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BP: CLOSE ENCOUNTERS OF THE $E_\infty$ KIND

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Abstract. Inspired by Stewart Priddy’s cellular model for the $p$-local Brown-Peterson spectrum $BP$, we give a construction of a $p$-local $E_\infty$ ring spectrum $R$ which is a close approximation to $BP$. Indeed we can show that if $BP$ admits an $E_\infty$ structure then these are weakly equivalent as $E_\infty$ ring spectra. Our inductive cellular construction makes use of power operations on homotopy groups to define homotopy classes which are then killed by attaching $E_\infty$ cells.

Introduction

The notion of an $E_\infty$ ring spectrum arose in the 1970s, and was studied in depth by Peter May et al in [8], then later reinterpreted in the framework of [10] as equivalent to that of a commutative $S$-algebra. A great deal of work on the existence of $E_\infty$ structures using various obstruction theories has led to a considerable enlargement of our range of known examples. A useful recent discussion of relationships between various aspects of these topics can be found in [26].

However, despite this, there are some gaps in our knowledge. The question that is a major motivation of this paper is

- **Does the $p$-local Brown-Peterson spectrum $BP$ for a prime $p$ admit an $E_\infty$ ring structure?**

This has been flagged up as an outstanding problem for almost four decades, despite various attempts to answer it.

Around 1980, Stewart Priddy [31] showed how to build an efficient cellular model for the spectrum $BP$. This stimulated the later work of [12] (where the basic method was analysed and extended to $E_\infty$ ring spectra), then [5] (where outstanding issues about the spectrum case were addressed) and [3] (where the analogous multiplicative theory was described using topological Andrè-Quillen homology in place of ordinary homology). However, none of this answers the above question!

Some other recent results also add to the uncertainty. Niles Johnson and Justin Noel [14] have shown that for some small primes at least, the natural orientation map of ring spectra $MU \to BP$ cannot be $E_\infty$ (or even $H_\infty$). On the other hand, Mike Hill, Tyler Lawson and Niko Naumann [11, 19] have shown that for the primes 2 and 3, $BP(2)$ admits an $E_\infty$ ring structure. Finally, partial results on higher coherence of the multiplication on $BP$ have been...
proved by Birgit Richter [32], and Maria Basterra and Mike Mandell [6] (the latter uses ideas pioneered in an influential but unpublished preprint of Igor Kriz [16]).

Our main purpose in this paper is to give a prescription for constructing a close approach to $BP$ at a prime $p$. We will show that there is a connective finite type $p$-local $E_\infty$ ring spectrum $R$ such that the following hold.

- The homotopy $\pi_* R$ is torsion-free.
- There is a morphism of ring spectra $BP \to R$ which is a rational weak equivalence.
- If $BP$ admits an $E_\infty$ ring structure then there is a weak equivalence of $E_\infty$ ring spectra $R \xrightarrow{\sim} BP$.

Our construction proceeds in two main stages, the first of which yields a morphism of $p$-local $E_\infty$ ring spectra $R_\infty \to MU(p)$ so that the composition

$$R_\infty \to MU(p) \xrightarrow{\varepsilon} BP$$

with the Quillen projection $\varepsilon$ is a morphism of ring spectra which induces an epimorphism on $\pi_*(-)$ and is a rational equivalence. The second stage gives a morphism of $E_\infty$ ring spectra $R_\infty \to R$ which is a rational equivalence and where $\pi_*(R)$ is torsion free. One source of difficulty with our construction is that if $R$ is an $E_\infty$ realisation of $BP$, then there can be no $E_\infty$ morphism $R \to MU(p)$ by [12, theorem 2.11]. If we could produce any map of spectra $R \to BP$ which is an equivalence on the bottom cell then the composition $BP \to R \to BP$ would be a weak equivalence and so would each of the maps $BP \to R$ and $R \to BP$.

1. Attaching $E_\infty$ cells to commutative $S$-algebras

We recall the idea of attaching $E_\infty$ cells to a commutative $S$-algebra. Details can be found in [10], and it was exploited in [3] to describe topological André-Quillen homology of CW commutative $S$-algebras. We will make use of various obstructions involving free commutative $S$-algebras. Recall from [10] that if $X$ is an $S$-module then the free commutative $S$-algebra on $X$ is

$$\mathcal{P}X = \mathcal{P}_S X = \bigvee_{r \geq 0} X^{(r)}/\Sigma_r.$$  

When $X$ is cofibrant, for each $r \geq 1$ the natural projection provides a weak equivalence

$$(1.1) \quad E\Sigma_r \ltimes_{\Sigma_r} X^{(r)} \xrightarrow{\sim} X^{(r)}/\Sigma_r.$$  

Let $E$ be a commutative $S$-algebra and let $f: \bigvee_i S^n \to E$ be a map from a finite wedge of $n$-spheres. Then there is a unique extension of $f$ to a morphism of commutative $S$-algebras $\tilde{f}: \mathcal{P}(\bigvee_i S^n) \to E$ from the free commutative $S$-algebra on $\bigvee_i S^n$. Then the pushout diagram of commutative $S$-algebras

$$\begin{array}{ccc}
\mathcal{P}(\bigvee_i S^n) & \xrightarrow{\tilde{f}} & E \\
\downarrow \mathcal{P}(\text{inc}) & & \downarrow \Gamma \\
\mathcal{P}(\bigvee_i D^{n+1}) & \xrightarrow{E/\tilde{f}} & E
\end{array}$$
defines $E//f$ which we can regard as obtained from $E$ by attaching $E_\infty$ cells. In fact, we can take
\[ E//f = \mathbb{P}\left( \bigvee_i D^{n+1}_i \right) \wedge_{\mathbb{P}(\bigvee, S^n)} E \]
where $\mathbb{P}(\bigvee, D^{n+1})$ and $E$ are $\mathbb{P}(\bigvee, S^n)$-algebras in the evident way.

The homology of extended powers has been well studied and we can deduce the following.

**Proposition 1.1.** For $n \in \mathbb{N}$, we have
\[ H_* (\mathbb{P}S^{2^{n-1}}; \mathbb{Q}) = \Lambda_{\mathbb{Q}}(x_{2n-1}), \quad H_* (\mathbb{P}S^{2^n}; \mathbb{Q}) = \mathbb{Q}[x_{2n}], \]
where $x_m \in H_m(\mathbb{P}S^m; \mathbb{Q})$ is the image of the homology generator of $H_m(S^m; \mathbb{Q})$.

**Proof.** The weak equivalences of (1.1) combine to give a weak equivalence
\[ \bigvee_{r \geq 0} E \Sigma_r \ltimes_{\Sigma_r} (S^{2^{n-1}})^{(r)} \sim \bigvee_{r \geq 0} (S^{2^{n-1}})^{(r)}/\Sigma_r = \mathbb{P}S^{2^n-1}. \]
By [20, chapter VIII], for $r \geq 2$ we have
\[ H_* (E \Sigma_r \ltimes_{\Sigma_r} (S^{2^{n-1}})^{(r)}; \mathbb{Q}) = H_* ((S^{2^{n-1}})^{(r)}; \mathbb{Q})_{\Sigma_r} = 0, \]
since the permutation action of $\Sigma_r$ on the factors is equivalent to the sign representation,
\[ H_* ((S^{2^{n-1}})^{(r)}; \mathbb{Q}) \cong \mathbb{Q} - \]
which is a summand of the regular representation $\mathbb{Q}[\Sigma_r]$, hence it has trivial cohomology, and in particular trivial coinvariants. Thus we have
\[ H_* (\mathbb{P}S^{2^{n-1}}; \mathbb{Q}) = \Lambda_{\mathbb{Q}}(x_{2n-1}), \]
where
\[ x_{2n-1} \in H_{2n-1}(D_1 S^{2^{n-1}}; \mathbb{Q}) \cong H_{2n-1}(E \Sigma_r \ltimes_{\Sigma_r} (S^{2^{n-1}})^{(r)}; \mathbb{Q}). \]
Similarly,
\[ \mathbb{P}S^{2^n} = \bigvee_{r \geq 0} D_r S^{2^n} \sim \bigvee_{r \geq 0} E \Sigma_r \ltimes_{\Sigma_r} (S^{2^n})^{(r)}, \]
but this time the $\Sigma_r$ action on the factors is trivial giving
\[ H_* ((S^{2^n})^{(r)}; \mathbb{Q}) \cong \mathbb{Q}, \]
hence
\[ H_* (E \Sigma_r \ltimes_{\Sigma_r} (S^{2^n})^{(r)}; \mathbb{Q}) = H_* ((S^{2^n})^{(r)}; \mathbb{Q})_{\Sigma_r} = \mathbb{Q}. \]
concentrated in degree $2nr$. It follows easily that $H_* (\mathbb{P}S^{2^n}; \mathbb{Q})$ is polynomial on the stated generator. \hfill \Box

The next result is fundamental, see [8, 17, 18, 24, 25]. Here we use the convention that the excess of the empty exponent sequence is $\text{exc}(\emptyset) = \infty$.

