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Following the procedure discussed in § 5, we have at once that  $G_\beta$  is all of  $SU(n)$ , so  $K_\beta = K \cong U(n-1)$ . Note  $K/C_K t_m = S^{2n-3}$ . On the other hand  $K_{2\beta} \cong SO(2)$  ( $G_{2\beta}$  is the  $SU(2)$  in the upper left corner). From the Dynkin diagram we conclude that our model for  $\Omega CP^{n-1}$  has one cell in each of the dimensions  $0, 1, 2n-2, 2n-1, 4n-4, 4n-3, \dots$  in other words, the cell series is  $(1+t)(1+t^{2n-2})^{-1}$ . (Recall that the affine Weyl group of type  $\tilde{A}_1$  is just the free product  $\mathbf{Z}/2 * \mathbf{Z}/2$ , so that the Bruhat cells are indexed by  $1, s_0, s_1 s_0, s_0 s_1 s_0, \dots$ , etc. By the above remarks,  $s_0$  receives weight one and  $s_1$  weight  $2n-3$ , hence our formula.)

## § 7. BOTT PERIODICITY

Bott's theorem, in its original form [6], is a general statement about the range in which certain maps  $K/L \xrightarrow{\phi} \Omega G/K$  are homotopy equivalences. The periodicity theorems proper are then deduced from this, taking  $G, K, L$  to be suitable classical groups. In this section we derive a version of Bott's theorem by showing that in many cases the map  $\phi$  is a homeomorphism onto a Schubert subspace of  $\Omega(G/K)$ ; then one merely counts cells. In fact, in these cases we will be able to read off the desired range directly from the Dynkin diagram of  $G/K$ .

We assume that  $G$  is simple and simply-connected. (As usual, the essential point is that  $G/K$  is simply-connected; then we can if necessary replace  $G$  by its universal cover.) Let  $\lambda: [0, 1] \rightarrow G$  be a path of the form  $\lambda(t) = \exp tX$ , where  $X$  belongs to the coweight lattice  $J_m$ . In otherwords,  $X \in t_m$  and  $\exp X$  is central in  $G$ . Then for all  $k \in K$ , the path  $\phi_\lambda \equiv \lambda k \lambda^{-1} k^{-1}$  actually lies in  $(\Omega_{alg} G)^\tau$ ; see the proof of 4.2. Hence  $\lambda \mapsto \phi_\lambda$  defines a *Bott map*  $K/C_k \xrightarrow{\phi} (\Omega_{alg} G)^\tau (\cong \Omega G/K)$ . Identifying  $J_m$  with the group of paths  $\lambda$  as above, the most interesting  $\lambda$  are obviously the fundamental coweights  $\varepsilon_i$  dual to the simple restricted roots  $\beta_i: \beta_j(\varepsilon_i) = \delta_{ij} (1 \leq i, j \leq l)$ . Among these one may single out the very convenient class of *minuscule coweights*. These are the  $\varepsilon_i$  dual to a *minuscule root*  $\beta_i$ -i.e. a simple root which occurs with coefficient one in the highest root  $\beta_0$ . The minuscule coweights are precisely the nonzero elements of the coweight lattice which are also vertices of the Cartan simplex. They exist whenever the root system is reduced and not of type  $G_2, F_4$  or  $E_8$ ; in terms of the Dynkin diagram, they correspond to nodes on the ordinary diagram which are conjugate to the special node  $-\alpha_0$  under an automorphism of the extended diagram. Thus for example in type  $A_n$  every simple root is minuscule,

whereas the number of minuscule roots in types  $B_n, C_n, D_n, E_6, E_7$  is respectively 1, 1, 3, 3, 1. Next, define the *distance*  $d(s_i, s_j)$  between two elements of  $\tilde{S}_{\mathbb{R}}$  (or nodes on the extended Dynkin diagram of  $G/K$ ) as follows. Given a path  $p$  from  $s_i$  to  $s_j$  on the extended Dynkin diagram, let  $m_p$  be the sum of the multiplicities of the vertices of the path (including  $s_i$  and  $s_j$ ). Then  $d(s_i, s_j)$  is the minimal possible value of  $m_p$  ( $p$  ranging over all paths). For example, in the split case, with  $m_{\beta} = 1$  for all simple restricted roots  $\beta$ ,  $d(s_i, s_j)$  is just the minimal number of vertices in a path linking  $s_i$  to  $s_j$ . (Arrows are ignored, and doubled or tripled edges in the diagram are counted as single edges.) We may now state our version of Bott's theorem:

(7.1) **THEOREM.** *Let  $\varepsilon_i$  be a minuscule coweight of the restricted root system  $\Sigma$ , and let  $\varphi: K/C_K\varepsilon_i \rightarrow \Omega G/K$  be the Bott map associated to  $\varepsilon_i^{-1}$ . Then  $\varphi$  is an isomorphism on homotopy groups in dimensions less than  $d(s_0, s_i) - 1$ , and is an epimorphism in dimension  $d(s_0, s_i) - 1$ .*

(7.2) **COROLLARY** (Bott Periodicity). *There exist Bott maps of the following form, which are isomorphisms on homotopy through the indicated range of dimensions:*

