected component of $M^{T'}$ is labeled by an element $\alpha_e \in t^*$ such that $\tilde{t}' = \ker \alpha_e$. As explained in the introduction, the equivariant cohomology ring $H^{\ast}_T(M)$ can be computed from the GKM graph $(\Gamma, \alpha)$ associated to $M$, and we will give the details of that construction in Section 3.1.

For the flag manifold $Fl(\mathbb{C}^n)$, the $T$-fixed point set is indexed by $S_n$, the group of permutations of $[n] = \{1, \ldots, n\}$. A permutation $u = u(1) \cdots u(n)$ of $[n]$ indexes the fixed flag

$$V_\bullet^\ast = (V_1^u, \ldots, V_n^u),$$

given by $V_i^u = C e_{u(1)} \oplus \cdots \oplus C e_{u(k)}$, for all $k = 1, \ldots, n$.

The codimension one subtori $T'$ of $T$ for which the fixed point set is not just the set of $T$-fixed points are the subtori $T_{ij} = \{t \in T \mid t_i = t_j\} = \exp(\ker(x_i - x_j))$. 

For a fixed flag $V_u^w$, the connected component of $\mathcal{F}(\mathbb{C}^n)^{T_u}$ that passes through $V_u^w$ also contains the fixed flag $V_v^w$, where $v = (i, j)u$ and $(i, j)$ is the transposition that swaps $i$ and $j$.

The GKM graph $\Gamma$ of the flag manifold $\mathcal{F}(\mathbb{C}^n)$ is the Cayley graph $(S_n, t)$ constructed from the group $S_n$ and generating set $t$, the set of transpositions: the vertices correspond to permutations in $S_n$ and two vertices are joined by an edge if they differ by a transposition. If $u \in S_n$, then $u \ast (i, j) = (u(i), u(j)) \ast u$, so two permutations that differ by a transposition on the right (operating on positions) also differ by a transposition on the left (operating on values). We denote the edge $e$ that joins $u$ and $v = u \ast (i, j)$ either by

$$u \ast (i, j) \mapsto v$$

or

$$u \ast (u(i), u(j)) \mapsto v,$$

to emphasize either right or left multiplication. If $1 \leq i < j \leq n$, then the value of the axial function $\alpha$ on this edge is

$$\alpha_e = x_{u(i)} - x_{u(j)}.$$

We will refer to $\Gamma$ as $S_n$, and it will be clear from the context when $S_n$ is the graph, the vertex set, or the group of permutations. Figure 1(b) shows the Cayley graph $(S_3, t)$. As a general convention throughout this paper, parallel edges have collinear labels. For example, $\alpha(123, 132) = \alpha(231, 321) = x_2 - x_3$.

**Figure 1.** The complete graph $K_3$ (a) and the Cayley graph $(S_3, t)$ (b)

For the Grassmannian $\mathcal{G}_k(\mathbb{C}^n)$, the $T$-fixed point set is indexed by $k$-element subsets of $[n]$. A subset $I = \{i_1, \ldots, i_k\}$ corresponds to the fixed $k$-dimensional subspace $V_I = \mathbb{C}e_{i_1} \oplus \cdots \oplus \mathbb{C}e_{i_k}$. Two vertices are joined by an edge if the intersection of their corresponding $k$-element subsets is a $(k-1)$-element subset. The resulting graph is the Johnson graph $J(n, k)$. If $I = (I \cap J) \cup \{i\}$ and $J = (I \cap J) \cup \{j\}$, then the value of the axial function on the edge $e$ from $I$ to $J$ is $\alpha_e = x_i - x_j$. In particular, when $k = 1$ we get the complex projective space $\mathbb{C}P^{n-1}$, and the associated graph is the complete graph $K_n$ with $n$ vertices. The complete graph $K_3$ is shown in Figure 1(a).

The discrete version of (2.1) is the morphism of graphs $\pi: S_n \to J(n, k)$, given by $\pi(u) = \{u(1), \ldots, u(k)\}$. This map is compatible with the axial functions on the two graphs, and for each subset $A \in J(n, k)$, the inverse image $\pi^{-1}(A)$ is a product $S_k \times S_{n-k}$. The axial functions on fibers are not identical, but they are compatible in a natural way.
The GKM fiber bundle $S_4 \to J(4, 2)$ is a combinatorial description of the fiber bundle $\mathcal{F}l_4(C) \to \mathcal{G}r_2(C^4)$ that sends a complete flag in $\mathcal{F}l_4(C)$ to its two dimensional component. Figure 2 shows the graphical representation of this fiber bundle. The fibers are the squares. (The internal edges of $S_4$ have been omitted.)

![Figure 2](image_url)

**Figure 2.** The GKM fiber bundle $S_4 \to J(4, 2)$

This example motivates one of the main goals of this paper: to define the discrete analog of a fiber bundle between GKM spaces for which the fibers are isomorphic GKM spaces. We then prove a discrete Leray-Serre theorem, showing how one can recover the graph cohomology of the total space from the cohomology of the base and invariant classes in the cohomology of the fiber.

Then we will revisit the example $\pi: \mathcal{F}l(n) \to \mathcal{G}r(k)$ and consider more general fiber bundles $G/B \to G/P$, with $B \subset P \subset G$ a Borel and parabolic subgroup of a complex semisimple Lie group $G$, and give a combinatorial description/construction of invariant classes for classical groups.

### 2.2. Abstract GKM Graphs

We start by recalling some general definitions. The reader should have in mind the examples of the Cayley graph $S_n$, the complete graph $K_n$, and the Johnson graph $J(n, k)$. We will return to these with a summarizing example at the end of Section 2.

Let $\Gamma = (V, E)$ be a regular graph, with $V$ the set of vertices and $E$ the set of oriented edges. We will consider oriented edges, so each unoriented edge $e$ joining vertices $p$ and $q$ will appear twice in $E$: once as $(p, q) = p \to q$ and a second time as $(q, p) = q \to p$. When $e$ is oriented from $p$ to $q$, we will call $p = i(e)$ the initial vertex of $e$, and $q = t(e)$ the terminal vertex of $e$. For a vertex $p$, let $E_p$ be the set of oriented edges with initial vertex $p$.

**Definition 2.1.** Let $e = (p, q)$ be an edge of $\Gamma$, oriented from $p$ to $q$. A **connection along the edge** $e$ is a bijection $\nabla_e: E_p \to E_q$ such that $\nabla_e(p, q) = (q, p)$. A connection on $\Gamma$ is a family $\nabla = (\nabla_e)_{e \in E}$ of connections along the oriented edges of $\Gamma$, such that $\nabla_{(q, p)} = \nabla_{(p, q)}^{-1}$ for every edge $e = (p, q)$ of $\Gamma$. 
Definition 2.2. Let $\nabla$ be a connection on $\Gamma$. A $\nabla$–compatible axial function on $\Gamma$ is a labeling $\alpha: E \to t^*$ of the oriented edges of $\Gamma$ by elements of a linear space $t^*$, satisfying the following conditions:

1. $\alpha(q,p) = -\alpha(p,q)$;
2. For every vertex $p$, the vectors $\{\alpha(e) \mid e \in E_p\}$ are mutually independent;
3. For every edge $e = (p,q)$, and for every $e' \in E_p$ we have
   $$\alpha(\nabla_e(e')) - \alpha(e') = c\alpha(e),$$
   for some scalar $c \in \mathbb{R}$ that depends on $e$ and $e'$.

An axial function on $\Gamma$ is a labeling $\alpha: E \to t^*$ that is a $\nabla$–compatible axial function for some connection $\nabla$ on $\Gamma$.

Definition 2.3. A GKM graph is a labeling $\alpha: E \to t^*$ that is a $\nabla$–compatible axial function for some connection $\nabla$ on $\Gamma$.

Example 1 (The complete graph). For the complete graph $\Gamma = K_n$ considered in Section 2.1 the axial function on oriented edges is defined as follows. Let $t^*$ be an $n$–dimensional linear space and $\{x_1, \ldots, x_n\}$ be a basis of $t^*$. Define $\alpha: E \to t^*$ by
$$\alpha(i,j) = x_i - x_j.$$ 
If $\nabla(i,j): E_i \to E_j$ sends $(i,j)$ to $(j,i)$ and $(i,k)$ to $(j,k)$ for $k \neq i, j$, then $\nabla$ is a connection compatible with $\alpha$. The image of $\alpha$ spans the $(n-1)$–dimensional subspace $t^*_0$ generated by $\alpha_1 = x_1 - x_2, \ldots, \alpha_{n-1} = x_{n-1} - x_n$.

When $n = 2$, the graph $\Gamma$ has two vertices, 1 and 2, joined by an edge. The oriented edge from 1 to 2 is labeled $\beta = x_1 - x_2$, and the oriented edge from 2 to 1 is labeled $-\beta = x_2 - x_1$. The second condition in the definition of an axial function is automatically satisfied.

Example 2 (The Cayley graph $(S_n,t)$). For the Cayley graph $\Gamma = (S_n,t)$ considered in Section 2.1 the axial function on oriented edges is defined as follows. Let $t^*$ be an $n$–dimensional linear space and $\{x_1, \ldots, x_n\}$ be a basis of $t^*$. Let $\alpha: E \to t^*$ be the axial function defined as follows. If $u \to v = u(i,j)$ is an oriented edge, with $1 \leq i < j \leq n$, define
$$\alpha(u,v) = x_{u(i)} - x_{u(j)}.$$ 
Note that $\alpha(u,v)$ is determined by the values changed from $u$ to $v$. For an edge $e = u \to v = u(i,j)$, define $\nabla_e: E_u \to E_v$ by
$$\nabla_e(u,u(a,b)) = (v,v(a,b)).$$
Then $\nabla$ is a connection compatible with $\alpha$ and, as above, the image of $\alpha$ spans the $(n-1)$–dimensional subspace $t^*_0$ generated by $\alpha_1 = x_1 - x_2, \ldots, \alpha_{n-1} = x_{n-1} - x_n$.

The examples above show that the image of $\alpha$ may not generate the entire linear space $t^*$. Let $(\Gamma, \alpha)$ be a GKM graph. For a vertex $p$, let
$$t^*_p = \text{span}\{\alpha_e \mid e \in E_p\} \subset t^*$$
be the subspace of $t^*$ generated by the image of the axial function on edges with initial vertex $p$. If $\Gamma$ is connected, then this subspace is the same for all vertices of $\Gamma$, and we will denote it by $t^*_0$. We can co-restrict the axial function $\alpha: E \to t^*$ to a function $\alpha_0: E \to t^*_0$, and the resulting pair $(\Gamma, \alpha_0)$ is also a GKM graph.

Definition 2.4. An axial function $\alpha: E \to t^*$ is called effective if $t^*_0 = t^*$. 
Let $(\Gamma, \alpha)$ be a GKM graph with $\Gamma = (V, E)$ and axial function $\alpha : E \to t^*$. Let $\nabla$ be a connection compatible with $\alpha$. Let $\Gamma_0 = (V_0, E_0)$ be a subgraph of $\Gamma$, with $V_0 \subset V$ and $E_0 \subset E$, such that, if $e \in E$ is an edge with $i(e), t(e) \in V_0$, then $e \in E_0$.

**Definition 2.5.** A connected subgraph $\Gamma_0$ is a $\nabla$-GKM subgraph if for every edge $e \in E_0$ with $i(e) = p$ and $t(e) = q$, we have $\nabla_e (E_0 \cap E_0) = E_0 \cap E_0$. The subgraph $\Gamma_0$ is a GKM subgraph if it is a $\nabla$-GKM subgraph for a connection $\nabla$ compatible with $\alpha$.

In other words, $\Gamma_0$ is a GKM subgraph if, for some connection $\nabla$ compatible with the axial function $\alpha$, the connection along edges of $\Gamma_0$ to edges of $\Gamma_0$ and edges not in $\Gamma_0$ to edges not in $\Gamma_0$. Then the connected subgraph $\Gamma_0$ is regular, the restriction $\alpha_0$ of $\alpha$ to $E_0$ is an axial function on $\Gamma_0$, and the connection $\nabla$ induces a connection $\nabla_0$ compatible with $\alpha_0$. Therefore a GKM subgraph is naturally a GKM graph.

**2.2.1. Isomorphisms of GKM Graphs.** Let $(\Gamma_1, \alpha_1)$ and $(\Gamma_2, \alpha_2)$ be two GKM graphs, with $\Gamma_1 = (V_1, E_1)$, $\alpha_1 : E_1 \to t_1^*$ and $\Gamma_2 = (V_2, E_2)$, $\alpha_2 : E_2 \to t_2^*$.

**Definition 2.6.** An isomorphism of GKM graphs from $(\Gamma_1, \alpha_1)$ to $(\Gamma_2, \alpha_2)$ is a pair $(\Phi, \Psi)$, where

1. $\Phi : \Gamma_1 \rightarrow \Gamma_2$ is an isomorphism of graphs;
2. $\Psi : t_1^* \rightarrow t_2^*$ is an isomorphism of linear spaces;
3. For every edge $(p, q)$ of $\Gamma_1$ we have
   $$\alpha_2(\Phi(p), \Phi(q)) = \Psi \circ \alpha_1(p, q).$$

The first condition implies that $\Phi$ induces a bijection from $E_1$ to $E_2$, and the third condition can be restated as saying that the following diagram commutes:

$$\begin{array}{ccc}
E_1 & \xrightarrow{\Phi} & E_2 \\
\downarrow{\alpha_1} & & \downarrow{\alpha_2} \\
t_1^* & \xrightarrow{\Psi} & t_2^*
\end{array}$$

**2.3. Fiber Bundles of Graphs.** We now introduce special types of morphisms between graphs. Later we will add the GKM package (axial function and connection) and define the corresponding types of morphisms between GKM graphs.

**2.3.1. Fibrations.** Let $\Gamma$ and $B$ be connected graphs and $\pi : \Gamma \rightarrow B$ be a morphism of graphs. Then $\pi$ is a map from the vertices of $\Gamma$ to the vertices of $B$ such that, if $(p, q)$ is an edge of $\Gamma$, then either $\pi(p) = \pi(q)$ or else $(\pi(p), \pi(q))$ is an edge of $B$. When $(p, q)$ is an edge of $\Gamma$ and $\pi(p) = \pi(q)$, we will say that the edge $(p, q)$ is *vertical*; otherwise $(\pi(p), \pi(q))$ is an edge of $B$ and we will say that $(p, q)$ is *horizontal*. For a vertex $q$ of $\Gamma$, let $E_q^+ = \{ e \in E_q \mid i(e) = q \}$ be the set of vertical edges with initial vertex $q$, and let $H_q$ be the set of horizontal edges with initial vertex $q$. Then $E_q = E_q^+ \cup H_q$ and $\pi$ canonically induces a map $(d\pi)_q : H_q \rightarrow (E_B)_{\pi(q)}$ given by

$$\pi(q, q') = (\pi(q), \pi(q')).$$

**Definition 2.7.** The morphism of graphs $\pi : \Gamma \rightarrow B$ is a *fibration of graphs* if for every vertex $q$ of $\Gamma$, the map $(d\pi)_q : H_q \rightarrow (E_B)_{\pi(q)}$ is bijective.