**Theorem 1.2.** If $X$ is connective then for a prime $p$, $H_* (\mathbb{P}X; \mathbb{F}_p)$ is the free commutative graded $\mathbb{F}_p$-algebra generated by elements $Q^I x_j$, where $x_j$ for $j \in J$ gives a basis for $H_* (X; \mathbb{F}_p)$, and $I = (\varepsilon_1, i_1, \varepsilon_2, \ldots, \varepsilon_t, i_\ell)$ is admissible with $\text{exc}(I) + \varepsilon_1 > \lvert x_j \rvert$ when $p$ is odd, while $I = (i_1, \ldots, i_\ell)$ is admissible with $\text{exc}(I) > \lvert x_j \rvert$ when $p = 2$. 

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Using the notation $R(G)$ for the free commutative graded algebra over $R$ on a collection of homogeneous generators $G$, this gives the following formulae. Thus for $p$ odd,

$$H_*(\mathbb{P}X;\mathbb{F}_p) = \mathbb{F}_p \langle Q^j x_j : j \in J, \text{exc}(I) + \varepsilon_1 > |x_j| \rangle$$

is polynomial on the stated generators with $|Q^j x_j|$ even and exterior on those generators with $|Q^j x_j|$ odd, while for $p = 2$,

$$H_*(\mathbb{P}X;\mathbb{F}_2) = \mathbb{F}_2 \langle Q^j x_j : j \in J, \text{exc}(I) > |x_j| \rangle = \mathbb{F}_2[Q^j x_j : j \in J, \text{exc}(I) > |x_j|].$$

**Remark 1.3.** If $E$ is a commutative $S$-algebra and that $f: X \to E$ is a map of spectra for which the induced homomorphism

$$f_*: H_*(X;\mathbb{F}_p) \to H_*(E;\mathbb{F}_p)$$

is trivial. Then by Theorem 1.2, the induced ring homomorphism

$$\tilde{f}_*: H_*(\mathbb{P}X;\mathbb{F}_p) \to H_*(E;\mathbb{F}_p)$$

is also trivial since it is a homomorphism of algebras over the Dyer-Lashof algebra.

We record some results on the attaching of $E_\infty$ cones to commutative $S$-algebras and its effect on ordinary homology. We will make repeated use of the Künneth spectral sequence of [H]. By [H] this is multiplicative, and for a prime $p$ an extension of the work of [B13] shows that it has Dyer-Lashof operations.

First we give some easy observations on rational homology.

**Proposition 1.4.** Suppose that $E$ is a connective commutative $S$-algebra and let $n \in \mathbb{N}$.

(a) If $f: S^{2n-1} \to E$ is a map for which the induced homomorphism $f_*: H_*(S^{2n-1};\mathbb{Q}) \to H_*(E;\mathbb{Q})$ is trivial, then

$$H_*(E//f;\mathbb{Q}) = H_*(E;\mathbb{Q})[w],$$

where $w \in H_{2n}(E//f;\mathbb{Q})$.

(b) If $f: S^{2n} \to E$ is a map for which the induced homomorphism $f_*: H_*(S^{2n};\mathbb{Q}) \to H_*(E;\mathbb{Q})$ is trivial, then

$$H_*(E//f;\mathbb{Q}) = \Lambda_{H_*(E;\mathbb{Q})}[z],$$

where $z \in H_{2n+1}(E//f;\mathbb{Q})$.

**Proof.** Recall Proposition 1.3.

(a) There is a multiplicative Künneth spectral sequence [B10] of form

$$E^2_{s,t} = \text{Tor}_s^{H_*(\mathbb{P}S^{2n-1};\mathbb{Q})}(Q, H_*(E;\mathbb{Q})) \Rightarrow H_{s+t}(E//f;\mathbb{Q}),$$

where we have

$$E^2_{s,*} = H_{s}(E;\mathbb{Q})(w) = H_*(E;\mathbb{Q})[w],$$

with $w \in E^2_{1,2n-1}$. As $w$ is an infinite cycle for degree reasons, the result follows.

(b) Here the relevant Künneth spectral sequence

$$E^2_{s,t} = \text{Tor}_s^{H_*(\mathbb{P}S^{2n};\mathbb{Q})}(Q, H_*(E;\mathbb{Q})) \Rightarrow H_{s+t}(E//f;\mathbb{Q}),$$

has

$$E^2_{s,*} = \Lambda_{H_*(E;\mathbb{Q})}(z)$$

with $z \in E^2_{1,2n}$ which is an infinite cycle for degree reasons. \hfill \square
Of course we can replace a single sphere by a wedge of spheres in this result.

Now we will describe analogous results in positive characteristic. When the context makes this unambiguous, we will often write \( H_*(-) \) for \( H_*(-; \mathbb{F}_p) \) and \( \otimes \) for \( \otimes \mathbb{F}_p \). In the following, a \( p \)-truncated algebra will mean a quotient \( \mathbb{F}_p \)-algebra of the form

\[
TP_p(x) = \mathbb{F}_p[x]/(x^p).
\]

and we will denote this by \( TP(x) \) when the prime \( p \) is clear. It is standard that a divided power algebra on an element \( x \),

\[
\Gamma_{\mathbb{F}_p}(x) = \mathbb{F}_p\{1, \gamma_1(x), \gamma_2(x), \ldots\},
\]

is a tensor product of \( p \)-truncated algebras:

\[
\Gamma_{\mathbb{F}_p}(x) = \bigotimes_{r \geq 0} TP(\gamma_{pr}(x)).
\]

Here the product is given by

\[
\gamma_r(x)\gamma_s(x) = \binom{r + s}{r}\gamma_{r+s}(x)
\]

and so for every \( r \),

\[
\gamma_r(x)^p = 0.
\]

Furthermore, if \( r \) has \( p \)-adic expansion

\[
r = r_0 + r_1p + \cdots + r_{\ell}p^\ell,
\]

where \( r_i = 0, 1, \ldots, p - 1 \), then there is a non-zero element \( c_r \in \mathbb{F}_p \) for which

\[
\gamma_r(x) = c_r\gamma_1(x)^{r_0}\gamma_p(x)^{r_1}\cdots\gamma_{pr}(x)^{r_{\ell}}.
\]

To prove the odd primary case in our next result, we make use of work of Hunter [13].

**Proposition 1.5.** Let \( p \) be an odd prime and let \( E \) be a connective commutative \( S \)-algebra. Suppose that \( n \in \mathbb{N} \) and \( f: S^{2n-1} \longrightarrow E \) is a map for which the induced homomorphism \( f_*: H_*(S^{2n-1}; \mathbb{F}_p) \longrightarrow H_*(E; \mathbb{F}_p) \) is trivial. Then the Künneth spectral sequence

\[
E^2_{s,t} = \text{Tor}_{H_*}^{H_*(S^{2n-1}; \mathbb{F}_p)}(\mathbb{F}_p, H_*(E; \mathbb{F}_p)) \Longrightarrow H_{s+t}(E//f; \mathbb{F}_p)
\]

has the following properties.

