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THE STEENROD ALGEBRA AND ITS DUAL[1]

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1. Summary

Let $\mathscr{S}^*$ denote the Steenrod algebra corrresponding to an odd prime p. (See §2 for definitions.) Our basic results (§3) is that $\mathscr{S}^*$ is a Hopf algebra. That is in addition to the product operation

$$\mathscr{S}^* \otimes \mathscr{S}^* \xrightarrow{\phi^*} \mathscr{S}^*$$

there is a homomorphism

$$\mathscr{S}^* \xrightarrow{\psi^*} \mathscr{S}^* \otimes \mathscr{S}^*$$

satisfying certain conditions. This homomorphism ψ^* relates the cup product structure in any cohomology ring $H^*(K, Z_p)$ with the action of $\mathscr{S}^*$ on $H^*(K, Z_p)$. For example if $\mathscr{P}^n \in \mathscr{S}^{2n(p-1)}$ denotes a Steenrod reduced p^{th} power then

$$\psi^*(\mathscr{P}^n) = \mathscr{P}^n \otimes 1 + \mathscr{P}^{n-1} \otimes \mathscr{P}^1 + \cdots + 1 \otimes \mathscr{P}^n .$$

The Hopf algebra

$$\mathscr{S}^* \xrightarrow{\psi^*} \mathscr{S}^* \otimes \mathscr{S}^* \xrightarrow{\phi^*} \mathscr{S}^*$$

has a dual Hopf algebra

$$\mathscr{S}_* \xleftarrow{\psi_*} \mathscr{S}_* \otimes \mathscr{S}_* \xleftarrow{\phi_*} \mathscr{S}_* .$$

The main tool in the study of this dual algebra is a homomorphism

$$\lambda^* \colon H^*(K, Z_p) \to H^*(K, Z_p) \otimes \mathscr{S}_*$$

which takes the place of the action of $\mathscr{S}^*$ on $H^*(K, Z_p)$. (See §4.) The dual Hopf algebra turns out to have a comparatively simple structure. In fact as an algebra (ignoring the "diagonal homomorphism" ϕ_*) it has the form

$$E(\tau_0, 1) \otimes E(\tau_1, 2p-1) \otimes \cdots \otimes P(\xi_1, 2p-2) \otimes P(\xi_2, 2p^2-2) \otimes \cdots ,$$

where $E(\tau_i, 2p^i - 1)$ denotes the Grassmann algebra generated by a certain element $\tau_i \in \mathscr{S}_{2p^i-1}$, and $P(\xi_i, 2p^i - 2)$ denotes the polynomial algebra generated by $\xi_i \in \mathscr{S}_{2p^i-2}$.

[1] The author holds an Alfred P. Sloan fellowship.

In §6 the above information about $\mathscr{S}_*$ is used to give a new description of the Steenrod algebra $\mathscr{S}^*$. An additive basis is given consisting of elements

$$Q_0^{\varepsilon_0}Q_1^{\varepsilon_1}\cdots\mathscr{P}^{r_1r_2\cdots}$$

with $\varepsilon_i = 0, 1$; $r_i \geqq 0$. Here the elements Q_i can be defined inductively by

$$Q_0 = \delta,\ Q_{i+1} = \mathscr{P}^{p^i}Q_i - Q_i\mathscr{P}^{p^i}\ ;$$

while each $\mathscr{P}^{r_1\cdots r_k}$ is a certain polynomial in the Steenrod operations,[2] of dimension

$$r_1(2p-2) + r_2(2p^2-2) + \cdots + r_k(2p^k-2)\ .$$

The product operation and the diagonal homomorphism in $\mathscr{S}^*$ are explicitly computed with respect to this basis.

The Steenrod algebra has a canonical anti-automorphism which was first studied by R. Thom. This anti-automorphism is computed in §7. Section 8 is devoted to miscellaneous remarks. The equation $\theta\mathscr{P}^1 = 0$ is studied; and a proof is given that $\mathscr{S}^*$ is nil-potent.

A brief appendix is devoted to the case $p = 2$. Since the sign conventions used in this paper are not the usual ones (see §2), a second appendix is concerned with the changes necessary in order to use standard sign conventions.

2. Prerequisites: sign conventions, Hopf algebras, the Steenrod algebra

If a and b are any two objects to which dimensions can be assigned, then whenever a and b are interchanged the sign $(-1)^{\dim a \dim b}$ will be introduced. For example the formula for the relationship between the homology cross product and the cohomology cross product becomes

$$(1)\qquad \langle \mu \times \nu, \alpha \times \beta \rangle = (-1)^{\dim \nu \dim \alpha}\langle \mu, \alpha \rangle \langle \nu, \beta \rangle\ .$$

This contradicts the usual usage in which no sign is introduced. In the same spirit we will call a graded algebra *commutative* if

$$ab = (-1)^{\dim a \dim b}\, ba\ .$$

Let $A = (\cdots, A_{-1}, A_0, A_1, \cdots)$ be a graded vector space over a field F. The dual A' is defined by $A'_n = \mathrm{Hom}\,(A_{-n}, F)$. The value of a homomorphism a' on $a \in A$ will be denoted by $\langle a', a \rangle$. It is understood that $\langle a', a \rangle = 0$ unless $\dim a' + \dim a = 0$. (By an element of A we mean an element of some A_n.) Similarly we can define the dual A'' of A'. Identify

[2] This has no relation to the generalized Steenrod operations $\mathscr{P}^I$ defined by Adem.

each $a \in A$ with the element $a'' \in A''$ which satisfies

$$\langle a'', a' \rangle = (-1)^{\dim a'' \dim a'} \langle a', a \rangle \tag{2}$$

for each $a' \in A'$. Thus every graded vector space A is contained in its double dual A''. If A is of finite type (that is if each A_n is a finite dimensional vector space) then A is equal to A''.

Now if $f\colon A \to B$ is a homomorphism of degree zero then $f'\colon B' \to A'$ and $f''\colon A'' \to B''$ are defined in the usual way. If A and B are both of finite type it is clear that $f = f''$.

The tensor product $A \otimes B$ is defined by $(A \otimes B)_n = \sum_{i+j=n} A_i \otimes B_j$, where "$\sum$" stands for "direct sum". If A and B are both of finite type and if $A_i = B_i = 0$ for all sufficiently small i (or for all sufficiently large i) then the product $A \otimes B$ is also of finite type. In this case the dual $(A \otimes B)'$ can be identified with $A' \otimes B'$ under the rule

$$\langle a' \otimes b', a \otimes b \rangle = (-1)^{\dim a \dim b'} \langle a', a \rangle \langle b', b \rangle . \tag{3}$$

In practice we will use the notation A_* for a graded vector space A satisfying the condition $A_i = 0$ for $i < 0$. The dual will then be denoted by A^* where $A^n = A'_{-n} = \mathrm{Hom}(A_n, F)$. A similar notation will be used for homomorphisms.

By a *graded algebra* (A_*, ψ_*) is meant a graded vector space A_* together with a homomorphism

$$\psi_*\colon A_* \otimes A_* \to A_* .$$

It is usually required that ψ_* be associative and have a unit element $1 \in A_0$. The algebra is *connected* if the vector space A_0 is generated by 1.

By a *connected Hopf algebra* (A_*, ψ_*, ϕ_*) is meant a connected graded algebra with unit (A_*, ψ_*), together with a homomorphism

$$\phi_*\colon A_* \to A_* \otimes A_*$$

satisfying the following two conditions.

2.1. ϕ_* is a homomorphism of algebras with unit. Here we refer to the product operation ψ_* in A_* and the product

$$(a_1 \otimes a_2)\cdot(a_3 \otimes a_4) = (-1)^{\dim a_2 \dim a_3} (a_1 \cdot a_3) \otimes (a_2 \cdot a_4)$$

in $A_* \otimes A_*$.

2.2. For $\dim a > 0$, the element $\phi_*(a)$ has the form $a \otimes 1 + 1 \otimes a + \sum b_i \otimes c_i$ with $\dim b_i$, $\dim c_i > 0$.

Appropriate concepts of associativity and commutativity are defined, not only for the product operation ψ_*, but also for the diagonal homomorphisms ϕ_*. (See Milnor and Moore [3]).

To every connected Hopf algebra (A_*, ψ_*, ϕ_*) of finite type there is associated the *dual Hopf algebra* (A^*, ϕ^*, ψ^*), where the homomorphisms

$$A^* \xrightarrow{\psi^*} A^* \otimes A^* \xrightarrow{\phi_*} A^*$$

are the duals in the sense explained above. For the proof that the dual is again a Hopf algebra see [3].

(As an example, for any connected Lie group G the maps $G \xrightarrow{d} G \times G \xrightarrow{p} G$ give rise to a Hopf algebra $(H_*(G), p_*, d_*)$. The dual algebra $(H^*(G), \smile, p^*)$ is essentially the example which was originally studied by Hopf.)

For any complex K the Steenrod operation $\mathscr{P}^i$ is a homomorphism

$$\mathscr{P}^i\colon H^j(K, Z_p) \to H^{j+2i(p-1)}(K, Z_p) .$$

The basic properties of these operations are the following. (See Steenrod [4].)

