

Commutative \mathbb{S} -algebras of prime characteristics and applications to unoriented bordism

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The notion of highly structured ring spectra of prime characteristic is made precise and is studied via the universal examples $\mathbb{S}//p$ for prime numbers p . These can be realized as Thom spectra, and therefore relate to other Thom spectra such as the unoriented bordism spectrum MO . We compute the Hochschild and André-Quillen invariants of the $\mathbb{S}//p$. Among other applications, we show that $\mathbb{S}//p$ is not a commutative algebra over the Eilenberg-Mac Lane spectrum $H\mathbb{F}_p$, although the converse is clearly true.

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Introduction

In the world of ordinary rings, those of prime characteristic are of special importance, and their algebras encode much of the elementary arithmetic of the ring \mathbb{Z} of integers. Let us recall: If A is a commutative ring, and p is a prime number, then A has characteristic p (written $\text{char}(A) = p$) if the image of p under the unit $\mathbb{Z} \rightarrow A$ is zero. Equivalently, there is a unique ring map $\mathbb{F}_p \rightarrow A$ from the prime field \mathbb{F}_p with p elements. The aim of this writing is to generalize and explore this notion of prime characteristic from the setting of ordinary commutative rings in the context of commutative ring spectra in the highly structured sense: E_∞ ring spectra, or commutative \mathbb{S} -algebras in more recent

terminology. This can be understood as an attempt to unveil some of the arithmetic surrounding the sphere spectrum \mathbb{S} .

There might be more than one way to achieve such a generalization. Clearly, the underlying ring $\pi_0(E)$ of a commutative \mathbb{S} -algebra E of characteristic p should be of characteristic p (in the ordinary sense), and the Eilenberg-Mac Lane spectrum HA of an ordinary ring A of characteristic p should be a commutative \mathbb{S} -algebra of characteristic p . This is fulfilled in the present approach.

If E is a commutative ring spectrum (up to homotopy or E_∞), then we will say that E has characteristic p and write $\text{char}(E) = p$ if p is mapped to zero under the ring map $\mathbb{Z} = \pi_0(\mathbb{S}) \rightarrow \pi_0(E)$ induced by the unit $\mathbb{S} \rightarrow E$ from the sphere spectrum \mathbb{S} . In Section 1 we briefly review the known results about commutative ring spectra of prime characteristic. In Section 2 we define universal examples—commutative \mathbb{S} -algebras $\mathbb{S}//p$ (one for each prime number p) such that the category of commutative $\mathbb{S}//p$ -algebras is an appropriate place to study commutative \mathbb{S} -algebras of characteristic p . Section 3 contains some homology and homotopy computations which are necessary for the later applications. Section 4 contains a description of all the universal examples $\mathbb{S}//p$ as E_∞ Thom spectra, see Theorems 4.5 and 4.6. This relates the spectra $\mathbb{S}//p$ to other Thom spectra, and it also enables us to describe the topological Hochschild and André-Quillen invariants of the spectra $\mathbb{S}//p$.

The final Section 5 contains various applications with an emphasis on the unoriented bordism spectrum MO . While MO is not an algebra under the Eilenberg-Mac Lane spectrum $\mathbb{H}\mathbb{F}_2$, it is an algebra under $\mathbb{S}//2$. This in turn implies that $\mathbb{S}//2$ is not an $\mathbb{H}\mathbb{F}_2$ -algebra. More generally, we are able to show that $\mathbb{S}//p$ is not an $\mathbb{H}\mathbb{F}_p$ -algebra for any prime p , see Theorem 5.3, although the converse is clearly true.

Throughout, commutative \mathbb{S} -algebras in the sense of [EKMM97] will be used as the preferred model for ring spectra with an E_∞ multiplication. There are by now various other models for this notion, most of them discussed and shown to be equivalent in [MMSS01], and each of them serves our purposes equally well. We will also continue to employ the more generic E_∞ terminology for spectra and maps to emphasize this fact. The notation \mathcal{E}_∞ , and \mathcal{S}_∞ , will be used for the category of \mathcal{E}_∞ ring spectra/commutative \mathbb{S} -algebras, and the category of \mathbb{S} -modules/spectra, respectively. We write \mathbb{S} for the sphere spectrum as a commutative \mathbb{S} -algebra, and $\mathbb{S}^n = \Sigma^n \mathbb{S}$ for the suspension spectra. The notation \mathbb{S}^n will also be used for the usual euclidean spheres. We will sometimes abbreviate $\mathbb{H}\mathbb{F}_p$ to \mathbb{H} when the prime is clear from the context.

Also, unless otherwise specified, all rings, algebras, ring spectra, and algebra spectra are assumed to be commutative from now on. While this will be our default, we may nevertheless use the word ‘commutative’ for emphasis.

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1 Examples and counterexamples

In this section, we will recall some known results on commutative ring spectra E with $\text{char}(E) = p$ in the following sense.

Definition 1.1. If E is a commutative ring spectrum (up to homotopy or E_∞), and p is a prime number, then we will say that E has characteristic p , if the ordinary commutative ring $\pi_0(E)$ has characteristic p in the usual sense. We will also use the notation $\text{char}(E) = p$.

We can now discuss some examples and counterexamples: graded Eilenberg-Mac Lane spectra, Morava K-theory spectra, and Moore spectra. See also [Rud98] for a treatment of some of the topics discussed here.

1.1 Graded Eilenberg-Mac Lane spectra

We will say that a spectrum E is *additively a graded Eilenberg-Mac Lane spectrum* if it is equivalent as a spectrum to HM_* for some graded group M_* . We will say that a ring spectrum E (up to homotopy) is *multiplicatively a graded Eilenberg-Mac Lane spectrum* if it is equivalent as a commutative ring spectrum (up to homotopy) to HA_* for some graded commutative ring A_* .

Note that HA_* is not only a ring spectrum up to homotopy, but has a preferred E_∞ structure, Boardman’s multiplication [Boa80]. In fact, Richter has shown more generally that for a differential graded commutative algebra A_* , the graded Eilenberg-MacLane

spectrum HA_* is an E_∞ -monoid in the category of $H\mathbb{Z}$ -module spectra. See [Ric03, Proposition 6.1], and [Ric06, Theorem 5.6.1]. Here, we only need the case where the differential is trivial, so that we have a graded commutative ring. Then the forgetful functor from $H\mathbb{Z}$ -modules to \mathbb{S} -modules gives rise to an E_∞ ring spectrum HA_* that is a commutative HA_0 -algebra. This E_∞ structure is essentially unique if A_* is concentrated in dimension 0, so that HA_* is discrete. We will see, in Theorem 5.4, that it is not unique in general.

1.2 Results for the mod- p case

Let us start with a result which reduces the more difficult multiplicative question to the easier additive question.

Theorem 1.2. ([Boa80, Theorem 1.1]) *Suppose E is a commutative ring spectrum (up to homotopy) which additively is a graded Eilenberg-Mac Lane spectrum, and $\text{char}(E) = p$ for some prime number p . Then E is multiplicatively a graded Eilenberg-Mac Lane spectrum (up to homotopy).*

The following result shows that in the case $p = 2$ the Eilenberg-Mac Lane hypothesis is superfluous: there are no other examples.