1This is what we called submersion in [GZ].
Fibrations have the unique lifting of paths property: Let \( \pi: \Gamma \to B \) be a fibration, \((p_0, p_1)\) an edge of \( B \), and \( q_0 \in \pi^{-1}(p_0) \) a point in the fiber over \( p_0 \). Since \((d\pi)_{q_0}: H_{q_0} \to (E_B)_{q_0}\) is a bijection, there exists a unique edge \((q_0, q_1)\) such that \((d\pi)_{q_0}(q_0, q_1) = (p_0, p_1)\). We will say that \((q_0, q_1)\) is the lift of \((p_0, p_1)\) at \( q_0 \). If \( \gamma \) is a path \( p_0 \to p_1 \to \cdots \to p_m \) in \( B \) and \( q_0 \in \pi^{-1}(p_0) \) is a point in the fiber over \( p_0 \), then we can lift \( \gamma \) uniquely to a path \( \tilde{\gamma}(q_0) = q_0 \to q_1 \to \cdots \to q_m \) in \( \Gamma \) starting at \( q_0 \), by successively lifting the edges of \( \gamma \).

2.3.2. Fiber Bundles. Let \( \pi: \Gamma \to B \) be a fibration of graphs. For a vertex \( p \) of \( B \), let \( V_p = \pi^{-1}(p) \subset V \) and let \( \Gamma_p \) be the induced subgraph of \( \Gamma \) with vertex set \( V_p \). For every edge \((p, q)\) of \( B \), define a map \( \Phi_{p,q}: \Gamma_p \to \Gamma_q \) as follows. For \( p' \in V_p \), define \( \Phi_{p,q}(p') = q' \), where \((p', q')\) is the lift of \((p, q)\). It is easy to see that \( \Phi_{p,q} \) is bijective, with inverse \( \Phi_{q,p} \).

We will be interested in fibrations for which \( \Phi_{p,q} \) is an isomorphism of graphs from the fiber \( \Gamma_p \) to the fiber \( \Gamma_q \).

Definition 2.8. A fibration \( \pi: \Gamma \to B \) is a fiber bundle if for every edge \((p, q)\) of \( B \), the maps \( \Phi_{p,q}: \Gamma_p \to \Gamma_q \) are morphisms of graphs.

If \( \pi: \Gamma \to B \) is a fiber bundle then \( \Phi_{p,q} \) is bijective, and both \( \Phi_{p,q}: \Gamma_p \to \Gamma_q \) and \( \Phi_{q,p}^{-1}: \Gamma_q \to \Gamma_p \) are morphisms of graphs. Therefore the maps \( \Phi_{p,q} \) are isomorphisms of graphs. The simplest example of a fiber bundle is the projection of a direct product of graphs onto one of its factors, \( \pi: \Gamma = B \times F \to B \). We will call such fiber bundles trivial bundles.

2.4. GKM Fiber Bundles. We now add the GKM package to a fibration, and define GKM fibrations. Let \( (\Gamma, \alpha) \) and \((B, \alpha_B)\) be two GKM graphs, with axial functions \( \alpha: E \to t^\ast \) and \( \alpha_B: E_B \to t^\ast \) taking values in the same linear space \( t^\ast \). Let \( \nabla \) and \( \nabla_B \) be connections on \( \Gamma \) and \( B \), compatible with \( \alpha \) and \( \alpha_B \), respectively.

Definition 2.9. A map \( \pi: (\Gamma, \alpha) \to (B, \alpha_B) \) is a \((\nabla, \nabla_B)\)-GKM fibration if it satisfies the following conditions:

1. \( \pi \) is a fibration of graphs;
2. If \( e \) is an edge of \( B \) and \( \tilde{e} \) is any lift of \( e \), then \( \alpha(\tilde{e}) = \alpha_B(e) \);
3. Along every edge \( e \) of \( \Gamma \) the connection \( \nabla \) sends horizontal edges into horizontal edges and vertical edges into vertical edges;
4. The restriction of \( \nabla \) to horizontal edges is compatible with \( \nabla_B \), in the following sense: Let \( e = (p, q) \) be an edge of \( B \) and \( \tilde{e} = (p', q') \) the lift of \( e \) at \( p' \). Let \( e' \in E_p \) and \( e'' = (\nabla_B)_{p'}(e') \in E_q \). If \( e' \) is the lift of \( e' \) at \( p' \) and \( e'' \) is the lift of \( e'' \) at \( q' \) then

\[
(\nabla)_{\tilde{e}}(e') = \tilde{e}'
\]

A map \( \pi: (\Gamma, \alpha) \to (B, \alpha_B) \) is a GKM fibration if it is a \((\nabla, \nabla_B)\)-GKM fibration for some connections \( \nabla \) and \( \nabla_B \) compatible with \( \alpha \) and \( \alpha_B \).

If \( \pi: (\Gamma, \alpha) \to (B, \alpha_B) \) is a GKM fibration, then for each \( p \in B \), the fiber \((\Gamma_p, \alpha_{\pi})\) is a GKM subgraph of \((\Gamma, \alpha)\). Let \( V_p \) be the subspace of \( t^\ast \) generated by values of axial functions \( \alpha_e \), for edges \( e \) of \( \Gamma_p \). Then the axial function on \( \Gamma_p \) can be co-restricted to \( \alpha_p \), from the oriented edges of \( \Gamma_p \) to \( V_p \), and \((\Gamma_p, \alpha_p)\) is a GKM graph.

---

This is what we called fibration in [12].
Suppose now that \( \pi \) is both a GKM fibration and a fiber bundle of graphs. Let \( e = (p, q) \) be an edge of \( B \). We say that the transition isomorphism \( \Phi_{p,q} : \Gamma_p \to \Gamma_q \) is compatible with the connection on \( \Gamma \) if for every lift \( \tilde{c} = (p_1, q_1) \) of \( e \) and for every edge \( e' = (p_1, p_2) \) of \( \Gamma_p \), the connection along \( \tilde{c} \) moves \( e' \) into the edge \( e'' = (q_1, q_2) = (\Phi_{p,q}(p_1), \Phi_{p,q}(p_2)) \) of \( \Gamma_q \).

**Definition 2.10.** A GKM fibration \( \pi : (\Gamma, \alpha) \to (B, \alpha_B) \) is a GKM fiber bundle if \( \pi \) is a fiber bundle and for every edge \( e = (p, q) \) of \( B \):

1. The transition isomorphism \( \Phi_{p,q} \) is compatible with the connection of \( \Gamma \).
2. There exists a linear isomorphism \( \Psi_{p,q} : \mathfrak{v}_p^* \to \mathfrak{v}_q^* \) such that

\[
\Upsilon_{p,q} = (\Phi_{p,q}, \Psi_{p,q}) : (\Gamma_p, \alpha_p) \to (\Gamma_q, \alpha_q)
\]

is an isomorphism of GKM graphs.

In other words, \( \pi : \Gamma \to B \) is a GKM fiber bundle if the fibers are canonically isomorphic as GKM graphs. For a GKM fiber bundle \( \pi : (\Gamma, \alpha) \to (B, \alpha_B) \) we can be more specific about the transition isomorphisms \( \Psi_{p,q} \). Let \( (p, q) \) be an edge of \( B \), let \( (p', q') \) be an edge of \( \Gamma_p \), and let \( (q', q'') \) be the corresponding edge of \( \Gamma_q \). The compatibility condition along the edge \( (p', q') \) implies that \( \alpha_{q', q''} - \alpha_{p', p''} \) is a multiple of \( \alpha_{p', q'} = \alpha_{p, q} \), hence there exists a unique constant \( c = c(\alpha_{p', q'}) \) such that

\[
\Psi_{p,q}(\alpha_{p', p''}) = \alpha_{p', p''} + c(\alpha_{p', q'}) \alpha_{p,q}.
\]

The linearity of \( \Psi_{p,q} \) implies that there exists a unique linear function \( c : \mathfrak{v}_p^* \to \mathbb{R} \) such that

\[
\Psi_{p,q}(x) = x + c(x) \alpha_{p,q}
\]

for all \( x \in \mathfrak{v}_p^* \).

For a path \( \gamma : p_0 \to p_1 \to \cdots \to p_{m-1} \to p_m \) in \( B \) from \( p_0 \) to \( p_m \), let

\[
\Upsilon_\gamma = \Upsilon_{p_{m-1}, p_m} \circ \cdots \circ \Upsilon_{p_0, p_1} : (\Gamma_{p_0}, \alpha_{p_0}) \to (\Gamma_{p_m}, \alpha_{p_m})
\]

be the GKM graph isomorphism given by the composition of the transition maps. Let \( p \in B \) be a vertex, and let \( \Omega(p) \) be the set of all loops in \( B \) that start and end at \( p \). If \( \gamma \in \Omega(p) \) is a loop based at \( p \), then \( \Upsilon_\gamma \) is an automorphism of the GKM graph \( (\Gamma_p, \alpha_p) \). The holonomy group of the fiber \( \Gamma_p \) is the group

\[
\text{Hol}_\gamma(\Gamma_p) = \{ \Upsilon_\gamma \mid \gamma \in \Omega(p) \} \subset \text{Aut}(\Gamma_p, \alpha_p).
\]

If the base \( B \) is connected, then all the fibers are isomorphic as GKM graphs. Let \( (F, \alpha_F) \) be a GKM graph isomorphic to all fibers, with \( \alpha_F : E_F \to \mathfrak{g}_F \), and, for each vertex \( p \) of \( B \), let \( \rho_p = (\varphi_p, \psi_p) : (F, \alpha_F) \to (\Gamma_p, \alpha) \) be a fixed isomorphism of GKM graphs. For every edge \( (p, p') \) of \( B \), let \( \rho_{p,p'} = (\varphi_{p,p'}, \psi_{p,p'}) : (F, \alpha_F) \to (F, \alpha_F) \) be the automorphism of \( (F, \alpha_F) \) given by

\[
\varphi_{p,p'} = \varphi_p^{-1} \circ \Phi_{p,p'} \circ \varphi_p
\]

\[
\psi_{p,p'} = \psi_p^{-1} \circ \Psi_{p,p'} \circ \psi_p.
\]

If \( \gamma \) is any path in \( B \), then the composition of the transition maps along the edges of \( \gamma \) defines an automorphism \( \rho_\gamma = (\varphi_\gamma, \psi_\gamma) \) of \( (F, \alpha_F) \). Let \( p \) be a vertex of \( B \) and

\[
\text{Hol}(F, p) = \{ \rho_\gamma \mid \gamma \in \Omega(p) \} \subset \text{Aut}(F, \alpha_F).
\]

Then \( \text{Hol}(F, p) \) is a subgroup of \( \text{Aut}(F, \alpha_F) \) and if \( p, p' \) are vertices of \( B \), then \( \text{Hol}(F, p) \) and \( \text{Hol}(F, p') \) are conjugated by \( \rho_\gamma \), where \( \gamma \) is any path in \( B \) connecting \( p \) and \( p' \).
2.5. Example. In this section we return to $\pi: \mathcal{F}(\mathbb{C}^n) \to \mathbb{C}P^{n-1}$ (as a particular case of $\mathcal{F}(\mathbb{C}^n) \to \mathcal{G}_k(\mathbb{C}^n)$). We show that the discrete version, $\pi: S_n \to K_n$, given by $\pi(u) = u(1)$, is an abstract GKM fiber bundle.

2.5.1. $\pi$ is a GKM fibration. Clearly $\pi$ is a morphism of graphs, because in $K_n$ all vertices are joined by edges. Moreover, let $u$ and $v = u(i,j)$ (with $1 \leq i < j \leq n$) be adjacent vertices in $S_n$. If $i \neq 1$, then $\pi(u) = \pi(v)$, hence the edge $u \to v$ is vertical. If $i = 1$, then $\pi(v) = u(j) \neq u(1)$, hence the edge $u \to v$ is horizontal.

Let $(d\pi)_u: H_u \to E_{\pi(u)}$ be the induced map \((2.3)\). If $\tilde{e}$ is the horizontal edge $u \to v = u(1,j)$, then $(d\pi)_u(\tilde{e}) = e$, the edge of $K_n$ joining $u(1)$ and $u(j)$. Therefore $(d\pi)_u$ is bijective, hence $\pi$ is a fibration of graphs.

The case $n = 3$ is shown in Figure 3. If $\gamma$ is the cycle $1 \to 2 \to 3 \to 1$ in $K_3$, then the lift of $\gamma$ at 123 is the path $\tilde{\gamma}: 123 \to 213 \to 312 \to 132$ in $S_3$.

In Section 4.3, we will prove in a more general case that $\pi$ is a GKM fibration. For now, we notice that it is compatible with the axial functions: if $\tilde{e}$ is the horizontal edge in $S_n$ from $u$ to $v = u(1,j)$, then $\tilde{e}$ is a lift of the edge $e$ in $K_n$ from $u(1)$ to $u(j)$, and both edges have the same label, $x_{u(1)} - x_{u(j)}$.

2.5.2. Transition isomorphisms. For each $i \in [n]$, the fiber $\Gamma_i = \pi^{-1}(i)$ consists of all permutations $u \in S_n$ for which $u(1) = i$ and is isomorphic, as a graph, with the Cayley graph $(S_{n-1}, t)$. For $1 \leq i \neq j \leq n$, the transition map $\Phi_{i,j}: \Gamma_i \to \Gamma_j$ is given by $\Phi_{i,j}(u) = (i,j)u$. Let $u$ be a vertex of $\Gamma_i$ and $u \to u' = u(a,b)$ an edge of $\Gamma_i$, hence $2 \leq a < b \leq n$. If $v = \Phi_{i,j}(u)$ and $v' = \Phi_{i,j}(u')$, then $v' = (i,j)u' = (i,j)u(a,b) = v(a,b)$, hence $v$ and $v'$ are joined by an edge in $\Gamma_j$.

This shows that $\Phi_{i,j}$'s are morphisms of graphs, and therefore $\pi$ is a fiber bundle.

The subspace generated by the values of the axial function on the edges of $\Gamma_i$ is the $(n-1)$-dimensional space

$$\mathbf{v}_i = \text{span}_\mathbb{R}\{x_r - x_s \mid 1 \leq r \neq i \neq s \leq n\}$$

and similarly for $\Gamma_j$. Let $\alpha_i$ and $\alpha_j$ be the axial functions on $\Gamma_i$ and $\Gamma_j$. Then $\alpha_i(u, u') = x_{u(a)} - x_{u(b)}$, and $\alpha_j(v, v') = x_{(i,j)u(a)} - x_{(i,j)u(b)}$. Let $\Psi_{i,j}$ be the linear automorphism of $\mathbf{v}_i$ induced by $\Psi_{i,j}(x_r) = x_{(i,j)r}$, for $1 \leq r \leq n$. Then $\Psi_{i,j}$ induces an isomorphism $\Psi_{i,j}: \mathbf{v}_i \to \mathbf{v}_j$ and

$$\alpha_j(\Phi_{i,j}(u), \Phi_{i,j}(u')) = \Psi_{i,j}(\alpha_i(u, u'))$$,
which proves that \((\Phi_{ij}, \Psi_{ij}) : (\Gamma, \alpha_i) \to (\Gamma_j, \alpha_j)\) is an isomorphism of GKM graphs. Since the fibers are canonically isomorphic as GKM graphs, the map \(\pi : S_n \to K_n\) is a GKM fiber bundle.

