DETERMINATION
OF $H^*(BO(k, \cdots, \infty), \mathbb{Z}_2)$ AND $H^*(BU(k, \cdots, \infty), \mathbb{Z}_2)$

BY
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Introduction. For any space $X$, we denote by $X(k, \cdots, \infty)$ the total space of
the $(k-1)$-connective fibering over $X$ (Hu [4]). This gives fiberings

$$X(k, \cdots, \infty) \to X(k-1, \cdots, \infty) \to K(n_{k-1}, \mathbb{Z}_2)$$

and

$$K(n_{k-1}, \mathbb{Z}_2) \to X(k, \cdots, \infty) \to X(k-1, \cdots, \infty).$$

The purpose of this paper is to calculate the cohomology with coefficients in
$\mathbb{Z}_2$ ($\mathbb{Z}_2$ will be used for all coefficients) for the spaces obtained in this way from
the universal base spaces of the infinite orthogonal and unitary groups, $BO$ and
$BU$, respectively. For $BU$, Adams [1] determined these groups in the stable range.

We shall show that if $k = 0, 1, 2, 4$ (modulo 8), then

$$H^*(BO(k, \cdots, \infty)) \cong H^*(K(n_k, BO(k))/I(Q_k) \otimes \mathbb{Z}_2 \langle L(i) \rangle > \phi(0, k)$$

where

$$Q_k = \begin{cases} S_2^2 & \text{if } k \equiv 0, 1 \pmod{8}, \\
S_3^3 & \text{if } k \equiv 2 \pmod{8}, \\
S_5^5 & \text{if } k \equiv 4 \pmod{8}, \\
\end{cases}$$

$I(Q_k)$ denotes the ideal generated by $Q_k$, $\phi(0, k)$ denotes the number of integers
$s$ such that $0 < s \leq k$ and $s \equiv 0, 1, 2, 4$ (modulo 8), $L(i)$ is one more than
the number of ones in the dyadic expansion of $i - 1$, and $\theta_i$ are classes in $H^*(BO)$
congruent to $w_i$ modulo decomposable elements. Similarly, we shall show that

$$H^*(BU(2p, \cdots, \infty)) \cong H^*(K(Z, 2p))/I(S_2^3) \otimes \mathbb{Z}_2 \langle L(2i) > p + 1 \rangle.$$

The proofs of these results and this paper can be outlined as follows. In §1
we construct a new system of generators, the $\theta_i$, for $H^*(BO)$ and $H^*(BU)$ which
are closely related to the action of the Steenrod algebras on these groups. In
§2, we make a partial determination of the groups $H^*(K(n_n))/I$ which were
mentioned above. These determinations are made by first analyzing the stable

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case in the Steenrod algebra and then reducing to the unstable case. In §3, we compute the spectral sequences of the fibrations given above, making use of the partially determined groups $H^*(K(n,n))/I$, to calculate the desired groups $H^*(X(k, \cdots, \infty))$ inductively. Finally in §4, we apply our calculations to obtain some results in cobordism theory. More specifically, we show that a $k$-parallelizable differentiable manifold of dimension less than $2^{k+1}$ is cobordic to zero in the unoriented sense. If in addition, the manifold is assumed to be weakly complex, this dimension can be raised to $2^{[k/2]+2}$.

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1. $H^*(BO)$ and $H^*(BU)$. As is well known (Milnor [5]), the cohomology of $BO$ is a polynomial algebra over $\mathbb{Z}_2$ with generators $w_i \in H^i(BO)$, $i \geq 0$, $w_0 = 1$, and the action of the Steenrod algebra is given by the formulae of Wu [7],

$$Sq^j w_i = \sum_{t=0}^{i} \left( j - i - 1 + \left[ \frac{t}{2} \right] \right) w_{i-t} w_{j+t}$$

for $i < j$. Further, the cohomology of $BU$ is the quotient of that of $BO$ by the ideal generated by all odd dimensional elements. Thus $H^*(BU)$ is the $\mathbb{Z}_2$ polynomial algebra on the classes $w_{2i}$.

Definition. An admissible sequence

$$1 = k_q, \cdots, k_{q-1}, k_{q-2}, \cdots, 1$$

with $k_i > 2^{i-1} + 1 k_{i-1}$, will be called a $\Theta^m$-sequence if

(a) $I$ is empty, or
(b) there exist integers $0 \leq r_q < \cdots < r_1 < m$ such that

$$k_1 = 2^m - 2^{r_1},$$
$$k_i = 2^{r_{i-1}} - 2^{r_i} + 2^{i-1} + k_{i-1}.$$

The excess of a $\Theta^m$-sequence of type (b) is $2^m - 2^m < 2^m$.

Definition. For any integer $j$, define $L(j)$ to be one plus the number of one's in the dyadic expansion of $j - 1$. ($L(0) = \infty$).

For each integer $j$ such that $L(j + 2^m) = m + 1$, there is a unique $\Theta^m$-sequence of degree $j$. In fact, if

$$i - 1 = 2^{p_1} + \cdots + 2^{p_{r_1}+r_1} + 2^{p_2} + \cdots + 2^{p_{r_2}+r_2},$$

with $q + \sum_i r_i = m$, $p_i > p_{i-1} + r_{i-1} + 1$, let
If $p_1 > 0$,
\[
i_1 = \begin{cases} \frac{i - 1}{2} & \text{if } p_1 > 0, \\ 2^{p_2-1} + \cdots + 2^{p_1+r_2-1} + \cdots + 2^{p_1-1} + \cdots + 2^{p_1+r_1-1} & \text{if } p_1 = 0. \end{cases}
\]

$i - i_1 - 1$ also has $m$ one's in its dyadic expansion, and iteration of this process gives a $\Theta^m$-sequence $(i_1, \ldots, i_r)$ of degree $i - 2m$.

**Definition.** For each integer $i$, if $L(i) = m + 1$, let $I_i$ denote the unique $\Theta^m$-sequence of degree $i - 2m$, and set $\theta_i = S_{\theta_1}^i w_2^m \in H^*(BO)$. (Let $\theta_0 = 1$.)

**Proposition.** $\theta_i \equiv w_i$ modulo decomposable elements.

**Proof.** By the Wu formulae,
\[
S_{\theta_i}^j w_j \equiv \binom{j - 1}{i} w_{i+j},
\]
so if $I = (i_1, \ldots, i_r)$,
\[
S_{\theta_I}^j w_{2m} \equiv \binom{2^m + i_2 + \cdots + i_r - 1}{i_1} \cdots \binom{2^m + i_r - 1}{i_{r-1}} \binom{2^m - 1}{i_r} w_{2m + \deg I}.
\]

If $I$ is a $\Theta^m$-sequence, it is immediate that all of these binomial coefficients are 1 (modulo 2).

**Corollary.** $H^*(BO)$ is the $\mathbb{Z}_2$ polynomial algebra on the classes $\theta_i$, and $H^*(BU)$ is the $\mathbb{Z}_2$ polynomial algebra on the classes $\Theta_i$ (or really, their images).

**Theorem.** (a) The polynomial ideal in $H^*(BO)$ generated by $\theta_i$ such that $L(i) \leq p + 1$ is an ideal under the action of the Steenrod algebra.

(b) $H^*(K(\mathbb{Z}_2,2p))/I(Sq^1_{12p}, \ldots, Sq^{2^{p-2}}_{12p})$ is isomorphic to the $\mathbb{Z}_2$ polynomial algebra on the $Sq^i_{12p}$ with $I$ a $\Theta^p$-sequence.

**Proof.** We shall induct on $p$. For $p = 0$, (b) says simply that $H^*(K(\mathbb{Z}_2,1))$ is the $\mathbb{Z}_2$ polynomial algebra on $i_1$. For $p = 0$, $L(i) \leq 1$ implies $i = 1$. Then $\theta_1 = w_1$, and the polynomial ideal generated by $w_1$ is all $\alpha \cdot w_1$. Since $Sq^i(\alpha \cdot w_1) = (Sq^i \alpha + Sq^{i-1} \alpha \cdot w_1) \cdot w_1$, this ideal is closed under the Steenrod algebra.

Now suppose (a) and (b) are true if $p < m$. If the $Sq^i_{12m}$ with $I$ a $\Theta^m$-sequence generate $H^*(K(\mathbb{Z}_2,2m))/I(Sq^1_{12m}, \ldots, Sq^{2^{m-2}}_{12m})$, (a) and (b) hold for $p = m$.