2.3. Naturality. If f maps K into L then $f^*\mathscr{P}^i = \mathscr{P}^i f^*$.

2.4. For $\alpha \in H^j(K, Z_p)$, if $i > j/2$ then $\mathscr{P}^i\alpha = 0$. If $i = j/2$ then $\mathscr{P}^i\alpha = \alpha^p$. If $i = 0$ then $\mathscr{P}^i\alpha = \alpha$.

2.5. $\mathscr{P}^n(\alpha \smile \beta) = \sum_{i+j=n} \mathscr{P}^i\alpha \smile \mathscr{P}^j\beta$.

We will also make use of the coboundary operation $\delta\colon H^j(K, Z_p) \to H^{j+1}(K, Z_p)$ associated with the coefficient sequence

$$0 \to Z_p \to Z_{p^2} \to Z_p \to 0 .$$

The most important properties here are

2.6. $\delta\delta = 0$ and

2.7. $\delta(\alpha \smile \beta) = (\delta\alpha) \smile \beta + (-1)^{\dim \alpha}\alpha \smile \delta\beta$, as well as the naturality condition.

Following Adem [1] the Steenrod algebra $\mathscr{S}^*$ is defined as follows. The free associative graded algebra $\mathscr{F}^*$ generated by the symbols δ, $\mathscr{P}^0$, $\mathscr{P}^1$, $\cdots$ acts on any cohomology ring $H^*(K, Z_p)$ by the rule $(\theta_1\theta_2 \cdots \theta_k)\cdot\alpha = (\theta_1(\theta_2 \cdots (\theta_k\alpha) \cdots))$. (It is understood that δ has dimension 1 in $\mathscr{F}^*$ and that $\mathscr{P}^i$ has dimension $2i(p-1)$.) Let $\mathscr{I}^*$ denote the ideal consisting of all $f \in \mathscr{F}^*$ such that $f\alpha = 0$ for all complexes K and all cohomology classes $\alpha \in H^*(K, Z_p)$. Then $\mathscr{S}^*$ is defined as the quotient algebra $\mathscr{F}^*/\mathscr{I}^*$. It is clear that $\mathscr{S}^*$ is a connected graded associative algebra of finite type over Z_p. However $\mathscr{S}^*$ is not commutative.

(For an alternative definition of the Steenrod algebra see Cartan [2]. The most important difference is that Cartan adds a sign to the operation δ.)

The above definition is non-constructive. However it has been shown by Adem and Cartan that $\mathscr{S}^*$ is generated additively by the "basic monomials"

$$\delta^{\varepsilon_0}\mathscr{P}^{s_1}\delta^{\varepsilon_1}\cdots\mathscr{P}^{s_k}\delta^{\varepsilon_k}$$

where each ε_i is zero or 1 and

$$s_1 \geqq ps_2 + \varepsilon_1,\ s_2 \geqq ps_3 + \varepsilon_2,\ \cdots,\ s_{k-1} \geqq ps_k + \varepsilon_{k-1},\ s_k \geqq 1\ .$$

Furthermore Cartan has shown that these elements form an additive basis for $\mathscr{S}^*$.

3. The homomorphism ψ^*

LEMMA 1. *For each element θ of $\mathscr{S}^*$ there is a unique element $\psi^*(\theta) = \sum \theta'_i \otimes \theta''_i$ of $\mathscr{S}^* \otimes \mathscr{S}^*$ such that the identity*

$$\theta(\alpha \smile \beta) = \sum (-1)^{\dim\theta''_i \dim\alpha}\, \theta'_i(\alpha) \smile \theta''_i(\beta)$$

is satisfied for all complexes K and all elements $\alpha, \beta \in H^*(K)$. Furthermore

$$\mathscr{S}^* \xrightarrow{\psi^*} \mathscr{S}^* \otimes \mathscr{S}^*$$

is a ring homomorphism.

(By an "element" of a graded module we mean a homogeneous element. The coefficient group Z_p is to be understood.)

It will be convenient to let $\mathscr{S}^* \otimes \mathscr{S}^*$ act on $H^*(X) \otimes H^*(X)$ by the rule

$$(\theta' \otimes \theta'')(\alpha \otimes \beta) = (-1)^{\dim\theta'' \dim\alpha}\, \theta'(\alpha) \otimes \theta''(\beta)\ .$$

Let $c\colon H^*(X) \otimes H^*(X) \to H^*(X)$ denote the cup product. The required identity can now be written as

$$\theta c(\alpha \otimes \beta) = c\psi^*(\theta)(\alpha \otimes \beta)\ .$$

PROOF OF EXISTENCE. Let $\mathscr{R}$ denote the subset of $\mathscr{S}^*$ consisting of all θ such that for some $\rho \in \mathscr{S}^* \otimes \mathscr{S}^*$ the required identity

$$\theta c(\alpha \otimes \beta) = c\rho(\alpha \otimes \beta)$$

is satisfied. We must show that $\mathscr{R} = \mathscr{S}^*$.

The identities

$$\delta(\alpha \smile \beta) = \delta\alpha \smile \beta + (-1)^{\dim\alpha}\, \alpha \smile \delta\beta$$

and

$$\mathscr{P}^n(\alpha \smile \beta) = \textstyle\sum_{i+j=n} \mathscr{P}^i\alpha \smile \mathscr{P}^j\beta$$

clearly show that the operations δ and $\mathscr{P}^n$ belong to $\mathscr{R}$. If θ_1, θ_2 belong to $\mathscr{R}$ then the identity

$$\theta_1\theta_2 c(\alpha \otimes \beta) = \theta_1 c\rho_2(\alpha \otimes \beta) = c\rho_1\rho_2(\alpha \otimes \beta)$$

show that $\theta_1\theta_2$ belongs to $\mathscr{R}$. Similarly $\mathscr{R}$ is closed under addition. Thus $\mathscr{R}$ is a subalgebra of $\mathscr{S}^*$ which contains the generators δ, $\mathscr{P}^n$ of $\mathscr{S}^*$. This proves that $\mathscr{R} = \mathscr{S}^*$.

PROOF OF UNIQUENESS. From the definition of the Steenrod algebra we see that given an integer n we can choose a complex Y and an element $\gamma \in H^*(Y)$ so that the correspondence

$$\theta \to \theta\gamma$$

defines an isomorphism of $\mathscr{S}^i$ into $H^{k+i}(Y)$ for $i \leqq n$. (For example take $Y = K(Z_p, k)$ with $k > n$.) It follows that the correspondence

$$\theta' \otimes \theta'' \xrightarrow{j} (-1)^{\dim\theta'' \dim\gamma}\, \theta'(\gamma) \times \theta''(\gamma)$$

defines an isomorphism j of $(\mathscr{S}^* \otimes \mathscr{S}^*)^i$ into $H^{2k+i}(Y \times Y)$ for $i \leqq n$.

Now suppose that $\rho_1, \rho_2 \in \mathscr{S}^* \otimes \mathscr{S}^*$ both satisfy the identity $\theta c(\alpha \otimes \beta) = c\rho_i(\alpha \otimes \beta)$ for the same element θ of $\mathscr{S}^n$. Taking $X = Y \times Y$, $\alpha = \gamma \times 1$, $\beta = 1 \times \gamma$, we have $c\rho_i(\alpha \otimes \beta) = j(\rho_i)$. But the equality $j(\rho_1) = j(\rho_2)$ with $\dim \rho_1 = \dim \rho_2 = n$ implies that $\rho_1 = \rho_2$. This completes the uniqueness proof. Since the assertion that ψ^* is a ring homomorphism follows easily from the proof used in the existence argument, this completes the proof.

As a biproduct of the proof we have the following explicit formulas:

$$\psi^*(\delta) = \delta \otimes 1 + 1 \otimes \delta$$

$$\psi^*(\mathscr{P}^n) = \mathscr{P}^n \otimes 1 + \mathscr{P}^{n-1} \otimes \mathscr{P}^1 + \cdots + 1 \otimes \mathscr{P}^n .$$

THEOREM 1. *The homomorphisms*

$$\mathscr{S}^* \xrightarrow{\psi^*} \mathscr{S}^* \otimes \mathscr{S}^* \xrightarrow{\phi^*} \mathscr{S}^*$$

give $\mathscr{S}^*$ the structure of a Hopf algebra. Furthermore the product ϕ^* is associative and the "diagonal homomorphism" ψ^* is both associative and commutative.

PROOF. It is known that $(\mathscr{S}^*, \phi^*)$ is a connected algebra with unit; and that ψ^* is a ring homomorphism. Hence to show that $\mathscr{S}^*$ is a Hopf algebra it is only necessary to verify Condition 2.2. But this condition is clearly satisfied for the generators δ, and $\mathscr{P}^n$ of $\mathscr{S}^*$, which implies that it is satisfied for all positive dimensional elements of $\mathscr{S}^*$.

It is also known that the product ϕ^* is associative. The assertions that ψ^* is associative and commutative are expressed by the identities

$$(1) \qquad (\psi^* \otimes 1)\psi^*\theta = (1 \otimes \psi^*)\psi^*\theta ,$$

$$(2) \qquad T\psi^*\theta = \psi^*\theta$$

for all θ, where $T(\theta' \otimes \theta'')$ is defined as $(-1)^{\dim \theta' \dim \theta''} \theta'' \otimes \theta'$. Both identities are clearly satisfied if θ is one of the generators δ or $\mathscr{P}^n$ of $\mathscr{S}^*$. But since each of the homomorphisms in question is a ring homomorphism, this completes the proof.