2.5.3. Typical fiber. For \(1 \leq i \leq n\), the fiber \((\Gamma, \alpha_i)\) is isomorphic to \(S_{n-1}\), and we construct an explicit isomorphism \(\varphi_i : S_{n-1} \to \Gamma_i\). For a permutation \(u \in S_{n-1}\), let \(\tilde{u} = u(1)u(2)\cdots u(n-1)n \in S_n\). For \(1 \leq a < b \leq n\), let \(c_{a,b}\) be the cycle \(a \to a + 1 \to \cdots \to b \to a\), and let \(c_{b,a}^{-1}\). Then the map \(\varphi_i : S_{n-1} \to \Gamma_i\),

\[
\varphi_i(u) = c_{i,n} \tilde{u} c_{n,1}
\]

is a graph isomorphism between \(S_{n-1}\) and \(\Gamma_i\). The cycle \(c_{i,n}\), operating on values, moves the value \(i\) to the last position and preserves the relative order of the values on the other positions. The cycle \(c_{n,1}\), operating on positions, moves \(i\) from the last position to the first and then shifts all the other positions to the right by one.

Let \(\psi_i\) be the linear isomorphism induced by \(\psi_i(x_k) = x_{c_{i,n}(k)}\) for all \(1 \leq k \leq n\). If \(u \in S_{n-1}\) and \(v = u(a, b)\), with \(1 \leq a < b \leq n - 1\), then

\[
\alpha_i(\varphi_i(u), \varphi_i(v)) = \psi_i(\alpha(u, v)),
\]

hence \((\varphi_i, \psi_i) : S_{n-1} \to \Gamma_i\) is an isomorphism of GKM graphs.

2.5.4. Holonomy action on the fiber. Let \(\text{Hol}(\Gamma_n)\) be the holonomy group of the fiber \(\Gamma_n\). It is generated by compositions of transition isomorphisms along loops in \(K_n\) based at \(n\). Each such nontrivial loop can be decomposed into triangles \(\gamma_{ij} : n \to i \to j \to n\), and for such a triangle we have \((j, n)(i, j)(n, i) = (i, j)\), hence the corresponding element of \(\text{Hol}(\Gamma_n)\) generated by \(\gamma_{ij}\) is

\[
\Upsilon_{\gamma_{ij}} = (\Phi_{\gamma_{ij}}, \Psi_{\gamma_{ij}}),
\]

with \(\Phi_{\gamma_{ij}}(u) = (i, j)u\) and \(\Psi_{\gamma_{ij}}(x_r) = x_{(i,j)r}\).

Since every permutation in \(S_{n-1}\) can be decomposed into transpositions, it follows that

\[
\text{Hol}(\Gamma_n) = \{ \Upsilon_w = (\Phi_w, \Psi_w) \mid w \in S_{n-1} \} \simeq S_{n-1},
\]

where, for a permutation \(w \in S_{n-1}\), \(\Phi_w : \Gamma_n \to \Gamma_n\) is given by \(\Phi_w(u) = wu\), and \(\Psi_w(x_a) = x_{w(a)}\).

Since the holonomy actions are conjugated, it follows that the holonomy group of all fibers are isomorphic to \(S_{n-1}\).

3. Cohomology of GKM Fiber Bundles

Let \(\pi : (\Gamma, \alpha) \to (B, \alpha_B)\) be a GKM fiber bundle, with typical fiber \((F, \alpha_F)\). One of the main goals of this paper is to describe how the cohomology ring of the total space \((\Gamma, \alpha)\) is determined by the cohomology rings of the base \((B, \alpha_B)\) and the fiber \((F, \alpha_F)\) and the holonomy action of the base on the fiber. We start by recalling the construction of the cohomology ring of a GKM graph.

3.1. Cohomology of GKM graphs. Let \((\Gamma, \alpha)\) be a GKM graph, with \(\Gamma = (V, E)\) a regular graph and \(\alpha : E \to t^*\) an axial function. Let \(S(t^*)\) be the symmetric algebra of \(t^*\); if \(\{x_1, \ldots, x_n\}\) is a basis of \(t^*\), then \(S(t^*) \simeq \mathbb{R}[x_1, \ldots, x_n]\).

**Definition 3.1.** A cohomology class on \((\Gamma, \alpha)\) is a map \(\omega : V \to S(t^*)\) such that for every edge \(e = (p, q)\) of \(\Gamma\), we have

\[
\omega(q) \equiv \omega(p) \pmod {\alpha_e}.
\]
The compatibility condition (3.1) means that ω(q) − ω(p) = αp f, for some element f ∈ S(t*), and is equivalent to ω(q) = ω(p) on ker(αp). If ω and τ are cohomology classes, then ω + τ and ωτ are also cohomology classes.

**Definition 3.2.** The cohomology ring of (Γ, α), denoted by Hα*(Γ), is the subring of Maps(V, S(t*)) consisting of all the cohomology classes.

Moreover, Hα*(Γ) is a graded ring, with the grading induced by S(t*). We say that ω ∈ Hα*(Γ) is a class of degree 2k if for every p ∈ V, the polynomial ω(p) ∈ Sk(t*) is homogeneous of degree k. (The fact that the class degree is twice the polynomial degree is a consequence of the convention that elements of t* have degree 2.) If Hk*(Γ) is the space of classes of degree 2k, then

\[ Hα*(Γ) = \bigoplus_{k \geq 0} H^2k_α(Γ). \]

If ω ∈ Hα*(Γ) and h ∈ S(t*), then hω ∈ Hα*(Γ), hence Hα*(Γ) is an S(t*)-module; it is in fact a graded S(t*)-module.

**Remark 3.3.** The main motivation behind these constructions is the fact that if M is a GKM manifold and Γ = ΓM is its GKM graph, then H2d(M) = 0 and H2d(M) isomorphic to H2k(Γ).

Let (Γ0, α) be a GKM subgraph of (Γ, α). If f : V → S(t*) is a cohomology class on Γ, then the restriction of f to V0 is a cohomology class on Γ0. Therefore the inclusion i : (Γ0, α) → (Γ, α) induces a ring morphism i* : Hα*(Γ) → Hα*(Γ0).

If ρ = (φ, ψ) : (Γ1, α1) → (Γ2, α2) is an isomorphism of GKM graphs, define ρ* : Maps(V2, S(t*)) → Maps(V1, S(t*)) by

\[ (ρ*(f))(p) = ψ^{-1}(f(φ(p))) \]

for p ∈ V1, where ψ−1 : S(t*) → S(t*) is the algebra isomorphism extending the linear isomorphism ψ−1 : t* → t*. Then ρ* is a ring isomorphism and (ρ*)−1 = (ρ−1)*, but, unless ψ : t* → t* is the identity, ρ* is not an isomorphism of S(t*)-modules.

### 3.2. Cohomology of GKM Fiber Bundles

Let f : V_B → S(t*) be a cohomology class on the base (B, α_B), and define the pull-back π*(f) : V_T → S(t*) by π*(f)(q) = f(π(q)). Then π*(f) is a cohomology class on (Γ, α), and π defines an injective morphism of rings π* : H_α_B*(B) → H_α*(Γ). In particular, H_α*(Γ) is an H_α_B*(B)-module.

**Definition 3.4.** A cohomology class h ∈ H_α*(Γ) is called basic if h ∈ π*(H_α_B*(B)).

Let (H_α*(Γ))bas = π*(H_α_B*(B)) ⊆ H_α*(Γ). Then (H_α*(Γ))bas is a subring of H_α*(Γ), and is isomorphic to H_α_B*(B). We will identify H_α_B*(B) and (H_α*(Γ))bas and regard H_α*(Γ) as a subring of H_α_B*(B).

The next theorem is one of the main results of this paper, and shows how the cohomology of the total space Γ is determined by the cohomology of the base B and special sets of cohomology classes with certain properties on fibers.

**Theorem 3.5.** Let π : (Γ, α) → (B, α_B) be a GKM fiber bundle, and let c_1, ..., c_m be cohomology classes on Γ such that, for every p ∈ B, the restrictions of these classes to the fiber Γ_p = π−1(p) form a basis for the cohomology of the fiber. Then, as H_α_B*(B)-modules, H_α*(Γ) is isomorphic to the free H_α_B*(B)-module on c_1, ..., c_m.
Proof. A linear combination of \( c_1, \ldots, c_m \) with coefficients in \( (H^*_\alpha(\Gamma))_{bas} \simeq H^*_\alpha(B) \) is clearly a cohomology class on \( \Gamma \). If such a combination is the zero class, then

\[
\sum_{k=1}^m \beta_k(p)c_k(p') = 0
\]

for every \( p \in B \) and \( p' \in \Gamma_p \). Since the restrictions of \( c_1, \ldots, c_m \) to \( \Gamma_p \) are independent, it follows that \( \beta_k(p) = 0 \) for every \( k = 1, \ldots, m \). This is valid for all \( p \in B \), hence the classes \( \beta_1, \ldots, \beta_m \) are zero. Therefore \( c_1, \ldots, c_m \) are independent over \( H^*_\alpha(B) \), and the free \( H^*_\alpha(B) \)-module they generate is a submodule of \( H^*_\alpha(\Gamma) \).

We prove that this submodule is the entire \( H^*_\alpha(\Gamma) \). Let \( c \in H^*_\alpha(\Gamma) \) be a cohomology class on \( \Gamma \). For \( p \in B \), the restriction of \( c \) to the fiber \( \Gamma_p \) is a cohomology class on \( \Gamma_p \). Since the restrictions of \( c_1, \ldots, c_m \) to \( \Gamma_p \) generate the cohomology of \( \Gamma_p \), there exist polynomials \( \beta_1(p), \ldots, \beta_m(p) \) in \( S(t^*) \) such that, for every \( p' \in \Gamma_p \),

\[
c(p') = \sum_{k=1}^m \beta_k(p)c_k(p').
\]

We will show that the maps \( \beta_k : B \rightarrow S(t^*) \) are in fact cohomology classes on \( B \). Let \( e = p \rightarrow q \) be an edge of \( B \), with weight \( \alpha_e = \alpha_{pq} \in t^* \). Let \( p' \in \Gamma_p \), and \( q' \in \Gamma_q \) such that \( p' \rightarrow q' \) is the lift of \( p \rightarrow q \). Then \( \alpha(p', q') = \alpha(p, q) = \alpha_e \) and

\[
c(q') - c(p') = \sum_{k=1}^m (\beta_k(q)c_k(q') - \beta_k(p)c_k(p')) = \\
= \sum_{k=1}^m (\beta_k(q) - \beta_k(p))c_k(p') + \sum_{k=1}^m \beta_k(q)(c_k(q') - c_k(p')).
\]

Since \( c, c_1, \ldots, c_m \) are classes on \( \Gamma \), the differences \( c(q') - c(p'), c_k(q') - c_k(p') \) are multiples of \( \alpha_e \), for all \( k = 1, \ldots, m \). Therefore, for all \( p' \in \Gamma_p \),

\[
\sum_{k=1}^m (\beta_k(q) - \beta_k(p))c_k(p') = \alpha_e \eta(p'),
\]

where \( \eta(p') \in S(t^*) \). We will show that \( \eta : \Gamma_p \rightarrow S(t^*) \) is a cohomology class on \( \Gamma_p \).

If \( p' \) and \( p'' \) are vertices in \( \Gamma_p \), joined by an edge \( (p', p'') \), then

\[
\sum_{k=1}^m (\beta_k(q) - \beta_k(p))(c_k(p'') - c_k(p')) = \alpha_e (\eta(p'') - \eta(p')).
\]

Each \( c_k \) is a cohomology class on \( \Gamma \), so \( c_k(p'') - c_k(p') \) is a multiple of \( \alpha(p', p'') \), for all \( k = 1, \ldots, m \). Then \( \alpha_e (\eta(p'') - \eta(p')) \) is also a multiple of \( \alpha(p', p'') \). But \( \alpha_e = \alpha(p', q') \) and \( \alpha(p', p'') \) point in different directions as vectors, so, as linear polynomials, they are relatively prime. Therefore \( \eta(p'') - \eta(p') \) must be a multiple of \( \alpha(p', p'') \). Therefore \( \eta \) is a cohomology class on \( \Gamma_p \).

The restrictions of \( c_1, \ldots, c_m \) form a basis for the cohomology ring of \( \Gamma_p \), hence there exist polynomials \( Q_1, \ldots, Q_m \in S(t^*) \) such that

\[
\eta(p') = \sum_{k=1}^m Q_k c_k(p').
\]
for all $p' \in \Gamma_p$. Then
\[ \sum_{k=1}^{m} (\beta_k(q) - \beta_k(p) - Q_k \alpha_e)c_k = 0 \]
on the fiber $\Gamma_p$. Since the classes $c_1, \ldots, c_m$ restrict to linearly independent classes on fibers, it follows that
\[ \beta_k(q) - \beta_k(p) = Q_k \alpha_e, \]
hence $\beta_k \in H^*_{\alpha_B}(B)$. Therefore every cohomology class on $\Gamma$ can be written as a linear combination of classes $c_1, \ldots, c_m$, with coefficients in $H^*_{\alpha_B}(B)$. \qed

3.3. Invariant Classes. In this section we describe a method of constructing global classes $c_1, \ldots, c_m$ with the properties required by Theorem 3.3.

Let $\pi: (\Gamma, \alpha) \to (B, \alpha_B)$ be a GKM fiber bundle, with typical fiber $(F, \alpha_F)$. Let $p$ be a fixed vertex of $B$ and let $\rho_p = (\varphi_p, \psi_p): (F, \alpha_F) \to (\Gamma_p, \alpha_p)$ be a GKM isomorphism from $F$ to the fiber above $p$. For a loop $\gamma \in \Omega(p)$, let $\rho_\gamma = (\varphi_\gamma, \psi_\gamma)$ be the GKM automorphism of $(F, \alpha_F)$ determined by $\gamma$. Let $K = \text{Hol}(F, p)$ be the holonomy subgroup of $\text{Aut}(F, \alpha_F)$ generated by all automorphisms $\rho_\gamma$, and let $f \in (H^*_{\alpha_F}(F))^K$ be a cohomology class on the fiber, invariant under all the automorphisms in $K$. Then $f_p = (\rho_p^{-1})^*[f] \in H^*_{\alpha}(\Gamma_p)$ is a class on the fiber over $p$, invariant under all the automorphisms in $\text{Hol}_x(\Gamma_p) \subset \text{Aut}(\Gamma_p, \alpha)$. For any vertex $q \in \Gamma_p$ we have $f_q(p) \in \Sigma(\nu^*_p) \subset \Sigma(t^*)$, where $\nu^*_p$ is the subspace of $t^*$ generated by the values of $\alpha$ on the edges of $\Gamma_p$.

