The Steenrod Algebra and Its Dual

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These are notes for the seminar "Advanced Topics in Homotopy Theory" given by Prof. Stefan Schwede and Dr. Jack Davies in Bonn during the WS2023/24. Our goal is to present the main results of Milnor's paper "The Steenrod Algebra and its Dual" [Mil58].

Contents

1 Hopf Algebras

1.1 Bi-Algebras

We start by studying Hopf algebras independently. Throughout, let k be a field.

Definition 1 (Algebra) *An **Algebra** is a triple $(\mathcal{A}, \mu, \eta)$ with $\mathcal{A}$ a k-vector space together with two maps $\mu \colon A \otimes A \to A$ (multiplication) , $\eta \colon k \to A$ (unit) making the following diagrams commute*

$$\begin{tikzcd}
\mathcal{A} \otimes \mathcal{A} \otimes \mathcal{A} \arrow[r, "\mathrm{Id} \otimes \mu"] \arrow[d, "\mu \otimes \mathrm{Id}"'] & A \otimes \mathcal{A} \arrow[d, "\mu"] \\
\mathcal{A} \otimes \mathcal{A} \arrow[r, "\mu"'] & \mathcal{A}
\end{tikzcd}$$

$$\begin{tikzcd} k \otimes \mathcal{A} \arrow[r, "i\otimes\eta"] \arrow[dr] & \mathcal{A} \otimes \mathcal{A} \arrow[d, dashed, "\mu"] & \mathcal{A} \otimes k \arrow[l, "\eta\otimes i"'] \arrow[dl] \\ & \mathcal{A} & \end{tikzcd}$$

Dualizing these definitions, we unsurprisingly obtain

Definition 2 (Coalgebra) *A **coalgebra** is a triple (C, Δ, ϵ) where C is a k-vector space togethere with two maps $\Delta\colon C \to C \otimes C$ (comultiplication) and $\epsilon\colon C \to k$ (augmentation) making the following diagrams commute*

$$\begin{tikzcd} C \arrow[r, "\Delta"] \arrow[d, "\Delta"'] & C \otimes C \arrow[d, "\mathrm{Id} \otimes \Delta"] \\ C \otimes C \arrow[r, "\Delta\otimes \mathrm{Id}"'] & C \otimes C \otimes C \end{tikzcd}$$

$$\begin{tikzcd} & C \arrow[dl] \arrow[d, "\Delta"] \arrow[dr] & \\ k \otimes C & C \otimes C \arrow[l, "\epsilon\otimes \mathrm{Id}"] \arrow[r, "\mathrm{Id} \otimes \epsilon"'] & C \otimes k \end{tikzcd}$$

Since taking duals commutes with tensor products, notice that the dual $C^\vee$ naturally gets an algebra structure.
We define (co-)algebra morphisms in the obvious way.

Definition 3 (Bialgebra) *A **bialgebra** is a tuple $(\mathcal{A}, \mu, \eta, \Delta, \epsilon)$ such that $(\mathcal{A}, \mu, \epsilon)$ is an algebra, $(\mathcal{A}, \Delta, \epsilon)$ is a coalgebra and such that Δ and ϵ are algebra morphisms*

Equivalently, one can also require μ and ϵ to be coalgebra morphisms.
If $\mathcal{A} = \bigoplus_{n\in\mathbb{N}} \mathcal{A}_n$ is a graded algebra, we define the **dual algebra** by

$$\mathcal{A}^* := A_n^*, \text{ with } A_n^* = \hom(A_{-n}, k)$$

We call a graded algebra $\mathcal{A}$ **graded commutative** if for all homogeneous elements $\alpha, \beta \in \mathcal{A}$, we have $\alpha\beta = (-1)^{\dim\alpha \dim\beta}\beta\alpha$. (omitting μ for sanity reasons) The graded algebra $\mathcal{A}$ is **connected** if $\mathcal{A}_0$ is generated by 1, equivalently $\eta\colon k \to \mathcal{A}_0$ is an isomorphism.
We can similarly define the notion of a graded coalgebra and of a connected coalgebra.