As an immediate consequence we have:

COROLLARY 1. *There is a dual Hopf algebra*

$$\mathscr{S}_* \xrightarrow{\phi_*} \mathscr{S}_* \otimes \mathscr{S}_* \xrightarrow{\psi_*} \mathscr{S}_*$$

with associative, commutative product operation.

4. The homomorphism λ^*

Let H_*, H^* denote the homology and cohomology, with coefficients Z_p, of a finite complex. The action of $\mathscr{S}^*$ on H^* gives rise to an action of $\mathscr{S}^*$ on H_* which is defined by the rule:

$$\langle \mu\theta, \alpha \rangle = \langle \mu, \theta\alpha \rangle$$

for all $\mu \in H_*$, $\theta \in \mathscr{S}^*$, $\alpha \in H^*$. This action can be considered as a homomorphism

$$\lambda_*: H_* \otimes \mathscr{S}^* \to H_* .$$

The dual homomorphism

$$\lambda^*: H^* \to H^* \otimes \mathscr{S}_*$$

will be the subject of this section.

Alternatively, the restricted homomorphism $H_{n+i} \otimes \mathscr{S}^i \to H_n$ has a dual which we will denote by

$$\lambda^i: H^n \to H^{n+i} \otimes \mathscr{S}_i .$$

In this terminology we have

$$\lambda^* = \lambda^0 + \lambda^1 + \lambda^2 + \cdots$$

carrying H^n into $\sum_i H^{n+i} \otimes \mathscr{S}_i$. The condition that H^* be the cohomology of a finite complex is essential here, since otherwise λ^* would be an infinite sum.

The identity

$$\mu(\theta_1\theta_2) = (\mu\theta_1)\theta_2$$

can easily be derived from the identity $(\theta_1\theta_2)\alpha = \theta_1(\theta_2\alpha)$ which is used to define the product operation in $\mathscr{S}^*$. In other words the diagram

$$\begin{array}{ccc} H_* \otimes \mathcal{S}^* \otimes \mathcal{S}^* & \xrightarrow{1 \otimes \phi^*} & H_* \otimes \mathcal{S}^* \\ \downarrow{\scriptstyle \lambda_* \otimes 1} & & \downarrow{\scriptstyle \lambda_*} \\ H_* \otimes \mathcal{S}^* & \xrightarrow{\lambda_*} & H_* \end{array}$$

is commutative. Therefore the dual diagram

$$\begin{array}{ccc} H^* \otimes \mathcal{S}_* \otimes \mathcal{S}_* & \xleftarrow{1 \otimes \phi_*} & H^* \otimes \mathcal{S}_* \\ \uparrow{\scriptstyle \lambda^* \otimes 1} & & \uparrow{\scriptstyle \lambda^*} \\ H^* \otimes \mathcal{S}_* & \xleftarrow{\lambda^*} & H^* \end{array}$$

is also commutative. Thus we have proved:

LEMMA 2. *The identity*

$$(\lambda^* \otimes 1)\lambda^*(\alpha) = (1 \otimes \phi_*)\lambda^*(\alpha)$$

holds for every $\alpha \in H^*$.

The cup product in H^* and the ψ_* product in $\mathcal{S}_*$ induce a product operation in $H^* \otimes \mathcal{S}_*$.

LEMMA 3. *The homomorphism* $\lambda^*: H^* \to H^* \otimes \mathcal{S}_*$ *is a ring homomorphism.*

PROOF. Let K and L be finite complexes, let θ be an element of $\mathcal{S}^*$, and let $\psi^*(\theta) = \sum \theta'_i \otimes \theta''_i$. Then for any $\alpha \in H^*(K)$, $\beta \in H^*(L)$ we have $\theta\cdot(\alpha \times \beta) = \sum (-1)^{\dim \theta''_i \dim \alpha}\, \theta'_i\alpha \times \theta''_i\beta$. Using the rule

$$\langle \mu \times \nu, \theta\cdot(\alpha \times \beta)\rangle = \langle (\mu \times \nu)\cdot\theta, \alpha \times \beta\rangle$$

we easily arive at the identity

$$(\mu \times \nu)\cdot\theta = \sum (-1)^{\dim \nu \dim \theta'_i}\, \mu\theta'_i \times \nu\theta''_i\ .$$

In other words the diagram

$$\begin{array}{ccccc} H_*(K) \otimes H_*(L) \otimes \mathcal{S}^* \otimes \mathcal{S}^* & \xleftarrow{1 \otimes 1 \otimes \psi^*} & H_*(K) \otimes H_*(L) \otimes \mathcal{S}^* & = & H_*(K \times L) \otimes \mathcal{S}^* \\ \downarrow{\scriptstyle 1 \otimes T \otimes 1} & & & & \downarrow{\scriptstyle \lambda_*} \\ H_*(K) \otimes \mathcal{S}^* \otimes H_*(L) \otimes \mathcal{S}^* & \xrightarrow{\lambda_* \otimes \lambda_*} & H_*(K) \otimes H_*(L) & = & H_*(K \times L) \end{array}$$

is commutative (where T interchanges two factors as in §3). Therefore the dual diagram is also commutative. Setting $K = L$, and letting $d: K \to K \times K$ be the diagonal homomorphism we obtain a larger commutative diagram

$$\begin{array}{ccccccc} H^* \otimes H^* \otimes \mathcal{S}_* \otimes \mathcal{S}_* & \xrightarrow{1 \otimes 1 \otimes \psi_*} & H^* \otimes H^* \otimes \mathcal{S}_* & = & H^*(K \times K) \otimes \mathcal{S}_* & \xrightarrow{d^* \otimes 1} & H^* \otimes \mathcal{S}_* \\ \uparrow{\scriptstyle 1 \otimes T \otimes 1} & & & & \uparrow{\scriptstyle \lambda^*} & & \uparrow{\scriptstyle \lambda^*} \\ H^* \otimes \mathcal{S}_* \otimes H^* \otimes \mathcal{S}_* & \xleftarrow{\lambda^* \otimes \lambda^*} & H^* \otimes H^* & = & H^*(K \times K) & \xrightarrow{d^*} & H^* \end{array}$$

Now starting with $\alpha \otimes \beta \in H^* \otimes H^*$ and proceeding to the right and up in this diagram, we obtain $\lambda^*(\alpha \smile \beta)$. Proceeding to the left and up, and then to the right, we obtain $\lambda^*(\alpha)\cdot\lambda^*(\beta)$. Therefore

$$\lambda^*(\alpha\beta) = \lambda^*(\alpha)\lambda^*(\beta)$$

which proves Lemma 3.

The following lemma shows how the action of $\mathscr{S}^*$ on $H^*(K)$ can be reconstructed from the homomorphism λ^*.

LEMMA 4. *If $\lambda^*(\alpha) = \sum \alpha_i \otimes \omega_i$ then for any $\theta \in \mathscr{S}^*$ we have*

$$\theta\alpha = \sum (-1)^{\dim \alpha_i \dim \omega_i} \langle \theta, \omega_i \rangle \alpha_i \, .$$

PROOF. By definition

$$\begin{aligned} \langle \mu, \theta\alpha \rangle &= \langle \mu\theta, \alpha \rangle = \langle \lambda_*(\mu \otimes \theta), \alpha \rangle \\ &= \langle \mu \otimes \theta, \lambda^*\alpha \rangle = \sum \pm \langle \mu, \alpha_i \rangle \langle \theta, \omega_i \rangle \, . \end{aligned}$$

Since this holds for each $\mu \in H_*$, the above equality holds.

REMARK. To complete the picture, the operation $\eta^*: \mathscr{S}^* \otimes H^* \to H^*$ has a dual $\eta_*: H_* \to \mathscr{S}_* \otimes H_*$. Analogues of Lemmas 2 and 4 are easily obtained for η_*. If a product operation $K \times K \to K$ is given, so that H_*, and hence $\mathscr{S}_* \otimes H_*$, have product operations; then a straightforward proof shows that η_* is a ring homomorphism. (As an example let K denote the loop space of an $(n+1)$-sphere, or an equivalent CW-complex. Then $H_*(K)$ is known to be a polynomial ring on one generator $\mu \in H_n(K)$. The element

$$\eta_*(\mu) \in (\mathscr{S}_0 \otimes H_n) \oplus (\mathscr{S}_1 \otimes H_{n-1}) \oplus \cdots \oplus (\mathscr{S}_n \otimes H_0)$$

is evidently equal to $1 \otimes \mu$. Therefore $\eta_*(\mu^k) = 1 \otimes \mu^k$ for all k. Passing to the dual, this proves that the action of $\mathscr{S}^*$ on $H^*(K)$ is trivial.)