More precisely, let $f : BO \to K(\mathbb{Z}_2,2^m)$ with $f^*(i_{2m}) = w_{2m}$. Then
\[
H^*(K(\mathbb{Z}_2,2^m)) \xrightarrow{f^*} H^*(BO) \xrightarrow{I(\theta_1)_{L(i) \leq m}} B = \mathbb{Z}_2[\theta_1, L(i) \geq m + 1],
\]

is by (a)$_{m-1}$ a homomorphism over the Steenrod algebra. Since $B \cong Z_2[\theta_1, L(i) \geq m + 1]$. 
B has no elements of dimension \( n \) with \( 2^m + 2^{m-1} > n > 2^m \), so this induces

\[
A = H^*(K(Z_2,2^m)) I(Sq^{1,i_2m},\cdots,Sq^{2^m-i_2m}) \xrightarrow{g} B.
\]

Since \( A \) is generated by the \( \Theta^m \)-sequences, the image of \( g \) is contained in \( Z_2[\theta_i | L(i) = m+1] \). Further, there is one \( \theta_i \) for each generator, so \( \theta_i \xrightarrow{h} Sq^{i,i_2m} \) gives

\[
Z_2[\theta_i | L(i) = m+1] \xrightarrow{h} A \xrightarrow{g} Z_2[\theta_i | L(i) = m+1].
\]

with \( h \) epic and \( g \circ h \) an isomorphism. Thus \( h \) and \( g \) are isomorphisms. Since \( h \) is an isomorphism, \( (b)_m \) is true. Since \( g \) is an epimorphism, the polynomial ideal generated by \( \{ \theta_i | L(i) = m+1 \} \) is an ideal over the Steenrod algebra in \( B \), so its inverse image, the polynomial ideal generated by \( \{ \theta_i | L(i) \leq m+1 \} \) in \( H^*(BO) \), is an ideal over the Steenrod algebra.

Thus it suffices to show \( A \) is generated by all \( Sq^{i,i_2m} \), with \( i \) a \( \Theta^m \)-sequence. Let \( C = H^*(K(Z_2,2^m)) \), \( K = I(Sq^{1,i_2m},\cdots,Sq^{2^m-i_2m}) \). Since \( C \) is generated by all \( Sq^{i,i_2m} \) with \( i \) admissible and the excess of \( i = e(I) \) less than \( 2^m \), it suffices to show that if \( i \) is admissible, \( e(I) < 2^m \), and \( i \) is not a \( \Theta^m \)-sequence, then \( Sq^{i,i_2m} \in K \). If \( I = (i_1,\cdots,i_r) \), \( r \) will be called the length of \( I \), and we shall prove this by induction on the length of \( I \).

If length \( I = 0 \), \( I \) is the empty sequence, which is a \( \Theta^m \)-sequence.

If length \( I = 1 \), \( I = (i) \) has excess less than \( 2^m \) only if \( i < 2^m \). If \( I \) is not a \( \Theta^m \)-sequence, \( i \neq 2^m - 2^a, n < m \). If \( i < 2^m-2^a \), then \( Sq^{i,i_2m} \in K \) since the \( Sq^{2^a} \) generate the Steenrod algebra. Thus \( i = 2^m - 1 + \cdots + 2^m - p + b \), with \( 0 < b < 2^{m-p-1} \).

The Adem relations [3] give

\[
Sq^{2^m-2+\cdots+2^m-p-1+b} = \sum_{t=0}^{2^m-3+\cdots+2^m-p-2} \left( 2^{m-2} + \cdots + 2^{m-p-1} + b - 1 - t \right) Sq^{i-1} Sq^t.
\]

\[
b - 1 < 2^{m-p-1} - 1 = 1 + \cdots + 2^{m-p-2}, \text{ so } \left( 2^{m-2} + \cdots + 2^{m-p-1} + b - 1 \right) \equiv 1 \pmod{2},
\]

and

\[
Sq^{i,i_2m} = Sq^{2^m-2+\cdots+2^m-p-1+b} Sq^{2^m-2+\cdots+2^m-p-1+b} + \sum Sq^{i-1} Sq^t \in_2m,
\]

the sum being over some \( t \) with \( 1 \leq t \leq 2^m-3+\cdots+2^m-p-2 \) and \( 2^m-2+\cdots+2^m-p-1+b < 2^{m-1} \). Thus \( Sq^{i,i_2m} \in K \) for all such \( t \), and \( 2^m-2+\cdots+2^m-p-1+b < 2^{m-1} \), so

\[
Sq^{2^m-2+\cdots+2^m-p-1+b} \in K.
\]

Hence \( Sq^{i,i_2m} \in K \).
Thus inductively, if $I$ is admissible, $e(I) < 2^m$, length $I \leq p$ ($p \geq 1$) and $I$ is not a $Θ^m$-sequence, then $Sq^I i_{2m} \in K$.

Now let $I = (i_1, \cdots, i_{p+1})$ be admissible, $e(I) < 2^m$, $I$ not a $Θ^m$-sequence. Let $J = (i_2, \cdots, i_{p+1})$, $J = (i_3, \cdots, i_{p+1})$. $J$ is admissible, $e(J) < 2^m$, and $J$ has length $p$, so if $J$ is not a $Θ^m$-sequence, $Sq^I i_{2m} = Sq^J Sq^J i_{2m} \in K$. Thus we may assume $J$ is a $Θ^m$-sequence.

Let $i = \text{dim}(Sq^I i_{2m})$. Then $i - 1 = 2^{p_1} + \cdots + 2^{p_1+r_1} + \cdots + 2^{p_q} + \cdots + 2^{p_q+r_q}$, $p_1 > p_{i-1} + r_{i-1} + 1$, $q + \sum r_i = m$.

If $p_1 > 0$, $i_2 = (i-1)/2$. Since $I$ is not a $Θ^m$-sequence and is admissible, $i_1 > 2i_2 = i - 1$, and $e(I) = 2i_1 - \text{deg}I = 2i_1 - (i_1 + i - 2m) = 2^m + i_1 - i < 2^m$ implies $i_1 < i$. This is impossible, so $p_1 = 0$.

Thus $i - 1 = 1 + \cdots + 2^{p_1} + 2^{p_2} + \cdots + 1 + \cdots + 2^{r_1} + i_2$, and by the above $2i_2 < i_1 < i$. Let $i_1 = 2i_2 + a$, $a = 2^{s_1} + \cdots + 2^{s_q}$, $0 \leq s_1 < \cdots < s_q \leq r_1$. Since $I$ is not a $Θ^m$-sequence, $s_q < r_1$ or $a = 2^{s_1} + \cdots + 2^{s_q} + 2^{r_1-s} + \cdots + 2^{r_1}$, $r_1 - s > s_q + 1$, $s_1 < \cdots < s_q$.

Consider $Sq^{2i_2} Sq^{i_2+a} Sq^J i_{2m}$. $Q = (i_2 + a, i_3, \cdots, i_{p+1})$ is admissible, has length $p$, and

$$
\begin{align*}
e(Q) &= 2(i_2 + a) - (i_2 + a + i_3 + \cdots + i_{p+1}) \\
&= 2i_2 - (i_2 + \cdots + i_{p+1}) + a \\
&= e(J) + a,
\end{align*}
$$

$$
\begin{align*}
e(I) &= 2i_1 - (i_1 + \cdots + i_{p+1}) \\
&= i_1 - (i_2 + \cdots + i_{p+1}) \\
&= 2i_2 + a - (i_2 + \cdots + i_{p+1}) \\
&= e(J) + a,
\end{align*}
$$

so $e(Q) < 2^m$. $Q$ is not a $Θ^m$-sequence, for

1. if $i_2 = 2i_3 + 2^p - 2^{r_1+1} = 2i_3 + 2^p - 1 + \cdots + 2^{r_1+1}$

\[i_2 + a = 2i_3 + 2^{p-1} + \cdots + 2^{r_1+1} + 2^{r_1+1} + \cdots + 2^{r_1-s} + 2^s + \cdots + 2^s\]  

or

\[= 2i_3 + 2^{p-1} + \cdots + 2^{r_1+1} + 2^s + \cdots + 2^s\]  

if $s_q < r_1$,

and so in either case there is a gap in the sum of powers of two.

2. If $i_2 = 2i_3$, then $i_2 + a \neq 2i_3$, $2i_3 + 2^{r_1+1} - 2^q$.

Thus $Sq^{2i_2} Sq^{i_2+a} Sq^J i_{2m} \in K$.

