ON THE SLICE SPECTRAL SEQUENCE FOR QUOTIENTS OF NORMS OF REAL BORDISM

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Abstract. In this paper, we study equivariant quotients of the multiplicative norm $\text{MU}^{G\langle C_{2n}\rangle}$ of the Real bordism spectrum by permutation summands, a concept defined here. These quotients are interesting because of their relationship to the so-called “higher real $K$-theories”. We provide new tools for computing the equivariant homotopy groups of such quotients of $\text{MU}^{G\langle C_{2n}\rangle}$ and quotients of the closely related spectrum $\text{BP}^{G\langle C_{2n}\rangle}$.

As a new example, we study spectra denoted by $\text{BP}^{G\langle C_{2n}\rangle}(m,m)$, which have non-trivial chromatic localizations only at heights equal to $r m$ where $0 \leq r \leq 2^{n-1}$. These spectra are natural equivariant generalizations of integral Morava-$K$-theories. For $\sigma$ the real sign representation of $C_{2n-1}$, we give a complete computation of the $a_\sigma$-localized slice spectral sequence of $i_{C_{2n-1}}^* \text{BP}^{G\langle C_{2n}\rangle}(m,m)$. We do this by establishing a correspondence between this localized slice spectral sequence and the $HF_2$-based Adams spectral sequence in the category of $HF_2$-modules. We also give a complete computation of the $a_\lambda$-localized slice spectral sequence of $\text{BP}^{G\langle C_4\rangle}(2,2)$ for $\lambda$ a rotation of $\mathbb{R}^2$ by an angle of $\pi/2$. The non-localized slice spectral sequences can be recovered completely from these localizations.

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1. Introduction

1.1. Motivation. Let $E(k, \Gamma)$ be the Lubin–Tate spectrum associated to a non-additive formal group $\Gamma$ of height $h$ over a finite field $k$ of characteristic 2. The Goerss–Hopkins–Miller theorem says that $E(k, \Gamma)$ is a commutative ring spectrum and that we have an action of $\text{Aut}(\Gamma)$ on $E(k, \Gamma)$ by commutative ring maps. For a finite subgroup $G$ of $\text{Aut}(\Gamma)$, we can therefore view $E(k, \Gamma)$ as a $G$-equivariant commutative ring spectrum via the cofree functor and define a theory $E_O(k, \Gamma)(G)$ by

$$E_O(k, \Gamma)(G) \simeq E(k, \Gamma)^h G.$$ 

These are the Hopkins–Miller higher real K-theory spectra, so named because when the height is 1 and $G = C_2$, these are a form of 2-complete real K-theory.

Up to an étale extension, these spectra do not depend on $(k, \Gamma)$ and we will suppress this choice by letting

$$E_h = E(k, \Gamma) \quad \text{and} \quad E_O(h)(G) = E_O(k, \Gamma)(G).$$

The spectra $E_O(h)(G)$ play a central role in chromatic homotopy theory. Reasons of their importance include:

1. The fact that they detect interesting elements in the homotopy groups of spheres. For example, Hill–Hopkins–Ravenel’s work on manifolds of Kervaire invariant one \cite{Kervaire} grew out of work of Ravenel \cite{Ravenel} which can be reinterpreted in terms of the Hurewicz image of the $E_O(p-1)(C_p)$. More recently Li–Shi–Wang–Xu study the Hurewicz image in $E_O(h)(C_2)$ \cite{LiShiWangXu}.

2. Their role as fundamental building blocks for the $K(h)$-local sphere via the theory of finite resolutions. The theory of finite resolutions was developed by Goerss–Henn–Mahowald–Rezk \cite{GoerssHennMahowaldRezk} and expanded by work of Henn \cite{Henn}, followed by work of Bobkova–Goerss \cite{BobkovaGoerss}.

3. The relative computability of their homotopy groups in contrast with the homotopy groups of spheres and its chromatic localizations. For example, the homotopy groups of $E_O(p-1)(C_p)$ were computed by Hopkins–Miller, see Nave \cite{Nave}, and those of $E_O(h)(p-1)(C_p)$ for $k > 1$ by Hill–Hopkins–Ravenel (unpublished). Computations for $p = 2$ are discussed below.