Theorem 1.3. ([Wür86, Theorem 1.1], [PR85]) *Suppose E is a commutative ring spectrum (up to homotopy) with $\text{char}(E) = 2$. Then E is multiplicatively an Eilenberg-Mac Lane spectrum (up to homotopy).*

Versions of this theorem are also attributed to unpublished work of Hopkins and Mahowald, see [Yan92, Theorem 5], [Yan94, Theorem 5.1] as well as [Rud98, Theorem IX.5.5], for example.

As mentioned above, we will see later, in Theorem 5.4, that both theorems become false when the weak up to homotopy notion is replaced by the strong E_∞ notion of a ring spectrum. In this latter setting, using Dyer-Lashof operations, Steinberger has obtained the following result.

Theorem 1.4. ([BMMS86, III.4.1]) *If E is a commutative \mathbb{S} -algebra of finite type with $\pi_0(E) = \mathbb{F}_p$ for some prime number p , then E is additively a graded Eilenberg-Mac Lane spectrum.*

1.3 Results for the p -local case

Let us add some results on the p -local situation. These will not be used in the following. For odd primes, the situation is fairly rigid.

Theorem 1.5. ([Boa80, Theorem 1.2]) *Let p be an odd prime. Suppose the ring spectrum E is additively a graded Eilenberg-Mac Lane spectrum with $\pi_*(E)$ a free module over $\mathbb{Z}_{(p)}$. Then E is multiplicatively a graded Eilenberg-Mac Lane spectrum.*

For the even prime, there are exotic examples.

Theorem 1.6. ([Boa80, Theorem 1.3]) *There exist ring spectra up to homotopy E with $\pi_*(E)$ a free $\mathbb{Z}_{(2)}$ -module and which are additively graded Eilenberg-Mac Lane spectra, but not multiplicatively.*

Boardman's result for the prime 2 is complemented by the following result of Astey's, which characterizes the 2-local ring spectra which are graded Eilenberg-Mac Lane spectra. It involves a 3-cell complex which is built using the stable Hopf map $\eta : S^1 \rightarrow S^0$ as well as another map t in the homotopy $\pi_2(\mathbb{S}_{(2)} \cup_{\eta} e^2) \cong \mathbb{Z}_{(2)}$ of its cone: The collapse map induces an injection $\pi_2(\mathbb{S}_{(2)} \cup_{\eta} e^2) \rightarrow \pi_2(S^2) = \mathbb{Z}$ with image consisting of the subgroup of even numbers, and t is defined as the (unique) pre-image of 2. The cone $I = (\mathbb{S}_{(2)} \cup_{\eta} e^2) \cup_t e^3$ is often called an inverted question mark complex—from the point of view of the action of the Steenrod algebra on its mod 2 cohomology.

Theorem 1.7. ([Ast97, Theorem 1.2]) *A 2-local ring spectrum up to homotopy E is additively a graded Eilenberg-Mac Lane spectrum if and only if the unit map extends over the inverted question mark complex I .*

Again, there are also results for commutative \mathbb{S} -algebras E that satisfy $\pi_0(E) = \mathbb{Z}_{(p)}$, see [BMMS86, III.4.2 and III.4.3].

1.4 Morava K-theory spectra

Recall that the Morava K-theory spectra $K(n)$ have $\pi_*K(n) \cong \mathbb{F}_p[v_n^{\pm 1}]$ with an element v_n of degree $2(p^n - 1)$. For p odd, these are homotopy commutative ring spectra of characteristic p . But, it is known that neither the spectra $K(n)$ nor their connective covers $k(n)$

admit an E_∞ structure. See Lemma 5.6.4 in [Rog08], for example, where this is proven for the $k(n)$ with the help of Dyer-Lashof operations. And, by [BR08], it suffices to prove the result for these. Of course, the non-existence of E_∞ multiplications also follows from Steinberger's Theorem 1.4.

1.5 Moore spectra

To conclude this section, let me comment upon multiplications on the Moore spectra S^0/p . These are the cofibers of the p -multiplication on S^0 . Additional information is contained in [AT65] and [AT66].

At the prime 2, the Moore spectrum $S^0/2$ is not a commutative \mathbb{S} -algebra. In fact, it is not even a ring spectrum up to homotopy. One reason is that $\pi_2(S^0/2) \cong \mathbb{Z}/4$ is not a module over $\pi_0(S^0/2) \cong \mathbb{Z}/2$. Another reason is that there is clearly no ring map from $\pi_0(S^0/2) \cong \mathbb{Z}/2$ to $\pi_0\text{Map}(S^0/2, S^0/2) \cong \mathbb{Z}/4$. And of course, it also follows from Theorem 1.3, because $S^0/2$ is not an Eilenberg-Mac Lane spectrum, since multiplication by the Hopf map η is non-trivial on the homotopy groups. In fact, the element η itself would have to be zero, because it is the power operation on $2 = 0$ in $\pi_0(S^0/2)$.

For other primes, one may use the power operation $\beta P^1: \pi_0(E) \rightarrow \pi_{2p-3}(E)$ for commutative \mathbb{S} -algebras E to show that there is no E_∞ structure on S^0/p : On the one hand $\beta P^1(0) = 0$, but on the other hand $\beta P^1(p)$ is a non-trivial multiple of α_1 , see [BMMS86, V.1.13], for example. This implies that the unit of a commutative \mathbb{S} -algebra E of characteristic p must map α_1 to zero. But this is not the case for S^0/p .

The Moore spectrum S^0/p is known to have an A_{p-1} -multiplication which is not A_p , see [Ang08, Example 3.3].

2 Universal examples

If A is an ordinary ring of characteristic p , then every A -algebra is also of characteristic p , and \mathbb{F}_p is the initial object. However, as it turns out, there is no commutative \mathbb{S} -algebra of characteristic p which is initial in the homotopical sense, see Proposition 3.10. The reason is that the existence of a homotopy $p \simeq 0$ does not imply the

uniqueness of such a homotopy. Therefore, we will instead turn our attention to commutative \mathbb{S} -algebras which come with a chosen homotopy $p \simeq 0$.

2.1 The commutative \mathbb{S} -algebras $\mathbb{S} // p$

Let p be a prime number. As a motivation for the following definition, consider the description of the corresponding prime field \mathbb{F}_p as a pushout

$$\begin{array}{ccc} \mathbb{Z}[T] & \xrightarrow{T \mapsto p} & \mathbb{Z} \\ T \mapsto 0 \downarrow & & \downarrow \\ \mathbb{Z} & \longrightarrow & \mathbb{F}_p \end{array}$$

in the category of rings. This can be built as a tensor product

$$\mathbb{F}_p = \mathbb{Z} \otimes_{\mathbb{Z}[T]} \mathbb{Z}$$

using the structure maps indicated in the diagram. The tensor product is already the derived tensor product: the higher Tor-terms vanish, since p is not a zero-divisor on \mathbb{Z} .

We will imitate this now in the category of commutative \mathbb{S} -algebras. Let \mathbb{P} be the left adjoint to the forgetful functor. In other words, $\mathbb{P}X$ is the free commutative \mathbb{S} -algebra on X . There is an adjunction equivalence

$$\mathcal{E}_\infty(\mathbb{P}X, E) \simeq \mathcal{S}_\infty(X, E)$$

for commutative \mathbb{S} -algebras E , induced by the unit $X \rightarrow \mathbb{P}X$ of the adjunction. The E_∞ map corresponding to $x: X \rightarrow E$ will be denoted by $\text{ev}(x): \mathbb{P}X \rightarrow E$; it is the E_∞ map which evaluates to x on the generator X .