We will extend the class $f_p$ from the fiber $\Gamma_p$ to the total space $\Gamma$. Let $p'$ be a vertex of $B$, and $\gamma$ a path in $B$ from $p' \to p$. Let $\Upsilon_{\gamma}^*: H^*_\alpha(\Gamma_p) \to H^*_\alpha(\Gamma_{p'})$ be the ring isomorphism induced by the GKM graph isomorphism $\Upsilon_{\gamma}: (\Gamma_{p'}, \alpha) \to (\Gamma_p, \alpha)$. Since $f_p$ is $\text{Hol}_x(\Gamma_p)$–invariant, it follows that if $\gamma_1$ and $\gamma_2$ are two paths in $B$ from $p'$ to $p$, then $\Upsilon_{\gamma_1}^*(f_p) = \Upsilon_{\gamma_2}^*(f_p)$. We define $f_{p'} = \Upsilon_{\gamma}^*(f_p) \in H^*_\alpha(\Gamma_{p'})$, where $\gamma$ is any path in $B$ from $p'$ to $p$. Then $f_{p'}(q') \in \Sigma(\nu^*_{p'}) \subset \Sigma(t^*)$ for every $q' \in \Gamma_{p'}$.

**Proposition 3.6.** Let $c = c_{f,p}: \nu_{\Gamma} \to \Sigma(t^*)$ be defined by $c_{\nu_q} = f_q$ for all $q \in B$. Then $c \in H^*_\alpha(\Gamma)$.

**Proof.** Since the restrictions of $c$ to fibers are classes on fibers, it suffices to show that $c$ satisfies the compatibility conditions along horizontal edges.

Let $(q_1, q_2)$ be a horizontal edge of $\Gamma$ and let $e = (p_1, p_2)$ be the corresponding edge of $B$. Then
\[ c(q_2) - c(q_1) = f_{p_2}(q_2) - f_{p_1}(q_1) = \Psi_e(f_{p_1}(q_1)) - f_{p_1}(q_1) \]
is a multiple of $\alpha_e = \alpha(q_1, q_2)$, because $\Psi_e(x) = x + c(x)\alpha_e$ on $\nu^*_{p_1}$. \qed

Note that $c$ depends not only on the class $f$ on the typical fiber $F$, but also on the point $p$ where we start realizing $f$ on $\Gamma$. The choice of $p$ is limited by the fact that $f$ has to be invariant under the subgroup $\text{Hol}(F, p)$ determined by $p$.

**Remark 3.7.** Suppose that the $\Sigma(t^*)$–module $H^*_\alpha_F(F)$ has a basis $\{f_1, \ldots, f_m\}$, consisting of $\text{Hol}(F, p)$–invariant classes, for some $p \in B$. Let $c_j = c_{f_j,p}$, for $j = 1, \ldots, m$. Then the classes $c_1, \ldots, c_m$ have the property that their restrictions to each fiber form a basis for the cohomology of the fiber.
4. Flag Manifolds as GKM Fiber Bundles

Let $G$ be a connected semisimple complex Lie group, let $P$ be a parabolic subgroup of $G$, and let $M = G/P$ be the corresponding flag manifold. Let $T$ be a maximal compact torus of $G$, acting on $M$ by left multiplication on $G$. Then $M$ is a GKM space and the equivariant cohomology ring $H^*_T(M)$ can be computed from the associated GKM graph.

The goal of this section is to briefly review flag manifolds and their GKM graphs. In the last subsection we will describe the discrete analog of the natural fiber bundle $G/P_1 \to G/P_2$, with $T \subset P_1 \subset P_2 \subset G$.

4.1. Flag Manifolds. In this subsection we review facts about semisimple Lie algebras and flag manifolds. Details and proofs can be found, for example, in [FH] or [Hu].

Let $g$ be a semisimple Lie algebra, $h \subset g$ a Cartan subalgebra, and $t \subset h$ a compact real form. Let $g = h \oplus \bigoplus_{\alpha \in \Delta} g_{\alpha}$ be the Cartan decomposition of $g$, where $\Delta \subset t^*$ is the set of roots. Let $\Delta^+ = \{\alpha_1, \ldots, \alpha_n\} \subset \Delta$ be the corresponding simple roots. The choice of $\Delta^+$ is equivalent to a choice of a Borel subalgebra $b$ of $g$, $b = h \oplus \bigoplus_{\alpha \in \Delta^+} g_{\alpha}$.

If $G$ is a connected Lie group with Lie algebra $g$ and $B$ is the Borel subgroup with Lie algebra $b$, then $M = G/B$ is the manifold of (generalized) complete flags corresponding to $G$.

For a subset $\Sigma \subset \Delta_0$ of simple roots, let $\langle \Sigma \rangle \subset \Delta^+$ be the set of positive roots that can be written as linear combinations of roots in $\Sigma$. Then $p(\Sigma) = b \oplus \bigoplus_{\alpha \in \langle \Sigma \rangle} g_{-\alpha} = h \oplus \bigoplus_{\alpha \in \langle \Sigma \rangle} (g_{\alpha} \oplus g_{-\alpha}) \oplus \bigoplus_{\alpha \in \Delta^+ \setminus \langle \Sigma \rangle} g_{\alpha}$ is a Lie subalgebra of $g$, and the corresponding Lie subgroup $P(\Sigma) \leq G$ is a parabolic subgroup of $G$. Up to conjugacy, every parabolic subgroup of $G$ is of this form. The Borel subgroup $B$ corresponds to $\Sigma = \emptyset$, and the whole group $G$ to $\Sigma = \Delta_0$. The homogeneous space $M = G/P(\Sigma)$ is the manifold of (generalized, partial) flags corresponding to $G$ and $\Sigma$.

The examples considered in Section 2.1 correspond to $G = SL(n, \mathbb{C})$.

4.2. GKM Graphs of Flag Manifolds. In this subsection we outline the construction of the GKM graph $(\Gamma, \alpha)$ for quotients of parabolic subgroups; more details are available in [GHZ].

4.2.1. Weyl groups. For flag manifolds, the construction of the GKM graph involves Weyl groups and their actions on roots, and we start with a few useful results. Let $W$ be the Weyl group of $g$, generated by reflections $s_{\alpha}: t^* \to t^*$ for $\alpha \in \Delta_0$. As a general convention, we will use Greek letters $\alpha, \beta$ for roots and axial functions (whose values are, in this case, roots, and it will be clear from the context whether $\alpha$ is a root or an axial function), and Roman letters $u, v, w$, for elements of the Weyl group $W$. Then $w\beta$ is the element of $t^*$ obtained by applying $w \in W$ to $\beta \in t^*$, and $ws_\beta$ is the element of the Weyl group obtained by multiplying $w \in W$
with the reflection \( s_\beta \in W \) corresponding to the root \( \beta \). Then \( ws_\beta = s_{w_\beta}v \), hence two elements of \( W \) that differ by a reflection to the left also differ by a reflection to the right.

For a subset \( \Sigma \subset \Delta_0 \), let \( W(\Sigma) \) be the subgroup of \( W \) generated by reflections \( s_\alpha \) corresponding to roots \( \alpha \in \Sigma \). Then, for a root \( \alpha \in \Delta \), the reflection \( s_\alpha \in W \) is in \( W(\Sigma) \) if and only if \( \alpha \in \Sigma \) ([Hu 1.14]). For subsets \( \Sigma_1 \subset \Sigma_2 \subset \Delta_0 \), let \( W_1 = W(\Sigma_1) \) and \( W_2 = W(\Sigma_2) \); then \( W_1 \leq W_2 \leq W \).

**Lemma 4.1.** The set \( \langle \Sigma_2 \rangle \setminus \langle \Sigma_1 \rangle \) is \( W_1 \)-invariant.

**Proof.** If \( \beta \in (\Sigma_2) \setminus (\Sigma_1) \), then the positive root \( \beta \) is a linear combination of simple roots in \( \Sigma_2 \), with all coefficients non-negative. Since \( \beta \) is not in \( (\Sigma_1) \), there exists at least one simple root, say \( \alpha_i \), that is not in \( \Sigma_1 \) and appears in \( \beta \) with a strictly positive coefficient. If \( \alpha \in \Sigma_1 \), then \( s_\alpha \beta = \beta - n_\beta,\alpha \alpha_i \), with \( n_\beta,\alpha \in \mathbb{Z} \). Then \( s_\alpha \beta \) and \( \beta \) have the same coefficients in front of the simple roots not in \( \Sigma_1 \). In particular, \( \alpha_i \) appears in \( s_\alpha \beta \) with a strictly positive coefficient, which proves that \( s_\alpha \beta \) is a positive root. The simple roots appearing in \( \alpha \) and \( \beta \) are all in \( \Sigma_2 \), hence \( s_\alpha \beta \in (\Sigma_2) \), and as \( \alpha \) is not in \( \Sigma_1 \), it follows that \( s_\alpha \beta \in (\Sigma_2) \setminus (\Sigma_1) \). Since \( W_1 \) is generated by the reflections \( s_\alpha \) with \( \alpha \in \Sigma_1 \), we conclude that \( (\Sigma_2) \setminus (\Sigma_1) \) is \( W_1 \)-invariant.

Let \( w \in W_2 \) and let \( w = s_{\beta_1} \cdots s_{\beta_m} \) be a decomposition of \( w \) into simple reflections, with \( \beta_i \in \Sigma_2 \) for all \( i = 1, \ldots, m \). If \( \alpha \in (\Sigma_1) \) and \( \beta \in (\Sigma_2) \setminus (\Sigma_1) \) then

\[
\begin{align*}
s_{\beta}s_\alpha &= s_\alpha s_{s_\beta} \\
\text{and } s_{\alpha \beta} &\in (\Sigma_2) \setminus (\Sigma_1).
\end{align*}
\]

We can therefore push all the reflections coming from roots in \( (\Sigma_1) \) to the left, and get \( w = us_{\beta_1} \cdots s_{\beta_k'} \) with \( u \in W_1 \) and \( \beta_1', \ldots, \beta_k' \in (\Sigma_2) \setminus (\Sigma_1) \).

We can also push all the reflections coming from roots in \( (\Sigma_1) \) to the right, and get \( w = s_{\beta''_1} \cdots s_{\beta''_k}u \) with \( u \in W_1 \) and \( \beta''_1, \ldots, \beta''_k \in (\Sigma_2) \setminus (\Sigma_1) \).

**4.2.2. Quotients of parabolic subgroups.** Let \( \Sigma_1 \subset \Sigma_2 \subset \Delta_0 \) be subsets of simple roots and \( B \leq P(\Sigma_1) := P_1 \leq P(\Sigma_2) := P_2 \leq G \) the corresponding parabolic subgroups. The compact torus \( T \) with Lie algebra \( t \) acts on \( M = P_2/P_1 \) by left multiplication on \( P_2 \), and the space \( M = P_2/P_1 \) is a GKM space. All flag manifolds are of this type, corresponding to \( \Sigma_2 = \Delta_0 \).

We describe now the GKM graph \((\Gamma, \alpha)\) associated to \( M = P_2/P_1 \). The fixed point set \( MT \) is identified with the set of right cosets

\[
W_2/W_1 = \{ vW_1 \mid v \in W_2 \} = \{ [v] \mid v \in W_2 \},
\]

where \([v] = vW_1\) is the right \( W_1 \)-coset containing \( v \in W_2 \). Vertices \([w], [v]\) are joined by an edge if and only if \([v] = [ws_\beta]\) for some \( \beta \in (\Sigma_2) \setminus (\Sigma_1) \). There are no loops, because the only reflections in \( W_1 \) are those generated by roots in \( (\Sigma_1) \). For \( w \in W_2 \) and \( \beta \in (\Sigma_2) \setminus (\Sigma_1) \), the edge \( e = ([w] \rightarrow [ws_\beta] = [s_{w_\beta}w]) \) is labeled by \( \alpha_e = \alpha([w], [ws_\beta]) = w \).

We show that the label \( \alpha_e \) is independent of the representative \( w \in W_2 \): if \([w'] = [w]\) and \([w_\beta] = [w's_\beta]\) with \( \beta, \gamma \in (\Sigma_2) \setminus (\Sigma_1) \), then there exist \( w_1, w_2 \in W_1 \) such that \( w' = w_1w \) and \( w's_\gamma = ws_\beta w_2 \). Then \( w's_\gamma = w_2w_1^{-1} \in W_1 \), which implies \( w_1\gamma = \pm \beta \). Since \( (\Sigma_2) \setminus (\Sigma_1) \) is \( W_1 \)-invariant, it follows that \( w_1\gamma = \beta \) and therefore \( w_\gamma = w_1w_1^{-1}w = w_1w_1^{-1}w = w \).

The connection along the edge \( e = ([w], [ws_\beta]) \) sends the edge \( e' = ([w], [ws_\beta]) \) to the edge \( e'' = ([ws_\beta], [ws_\beta s_{w_\beta}]) \).
Then \((\Gamma(W_2/W_1), \alpha)\) is the GKM graph of the GKM space \(M = P_2/P_1\). We will refer to it simply as \(W_2/W_1\), and it will be clear from the context when we mean the GKM graph, when just the graph, and when just the vertices.

**Example 3.** We describe the particular cases when \(P_2 = G\) or \(P_1 = B\), or both.

For \(M = G/B\) we have \(\Sigma_1 = \emptyset\), \(\Sigma_2 = \Delta_0\), \(W_1 = \{1\}\) and \(W_2 = W\), hence \(W_2/W_1 = W\). Vertices \(w, v \in W\) of the corresponding GKM graph \(\Gamma(W)\) are joined by an edge if and only if \(w^{-1}v = s_\beta\) for some \(\beta \in \Delta^+\) (or, equivalently, if \(v = ws_\beta = s_w\beta w\)), and the edge \(w \to ws_\beta = s_w\beta w\) is labeled by \(w\beta\).

For \(M = P(\Sigma)/B\), we have \(\Sigma_1 = \emptyset\), \(\Sigma_2 = \Sigma \subset \Delta_0\), \(W_2 = W(\Sigma)\), and \(W_1 = \{1\}\). The GKM graph \(\Gamma(W(\Sigma))\) is the induced subgraph of \(\Gamma(W)\) with vertex set \(W(\Sigma)\): vertices \(w, v \in W(\Sigma)\) are joined by an edge in \(\Gamma(W(\Sigma))\) if and only if they are joined by an edge in \(\Gamma(W)\). That happens if \(v = ws_\beta = s_w\beta w\) for some \(\beta \in \langle \Sigma \rangle\).

The edge \(w \to ws_\beta = s_w\beta w\) is labeled by \(w\beta\).

For \(M = G/P(\Sigma)\), we have \(\Sigma_2 = \Delta_0\) and \(\Sigma_1 = \Sigma \subset \Delta_0\). The GKM graph is a graph with vertex set \(W/W(\Sigma)\). Vertices \([w], [v] \in W/W(\Sigma)\) are joined by an edge if and only if \(w^{-1}v = s_\beta\) for some \(\beta \in \Delta^+ \setminus \langle \Sigma \rangle\); equivalently, if \(v = ws_\beta = s_w\beta w\).

The edge \(w \to ws_\beta = s_w\beta w\) is labeled by \(w\beta\).