5. The structure of the dual algebra $\mathscr{S}_*$

As an example to illustrate this operation λ^* consider the Lens space $X = S^{2N+1}/Z_p$ where N is a large integer, and where the cyclic group Z_p acts freely on the sphere S^{2N+1}. Thus X can be considered as the $(2N+1)$-skeleton of the Eilenberg-MacLane space $K(Z_p, 1)$. The cohomology ring $H^*(X)$ is known to have the following form. There is a generator $\alpha \in H^1(X)$ and $H^2(X)$ is generated by $\beta = \delta\alpha$. For $0 \leqq i \leqq N$, the group $H^{2i}(X)$ is generated by β^i and $H^{2i+1}(X)$ is generated by $\alpha\beta^i$.

The action of the Steenrod algebra on $H^*(X)$ is described as follows. It will be convenient to introduce the abbreviations

$$M_0 = 1 \, , \; M_1 = \mathscr{P}^1 \, , \; M_2 = \mathscr{P}^p \mathscr{P}^1, \cdots, M_k = \mathscr{P}^{p^{k-1}} \cdots \mathscr{P}^p \mathscr{P}^1, \cdots \, .$$

LEMMA 5. *The element* $M_k \in \mathscr{S}^{2p^k-2}$ *satisfies* $M_k\beta = \beta^{p^k}$. *However if* θ *is any monomial in the operations* δ, $\mathscr{P}^1$, $\mathscr{P}^2$, $\cdots$ *which is not of the form* $\mathscr{P}^{p^{k-1}} \cdots \mathscr{P}^p\mathscr{P}^1$ *then* $\theta\beta = 0$. *Similarly* $(M_k\delta)\alpha = \beta^{p^k}$ *but* $\theta\alpha = 0$ *if* θ *is any monomial in the operations* δ, $\mathscr{P}^1$, $\mathscr{P}^2$, $\cdots$ *which does not have the form* $\theta = \mathscr{P}^{p^{k-1}} \cdots \mathscr{P}^1\delta$ *or* $\theta = 1$.

PROOF. It is convenient to introduce the formal operation $\mathscr{P} = 1 + \mathscr{P}^1 + \mathscr{P}^2 + \cdots$. It follows from 2.4 that $\mathscr{P}\beta = \beta + \beta^p$. Since $\mathscr{P}$ is a ring homomorphism according to 2.5, it follows that $\mathscr{P}\beta^i = (\beta + \beta^p)^i$. In particular if $i = p^r$ this gives $\mathscr{P}\beta^{p^r} = (\beta + \beta^p)^{p^r} = \beta^{p^r} + \beta^{p^{r+1}}$. In other words

$$\mathscr{P}^j\beta^{p^r} = \begin{cases} \beta^{p^r} & \text{if } j = 0 \\ \beta^{p^{r+1}} & \text{if } j = p^r \\ 0 & \text{otherwise} . \end{cases}$$

Since $\delta\beta^i = i\beta^{i-1}\delta\beta = i\beta^{i-1}\delta\delta\alpha = 0$ it follows that the only nontrivial operation δ or $\mathscr{P}^j$ which can act on β^{p^r} is $\mathscr{P}^{p^r}$. Using induction, this proves the first assertion of Lemma 5. To prove the second it is only necessary to add that $\mathscr{P}^j\alpha = 0$ for all $j > 0$, according to 2.4.

Now consider the operation $\lambda^*\colon H^*(X) \to H^*(X) \otimes \mathscr{S}_*$.

LEMMA 6. *The element* $\lambda^*\alpha$ *has the form* $\alpha \otimes 1 + \beta \otimes \tau_0 + \beta^p \otimes \tau_1 + \cdots + \beta^{p^r} \otimes \tau_r$ *where each* τ_k *is a well defined element of* $\mathscr{S}_{2p^k-1}$, *and where* p^r *is the largest power of* p *with* $p^r \leqq N$. *Similarly* $\lambda^*\beta$ *has the form*

$$\beta \otimes \xi_0 + \beta^p \otimes \xi_1 + \cdots + \beta^{p^r} \otimes \xi_r ,$$

where $\xi_0 = 1$, *and where each* ξ_k *is a well defined element of* $\mathscr{S}_{2p^k-2}$.

PROOF. For any element θ of $\mathscr{S}^i$, Lemma 5 implies that $\theta\beta = 0$ unless i is the dimension of one of the monomials $M_0, M_1, \cdots$: that is unless i has the form $2p^k - 2$. Therefore, according to Lemma 4, we see that $\lambda^i\beta = 0$ unless i has the form $2p^k - 2$. Thus

$$\lambda^*\beta = \lambda^0(\beta) + \lambda^{2p-2}(\beta) + \cdots + \lambda^{2p^r-2}(\beta) .$$

Since $\lambda^{2p^k-2}(\beta)$ belongs to $H^{2p^k}(X) \otimes \mathscr{S}_{2p^k-2}$, it must have the form $\beta^{p^k} \otimes \xi_k$ for some uniquely defined element ξ_k. This proves the second assertion of Lemma 6. The first assertion is proved by a similar argument.

REMARK. These elements ξ_k and τ_k have been defined only for $k \leqq r = [\log_p N]$. However the integer N can be chosen arbitrarily large, so we have actually defined ξ_k and τ_k for all $k \geqq 0$.

Our main theorem can now be stated as follows.

THEOREM 2. *The algebra* $\mathscr{S}_*$ *is the tensor product of the Grassmann algebra generated by* $\tau_0, \tau_1, \cdots$ *and the polynomial algebra generated by* $\xi_1, \xi_2, \cdots$.

The proof will be based on a computation of the inner products of monomials in τ_i and ξ_j with monomials in the operations $\mathscr{P}^n$ and δ. The following lemma is an immediate consequence of Lemmas 4, 5 and 6.

LEMMA 7. *The inner product*

$$\langle M_k, \xi_k \rangle$$

equals one, but $\langle \theta, \xi_k \rangle = 0$ *if* θ *is any other monomial. Similarly*

$$\langle M_k\delta, \tau_k \rangle = 1$$

but $\langle \theta, \tau_k \rangle = 0$ *if* θ *is any other monomial.*

Consider the set of all finite sequences $I = (\varepsilon_0, r_1, \varepsilon_1, r_2, \cdots)$ where $\varepsilon_i = 0, 1$ and $r_i = 0, 1, 2, \cdots$. For each such I define

$$\omega(I) = \tau_0^{\varepsilon_0}\xi_1^{r_1}\tau_1^{\varepsilon_1}\xi_2^{r_2} \cdots .$$

Then we must prove that the collection $\{\omega(I)\}$ forms an additive basis for $\mathscr{S}_*$.

For each such I define

$$\theta(I) = \delta^{\varepsilon_0}\mathscr{P}^{s_1}\delta^{\varepsilon_1}\mathscr{P}^{s_2} \cdots$$

where

$$s_1 = \textstyle\sum_{i=1}^{\infty} (\varepsilon_i + r_i)p^{i-1}, \cdots, \; s_k = \sum_{i=k}^{\infty} (\varepsilon_i + r_i)p^{i-k} .$$

It is not hard to verify that these elements $\theta(I)$ are exactly the "basic monomials" of Adem or Cartan. Furthermore $\theta(I)$ has the same dimension as $\omega(I)$. Order the collection $\{I\}$ lexicographically from the right. (For example $(1, 2, 0, \cdots) < (0, 0, 1, \cdots)$.)

LEMMA 8. *The inner product* $\langle \theta(I), \omega(J) \rangle$ *is equal to zero if* $I < J$ *and* ± 1 *if* $I = J$.

Assuming this lemma for the moment, the proof of Theorem 2 can be completed as follows. If we restrict attention to sequences I such that

$$\dim \omega(I) = \dim \theta(I) = n ,$$

then Lemma 8 asserts that the resulting matrix $\langle \theta(I), \omega(J) \rangle$ is a non-singular triangular matrix. But according to Adem or Cartan the elements $\theta(I)$ generate $\mathscr{S}^n$. Therefore the elements $\omega(J)$ must form a basis for $\mathscr{S}_n$; which proves Theorem 2. (Incidentally this gives a new proof of Cartan's assertion that the $\theta(I)$ are linearly independent.)

PROOF OF LEMMA 8. We will prove the assertion $\langle \theta(I), \omega(I) \rangle = \pm 1$ by induction on the dimension. It is certainly true in dimension zero.