(a) The homology of \( \mathbb{F}S^{2n-1} \) is the free commutative graded algebra

\[
H_*(\mathbb{F}S^{2n-1}; \mathbb{F}_p) = \mathbb{F}_p \langle Q^I x_{2n-1} : \text{exc}(I) + \varepsilon_1 > 2n - 1 \rangle.
\]

(b) The \( E^2 \)-term is a tensor product

\[
E^2_{s,s} = H_*(E; \mathbb{F}_p) \otimes \mathcal{D} \otimes \mathcal{E},
\]

of subalgebras, where \( \mathcal{D} \) and \( \mathcal{E} \) have the following descriptions:

- \( \mathcal{D} \) is a tensor product of infinitely many divided power algebras each having the form \( \Gamma_{\mathbb{F}_p}([Q^I x_{2n-1}]) \) with a generator \([Q^I x_{2n-1}] \in E^2_{1,[Q^I x_{2n-1}]} \) for each odd degree exterior generator occurring in \( \mathcal{D} \);
- \( \mathcal{E} \) is an exterior algebra with a generator \([Q^I x_{2n-1}] \in E^2_{1,[Q^I x_{2n-1}]} \) for each even degree polynomial generator \( Q^I x_{2n-1} \) occurring in \( \mathcal{D} \).
(c) In the above spectral sequence,

$$E_{s,t}^2 = \cdots = E_{s,t}^{p-1}, \quad E_{s,t}^p = E_{s,t}^\infty,$$

where the differential $d^{p-1}$ acts on the divided power generators of $\mathcal{D}$ by

$$d^{p-1}\gamma_p^{\langle i \rangle}\left(\left[Q^J x_{2n-1}\right]\right) = \begin{cases} 
[\beta Q\left(Q^J x_{2n-1}\right)]^{1/2}Q^J x_{2n-1} & \text{if } r \geq 1, \\
0 & \text{if } r = 0,
\end{cases}$$

where $\hat{=} \text{ means ‘equal up to multiplication by a unit in } \mathbb{F}_p.$

Proof. Using a standard Koszul resolution over the free algebra $H_*(\mathbb{P}S^{2n-1})$ we obtain the stated form for the $E^2$-term. The statement about the differentials involves a suitable reinterpretation of [13, proposition 11] together with the multiplicative structure of the spectral sequence. \(\square\)

The situation for $p = 2$ is simpler to describe and we state it in greater generality than we actually need for the present work.

**Proposition 1.6.** Let $p = 2$ and let $E$ be a connective commutative $S$-algebra. Suppose that $0 \leq n \in \mathbb{Z}$ and $f: S^n \longrightarrow E$ is a map whose induced homomorphism $f_*: H_*(S^n; \mathbb{F}_2) \longrightarrow H_*(E; \mathbb{F}_2)$ is trivial. Then the Künneth spectral sequence

$$E_{s,t}^2 = \text{Tor}_{s,t}^{H_*(\mathbb{P}S^n; \mathbb{F}_2)}(\mathbb{F}_2, H_*(E; \mathbb{F}_2)) \longrightarrow H_{s+t}(E//f; \mathbb{F}_2)$$

has the following properties.

(a) The homology of $\mathbb{P}S^n$ is the graded polynomial algebra

$$H_*(\mathbb{P}S^n; \mathbb{F}_2) = \mathbb{F}_2\{Q^I x_n : \text{exc}(I) > n \}.$$

(b) The $E^2$-term is the exterior algebra

$$E_{s,t}^2 = \Lambda_{H_*(E; \mathbb{F}_2)}(\langle Q^I x_n \rangle : \text{exc}(I) > n),$$

with a generator $\left[Q^I x_n\right] \in E_{2|Q^I x_n|}^2$ for each polynomial generator $Q^I x_n$ in (a).

(c) This spectral sequence has trivial differentials from $E^2$ onwards.

Proof. Using a standard Koszul resolution over the free algebra $H_*(\mathbb{P}S^n)$ we obtain the stated form for the $E^2$-term. The exterior generators all lie in $E_{1,*}^2$ and so must be infinite cycles. The multiplicative structure of the spectral sequence shows that all differentials are trivial. \(\square\)

**Theorem 1.7.** Let $p$ be a prime. Suppose that $E$ is a connective commutative $S$-algebra and that $f: S^{2n-1} \longrightarrow E$ is a map for which the induced homomorphism $f_*: H_*(S^{2n-1}; \mathbb{F}_p) \longrightarrow H_*(E; \mathbb{F}_p)$ is trivial. Then there is an element $u \in H_{2n}(E//f; \mathbb{F}_p)$ such that if $p$ is odd,

$$H_*(E//f; \mathbb{F}_p) = H_*(E; \mathbb{F}_p)\langle Q^I u : \text{exc}(I) + \varepsilon_1 > 2n, \text{ with } i_1 = 0 \text{ if } \varepsilon_1 = 1 \text{ and } |Q^I u| \text{ odd} \rangle,$$

while if $p = 2$,

$$H_*(E//f; \mathbb{F}_2) = H_*(E; \mathbb{F}_2)\langle Q^I u : \text{exc}(I) > 2n \rangle.$$

Proof. Taking into account the results of Propositions [1.5] and [1.6] we find that the $E^\infty$-term is a tensor product of algebras

$$E_{*,*}^\infty = H_*(E) \otimes \mathcal{D} \otimes \mathcal{E},$$

where
• $D'$ is a tensor product of infinitely many $p$-truncated algebras each having the form $\text{TP}([Q^I x_{2n-1}])$ with a generator $[Q^I x_{2n-1}] \in \mathrm{E}_1^\infty, [Q^I x_{2n-1}]$ for each exterior generator in (1.2).

• $E'$ is an exterior algebra with a generator $[Q^I x_{2n-1}] \in \mathrm{E}_1^\infty, [Q^I x_{2n-1}]$ for each polynomial generator $Q^I x_{2n-1}$ listed in (1.2).

When $p$ is odd, each exterior generator $Q^I x_{2n-1}$ is of odd degree so it gives rise to a $p$-truncated algebra $\text{TP}([Q^I x_{2n-1}])$ concentrated in even degrees. When $p = 2$, $D'$ is trivial and $E'$ is generated by elements $[Q^I x_{2n-1}]$ satisfying $[Q^I x_{2n-1}]^2 = 0$. In each case we need to show these generators represent elements which are not nilpotent in $H_*(\mathrm{E}/\gamma)$. We do this using Dyer-Lashof operations, using a well known argument, see for example [21].

If $p$ is an odd prime, set $k = |Q^I x_{2n-1}| + 1$. If $p = 2$, take $k = |Q^I x_{2n-1}| + 1$.

Then in the $E^2$-term we have

$$Q^k [Q^I x_{2n-1}] = [Q^k Q^I x_{2n-1}] \neq 0$$

since $Q^k Q^I$ is admissible. This shows that in $H_*(\mathrm{E}/\gamma)$ $[Q^I x_{2n-1}]$ represents an element whose $p$-th power is represented by $[Q^k Q^I x_{2n-1}]$, thus resolving the multiplicative extensions in the filtration. □

Remark 1.8. When $p = 2$ this results applies to all the cases of Proposition 1.6. Thus for $f: S^n \to \mathrm{E}$ with $n \geq 0$ we have

$$H_*(\mathrm{E}/f; \mathbb{F}_2) = H_* (\mathrm{E}; \mathbb{F}_2) [Q^I u : \text{exc}(I) > n + 1].$$

2. Power operations for $E_\infty$ ring spectra

We refer to [7] for work on power operations, in particular Bruner’s chapters IV and V. Our main use of this is in connection with applying ‘the first operation above the $p$-th power’ $\beta p^{k+1}$ to give a homotopy element of degree $2k$. Here are the results we will use.