Now $2i_2 < 2(i_2 + a)$, so the Adem relations give

$$
\sum_{t=0}^{i_2} \left( \frac{i_2 + a - t - 1}{2i_2 - 2t} \right) Sq^{3i_2+a-t} Sq^I i_{2m} \in K
$$

or, since
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unless $i_2 + a - t - 1 \geq 2i_2 - 2t$, $t \geq i_2 - a + 1$ and

$$\begin{pmatrix} i_2 + a - t - 1 \\ 2i_2 - 2t \end{pmatrix} = \begin{pmatrix} a - 1 \\ 0 \end{pmatrix} = 1,$$

$$Sq^i i_{2m} = Sq^{2i_1 + a} Sq^{i_1} Sq^i i_2,$$

$$= \sum_{t = i_2 - a + 1}^{i_2 - 1} \begin{pmatrix} i_2 + a - t - 1 \\ 2i_2 - 2t \end{pmatrix} Sq^{3i_1 + a - t} Sq^{a} Sq^i i_{2m} \pmod{K}.$$ 

Now consider $(t,J) = (i, j_3, \cdots, j_{p+1})$. Let $t = i_2 - z$, $1 \leq z \leq a - 1$. Then $(t,J) = \sum J_a$, with $J_a$ admissible. By the Adem relations, length of $J_a \leq$ length of $(t,J) = p$. If $e(J_a) > 2^m$, $Sq^i i_{2m} = 0$. If $e(J_a) = 2^m$, $Sq^i i_{2m} = (Sq^{L_a i_{2m}})^{2^k}$, where $L_a$ is admissible, length $L_a <$ length $J_a$, and $e(L_a) < 2^m$. Thus $Sq^i Sq^i i_{2m} = \sum Sq^i i_{2m} + \sum (Sq^i i_{2m})^{2^k}$ (modulo $K$), where $J_p, J_\beta$ are $\Theta^m$-sequences.

Now $\dim(Sq^i Sq^i i_{2m}) - 1 = i - 1 - z = 1 + \cdots + 2^{r_1} + (2^{p_2} + \cdots + 2^{p_{r_2} + \cdots}) - z$ with $1 \leq z \leq a - 1 < a < 1 + \cdots + 2^{r_1}$. Thus $z$ cancels some powers of 2 from the part $1 + \cdots + 2^{r_1}$, and hence $L(\dim(Sq^i Sq^i i_{2m})) < m + 1$.

Further, if $J_a, L_a$ are $\Theta^m$-sequences, $L(\dim(Sq^i i_{2m})) = m + 1$, and if

$$\dim(Sq^{L_a i_{2m}}) - 1 = 2^{t_1} + \cdots + 2^{t_m} \quad t_1 < \cdots < t_m,$$

$$\dim((Sq^{L_a i_{2m}})^{2^k}) = 2^k(1 + 2^{t_1} + \cdots + 2^{t_m})$$

$$= 2^k + 2^{k + t_1} + \cdots + 2^{k + t_m},$$

so

$$\dim((Sq^{L_a i_{2m}})^{2^k}) - 1 = 1 + \cdots + 2^{k-1} + 2^{k + t_1} + \cdots + 2^{k + t_m}$$
or

$$L(\dim((Sq^{L_a i_{2m}})^{2^k})) = 1 + m + k > 1 + m.$$

Thus since both sides of

$$Sq^i Sq^i i_{2m} = \sum Sq^3 i_{2m} + \sum (Sq^i i_{2m})^{2^k}$$

must have the same value of $L \cdot \dim$, we have $Sq^i Sq^i i_{2m} \equiv 0 \pmod{K}$ for all in the given range, and thus $Sq^i i_{2m} \in K$.

2. $H^*(K(\pi,n))/I$. In this section, we will determine part of the structure of the groups

$$\begin{pmatrix} i_2 + a - t - 1 \\ 2i_2 - 2t \end{pmatrix} = 0,$$
\[ H^*(K(Z,2p))/I(Sq^3i_{2p}), \]
\[ H^*(K(Z,8k))/I(Sq^{2i_8k}), H^*(K(Z,2,8k + 1))/I(Sq^{2i_{8k+1}}), \]
\[ H^*(K(Z,8k + 2))/I(Sq^{3i_{8k+2}}), \]
and
\[ H^*(K(Z,8k + 4))/I(Sq^{5i_{8k+4}}), \]
since these groups form the building blocks for \( H^*(BO) \) and \( H^*(BU) \). Our main tool will be the exact sequences of Toda [6],

\[
\begin{array}{c}
\mathcal{A} \xrightarrow{\mathcal{S}q^2} \mathcal{A}/\mathcal{A}Sq^1 \\
\mathcal{S}q^2 \xrightarrow{\mathcal{S}q^3} \mathcal{S}q^5 \\
\mathcal{A} \xleftarrow{\mathcal{S}q^3} \mathcal{A}/\mathcal{A}Sq^1
\end{array}
\]

and

\[
\begin{array}{c}
\mathcal{A}/\mathcal{A}Sq^1 \xrightarrow{\mathcal{S}q^3} \mathcal{A}/\mathcal{A}Sq^1 \xrightarrow{\mathcal{S}q^3} \mathcal{A}/\mathcal{A}Sq^1,
\end{array}
\]

where \( \mathcal{A} \) denotes the Steenrod algebra, and the mappings are given by right multiplication by the given elements.

In the following we shall write

\[ I = (i_1, \ldots, i_r) = [i_1 - 2i_2, \ldots, i_{r-1} - 2i_r, i_r]. \]

**Proposition.** \( \mathcal{A}/\mathcal{A}Sq^1 + \mathcal{A}Sq^3 \) has a basis consisting of elements of the form \( I + \sum J, J > I \) in lexicographic order; \( I,J \) being admissible sequences; with \( I = (I_0, I_1) \) where

1. \( I_1 \) is empty, or

\[
I_1 = \begin{cases} [0, \ldots, 0, 2, 0, \ldots, 0, 2, 0, \ldots, 0, 2] = A \\ [0, \ldots, 0, 4, 0, \ldots, 0, 2, 0, \ldots, 0, 2] = B \\ [0, \ldots, 0, 4] = C, \end{cases}
\]

and

2. \( I_0 \) is empty, or \( i_r(0) \geq 2i_1(I_1) + N(I_1) \), where \( N(I_1) = 6 \) if \( I_1 \) is empty or has type \( A \), and \( N(I_1) = 2 \) if \( I_1 \) has type \( B \) or \( C \).

Further, the map \( \mathcal{A}/\mathcal{A}Sq^1 + \mathcal{A}Sq^3 \to \mathcal{S}q^3 \mathcal{A}/\mathcal{A}Sq^1 \) takes \( I + \sum J \to I' + \sum J', \) where \( J' > I' \) in lexicographic order, and \( I' = (I_0, I_1) \), with

a) \( I_1' = (3) \) if \( I_1 \) is empty,

b) \( I_1' = [5, 0, \ldots, 0, 2, 0, \ldots, 2, 0, \ldots, 2] \) if \( I_1 = [2, 0, \ldots, 0, 2, 0, \ldots, 2, 0, \ldots, 2], \)

c) \( I_1' = [3, 0, \ldots, 0, 2, 0, \ldots, 2, 0, \ldots, 2] \) if \( I_1 = [0, \ldots, 0, 2, 0, \ldots, 2, 0, \ldots, 2], \)

d) \( I_1' = [1, 0, \ldots, 0, 4, 0, \ldots, 2, 0, \ldots, 2] \) if \( I_1 = [0, \ldots, 0, 4, 2, 0, \ldots, 2, 0, \ldots, 2], \)

e) \( I_1' = [1, 0, \ldots, 0, 2, 0, \ldots, 0, 2, \ldots, 2] \) if \( I_1 = [0, \ldots, 0, 4, 0, \ldots, 0, 2, \ldots, 2], \) and

f) \( I_1' = [1, 0, \ldots, 0, 2] \) if \( I_1 = [0, \ldots, 0, 4]. \)
Proof. We will say that an element $\alpha = I + \sum J$, $J > I$, has rank $k$ if $I = [0, \ldots, 0, 2, 0, \ldots, 0, 2, 0, \ldots, 0, 2]$ with $k$ 2's or $I = [\ldots, a, 0, \ldots, 0, 2, 0, \ldots, 0, 2, 0, \ldots, 0, 2]$ with $a \neq 0, 2$ and with $k$ 2's.