Definition 2.1. The commutative \mathbb{S} -algebra $\mathbb{S} // p$ is the homotopy pushout

$$\begin{array}{ccc} \mathbb{P}\mathbb{S}^0 & \xrightarrow{\text{ev}(p)} & \mathbb{S} \\ \text{ev}(0) \downarrow & & \downarrow \\ \mathbb{S} & \longrightarrow & \mathbb{S} // p \end{array}$$

in commutative \mathbb{S} -algebras.

Homotopy pushout here means that we will have to replace $\mathbb{S} = \mathbb{P}*$ cofibrantly, for example by $\mathbb{P}D^1$. In other words, the commutative \mathbb{S} -algebra $\mathbb{S}//p$ is obtained from the sphere spectrum \mathbb{S} by attaching an E_∞ -cell so as to ensure $p \simeq 0$. The commutative \mathbb{S} -algebra $\mathbb{S}//p$ has the property, in analogy with the above description of \mathbb{F}_p as $\mathbb{Z}[T]/(0 = T = p)$, that an E_∞ map $\mathbb{S}//p \rightarrow E$ is the same as a null-homotopy from p to 0 in E . In particular, there might be more than one such map, in contrast to the discrete case, where a ring map $\mathbb{F}_p \rightarrow A$ is unique if it exists. We will discuss spaces of E_∞ maps out of $\mathbb{S}//p$ in more detail later, see Section 2.3.

A p -local commutative \mathbb{S} -algebra Q is called *nuclear* if it is a colimit of commutative \mathbb{S} -algebras Q_n , where $Q_0 = \mathbb{S}$ and, inductively, the commutative \mathbb{S} -algebra Q_{n+1} is obtained from the commutative \mathbb{S} -algebra Q_n by coning off (in the E_∞ sense) finitely many elements in $\pi_n(Q_n)$ in such a way that the kernel of the corresponding map $\pi_n(\vee \mathbb{S}^n) \rightarrow \pi_n(Q_n)$ consists of multiples of p . See [HKM01, Definition 2.7].

Proposition 2.2. *For all primes p , the commutative \mathbb{S} -algebra $\mathbb{S}//p$ is nuclear.*

Proof. Set $\mathbb{S}//p = Q = Q_1$. By Definition 2.1, this is obtained from $Q_0 = \mathbb{S}$ by coning off (in the E_∞ sense) the element $p \in \pi_0(Q_0) = \pi_0(\mathbb{S}) = \mathbb{Z}$. The assumption on the kernel is satisfied, because the corresponding map $\pi_0(\mathbb{S}^0) \rightarrow \pi_0(\mathbb{S})$ that sends the identity to p is even injective. \square

The following observation will be useful later, in Section 4, when we relate the spectra $\mathbb{S}//p$ to Thom spectra.

Proposition 2.3. *The commutative \mathbb{S} -algebra $\mathbb{S}//p$ may be described as the following iterated homotopy pushout in commutative \mathbb{S} -algebras.*

$$\begin{array}{ccccc}
 \mathbb{P}\mathbb{S}^0 & \xrightarrow{\mathbb{P}(p)} & \mathbb{P}\mathbb{S}^0 & \xrightarrow{\text{ev}(1)} & \mathbb{S} \\
 \text{ev}(0) \downarrow & & \downarrow & & \downarrow \\
 \mathbb{S} & \longrightarrow & \mathbb{P}(\mathbb{S}^0/p) & \longrightarrow & \mathbb{S}//p
 \end{array}$$

This statement is analogous to the description of \mathbb{F}_p as $\mathbb{Z}[T]/(p = 0, T = 1)$. Note that the left hand square is a pushout because the left adjoint \mathbb{P} commutes with colimits.

Proof. This follows immediately from the fact that the map $\text{ev}(p): \mathbb{P}\mathbb{S}^0 \rightarrow \mathbb{S}$ factors as the composition of $\mathbb{P}(p): \mathbb{P}\mathbb{S}^0 \rightarrow \mathbb{P}(\mathbb{S}^0/p)$ and $1: \mathbb{P}(\mathbb{S}^0/p) \rightarrow \mathbb{S}$, as can be seen by composition with the unit $\mathbb{S} \rightarrow \mathbb{P}\mathbb{S}^0$. \square

2.2 The underlying ring of components

At this point, one might wish to compute the homology and homotopy of $\mathbb{S}//p$ directly or with the help of the Hurewicz homomorphism. This will be done later, in Section 3, see in particular Proposition 3.7. For a start, only the following result will be needed.

Proposition 2.4. *We have $\pi_0(\mathbb{S}//p) = \mathbb{F}_p$.*

Proof. Because the spectrum $\mathbb{S}//p$ is connective, it suffices to compute the integral homology of it. Smashing the defining homotopy pushout diagram for $\mathbb{S}//p$ with the integral Eilenberg-Mac Lane spectrum yields another homotopy pushout diagram, and the integral Eilenberg-Moore spectral sequence then implies that π_0 must be $\mathbb{Z}[T]/(0 = T = p) = \mathbb{F}_p$, as in the motivation given for the definition of $\mathbb{S}//p$ at the beginning. \square

This result implies that we have

$$\text{char}(\mathbb{S}//p) = p,$$

as it should be.

2.3 Spaces of E_∞ maps out of $\mathbb{S}//p$

The following result identifies the space of E_∞ maps $\mathbb{S}//p \rightarrow E$ into any commutative \mathbb{S} -algebra E .

Proposition 2.5. *Let E be a commutative \mathbb{S} -algebra. If $\text{char}(E) = p$, then there is an equivalence*

$$\mathcal{E}_\infty(\mathbb{S}//p, E) \simeq \Omega^{\infty+1}(E)$$

of spaces. Otherwise, the left hand side is empty.

Proof. The definition of $\mathbb{S}//p$ as a homotopy pushout implies that there is a homotopy pullback

$$\begin{array}{ccc} \mathcal{E}_\infty(\mathbb{S}//p, E) & \longrightarrow & \mathcal{E}_\infty(\mathbb{S}, E) \\ \downarrow & & \downarrow \\ \mathcal{E}_\infty(\mathbb{S}, E) & \longrightarrow & \mathcal{E}_\infty(\mathbb{P}\mathbb{S}^0, E). \end{array}$$

Now use that the spaces $\mathcal{E}_\infty(\mathbb{S}, E)$ are contractible, and that their images in $\mathcal{E}_\infty(\mathbb{P}\mathbb{S}^0, E)$ can be connected by a path if $p \simeq 0$. The result follows using the equivalences

$$\mathcal{E}_\infty(\mathbb{P}\mathbb{S}^0, E) \simeq \mathcal{S}_\infty(\mathbb{S}, E) \simeq \Omega^\infty(E)$$

given by the adjunctions. □

Example 2.6. If $E = \mathbf{H}A$ for some discrete commutative ring A of characteristic p , then the space $\mathcal{E}_\infty(\mathbb{S} // p, \mathbf{H}A) \simeq \Omega^{\infty+1} \mathbf{H}A$ is contractible. The following result states that the converse also holds in the connective case.