1.2 Antipode maps

Let C be a bi-algebra as above and let $f, g\colon C \to C$ be linear maps, we define the convolution $f * g$ of f with g as the composition

$$C \xrightarrow{\Delta} C \otimes C \xrightarrow{f\otimes g} C \otimes C \xrightarrow{\mu} C.$$

Definition 4 (Antipode) *An antipode* $S\colon C \to C$ *is an endomorphism such that*

$$S * \mathrm{Id} = \mathrm{Id} * S = \eta \circ \epsilon.$$

Definition 5 (Hopf Algebra) *A Hopf Algebra is a bi-algebra with an antipode*

For specific classes of bialgebras, there is a way of constructing an antipode map.

Theorem 1 *Let* $\mathcal{A}$ *be a graded bialgebra such that* $\Delta(x) = x \otimes 1 + 1 \otimes x + \sum_i a_i \otimes b_i$ *with* $\dim a_i, \dim b_i > 0$*, then* $\mathcal{A}$ *admits an antipode map.*

Proof Let $x \in \mathcal{A}$, to define S, we proceed inductively on the degree of x. If $\dim x = 0$, we define $S(x) = x$.
Inductively, suppose we've defined S for all x of degree $< n$ and write $\Delta(x) = x \otimes 1 + 1 \otimes x + \sum_i a_i \otimes b_i$ as above. Since Δ respects the grading, we may suppose that $\dim b_i < n$, we let

$$S(x) \coloneqq -x - \sum_i a_i S(b_i)$$

One now easily checks that S is an antipode. □

2 The Steenrod Algebra

Let p be a prime.

Definition 6 (Stable Cohomology operation) *A **stable*** $\mathrm{mod}\, p$ ***cohomology operation*** θ *of type* $r \in \mathbb{Z}$ *is a family of natural transformations* $(\theta_n)_{n \in \mathbb{N}}$

$$\theta_n\colon H^n(-, \mathbb{F}_p) \to H^{n+r}(-, \mathbb{F}_p)$$

such that the following diagram commutes for every space X

$$\begin{tikzcd} H^n(X, \mathbb{F}_p) \arrow[r, "\theta_n"] \arrow[d] & H^{n+r}(X, \mathbb{F}_p) \arrow[d] \\ H^{n+1}(\Sigma X, \mathbb{F}_p) \arrow[r, "\theta_{n+1}"'] & H^{n+r+1}(\Sigma X, \mathbb{F}_p) \end{tikzcd}$$

We can trivially compose two cohomology operations θ, θ' of type r (resp. r') to obtain a cohomology operation of type $r + r'$, this motivates the following definition.

Definition 7 (Steenrod Algebra) *The* $\mathrm{mod}\, p$ ***Steenrod Algebra*** $\mathcal{A}_p$ *is the ring freely generated by the stable cohomology operations. This ring comes with a natural grading coming from the type of the cohomology operation.*

For those familiar with (maps of) spectra, the most natural way to define the Steenrod algebra is by the formula $\mathcal{A}_p = H\mathbb{F}_p^*(H\mathbb{F}) = \bigoplus_n H\mathbb{F}_p^n(H\mathbb{F}_p)$.

Remark 2 *Notice that if* θ *and* θ' *are two cohomology operations of different types, their sum* $\theta + \theta'$ *in* $\mathcal{A}_p$ *does **not** define a cohomology operation in any natural way.*
Despite this, $\mathcal{A}_p$ *still naturally acts on the **full** cohomology* $H^*(X)$ *of a space, when viewed as an abelian group.*

As we will establish in the next section, $\mathcal{A}_p$ carries a Hopf algebra structure which makes $H^*(X)$ into a (Hopf-)module. Before showing this, we present structural results about the Steenrod algebra.

2.1 Steenrod Powers

From now on, $H^*(-)$ will always denote mod p cohomology for a fixed prime p.