The principal assertion of the proposition is that there exist elements $\alpha_k = (2^{k+1} - 2, \ldots, 2^2 - 2) + \sum J$, $J > (2^{k+1} - 2, \ldots, 2^2 - 2)$, such that $Sq^3(\alpha_k) = (2^{k+1} + 1, \alpha_{k-1})$. We take $\alpha_0 = (\phi)$, $\alpha_1 = (2)$, $\alpha_2 = (6, 2) + (8)$. Now we suppose $\alpha_k$ exists for $k \leq p$.

Now

$$\alpha_p = \left[ \frac{2, \ldots, 2}{p} \right] + \cdots \rightarrow (2^{p+1} + 1, \alpha_{p-1}) = \left[ \frac{5, 2, \ldots, 2}{p-1} \right] + \cdots$$

From $\alpha_p$, we will construct all other elements of rank $p$ in our basis, and construct their images.

First consider (b)

$$[2, 0, \ldots, 0, 2, \ldots, 2] \rightarrow [5, 0, \ldots, 0, 2, \ldots, 2].$$

In the Adem formulae,

$$Sq^{2p}Sq^{p+2} = \sum_0^p \left( \frac{p+1-t}{2p-2t} \right) Sq^{3p+2} - Sq^t,$$

$$= Sq^{2p+2}Sq^p + \text{terms larger than } (2p+2, p),$$

and similarly

$$Sq^{2p}Sq^{p+5} = Sq^{2p+5}Sq^p + \text{terms larger than } (2p+5, p),$$

and

$$\begin{align*}
(8i, 4i + 4 + a, 2i + 2, i) &= (8i + 4 + a, 4i, 2i + 2, i) + \cdots, \\
&= (8i + 4 + a, 4i + 2, 2i, i) + \cdots,
\end{align*}$$

etc. Now apply these relations on both sides of the desired map to push the 2's and the 5 as far as possible to the right. By the complete symmetry we get

$$\left( J, \left[ \frac{2, \ldots, 2}{p} \right] \right) + \cdots \rightarrow \left( J, \left[ \frac{5, 2, \ldots, 2}{k-1} \right] \right) + \cdots$$

to be shown. Thus we may obtain the generators of the form $[2, 0, \ldots, 0, 2]$ by applying an admissible sequence to $\alpha_p$, and their images satisfy (b).

For (c), consider the expression from (b),

$$[2, 0, \ldots, 0, 2] \rightarrow [5, 0, \ldots, 0, 2].$$

The first terms on each side are

$$(2i + 2, i, \cdots) \rightarrow (2i + 5, i, \cdots),$$
to this apply \((2(2i + 2))\). We have

\[
Sq^{2p}Sq^{p+3} = Sq^{2p+3}Sq^p + \text{higher terms}
\]

so

\[
(2(2i + 2), 2i + 2, i, \cdots) \rightarrow (2(2i + 2), (2i + 2) + 3, i, \cdots),
\]

\[
= (2(2i + 2) + 3, 2i + 2, i, \cdots) + \cdots.
\]

Continuing in this manner, we get

\[
[0, \cdots, 0, 2, 0, \cdots, 0, 2] \rightarrow [3, 0, \cdots, 0, 2, 0, \cdots, 0, 2].
\]

For (d), consider

\[
[2, 0, \cdots, 0, 2] \rightarrow [5, 0, \cdots, 0, 2]
\]

and to

\[
(2i + 2, i, \cdots) \rightarrow (2i + 5, i, \cdots)
\]

apply \((2(2i + 2) + 4)\). Since \(Sq^{2p+4}Sq^{p+3} = Sq^{2p+5}Sq^{p+2} + \text{higher terms}\),

\[
(2(2i + 2) + 4, 2i + 2, i, \cdots) \rightarrow (2(2i + 2) + 4, 2i + 2 + 3, i, \cdots),
\]

\[
= (2(2i + 2) + 5, 2i + 2, i, \cdots) + \cdots,
\]

\[
= (2(2i + 4) + 1, 2i + 4, i, \cdots) + \cdots.
\]

Now \(2(2i + 2) + 4 = 2(2i + 4)\), so we now apply \(4(2i + 4) = 2 \cdot 2(2i + 4)\) and apply the relation

\[
Sq^{2p}Sq^{p+1} = Sq^{2p+1}Sq^p
\]

to complete part (d).

For part (e) begin with the relation from (c)

\[
[0, \cdots, 0, 2, \cdots, 2] \rightarrow [3, 0, \cdots, 0, 2, \cdots, 2].
\]

The last terms are

\[
(2i, i, \cdots) \rightarrow (2i + 3, i, \cdots).
\]

To this apply 
\((4i + 4)\) and use

\[
Sq^{2p}Sq^{p+1} = Sq^{2p+1}Sq^p
\]

to get

\[
(4i + 4, 2i, i, \cdots) \rightarrow (2(2i + 2), (2i + 2) + 1, i, \cdots),
\]

\[
= (2(2i + 2) + 1, 2i + 2, i, \cdots).
\]

This clearly continues to give

\[
[0, \cdots, 0, 4, 0, \cdots, 2, \cdots] \rightarrow [1, 0, \cdots, 0, 2, 0, \cdots, 2, \cdots].
\]
Finally, (a) and (f) are just the special cases when there are no 2's.

Thus we may assume \( \alpha_k \) and all our basis elements of rank \( k \) and their images known for \( k \leq p \), and must show the existence of \( \alpha_{p+1} \).

Consider \( (2^{p+2} + 1)\alpha_p \xrightarrow{Sq^3} (2^{p+2} + 1, 2^{p+1} + 1)\alpha_{p-1} = 0 \), since \( (2^{p+2} + 1, 2^{p+1} + 1) = 0 \) by the Adem relations. By exactness of \( A/ASq^1 \xrightarrow{Sq^3} A/ASq^1 \), this means \((Sq^3)^{-1}(2^{p+2} + 1)\alpha_p\) is not empty.

Let \( Q = 1 + \sum J, J > I, \) be an element of \((Sq^3)^-(2^{p+2} + 1)\alpha_p\) which has \( I \) largest in lexicographic order among all such elements. We shall show that \( I = (2^{p+2} - 2, \cdots, 2^2 - 2) \), and hence that \( Q \) may be taken to be \( \alpha_{p+1} \).

Suppose \( I \neq (2^{p+2} - 2, \cdots, 2^2 - 2) \). These two elements have the same degree, since \((2^{p+2} + 1)\alpha_p = (2^{p+2} + 1, 2^{p+1} - 2, \cdots, 2^2 - 2) \cdots \). Thus \( I \) does not have rank \( p + 1 \), since \((2^{p+2} - 2, \cdots, 2^2 - 2) \) is the only element of this degree with rank \( p + 1 \). Since there are no elements of rank \( p \) of this degree, rank \( I \leq p - 1 \).

If \( I \) is not the smallest term of one of our basis elements, then by (a)-(f), \( I + \sum K, K > I, \) is in the image of \( Sq^3 \). (Note: here we need that the map \( Sq^3 \) is known on all basis elements of rank \( \leq p \) only.) Thus \( I + \sum J \) and \( \sum K \) maps into \((2^{p+2} + 1)\alpha_p\) and is larger than \( Q \), contradicting our choice of \( Q \). Thus \( I \) is the smallest term of one of our basis elements.

Now we note that \((A/ASq^1)^{sq}Q\) has as basis our basis vectors (of rank \( \leq p - 1 \)), the images under \( Sq^3 \) of our basis vectors (of rank \( \leq p \)), and \((2^{p+2} - 2, \alpha_p)\), by considering the least terms of each of these.

Write

\[
Q = (I + \sum K) + \sum \alpha + \sum \beta + \begin{cases} 
0 \\
(2^{p+2} - 2, \alpha_p),
\end{cases}
\]

with \( I + \sum K \), \( \alpha \) in our basis and \( \beta \) in the image under \( Sq^3 \) of our basis. The term \((2^{p+2} - 2, \alpha_p)\) must occur, since if not \( Sq^3(Q) \) has as its lowest term one of the images of our basis vectors, none of which is \([5, 2, \cdots, 2] \). Since this expression is formable by subtracting from \( Q \) the basis vectors in their lexicographic order, \( I < (2^{p+2} - 2, \cdots, 2^2 - 2) \).