Proposition 2.7. *If E is a connective commutative \mathbb{S} -algebra, with the property that the space $\mathcal{E}_\infty(\mathbb{S} // p, E)$ is contractible, then $E \simeq \mathbf{H}\pi_0(E)$ is discrete.*

Proof. If $\Omega^{\infty+1}(E)$ is contractible, then the higher homotopy groups of E vanish, so that E is an Eilenberg-Mac Lane spectrum. □

Example 2.8. Let us consider the unoriented bordism spectrum $\mathbf{M}\mathbf{O}$. Since the underlying ring is $\pi_0(\mathbf{M}\mathbf{O}) = \mathbb{F}_2$, this spectrum satisfies

$$\text{char}(\mathbf{M}\mathbf{O}) = 2.$$

Because $\pi_1(\mathbf{M}\mathbf{O})$ is trivial, it admits an E_∞ map from $\mathbb{S} // 2$ which is unique up to homotopy (of E_∞ maps). However, since $\pi_2(\mathbf{M}\mathbf{O}) \neq 0$, the space of all such maps is not contractible.

Corollary 2.9. *There is an equivalence $\mathcal{E}_\infty(\mathbb{S} // p, \mathbb{S} // p) \simeq \Omega^{\infty+1}(\mathbb{S} // p)$.*

We will see later, in Proposition 3.7, that $\pi_1(\mathbb{S} // p) = 0$, but that $\mathbb{S} // p$ has non-trivial higher homotopy groups, so that the space $\mathcal{E}_\infty(\mathbb{S} // p, \mathbb{S} // p)$ is connected but not contractible.

2.4 Commutative $\mathbb{S} // p$ -algebras

Let us begin by recalling the following definition.

Definition 2.10. A commutative $\mathbb{S} // p$ -algebra is a commutative \mathbb{S} -algebra E together with an E_∞ map $s_E: \mathbb{S} // p \rightarrow E$, the structure map. The space $\mathcal{E}_\infty(\mathbb{S} // p, E)$ is the space of $\mathbb{S} // p$ -algebra structures on E .

Proposition 2.5 and the examples which follow it show that being a commutative $\mathbb{S} // p$ -algebra is not a *property* of commutative \mathbb{S} -algebras, but an extra *structure*, which if it exists, need not be unique. And if it is unique, it need not be canonically so. In more conceptual terms, the property $\text{char}(E) = p$ defines a full subcategory of the category of commutative \mathbb{S} -algebras. Rather than work in this full subcategory defined by a property, it seems better to keep track of the choice of a structure map $s_E: \mathbb{S} // p \rightarrow E$, and work in the category $\mathcal{E}_\infty^{\mathbb{S} // p}$ of commutative $\mathbb{S} // p$ -algebras.

If E and F are commutative $\mathbb{S} // p$ -algebras, then there is a homotopy fibration square

$$\begin{array}{ccc} \mathcal{E}_\infty^{\mathbb{S} // p}(E, F) & \xrightarrow{\subseteq} & \mathcal{E}_\infty(E, F) \\ \downarrow & & \downarrow s_E^* \\ \{s_F\} & \xrightarrow{\subseteq} & \mathcal{E}_\infty(\mathbb{S} // p, F) \end{array}$$

for the derived mapping spaces. Therefore, Proposition 2.5 also describes the difference between the space of all E_∞ maps and that of $\mathbb{S} // p$ -algebra maps.

For example, in contrast to Corollary 2.9, it is clear that there is an essentially unique map $\mathbb{S} // p \rightarrow \mathbb{S} // p$ of algebras over $\mathbb{S} // p$. Compare with Proposition 3.10.

3 Homology and homotopy of the universal examples

In this section, we will give some basic information on the homotopy type of $\mathbb{S} // p$ and the associated algebraic invariants: its homology and homotopy groups.

Proposition 3.1. *For each prime p , the spectrum $\mathbb{S} // p$ is a graded Eilenberg-Mac Lane spectrum.*

Proof. Since $\pi_0(\mathbb{S} // p) = \mathbb{F}_p$ by Proposition 2.4, this is a consequence of Steinberger's result, see Theorem 1.4. \square

As a consequence, the homotopy type of $\mathbb{S} // p$ can be read off from its homotopy groups, and the homotopy groups of $\mathbb{S} // p$ will be computable once the $(\text{mod } p)$ homology is known.

3.1 The homology of $\mathbb{S} // p$

The backbone of the homology computation is the following result.

Proposition 3.2. *If A is a commutative \mathbb{S} -algebra of characteristic p , then there exists an equivalence*

$$A \wedge \mathbb{S} // p \simeq A \wedge \mathbb{P}\mathbb{S}^1$$

of commutative A -algebras.

Proof. Both A -algebras are homotopy pushouts of diagrams

$$\begin{array}{ccc} A \wedge \mathbb{P}\mathbb{S}^0 & \xrightarrow{A \wedge \text{ev}(0)} & A \wedge \mathbb{S} \\ \downarrow & & \\ A \wedge \mathbb{S}, & & \end{array}$$

where the left arrow is $A \wedge \text{ev}(p)$ and $A \wedge \text{ev}(0)$, respectively. The space of maps of A -algebras from $A \wedge \mathbb{P}\mathbb{S}^0$ to $A \wedge \mathbb{S} \simeq A$ is, by the adjunction equivalences

$$\mathcal{E}_\infty^A(A \wedge \mathbb{P}\mathbb{S}^0, A) \simeq \mathcal{E}_\infty(\mathbb{P}\mathbb{S}^0, A) \simeq \mathcal{S}_\infty(S^0, A) \simeq \Omega^\infty A,$$

equivalent to the underlying infinite loop spaces of A . Since p and 0 are in the same component by hypothesis on A , these maps of commutative A -algebras are homotopic. As a result, the homotopy pushouts are equivalent. \square

Corollary 3.3. *If A is a commutative \mathbb{S} -algebra with $\text{char}(A) = p$, then there is an isomorphism*

$$A_*(\mathbb{S} // p) \cong A_*(\mathbb{P}\mathbb{S}^1)$$

of A_ -algebras.*

We hasten to point out that neither the equivalence in Proposition 3.2, nor the isomorphism in Corollary 3.3 can be induced by a map between $\mathbb{S} // p$ and $\mathbb{P}\mathbb{S}^1$. If it were, then the isomorphism would be compatible with the natural A -homology operations for all A . Example 3.4 below shows that this need not be the case.

The preceding results can be applied in the case $A = \mathbb{S} // p$ itself, and in the case $A = \text{MO}$ when $p = 2$. We will mostly be interested in the case $A = \text{HF}_p$, when the preceding corollary shows the existence of an isomorphism

$$H_*(\mathbb{S} // p) \cong H_*(\mathbb{P}\mathbb{S}^1). \tag{3.1}$$

The right hand side is the free algebra over the Araki-Kudo-Dyer-Lashof algebra on one generator in degree 1, see [CLM76, II.4] and [Bak']. In particular,

$$H_1(\mathbb{S}//p) \cong H_1(\mathbb{P}\mathbb{S}^1) \cong \mathbb{Z}/p. \quad (3.2)$$

The consequences for the uniqueness of the isomorphism (3.1) will be discussed below.

Example 3.4. The natural A -homology operations on $A_*(\mathbb{S}//p)$ and $A_*(\mathbb{P}\mathbb{S}^1)$ differ in the case $A = \mathbf{HF}_p$ of the Eilenberg-Mac Lane spectrum. To see this, note that on the one hand we have an isomorphism $\mathbf{HZ}_0(\mathbb{P}\mathbb{S}^1) = \mathbb{Z}$, while on the other hand we have an isomorphism $\mathbf{HZ}_0(\mathbb{S}//p) = \mathbb{F}_p$. Consequently, the homology Bockstein from dimension 1 to 0 is zero on the homology of $\mathbb{P}\mathbb{S}^1$, but an isomorphism on the homology of $\mathbb{S}//p$.