**4.3. GKM Fiber Bundles of Flag Manifolds.** Let \(\Sigma_1 \subsetneq \Sigma_2 \subset \Delta_0\) be, as above, subsets of simple roots, and let \(W_1 = W(\Sigma_1)\) and \(W_2 = W(\Sigma_2)\) be the corresponding subgroups of \(W\). For an element \(w \in W\), let \(wW_1\) be its class in \(W/W_1\), and \(wW_2\) its class in \(W/W_2\). One has a natural map \(\pi: W/W_1 \to W/W_2\), given by \(\pi(wW_1) = wW_2\), from the vertices of \(\Gamma(W/W_1)\) to the vertices of \(\Gamma(W/W_2)\).

If \(\Sigma_2 = \Delta_0\), then the base \(W/W_2\) is just a point and the map \(\pi\) is trivial. For the rest of this section we will assume that \(\Sigma_2 \subsetneq \Delta_0\). The goal of this section is to show that \(\pi\) is a GKM fiber bundle between the corresponding GKM graphs.

**Theorem 4.2.** The projection \(\pi: W/W_1 \to W/W_2\) is a GKM fiber bundle with typical fiber \(W_2/W_1\).

**Proof.** Let \(wW_1\) be a vertex of \(W/W_1\) and let \(e = (wW_1, ws_\beta W_1)\) be an edge of \(W/W_1\), with \(\beta \in \Delta^+ \setminus \langle \Sigma_1 \rangle\). This edge is vertical if and only if \(s_\beta \in W_2\), and this happens exactly when \(\beta \in \langle \Sigma_2 \rangle\). Therefore the vertical edges at \(wW_1\) are

\[E_{wW_1}^\perp = \{ (wW_1, ws_\beta W_1) \mid \beta \in \langle \Sigma_2 \rangle \setminus \langle \Sigma_1 \rangle \},\]

and the horizontal edges are

\[H_{wW_1} = \{ (wW_1, ws_\beta W_1) \mid \beta \in \Delta^+ \setminus \langle \Sigma_2 \rangle \}.\]

If \((wW_1, ws_\beta W_1)\) is a horizontal edge, then \((wW_2, ws_\beta W_2)\) is an edge of \(W/W_2\), hence \(\pi\) is a morphism of graphs, and \((d\pi)_{wW_1}: H_{wW_1} \to E_{wW_2}\), is defined by

\[(d\pi)_{w}(wW_1, ws_\beta W_1) = (wW_2, ws_\beta W_2).\]

It is clear that \((d\pi)_{wW_1}\) is a bijection, hence \(\pi\) is a fibration of graphs.

Next we show that \(\pi\) is a GKM fibration. Let \(e = (wW_2, ws_\beta W_2)\) be an edge of \(W/W_2\), with \(\beta \in \Delta^+ \setminus \langle \Sigma_2 \rangle\). If \(vW_1\) is a vertex of \(W/W_1\) in the fiber above \(wW_2\), then \(v = uw\), for some \(u \in W_2\). Let \(\beta' = u^{-1}\beta\). By Lemma 4.11 applied to the pair \((\Delta_0, \Sigma_2)\) corresponding to \((W, W_2)\), the set \(\Delta^+ \setminus \langle \Sigma_2 \rangle\) is \(W_2\)-invariant, hence \(\beta' \in \Delta^+ \setminus \langle \Sigma_2 \rangle\). Therefore \(e' = (vW_1, vs_\beta' W_1)\) is an edge of \(W/W_1\). Since

\[\pi(vs_\beta' W_1) = vs_\beta' W_2 = wus_{u^{-1}\beta} W_2 = ws_\beta u W_2 = ws_\beta W_2,\]
it follows that \( \tilde{e} \) is the lift of \( e \) at \( vW_1 \). Moreover, if \( \alpha_1 \) and \( \alpha_2 \) are the axial functions on \( W/W_1 \) and \( W/W_2 \), respectively, then

\[
\alpha_1(vW_1, ws\beta W_1) = v\beta' = wuu^{-1}\beta = w\beta = \alpha_2(wW_2, ws\beta W_2),
\]

hence the axial functions are compatible with \( \pi \).

Let \( e = (vW_1, ws\beta W_1) \) and \( e' = (vW_1, vs\beta W_1) \) be edges of \( W/W_1 \). The connection \( \nabla_1 \) along \( e \) moves \( e' \) to \( e'' = (ws\beta W_1, vs\beta W_1) \). If \( \beta' \in \Delta^+ \setminus \{\Sigma_2\} \), then both \( e' \) and \( e'' \) are horizontal, and if \( \beta' \in \{\Sigma_2\} \), then both are vertical. Hence the connection along any edge of \( W/W_1 \) moves horizontal edges to horizontal edges and vertical edges to vertical edges. Moreover, if both \( e \) and \( e' \) are horizontal (and hence so is \( e'' \)), then the connection \( \nabla_2 \) along the projection of \( e \) moves the projection of \( e' \) to the projection of \( e'' \), which shows that the restriction of \( \nabla_1 \) to horizontal edges is compatible with \( \nabla_2 \), and we have shown that \( \pi \) is a GKM fibration.

Finally, we prove that \( \pi \) is a GKM fiber bundle. Let \( p = wW_2 \) and \( q = ws\beta W_2 \) be two adjacent vertices of \( W/W_2 \), with \( \beta \in \Delta^+ \setminus \{\Sigma_2\} \). A straightforward computation shows that the transition map \( \Phi_{p,q} : \pi^{-1}(p) \to \pi^{-1}(q) \) is given by

\[
\Phi_{p,q}(vW_1) = s_{w\beta}vW_1,
\]

and hence, if \( e' = (vW_1, vs\beta W_1) \) is an edge of \( \pi^{-1}(p) \), then

\[
e'' = (\Phi_{p,q}(vW_1),\Phi_{p,q}(vs\beta W_1)) = (s_{w\beta}vW_1, s_{w\beta}vs\beta W_1)
\]

is an edge of \( \pi^{-1}(q) \). Therefore \( \Phi_{p,q} \) is a morphism of graphs, hence an isomorphism, with inverse \( \Phi_{q,p}^{-1} = \Phi_{q,p} \). In addition, the connection \( \nabla_1 \) along the lift of \( e = (p, q) \) at \( vW_1 \) moves \( e' \) to \( e'' \). Moreover

\[
\alpha_1(e'') = s_{w\beta}v\beta' = s_{w\beta}(\alpha_1(e')),
\]

hence, if \( \Psi_{p,q} : t^* \to t^* \) is given by \( \Psi_{p,q}(x) = s_{w\beta}(x) \), then its induced restriction and co-restriction \( \Psi_{p,q} : v^*_p \to v^*_q \) is compatible with \( \Phi_{p,q} \). This proves that

\[
(\Phi_{p,q},\Psi_{p,q}) : (W/W_1)_p \to (W/W_1)_q
\]

is an isomorphism of GKM graphs, hence the fibers are canonically isomorphic, through an isomorphism compatible with the connection of \( \Gamma_1 \). We conclude that \( \pi \) is a GKM fiber bundle.

All that remains is to show that the fibers are isomorphic, as GKM graphs, to \( W_2/W_1 \). Let \( p \) be a vertex of \( W/W_2 \) and \( w \in W \) a representative for \( p \). Let \( \varphi_w : W_2/W_1 \to \pi^{-1}(p) \), \( \varphi_w(vW_1) = wvW_1 \) and \( \psi_w \) the restriction and co-restriction of \( \psi_w : t^* \to t^* \), \( \psi_w(x) = wx \). Note that \( \varphi_w \) and \( \psi_w \) depend not just on the class \( p \), but on the particular representative \( w \). If \( e = (vW_1, vs\beta W_1) \) is an edge of \( W_2/W_1 \), with \( \beta \in \{\Sigma_2\} \setminus \{\Sigma_1\} \), then \( e' = (\varphi_w(vW_1),\varphi_w(vs\beta W_1)) = (wvW_1, wvs\beta W_1) \) is an edge of the fiber, and

\[
\alpha_1(e') = wv\beta = \psi_w(\alpha(e)).
\]

It is not hard to see that \( (\varphi_w, \psi_w) : W_2/W_1 \to \pi^{-1}(p) \) is in fact an isomorphism of GKM graphs, and this concludes the proof of the theorem. \( \square \)

The example considered in Section 2.5 is the particular case of a root system of type \( A_{n-1} \), with \( \Sigma_1 = \emptyset \) and \( \Sigma_2 = \Delta_0 \setminus \{\alpha_1\} \). The fiber bundle \( \mathcal{F}_4(C) \to \mathcal{G}_r(C) \) shown in Figure 2 corresponds to the root system \( A_3 \), with \( \Delta_0 = \{\alpha_1, \alpha_2, \alpha_3\} \), \( \Sigma_1 = \emptyset \) and \( \Sigma_2 = \{\alpha_1, \alpha_3\} \).
4.4. Holonomy Subgroup. In this section we determine the holonomy subgroup of $\text{Aut}(W_2/W_1, \alpha)$ determined by loops in the base $W/W_2$.

Let $w \in W_2$, let $\Phi_w: W_2/W_1 \to W_2/W_1$, $\Phi_w(uW_1) = uwW_1$, and $\Psi_w: t^* \to t^*$, $\Psi_w(\beta) = w\beta$. Then $\Upsilon_w = (\Phi_w, \Psi_w): W_2/W_1 \to W_2/W_1$ is a GKM automorphism. Moreover, the map $\Upsilon: W_2 \to \text{Aut}(W_2/W_1, \alpha)$, $\Upsilon(w) = \Upsilon_w$ is a morphism of groups with kernel included in $W_1$. When $W_1$ is a normal subgroup of $W_2$, the kernel is $W_1$, and then the image $\Upsilon(W_2)$ is isomorphic with the quotient group $W_2/W_1$.

Proposition 4.3. The holonomy subgroup of $\text{Aut}(W_2/W_1, \alpha)$ is $\Upsilon(W_2)$.

Proof. For $v_0 \in W$ let $\pi^{-1}(v_0W_2) \subset W/W_1$ be the fiber through $v_0W_2$, identified with $W_2/W_1$ by $(\varphi_{v_0}, \psi_{v_0}): W_2/W_1 \to \pi^{-1}(v_0W_2)$.

Let $v_0W_2 \to v_1W_2 \to \cdots \to v_mW_2 \to v_mW_2 = v_0W_2$, where $v_k = v_{k-1}s_{\beta_k}$, with $\beta_k \in \Delta^+ \setminus \langle \Sigma_2 \rangle$ for $k = 1, \ldots, m$, and let $w = v_0^{-1}v_m$. Then $w = s_{\beta_1} \cdots s_{\beta_m}$, and since $\gamma$ is a loop, we have $w \in W_2$.

Let $\varphi_2: W_2/W_1 \to W_2/W_1$ be the map

$$\varphi_2 = \varphi^{-1}_{v_0} \circ \varphi_{v_0} = \varphi^{-1}_{v_0} \circ \varphi_{\epsilon, s_{\beta_1}, v_0W_1} \circ \cdots \circ \varphi_{v_0W_2, v_1W_2} \circ \varphi_{v_0W_2}.$$

Then

$$\Phi_{v_0W_2, v_1W_2} \circ \varphi_{v_0}(uW_1) = s_{v_0s_{\beta_1}}v_0uW_1 = v_0s_{\beta_1}uW_1 = \varphi_{v_0}(uW_1).$$

Continuing with the other edges of $\gamma$, we get

$$\varphi_\gamma(uW_1) = \varphi^{-1}_{v_0} \varphi_{v_m}(uW_1) = \Phi_w(uW_1),$$

hence $\varphi_\gamma = \Phi_w$. Similarly, $\psi_\gamma = \psi_w$, and hence $\rho_\gamma = \Upsilon_w$. We conclude that

$$\text{Hol}(W_2/W_1, v_0W_2) \subset \Upsilon(W_2).$$

We now show that for every $v \in W_2$, there exists a loop $\gamma$ in $W/W_2$, starting and ending at $v_0W_2$ and such that $\rho_\gamma = \Upsilon(v)$.

Let $\alpha \in \Sigma_2 \subseteq \Delta_0$. The Weyl group $W$ acts transitively on $\Delta$, hence there exists $w \in W$ such that $w\alpha \in \Delta^+ \setminus \langle \Sigma_2 \rangle$. Let $w = uv$ be a decomposition of $w$ such that $u \in W_2$ and $v = s_{\beta_1} \cdots s_{\beta_m}$ with $\beta_1, \ldots, \beta_m \in \Delta^+ \setminus \langle \Sigma_2 \rangle$. Then $u^{-1}w\alpha \in \Delta^+ \setminus \langle \Sigma_2 \rangle$, because $\Delta^+ \setminus \langle \Sigma_2 \rangle$ is $W_2$-invariant. Consider the path $\gamma$ in $W/W_2$ that starts with

$$v_0W_2 \to v_0s_{\beta_1}W_2 \to \cdots \to v_0s_{\beta_1} \cdots s_{\beta_m}W_2 = v_0v^{-1}W_2,$$

continues with

$$v_0v^{-1}W_2 \to v_0v^{-1}s_{u^{-1}w\alpha}W_2 \to v_0v^{-1}s_{u^{-1}w\alpha}s_{\beta_1}W_2 \to v_0v^{-1}s_{u^{-1}w\alpha} \cdots s_{\beta_1}s_{\beta_2}W_2,$$

and ends with

$$v_0v^{-1}s_{u^{-1}w\alpha}s_{\beta_1} \cdots s_{\beta_m}W_2 = v_0v^{-1}s_{u^{-1}w\alpha}, vW_2.$$

This path is a loop because $v_0v^{-1}s_{u^{-1}w\alpha}, v = v_0s_{\alpha_1}$ and $\alpha_1 \in \Sigma_2$, and

$$\rho_\gamma = \Upsilon_{v_0v^{-1}s_{\alpha_1}} = \Upsilon(s_1).$$

Since $W_2$ is generated by $s_1 = s_\alpha$, for $\alpha_1 \in \Sigma_2$, we conclude that

$$\text{Hol}(W_2/W_1, v_0W_2) = \Upsilon(W_2),$$

and the holonomy group of the typical fiber does not depend on the base point. □
4.5. Bases of Invariant Classes. We use the GKM graph of \( M = G/B \) to describe equivariant cohomology classes in \( H^*_T(M) \). The ring \( H^*_a(W) \) consists of the maps \( f : W \to S(t^*) \) such that
\[
f(ws\beta) - f(w) \in (w\beta)S(t^*)
\]
for every \( w \in W \) and \( \beta \in \Delta^+ \).

The Weyl group action on \( t^* \) induces an action of \( W \) on \( H^*_a(W) \), given by
\[
w \cdot f = f^w : W \to S(t^*) , \quad f^w(v) = w^{-1}f(wv) .
\]

Let \( K \) be a compact real form of \( G \) containing \( T \). Then (see, for example, [GS, Section 4.7]) the subring of \( W \)-invariant classes is
\[
H^*_a(W)^W \simeq H^*_Y(M)^W \simeq H^*_K(M) = H^*_K(G/B) = H^*_T(K/T) \simeq S(t^*),
\]
An explicit ring isomorphism from \( S(t^*) \) to \( H^*_a(W)^W \) is given by
\[
c_T : S(t^*) \to H^*_a(W)^W, \quad c_T(f)(v) = v \cdot f , \quad (4.1)
\]
for all \( f \in S(t^*) \) and \( v \in W \).