Now

\[
Q + (2^{p+2} - 2, \alpha_p) \xrightarrow{Sq^3}(2^{p+2} + 1, \alpha_p) + (2^{p+2} - 2, 2^{p+1} + 1, \alpha_{p-1}),
\]

\[
= (2^{p+2} + 1, \alpha_p) + (2^{p+2} + 1, 2^{p+1} - 2, \alpha_{p-1})
\]

\[
+ (2^{p+2}, 2^{p+1} - 1, \alpha_{p-1})
\]

is an image of our basis vectors, namely \((I + \sum K) + \sum \alpha\). Taking the least terms of the right side lexicographically, begin to find the basis vectors which map to this image.

In our basis, \( I' + \sum J' \rightarrow I'' + \sum J'' \), with \( i_1(I'') \) even implies by (a)-(f) that
Thus the terms in $Sq^3(Q + (2^{p+2} - 2, \alpha_p))$ having $i_1 = 2^{p+2}$ come from elements $I' + \Sigma J'$ with $i_1(I') = 2^{p+2}$, which are larger than $(2^{p+2} - 2, \cdots, 2^2 - 2)$. Since all other terms in $Sq^3(Q + (2^{p+2} - 2, \alpha_p))$ have $i_1 \geq 2^{p+2} + 1$, we must have $I + \Sigma K \rightarrow L + \Sigma M$ with $i_1(L) \geq 2^{p+2} + 1$. Since $I < (2^{p+2} - 2, \cdots, 2^2 - 2)$, $i_1(L) \leq 2^{p+2} - 2$. Thus under $Sq^3$ the leading coefficient of $I$ increases by 3 or more. From our calculations, the increase is always $\leq 3$, and is 3 only if the element has leading term $[0, \cdots, 0, 2, \cdots, 2]$. 

Thus $I = [0, \cdots, 0, 2, 0, \cdots, 0, 2, \cdots, 2]$ with $\leq p-1$ 2's. This is impossible, since the coefficient $i_1$ in such a sequence is $2k_1 + \cdots + 2^n$, where $n$ is the number of 2's, and $i_1(I) = 2^{p+2} - 2 = 2^{p+1} + \cdots + 2$ has $p$ 2's.

Thus $I = (2^{p+2} - 2, \cdots, 2^2 - 2)$, which completes the proof.

**Corollary.** There exists an epimorphism

$$f : Sq^3(H^*(K(Z,2p))) \otimes Z_2[\psi_{2i}, \psi | L(2i) = p + 1] \rightarrow H^*(K(Z,2p))/I(Sq^3i_{2p})$$

such that the composition $Sq^3 \cdot f$ is an isomorphism of the first factor of the tensor product with the image of $Sq^3$ and is zero on the second factor.

**Proof.** $H^*(K(Z,2p))/I(Sq^3i_{2p})$ is a quotient of the polynomial algebra on classes $Sq^I + Sq^Ji_{2p}$, where $I + \Sigma J$ belongs to our basis of $\mathcal{A}/\mathcal{A}SQ^1 + \mathcal{A}SQ^3$, and the excess of $I$ is less than $2p$. Consider the map from this polynomial algebra into $H^*(K(Z,2p-3))$ by $Sq^3$.

If $I = (I_0, I_1)$ with $e(I) < 2p$, $I_0 \neq \phi$, then $Sq^3(I + \Sigma J) = I' + \Sigma J'$, and $i_1(I_0) = i_1(I_0) = i_1$ so $e(I') = 2i_1 - \deg I' = 2i_1 - \deg I - 3 = e(I) - 3 < 2p - 3$.

If $I_0$ is empty:

$I_1 = [0, \cdots, 0, 2, 0, \cdots, 0, 2, \cdots, 2]$ has excess $< 2p$ only if $I_1$ has less than $p$ 2's, and $e(I') = e(I) + 3$, so $e(I) < 2p, e(I') \geq 2p - 3$ implies $e(I) = 2p - 6, 2p - 4, 2p - 2$. If $e(I) = 2p - 6, e(I') = 2p - 3$.

$$I_1 = [0, \cdots, 0, 4, 0, \cdots, 2, \cdots, 2]$$

has excess $4 + \text{number of 2's} \leq 2p$ only if there are less than $p - 2$ 2's. If $q = 0, e(I') = e(I) - 1$, and if $q > 0, e(I') = e(I) - 1$. Thus $e(I') \geq 2p - 3, e(I) < 2p$ implies $e(I) = 2(p - 3) + 4, e(I') = 2p - 3$.

Now the sequences $[0, \cdots, 0, 2, \cdots, 2]$ and $[0, \cdots, 0, 4, 0, \cdots, 2, \cdots, 2]$ with $p - 3$ 2's give images with excess $2p - 3$ which thus have the form $(Sq^l i_{2p - 3})^2$, where $L = I'' + \Sigma J'$,

$$I'' = [0, \cdots, 0, 2, \cdots, 2] \quad \text{with} \quad p - 4, p - 3, \quad \text{or} \quad p - 2 \quad \text{2's;} \quad \text{or}$$

$$= [0, \cdots, 0, 4, 0, \cdots, 2, \cdots, 2] \quad \text{with} \quad p - 4 \quad \text{2's}$$

in cases b, c, e and d, respectively. Since these elements are not in our previous
image, we see that our polynomial algebra maps to \( H^*(K(Z, 2p - 3)) \) with kernel the polynomial ideal generated by

\[
Z_2[\{Sq^{10, \cdots, 0, 2, \cdots, 2}\} + \Sigma i_{2p} | p - 1 \text{ or } p - 2 2^t's].
\]

Now consider sequences \([0, \cdots, 0, 2, \cdots, 2, \cdots, 2]\) with \( k \) 2's. This clearly divides into the termwise sum of \( k \) sequences \([0, \cdots, 0, 2, \cdots, 2, \cdots, 2]\) of distinct lengths, and these have degree \( 2 + 4 + \cdots + 2^t = 2^{t+1} - 2 \). Thus the degree of \([0, \cdots, 0, 2, \cdots, 2, \cdots, 2]\) is

\[
2^t + \cdots + 2^k - 2k \text{ with } 2 \leq t_1 < \cdots < t_k.
\]

Now a sequence \( I = [0, \cdots, 0, 2, \cdots, 2] \) with \( p - 1 \) 2's when applied to a class of dimension \( 2p \) has dimension \( 2^t + \cdots + 2^{t_p - 1} - 2(p - 1) + 2p = 2 + 2^t + \cdots + 2^{t_p - 1} \). \( L \) of this is \( p + 1 \).

For a sequence \( I = [0, \cdots, 0, 2, \cdots, 2] \) with \( p - 2 \) 2's when applied to a class of dimension \( 2p \), we have dimension \( 2^t + \cdots + 2^{t_p - 1} - 2(p - 2) + 2p = 4 + 2^t + \cdots + 2^{t_p - 2} \) or \( L(i) = p + 1 \).

In §3, we will see that this epimorphism is in fact an isomorphism. This will show that \( H^*(K(Z, 2p))/I(Sq^3 i_{2p}) \) is a polynomial algebra. The situation is more difficult for \( H^*(K(Z, 2p + 1))/I(Sq^3 i_{2p+1}) \) for we have seen that

\[
(Sq^L i_{2p+4-3})^2 \equiv 0 \mod I(Sq^3 i_{2p+1}),
\]

while \( Sq^b i_{2p+4-3} \neq 0 \).

**PROPOSITION.** There exist epimorphisms

\[
\begin{align*}
\tilde{Sq}^5(H^*(K(Z, 8k))) \otimes \frac{H^*(K(Z, 2^{4k-1}))}{I(Sq^{1i}, \cdots, Sq^{2^{4k-3}i})} & \rightarrow H^*(K(Z, 8k))/I(Sq^2 i_{8k}), \\
\tilde{Sq}^2(H^*(K(Z, 2^{4k}))) \otimes \frac{H^*(K(Z, 2^{4k+1}))}{I(Sq^{1i}, \cdots, Sq^{2^{4k-2}i})} & \rightarrow H^*(K(Z, 2^{4k+1}))/I(Sq^2 i_{8k+1}), \\
\tilde{Sq}^2(H^*(K(Z, 2^{4k}))) \otimes \frac{H^*(K(Z, 2^{4k+2}))}{I(Sq^{1i}, \cdots, Sq^{2^{4k-1}i})} & \rightarrow H^*(K(Z, 2^{4k+2}))/I(Sq^3 i_{8k+2}), \\
\tilde{Sq}^3(H^*(K(Z, 8k + 4))) \otimes \frac{H^*(K(Z, 2^{4k+4}))}{I(Sq^{1i}, \cdots, Sq^{2^{4k}i})} & \rightarrow H^*(K(Z, 8k + 4))/I(Sq^5 i_{8k+4})
\end{align*}
\]

such that the compositions with \( \tilde{Sq}^j \) (\( j = 5, 2, 2, 3 \) respectively) give an isomorphism of the first factor with the image of \( \tilde{Sq}^j \) and are zero on the second factor.