In the case $p = 2$, the homology of the cell commutative \mathbb{S} -algebra $\mathbb{S}//2$ can also be obtained as a special case of Baker's calculations in [Bak].

Let us now address the question of the uniqueness of the equivalence in Proposition 3.2 in the specific case $A = \mathbf{HF}_p$.

Proposition 3.5. *There exist precisely $p - 1$ homotopy classes of equivalences*

$$\mathbf{HF}_p \wedge \mathbb{P}\mathbb{S}^1 \longrightarrow \mathbf{HF}_p \wedge \mathbb{S}//p$$

of commutative \mathbf{HF}_p -algebras.

Proof. There are adjunction equivalences

$$\mathcal{E}_\infty^A(A \wedge \mathbb{P}\mathbb{S}^1, A \wedge \mathbb{S}//p) \simeq \mathcal{E}_\infty(\mathbb{P}\mathbb{S}^1, A \wedge \mathbb{S}//p) \simeq \mathcal{S}_\infty(\mathbb{S}^1, A \wedge \mathbb{S}//p),$$

so that the homotopy classes of maps $A \wedge \mathbb{P}\mathbb{S}^1 \rightarrow A \wedge \mathbb{S}//p$ of commutative A -algebras are parametrized by

$$\pi_1(A \wedge \mathbb{S}//p) = A_1(\mathbb{S}//p).$$

In the present case $A = \mathbf{HF}_p$ this means that there are precisely p homotopy classes of maps $\mathbf{HF}_p \wedge \mathbb{P}\mathbb{S}^1 \rightarrow \mathbf{HF}_p \wedge \mathbb{S}//p$ of commutative \mathbf{HF}_p -algebras, and one of them (the zero) is not an equivalence. \square

Clearly, for $p = 2$, we have $p - 1 = 1$, so that there is in fact a unique equivalence

$$\mathbf{HF}_2 \wedge \mathbb{P}\mathbb{S}^1 \simeq \mathbf{HF}_2 \wedge \mathbb{S}//2$$

of \mathbf{HF}_2 -algebras! The non-uniqueness at the odd primes p comes from the \mathbb{F}_p^\times -action on the 1-dimensional \mathbb{F}_p -vector space $H_1(\mathbb{S}^1)$. It seems fair to say that this is well under control.

3.2 Some homotopy groups of $\mathbb{S} // p$

The following is our device for passing from homology to homotopy.

Proposition 3.6. *The Hurewicz map $\pi_*(\mathbb{S} // p) \rightarrow H_*(\mathbb{S} // p)$ is injective, and there is an isomorphism $H_*(\mathbb{S} // p) \cong \pi_*(\mathbb{S} // p) \otimes H_*(\mathbf{HF}_p)$.*

Proof. This follows immediately from the fact that $\mathbb{S} // p$ is a graded Eilenberg-Mac Lane spectrum. \square

As a consequence of Proposition 3.6, the Poincaré series of the homotopy of $\mathbb{S} // p$ is the quotient of the Poincaré series of the homology of $\mathbb{S} // p$ by the Poincaré series of the dual Steenrod algebra. The Poincaré series of the (dual) Steenrod algebra is well-known, and the Poincaré series of $H_*(\mathbb{S} // p) \cong H_*(\mathbb{P}S^1)$ is a matter of combinatorics, because this algebra is free on admissible generators of prescribed excess. However, a closed formula does not seem to be in the literature, and we will not pursue this here, either. For our purposes, it will be sufficient to determine the homotopy groups in low dimensions.

Proposition 3.7. *In low dimensions, the homotopy groups of $\mathbb{S} // p$ are as follows.*

$$\pi_n(\mathbb{S} // p) \cong \begin{cases} \mathbb{Z}/p & \text{if } n = 0 \\ 0 & \text{if } 0 < n < 4(p-1) \\ \mathbb{Z}/p & \text{if } n = 4(p-1) \end{cases}$$

Proof. Let me explain this for odd primes p . The case $p = 2$ is similar but easier; see the proof of Proposition 5.5 for hints.

In degrees at most $4(p-1)$, the additive generators of the (dual) Steenrod algebra are

$$1, \tau_0, \xi_1, \tau_0 \xi_1, \tau_1, \tau_0 \tau_1, \xi_1^2.$$

In the free algebra over the Dyer-Lashof algebra on one generator a in dimension 1, the corresponding generators are

$$1, a, \beta Q^1 a, a \beta Q^1 a, Q^1 a, a Q^1 a, (\beta Q^1 a)^2.$$

But, these are not the only classes in degrees at most $4(p-1)$: in degree $4(p-1)$ itself, there is not only $(\beta Q^1 a)^2$ but also $\beta Q^2 a$, and these two are linearly independent. \square

3.3 An application to E_∞ self-maps of $\mathbb{S} // p$

The equivalence $\mathcal{E}_\infty(\mathbb{S} // p, \mathbb{S} // p) \simeq \Omega^{\infty+1}(\mathbb{S} // p)$ from Corollary 2.9 implies that there are isomorphisms $\pi_n \mathcal{E}_\infty(\mathbb{S} // p, \mathbb{S} // p) \cong \pi_{n+1}(\mathbb{S} // p)$ for all $n \geq 0$. In particular, we have $\pi_0 \mathcal{E}_\infty(\mathbb{S} // p, \mathbb{S} // p) = \pi_1(\mathbb{S} // p) = 0$ by the preceding Proposition 3.7, which also yields the non-triviality of some higher homotopy groups.

Corollary 3.8. *Every E_∞ self-map of $\mathbb{S} // p$ is E_∞ homotopic to the identity. But, the space of E_∞ self-map of $\mathbb{S} // p$ is not contractible: The first non-trivial homotopy group is in dimension $4p - 5$.*

In particular, there is an essential 3-sphere in the space of E_∞ self-map of $\mathbb{S} // 2$.

In [HKM01, Definition 2.8], a connective commutative \mathbb{S} -algebra E whose unit $\mathbb{S} \rightarrow E$ induces an isomorphism on underlying rings is called *atomic* if every self-map of \mathbb{S} -algebras $E \rightarrow E$ is a weak equivalence. This property is already useful in the case when the unit is only surjective, and the following statement uses that terminology in this broader sense.

Corollary 3.9. *For each prime p , the commutative \mathbb{S} -algebra $\mathbb{S} // p$ is atomic.*

3.4 Initial commutative \mathbb{S} -algebras of prime characteristic

These do not exist! While the ordinary commutative ring \mathbb{F}_p is initial among commutative rings of characteristic p , there is no commutative \mathbb{S} -algebra of characteristic p which is initial in the homotopical sense. This is the content of the following result.

Proposition 3.10. *If p is a prime number, then there is no commutative \mathbb{S} -algebra T with $\text{char}(T) = p$ such that the derived space of commutative \mathbb{S} -algebra maps $T \rightarrow E$ is contractible for all commutative \mathbb{S} -algebras A with $\text{char}(E) = p$.*

Proof. Assume that there were such a commutative \mathbb{S} -algebra T . Because we have assumed $\text{char}(T) = p$, there is a structure map $s: \mathbb{S} // p \rightarrow T$. We will first prove that this is an equivalence. By hypothesis, the mapping spaces

$$\mathcal{E}_\infty(T, \mathbb{S} // p) \simeq * \tag{3.3}$$

and

$$\mathcal{E}_\infty(T, T) \simeq * \tag{3.4}$$

are contractible. We will use (3.3) to pick a map $t: T \rightarrow \mathbb{S} // p$ of commutative \mathbb{S} -algebras. This is an inverse (up to homotopy) of s : By (3.4) and Corollary 3.8, both compositions st and ts are homotopic to the identities via maps of commutative \mathbb{S} -algebras. This implies that T is equivalent to $\mathbb{S} // p$.