Case 1. The last non-zero element of the sequence $I = (\varepsilon_0, r_1, \cdots, \varepsilon_{k-1}, r_k, 0, \cdots)$ is r_k. Set $I' = (\varepsilon_0, r_1, \cdots, \varepsilon_{k-1}, r_k - 1, 0, \cdots)$ so that $\omega(I) = \omega(I')\xi_k$. Then

$$\langle \theta(I), \omega(I) \rangle = \langle \theta(I), \psi_*(\omega(I') \otimes \xi_k) \rangle$$
$$= \langle \psi^*\theta(I), \omega(I') \otimes \xi_k \rangle .$$

Since $\theta(I) = \delta^{\varepsilon_0}\mathscr{P}^{s_1} \cdots \delta^{\varepsilon_{k-1}}\mathscr{P}^{s_k}$ we have

$$\psi^*\theta(I) = \sum \pm \delta^{\varepsilon_0'} \cdots \mathscr{P}^{s_k'} \otimes \delta^{\varepsilon_0''} \cdots \mathscr{P}^{s_k''}$$

where the summation extends over all sequences $(\varepsilon_0', \cdots, s_k')$ and $(\varepsilon_0'', \cdots, s_k'')$ with $\varepsilon_i' + \varepsilon_i'' = \varepsilon_i$ and $s_i' + s_i'' = s_i$. Substituting this in the previous expression we have

$$\langle \theta(I), \omega(I) \rangle = \sum \pm \langle \delta^{\varepsilon_0'} \cdots \mathscr{P}^{s_k'}, \omega(I') \rangle \langle \delta^{\varepsilon_0''} \cdots \mathscr{P}^{s_k''}, \xi_k \rangle .$$

But according to Lemma 7 the right hand factor is zero except for the special case

$$\delta^{\varepsilon_0''} \cdots \mathscr{P}^{s_k''} = \mathscr{P}^{p^{k-1}} \cdots \mathscr{P}^{p}\mathscr{P}^{1} ,$$

in which case the inner product is one. Inspection shows that the corresponding expression $\delta^{\varepsilon_0'} \cdots \mathscr{P}^{s_k'}$ on the left is equal to $\theta(I')$; and hence that $\langle \theta(I), \omega(I) \rangle = \pm \langle \theta(I'), \omega(I') \rangle = \pm 1$.

Case 2. The last non-zero element of $I = (\varepsilon_0, r_1, \cdots, r_k, \varepsilon_k, 0, \cdots)$ is $\varepsilon_k = 1$. Define $I' = (\varepsilon_0, r_1, \cdots, r_k, 0, \cdots)$ so that

$$\omega(I) = \omega(I')\tau_k .$$

Carrying out the same construction as before we find that the only non-vanishing right hand term is $\langle \mathscr{P}^{p^{k-1}} \cdots \mathscr{P}^{1}\delta, \tau_k \rangle = 1$. The corresponding left hand term is again $\langle \theta(I'), \omega(I') \rangle$; so that $\langle \theta(I), \omega(I) \rangle = \pm \langle \theta(I'), \omega(I') \rangle = \pm 1$, with completes the induction.

The proof that $\langle \theta(I), \omega(J) \rangle = 0$ for $I < J$ is carried out by a similar induction on the dimension.

Case 1a. The sequence J ends with the element r_k and the sequence I ends at the corresponding place. Then the argument used above shows that

$$\langle \theta(I), \omega(J) \rangle = \pm \langle \theta(I'), \omega(J') \rangle = 0 .$$

Case 1b. The sequence J ends with the elements r_k, but I ends earlier. Then in the expansion used above, every right hand factor

$$\langle \delta^{\varepsilon_0''}\mathscr{P}^{s_1''} \cdots \delta^{\varepsilon_{k-1}''}, \xi_k \rangle$$

is zero. Therefore $\langle \theta(I), \omega(J) \rangle = 0$.

Similarly Case 2 splits up into two subcases which are proved in an analogous way. This completes the proof of Lemma 8 and Theorem 2.

To complete the description of $\mathscr{S}_*$ as a Hopf algebra it is necessary to compute the homomorphism ϕ_*. But since ϕ_* is a ring homomorphism it is only necessary to evaluate it on the generators of S_*.

THEOREM 3. *The following formulas hold.*

$$\phi_*(\xi_k) = \sum_{i=0}^{k} \xi_{k-i}^{p^i} \otimes \xi_i$$
$$\phi_*(\tau_k) = \sum_{i=0}^{k} \xi_{k-i}^{p^i} \otimes \tau_i + \tau_k \otimes 1 .$$

The proof will be based on Lemmas 2 and 3. Raising both sides of the equation

$$\lambda^*(\beta) = \sum \beta^{p^j} \otimes \xi_j$$

to the power p^i we obtain

$$\lambda^*(\beta^{p^i}) = \sum \beta^{p^{i+j}} \otimes \xi_j^{p^i} .$$

Now

$$(\lambda^* \otimes 1)\lambda^*(\beta) = (\lambda^* \otimes 1) \sum \beta^{p^i} \otimes \xi_i$$
$$= \sum_{i,j} \beta^{p^{i+j}} \otimes \xi_j^{p^i} \otimes \xi_i .$$

Comparing this with

$$(1 \otimes \phi_*)\lambda^*(\beta) = \sum \beta^{p^k} \otimes \phi_*(\xi_k)$$

We obtain the required expression for $\phi_*(\xi_k)$.

Similarly the identity

$$(\lambda^* \otimes 1)\lambda^*(\alpha) = (1 \otimes \phi_*)\lambda^*(\alpha)$$

can be used to obtain the required formula for $\phi_*(\tau_k)$.

6. A basis for $\mathscr{S}^*$

Let $R = (r_1, r_2, \cdots)$ range over all sequences of non-negative integers which are almost all zero, and define $\xi(R) = \xi_1^{r_1}\xi_2^{r_2} \cdots$. Let $E = (\varepsilon_0, \varepsilon_1, \cdots)$ range over all sequences of zeros and ones which are almost all zero, and define $\tau(E) = \tau_0^{\varepsilon_0}\tau_1^{\varepsilon_1} \cdots$. Then Theorem 2 asserts that the elements

$$\{\tau(E)\xi(R)\}$$

form an additive basis for $\mathscr{S}_*$. Hence there is a dual basis $\{\rho(E, R)\}$ for $\mathscr{S}^*$. That is we define $\rho(E, R) \in \mathscr{S}^*$ by

$$\langle \rho(E, R), \tau(E')\xi(R') \rangle = \begin{cases} 1 & \text{if } \quad E = E',\ R = R' \\ 0 & \text{otherwise.} \end{cases}$$

Using Lemma 8 it is easily seen that $\rho(\mathbf{0}, (r, 0, 0, \cdots))$ is equal to the Steenrod power $\mathscr{P}^r$. This suggests that we define[2] $\mathscr{P}^R$ as the basis element $\rho(\mathbf{0}, R)$ dual to $\xi(R)$. (Abbreviations such as $\mathscr{P}^{01}$ in place of $\mathscr{P}^{(0,1,0,0,\cdots)}$ will be frequently be used.)

Let Q_k denote the basis element dual to τ_k. For example $Q_0 = \rho(1, 0, \cdots), \mathbf{0})$ is equal to the operation δ. It will turn out that any basis element $\rho(E, R)$ is equal to the product $\pm Q_0^{\varepsilon_0} Q_1^{\varepsilon_1} \cdots \mathscr{P}^R$.

THEOREM 4a. *The elements*

$$Q_0^{\varepsilon_0} Q_1^{\varepsilon_1} \cdots \mathscr{P}^R$$

form an additive basis for the Steenrod algebra $\mathscr{S}^*$ *which is, up to sign, dual to the known basis* $\{\tau(E)\xi(E)\}$ *for* $\mathscr{S}_*$. *The elements* $Q_k \in \mathscr{S}^{2p^k-1}$ *generate a Grassmann algebra: that is they satisfy*

$$Q_j Q_k + Q_k Q_j = 0 \ .$$

They permute with the elements $\mathscr{P}^R$ *according to the rule*

$$\mathscr{P}^R Q_k - Q_k \mathscr{P}^R = Q_{k+1} \mathscr{P}^{R-(p^k, 0, \cdots)} + Q_{k+2} \mathscr{P}^{R-(0, p^k, 0, \cdots)} + \cdots \ .$$

(By the difference $(r_1, r_2, \cdots) - (s_1, s_2, \cdots)$ of two sequences we mean the sequence $(r_1 - s_1, r_2 - s_2, \cdots)$. It is understood, for example, that $\mathscr{P}^{R-(p^k, 0, \cdots)}$ is zero in case $r_1 < p^k$.)

As an example we have the following where $[a, b]$ denote the "commutator" $ab - (-1)^{\dim a \dim b} ba$.

COROLLARY 2. *The elements* $Q_k \in \mathscr{S}^{2p^k-1}$ *can be defined inductively by the rule*

$$Q_0 = \delta \ , \quad Q_{k+1} = [\mathscr{P}^{p^k}, Q_k] \ .$$

To complete the description of $\mathscr{S}^*$ as an algebra it is necessary to find the product $\mathscr{P}^R \mathscr{P}^S$. Let X range over all infinite matrices

$$\left\| \begin{matrix} * & x_{01} & x_{02} & \cdots \\ x_{10} & x_{11} & \cdots & \\ x_{20} & \cdots & & \\ \cdots & & & \end{matrix} \right\|$$

of non-negative integers, almost all zero, with leading entry ommitted. For each such X define $R(X) = (r_1, r_2, \cdots)$, $S(X) = (s_1, s_2, \cdots)$, and $T(X) = (t_1, t_2, \cdots)$, by

$$\begin{aligned} r_i &= \textstyle\sum_j p^j x_{ij} && \text{(weighted row sum)}, \\ s_j &= \textstyle\sum_i x_{ij} && \text{(column sum)}, \\ t_n &= \textstyle\sum_{i+j=n} x_{ij} && \text{(diagonal sum)}. \end{aligned}$$

Define the coefficient $b(X) = \prod t_n! / \prod x_{ij}!$.