The proof of this proposition is nearly identical to the proof of the preceding proposition and corollary. This result is based on the exact rectangle of Toda [6]
and uses the same method of ordering the Cartan basis lexicographically. The important point is the existence of elements

\[ \alpha_k = (2^k - 4, 2^{k-1} - 2, 2^{k-2} - 1, 2^{k-3} - 1, 2^{k-4} - 4, \ldots) + \ldots \]

and

\[ \alpha'_k = (2^{k-1} - 2, 2^{k-2} - 1, 2^{k-3} - 1, 2^{k-4} - 4, \ldots) + \ldots \]

such that \( Sq^{l}(\alpha_k) = (2^{k+1} - 1, \alpha_{k-1}) \) and \( Sq^{l}(\alpha'_k) = (2^{k-1} + 1, \alpha'_{k-1}) \). Here \( \alpha_{k+1}, \alpha'_{k+1} \in \mathcal{F}/\mathcal{F} Sq^3; \alpha_{k+1}, \alpha'_{k+1} \in \mathcal{F}/\mathcal{F} Sq^5 \); \( \alpha_{k+2}, \alpha'_{k+2} \in \mathcal{F}/\mathcal{F} Sq^{1+} + \mathcal{F} Sq^5 \); and \( \alpha_{k+3}, \alpha'_{k+3} \in \mathcal{F}/\mathcal{F} Sq^2 \).

3. \( H^*(BO(k, \ldots, \infty)) \) and \( H^*(BU(k, \ldots, \infty)) \). By the Bott periodicity results, we have

\[
\begin{array}{c|cccccccc}
   i \pmod{8} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\pi_i(BO) & \mathbb{Z} & \mathbb{Z}_2 & \mathbb{Z}_2 & 0 & \mathbb{Z} & 0 & 0 & 0 \\
\end{array}
\]

Thus \( BO(k, \ldots, \infty) = BO(k + 1, \ldots, \infty) \) if \( k \not\equiv 0, 1, 2, 4 \pmod{8} \) and \( BU(2p - 1, \ldots, \infty) = BU(2p, \ldots, \infty) \).

Let \( \phi(0, k) \) be the number of integers \( s \) such that \( 0 < s \leq k \) and such that \( s \equiv 0, 1, 2, 4 \pmod{8} \).

Let \( \pi_k = \pi_k(BO) \).

We wish to prove:

**Theorem A.** If \( k \equiv 0, 1, 2, 4 \pmod{8} \):

- (a) \( H^*(BO(k, \ldots, \infty)) \cong H^*(K(\pi_k, k))/I(Q_k) \otimes \mathbb{Z}_2[\theta_i] \, L(i) > \phi(0, k) \]

\( Q_k = \begin{cases} 
   Sq^2 & \text{if } k \equiv 0, 1 \pmod{8}, \\
   Sq^3 & \text{if } k \equiv 2 \pmod{8}, \\
   Sq^5 & \text{if } k \equiv 4 \pmod{8}.
\end{cases} \)

- (b) The spectral sequence with fiber \( H^*(K(\pi_k, k-1)) \), base \( H^*(K(\pi_k, k))/I(Q_k) \), and \( i_{k-1} \) transgressive to \( i_k \) (deduced from the spectral sequence of the fibration \( K(\pi_k, k) \to PK(\pi_k, k) \to K(\pi_k, k) \) by taking quotients) has as its \( E^\infty \) term only those elements of the fiber belonging to the polynomial subalgebra generated by all \( Sq^l(Q_k) \) \( (k > 1) \).

**Theorem B.**

- (a) \( H^*(BU(2p, \ldots, \infty)) \cong H^*(K(\mathbb{Z}, 2p))/I(Sq^3 i_{2p}) \otimes \mathbb{Z}_2[\theta_{2i}] \, L(2i) > p + 1 \).

- (b) The spectral sequence with fiber \( H^*(K(\mathbb{Z}, 2p - 1)) \), base \( H^*(K(\mathbb{Z}, 2p))/I(Sq^3 i_{2p}) \), and \( i_{2p-1} \) transgressive to \( i_{2p} \) has as its \( E^\infty \) term only those elements of the fiber.
belonging to the polynomial subalgebra generated by all $Sq^1 Sq^{3i_2-p-1}$
($p \geq 1$).

**Proof of Theorem A.** The proof is by induction on $k$.

For $k = 1$, $H^*(BO(1, \cdots, \infty)) = H^*(BO) = Z_2[\theta]$. But $\phi(0,1) = 1$, so $Z_2[\theta] \cong Z_2[\theta_1] \otimes Z_2[\theta_1 | L(i) > 1]$ and $Z_2[\theta_1] \cong H^*(K(Z_2,1))$, which completes this case.

For $k = 2$, $BO(2, \cdots, \infty) = BSO$ and is well known,

$$H^*(BSO) \cong Z_2[\theta_i | i > 1] \cong Z_2[\theta_i | L(i) > 1] \cong Z_2[\theta_i | L(i) = 2] \otimes Z_2[\theta_i | L(i) > 0(0,2) = 2].$$

Now the only admissible sequences of excess $< 2$ are $i = (\phi)$ and $i = (2^k, \cdots, 1)$, which are $\Theta^1$-sequences, so

$$Z_2[\theta_i | L(i) = 2] \cong H^*(K(Z_2,2)) \cong H^*(K(Z_2,2))/I(Sq^1 i_2).$$

Also, for $k = 2$, the spectral sequence is just the spectral sequence of $K(Z_2,1) \to PK(Z_2,2) \to K(Z_2,2)$ which has $\varepsilon^\infty = 0$.

Now suppose $k \equiv 0, 1, 2, 4 \pmod{8}$, $k > 2$, and that the theorem is true for all $u \equiv 0, 1, 2, 4 \pmod{8}$ with $u < k$. In particular, choose $j \equiv 0, 1, 2, 4 \pmod{8}$, $j < k$, such that if $j < v < k$ then $v \not\equiv 0, 1, 2, 4 \pmod{8}$.

Thus we have the fibration

$$K(\pi_j, j-1) \to BO(k, \cdots, \infty) \to BO(j, \cdots, \infty)$$

which is induced from

$$K(\pi_j, j-1) \to PK(\pi_j, j) \to K(\pi_j, j).$$

Thus the spectral sequence of $BO(k, \cdots, \infty) \to BO(j, \cdots, \infty)$ has fiber $H^*(K(\pi_j, j-1))$, base $H^*(BO(j, \cdots, \infty)) \cong H^*(K(\pi_j, j))/I(Q, i_j) \otimes Z_2[\theta_i | L(i) > \phi(0,j)]$, and $i_{j-1}$ transgresses to $i_j \otimes 1$. This is the tensor product of the spectral sequence in (b) with the algebra $Z_2[\theta_i | L(i) > \phi(0,j)]$, so by (b), $E^\infty$ of this spectral sequence is $(PQ, i_{j-1}) \otimes Z_2[\theta_i | L(i) > \phi(0,j)]$ where $(PQ, i_{j-1})$ denotes the polynomial subalgebra of $H^*(K(\pi_j, j-1))$ generated by all $Sq^i Q, i_{j-1}$.

Thus $H^*(BO(k, \cdots, \infty)) \cong (PQ, i_{j-1}) \otimes Z_2[\theta_i | L(i) > \phi(0,j)]$. The class of dimension $k$ in $H^*(BO(k, \cdots, \infty))$ is $Q, i_{j-1}$ if $j > 4$ and $\theta_k$ if $j \leq 4$.

If $j > 4$, $BO(k, \cdots, \infty) \to K(\pi_k, k)$ gives

$$H^*(K(\pi_k, k)) \to H^*(BO(k, \cdots, \infty)) \to H^*(K(\pi_j, j-1))$$

$$i_k \quad \rightarrow \quad Q, i_{j-1}.$$

By the exact rectangle of Toda [6] used in §2, we have $Q, i_k \rightarrow 0$. Further, if $j > 4$, $2^{\phi(0,j)} > k + \deg Q, k$, so that $Q, i_k$ projects to zero in the second factor of $H^*(BO(k, \cdots, \infty))$ and hence $Q, i_k$ goes to zero in $H^*(BO(k, \cdots, \infty))$. 