Thus, if T exists, then $T \simeq \mathbb{S} // p$. But, we have already seen that $\mathbb{S} // p$ does not satisfy the strong uniqueness as in the statement of the proposition. For example, the derived space of commutative \mathbb{S} -algebra maps of $\mathbb{S} // p \rightarrow E$ is not contractible for $E = \mathbb{S} // p$ itself, by Corollary 3.8 above. \square

4 The universal examples as Thom spectra

The aim of this section is to identify the spectra $\mathbb{S} // p$ for the various primes with certain E_∞ Thom spectra. This is clearly useful, as it will allow us to relate the spectra $\mathbb{S} // p$ to other Thom spectra, such as the unoriented bordism spectrum MO if $p = 2$, and it will also allow for the description of the Hochschild and André-Quillen invariants of the universal examples.

4.1 Thom spectra

There is a Thom spectrum M_f associated with every stable spherical fibration, classified by a map $f: X \rightarrow \text{BGL}_1(\mathbb{S})$, on a connected space X . In order to deal with the $\mathbb{S} // p$ for odd primes p , we also require the generalized Thom spectra of [Blu10], and [ABGHR], where \mathbb{S} can be replaced by the p -local or p -adic sphere.

Example 4.1. The original and most prominent example of a Thom spectrum is certainly given by the embedding $\text{BO} \rightarrow \text{BGL}_1(\mathbb{S})$ of the linear isomorphisms into the homotopy equivalences: This gives rise to the spectrum MO for unoriented bordism.

Example 4.2. If X is a point, then the Thom spectrum M_f is equivalent to the sphere spectrum \mathbb{S} . More generally, if f is null-homotopic, so that it classifies the trivial bundle, then the Thom spectrum is equivalent to the suspension spectrum $\mathbb{S} \wedge X_+$.

Example 4.3. The generator of $\pi_1 \mathrm{BGL}_1(\mathbb{S}) = \mathbb{Z}/2$ classifies the (stable) Möbius bundle, and the associated Thom spectrum is the Moore spectrum $\mathbb{S}^0/2$ at the prime $p = 2$.

If X is an infinite loop space and f is an infinite loop map, then the Thom spectrum M_f is an E_∞ ring spectrum. See [LMS86, IX.7]. This applies in Example 4.1 as well as in Example 4.2. But, if X is only a two-fold loop space and f is a two-fold loop map, then we can only infer that M_f is a commutative ring spectrum up to homotopy.

Example 4.4. We may apply this to the two-fold delooping $\Omega^2 S^3 \rightarrow \mathrm{BO}$ of the previous Example 4.3. The resulting Thom spectrum is known to be the Eilenberg-Mac Lane spectrum HF_2 . See [Mah79]. Note that this turns out to admit an E_∞ multiplication, but this is not clear from its construction as a Thom spectrum.

4.2 The examples $\mathbb{S} // 2$ and $\mathbb{S} // p$

We are now able to show that the examples $\mathbb{S} // 2$ and $\mathbb{S} // p$ can be realized as Thom spectra.

Theorem 4.5. *The spectrum $\mathbb{S} // 2$ is the E_∞ Thom spectrum of the infinite delooping*

$$Q(S^1) \rightarrow \mathrm{BGL}_1(\mathbb{S})$$

of the classifying map of the Möbius bundle.

Proof. The free E_∞ -spectrum on the Thom spectrum of f is the Thom spectrum of $Q(f)$, see [LMS86], Theorem 7.1 on page 444. Beware that the base cell acts as a unit. Therefore, the identification of the Thom spectrum of the essential map $S^1 \rightarrow \mathrm{BO}$ with the Moore spectrum, and the description of $\mathbb{S} // 2$ as an iterated pushout from Proposition 2.3 immediately imply the result. \square

An argument due to Hopkins, see [MRS01] or [Blu10], allows us to extend the preceding result to odd primes. We need to know that, also for these primes p , the Moore spectrum \mathbb{S}^0/p is the Thom spectrum of a map

$$f: S^1 \longrightarrow \mathrm{BGL}_1(\mathbb{S}_p), \tag{4.1}$$

where the target now classifies stable p -adic spherical fibrations, and such an f is a class in $\pi_1(\mathrm{BGL}_1(\mathbb{S}_p)) \cong \mathbb{Z}_p^\times$, the group of p -adic units. To obtain the Moore spectrum we

may chose f to be a representative of the unit $1 - p$. Now a similar argument as above implies that $\mathbb{S} // p$ can be obtained as the Thom spectrum of the infinite delooping of the map (4.1).

Theorem 4.6. *The spectrum $\mathbb{S} // p$ is the E_∞ Thom spectrum of the infinite delooping*

$$Q(\mathbb{S}^1) \rightarrow \mathrm{BGL}_1(\mathbb{S}_p)$$

of the map f such that M_f is the Moore spectrum.

4.3 The topological Hochschild homology of $\mathbb{S} // p$

Recall that the topological Hochschild homology spectrum $\mathrm{THH}^{\mathbb{S}}(E)$ of a commutative \mathbb{S} -algebra E is an important invariant of E , not the least because it is an approximation to the algebraic K-theory of E . We will now determine it for $\mathbb{S} // 2$ and $\mathbb{S} // p$, based on the identification of these spectra as E_∞ Thom spectra, and general results due to Blumberg [Blu10] which apply for this class.

Theorem 4.7. *For each prime number p there is an equivalence*

$$\mathrm{THH}^{\mathbb{S}}(\mathbb{S} // p) \simeq \mathbb{S} // p \wedge Q(\mathbb{S}^2)_+$$

of spectra.

Proof. The topological Hochschild homology of commutative \mathbb{S} -algebras which are Thom spectra has been determined by Blumberg, see [Blu10, Theorem 1.5]. He shows that, if $f: X \rightarrow \mathrm{BGL}_1(\mathbb{S})$ is a map of E_∞ spaces which is good (a fibration, for example) and such that X is a cofibrant and group-like E_∞ -space, then there is a weak equivalence of commutative \mathbb{S} -algebras as follows.

$$\mathrm{THH}^{\mathbb{S}}(M_f) \simeq M_f \wedge \mathrm{BX}_+$$

If X is only a group like E_2 -space, and f is only a good map of E_2 -spaces, then Blumberg can still show that there is an equivalence of spectra as above, provided that at least the homotopy commutative multiplication on M_f admits an E_∞ refinement, see [Blu10, Theorem 1.6].

The spectra $\mathbb{S} // 2$ and $\mathbb{S} // p$ in question have been identified as Thom spectra in Theorems 4.5 and 4.6. Once we have replaced the relevant map f by a fibration, we may

apply this theory, which works the same if \mathbb{S} is replaced by \mathbb{S}_p . We obtain an equivalence

$$\mathrm{THH}^{\mathbb{S}}(\mathbb{S} // p) \simeq \mathbb{S} // p \wedge \mathrm{BQ}(\mathbb{S}^1)_+$$

of spectra, and it remains to note that $\mathrm{BQ}(\mathbb{S}^1) \simeq \mathrm{Q}(\mathbb{S}^2)$. \square

An extra argument is needed to obtain an equivalence of commutative \mathbb{S} -algebras in Theorem 4.7: One has to ensure that the fibrant replacement is still sufficiently well-behaved with respect to the smash product. However, this will not be used in the following.