The isomorphism \( c_T \) establishes an explicit correspondence between \( S(t^*) \)-module bases of \( H^*_a(W) \) consisting of invariant classes and \( S(t^*)^W \)-module bases of \( S(t^*) \).

**Proposition 4.4.** Let \( \{ f_1, \ldots, f_N \} \) be a basis of the \( S(t^*) \)-module \( H^*_a(W) \) such that \( f_k \) is \( W \)-invariant for all \( k = 1, \ldots, N \). If \( u_k = c_k(1) \), for \( k = 1, \ldots, N \), then \( \{ u_1, \ldots, u_N \} \) is a basis of the \( S(t^*)^W \)-module \( S(t^*) \).

**Proof.** Suppose \( a_1, \ldots, a_N \) are elements of \( S(t^*)^W \) such that
\[
a_1u_1 + \cdots + a_Nu_N = 0 .
\]
Then for every \( v \in W \) we have
\[
v \cdot (a_1u_1 + \cdots + a_Nu_N) = 0 \implies a_1f_1(v) + \cdots + a_Nf_N(v) = 0
\]
and since this is valid for every \( v \in W \), we conclude that
\[
a_1f_1 + \cdots + f_Nc_N = 0 .
\]

But the classes \( f_1, \ldots, f_N \) are independent, hence \( a_1 = \cdots = a_N = 0 \). Therefore \( u_1, \ldots, u_N \) are linearly independent over \( S(t^*)^W \).

Let \( f \in S(t^*) \). Then \( c_T(f) \in H^*_a(W) \), hence there exist \( a_1, \ldots, a_N \) in \( S(t^*) \) such that
\[
c_T(f) = a_1f_1 + \cdots + a_Nf_N .
\]
Then for every \( v \in W \) we have
\[
c_T(f)(v^{-1}) = a_1f_1(v^{-1}) + \cdots + a_Nf_N(v^{-1}) \implies
\]
\[
v^{-1} \cdot f = a_1v^{-1} \cdot u_1 + \cdots + a_Nv^{-1} \cdot u_N \implies
\]
\[
f = (v \cdot a_1) u_1 + \cdots + (v \cdot a_N) u_N .
\]

Averaging over \( W \) we get
\[
f = b_1u_1 + \cdots + b_Nu_N ,
\]
where for each \( k = 1, \ldots, N \),
\[
b_k = \frac{1}{|W|} \sum_{v \in W} v \cdot a_k
\]
is an element of \( S(t^*)^W \). This proves that \( u_1, \ldots, u_N \) generate \( S(t^*) \) over \( S(t^*)^W \). \( \square \)
5. Fibrations of Classical Groups

In this section we consider the GKM bundle $W \to W/W_S$ when $S = \Delta_0 \setminus \{\alpha_1\}$, where $\Delta_0$ is the set of simple roots for a classical root system and $\alpha_1$ is one of the endpoint roots in the Dynkin diagram.

5.1. Type A. The set of simple roots of $A_n$ (for $n \geq 2$) is $\Delta_0 = \{\alpha_1, \ldots, \alpha_n\}$, where $\alpha_i = x_i - x_{i+1}$, for $i = 1, \ldots, n$. The set of positive roots is
\[
\Delta^+ = \{x_i - x_j \mid 1 \leq i < j \leq n + 1\}
\]
and $x_i - x_j = \alpha_i + \cdots + \alpha_{j-1}$. If $S = \{\alpha_2, \ldots, \alpha_n\}$, then
\[
\langle S \rangle = \{x_i - x_j \mid 2 \leq i < j \leq n + 1\},
\]
is the set of positive roots for a root system of type $A_{n-1}$, and
\[
\Delta^+ \setminus \langle S \rangle = \{\beta_j \mid \beta_j = x_i - x_j, 2 \leq j \leq n + 1\} = \{\alpha_1 + \cdots + \alpha_j \mid 1 \leq j \leq n\}.
\]
Let
\[
\omega_1 = [id] \text{ and } \omega_j = [s_{\beta_j}], \text{ for } 2 \leq j \leq n + 1.
\]
Then $W/W_S = \{\omega_1, \ldots, \omega_{n+1}\}$, and the graph structure of $W/W_S$ is that of a complete graph with $n + 1$ vertices. If $\tau: W/W_S \to \mathfrak{t}^*$ is given by $\tau(\omega_i) = x_i$ for all $i = 1, \ldots, n + 1$, then the axial function $\alpha$ on $W/W_S$ is given by
\[
\alpha(\omega_i, \omega_j) = \tau(\omega_i) - \tau(\omega_j) = x_i - x_j
\]
and $\tau \in H^1(\alpha(W/W_S))$ is a class of degree 1. Using a Vandermonde determinant argument, one can show that the classes $\{1, \tau, \ldots, \tau^n\}$ are linearly independent over $\mathbb{S}(\mathfrak{t}^*)$, and in fact form a basis of the free $\mathbb{S}(\mathfrak{t}^*)$–module $H^*_S(W/W_S)$.

The Weyl group $W$ is isomorphic with the symmetric group $S_{n+1}$, acting on roots by
\[
w \cdot (x_i - x_j) = x_{w(i)} - x_{w(j)}.
\]
The simple reflection $s_i$ acts as the transposition $(i, i+1)$, and, more generally, the reflection generated by the root $x_i - x_j$ acts as the transposition $(i, j)$. The subgroup $W_S$ is the subgroup of $W = S_{n+1}$ consisting of the permutations that fix the element 1. With the identification $W/W_S \cong K_{n+1}$, the projection $\pi: W \to W/W_S$ is the map $\pi: S_{n+1} \to K_{n+1}$, $\pi(w) = w(1)$.

**Remark 5.1.** This is essentially the example discussed in Section 2.5 and corresponds to the fiber bundle of complete flags over a projective space. The group $G$ is $SL_{n+1}(\mathbb{C})$, the Borel subgroup $B$ is the subgroup of upper triangular matrices, and the parabolic subgroup $P$ is the subgroup of $G$ consisting of block-diagonal matrices, with one block of size $1 \times 1$ and a second block of size $n \times n$. Then $G/B \cong \text{Fl}(\mathbb{C}^{n+1})$ and $G/P \cong \mathbb{C}P^n$. The projection $\pi: \text{Fl}(\mathbb{C}^{n+1}) \to \mathbb{C}P^n$ sends the flag
\[
V_\bullet: V_1 \subset V_2 \subset \cdots \subset V_n \subset \mathbb{C}^{n+1}
\]
to $\pi(V_\bullet) = V_1$. For an element $L \in \mathbb{C}P^n$, hence a one-dimensional subspace of $\mathbb{C}^{n+1}$, the fiber $\pi^{-1}(L)$ is diffeomorphic to $\text{Fl}(\mathbb{C}^{n+1}/L) \cong \mathbb{C}P^n$.

For a multi-index $I = [i_1, \ldots, i_n]$ of non-negative integers, we define
\[
x^I = x_1^{i_1}x_2^{i_2} \cdots x_n^{i_n}
\]
and let $c_I = c_T(x^I)$ be the corresponding $W$–invariant class $c_I: S_{n+1} \to \mathbb{S}(\mathfrak{t}^*)$,
\[
c_I(u) = u \cdot x^I = x_{u(1)}^{i_1} \cdots x_{u(n)}^{i_n};
\]
then $x^I = c_I(id)$, where $id$ is the identity element of the Weyl group $W = S_{n+1}$. We will construct a basis of the $S(t^*)$–module $H^*_a(W)$ consisting of classes of the type $c_I$ for specific indices $I$.

Consider the GKM fiber bundle $\pi: S_3 \to K_3$, $\pi(u) = u(1)$. The fiber $\pi^{-1}(3)$ is canonically isomorphic to $S_2$, and since $S_2 \cong K_2$, the cohomology of $S_2$ is a free $S(t^*)$–module with a basis given by the invariant classes $c_{[0]}$ and $c_{[1]}$. The invariant class $c_{[0]}$ on this fiber is extended, using transition maps between fibers to the constant class $c_{[0,0]} \equiv 1$ on the total space. The invariant class $c_{[1]}$ extends to the class $c_{[0,1]}$; the shift in index is due to the fact that the axial functions on fibers are different. The cohomology of the base $K_3$ is generated, over $S(t^*)$, by $1$, $\tau$, and $\tau^2$, and these classes lift to basic classes $c_{[0,0]}$, $c_{[1,0]}$, and $c_{[2,0]}$ on $S_3$. Theorem 3.9 implies that the cohomology of $S_3$ is a free $S(t^*)$–module, with a basis given by

\[ \{ c_I \mid I = [i_1, i_2], 0 \leq i_1 \leq 2, 0 \leq i_2 \leq 1 \} . \]

Their values on $W(A_2) = S_3$ are given in Table 1.

| $id$ | $c_{[0,0]}$ | $c_{[0,1]}$ | $c_{[1,0]}$ | $c_{[1,1]}$ | $c_{[2,0]}$ | $c_{[2,1]}$ |
|------|-------------|-------------|-------------|-------------|-------------|-------------|
| 213  | 1           | $x_1$       | $x_1 x_2$   | $x_2^2$     | $x_1 x_2^2$ |
| 312  | 1           | $x_3$       | $x_3 x_2$   | $x_2^2$     | $x_1 x_3 x_2^2$ |
| 321  | 1           | $x_2$       | $x_3 x_2$   | $x_2^2$     | $x_1 x_2 x_3^2$ |

**Table 1. Invariant classes on $W(A_2)$**

Repeating the procedure further, we get the following result.

**Theorem 5.2.** Let

\[ \mathcal{A}_n = \{ I = [i_1, \ldots, i_n] \mid 0 \leq i_1 \leq n, 0 \leq i_2 \leq n - 1, \ldots, 0 \leq i_n \leq 1 \} . \]

Then

\[ \{ c_I = c_I(x^I) \mid I \in \mathcal{A}_n \} \]

is an $S(t^*)$–module basis of $H^*_a(A_n)$, consisting of invariant classes.

By Proposition 4.4 it follows that, in type $A_n$, $\{ x^I \mid I \in \mathcal{A}_n \}$ is a basis of $S(t^*)$ as an $S(t^*)^W$–module.

**5.2. Type B.** The set of simple roots of $B_n$ (for $n \geq 2$) is $\Delta_0 = \{ \alpha_1, \ldots, \alpha_n \}$, where $\alpha_i = x_i - x_{i+1}$, for $i = 1, \ldots, n-1$ and $\alpha_n = x_n$. The set of positive roots is

\[ \Delta^+ = \{ x_i \mid 1 \leq i \leq n \} \cup \{ x_i \pm x_j \mid 1 \leq i < j \leq n \} . \]

If $S = \{ \alpha_2, \ldots, \alpha_n \}$, then

\[ (S) = \{ x_i \mid 2 \leq i \leq n \} \cup \{ x_i \pm x_j \mid 2 \leq i < j \leq n \} \]

is the set of positive roots for a root system of type $B_{n-1}$, and

\[ \Delta^+ \setminus (S) = \{ \beta_1 = x_1 \} \cup \{ \beta_j^\pm = x_1 \mp x_j \mid 2 \leq j \leq n \} . \]
Let
\[ \omega_1^+ = [id], \quad \omega_1^- = [s_{\beta_1}] \]
\[ \omega_j^+ = [s_{\beta_j}] = [s_{x_{j-x_j}}] \text{ for } 2 \leq j \leq n \]
\[ \omega_j^- = [s_{\beta_j}] = [s_{x_{j+x_j}}] \text{ for } 2 \leq j \leq n. \]

Then \( W/W_S = \{ \omega_1^+, \omega_1^-, \ldots, \omega_n^+, \omega_n^- \} \), and the graph structure of \( W/W_S \) is that of a complete graph with \( 2n \) vertices. If \( \tau \) is the map \( \tau: W/W_S \to \mathfrak{t}^*, \tau(\omega_j^+) = \epsilon x_j, \) with \( 1 \leq j \leq n \) and \( \epsilon \in \{+,-\} \), then the axial function
\[ \alpha(\omega_i^+, \omega_j^+) = \tau(\omega_i^+ - \tau(\omega_j^+)), \quad \text{for } 1 \leq i \neq j \leq n \]
\[ \alpha(\omega_i^+, \omega_j^-) = \frac{1}{2}(\tau(\omega_i^+) - \tau(\omega_j^-)) \quad \text{for } 1 \leq i \leq n. \]

Note that although \( W/W_S \) and \( K_{2n} \) are isomorphic as graphs, they are not isomorphic as GKM graphs. One way to see that is to notice that
\[ \alpha(\omega_1^+, \omega_1^-) + \alpha(\omega_1^-, \omega_2^-) + \alpha(\omega_2^-, \omega_1^+) = -x_1 \neq 0. \]

Nevertheless, as in the \( K_{2n} \) case, the set of classes \( \{1, \tau, \ldots, \tau^{2n-1}\} \) is a basis for the free \( \mathbb{S}(\mathfrak{t}^*) \)–module \( H^*_\alpha(W/W_S) \).

![Figure 4: Fibration of \( B_2 \)](image)

An alternative description of the Weyl group \( W \) is that of the group of signed permutations \( (u,\epsilon) \), with \( u \in S_n \) and \( \epsilon = (\epsilon_1, \ldots, \epsilon_n) \), \( \epsilon_j = \pm 1 \). The element \( (u,\epsilon) \) is represented as \( (\epsilon_1 u(1), \ldots, \epsilon_n u(n)) \) or by underlying the negative entries.

Then \( s_{x_i} \) is just a change of the sign of \( x_i \), \( s_{x_i-x_j} \) corresponds to the transposition \( (i,j) \), with no sign changes, and \( s_{x_i+x_j} \) corresponds to the transposition \( (i,j) \) with both signs changed. In particular, \( id \) is the identity permutation with no sign changes, \( s_{\beta_1} \) is the identity permutation with the sign of 1 changed, \( s_{\beta_1}^+ \) is the transposition \( (1,j) \) with no sign changes, and \( s_{\beta_1}^- \) is the transposition \( (1,j) \) with sign changes for 1 and \( j \). In general, if \( u \in S_n \) and \( \epsilon = (\epsilon_1, \ldots, \epsilon_n) \in \mathbb{Z}_2^n \), then the element \( w = (u,\epsilon) \in W \) acts by \((u,\epsilon) \cdot x_k = \epsilon_k x_{u(k)} \). Then \( W/W_S \) can be identified with \( \{\pm 1, \pm 2, \ldots, \pm n\} \) by \( \omega_j^+ = \epsilon_j \), and the projection \( \pi: W \to W/W_S \) is \( \pi((u,\epsilon)) = \epsilon_1 u(1). \)
For $I = [i_1, \ldots, i_n]$, let $c_I = c_T(x^I) : W \to S(t^*)$ be given by
\[
c_I((u, \epsilon)) = (\epsilon_1 x_{u(1)})^{i_1} \cdots (\epsilon_n x_{u(n)})^{i_n}.
\]
Then $c_I \in (H^*_\alpha(W))^W$ is an invariant class, and we will construct a basis of the free $\mathbb{S}(t^*)$–module $H^*_\alpha(W)$ consisting of classes of the type $c_I$, for specific indices $I$.