Thus

\[ H^*(K(\pi_k,k))/I(Q_k i_k) \to H^*(BO(k, \cdots, \infty)). \]

mapping \( i_k \to q_{ij} - 1 \otimes 1. \)

Now consider the bundle induced by \( BO(k, \cdots, \infty) \to BO \) from the universal vector bundle and form the Thom space \( TBO(k, \cdots, \infty). \) Letting \( U \) be the basic class, we have

\[ Sq^i U = 0 \quad \text{if} \quad 1 \leq i < 2^{\Phi(0,j)} \]

\[ Sq^{2^{\Phi(0,j)}} U = w_2^{\Phi(0,j)} \cdot U = [1 \times \theta_2^{\Phi(0,j)}]. \]

For \( j > 4, 2^{\Phi(0,j)} \geq 16 \) and by Adams [2], there are secondary cohomology operations \( \Phi_\lambda \), and primary cohomology operations \( P_\lambda \) such that

\[ \sum P_\lambda(\Phi_\lambda U) = Sq^{2^{\Phi(0,j)}} U. \]

Further, the secondary operations \( \Phi_\lambda U \in H^4(TBO(k, \cdots, \infty))/J \) and \( P_\lambda(J) = 0. \) Thus picking classes \( x_\lambda \cdot U \) in \( H^4(TBO(k, \cdots, \infty)) \) representing \( \Phi_\lambda U \), we have

\[ \sum P_\lambda(x_\lambda \cdot U) = Sq^{2^{\Phi(0,j)}} U. \]

Now degree \( P_\lambda < 2^{\Phi(0,j)} \) so expanding by the Cartan formula,

\[ \sum P_\lambda(x_\lambda \cdot U) = \sum (P_\lambda x_\lambda) \cdot U. \]

Now degree \( P_\lambda > 0, \) so \( \dim x_\lambda < 2^{\Phi(0,j)} \), and so \( x_\lambda \) is in the image of a class \( \alpha_\lambda \in H^4(K(\pi_k,k)). \) Thus \( \alpha = \sum P_\lambda \alpha_\lambda H^4(K(\pi_k,k)) \) maps to \( w_2^{\Phi(0,j)} = 1 \otimes \theta_2^{\Phi(0,j)} \) in \( H^4(BO(k, \cdots, \infty)). \)

If \( j \leq 4, \alpha = i_k \) maps to \( 1 \otimes \theta_2^{\Phi(0,j)}. \)

Thus

\[ H^*(BO(k, \cdots, \infty)) \mapsto (PQ_{ij} - 1) \otimes Z_2[\theta_1 | L(i) = \phi(0,j) + 1] \]

maps \( H^*(K(\pi_k,k))/I(Q_k i_k) \) onto the latter. Thus by the results of §2, we have epimorphisms

\[ \bar{Q}_{ij}(H^*(K(\pi_k,k))) \otimes Z_2[\theta_1 | L(i) = \phi(0,k)] \xrightarrow{f} H^*(K(\pi_k,k))/I(Q_k i_k) \]

and

\[ H^*(K(\pi_k,k))/I(Q_k i_k) \xrightarrow{g} (PQ_{ij}-1) \otimes Z_2[\theta_1 | L(i) = \phi(0,j) + 1], \]

but \( \bar{Q}_{ij}(H^*(K(\pi_k,k))) = (PQ_{ij} - 1) \) and \( \phi(0,j) + 1 = \phi(0,k), \) and by considering the mappings, \( g \circ f \) is an isomorphism. Thus \( f \) and \( g \) are isomorphisms.

This implies that

\[ H^*(K(\pi_k,k))/I(Q_k i_k) \otimes Z_2[\theta_1 | L(i) > \phi(0,k)] \to H^*(BO(k, \cdots, \infty)) \]

is an isomorphism.
Now consider (b)_k. Let \( \mathcal{A}_0 = 0 \) if \( k \equiv 1,2 \) (8), \( \mathcal{A}_0 = \mathcal{A} Sq^1 \) if \( k \equiv 0,4 \) (8). By the results in §2, \( \mathcal{A}/\mathcal{A}_0 \) has a basis consisting of our basis vectors, and the images of our basis vectors.

Let \( B_q \subset \mathcal{A}/\mathcal{A}_0 \) be the set of all our basis vectors of degree \( q \), \( I + \Sigma J \), with the excess of \( I \) less than \( k \). Let \( C_q \subset \mathcal{A}/\mathcal{A}_0 \) be the set of all images \( I'+\Sigma J' \) of our basis vectors, with excess of \( I' \) less than \( k \).

Now for each \( I + \Sigma J \) in \( B_q \), define a spectral sequence \( _rE \) by

\[
_iE^{r,s} = \begin{cases} 
0 & \text{if } r \neq 0, q + k - 1 \text{ or } s \neq 0 \text{ (modulo } q + k), \\
(Sq^{I+\Sigma J}i_{k-1}) \cdot (Sq^{I+\Sigma J}i_k)^p & \text{if } r = q + k - 1, s = p(q + k), \\
(Sq^{I+\Sigma J}i_k)^p & \text{if } r = 0, s = p(q + k),
\end{cases}
\]

\( (r = \text{fiber degree}, s = \text{base degree}) \) and in which the only nonzero differentials are

\[
d : _iE^{q+k-1,p(q+k)} \to _{i+1}E^0 = (q + k - 1,0) \to (0,0),
\]

\[
d : _iE^{q+k-1,p(q+k)} \to _{i+1}E^0 = (q + k - 1,0) \to (0,0),
\]

and all differentials are zero.

Now let \( E \) denote the spectral sequence of (b)_k. For each \( I + \Sigma J \in B_q \), there is an obvious inclusion map \( _rE \to E \), which commutes with differentials. Further, there is a map \( _rE \to E \) for all \( I' + \Sigma J' \in C_q \) (since \( Sq^{I'+\Sigma J'}i_{k-1} \) in \( E \) transgresses in the spectral sequence of the fibration \( K(\pi_k,k-1) \to PK(\pi_k,k) \to K(\pi_k,k) \) to \( Sq^{I'+\Sigma J'}i_k \), which belongs to \( I(Q_k\pi) \). Note that in \( K(\pi_k,k-1) \to PK(\pi_k,k) \to K(\pi_k,k) \) the elements \( Sq^{I'+\Sigma J}i_{k-1} \) and \( Sq^{I'+\Sigma J'}i_{k-1} \) transgress to \( Sq^{I'+\Sigma J}i_k \) and \( Sq^{I'+\Sigma J'}i_k \) modulo elements \( Sq^Ki_k \), with excess of \( K \) equal to \( k \). However, in the spectral sequence of the fibration, \( Sq^Ki_k \) is in the image of a \( d_t \) for a lesser \( t \), and so the transgressions are as asserted).

Thus by using the products in \( E \), we have a map of spectral sequences

\[
\left( \otimes _{\mathcal{B}} _rE \right) \left( \otimes _{\mathcal{C}} _rE \to E \right).
\]

Now the elements of \( \left( \bigcup_q B_q \right) \cup \left( \bigcup_q C_q \right) \) give a simple system of transgressive generators for \( H^*(K(\pi_k,k-1)) \) in the fibration, so \( \rho \) is an isomorphism (as vector spaces) on the fiber.

The base in

\[
\left( \otimes _{\mathcal{B}} _rE \right) \otimes \left( \otimes _{\mathcal{C}} _rE \right)
\]
is by definition the polynomial algebra over \( \mathbb{Z}_2 \) on \( \{Sq^{I + \sum J}_k | I + \sum J \in B_{\text{deg}}\} \), which from \( \S 2 \) and \( (a)_k \) is in fact \( H^*(K(n_k,k))/I(Q_ki_k) \). Thus \( \rho \) is an isomorphism (as algebras) on the base.

Then

\[
E^\infty \cong \left( \bigotimes_{B_k} E^\infty \right) \otimes \left( \bigotimes_{C_k} E^\infty \right) \cong \bigotimes_{C_k} E^\infty \cong \bigotimes_{C_k} I, E
\]

for the tensor products are finite in degree \((r,s)\) for all \((r,s)\). Thus \( E^\infty \) has as its only terms the elements of the fiber which belong to the polynomial algebra on \( Sq^{I + \sum J}_k \) with \( I + \sum J \in C_k \). By the results of \( \S 2 \) and \( (a)_k \) this is precisely \( (PQ_ki_k)_{-1} \).