Definition 8 (Steenrod Powers) *Suppose* $p > 2$*, the **Steenrod powers** are the stable cohomology operations*

$$P^i \colon H^q(-, \mathbb{F}_p) \to H^{q+2i(p-1)}(-, \mathbb{F}_p)$$

uniquely determined by the following properties

1. $P^0 = \mathrm{Id}$
2. *if* $x \in H^{2n}(X, A, \mathbb{F}_p)$*, then* $P^n x = x^p$
3. *if* $x \in H^n(X, A)$*, then* $P^i x = 0$ *for all* $2i > n$
4. $\delta P^i = P^i \delta$ *where* δ *is the boundary homomorphism*
5. $P^i(xy) = \sum_{j+k=i} P^j x P^k y$

Definition 9 (Steenrod Squares) *The **Steenrod squares** are the unique stable* mod 2 *cohomology operations*

$$Sq^i \colon H^q(-, \mathbb{F}_2) \to H^{q+i}(-, \mathbb{F}_2)$$

uniquely determined by

1. $P^0 = \mathrm{Id}$
2. *if* $x \in H^n(X, A, \mathbb{F}_2)$*, then* $Sq^n(x) = x^2$
3. *if* $x \in H^n(X, A, \mathbb{F}_2)$*, then* $Sq^i x = 0$ *for all* $i > n$
4. $Sq^n(xy) = \sum_{i+j=n} Sq^i x Sq^j y$
5. $\delta Sq^i = Sq^i \delta$

The natural transformation $\beta \colon H^n(-) \to H^{n+1}(-)$ induced by the short exact sequence $0 \to \mathbb{Z}_p \to \mathbb{Z}_{p^2} \to \mathbb{Z}_p \to 0$ is also stable, we call it the **Bockstein morphism**.
For $p = 2$, the Bockstein coincides with Sq^1. It is a famed result of Steenrod that these operations generate the Steenrod algebra.

Theorem 3 (Structure of the Steenrod Algebra) *[SE62, Ch. VI, Sec. 2] Let p be an odd prime. Call a sequence $I = (\epsilon_0, s_1, \epsilon_1, s_2, \ldots)$* ***admissible*** *if it is finite, $s_i \geq 1, \epsilon = 0, 1$ and $s_i \geq p s_{i+1} + \epsilon_i$. The set*

$$P^I := \beta^{\epsilon_0} P^{s_1} \beta^{\epsilon_1} P^{s_2}, \quad I \text{ admissible}$$

is a basis for the Steenrod algebra.

There is a similar result for $p = 2$, which we do not make explicit.

3 The Diagonal Morphism

From now on, p is a prime different from 2 and $\mathcal{A} := \mathcal{A}_p$.

The main goal of this talk is to present a proof that $\mathcal{A}_p$ has the structure of a Hopf algebra and to make its structure more explicit.
Throughout, let X be a space. We start by constructing the diagonal morphism $\psi^* \colon \mathcal{A}^* \to \mathcal{A}^* \otimes \mathcal{A}^*$.

Proposition 4 *There is a unique diagonal morphism $\psi^* \colon \mathcal{A}^* \to \mathcal{A}^* \otimes \mathcal{A}^*$ such that*

1. *For all $\theta \in \mathcal{A}^*$, $\psi^*(\theta) = \sum_i \theta_i' \otimes \theta_i$" and $\alpha, \beta \in H^*(X)$ we have*

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

2. *The morphism ψ^* is a ring morphism.*

Proof Let $\mathcal{A}^* \otimes \mathcal{A}^*$ act on $H^*(X) \otimes H^*(X)$ by

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

and we let $c : H^*(X) \otimes H^*(X) \to H^*(X)$ denote the cup product.
ψ^* exists
Let $R \subset \mathcal{A}^*$ be the set of all θ such that

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

for some $\rho \in \mathcal{A}^* \otimes \mathcal{A}^*$. We want to show that $R = \mathcal{A}^*$.
Notice that R is closed under multiplication and addition. If $\theta_1, \theta_2 \in R$, then

$$\theta_1\theta_2(\alpha \smile \beta) = c\rho_1\rho_2(\alpha \otimes \beta) \text{ and } (\theta_1 + \theta_2)(\alpha \smile \beta) = c((\rho_1 + \rho_2)(\alpha \otimes \beta))$$

Hence, it suffices to show that R contains the Bockstein and the Steenrod powers which follows from the formulas

$$\delta(\alpha \smile \beta) = \delta\alpha \smile \beta + (-1)^{\dim \alpha} \alpha \smile \delta(\beta)$$
$$P^n(\alpha \smile \beta) = \sum_{i+j=n} P^i(\alpha) \smile P^j(\beta)$$