At the prime 2, we have

**Theorem 2.1.** Suppose that $E$ is a connective 2-local $E_\infty$ ring spectrum for which $0 = \eta 1 \in \pi_1 E$. Then for $r \geq 1$, the operation $\mathcal{P}^{2r+1-1}$ is defined on $\pi_{2r+1-2} E$, giving a map

$$\mathcal{P}^{2r+1-1}: \pi_{2r+1-2} E \to \pi_{2r+2-3} E.$$ 

Moreover, the indeterminacy is trivial and the operation $2\mathcal{P}^{2r+1-1}$ is trivial.

**Proof.** We will write $n = 2r+1 - 2$.

Applying [12] proposition V.1.5] to the skeleton $D_2 S^{2n}$, we have

$$i = 1, \quad j = n + 1, \quad \varphi(i) = 1,$$

and so

$$n \equiv -2 \mod (2),$$
hence the operation $P^{2r+1-1}$ is defined on $\pi_{2r+1-2}E$. Also, by [7, theorem V.1.8] we have with $j = a = b = 0$ and $w \in \pi_{2r+1-2}E$,

$$2P^{2r+1-1}w = 0$$

since by assumption the natural map $\pi_1S \to \pi_1E$ is trivial. Similarly, since $n \equiv 2 \mod (4)$, the indeterminacy is trivial by [7, table V.1.3]. □

For odd primes we have

**Theorem 2.2.** Let $p$ be an odd prime. Suppose that $E$ is a connective $p$-local $E_\infty$ ring spectrum for which $0 = \alpha_1 \in \pi_{2p-3}E$.

Then for $r \geq 1$, the operation $\beta P^r$ is defined on $\pi_{2(p^r-1)}E$ giving a map

$$\beta P^r : \pi_{2(p^r-1)}E \to \pi_{2(p^{r+1}-1)}E.$$ 

Moreover the indeterminacy is trivial and the operation $p\beta P^r$ is trivial.

**Proof.** We will assume that all spectra are localised at $p$. Recall that $\alpha_1 \in \pi_{2p-3}S$ is a non-zero $p$-primary stable homotopy element of lowest positive degree.

Using the results and notation of [7, proposition V.1.5], the fact that this operation is defined on $\pi_{2(p^r-1)}E$ this follows since

$$\psi\left(2p^r(p-1) - 1 - 2(p^r-1)(p-1)\right) = \psi(2(p-1) - 1) = \left[\frac{2(p-1) - 1}{2(p-1)}\right] = 0.$$ 

For triviality of the indeterminacy, see [7, table V.1.1].

By [7, theorem V.1.8], for each $y \in \pi_{2(p^r-1)}E$ there is an element $\alpha \in \pi_{2(p^r-1)-2}S$ for which

$$p(\beta P^r y) = \alpha y^p.$$ 

But $\alpha \in \pi_{2(p^r-2)}S = 0$, hence $p(\beta P^r)$ is indeed trivial. □

The next result tells us how this works in the Adams spectral sequence in good situations.

**Lemma 2.3.** Let $p$ be a prime

(i) If $p = 2$, then under the assumptions of Theorem 2.1, if $w \in \pi_{2r+1-2}E$ is detected in the 1-line of the Adams spectral sequence by $W \in \text{Ext}_{A(2)}^{1,2r+1-1}(F_2,H_*E)$, then $P^{2r+1-1}w$ is detected in the 1-line by

$$P^{2r+1-1}W \in \text{Ext}_{A(2)}^{1,2r+2-2}(F_2,H_*E),$$

where $P^{2r+1-1}$ is the algebraic Steenrod operation of [7,23,29]. This can be calculated by applying the Dyer-Lashof operation $Q^{2r+1-1}$ to the element of $A(2)\otimes H_*E = H_*(H \wedge E)$ representing $W$.

(ii) If $p$ is odd, then under the assumptions of Theorem 2.2, if $w \in \pi_{2(p^r-1)}E$ is detected in the 1-line of the Adams spectral sequence by $W \in \text{Ext}_{A(p)}^{1,2p^r-1}(F_p,H_*E)$, then $\beta P^r w$ is detected in the 1-line by

$$\beta P^r W \in \text{Ext}_{A(p)}^{1,2(p^r+2-1)}(F_p,H_*E),$$

where $\beta P^r$ is the algebraic Steenrod operation of [7,23,29]. This can be calculated by applying the Dyer-Lashof operation $\beta Q^r$ to the element of $A(p)\otimes H_*E = H_*(H \wedge E)$ representing $W$.

**Proof.** This follows from work of Milgram and Bruner [7,29]. Note that for $p = 2$, [7, theorem 2.5(i)] should read

$$\beta P^t : \text{Ext}^{s,t} \to \text{Ext}^{s+t-1,2t}. $$
3. Outline of a construction

In this section and later ones, we will always be working with (connective) \( p \)-local spectra for some prime \( p \). When referring to cells, finite type conditions, etc., we will always mean in that context.

Starting with the \( p \)-local sphere \( S \), we will construct a sequence of commutative \( S \)-algebras

\[
S = R_0 \longrightarrow R_1 \longrightarrow \cdots \longrightarrow R_{n-1} \longrightarrow R_n \longrightarrow \cdots,
\]

where \( R_n \) is obtained from \( R_{n-1} \) by attaching a single \( E_\infty \) cell of dimension \( 2(p^n - 1) \). The rational homotopy of the colimit \( R_\infty = \colim_n R_n \) is

\[
\mathbb{Q} \otimes \pi_* R_\infty = \mathbb{Q}[u_n : n \geq 1],
\]

where \( u_n \in \pi_{2(p^n - 1)} R_n \). Next we could inductively kill the torsion part of the homotopy of \( R \) by non-trivially attaching \( E_\infty \) cones on Moore spectra, thus we do not change the rational homotopy. Then we obtain a commutative \( R_\infty \)-algebra \( R \) for which

\[
\mathbb{Q} \otimes \pi_* R = \mathbb{Q} \otimes \pi_* R = \mathbb{Q}[u_n : n \geq 1].
\]

4. Construction of the \( R_n \)

We begin with the construction of the sequence (3.1). We will use the notation \( u_0 = p \). Let \( n \geq 1 \). Suppose that a sequence of cofibrations of commutative \( S \)-algebras

\[
S = R_0 \longrightarrow R_1 \longrightarrow \cdots \longrightarrow R_{n-1}
\]

exists in which there are compatible homotopy elements \( u_r \in \pi_{2(p^r - 1)} R_k \) for \( 0 \leq r \leq k \), satisfying

\[
\mathbb{Q} \otimes \pi_* R_k = \mathbb{Q} \otimes \pi_* R_k[u_k].
\]

Then by Theorem 2.2, assuming that it is not trivial, the element \( \beta \mathbb{P}^{p^n-1} u_{n-1} \) is of order \( p \); we let \( f_n : S^{2p^n-3} \longrightarrow R_{n-1} \) be a representative of this homotopy class. Thus as in [3,10] we can form the pushout diagram of commutative \( S \)-algebras

\[
\begin{array}{ccc}
\mathbb{P}S^{2p^n-3} & \xrightarrow{\tilde{f}_n} & R_{n-1} \\
\downarrow & & \downarrow \\
\mathbb{P}D^{2p^n-2} & \longrightarrow & R_n
\end{array}
\]

in which \( \tilde{f}_n \) is the extension of \( f_n \) to a map from the free commutative \( S \)-algebra \( \mathbb{P}S^{2p^n-3} \). We remark that we can work equally well with commutative \( R_{n-1} \)-algebras and define \( R_n \) using the pushout diagram

\[
\begin{array}{ccc}
\mathbb{P}R_{n-1} S^{2p^n-3} & \xrightarrow{\tilde{f}_n} & R_{n-1} \\
\downarrow & & \downarrow \\
\mathbb{P}R_{n-1} D^{2p^n-2} & \longrightarrow & R_n
\end{array}
\]

and we will make use of both viewpoints. We also have

\[
R_n \cong R_{n-1} \wedge \mathbb{P}S^{2p^n-3} \mathbb{P}D^{2p^n-2} \cong R_{n-1} \wedge \mathbb{P}R_{n-1} S^{2p^n-3} \mathbb{P}R_{n-1} D^{2p^n-2}
\]
Since $f_n$ has order $p$, there is a commutative diagram of $R_{n-1}$-modules

\[
\begin{array}{cccccc}
S^{2p^n-2} & & & & & \\
\downarrow & & & & & \\
C_{f_n} & \xrightarrow{p} & S^{2p^n-2} & \downarrow & & \\
\downarrow & & & & & \\
R_n & & & & & \\
\end{array}
\]

in which the dashed arrow provides a homotopy class $u_n \in \pi_{2p^n-2}R_n$.