The proof of Theorem B can be easily seen to be formally identical except in the lowest dimensions. For these we have the following:

\[ H^*(BU(2,\cdots,\infty)) = H^*(BU) = \mathbb{Z}_2[\theta_2], \]

and the map \( BU \to K(Z,2) \) sends \( i_2 \) into \( \theta_2 \). \( H^*(K(Z,2)) \) is the \( \mathbb{Z}_2 \) polynomial algebra on all \( Sq^{I}_i \) with \( I \) admissible, \( e(I) < 2, i, i(I) > 1 \). There are no such sequences, so

\[
H^*(K(Z,2)) = H^*(K(Z,2))/I(Sq^3i_2) \cong \mathbb{Z}_2[\theta_2] \cong \mathbb{Z}_2[\theta_2_2].
\]

The spectral sequence then gives \( H^*(BU(4,\cdots,\infty)) = \mathbb{Z}_2[\theta_2_1 | L(2i) > 2] \). Now \( H^*(K(Z,4)) \) is the \( \mathbb{Z}_2 \) polynomial algebra on all \( Sq^3i_4 \) with \( I \) admissible, \( e(I) < 4, i, i(I) > 1 \), so

\[
I = (2^k3,\cdots,3), (2^k,\cdots,2), (2^l(2^k+1),...,2^k+1 + 1,2^k,...,2)
\]

so

\[
H^*(K(Z,4))/I(Sq^3i_4) \cong \mathbb{Z}_2[Sq^{2k+1}|L(2i) = 3].
\]

The general argument then gives \( H^*(BU(6,\cdots,\infty)) \equiv (PSq^3i_2) \otimes \mathbb{Z}_2[\theta_2_1 | L(2i) > 3] \) and the problem becomes to consider the map

\[
H^*(K(Z,6))/I(Sq^3i_3) \rightarrow H^*(BU(6,\cdots,\infty)) \rightarrow (PSq^3i_2) \otimes \mathbb{Z}_2[\theta_2_1 | L(2i) = 4],
\]

in which \( i_6 \rightarrow Sq^3i_3 \otimes 1 = i_3^2 \otimes 1 \). We must show that \( Sq^2i_6 \rightarrow 1 \otimes \theta_8 \) in order to show that this is epic. The map \( BU(6,\cdots,\infty) \rightarrow K(Z,6) \) induces the fibration \( K(Z,5) \to BU(8,\cdots,\infty) \to BU(6,\cdots,\infty) \) and in the spectral sequence of this fibration, the transgression (either 0 or 1 \( \otimes \theta_8 \) of \( Sq^2i_5 \) is the image of \( Sq^2i_6 \). However, if the transgression of \( Sq^2i_5 \) is zero, then \( Sq^2i_3 \) lasts to \( E^\infty \), so \( H^*(BU(8,\cdots,\infty)) \neq 0 \). Since \( BU(8,\cdots,\infty) \) is 7-connected, this is impossible. Thus \( Sq^2i_6 \rightarrow 1 \otimes \theta_8 \).

The remainder of the proof of the theorem then follows the general pattern as given for \( BO(k,\cdots,\infty) \).

Corollary. \( H^*(BO(k,\cdots,\infty)), H^*(BU(k,\cdots,\infty)), H^*(K(Z,2p))/I(Sq^3i_{2p}), \) and \( H^*(K(n_k,k))/I(Q_ki_k) \) are all polynomial algebras over \( \mathbb{Z}_2 \).
Note. The only problems remaining for the determination of the action of the Steenrod algebra on \( H^*(BO(k, \cdots, \infty)) \) and \( H^*(BU(k, \cdots, \infty)) \) are the relations for the 0's and the relation between \( H^*(K(nk,k)) \) and the 0's. This last is given by knowing the classes \( \alpha_k \in H^{2\phi(0,k)-1}(K(\pi_k,k);Z_2) \) and \( \beta_p \in H^{2p}(K(Z,2p);Z_2) \) which map into \( \theta_{2\phi(0,k)-1} \) and \( \theta_{2p} \) respectively. These are in fact the elements \( Sq^2 \alpha \), where \( \alpha \) were the elements found in §2.

One can show that

\[
\begin{align*}
\alpha_k &= i_k \quad \text{for } k = 1, 2, 4, 8, \\
\alpha_9 &= (Sq^4 Sq^2 + Sq^7) i_9, \\
\alpha_{10} &= (Sq^{12} Sq^6 Sq^3 + Sq^{14} Sq^6 Sq^2 + Sq^{15} Sq^4 Sq^2 Sq^1 + Sq^{15} Sq^7 + Sq^{16} Sq^4 Sq^2) i_{10},
\end{align*}
\]

and

\[
\begin{align*}
\beta_p &= i_{2p} \quad \text{for } p = 1, 2, \\
\beta_3 &= Sq^2 i_6, \\
\beta_4 &= (Sq^6 Sq^2 + Sq^8) i_8.
\end{align*}
\]

4. Applications.

Definition. A manifold \( M \) is \( k \)-parallelizable if for every complex \( K \) of dimension \( \leq k \), and for every map \( f: K \to M \), the bundle induced from the tangent bundle of \( M \) is trivial.

Theorem. A \( k \)-parallelizable differentiable manifold of dimension less than \( 2^{\phi(0,k)+1} \) is cobordic to zero (in the unoriented sense).

Proof. Let \( j \leq k \) with \( j = 0, 1, 2, 4 \) (8) and such that there is no integer \( u \) with \( j < u \leq k \) and \( u = 0, 1, 2, 4 \) (8). Then \( \phi(0,j) = \phi(0,k) \) and so we may assume \( k = 0, 1, 2, 4 \) (8).

Since \( M^n \) is \( k \)-parallelizable, the classifying map \( \tau: M^n \to BO \) for the tangent bundle induces the zero map in homotopy in dimensions less than or equal to \( k \). Thus \( \tau \) lifts to a map \( \tilde{\tau}: M^n \to BO(k, \cdots, \infty) \) and in the induced map on cohomology, the class of dimension \( k \) goes to zero.

Thus \( \tau^*(H^*(BO)) = \tilde{\tau}^*(Z_2[\theta_i \mid L(i) > \phi(0,k)]) \), or \( w_i(M^n) = 0 \) for \( i < 2^{\phi(0,k)} \). Thus \( v_i(M^n) = \tau^*(v_i) = 0 \) for \( i < 2^{\phi(0,k)} \), where \( v_i \) are defined by the equations \( w_p = \sum_{r=0}^p Sq^{p-r} v_r \). Since \( n < 2^{\phi(0,k)+1} \), \( n/2 < 2^{\phi(0,k)} \) and \( v_i(M^n) = 0 \) for \( i > n/2 \) or \( i \geq 2^{\phi(0,k)} \).

Then \( v_i(M^n) = 0 \) if \( i > 0 \) or \( w_i(M^n) = 0 \) for all \( i > 0 \). Thus all Whitney classes and numbers of \( M^n \) are zero so \( M^n \) is cobordic to zero.

Definition. A manifold \( M^n \) is weakly complex if the structure group of the bundle of \( M^n \) is reducible to the unitary group.

Theorem. A \( k \)-parallelizable weakly complex differentiable manifold of dimension less than \( 2^{(k/2)+2} \) is cobordic to zero (in the unoriented sense).
Proof. Being weakly complex, the classifying map for the tangent bundle of \( M^n \) lifts to \( BU \), and then to \( BU(2[k/2], \cdots, \infty) \) by \( k \)-parallelizability. Further, the class of dimension \( 2[k/2] \) in cohomology goes to zero in \( M^n \). Thus \( \tau^*(H^*(BO)) = \tau^*(H^*(BU)) = \tau^*(Z_{2i}[\theta_{2i}\theta(2i) > [k/2] + 1]) \), or \( w_i(M^n) = 0 \) for \( i < 2[k/2]+1 \). As in the preceding theorem \( M^n \) is then cobordicto zero for \( n < 2(k/2)+2 \).

Note. \( [k/2] + 2 \equiv \phi(0, k) + 1 \), and \( [k/2] + 2 > \phi(0, k) + 1 \) for \( k \equiv 0, 6, 7 \) (modulo 8).

REFERENCES


United States Army