ψ^* is unique
Let $K := K(\mathbb{F}_p, n+1)$ and $\gamma \in H^{n+1}(K)$ correspond to the identity map, the map

$$\begin{aligned} \mathrm{ev}_\gamma \colon \mathcal{A}^*_i &\to H^{n+1+i}(K) \\ \theta &\mapsto \theta\gamma \end{aligned}$$

is an isomorphism for all $i \leq n$, it follows that

$$\begin{aligned} j\colon \ (\mathcal{A}^* \otimes \mathcal{A}^*)_i &\to H^{2n+2+i}(K \times K) \\ \theta \otimes \theta' &\mapsto (-1)^{\dim\theta' \dim\gamma}\theta(\gamma) \otimes \theta'(\gamma) \end{aligned}$$

is too.
Let $\theta \in \mathcal{A}^*_i$, suppose ρ, ρ' both satisfy the required equality, then

$$j(\rho) = c\rho\left((\gamma \otimes 1) \otimes (1 \otimes \gamma)\right) = c\rho'\left((\gamma \otimes 1) \otimes (1 \otimes \gamma)\right) = j(\rho')$$

The unicity of ψ^* implies that it is a ring morphism. □

Remark 5 *From this proof, we can in particular single out the action of ψ^* on generators, namely, it follows that*

$$\begin{aligned} \psi^*(\delta) &= \delta \otimes 1 + 1 \otimes \delta \\ \psi^*(P^n) &= \sum_{i+j=n} P^i \otimes P^j. \end{aligned}$$

Theorem 6 (The Steenrod Algebra is a Hopf Algebra) *The maps*

$$\mathcal{A} \xrightarrow{\psi^*} \mathcal{A} \otimes \mathcal{A} \xrightarrow{\phi^*} \mathcal{A}$$

Give $\mathcal{A}$ the structurre of a Hopf algebra. Furthermore ϕ^* is associative and ψ^* is associative and commutative.

Proof It suffices to show that ψ^* is associative and commutative.

Associativity

It suffices to check the identity

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

This identity clearly holds on generators, namely

$$\begin{aligned} (\psi^* \otimes 1)\left(\delta \otimes 1 + 1 \otimes \delta\right) &= \delta \otimes 1 \otimes 1 + 1 \otimes \delta \otimes 1 + 1 \otimes 1 \otimes \delta \\ &= (1 \otimes \psi^*)\left(\delta \otimes 1 + 1 \otimes \delta\right) \end{aligned}$$

and

$$
\begin{aligned}
(\psi^* \otimes 1)\left(\sum_{i+j=n} P^i \otimes P^j\right) &= \sum_{i+j=n}\left(\sum_{i'+j'=i} P^{i'} \otimes P^{j'}\right) \otimes P^j \\
&= \sum_{i+j+k=n} P^i \otimes P^j \otimes P^k \\
&= (1 \otimes \psi^*)\left(\sum_{i+j=n} P^i \otimes P^j\right).
\end{aligned}
$$

Commutativity

Let

$$
\begin{aligned}
T\colon \mathcal{A} \otimes \mathcal{A} &\to \mathcal{A} \otimes \mathcal{A} \\
\theta \otimes \theta' &\mapsto (-1)^{\dim\theta \dim\theta'} \theta' \otimes \theta.
\end{aligned}
$$

We have to check that $\psi^* = T\psi^*$, which one can check again on generators:

$$T(1 \otimes \delta + \delta \otimes 1) = 1 \otimes \delta + \delta \otimes 1$$

and

$$T(\sum_{i+j=n} P^i \otimes P^j) = \sum_{i+j=n} (-1)^{4ij(p-1)^2} P^j \otimes P^i \qquad \square$$

4 The dual Steenrod Algebra

For the rest of this talk, we focus on the dual Steenrod algebra $\mathcal{A}_* := \mathcal{A}^\vee$, whose multiplication is induced by ψ^*. Our goal is to fully determine the structure of $\mathcal{A}_*$.
To single out an appropriate set of generators for $\mathcal{A}_*$, we analyze how $\mathcal{A}_*$ (co-)acts on the cohomology ring of a specific space. We start by describing this co-action formally and then introduce the relevant space.