To round off the discussion of topological Hochschild homology, let us also remind ourselves that the Thom spectrum of the canonical map $\mathrm{BO} \rightarrow \mathrm{BGL}_1(\mathbb{S})$ is MO , so that Blumberg obtains equivalences

$$\mathrm{THH}^{\mathbb{S}}(\mathrm{MO}) \simeq \mathrm{MO} \wedge \mathrm{BBO}_+ \simeq \mathrm{MO} \wedge \widetilde{\mathrm{U}/\mathrm{O}}_+ \quad (4.2)$$

of commutative \mathbb{S} -algebras, where $\widetilde{\mathrm{U}/\mathrm{O}}$ is the universal cover of U/O . He also obtains equivalences

$$\mathrm{THH}^{\mathbb{S}}(\mathrm{HF}_p) \simeq \mathrm{HF}_p \wedge \Omega \mathbb{S}_+^3 \quad (4.3)$$

of spectra, which shed new light on Bökstedt's calculation of $\mathrm{THH}_*^{\mathbb{S}}(\mathrm{HF}_p)$.

4.4 The cotangent complex of $\mathbb{S} // p$

We will now determine the topological André-Quillen invariants of $\mathbb{S} // 2$ and $\mathbb{S} // p$. As with our calculation of the topological Hochschild invariants, this can be based on the identification of these spectra as E_∞ Thom spectra, and general results which apply for this class, this time due to Basterra and Mandell [BM05]. However, we will also present a more direct approach which leads to the same result.

Recall that the André-Quillen invariants of an extension F/E are defined using the F -module cotangent complex $\Omega_E(F)$ which classifies derivations. The result for $\mathbb{S} // 2$ and $\mathbb{S} // p$ (over \mathbb{S}) is as follows.

Theorem 4.8. *For each prime number p there is an equivalence*

$$\Omega_{\mathbb{S}}(\mathbb{S} // p) \simeq \Sigma \mathbb{S} // p$$

of $\mathbb{S} // p$ -modules.

Proof of Theorem 4.8 for $p = 2$ using Thom technology. In general, if T is a connective spectrum, and if $f: \Omega^\infty(T) \rightarrow \mathrm{BGL}_1(\mathbb{S})$ is an E_∞ map, then a corollary of [BM05, Theorem 5] identifies the cotangent complex of the E_∞ Thom spectrum \mathbf{M}_f of f : There is an equivalence

$$\Omega_{\mathbb{S}}(\mathbf{M}_f) \simeq \mathbf{M}_f \wedge T$$

of \mathbb{S} -modules. We may apply this theory to the spectrum $\mathbb{S} // 2$, because it has been identified as a Thom spectrum of this type in Theorem 4.5. In this case, we may take $T = \mathbb{S}^1$ so that we obtain $\Omega^\infty(T) = \mathbb{Q}(\mathbb{S}^1)$, and the result follows. \square

The preceding proof would immediately generalize to the case of odd primes p as soon as the work of Basterra and Mandell would be extended to cover Thom spectra for p -adic spherical fibrations as in Blumberg's work. For the time being, we will here provide for another proof which uses more traditional techniques associated with cotangent complexes.

Proof of Theorem 4.8 for all primes p using base change and transitivity. Since $\mathbb{S} // p$ is defined as a homotopy pushout (Definition 2.1), the flat base change formula [Bas99, Proposition 4.6] applies to give an equivalence

$$\Omega_{\mathbb{S}}(\mathbb{S} // p) \simeq \Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S}) \wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S}$$

of $\mathbb{S} // p$ -modules. Since it will be important to keep track of the maps $\mathbb{P}\mathbb{S}^0 \rightarrow \mathbb{S}$ of E_∞ algebras involved, let us agree that we use $\mathrm{ev}(0)$ in $\Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S})$ and $\mathrm{ev}(p)$ in the base change $?\wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S}$.

In order to determine $\Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S})$, we may invoke the transitivity exact sequence [Bas99, Proposition 4.2]. For the extensions $\mathbb{S} \rightarrow \mathbb{P}\mathbb{S}^0 \rightarrow \mathbb{S}$, it yields a fibration sequence

$$\Omega_{\mathbb{S}}(\mathbb{P}\mathbb{S}^0) \wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S} \longrightarrow \Omega_{\mathbb{S}}(\mathbb{S}) \longrightarrow \Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S})$$

in spectra. Now the middle term $\Omega_{\mathbb{S}}(\mathbb{S})$ is contractible. In general, the cotangent complex $\Omega_{\mathbb{S}}(\mathbb{P}T) \simeq \mathbb{P}T \wedge T$ of the free commutative \mathbb{S} -algebra on T is the free $\mathbb{P}T$ -module on T , see [Kuh06, Example 3.8], [BGR08, Proposition 1.6], and the Appendix to [Bak']. In particular, there is an equivalence $\Omega_{\mathbb{S}}(\mathbb{P}\mathbb{S}^0) \simeq \mathbb{P}\mathbb{S}^0 \wedge \mathbb{S}^0 \simeq \mathbb{P}\mathbb{S}^0$. This shows

$$\Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S}) \simeq \Sigma(\mathbb{P}\mathbb{S}^0 \wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S}) \simeq \Sigma\mathbb{S}$$

as $\mathbb{P}\mathbb{S}^0$ -modules, so that

$$\Omega_{\mathbb{P}\mathbb{S}^0}(\mathbb{S}) \wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S} \simeq \Sigma(\mathbb{S} \wedge_{\mathbb{P}\mathbb{S}^0} \mathbb{S}) \simeq \Sigma\mathbb{S} // p$$

as $\mathbb{S}//p$ -modules. As often before, we have used that the forgetful functor from commutative \mathbb{S} -algebras to spectra is a right adjoint, so that it commutes with limits. Here, this determines the homotopy type of the pushouts involved. \square

In [BGR08, Definition 3.1], a p -local commutative \mathbb{S} -algebra with a CW structure is called *minimal* if for each n the inclusion of the n -skeleton induces an isomorphism in topological André-Quillen homology $\mathrm{TAQ}_n^{\mathbb{S}}(?; \mathbb{F}_p)$.

Corollary 4.9. *For each prime p the commutative \mathbb{S} -algebra $\mathbb{S}//p$ is minimal.*

Proof. By Theorem 4.8, we have

$$\mathrm{TAQ}^{\mathbb{S}}(\mathbb{S}//p; \mathbb{F}_p) = \Omega_{\mathbb{S}}(\mathbb{S}//p) \wedge_{\mathbb{S}//p} \mathbf{HF}_p \simeq \Sigma \mathbb{S}//p \wedge_{\mathbb{S}//p} \mathbf{HF}_p \simeq \Sigma \mathbf{HF}_p,$$

so that

$$\mathrm{TAQ}_n^{\mathbb{S}}(\mathbb{S}//p; \mathbb{F}_p) = \pi_n \mathrm{TAQ}^{\mathbb{S}}(\mathbb{S}//p; \mathbb{F}_p) \cong \begin{cases} \mathbb{Z}/p & n = 1 \\ 0 & n \neq 1. \end{cases}$$

Since $\mathbb{S}//p$, by definition, has a CW structure with only two E_{∞} cells, minimality is now easily checked. \square

To round off the discussion of the cotangent complex, let us also note that Basterra and Mandell obtain an equivalence

$$\Omega_{\mathbb{S}}(\mathbf{MO}) \simeq \mathbf{MO} \wedge \mathbf{bo}, \tag{4.4}$$

of \mathbf{MO} -modules, where \mathbf{bo} is the connective cover of the real topological K-theory spectrum that has $\Omega^{\infty} \mathbf{bo} = \mathbf{BO}$. This is a corollary of [BM05, Theorem 5], stated in *loc.cit.* for the complex bordism spectrum, but the real case is similar.