There is a Kunneth spectral sequence [10] of the form

\[
E^2_{r,s} = \text{Tor}_{r,s}^{Q \otimes \pi_\ast R_{n-1}[w_{2p^n-3}]}(Q \otimes \pi_\ast R_{n-1}, Q \otimes \pi_\ast R_{n-1}) \Rightarrow Q \otimes \pi_{s+1}R_n,
\]

where

\[
Q \otimes \pi_\ast R_{n-1}[w_{2p^n-3}] = Q \otimes \pi_\ast \mathbb{P}R_{n-1}S^{2p^n-3}
\]

is an exterior algebra, so

\[
E^2_{r,s} = Q \otimes \pi_\ast R_{n-1}[U_n]
\]

with generator $U_n$ of bidegree $(1, 2p^n - 3)$. Thus the spectral sequence collapses and we easily obtain

\[
Q \otimes \pi_\ast R_n = Q \otimes \pi_\ast R_{n-1}[u_n].
\]

We still need to verify the following key result.

**Lemma 4.1.** The element $\beta \mathbb{P}p^{p^n-1}u_{n-1} \in \pi_{2p^n-3}R_{n-1}$ is non-zero and has order $p$. Furthermore, the mod $p$ Hurewicz image of $u_n$ is trivial.

Passing to the limit, we see that since each morphism $R_{n-1} \to R_n$ is a cofibration,

\[
R_\infty = \text{hocolim}_n R_n
\]

and

\[
\pi_\ast R_\infty = \text{colim}_n \pi_\ast R_n.
\]

Working rationally this gives

\[
Q \otimes \pi_\ast R_\infty = Q \otimes \pi_\ast S[u_n : n \geq 1] = Q[u_n : n \geq 1].
\]

5. **Killing the torsion**

The homotopy of the commutative $S$-algebra $R_\infty$ has finite type and $R$ is a CW commutative $S$-algebra with one $E_\infty$ cell in each degree of the form $2(p^n - 1)$ with $n \geq 1$.

Now we proceed to kill the torsion in $\pi_\ast R_\infty$ by induction on degree. Let $R^0 = R_\infty$. Suppose that we have constructed $R^0 \to R^{m-1}$ so that $\pi_k R^{m-1}$ is torsion free for $k \leq m - 2$ and the natural map induces an isomorphism

\[
Q \otimes \pi_\ast R^0 \cong Q \otimes \pi_\ast R^{m-1}.
\]
Now following [3, 5] we attach \( m \)-cells minimally to kill the torsion of \( \pi_{m-1} R^{m-1} \). In fact, following a suggestion of Tyler Lawson, we can do slightly more: factoring the attaching maps through Moore spectra of the form \( S^{m-1} \cup_{p^r} D^m \), we can define \( R^m \) using the pushout diagram

\[
\begin{array}{ccc}
P(\bigvee_i S^{m-1} \cup_{p^r} D^m) & \rightarrow & R^{m-1} \\
\downarrow & & \downarrow \\
P(\bigvee_i C(S^{m-1} \cup_{p^r} D^m)) & \rightarrow & R^m
\end{array}
\]

and so we have

\[
\mathbb{Q} \otimes \pi_* R^0 \cong \mathbb{Q} \otimes \pi_* R^m.
\]

Continuing in this way, we obtain a sequence of cofibrations

\[
R_\infty = R^0 \rightarrow R^1 \rightarrow \cdots \rightarrow R^{m-1} \rightarrow R^m \rightarrow \cdots
\]

whose limit is

\[
R = \colim_m R^m = \hocolim_m R^m.
\]

Furthermore, the natural map \( R_\infty \rightarrow R \) induces an epimorphism

\[
\pi_* R_\infty \rightarrow \pi_* R
\]

and a rational isomorphism

\[
\mathbb{Q} \otimes \pi_* R \rightarrow \mathbb{Q} \otimes \pi_* R_\infty = \mathbb{Q}[u_n : n \geq 1].
\]

6. SOME RECURSIVE FORMULAE

We give the odd primary case first, the 2-primary case is similar.

The case \( p > 2 \). Let \( p \) be an odd prime and assume that all spectra are \( p \)-local. Starting with \( R_0 = S \), the \( p \)-local sphere, we will inductively assume that there is a sequence of \( E_\infty \) ring spectra

\[
S = R_0 \rightarrow R_1 \rightarrow \cdots \rightarrow R_{n-1}
\]

so that the following hold:

(A) for \( 1 \leq r \leq n \) there are homotopy classes \( \alpha_{[r]} \in \pi_{2(p^r-1)} R_{r-1} \) of order \( p \), and homology classes \( z_r \in H_{2(p^r-1)}(R_r; \mathbb{F}_p) \);

(B) the \( A(p)_* \)-coaction is given by

\[
\psi(z_r) = 1 \otimes z_r + \zeta_1 \otimes z_{p^r-1} + \zeta_2 \otimes z_{p^r-2}^2 + \cdots + \zeta_{r-1} \otimes z_1^{p^r-1} + \zeta_r \otimes 1,
\]

where we identify \( z_i \in H_*(R_i; \mathbb{F}_p) \) with the image of \( z_i \in H_*(R_i; \mathbb{F}_p) \) under the induced homomorphism \( H_*(R_i; \mathbb{F}_p) \rightarrow H_*(R_r; \mathbb{F}_p) \) whenever \( i < r \);

(C) \( \alpha_{[r]} \) is detected in filtration 1 the Adams spectral sequence by the class with cobar representative

\[
\zeta_1 \otimes z_{p^r-1} + \zeta_2 \otimes z_{p^r-2}^2 + \cdots + \zeta_{r-1} \otimes z_1^{p^r-1} + \zeta_r \otimes 1,
\]

and \( \alpha_{[1]} = \alpha_1 \pi_{2p-3} S \).

Given this data, we construct the morphism of \( E_\infty \) ring spectra \( R_{n-1} \rightarrow R_n \) as follows.
Choose a representative $f_n : S^{2p^n - 3} \rightarrow R_{n-1}$ for $\alpha_{[n]}$. Attach an $E_\infty$ cone to $R_{n-1}$ by forming the pushout $R_{n-1} / \alpha_{[n]}$ in the diagram

$$
\begin{array}{ccc}
S^{2p^n - 3} & \xrightarrow{f_n} & R_{n-1} \\
\downarrow & & \downarrow \\
D^{2p^n - 2} & \xrightarrow{\text{cone}} & R_{n-1} / \alpha_{[n]} \\
\end{array}
$$

and set $R_n = R_{n-1} / \alpha_{[n]}$. Since $\alpha_{[n]}$ has order $p$, there is a commutative diagram of $S$-modules

$$
\begin{array}{ccc}
S^{2p^n - 2} & \xrightarrow{p} & S^{2p^n - 2} \\
\downarrow & & \downarrow \\
S^{2p^n - 3} & \xrightarrow{f_n} & R_{n-1} \\
\downarrow & & \downarrow \\
C_{f_n} & \xrightarrow{} & S^{2p^n - 2} \\
\downarrow & & \downarrow \\
R_n & \xrightarrow{} & R_n \\
\end{array}
$$

in which the dashed arrow provides a homotopy class $u_n \in \pi_{2p^n - 2}R_n$. The homology class $z_n$ is represented by the image of the ordinary cell attached to form the mapping cone $C_{f_n}$.