4.1 The coaction of $\mathcal{A}_*$

Given that we are working over a vector space, cohomology and homology are dual. Hence, given $\theta \in \mathcal{A}$ and $\mu \in H_*$, the rule

$$\theta \cdot \mu(\alpha) := \mu(\theta(\alpha)) \text{ for all } \alpha \in H^*$$

gives a well defined action

$$\lambda_*\colon \mathcal{A} \otimes H_* \to H_*$$

We denote the dual of this action by $\lambda^*\colon H^* \to \mathcal{A}_* \otimes H^*$. The restriction of λ_*

$$\lambda_i\colon \mathcal{A} \otimes H^{n+i} \to H^n$$

also gives rise to dual morphisms $\lambda^i\colon H^n \to \mathcal{A}_* \otimes H^{n+i}$ which satisfy

$$\lambda^* = \lambda^1 + \lambda^2 + \dots .$$ [1]

We can also understand the action of $\mathcal{A}$ better in terms of λ^*.

Lemma 7 *Let* $\lambda^*(\alpha) = \sum_i \alpha_i \otimes \omega_i$ *and* $\theta \in \mathcal{A}$, *then*

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

Proof By definition of the action, we have

$$\begin{aligned} \langle \mu, \theta\alpha \rangle &= \langle \mu\theta, \alpha \rangle \\ &= \langle \mu \otimes \theta, \lambda^* \alpha \rangle \\ &= \sum_i (-1)^{\dim \alpha_i \dim \omega_i} \langle \mu, \alpha_i \rangle \langle \theta, \omega_i \rangle \end{aligned}$$ □

And the general equality follows.

4.2 Generators for $\mathcal{A}_*$

Fix some large integer N and let $X = S^{2N+1}/\mathbb{Z}_p = sk_{2N+1}K(\mathbb{F}_p, 1)$. The (mod p) cohomology ring of X has the following properties

$$H^1(X) = \langle \alpha \rangle, H^2(X) = \langle \beta \rangle, H^{2i}(X) = \langle \beta^i \rangle, H^{2i+1}(X) = \langle \alpha\beta^i \rangle,$$

where $\beta = \delta\alpha$ and $i \leq N$

Notation 8 *We define*

$$M^k := P^{p^{k-1}} \cdots P^p P^1$$

Lemma 9 *For all* $\theta \in \mathcal{A}$

$$\theta\beta = \begin{cases} \beta^{p^k} & \textit{if } \theta = M_k \\ 0 & \textit{else.} \end{cases}$$

Proof Let $\mathcal{P} = 1 + P^1 + P^2 + \dots$, from the properties of the Steenrod powers, we notice that

$$\mathcal{P}\beta = \beta + \beta^p \text{ thus } \mathcal{P}\left(\beta^{p^r}\right) = \beta^{p^r} + \beta^{p^{r+1}}.$$

Hence $P^{p^r}(\beta^{p^r}) = \beta^{p^{r+1}}$ and $P^j(\beta^{p^r})$ for $j \neq p^r$ and $j > 0$. From this, we deduce the statement. □

[1] Elements in H^* are always finite sums, so this sum should be understood as $\bigoplus_i \lambda^i$

We will now explicitly determine a basis for $\mathcal{A}_*$.

Lemma 10 *There exist elements* $\tau_i, \in \mathcal{A}_*^{2p^k-1}$ *such that*

$$\lambda^*\alpha = \alpha \otimes 1 + \beta \otimes \tau_0 + \ldots + \beta^{p^r} \otimes \tau_r.$$

Similarly, there exist elements $\xi_i \in \mathcal{A}_*^{2p^i-2}$ *with* $\xi_0 = 1$ *such that*

$$\lambda^*\beta = \beta \otimes \xi_0 + \beta^p \otimes \xi_1 + \ldots + \beta^{p^r} \otimes \xi_r$$