THEOREM 4b. *The product* $\mathscr{P}^R \mathscr{P}^S$ *is equal to*

$$\textstyle\sum_{R(X)=R,\ S(X)=S} b(X) \mathscr{P}^{T(X)}$$

where the sum extends over all matrices X satisfying the conditions $R(X) = R$, $S(X) = S$.

As an example consider the case $R = (r, 0, \cdots)$, $S = (s, 0, \cdots)$. Then the equations $R(X) = R$, $S(X) = S$ become

$$x_{10} + px_{11} + \cdots = r\ , \quad x_{ij} = 0 \quad \text{for } i > 1\ ,$$
$$x_{01} + x_{11} + \cdots = s\ , \quad x_{ij} = 0 \quad \text{for } j > 1, \text{ respectively.}$$

Thus, letting $x = x_{11}$, the only suitable matrices are those of the form

$$\left\| \begin{matrix} * & s - x & 0 & \cdot \\ r - px & x & 0 & \cdot \\ 0 & 0 & 0 & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{matrix} \right\|$$

with $0 \leqq x \leqq \operatorname{Min}(s, [r/p])$. The corresponding coefficients $b(X)$ are the binomial coefficients $(r - px, s - x)$. Therefore we have

COROLLARY 3. *The product $\mathscr{P}^r \mathscr{P}^s$ is equal to*

$$\sum_{x=0}^{\operatorname{Min}(s,[r/p])} (r - px, s - x) \mathscr{P}^{r-px+s-x,\, x}\ .$$

(For example $\mathscr{P}^{p+1}\mathscr{P}^1 = 2\mathscr{P}^{p+2} + \mathscr{P}^{1,1}$.)

The simplest case of this product operation is the following

COROLLARY 4. *If $r_1 < p, r_2 < p, \cdots$ then $\mathscr{P}^R \mathscr{P}^S = (r_1, s_1)(r_2, s_2) \cdots \mathscr{P}^{R+S}$.*

As a final illustration we have:

COROLLARY 5. *The elements $\mathscr{P}^{(0\cdots 010\cdots)}$ can be defined inductively by*

$$\mathscr{P}^{0,1} = [\mathscr{P}^p, \mathscr{P}^1],\ \mathscr{P}^{0,0,1} = [\mathscr{P}^{p^2}, \mathscr{P}^{0,1}]\ , \quad \text{etc.}$$

The proofs are left to the reader.

PROOF OF THEOREM 4b. Given any Hopf algebra A_* with basis $\{a_i\}$ the diagonal homomorphism can be written as

$$\phi_*(a_i) = \sum_{j,k} c_i^{jk} a_j \otimes a_k\ .$$

The product operation in the dual algebra is then given by

$$a^j a^k = \phi^*(a^j \otimes a^k) = \sum_i (-1)^{\dim a^j \dim a^k} c_i^{jk} a^i\ ,$$

where $\{a^i\}$ is the dual basis. In carrying out this program for the algebra $\mathscr{S}_*$ we will first use Theorem 3 to compute $\phi_*(\xi(T))$ for any sequence $T = (t_1, t_2, \cdots)$.

Let $[i_1, i_2, \cdots, i_k]$ denote the generalized binomial coefficient

$$(i_1 + i_2 + \cdots + i_k)!/i_1!\,i_2! \cdots i_k!\ ;$$

so that the following identity holds

$$(y_1 + \cdots + y_k)^n = \sum_{i_1+\cdots+i_k=n} [i_1, \cdots, i_k] y_1^{i_1} \cdots y_k^{i_k}$$

Applying this to the expression

$$\phi_*(\xi_k) = \xi_k \otimes 1 + \xi_{k-1}^p \otimes \xi_1 + \cdots + \xi_1^{p^{k-1}} \otimes \xi_{k-1} + 1 \otimes \xi_k$$

we obtain

$$\begin{aligned}\phi_*(\xi_k^{t_k}) &= \sum [x_{k0}, \cdots, x_{0k}](\xi_k^{x_{k0}} \xi_{k-1}^{px_{k-1\,1}} \cdots \xi_1^{p^{k-1}x_{1\,k-1}}) \otimes (\xi_1^{x_{k-1\,1}} \cdots \xi_k^{x_{0k}}) \\ &= \sum [x_{k0}, \cdots, x_{0k}] \xi(p^{k-1}x_{1\,k-1}, \cdots, x_{k0}) \otimes \xi(x_{k-1\,1}, \cdots, x_{0k})\end{aligned}$$

summed over all integers $x_{k0}, \cdots, x_{0k}$ satisfying $x_{i\,k-i} \geqq 0$, $x_{k0} + \cdots + x_{0k} = t_k$. Now multiply the corresponding expressions for $k = 1, 2, 3, \cdots$. Since the product $[x_{10}, x_{01}][x_{20}, x_{11}, x_{02}][x_{30}, \cdots, x_{03}] \cdots$ is equal to $b(X)$, we obtain

$$\phi_*(\xi(T)) = \sum_{T(X)=T} b(X) \xi(R(X)) \otimes \xi(S(X)) ,$$

summed over all matrices X satisfying the condition $T(X) = X$.

In order to pass to the dual ϕ^* we must look for all basis elements $\tau(E)\xi(T)$ such that $\phi_*(\tau(E)\xi(T))$ contains a term of the form

$$(\text{non-zero constant}) \cdot \xi(R) \otimes \xi(S) .$$

However inspection shows that the only such basis elements are the ones $\xi(T)$ which we have just studied. Hence we can write down the dual formula

$$\phi^*(\mathscr{P}^R \otimes \mathscr{P}^S) = \sum_{R(X)=R,\, S(X)=S} b(X) \mathscr{P}^{T(X)} .$$

This completes the proof of Theorem 4b.

PROOF OF THEOREM 4a. We will first compute the products of the basis elements $\rho(E, \mathbf{0})$ dual to $\tau_0^{\varepsilon_0}\tau_1^{\varepsilon_1} \cdots$. The dual problem is to study the homomorphism $\phi_* : \mathscr{S}_* \to \mathscr{S}_* \otimes \mathscr{S}_*$ ignoring all terms in $\mathscr{S}_* \otimes \mathscr{S}_*$ which involve any factor ξ_k. The elements $1 \otimes \xi_1, 1 \otimes \xi_2, \cdots, \xi_1 \otimes 1, \cdots$ of $\mathscr{S}_* \otimes \mathscr{S}_*$ generate an ideal $\mathscr{I}$. Furthermore according to Theorem 3:

$$\begin{aligned}\phi_*(\tau_k) &\equiv \tau_k \otimes 1 + 1 \otimes \tau_k \qquad &(\text{mod } \mathscr{I}) \\ \phi_*(\xi_k) &\equiv 0 &(\text{mod } \mathscr{I}) .\end{aligned}$$

Therefore $\phi_*(\tau(E)\xi(R) \equiv 0$ if $R \neq 0$ and $\phi_*(\tau(E)) \equiv \sum_{E_1+E_2=E} \pm \tau(E_1) \otimes \tau(E_2)$ (mod $\mathscr{I}$). The dual statement is that

$$\rho(E_1, \mathbf{0})\rho(E_2, \mathbf{0}) = \pm \rho(E_1 + E_2, \mathbf{0}) ,$$

where it is understood that the right side is zero if the sequences E_1 and E_2 both have a "1" in the same place. Thus the basis elements $\rho(E, \mathbf{0})$ multiply as a Grassmann algebra.

Similar arguments show that the product $\rho(E, \mathbf{0})\rho(\mathbf{0}, R)$ is equal to

$\rho(E, R)$. From this the first assertion of 4a follows immediately.

Computation of $\mathscr{P}^R Q_k$: We must look for basis elements $\tau(E)\xi(R')$ such that $\phi_*(\tau(E)\xi(R'))$ contains a term

$$(\text{non-zero constant})\cdot \xi(R) \otimes \tau_k .$$

Inspection shows that the only such basis elements are $\tau_k\xi(R)$, $\tau_{k+1}\xi(R - (p^k, 0, \cdots))$, $\tau_{k+2}\xi(R - (0, p^k, 0, \cdots))$, $\cdots$ etc. Furthermore the corresponding constants are all $+1$. This proves that

$$\mathscr{P}^R Q_k = Q_k \mathscr{P}^R + Q_{k+1}\mathscr{P}^{R-(p^k, 0, \cdots)} + \cdots ,$$

and completes the proof of Theorem 4.

To complete the description of $\mathscr{S}^*$ as a Hopf algebra we must compute the homomorphism ψ^*.

LEMMA 9. *The following formulas hold*

$$\psi^*(Q_k) = Q_k \otimes 1 + 1 \otimes Q_k$$
$$\psi^*(\mathscr{P}^R) = \textstyle\sum_{R_1+R_2=R} \mathscr{P}^{R_1} \otimes \mathscr{P}^{R_2} .$$

(For example $\psi^*(\mathscr{P}^{011}) = \mathscr{P}^{011} \otimes 1 + 1 \otimes \mathscr{P}^{011} + \mathscr{P}^{01} \otimes \mathscr{P}^{001} + \mathscr{P}^{001} \otimes \mathscr{P}^{01}$.)