When $n = 2$, the fiber over 2 is $\pi^{-1}(2) = \{(2, 1), (2, -1)\}$ and is identified with $W_S = S_2 = \{1, -1\}$. A basis for $H^*_\alpha(W_S)$ is given by the invariant classes $\{c_{[0]}, c_{[1]}\}$, where $c_{[0]} = 1$ and $c_{[1]}(1) = x_1, c_{[1]}(-1) = -x_1$. These classes are extended to the invariant classes $c_{[0, 0]}$ and $c_{[0, 1]}$ on $W$.

The classes $1, \tau, \tau^2$, and $\tau^3$ on the base lift to the basic classes $c_{[0, 0]}, c_{[1, 0]}, c_{[2, 0]},$ and $c_{[3, 0]}$ on $W$. Then a basis for the free $\mathbb{S}(t^*)$–module $H^*_\alpha(W)$ is
\[
\{c_I \mid I = [i_1, i_2], \ 0 \leq i_1 \leq 3, 0 \leq i_2 \leq 1\}.
\]

The values of these classes on the elements of $W(B_2)$ are shown in Table 2.

| id | $c_{[0, 0]}$ | $c_{[0, 1]}$ | $c_{[1, 0]}$ | $c_{[1, 1]}$ | $c_{[2, 0]}$ | $c_{[2, 1]}$ | $c_{[3, 0]}$ | $c_{[3, 1]}$ |
|----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 12 | 1           | $x_2$      | $x_1$      | $x_1 x_2$  | $x_1^2$    | $x_1^2 x_2$ | $x_1^3$    | $x_1^3 x_2$ |
| 21 | $x_1$      | $x_2$      | $x_1 x_2$  | $x_1^2$    | $x_1 x_2^2$| $x_1^2 x_2$ | $x_1^3$    | $x_1^3 x_2$ |
| 22 | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    | $x_1^4 x_2$ |
| 12 | 1           | $x_2$      | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    |
| 21 | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    | $x_1^4 x_2$ |
| 22 | 1           | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    |
| 12 | 1           | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    |
| 21 | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    | $x_1^4 x_2$ |
| 22 | 1           | $-x_2$     | $-x_1 x_2$ | $x_1^2$    | $-x_1 x_2^2$| $x_1^3$    | $x_1^3 x_2$ | $x_1^4$    |
Let

\[ \omega_1^+ = [id], \quad \omega_1^- = [s_{\beta_1}] \]
\[ \omega_j^+ = [s_{\beta_j^+}] = [s_{x_{i-1}x_j}] \text{ for } 2 \leq j \leq n \]
\[ \omega_j^- = [s_{\beta_j^-}] = [s_{x_i+x_j}] \text{ for } 2 \leq j \leq n. \]

This is essentially the same as the type B case, and \( W(C_n) \simeq W(B_n) \) is the group of signed permutations of \( n \) letters. Then \( W/W_S = \{ \omega_1^+, \omega_1^-, \ldots , \omega_n^+, \omega_n^- \} \), and the graph structure of \( W/W_S \) is that of a complete graph with \( 2n \) vertices. The axial function on \( W/W_S \) is given by

\[ \alpha(\omega_i^+, \omega_j^+) = \tau(\omega_i^+) - \tau(\omega_j^+), \]

hence \( W/W_S \) is isomorphic, as a GKM graph, with a projection of the complete graph \( K_{2n} \). Then \( H^*_\alpha(W(C_n)) \simeq H^*_\alpha(W(B_n)), \) with \( B(C_n) = B(B_n) \) as a basis consisting of invariant classes.

5.4. Type D. The set of simple roots of \( D_n \) (for \( n \geq 3 \)) is \( \Delta_0 = \{ \alpha_1, \ldots , \alpha_n \} \), where \( \alpha_i = x_i - x_{i+1} \), for \( i = 1, \ldots , n-1 \) and \( \alpha_n = x_{n-1} + x_n \). The set of positive roots is

\[ \Delta^+ = \{ x_i - x_j \mid 1 \leq i < j \leq n \} \cup \{ x_i + x_j \mid 1 \leq i < j \leq n \}. \]

If \( S = \{ \alpha_2, \ldots , \alpha_n \} \), then

\[ \langle S \rangle = \{ x_i - x_j \mid 2 \leq i < j \leq n \} \cup \{ x_i + x_j \mid 2 \leq i < j \leq n \}. \]

If \( n \geq 4 \), then \( \langle S \rangle \) is the set of positive roots for a root system of type \( D_{n-1} \) and if \( n = 3 \), then \( \langle S \rangle \) is the set of positive roots of \( A_1 \times A_1 \). In both cases

\[ \Delta^+ \setminus \langle S \rangle = \{ \beta_i^+ = x_i - x_j \mid 2 \leq i < j \leq n \} \cup \{ \beta_i^- = x_i + x_j \mid 2 \leq i < j \leq n \}. \]

Let

\[ \omega_1^+ = [id], \quad \omega_1^- = [s_{\beta_1^-} - s_{\beta_1^+}] = [s_{\beta_1^+} s_{\beta_1^-}], \quad \text{for all } 2 \leq j \leq n \]
\[ \omega_i^+ = [s_{\beta_i^+}], \quad \omega_i^- = [s_{\beta_i^-}], \quad \text{for all } 2 \leq i \leq n. \]

Then \( W/W_S = \{ \omega_1^+, \omega_1^-, \ldots , \omega_n^+, \omega_n^- \} \) and the graph structure of \( W/W_S \) is that of the complete \( n \)-partite graph \( K_{2n}^0 \), with partition classes \( \{ \omega_i^+, \omega_i^- \} \) for \( 1 \leq i \leq n \).

If \( \tau: W/W_S \to \mathbb{S}(t^*) \) is given by \( \tau(\omega_i^+) = \epsilon \omega_i \), where \( \epsilon \in \{ +, - \} \), then the axial function \( \alpha \) on \( W/W_S \) is

\[ \alpha(\omega_i^+, \omega_j^+) = \tau(\omega_i^+) - \tau(\omega_j^+) = \epsilon_i \omega_i - \epsilon_j \omega_j. \]

Then \( H^*_\alpha(W/W_S) \) is a free \( \mathbb{S}(t^*) \)-module, and a Vandermonde determinant argument shows that a basis is given by \( 1, \tau, \ldots , \tau^{2n-2}, \) and \( \eta = x_1 \cdots x_n \tau^{-1} \).

An alternative description of the Weyl group \( W \) is that of the group of signed permutations \( (u, \epsilon) \) with an even number of sign changes. Then \( s_{x_i-x_j} \) corresponds to the transposition \( (i, j) \), with no sign changes, and \( s_{x_i+x_j} \) corresponds to the transposition \( (i, j) \) with both signs changed. In particular, \( id \) is the identity permutation with no sign changes, \( s_{\beta_1^+} \) is the transposition \( (1, j) \) with no sign changes, \( s_{\beta_1^-} \) is the transposition \( (1, j) \) with sign changes for \( 1 \) and \( j \), and \( s_{\beta_1^+} s_{\beta_1^-} \) is the identity permutation with the sign changes for \( 1 \) and \( j \). In general, if \( u \in S_n \) and \( \epsilon = (\epsilon_1, \ldots , \epsilon_n) \in \mathbb{Z}^n_2 \) with \( \epsilon_1 \cdots \epsilon_n = 1 \), then the element \( w = (u, \epsilon) \in W \) acts by \( (u, \epsilon) \cdot x_k = \epsilon_k x_{u(k)} \). Then \( W/W_S \) can be identified with \( \{ \pm 1, \pm 2, \ldots , \pm n \} \) by \( \omega_i^+ \mapsto \epsilon_i \), and the projection \( \pi: W \to W/W_S \) is \( \pi((u, \epsilon)) = \epsilon_1 u(1) \).
For $I = [i_1, \ldots, i_n]$, let $c_I = c_I(x^I) : W \to \mathbb{S}(t^*)$ be given by
\[ c_I((u, \epsilon)) = (\epsilon_1 x_{u(1)})^{i_1} \cdots (\epsilon_n x_{u(n)})^{i_n}. \]

Then $c_I \in (H^*_A(W))^W$ is an invariant class, and we will construct a basis of the free $\mathbb{S}(t^*)$-module $H^*_A(W)$ consisting of classes of the type $c_I$, for specific indices $I$.

When $n = 3$, the fiber $\pi^{-1}(3)$ of the GKM fiber bundle $\pi : D_3 \to K^3$ is
\[ \pi^{-1}(3) = \{(3, 1, 2), (3, 2, 1), (3, -2, -1), (3, -1, -2)\} \]
and is identified with $W_3 = S_2 \times S_2 = \{(1, 2), (2, 1), (-2, -1), (-1, -2)\}$. Then $H^*_A(W_3)$ is generated by the $W_3$-invariant classes \(\{c_I | I \in \mathcal{D}_2\}\), where
\[ \mathcal{D}_2 = \{[0, 0], [1, 0], [2, 0], [0, 1]\}. \]

The classes $1, \tau, \tau^2, \tau^3, \tau^4, \eta$ on $K^3_2$ lift to the basic classes $c_{[0, 0, 0]}, c_{[1, 0, 0]}, c_{[2, 0, 0]}, c_{[3, 0, 0]}, c_{[4, 0, 0]}$, and $c_{[0, 1, 1]}$. Then a basis for the free $\mathbb{S}(t^*)$-module $H^*_A(W)$ is
\[ \{c_I | I = [i_1, i_2, i_3] \in \mathcal{D}_3\}, \]
where $\mathcal{D}_3$ is the set of triples $[i_1, i_2, i_3] \in \mathbb{Z}_+^3$, such that $i_1 i_2 i_3 = 0$ and either $i_1 \leq 4, i_2 \leq 2, i_3 \leq 1$ or $[i_1, i_2, i_3] = [0, 1, 2]$ or $[0, 3, 1]$.

Repeating this process further, we get the following general result.

**Theorem 5.4.** Let $\mathcal{D}_n$ be a set of multi-indices defined inductively by
\[
\begin{align*}
(1) \quad & \mathcal{D}_2 = \{[0, 0], [1, 0], [2, 0], [0, 1]\}; \\
(2) \quad & [i_1, \ldots, i_n] \in \mathcal{D}_n \text{ if} \\
& \quad \cdot 0 \leq i_1 \leq 2n - 2 \text{ and } [i_2, \ldots, i_n] \in \mathcal{D}_{n-1}, \text{ or} \\
& \quad \cdot i_1 = 0 \text{ and } [i_2 - 1, \ldots, i_n - 1] \in \mathcal{D}_{n-1}.
\end{align*}
\]
Then
\[ \{c_I | I \in \mathcal{D}_n\} \]
is an $\mathbb{S}(t^*)$-module basis of $H^*_A(D_n)$ consisting of $W$-invariant classes.

By Proposition 4.3 it follows that, in type $D_n$, $\{x^I | I \in \mathcal{D}_n\}$ is a basis of $\mathbb{S}(t^*)$ as a free $\mathbb{S}(t^*)^W$-module.

**6. Symmetrization of Schubert Classes**

In Section 5, we constructed invariant classes for classical groups by iterating the GKM fiber bundle construction. In this section we present a different method of constructing invariant classes.

**6.1. Symmetrization of Classes.** Recall that the ring $H^*_A(W)$ consists of the maps $f : W \to \mathbb{S}(t^*)$ such that
\[ f(w_{\beta}) - f(w) \in (w\beta)\mathbb{S}(t^*) \]
for every $w \in W$ and $\beta \in \Delta^+$, and the holonomy action of the Weyl group $W$ is
\[ w \cdot f = f^w : W \to \mathbb{S}(t^*), \quad f^w(v) = w^{-1} f(wv). \]

For every $u \in W$, there exists a unique class $\tau_u \in H^*_A(W)$, called the equivariant Schubert class of $u$, that satisfies the following conditions:
\[
\begin{align*}
(1) \quad & \tau_u \text{ is homogeneous of degree } 2\ell(u), \text{ where } \ell(u) \text{ is the length of } u; \\
(2) \quad & \tau_u \text{ is supported on } \{v | u \preceq v\}, \text{ where } \preceq \text{ is the strong Bruhat order, and} \\
(3) \quad & \tau_u \text{ is normalized by the condition} \\
& \tau_u(u) = \prod \{\beta | \beta \in \Delta^+, u^{-1}\beta \in \Delta^-\}
\end{align*}
\]
The set \( \{ \tau_u \mid u \in W \} \) of equivariant Schubert classes is a basis of the \( \mathbb{S}(t^*) \)-module \( H^*_\alpha(W) \); however, these classes are not invariant under the action of \( W \) on \( H^*_\alpha(W) \).

For \( f \in H^*_\alpha(W) \) we define the \( W \)-invariant class \( f_{\text{sym}} : W \to \mathbb{S}(t^*) \) by

\[
f_{\text{sym}} = \frac{1}{|W|} \sum_{w \in W} f^w,
\]

where the permuted class \( f^w : W \to \mathbb{S}(t^*) \) is given by \( f^w(u) = w^{-1} \cdot f(wu), u \in W \).

For every \( w \in W \), the permuted classes \( \{ \tau^w_u \mid u \in W \} \) form a basis of the \( \mathbb{S}(t^*) \)-module \( H^*_\alpha(W) \). The main result of this section is that the \( \text{symmetrized} \) classes also form a basis of the \( H^*_\alpha(W) \), and these classes are \( W \)-invariant.

### 6.2. NilCoxeter Rings

We start by recalling a few things about nilCoxeter rings, and we use the notation introduced in Section 4.

Let \( \mathcal{H} \) be the nilCoxeter ring with generators \( \{ u_i \mid i = 1, \ldots, n \} \) satisfying \( u_i^2 = 0 \) for all \( i = 1, \ldots, n \) and the same commutation relations as \( \{ s_i \mid i = 1, \ldots, n \} \), where \( s_i = s_{\alpha_i} \) is the reflection generated by the simple root \( \alpha_i \), for \( 1 \leq i \leq n \).

If \( w = s_{i_1} \cdots s_{i_r} \) is a reduced decomposition of \( w \in W \) (hence \( \ell(w) = r \)),

\[
u_w = u_{i_1} \cdots u_{i_r}.
\]

The definition does not depend on the reduced decomposition, and

\[
u_w = \begin{cases} u_{wv} & \text{if } \ell(wv) = \ell(w) + \ell(v) \\ 0 & \text{otherwise.} \end{cases}
\]

For every \( i = 1, \ldots, n \), let \( h_i(x) = 1 + x u_i \), where \( x \) is a variable that commutes with all the generators \( u_1, \ldots, u_n \). Then \( h_i(x) \) is invertible and \( h_i(x)^{-1} = h_i(-x) \).