- (a)  $G_{2n, 2}^{\mathbf{C}} \rightarrow \Omega SU(2n)$   $(2n)$
- (b)  $SO(4n)/U(2n) \rightarrow \Omega_0 SO(4n)$   $(4n-4)$
- (c)  $U(2n)/Sp(n) \rightarrow \Omega SO(4n)/U(2n)$   $(4n-4)$
- (d)  $G_{2n, n}^{\mathbf{H}} \rightarrow \Omega SU(4n)/Sp(2n)$   $(4n+2)$
- (e)  $Sp(n)/U(n) \rightarrow \Omega Sp(n)$   $(2n)$
- (f)  $U(n)/O(n) \rightarrow \Omega Sp(n)/SU(n)$   $(n)$
- (g)  $G_{2n, n}^{\mathbf{R}} \rightarrow \Omega SU(2n)/SO(2n)$   $(n-1)$

*Proof of Corollary.* We need only exhibit minuscule coweights  $\varepsilon_i$  such that  $d(s_0, s_i) - 2$  is the number indicated and  $K/C_K\varepsilon_i$  is as shown. We will do this for (c) and (d) and leave the rest of the fun to the reader (see § 6). In case (d), we have seen that  $\Sigma$  has type  $A_{4n-1}$  and hence every simple root is minuscule; we also know the multiplicities all equal four. Taking  $\varepsilon_i = \varepsilon_n$ , we obviously have  $d(s_0, s_n) = 4n + 4$ . In case (c),  $\Sigma$  has type  $C_{2n}$ ; there is one minuscule root  $\alpha_{2n}$ . From (6.2) we compute  $d(s_0, s_{2n}) = 4n - 2$ .  $\square$

*Proof of (7.1).* The proof is an easy generalization of that of Propositions 2.2 and 2.6 in [25] (note, however, that  $d(s_i, s_j)$  is defined somewhat

differently there). Therefore it will only be sketched. First of all, consider the set of restricted roots  $\beta$  such that  $\beta(\varepsilon) = 0$ . This set is spanned by the set  $I$  of simple roots it contains, and if  $I'$  is the corresponding set in  $S$  (as usual),  $C_K\varepsilon = (C_G\varepsilon)^\sigma = K_I$ . Since  $K_I$  is a maximal compact subgroup of the parabolic  $\mathcal{O}_I((=P_{I'})^\sigma)$ , the Iwasawa decomposition  $\mathcal{O}_I = K_I Q$  shows that  $K/C_K\varepsilon = G_{\mathbf{R}}/\mathcal{O}_I$ . Since  $(\Omega_{alg})^\tau = \tilde{G}_{\mathbf{R}}/P^\tau$ , the Bott map can be thought of as a map  $G_{\mathbf{R}}/\mathcal{O}_I \rightarrow \tilde{G}_{\mathbf{R}}/P^\tau$ . To describe this map in terms of Bruhat cells we need to alter it slightly. First, let  $y_i = \varepsilon_i w$ , where  $w = w_{[i]} w_0 \in W_{\mathbf{R}}$ . Here  $W_{[i]}$  denotes the maximal length element of  $W_{[i]}$ , where  $[i] = S_{\mathbf{R}} - \{i\}$ . (This definition is due to Iwahori and Matsumoto [16], among other things it provides a splitting of the projection  $\tilde{W} \rightarrow \tilde{W}/\tilde{W}$ .) Then the map  $\varphi': K/C_K\varepsilon \rightarrow (L_{alg}G)^\tau/K = (\Omega_{alg}G)^\tau$  given by  $k \mapsto \mu_i^{-1} k \mu_i$  is homotopic to  $\varphi$ , since  $\varphi' = w^{-1} \varphi$  and  $K$  is connected. Hence in the proof we may replace  $\varphi$  by  $\varphi'$ . The point of this is:

(7.3) LEMMA.

- (a) The map  $\Theta: f \mapsto \mu_i^{-1} f \mu_i$  defines an automorphism of  $\tilde{G}_{\mathbf{C}}$  preserving  $\tilde{G}_{\mathbf{R}}$ .
- (b)  $\Theta: \tilde{G}_{\mathbf{R}} \rightarrow \tilde{G}_{\mathbf{R}}$  preserves  $\tilde{Q}$ , and in fact permutes the simple roots (defining an automorphism of the extended Dynkin diagram). In particular  $\mu_i \cdot (1, \beta_0) = (0, -\beta_i)$ .
- (c)  $\Theta|_{G_{\mathbf{R}}}$  induces an embedding  $G_{\mathbf{R}}/\mathcal{O}_I \rightarrow \tilde{G}_{\mathbf{R}}/P^\tau$ , which corresponds to  $\varphi'$  and is a homeomorphism onto a Schubert subspace.

*Remarks.* In (a) we have identified  $\tilde{G}_{\mathbf{C}}$  with the group of paths:  $[0, 1] \rightarrow G_{\mathbf{C}}$  of the form  $f(e^{2\pi it})$ , where  $f: S^1 \rightarrow G_{\mathbf{C}}$  is algebraic. In (b), the automorphism of the Dynkin diagram preserves multiplicities.

It remains to show that every cell not in the image of  $\varphi'$  has dimension at least  $d(s_0, s_j)$ . Now  $\Theta$  preserves the simple reflections  $\tilde{S}_{G/K}$ , with  $\Theta(s_i) = s_0$ , and clearly the cells which are in the image of  $\varphi'$  are precisely the  $E_w$  such that  $w \in W^{S_{\mathbf{R}}}$  and  $\Theta(s_0)$  does not occur in a reduced expression for  $w$ . Since every such expression must begin on the right with  $s_0$ , a moment's reflection should convince the reader that the minimal dimension of a cell involving  $\Theta(s_0)$  is  $d(s_0, \Theta(s_0))$ . Since

$$d(s_0, \Theta(s_0)) = d(\Theta^{-1}(s_0), s_0) = d(s_0, s_i),$$

this completes the proof. □