Few computations have been done of homotopy groups of $E_O(h)(G)$ when $p = 2$ for chromatic heights $h > 2$. At height $h = 1$, these computation are well understood via the relationship with complex and real K-theory. At $h = 2$, computations are done using the close relationship of the higher real K-theories with the spectrum $tmf$ of topological modular forms and its analogues with level structures. Computations for $tmf$ are due to Hopkins–Mahowald (see \cite{ HopkinsMahowald, Mahowald}), and are related to $E_O(2)(G)$ where $G$ is the binary tetrahedral group. Topological modular forms
with level 5 structures is related to $EO_2(C_4)$ and those computations are due to Behrens–Ormsby [9], while tmf with level 3 structures is related to $EO_2(C_6)$ and its homotopy was first computed by Mahowald–Rezk [33]. See also work of Hill–Meier [25] and Hill–Hopkins–Ravenel [24].

But at chromatic heights $h > 2$, such computations have been out of reach for a long time, one reason being the lack of nice geometric “global models” for the higher real $K$-theories such as $ko$ and $tmf$.

However, the work of Hill–Hopkins–Ravenel [19] has made such computations more achievable. This is the approach we take in this paper, as we now describe.

By work of Hewett, when $p = 2$ a finite 2-subgroup of $\text{Aut}(\Gamma)$ is either a cyclic 2-group of order $2^n$ whenever $h = 2^{n-1}m$ for a natural number $m$, or, when $h = 2m$ for $m$ odd, $G$ may be the quaternions [18]. In this paper, we restrict to the case of cyclic 2-groups. Our reason for this restriction is that, in this case, we can use the slice filtration and related machinery developed in [19] for cyclic groups. So, moving forward, we assume that that $G = C_2^n$ and that $h = 2^{n-1}m$ for $m$ any natural number.

The case of $G = C_2$. The first case to consider is when $G = C_2$. On the one hand, there is a central subgroup $C_2$ in $\text{Aut}(\Gamma)$ coming from “formal inversion” as an automorphism of any formal group and we obtain a spectrum $EO_h(C_2)$. On the other hand, complex conjugation gives an action of $C_2$ on the spaces of $MU$, which can be used to construct the Real bordism $MU_R$, a $C_2$-spectrum first considered by Fujii [14] and Landweber [31]. Hahn–Shi [15] have produced a Real orientation for any of the Lubin–Tate spectra at the prime 2:

$$MU_R \to i_C^* E_h.$$ 

This allows us to combine the two $C_2$-actions under one perspective, and to construct $E_h$ as localizations of quotients of $MU_R$.

We first discuss two families of $C_2$-spectra that refine classical spectra of interest in chromatic homotopy theory and are constructed as quotients of $MU_R$. More specifically, after localization at 2, $MU_R$ splits as a wedge of suspensions of the Real Brown–Peterson spectrum $BP_R$ and the spectra we discuss are quotients of the latter.

Let $\rho_2$ be the real regular representation. By work of Araki [2] and Landweber [31], we have

$$\pi_{i \rho_2}^C BP_R \cong \mathbb{Z}_2[\bar{v}_1, \bar{v}_2, \bar{v}_3, \ldots]$$

for generators $\bar{v}_r \in \pi_{(2^r-1)\rho_2}^C BP_R$ whose underlying homotopy classes give generators $v_i \in \pi_{(2^i-1)2} BP$ for $BP_*$.

(1) First, we have Real truncated Brown–Peterson spectra

$$BP_R(h) = BP_R/(\bar{v}_j \ | \ j > h)$$

The underlying non-equivariant spectrum is a classical truncated Brown–Peterson spectrum $BP(h)$, which has chromatic height $\leq h$ in the sense that $L_{K(r)} BP(h)$ is trivial if and only if $r > h$.

The $K(h)$-localization of $i_*^* BP_R(h)$ gives, up to periodization, a model of Lubin–Tate theory $E_h$ with its canonical $C_2$-action obtained through Goerss–Hopkins–Miller theory. The fixed points of $BP_R(h)$ are thus global models for $EO_h(C_2)$.
These equivariant spectra and their $\bar{v}_h$-localizations were first studied by Hu–Kriz [29] and Kitchloo–Wilson [30]. They give a chromatic filtration of the fixed point spectrum $(BP_R)^G$ via the tower
\[
\ldots \to BP_R\langle h \rangle^{C_2} \to \ldots \to BP_R\langle 1 \rangle^{C_2} \to BP_R\langle 0 \rangle^{C_2} \simeq HZ^{C_2}.
\]
(2) Another example are the Real integral Morava $K$-theories, which we denote by
\[
BP_R^{\langle h \rangle} := BP_R/\left(\bar{v}_i \mid i \neq 0, h\right).
\]
The underlying spectra are classical integral Morava $K$-theories, which have chromatic height concentrated at $r = 0, h$ in the sense that $L_{K(r)}BP^{\langle h \rangle}$ is non-trivial in exactly these two cases. These are closely related to the classical Morava $K$-theories $K^{\langle h \rangle}$. Their equivariant generalizations introduced below are among the main examples we study in this paper.