5 Applications

In this section, we collect some applications, with an emphasis on the relationship to the unoriented bordism spectrum \mathbf{MO} .

5.1 Non-existence of E_∞ maps

The starting point for our applications is the following result.

Proposition 5.1. *There does not exist an E_∞ map $\mathbf{HF}_2 \rightarrow \mathbf{MO}$.*

According to [BR], this is shown in Gilmour's thesis, generalizing an argument with power operations by Hu, Kriz, and May [HKM01]. See [Bak'] for a proof. Since there does exist an E_∞ map $\mathbb{S} // 2 \rightarrow \mathbf{MO}$ by Example 2.8, we have the following corollary.

Corollary 5.2. *There does not exist an E_∞ map $\mathbf{HF}_2 \rightarrow \mathbb{S} // 2$.*

Continuing the discussion in Example 4.4, the factorization of $\mathbb{S}^1 \rightarrow \mathbf{Q}(\mathbb{S}^1)$ over $\Omega^2 \mathbb{S}^3$ gives a map

$$\mathbf{HF}_2 \longrightarrow \mathbb{S} // 2 \tag{5.1}$$

of commutative ring spectra up to homotopy. The existence of such a map is also clear from Theorem 1.3. The map (5.1) is a section of the truncation map $\mathbb{S} // 2 \rightarrow \mathbf{HF}_2$. However, while the truncation map is E_∞ , this section can not have an E_∞ representative.

The first aim of this section is to generalize the preceding corollary to all primes.

Theorem 5.3. *There does not exist an E_∞ map $\mathbf{HF}_p \rightarrow \mathbb{S} // p$.*

While we have already seen this to be true in the case $p = 2$, the following proof works for all primes.

Proof. Suppose there were such a map. Then the composition

$$\mathbf{HF}_p \longrightarrow \mathbb{S} // p \longrightarrow \mathbf{HF}_p$$

with the truncation to $\mathbf{H}\pi_0(\mathbb{S} // p) = \mathbf{HF}_p$ would be E_∞ and an equivalence, hence an equivalence of commutative \mathbb{S} -algebras. Therefore it would induce an equivalence in topological André-Quillen homology $\mathrm{TAQ}^{\mathbb{S}}(?, \mathbb{F}_2) = \Omega_{\mathbb{S}}(?) \wedge_{\mathbb{S}} \mathbf{HF}_2$. However, by Theorem 4.8, we have

$$\mathrm{TAQ}^{\mathbb{S}}(\mathbb{S} // 2; \mathbb{F}_2) = \Omega_{\mathbb{S}}(\mathbb{S} // 2) \wedge_{\mathbb{S} // 2} \mathbf{HF}_2 \simeq \Sigma \mathbb{S} // 2 \wedge_{\mathbb{S} // 2} \mathbf{HF}_2 \simeq \Sigma \mathbf{HF}_2,$$

while $\mathrm{TAQ}^{\mathbb{S}}(\mathbf{HF}_2; \mathbb{F}_2)$ is known to be non-trivial in other dimensions as well. In fact, it has been completely computed in unpublished work of Kriz, and Basterra-Mandell. See [Laz04] and [Bak'] for the precise statements. \square

5.2 Exotic E_∞ structures on graded Eilenberg-Mac Lane spectra

By Theorem 1.3, Theorem 1.2, and Theorem 1.4, the commutative \mathbb{S} -algebras \mathbf{MO} , $\mathbb{S}//2$, and $\mathbb{S}//p$ are equivalent, as homotopy commutative ring spectra, to graded Eilenberg-Mac Lane spectra with the Boardman multiplication.

Theorem 5.4. *The multiplications on the commutative \mathbb{S} -algebras \mathbf{MO} , $\mathbb{S}//2$, and $\mathbb{S}//p$ are not E_∞ equivalent to the Boardman multiplications.*

Proof. Otherwise, these spectra would be commutative \mathbf{HF}_p -algebras for suitable prime numbers p , and they would receive an E_∞ -structure map from \mathbf{HF}_p , contradicting Proposition 5.1, Corollary 5.2, or Theorem 5.3, respectively. \square

We see again that, while E_∞ structures on discrete Eilenberg-Mac Lane spectra are unique, this is not the case for graded Eilenberg-Mac Lane spectra, no matter what the prime in question is.

5.3 The structure map of unoriented bordism

Recall, from Example 2.8, that there is an E_∞ map $s: \mathbb{S}//2 \rightarrow \mathbf{MO}$ which is unique up to homotopy of E_∞ maps.

Proposition 5.5. *The structure map $s: \mathbb{S}//2 \rightarrow \mathbf{MO}$ is not injective in homology and homotopy.*

Proof. In [LMS86, IX.7.4], Lewis has shown that the Thom isomorphism commutes with the Araki-Kudo-Dyer-Lashof operations. This reduces the statement about the homology to the same question about the map $Q(S^1) \rightarrow \mathbf{BO}$. The homology of $Q(S^1)$ is the free algebra over the Araki-Kudo-Dyer-Lashof algebra on one generator, say a , in degree 1, see [CLM76, II.4]. The homology of \mathbf{BO} is polynomial on generators e_1, e_2, \dots with $\dim(e_j) = j$, and the operations have been computed in [Koc73, p. 133] and [Pri75]. In particular, we know that $Q^3 e_1 = e_1^4$. By definition of s , we also have $s_* a = e_1$, so that the different elements $Q^3 a$ and a^4 are both mapped to the same element e_1^4 . This proves the non-injectivity of the map in homology.

The statement for homotopy follows immediately from the statement for homology and the fact that the homotopy embeds into the homology as the primitive elements. \square

The preceding proof gives slightly more information: In positive dimensions, the first non-trivial element in the higher homotopy of $\mathbb{S}/2$, which lives in dimension 4 by Proposition 3.7, is mapped to zero in $\pi_4(\mathbf{MO})$.

Corollary 5.6. *The structure map $\mathbb{S}/2 \rightarrow \mathbf{MO}$ does not admit a retraction.*

This is clearly true in the homotopy category spectra, and *a fortiori* in that of commutative \mathbb{S} -algebras. In the latter, even more is true:

Proposition 5.7. *There does not exist an E_∞ map $\mathbf{MO} \rightarrow \mathbb{S}/2$.*

Proof. Otherwise, the composition with the structure map $\mathbb{S}/2 \rightarrow \mathbf{MO}$ would be an E_∞ self-map of $\mathbb{S}/2$. By Corollary 3.8, this composition would be homotopic (even as E_∞ maps) to the identity. Therefore, the hypothetical map would be a retraction for the structure map, contradicting the preceding corollary. \square

In particular, the truncation $\mathbf{MO} \rightarrow \mathbf{HF}_2$ does not factor through $\mathbb{S}/2$ as an E_∞ map.

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