If \( w = s_{i_1} \cdots s_{i_r} \) is a reduced decomposition of \( w \in W \), define

\[
\mathcal{H}_w = h_i(\alpha_{i_1})h_i(s_{i_1}\alpha_{i_2}) \cdots h_i(s_{i_1} \cdots s_{i_{r-1}} \alpha_{i_r}) \in \mathcal{H} \otimes \mathbb{S}(t^*) .
\]

The definition does not depend on the reduced decomposition, and

\[
\mathcal{H}_w = \sum_{v \in W} \tau_{\nu}(w)u_v
\]

(see [B] Theorem 3, [Ku] Section 11.1)). Moreover, \( \mathcal{H}_w \) is invertible, and

\[
\mathcal{H}_w^{-1} = h_i(-s_{i_1} \cdots s_{i_{r-1}} \alpha_i) \cdots h_i(-\alpha_i) = \sum_{v \in W} (-1)^{\ell(w^{-1})} \tau_{\nu^{-1}}(w)u_v.
\]

**Lemma 6.1.** If \( w, v \in W \), then

\[
\mathcal{H}_{wv} = \mathcal{H}_w \cdot w \mathcal{H}_v.
\]

**Proof.** If \( \ell(v) = 0 \), then \( v = 1 \), \( \mathcal{H}_v = 1 \), and the formula is clearly true.

The proof is made in four steps.

**Step 1:** \( v = s_i \) and \( \ell(ws_i) = \ell(w) + 1 \). Let \( w = s_{i_1} \cdots s_{i_r} \) be a reduced decomposition of \( w \); then \( ws_i = s_{i_1} \cdots s_{i_r} s_i \) is a reduced decomposition for \( ws_i \), hence

\[
\mathcal{H}_{ws_i} = h_i(\alpha_{i_1})h_i(s_{i_1}\alpha_{i_2}) \cdots h_i(s_{i_1} \cdots s_{i_{r-1}} \alpha_i)h_i(s_{i_1} \cdots s_{i_r} \alpha_i) = \mathcal{H}_w \cdot h_i(s_{i_1}\alpha_i) = \mathcal{H}_w \cdot w \mathcal{H}_s.
\]

**Step 2:** \( \ell(wv) = \ell(w) + \ell(v) \). If \( v = s_{i_1} \cdots s_{i_r} \) is a reduced decomposition for \( v \), then \( ws_{i_1} \cdots s_{i_k} \) is a reduced decomposition for every \( k = 1, \ldots, r \), and hence
Step 1 applies in all those cases. Hence
\[ H_wv = H_{ws_1 \cdots s_{i_r - 1} s_{i_r}} = H_{ws_1 \cdots s_{i_r - 1}} \cdot w s_1 \cdots s_{i_r - 1} h_{s_i} (\alpha_{s_i}) = \]
\[ = H_{ws_1 \cdots s_{i_r - 1}} \cdot w h_{s_i} (s_{i_1} \cdots s_{i_r - 1} \alpha_{s_i}) = \]
\[ = H_w \cdot w h_{s_i} (\alpha_{s_i}) \cdots w h_{s_i} (s_{i_1} \cdots s_{i_r - 1} \alpha_{s_i}) = H_w \cdot w H_s . \]
Step 3: \( v = s_i \) and \( \ell(ws_i) = \ell(w) - 1 \). Let \( w = s_{i_1} \cdots s_{i_r} \) be a reduced decomposition of \( w \); then by the Exchange Condition, there exists an index \( k \) such that \( ws_i = w_{1} w_2 \), where \( w_1 = s_{i_1} \cdots s_{i_{k-1}} \) and \( w_2 = s_{i_{k+1}} \cdots s_{i_r} \) are reduced decompositions. Let \( j = i_k \). Then \( w = w_1 s_j w_2, s_j w_2 = w_2 s_i \), and \( \ell(w_2 s_i) = \ell(w_2) + 1 \).
Then, by the result of Step 2, we have \( H_w = H_{w_1 s_j w_2} = H_{w_1} \cdot w H_{s_j} w_2 \), hence
\[ H_w \cdot w H_{s_i} = H_{w_1} \cdot w_{1} H_{s_j} w_{2} \cdot w_{1} s_j w_{2} H_{s_i} = H_{w_1} \cdot w_{1} (H_{w_2 s_i} \cdot w_{2} s_i H_{s_i}) = \]
\[ = H_{w_1} \cdot w_{1} (H_{w_{2}} \cdot w_{2} H_{s_i} \cdot w_{2} s_i H_{s_i}) = H_{w_1} \cdot w_{1} (H_{w_{2}} \cdot w_{2} (H_{s_i} \cdot s_i H_{s_i})) . \]
But \( H_{s_i} \cdot s_i H_{s_i} = (1 + \alpha_i u_i)(1 - \alpha_i u_i) = 1 \), hence
\[ H_w \cdot w H_{s_i} = H_{w_1} \cdot w_1 H_{w_2} = H_{w_1 w_2} = H_{w s_i} . \]
At this point we have proved that the formula is true for all \( w \) and \( v = s_i \).

Step 4: For the general case we follow the same argument as for Step 2, using Step 1 or 3 to move over a simple reflection in the reduced decomposition of \( v \). □

We use Lemma 6.1 to obtain the transition matrices between a basis of permuted Schubert classes and the original basis of Schubert classes.

**Theorem 6.2.** Let \( a, b, w \in W \). Then
\[ \tau_a = \sum_{b \leq L a} \tau_{ab^{-1}} (w^{-1}) \tau_b^w , \quad (6.4) \]
\[ \tau_a^w = \sum_{b \leq L a} (-1)^{\ell(ba^{-1})} \tau_{ba^{-1}} (w^{-1}) \tau_b . \quad (6.5) \]
where \( \leq L \) is the left weak order, defined by \( v \leq L u \iff \ell(v^{-1}) = \ell(u) - \ell(v) \).

**Proof.** Let \( v \in W \). By equation (6.3) we have
\[ H_v = H_{w^{-1}} \cdot w^{-1} H_{w v} \quad (6.6) \]
which, using equation (6.1) and identifying the corresponding coefficients, yields
\[ \tau_a (v) = \sum_{\ell(t) + \ell(b) = \ell(a)} \tau_t (w^{-1}) \cdot w^{-1} \tau_b (w v) = \sum_{b \leq L a} \tau_{ab^{-1}} (w^{-1}) \tau_b^w (v) . \]

Since this is true for all \( v \in W \), we get (6.4).

From (6.6) we get
\[ w^{-1} H_{w v} = H_{w^{-1}} H_v , \]
which, using (6.1) and (6.2) and identifying the corresponding coefficients, yields
\[ \tau_a^w (v) = \sum_{\ell(t) + \ell(b) = \ell(a)} (-1)^{\ell(ba^{-1})} \tau_{ba^{-1}} (w^{-1}) \tau_b (v) = \sum_{b \leq L a} (-1)^{\ell(ba^{-1})} \tau_{ba^{-1}} (w^{-1}) \tau_b (v) . \]

Since this is true for all \( v \in W \), we get (6.5). □
If \( w \in W \) then \( B^w = \{ \tau_u^w | u \in W \} \) is a basis of \( H_\alpha^*(W) \) as an \( \mathbb{S}(t^*) \)-module. By [6.3] the transition matrix \( a^w \) between \( B^w \) and the basis \( B = \{ \tau_u | u \in W \} \) is the lower triangular (with respect to the weak left order) matrix

\[
a^w_{u,v} = \begin{cases} (-1)^{\ell(vu^{-1})} \tau_{vu^{-1}}(w^{-1}) , & \text{if } v \leq L u \\ 0 , & \text{otherwise}. \end{cases}
\]

Since \( \tau_{vu^{-1}}(w^{-1}) \in \mathbb{Z}_{\geq 0}[\alpha_1, \ldots, \alpha_n] \) is homogeneous of degree \( \ell(vu^{-1}) \), we have

\[
a^w_{u,v} \in \mathbb{Z}_{\geq 0}^{\ell(u) - \ell(v)}[-\alpha_1, \ldots, -\alpha_n].
\]

Hence the nonzero entries of \( a^w \) are homogeneous polynomials in the negative simple roots, with non-negative integer coefficients, and the diagonal entries are 1. By [6.5], the inverse of \( a^w \) is the lower triangular matrix \( b^w \) with entries

\[
b^w_{u,v} = \begin{cases} \tau_{vu^{-1}}(w^{-1}) , & \text{if } v \leq L u \\ 0 , & \text{otherwise}. \end{cases}
\]

The nonzero entries of \( b^w \) are homogeneous polynomials in the positive simple roots, with non-negative integer coefficients, and, again, the diagonal entries are 1.

6.3. Symmetrized Schubert Classes. The next result gives the decompositions of symmetrized Schubert classes in terms of Schubert classes and proves that the set \( B^{sym} = \{ \tau_u^{sym} | u \in W \} \) of symmetrized classes is a basis of \( H_\alpha^*(W) \).

**Theorem 6.3.** For every \( u \in W \), let \( \tau_u^{sym} \) be the symmetrization of \( \tau_u \). If

\[
\tau_u^{sym} = \sum_{v \in W} a_{u,v} \tau_v,
\]

is the decomposition of \( \tau_u^{sym} \) in the Schubert basis, then

1. The matrix \( (a_{u,v})_{u,v} \) is lower triangular with respect to the left weak order:

\[
a_{u,v} \neq 0 \implies v \leq L u.
\]

2. The entries on the diagonal are all 1:

\[
a_{u,u} = 1 \quad \text{for all } u \in W.
\]

3. The set \( B^{sym} = \{ \tau_u^{sym} | u \in W \} \) is a basis of the \( \mathbb{S}(t^*) \)-module \( H_\alpha^*(W) \).

**Proof.** If \( u \in W \) then

\[
\tau_u^{sym} = \frac{1}{|W|} \sum_{w \in W} \tau_u^w = \frac{1}{|W|} \sum_{w \in W} \sum_{v \leq L u} a^w_{u,v} \tau_v = \sum_{v \leq L u} \left( \frac{1}{|W|} \sum_{w \in W} a^w_{u,v} \right) \tau_v.
\]

Therefore

\[
a_{u,v} = \frac{1}{|W|} \sum_{w \in W} a^w_{u,v},
\]

hence \( (a_{u,v})_{u,v} \) is lower triangular with respect to the left weak order, with entries on the diagonal equal to 1. Such a matrix is invertible, and since \( B \) is a basis of \( H_\alpha^*(W) \), it follows that \( B^{sym} \) is also a basis. \( \square \)

**Remark 6.4.** For \( v \leq L u \) we have

\[
|W| a_{u,v} \in \mathbb{Z}_{\geq 0}^{\ell(u) - \ell(v)}[-\alpha_1, \ldots, -\alpha_n],
\]

because for all \( w \in W \), \( a^w_{u,v} \) is a homogeneous polynomial of degree \( \ell(u) - \ell(v) \) in the negative simple roots, with non-negative integer coefficients.
6.4. Decomposition of Invariant Classes. Theorem 6.3 gives the decomposition of a symmetrized Schubert class $\tau_{w}^{\text{sym}}$ in the Schubert basis $\{\tau_{w}\}_{w}$. In this section we show how a general invariant class $c_f = c_f(f) \in H^\alpha_*(W)^W$ decomposes in the Schubert basis.

For $i = 1, \ldots, n$ let $\partial_i : S(t^*) \rightarrow S(t^*)$ be the divided difference operator

$$\partial_i = \frac{E - s_i \cdot E}{\alpha_i}.$$ 

If $w = s_{i_1} s_{i_2} \cdots s_{i_m}$ is a reduced decomposition for $w \in W$, let $\epsilon(w) = (-1)^{\ell(w)}$ and

$$\partial_w = \partial_{i_1} \partial_{i_2} \cdots \partial_{i_m};$$

the notation is justified by the fact that the result of the composition depends only on $w$ and not on the reduced decomposition of $w$.

Proposition 6.5. If $f \in S(t^*)$, then

$$c_f = \sum_{w \in W} \epsilon(w) \partial_w f \tau_w.$$ 

Proof. We have to show that for every $v \in W$ we have

$$v \cdot f = \sum_{w \in W} \epsilon(w) \partial_w f \tau_w(v),$$

and we prove this by induction on the length $\ell(v)$ of $v$.

When $\ell(v) = 0$ we have $v = 1$ and the only Schubert class $\tau_w$ that has a nonzero value at $v = 1$ is the one corresponding to $w = 1$, with $\tau_1(1) = 1$. Then $\partial_w f = f$ and the formula is obviously true.

Now suppose the formula is true for all $v$ such that $\ell(v) \leq k$ and let $u \in W$ such that $\ell(u) = k + 1$. Then $u$ can be written as $u = s_i v$ for some $i = 1, \ldots, n$ and some $v \in W$ such that $\ell(v) = \ell(u) - 1 = k$. Then

$$\sum_{w \in W} \epsilon(u) \tau_w(u) = \sum_{w \in W} \epsilon(w) \tau_w(s_i v).$$

But

$$\tau_w(s_i v) = s_i \tau_w(v) + \alpha_i s_i \tau_{s_i w}(v), \quad \text{if } s_i w < w,$$

$$0 \quad \text{otherwise}.$$

This follows from $\tau_w(s_i v) = s_i \cdot \tau^w_{s_i}(v)$ and our formula for $\tau^w_{s_i}$ or from [Kn]. Hence

$$\sum_{w \in W} \epsilon(u) \partial_w f \tau_w(s_i v) = \sum_{w \in W} \epsilon(w) \partial_w f s_i \tau_w(v) + \sum_{s_i w < w} \epsilon(w) \partial_w f \alpha_i s_i \tau_{s_i w}(v).$$

However, since

$$\partial_i \partial_{s_i w} = \begin{cases} \partial_w & \text{if } s_i w < w, \\ 0 & \text{otherwise}, \end{cases}$$
we can rewrite the last sum and using $\epsilon(w) = -\epsilon(s_i w)$ we get
\[
\sum_{w \in W} (\epsilon(w) \partial_{w f}) \tau_w(s_i v) = \sum_{w \in W} (\epsilon(w) \partial_{w f}) s_i \tau_w(v) - \sum_{w \in W} (\epsilon(s_i w) \partial_{s_i w f}) \alpha_i s_i \tau_{s_i w}(v) =
\]
\[
= \sum_{w \in W} (\epsilon(w) \partial_{w f}) s_i \tau_w(v) - \sum_{w \in W} (\epsilon(w) \partial_{s_i w f}) \alpha_i \tau_{s_i w}(v) =
\]
\[
= \sum_{w \in W} (\epsilon(w) \partial_{w f}) s_i \tau_w(v) - \sum_{w \in W} (\epsilon(w)) \partial_{w f} s_i \tau_w(v) =
\]
\[
= \sum_{w \in W} \epsilon(w) s_i \tau_w(v) = s_i \sum_{w \in W} (\epsilon(w) \partial_{w f}) \tau_w(v).
\]
From the induction hypothesis the last sum is $v \cdot f$ and therefore
\[
\sum_{w \in W} (\epsilon(w) \partial_{w f}) \tau_w(u) = \sum_{w \in W} (\epsilon(w) \partial_{w f}) \tau_w(s_i v) = s_i \cdot (v \cdot f) = (s_i v) \cdot f = u \cdot f.
\]
The induction is complete and that concludes the proof. \hfill \Box

**Remark 6.6.** Comparing Proposition 6.5 with [Hi, p. 65], we see that $c_T : S(t^*) \to H^*_K(M) = H^*_\alpha(W)$ is an equivariant version of the characteristic homomorphism $c : S(t^*) \to H^*(M)$. 

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