**Lemma 6.1.** The homotopy class $u_n$ lies in the Toda bracket $\langle p, \alpha_{[n]}, 1 \rangle \subseteq \pi_{2(p^n - 1)}R_n$, and in the Adams spectral sequence it has filtration 1 and cobar representative

$$
\bar{\tau}_0 \otimes z_n + \bar{\tau}_1 \otimes z_{p^{n-1}}^n + \bar{\tau}_2 \otimes z_{p^{n-2}}^n + \cdots + \bar{\tau}_{n-1} \otimes z_1^{p^n} + z_n \otimes 1,
$$

where $\bar{\tau}_j$ denotes the conjugate of the exterior generator $\tau_j \in A(p)_{2p^j - 1}$.

**Proof.** This Toda bracket should be interpreted in the sense of modules over $R_{n-1}$. Thus the first two variables are in $\pi_* R_{n-1}$ while the last is in $\pi_* R_n$ viewed as a module over $\pi_* R_{n-1}$.

Now in the Adams $E_2$-term, we have the relation

$$
h_0[\zeta_1 \otimes z_{n-1}^p + \zeta_2 \otimes z_{n-2}^{p^2} + \cdots + \zeta_{n-1} \otimes z_1^{p^n} + \zeta_n \otimes 1] = 0
$$
since $p_0[n] = 0$, and using (6.1) we obtain

$$d_1 \left( \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right) = \sum_{1 \leq s \leq n} 1 \otimes \bar{\tau}_s \otimes z_{n-s}^{p^s}$$

$$- \left( \sum_{1 \leq j \leq s \leq n} \bar{\tau}_j \otimes \epsilon_{s-j}^{p^j} \otimes z_{n-s}^{p^s} + \sum_{1 \leq s \leq n} 1 \otimes \bar{\tau}_s \otimes z_{n-s}^{p^s} \right)$$

$$+ \left( \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes 1 \otimes z_{n-s}^{p^s} + \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes \zeta_{p^s}^{p^s} \otimes z_{n-s-k}^{p+k} \right)$$

$$= - \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes \zeta_s \otimes z_{n-s}^{p^s}$$

$$- \left( \sum_{1 \leq j \leq s \leq n} \bar{\tau}_j \otimes \zeta_{s-j}^{p^j} \otimes z_{n-s}^{p^s} - \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes \zeta_{p^s}^{p^s} \otimes z_{n-s-k}^{p+k} \right)$$

$$= \sum_{1 \leq s \leq n} -\bar{\tau}_s \otimes \zeta_s \otimes z_{n-s}^{p^s}.$$

We also have

$$d_1(-z_n) = -1 \otimes z_n + \left( \sum_{1 \leq s \leq n} \zeta_s \otimes z_{n-s}^{p^s} + 1 \otimes z_n \right)$$

$$= \sum_{1 \leq s \leq n} \zeta_s \otimes z_{n-s}^{p^s}.$$

Therefore we have

$$\left[ \sum_{0 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right] = \left[ \bar{\tau}_0 \otimes z_n + \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right] \in \left\langle h_0, \left[ \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right], 1 \right\rangle.$$

So modulo higher Adams filtration, the Toda bracket $\langle p, \alpha[n], 1 \rangle$ is represented in the Adams spectral sequence by

$$\left\langle h_0, \left[ \sum_{1 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right], 1 \right\rangle.$$  \hfill \square

Note that Lemma 2.3(ii) gives

$$\beta p^{p^n} \left[ \sum_{0 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right] = \left[ \beta Q^{p^n} \sum_{0 \leq s \leq n} \bar{\tau}_s \otimes z_{n-s}^{p^s} \right]$$

$$= \left[ \sum_{0 \leq s \leq n} \beta Q^{p^s} (\bar{\tau}_s) \otimes Q^{p^n-p^s} (z_{n-s}^{p^s}) \right]$$

$$= \left[ \sum_{0 \leq s \leq n} \beta \bar{\tau}_{s+1} \otimes (Q^{p^n-s-1} z_{n-s}^{p^s}) \right]^{p^s}$$
\[(by \ [7, \text{ theorem III.2.3}])\]
\[
\sum_{0 \leq s \leq n} \beta_{s+1} \otimes (z_{n-s}^p)^{\lambda_{s+1}}
\]
\[
= \sum_{0 \leq s \leq n} \zeta_{s+1} \otimes z_{n-s}^{\lambda_{s+1}}
\]
\[(by \ [7, \text{ theorem III.2.3}] \text{ again})\]
\[
\sum_{1 \leq s \leq n} \zeta_s \otimes z_{n+1-s}^{\lambda_s}
\]
\[= \alpha_{[n+1]}.
\]

**The case** \(p = 2\). With similar notation to that for odd primes, we have

**Lemma 6.2.** The element \(u_n\) lies in the Toda bracket \(\langle 2, w_{n-1}, 1 \rangle \subseteq \pi_{2n+1 - 2} R(\mathbb{n})\), and in the Adams spectral sequence it has filtration 1 with cobar representative

\[
\zeta_1 \otimes s_n + \zeta_2 \otimes s_{n-1}^2 + \zeta_3 \otimes s_{n-2}^2 + \cdots + \zeta_n \otimes s_1^{2n-1} + \zeta_{n+1} \otimes 1,
\]

where \(\zeta_j\) denotes the conjugate of the Milnor generator \(\xi_j \in \mathcal{A}(2)_{2^j-1}\).

**7. The map to** \(HF_p\)

There is a morphism of commutative \(S\)-algebras \(R_\infty \rightarrow MU_{(p)}\), and composing this with the Quilen morphism of ring spectra \(\varepsilon : MU_{(p)} \rightarrow BP\) we obtain morphisms of ring spectra

\[
R_\infty \rightarrow BP \rightarrow HF_p
\]

and we would like to understand their induced maps in homotopy and homology.

**Lemma 7.1.** Let \(p\) be a prime.

(i) If \(p\) is odd, suppose that \(s_1, s_2, s_3, \ldots\) is a sequence of elements \(s_n \in \mathcal{A}(p)_{2(p^n-1)}\) with coproducts

\[
\psi(s_n) = \zeta_n \otimes 1 + \zeta_{n-1} \otimes s_1^{p^{n-1}} + \cdots + \zeta_1 \otimes s_{n-1}^p + 1 \otimes s_n.
\]

Then \(s_n = \zeta_n\).

(ii) If \(p = 2\), suppose that \(s_1, s_2, s_2, \ldots\) is a sequence of elements \(s_n \in \mathcal{A}(p)_{2^n-1}\) with coproducts

\[
\psi(s_n) = \zeta_n \otimes 1 + \zeta_{n-1} \otimes s_1^{2^{n-1}} + \cdots + \zeta_1 \otimes s_{n-1}^2 + 1 \otimes s_n.
\]

Then \(s_n = \zeta_n\).