REMARK. An operation $\theta \in \mathscr{S}^*$ is called a *derivation* if it satisfies

$$\theta(\alpha \smile \beta) = (\theta\alpha) \smile \beta + (-1)^{\dim\theta \dim\alpha}\, \alpha \smile \theta\beta .$$

This is clearly equivalent to the assertion that θ is primitive. It can be shown that the only derivations in $\mathscr{S}^*$ are the elements $Q_0, Q_1, \cdots, \mathscr{P}^1$, $\mathscr{P}^{0,1}$, $\mathscr{P}^{0,0,1}$, $\cdots$ and their multiples.

7. The canonical anti-automorphism

As an illustration consider the Hopf algebra $H_*(G)$ associated with a Lie group G. The map $g \to g^{-1}$ of G into itself induces a homomorphism $c\colon H_*(G) \to H_*(G)$ which satisfies the following two identities:

(1) $c(1) = 1$

(2) if $\psi_*(a) = \sum a'_i \otimes a''_i$, where $\dim a > 0$, then $\sum a'_i c(a''_i) = 0$.

More generally, for any connected Hopf algebra A_*, there exists a unique homomorphism $c\colon A_* \to A_*$ satisfying (1) and (2). We will call $c(a)$ the *conjugate* of a. Conjugation is an anti-automorphism in the sense that

$$c(a_1a_2) = (-1)^{\dim a_1 \dim a_2} c(a_2)c(a_1) .$$

The conjugation operations in a Hopf algebra and its dual are dual homomorphisms. For details we refer the reader to [3].

For the Steenrod algebra $\mathscr{S}^*$ this operation was first used by Thom. (See [5] p. 60). More precisely the operation used by Thom is $\theta \to (-1)^{\dim\theta}\, c(\theta)$.

If θ is a primitive element of $\mathscr{S}^*$ then the defining relation becomes $\theta\cdot 1 + 1\cdot c(\theta) = 0$ so that $c(\theta) = -\theta$. This shows that $c(Q_k) = -Q_k$, $c(\mathscr{P}^1) = -\mathscr{P}^1$. The elements $c(\mathscr{P}^n)$, $n > 0$, could be computed from Thom's identity

$$\sum_i \mathscr{P}^{n-i} c(\mathscr{P}^i) = 0 \ ;$$

however it is easier to first compute the operation in the dual algebra and then carry it back.

By an *ordered partition* α of the integer n with *length* $l(\alpha)$ will be meant an ordered sequence

$$(\alpha(1), \alpha(2), \cdots, \alpha(l(\alpha)))$$

of positive integers whose sum is n. The set of all ordered partitions of n will be denoted by Part (n). (For example Part (3) has four elements: (3), (2,1) (1,2), and (1,1,1). In general Part (n) has 2^{n-1} elements.) Given an ordered partition $\alpha \in$ Part (n), let $\sigma(i)$ denote the partial sum $\sum_{j=1}^{i-1} \alpha(j)$.

LEMMA 10. *In the dual algebra* $\mathscr{S}_*$ *the conjugate* $c(\xi_n)$ *is equal to*

$$\sum_{\alpha \in \mathrm{Part}(n)} (-1)^{l(\alpha)} \prod_{i=1}^{l(\alpha)} \xi_{\alpha(i)}^{p^{\sigma(i)}} \ .$$

(For example $c(\xi_3) = -\xi_3 + \xi_1\xi_2^p + \xi_2\xi_1^{p^2} - \xi_1\xi_1^p\xi_1^{p^2}$.)

PROOF. Since $\phi_*(\xi_n) = \sum_{i=0}^n \xi_{n-i}^{p^i} \otimes \xi_i$, the defining identity becomes

$$\sum_{i=0}^n \xi_{n-i}^{p^i} c(\xi_i) = 0 \ .$$

This can be written as

$$c(\xi_n) = -\xi_n - c(\xi_1)\xi_{n-1}^p - \cdots - c(\xi_{n-1})\xi_1^{p^{n-1}} \ .$$

The required formula now follows by induction.

Since the operation $\omega \to c(\omega)$ is an anti-automorphism, we can use Lemma 10 to determine the conjugate of an arbitrary basis element $\xi(R)$. Passing to the dual algebra $\mathscr{S}^*$ we obtain the following formula. (The details of the computation are somewhat involved, and will not be given.)

Given a sequence $R = (r_1, \cdots, r_k, 0, \cdots)$ consider the equations

$$(*) \qquad r_i = \sum_{n=1}^{\infty} \sum_{\alpha \in \mathrm{Part}(n)} \sum_{j=1}^{l(\alpha)} \delta_{i\alpha(j)}\, p^{\sigma(j)} y_\alpha \ ,$$

for $i = 1, 2, 3, \cdots$; where the symbol $\delta_{i\alpha(j)}$ denotes a Kronecker delta; and where the unknowns y_α are to be non-negative integers. For each solution Y to this set of equations define $S(Y) = (s_1, s_2, \cdots)$ by

$$s_n = \sum_{\alpha \in \mathrm{Part}(n)} y_\alpha \ .$$

(Thus $s_1 = y_1$, $s_2 = y_2 + y_{1,1}$, etc.) Define the coefficient $b(Y)$ by

$$b(Y) = [y_2, y_{11}][y_3, y_{21}, y_{12}, y_{111}] \cdots$$
$$= \prod_n s_n! / \prod_\alpha y_\alpha! \;.$$

THEOREM 5. *The conjugate* $c(\mathscr{P}^R)$ *is equal to*

$$(-1)^{r_1+\cdots+r_k} \sum b(Y) \mathscr{P}^{S(Y)}$$

where the summation extends over all solutions Y *to the equations* $(*)$.

To interpret these equations $(*)$ note that the coefficient

$$\sum_{j=1}^{l(\alpha)} \delta_{i\alpha(j)}\, p^{\sigma(j)}$$

of y_α in the i^{th} equation is positive if the sequence

$$\alpha = (\alpha(1), \cdots, \alpha(l(\alpha)))$$

contains the integer i, and zero otherwise. In case the left hand side r_i is zero, then for every sequence α containing the integer i it follows that $y_\alpha = 0$. In particular this is true for all $i > k$.

As an example, suppose that $k = 1$ so that $R = (r, 0, 0, \cdots)$. Then the integers y_α must be zero whenever α contains an integer larger than one. Thus the only partitions α which are left are: (1), (1,1), (1,1,1), $\cdots$. Therefore we have $s_1 = y_1$, $s_2 = y_{11}$, $s_3 = y_{111}$, etc. The equations $(*)$ now reduce to the single equation

$$r = s_1 + (1+p)s_2 + (1+p+p^2)s_3 + \cdots \;.$$

But this is just the dimensional restriction that $\dim \mathscr{P}^S = (2p-2)s_1 + (2p^2-2)s_2 + \cdots$ be equal to $\dim \mathscr{P}^r = (2p-2)r$. Thus we obtain:

COROLLARY 6. *The conjugate* $c(\mathscr{P}^r)$ *is equal to* $(-1)^r \sum \mathscr{P}^S$ *where the sum extends over all* $\mathscr{P}^S$ *having the correct dimension.* (For example $c(\mathscr{P}^{2p+3}) = -\mathscr{P}^{2p+3} - \mathscr{P}^{p+2,1} - \mathscr{P}^{1,2}$.)

8. Miscellaneous remarks

The following question, which is of interest in the study of second order cohomology operations, was suggested to the author by A. Dold: *What is the set of all solutions* $\theta \in \mathscr{S}^*$ *to the equation* $\theta\mathscr{P}^1 = 0$? In view of the results of §7 we can equally well study the equation $\mathscr{P}^1\theta = 0$. The formula

$$\mathscr{P}^1 \mathscr{P}^{r_1 r_2 \cdots} = (1 + r_1)\mathscr{P}^{1+r_1, r_2 \cdots}$$

implies that this equation $\mathscr{P}^1\theta = 0$ has as solution the vector space spanned by the elements

$$\mathscr{P}^{r_1 r_2 \cdots} Q_0^{\varepsilon_0} Q_1^{\varepsilon_1} \cdots$$

with $r_1 \equiv -1 \pmod p$. The first such element is $\mathscr{P}^{p-1}$, and every element of the ideal $\mathscr{P}^{p-1}\mathscr{S}^*$ will also be a solution. Now the identity

$$\mathscr{P}^{p-1}\cdot\mathscr{P}^{s_1 s_2 \cdots} = (p-1, s_1)\mathscr{P}^{s_1+p-1, s_2, \cdots}$$
$$= \begin{cases} 0 & \text{if } s_1 \not\equiv 0 \pmod p \\ -\mathscr{P}^{s_1+p-1, s_2, \cdots} & \text{if } s_1 \equiv 0 \pmod p \end{cases}$$

shows that every element $\mathscr{P}^{r_1 r_2 \cdots} Q_0^{\varepsilon_0} \cdots$ with $r_1 \equiv -1 \pmod p$ actually belongs to the ideal. Applying the conjugation operation, this proves the following:

PROPOSITION 1. *The equation* $\theta\mathscr{P}^1 = 0$ *has as solutions the elements of the ideal* $\mathscr{S}^*\mathscr{P}^{p-1}$. *An additive basis is given by the elements*

$$Q_0^{\varepsilon_0} Q_1^{\varepsilon_1} \cdots c(\mathscr{P}^{r_1 r_2 \cdots}) \text{ with } r_1 \equiv -1 \pmod p .$$

Next we will study certain subalgebras of the Steenrod algebra. Adem shown that $\mathscr{S}^*$ is generated by the elements Q_0, $\mathscr{P}^1$, $\mathscr{P}^p$, $\cdots$. Let $\mathscr{S}^*(n)$ denote the subalgebra generated by Q_0, $\mathscr{P}^1$, $\cdots$, $\mathscr{P}^{p^{n-1}}$.