Proof From the above, it follows that

$$\lambda^*\beta = \lambda^0\beta + \lambda^{2p-2}\beta + \ldots + \lambda^{2p^k-2}\beta.$$

As the cohomology of X is one-dimensional in all degrees, we deduce that $\lambda^{2p^k-2}(\beta) = \beta^{p^k} \otimes \xi^k$. The exact same argument works for $\lambda^*\alpha$. $\square$

We now study the evaluation pairing $\mathcal{A}_* \times \mathcal{A} \to \mathbb{F}_p$. We easily establish the following lemma

Lemma 11 *We have* $\xi_k(M_k) = 1$ *but* $\xi_k(\theta)$ *for any other monomial. Furthermore*

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

and $\langle \theta, \tau_k \rangle$ *for any other monomial.*

Proof We know that

$$M_k\beta = \beta^{p^k} = \sum_i (-1)^{2p^i \dim \xi^i} \langle M_k, \xi_i \rangle \beta^{p^i}$$

Proving the equality. The second equality follows from the same argument applied to α and $M_k\delta$. $\square$

We are ready to prove the main structure theorem for the dual Hopf algebra.

Theorem 12 *There is an isomorphism*

$$\mathcal{A}_* \simeq \Lambda[\tau_0, \tau_1, \ldots] \otimes \mathbb{F}_p[\xi_1, \xi_2, \ldots].$$

where $\Lambda[\tau_0, \ldots]$ *denotes the exterior algebra and* $\mathbb{F}_p[\xi_1, \xi_2, \ldots]$ *is the polynomial algebra. This isomorphism respects the grading. define weights on generators*

Proof Let $\mathcal{I}$ be the set of finite sequences $(\epsilon_0, r_1, \epsilon_1, \ldots)$ with $\epsilon_i = 0, 1$ and $r_i \in \mathbb{N}$. Given $I \in \mathcal{I}$, we define

$$\omega(I) := \tau_0^{\epsilon_0}\xi_1^{r_1}\tau_1^{\epsilon_1}\xi_2^{r_2}\cdots.$$

We claim it is sufficient to show that the set of $\omega(I)$ form a basis for $\mathcal{A}_*$. Indeed, the τ_i, ξ_j then don't observe any additional identities and the graded commutativity gives

the desired isomorphism.
We may order the set $\mathcal{I}$ colexicographically, ie. $(a_1, \epsilon_1, a_2, \cdots) < (b_1, \epsilon_1', b_2, \cdots)$ if $a_i < b_i$ for the largest i such that a_i and b_i differ (remember that the sequences are finite).

We also associated to a $J = (\epsilon_0, r_1, \epsilon_1, \ldots) \in \mathcal{I}$ an element of $\mathcal{A}$.

$$\theta(J) = \delta^{\epsilon_0} P^{s_1} \delta^{\epsilon_1} P^{s_2} \cdots,$$

where $s_j = \sum_{i=k}^{\infty} (\epsilon_i + r_i) p^{i-k}$.

One can check that the $\theta(J)$ are the basic monomials of the Cartan basis for $\mathcal{A}$.

To show the isomorphism, we show that the basic monomials in $\mathcal{A}$ form an "almost dual" basis to the set of $\omega(I)$.
More precisely, we will show the following lemma.

$$\text{Let } I < J \in \mathcal{I}\text{, then } \langle \theta(J), \omega(I) \rangle = 0 \text{ if } I < J\text{, furthermore } \langle \theta(I), \omega(I) \rangle = \pm 1. \qquad (\star)$$

The proof of $(\star)$ will constitute the main part of the proof, let us see how to conclude given $(\star)$.
Let $\mathcal{I}_n \subset \mathcal{I}$ be the set of sequences such that $\dim \omega(I) = \dim \theta(I) = n$. The matrix $(\langle \theta(J), \omega(I) \rangle)_{I,J \in \mathcal{I}_n}$ is upper-triangular with ± 1 on the diagonal, hence, the pairing is non-degenerate and the $\omega(I)$ generate the n-th graded part of $\mathcal{A}_*$. $\square$

References

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[SE62] Norman Earl Steenrod **and** David Bernard Alper Epstein. "Cohomology Operations". **in***Ann. of Math. Stud.*: (1962).