**Proof.** We recall that there are no non-trivial coaction primitives in positive degrees, i.e., viewing \(\mathcal{A}(p)_*\) as a left \(\mathcal{A}(p)_*\)-comodule, a standard change of rings isomorphism gives

\[
\text{Ext}^{0,*}_{\mathcal{A}(p)_*}(F_p, \mathcal{A}(p)_*) \cong \text{Ext}^{0,*}_{F_p}(F_p, F_p) = F_p.
\]

(i) For \(n = 1\), we have

\[
\psi(s_1 - \zeta_1) = (\zeta_1 \otimes 1 + 1 \otimes s_1) - (\zeta_1 \otimes 1 + 1 \otimes \zeta_1)
\]
\[= 1 \otimes (s_1 - \zeta_1).
\]

So \(s_1 = \zeta_1\).
Now suppose that for \( k < n, s_k = \zeta_k \). Then
\[
\psi(s_n - \zeta_n) = \sum_{0 \leq j \leq n} \zeta_j \otimes s_{n-j}^p - \sum_{0 \leq j \leq n} \zeta_j \otimes \zeta_{n-j}^p
\]
\[
= 1 \otimes (s_n - \zeta_n)
\]
so we have \( s_n = \zeta_n \). By induction this holds for all \( n \).

The proof of (ii) is similar. \( \square \)

**Remark 7.2.** Since \( H_\ast(BP; \mathbb{F}_p) \) can be identified with a subalgebra of \( \mathcal{A}(p)_\ast \), we can also characterize a family of polynomial generators \( t_n \in H_{2(p^n-1)}(BP; \mathbb{F}_p) \) by the coaction formulae
\[
\psi(t_n) = \begin{cases} 
\sum_{0 \leq j \leq n} \zeta_j \otimes t_{n-j}^p & \text{if } p \text{ is odd}, \\
\sum_{0 \leq j \leq n} \zeta_j^2 \otimes t_{n-j}^{2^j} & \text{if } p = 2.
\end{cases}
\]

**Theorem 7.3.** The morphism of ring spectra \( R_\infty \longrightarrow BP \) induces epimorphisms in \( \pi_\ast(-) \), \( H_\ast(-; \mathbb{Z}(p)) \) and \( H_\ast(-; \mathbb{F}_p) \).

**Proof.** We indicate two rather different proofs.

**First proof:** The morphism of ring spectra \( R_\infty \longrightarrow BP \longrightarrow H\mathbb{F}_p \) induces a homomorphism in homology sending the elements \( z_n \) to elements \( s_n \in \mathcal{A}(p)_\ast \) for which Lemma 7.1 applies. By Remark 7.2 this means that \( z_n \mapsto \zeta_n \) if \( p \) is odd, and \( z_n \mapsto \zeta_n^2 \) if \( p = 2 \).

**Second proof:** First assume that \( p \) is odd. Consider the morphism of ring spectra \( R_1 \longrightarrow R_\infty \longrightarrow BP \). The \( z_1 \in H_{2(p^n-1)}(R_1; \mathbb{F}_p) \) maps to an element \( t \in H_{2(p^n-1)}(BP; \mathbb{F}_p) \) with \( \mathcal{A}_\ast \)-coaction
\[
\psi(t) = \zeta_1 \otimes 1 + 1 \otimes t.
\]
The only such element is \( t_1 \).

The homomorphism \( H_\ast(BP; \mathbb{F}_p) \longrightarrow H_\ast(H\mathbb{F}_p; \mathbb{F}_p) = \mathcal{A}(p)_\ast \). Also \( MU \longrightarrow H\mathbb{F}_p \) is a morphism of commutative \( S \)-algebras whose image is \( H_\ast(BP; \mathbb{F}_p) \subseteq H_\ast(H\mathbb{F}_p; \mathbb{F}_p) \). Therefore the action of the Dyer-Lashof operations on \( H_\ast(H\mathbb{F}_p; \mathbb{F}_p) \) restricts to \( H_\ast(BP; \mathbb{F}_p) \). Now \( t_r \) maps to \( \zeta_r \), so we can determine the Dyer-Lashof action using [7, theorem III.2.3]. Then
\[
Q^{p^r-1} \cdots Q^{p^2} Q^p \zeta_1 = \zeta_s,
\]
hence
\[
Q^{p^r-1} \cdots Q^{p^2} Q^p t_1 = t_s.
\]
Thus the element \( Q^{p^r-1} \cdots Q^{p^2} Q^p z_1 \in H_\ast(R_1; \mathbb{F}_p) \) maps to \( t_s \in H_\ast(BP; \mathbb{F}_p) \). Since
\[
H_\ast(BP; \mathbb{F}_p) = \mathbb{F}_p[t_s : s \geq 1],
\]
we see that \( H_\ast(R_1; \mathbb{F}_p) \longrightarrow H_\ast(BP; \mathbb{F}_p) \) is epic, hence so is \( H_\ast(R_\infty) \longrightarrow H_\ast(BP; \mathbb{F}_p) \).

In fact the \( z_s \) all lift to elements of \( H_\ast(R_\infty; \mathbb{Z}(p)) \) and it easily follows that \( H_\ast(R_\infty; \mathbb{Z}(p)) \longrightarrow H_\ast(BP; \mathbb{Z}(p)) \) is epic.

For \( p = 2 \), the arguments are similar, but with \( \zeta_s^2 \) in place of \( \zeta_s \), and \( Q^{2^{r+1}} \) in place of \( Q^{p^r} \) throughout.

To show that the induced homomorphism \( \pi_\ast R_\infty \longrightarrow \pi_\ast BP \) in homotopy is epic, we need to verify that a family of polynomial generators for \( \pi_\ast BP \) is in the image. When \( p \) is odd,
Lemma 6.1 together with the above discussion, shows that in the Adams spectral sequence for $\pi_\ast BP$, $u_n$ maps to an element represented by
\[
\left[\tau_0 \otimes t_n + \tau_1 \otimes t_{n-1}^p + \tau_2 \otimes t_{n-2}^{p^2} + \cdots + \tau_{n-1} \otimes t_1^{p^{n-1}}\right] \in \text{Ext}^{1,2p^{n-1}}_{A(p)_*}(F_p, H_\ast(BP; F_p))
\]
which correspond to a homotopy element with Hurewicz image in $H_\ast(BP; \mathbb{Z}_{(p)})$ of the form $pt_n \pmod{p}$, decomposables).

By Milnor’s criterion, this is a polynomial generator.

The argument for $p = 2$ is similar, with $u_n$ mapping to an element having cobar representative
\[
\left[\zeta_1 \otimes t_n + \zeta_2 \otimes t_{n-1}^{2} + \zeta_3 \otimes t_{n-2}^{2^2} + \cdots + \zeta_{n+1} \otimes 1\right] \in \text{Ext}^{1,2n-1}_{A(2)_*}(F_2, H_\ast(BP; F_2)).
\]

8. RELATIONSHIP TO $BP$

We start with an easy lemma. For an abelian group $G$, we write $\text{tors} G$ for the torsion subgroup.

**Lemma 8.1.** Let $Y \stackrel{g}{\rightarrow} Z$ be a fibration of $p$-local spectra and let

\[
\begin{array}{ccc}
X & \xrightarrow{f} & Y \\
\downarrow & & \downarrow \\
* & \xrightarrow{g} & Z
\end{array}
\]

be a pullback square. Assume that the following hold:

- $f_\ast \colon \pi_\ast(X) \rightarrow \pi_\ast(Y)$ is monic;
- $\text{tors} \pi_\ast(Z) = 0$;
- $\text{tors} \pi_\ast(X) = \pi_\ast(X)$.

Suppose that $\alpha \in \text{tors} \pi_m(Y)$ is non-zero and has order $p^e$. Then there is a map

\[u \colon S^m \cup_{p^e} D^{m+1} \rightarrow X\]

for which the composition

\[
\begin{array}{ccc}
S^m & \xrightarrow{\text{inc}} & S^m \cup_{p^e} D^{m+1} \\
\downarrow & & \downarrow \\
X & \xrightarrow{f} & Y
\end{array}
\]

represents $\alpha$.

**Proof.** By assumption, $f_\ast$ induces an isomorphism

\[f_\ast \colon \pi_\ast(X) \xrightarrow{\cong} \text{tors} \pi_\ast(Y),\]

hence there is a unique element $\alpha' \in \pi_m(X)$ for which $f_\ast(\alpha') = \alpha$ and the order of $\alpha'$ is also $p^e$.