PROPOSITION 2. *The algebra* $\mathscr{S}^*(n)$ *is finite dimensional, having as basis the collection of all elements*

$$Q_0^{\varepsilon_0} \cdots Q_n^{\varepsilon_n}\mathscr{P}^{r_1, \cdots, r_n}$$

which satisfy

$$r_1 < p^n, r_2 < p^{n-1}, \cdots, r_n < p .$$

Thus $\mathscr{S}^*$ is a union of finite dimensional subalgebras $\mathscr{S}^*(n)$. This clearly implies the following.

COROLLARY 7. *Every positive dimensional element of* $\mathscr{S}^*$ *is nil-potent.*

It would be interesting to discover a complete set of relations between the given generators of $\mathscr{S}^*(n)$. For $n = 0$ there is the single relation $[Q_0, Q_0] = 0$, where $[a, b]$ stands for $ab - (-1)^{\dim a \dim b} ba$. For $n = 1$ there are three new relations

$$[Q_0, [\mathscr{P}^1, Q_0]] = 0 , \quad [\mathscr{P}^1, [\mathscr{P}^1, Q_0]] = 0 \quad \text{and} \quad (\mathscr{P}^1)^p = 0 .$$

For $n = 2$ there are the relations

$$[\mathscr{P}^1, [\mathscr{P}^p, \mathscr{P}^1]] = 0 , \quad [\mathscr{P}^p, [\mathscr{P}^p, \mathscr{P}^1]] = 0 ,$$
$$\text{and} \quad (\mathscr{P}^p)^p = \mathscr{P}^1[\mathscr{P}^p, \mathscr{P}^1]^{p-1} ,$$

as well as several new relations involving Q_0. (The relations $(\mathscr{P}^p)^{2p} = 0$ and $[\mathscr{P}^p, \mathscr{P}^1]^p = 0$ can be derived from the relations above.) The author has been unable to go further with this.

PROOF OF PROPOSITION 2. Let $\mathscr{A}(n)$ denote the subspace of $\mathscr{S}^*$ spanned by the elements $Q_0^{\varepsilon_0} \cdots Q_n^{\varepsilon_n}\mathscr{P}^{r_1 \cdots r_n}$ which satisfy the specified restrictions. We will first show that $\mathscr{A}(n)$ is a subalgebra. Consider the product

$$\mathscr{P}^{r_1 \cdots r_n} \mathscr{P}^{s_1 \cdots s_n} = \sum_{R(X)=(r_1 \cdots),\, S(X)=(s_1, \cdots)} b(X) \mathscr{P}^{T(X)}$$

where both factors belong to $\mathscr{A}(n)$. Suppose that some term $b(X)\mathscr{P}^{t_1 t_2 \cdots}$ on the right does not belong to $\mathscr{A}(n)$. Then t_l must be $\geqq p^{n+1-l}$ for some l. If $x_{l0}, x_{l-1,1}, \ldots, x_{0l}$ were all $< p^{n+1-l}$, then the factor

$$\frac{t_l!}{x_{l0}! \cdots x_{0l}!}$$

would be congruent to zero modulo p. Therefore $x_{ij} \geqq p^{n+1-l}$ for some $i + j = l$. If $i > 0$ this implies that

$$r_i = \sum_j p^j x_{ij} \geqq p^j p^{n+1-l} = p^{n+1-i}$$

which contradicts the hypothesis that $\mathscr{P}^{r_1 \cdots r_n} \in \mathscr{A}(n)$. Similarly if $i = 0$, $j = l$, then

$$s_j = \sum_i x_{ij} \geqq p^{k+1-l} = p^{k+1-j}$$

which is also a contradiction.

Since it is easily verified that $\mathscr{A}(n)Q_k \subset \mathscr{A}(n)$ for $k \leqq n$, this proves that $\mathscr{A}(n)$ is a subalgebra of $\mathscr{S}^*$. Since $\mathscr{A}(n)$ contains the generators of $\mathscr{S}^*(n)$, this implies that $\mathscr{A}(n) \supset \mathscr{S}^*(n)$.

To complete the proof we must show that every element of $\mathscr{A}(n)$ belongs to $\mathscr{S}^*(n)$. Adem's assertion that $\mathscr{S}^*$ is the union of the $\mathscr{S}^*(n)$ implies that every element of $\mathscr{S}^k$ with $k < \dim(\mathscr{P}^{p^n})$ automatically belongs to $\mathscr{S}^*(n)$. In particular we have:

Case 1. Every element $\mathscr{P}^{0 \cdots 0 p^i}$ in $\mathscr{A}(n)$ belongs to $\mathscr{S}^*(n)$.

Ordering the indices $(r_1, \cdots, r_n)$ lexicographically from the right, the product formulas can be written as

$$\mathscr{P}^{r_1 \cdots r_n} \mathscr{P}^{s_1 \cdots s_n} = (r_1, s_1) \cdots (r_n, s_n) \mathscr{P}^{r_1+s_1, \cdots, r_n+s_n} + \text{(higher terms)} .$$

Given $\mathscr{P}^{t_1 \cdots t_n} \in \mathscr{A}(n)$ assume by induction that

(1) every $\mathscr{P}^{r_1 \cdots r_n} \in \mathscr{A}(n)$ of smaller dimension belongs to $\mathscr{S}^*(n)$, and

(2) every "higher" $\mathscr{P}^{r_1 \cdots r_n} \in \mathscr{A}(n)$ in the same dimension belongs to $\mathscr{S}^*(n)$. We will prove that $\mathscr{P}^{t_1 \cdots t_n} \in \mathscr{S}^*(n)$.

Case 2. $(t_1 \cdots t_n) = (0 \cdots 0 t_i 0 \cdots 0)$ where t_i is not a power of p. Choose $r_i, s_i > 0$ with $r_i + s_i = t_i$, $(r_i, s_i) \not\equiv 0$. Then $\mathscr{P}^{0 \cdots r_i} \mathscr{P}^{0 \cdots s_i} = (r_i, s_i)\mathscr{P}^{0 \cdots t_i} + \text{(higher terms)}$.

Case 3. Both t_i and t_j are positive, $i < j$. Then

$$\mathscr{P}^{t_1 \cdots t_i} \mathscr{P}^{0 \cdots 0 t_{i+1} \cdots t_n} = \mathscr{P}^{t_1 \cdots t_n} + \text{(higher terms)} .$$

In either case the inductive hypothesis shows that $\mathscr{P}^{t_1 \cdots t_n}$ belongs to $\mathscr{S}^*(n)$. Since $Q_0, \cdots, Q_n$ belong to $\mathscr{S}^*(n)$ by Corollary 3, this completes the proof of Proposition 2.

Appendix 1. The case $p = 2$

All the results in this paper apply to the case $p = 2$ after some minor changes. The cohomology ring of the projective space $\mathscr{P}^N$ is a truncated polynomial ring with one generator α of dimension 1. It turns out that $\lambda^*(\alpha) \in H^*(P^N, Z_2) \otimes \mathscr{S}_*$ has the form

$$\alpha \otimes \zeta_0 + \alpha^2 \otimes \zeta_1 + \cdots + \alpha^{2^r} \otimes \zeta_r$$

where $\zeta_0 = 1$ and where each ζ_i is a well defined element of $\mathscr{S}_{2^i-1}$. The algebra $\mathscr{S}_*$ is a polynomial algebra generated by the elements $\zeta_1, \zeta_2, \cdots$.

Corresponding to the basis $\{\zeta_1^{r_1}\zeta_2^{r_2}\cdots\}$ for $\mathscr{S}_*$ there is a dual basis $\{Sq^R\}$ for $\mathscr{S}^*$. These elements $Sq^{r_1 r_2 \cdots}$ multiply according to the same formula as the $\mathscr{P}^R$. The other results of this paper generalize in an obvious way.

Appendix 2. Sign conventions

The standard convention seems to be that no signs are inserted in formulas 1, 2, 3 of §2. If this usage is followed then the definition of λ^* becomes more difficult. However Lemmas 2 and 3 still hold as stated, and Lemma 4 holds in the following modified form.

LEMMA 4′. *If* $\lambda^*(\alpha) = \sum \alpha_i \otimes \omega_i$ *then for any* $\theta \in \mathscr{S}^*$:

$$\theta\alpha = (-1)^{\frac{1}{2}d(d-1)+d\dim\alpha} \sum \langle \theta, \omega_i \rangle \alpha_i$$

where $d = \dim \theta$.

It is now necessary to define $\tau_i \in \mathscr{S}_{2p^i-1}$ by the equation

$$\lambda^*(\alpha) = \alpha \otimes 1 - \beta \otimes \tau_0 - \beta^p \otimes \tau_1 - \cdots .$$

Otherwise there are no changes in the results stated.

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