A representative of $\alpha'$ must factor through $S^m \cup_{p^e} D^{m+1}$,

\[
\begin{array}{ccc}
S^m & \xrightarrow{u} & X \\
\downarrow & & \downarrow f \\
S^m \cup_{p^e} D^{m+1} & & Y
\end{array}
\]

showing that the desired $u$ exists, and the dashed arrow represents $\alpha$. 

\[\square\]
Corollary 8.2. The map $g$ factors through the mapping cone of $fu$.

\[
\begin{array}{ccc}
S^m \cup_{p^e} D^{m+1} & \xrightarrow{fu} & Y \\
\downarrow g & & \downarrow C_{fu} \\
& Z & \\
\end{array}
\]

Proof. This follows from the commutative diagram

\[
\begin{array}{ccc}
S^m \cup_{p^e} D^{m+1} & \xrightarrow{u} & Y \\
\downarrow f & & \downarrow C_u \\
S^m \cup_{p^e} D^{m+1} & \xrightarrow{fu} & Y \\
\downarrow g & & \downarrow C_{fu} \\
& Z & \\
\end{array}
\]

in which $gf$ is the trivial map and the dashed arrow is obtained by mapping the cone trivially. □

Theorem 8.3. Let $p$ be a prime. If $BP$ admits an $E_\infty$ structure then there is a weak equivalence of commutative $S$-algebras $R \xrightarrow{\sim} BP$.

Proof. Since $\pi_*BP$ is torsion-free, the inductive construction of $R_n$ from $R_{n-1}$ gives morphisms of commutative $S$-algebras

\[
\begin{array}{ccc}
R_{n-1} & \xrightarrow{} & R_n \\
& \searrow & \searrow BP \\
& & \\
\end{array}
\]

and passing to the colimit we obtain a morphism $R_\infty \rightarrow BP$. By Theorem 7.3, $\pi_*R_\infty \rightarrow \pi_*BP$ is an epimorphism and on tensoring with $\mathbb{Q}$ it becomes an isomorphism.

On replacing $R_\infty \rightarrow BP$ with a fibration of commutative $S$-algebras $T^0 \rightarrow BP$ with fibre $J_0$, we are in the situation of Lemma 8.1. Now we can inductively adjoin cones on wedges of Moore spectra $S^m \cup_{p^e} D^{m+1}$ where $m \geq 1$ to form morphisms of $E_\infty$ ring spectra $T^{m-1} \rightarrow T^m$.

At each stage Corollary 8.2 shows that we can extend to a diagram of morphisms

\[
\begin{array}{cccc}
T^0 & \rightarrow & T^1 & \rightarrow \ldots \rightarrow T^{m-1} & \rightarrow T^m & \rightarrow \ldots \\
& & & \searrow & \searrow & \searrow \\
& & & & BP & \\
\end{array}
\]

and the homotopy colimit $\hocolim T^m$ is easily seen to admit a weak equivalence to $\hocolim T^m \xrightarrow{\sim} BP$.

As $R \sim \hocolim T^m$, this shows that $R \sim BP$. □

As defined, it is not clear if $R$ is a minimal atomic commutative $S$-algebra; however, by construction, $R_\infty$ is nuclear and hence is minimal atomic according to results of [3]. We can produce a core $R^c \rightarrow R$, i.e., a morphism of commutative $S$-algebras with $R^c$ nuclear and which induces a monomorphism on $\pi_*(-)$. In particular, $\pi_*(R^c)$ is torsion-free.
Lemma 8.4. Let $A$ be a connective $p$-local commutative $S$-algebra for which $\pi_s(A)$ is torsion-free. Then there is a morphism of commutative $S$-algebras $R_\infty \rightarrow A$. In particular, the natural morphism $R_\infty \rightarrow R$ admits a factorisation through any core $R^c \rightarrow R$ for $R$.

Proof. Since our cellular construction of $R_\infty$ involves attaching $E_\infty$ cells to kill torsion elements in homotopy, it is straightforward to see that at each stage we can extend the unit $S \rightarrow A$, in the limit this gives a morphism $R_\infty \rightarrow A$. □

As $R$ and more generally any core $R^c$ have torsion-free homotopy concentrated in even degrees, standard arguments of [1] show that there are morphisms of ring spectra $BP \rightarrow R$ and $BP \rightarrow R^c$ associated with complex orientations with $p$-typical formal group laws. Our earlier arguments show that these are rational weak equivalences. Of course we have not shown that $BP \sim R$ even as (ring) spectra. One way to prove this would be to produce any map of spectra $R \rightarrow BP$ that is an equivalence on the bottom cell, for then the composition $BP \rightarrow R \rightarrow BP$ would be a weak equivalence, therefore so would each of the maps $BP \rightarrow R$ and $R \rightarrow BP$. It is tempting to conjecture that $R$ (or equivalently $R^c$) is always weakly equivalent to $BP$, but we have no hard evidence for this beyond what we have described above.

Appendix A. Toda brackets and Massey products

For the sake of completeness, we describe the kind of Toda brackets and Massey products we use. Details of this material can be developed in the spirit of the exposition of Toda brackets by Whitehead [33].

Toda brackets in the homotopy of $R$-modules. We will work with (left) $S$-modules in the sense of [10]. We will usually omit $S$ from notation, for example $\wedge$ will denote $\wedge_S$ and so on.

Let $R$ be a commutative $S$-algebra and let $M$ be a left $R$-module. We will require Toda brackets of the following form. Let $\alpha \in \pi_a R$, $\beta \in \pi_b R$ and let $\gamma \in \pi_c M$, and suppose that $\alpha \beta = 0 = \beta \gamma$.

Choosing representatives $f: S^a \rightarrow R$, $g: S^b \rightarrow R$, $h: S^c \rightarrow M$, the maps

$$
S^{a+b} \xrightarrow{fg} S^a \wedge S^b \xrightarrow{f \wedge g} R \wedge R \xrightarrow{\gamma} R \xrightarrow{\gamma} S^{b+c} \xrightarrow{gh} S^b \wedge S^c \xrightarrow{g \wedge h} R \wedge M \xrightarrow{g \wedge h} M
$$

are null homotopic. Now choosing explicit null homotopies

$$
k: D^{a+b+1} \rightarrow R, \quad \ell: D^{b+c+1} \rightarrow M,$$

we obtain maps

$$
D^{a+b+1} \wedge S^c \xrightarrow{k \wedge h} R \wedge M \xrightarrow{g \wedge h} M \quad S^a \wedge D^{b+c+1} \xrightarrow{f \wedge k} S^b \wedge S^c \xrightarrow{f \wedge k} M
$$

which agree on the boundary $S^{a+b+c} \simeq S^{a+b} \wedge S^c \simeq S^a \wedge S^{b+c}$. Therefore we obtain a map $S^{a+b+c+1} \rightarrow M$ in the usual way representing the bracket $\langle \alpha, \beta, \gamma \rangle$. 

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Recollections on Massey products. We follow the sign conventions of [15, section 5.4].

Let $(A, d)$ be a dga where $A = A^*$ is $\mathbb{Z}$-graded. If $W \in A^*$ is a homogeneous element, we set

$$\bar{W} = (-1)^{1+\deg W} W.$$ 

Suppose that $X, Y, Z \in A^*$ are homogeneous elements which are cycles so that the Massey product $\langle [X], [Y], [Z] \rangle$ is defined, i.e., $[X][Y] = 0 = [Y][Z]$. Choose $U, V \in A^*$ so that $d(U) = \bar{X}Y, d(V) = \bar{Y}Z$.

Then $d(\bar{X}V + \bar{U}Z) = 0$ and

$$\bar{X}V + \bar{U}Z \in \langle [X], [Y], [Z] \rangle \subseteq H^*(A, d).$$

The indeterminacy is the subset

$$[X] \cdot H^*(A, d) + [Z] \cdot H^*(A, d) \subseteq H^*(A, d).$$

REFERENCES


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