Nonequivariant versions of these integral Morava $K$-theories have been previously studied, e.g. in [37].

Larger cyclic $2$-groups. In this paper, we study generalizations of the above examples to larger cyclic groups $G = C_{2^n}$. In particular, we will study the generalizations of the integral Morava $K$-theories $BP_R^{\langle h \rangle}$ in great computational depth.

Let $G$ be a finite subgroup of $\text{Aut}(\Gamma)$ which contains $C_2$. Since $E_h$ is an equivariant commutative ring spectrum, the norm-forgetful adjunction produces a $G$-equivariant orientation map
\[
MU^{\langle G \rangle} := N_{C_2}^G MU_R \to E_h.
\]
Again, since we are working 2-locally, using Quillen’s idempotent we can replace $MU_R$ with $BP_R$ and get a map
\[
BP^{\langle G \rangle} := N_{C_2}^G BP_R \to E_h
\]
This allows us to view
\[
\left(BP^{\langle G \rangle}\right)^G
\]
as a global approximation to any $EO_h(G)$.

Thus, the spectrum $\left(BP^{\langle G \rangle}\right)^G$ contains transchromatic information for all heights $h$ where $\text{Aut}(\Gamma)$ contains $G$ as a subgroup.

Remark 1.1. In fact, to capture more global phenomena from the $\left(BP^{\langle G \rangle}\right)^G$-perspective, we can assemble these fixed point spectra as $G$ varies into a “detection tower” of ring spectra
\[
\ldots \to (BP^{\langle C_{2^n} \rangle})^{C_{2^n}} \to (BP^{\langle C_{2^{n-1}} \rangle})^{C_{2^{n-1}}} \to \ldots \to (BP^{\langle C_2 \rangle})^{C_2} \to BP,
\]
where the maps are constructed using the unit of the restriction-coinduction adjunction. The Hurewicz image for any $(BP^{\langle C_{2^n} \rangle})^{C_{2^n}}$ is therefore bounded by that of the limit
\[
\lim \left(\left(BP^{\langle C_{2^n} \rangle}\right)^{C_{2^n}}\right).
\]

We continue to focus on $G = C_{2^n}$ and $h = 2^{n-1}m$. To compute the homotopy groups of $\left(BP^{\langle G \rangle}\right)^G$, Hill, Hopkins, and Ravenel introduced the equivariant slice spectral sequence [19] [22]. However, due to the complexity of the equivariant computations, besides $\left(BP^{\langle C_2 \rangle}\right)^{C_2}$, not much is known about the homotopy groups of $\left(BP^{\langle G \rangle}\right)^G$. 

The current approach has been to pass to fixed points of quotients of $BP^{(G)}$ that are generalizations of the $BP_2\langle h\rangle$. To define these quotients, note that as in [19], one can compute the $C_2$-equivariant homotopy groups of $BP^{(G)}$ in degrees an integer multiple of $\rho_2$ to be

$$\pi_{*\rho_2}^{C_2}BP^{(G)} \cong \mathbb{Z}_2[G \cdot \bar{v}_1, G \cdot \bar{v}_2, \ldots]$$

where $\bar{v}_r \in \pi_{(2^r-1)\rho_2}^{C_2}$. Here, $G \cdot \bar{v}_r^G$ denotes a set of $2^n$ elements

$$\bar{v}_r^G, \gamma \bar{v}_r^G, \ldots, \gamma^{2^n-1} \bar{v}_r^G,$$

where $\gamma$ represents a generator of $G$ and the Weyl action of $G$ is made obvious by the notation except for $\gamma^{2^n-1} \bar{v}_r^G = -\bar{v}_r^G$. The method of twisted monoid rings of Hill–Hopkins–Ravenel [19] then allows one to form quotients of $BP^{(G)}$ by collections of permutation summands of the form $G \cdot \bar{v}_r^G$. This is the first thing we explain and explore in Section 2. Such quotients by permutation summands are our main objects of study.

The generalizations of the quotients of $BP_2$ mentioned above are the following quotients by permutation summands:

1. The spectra

$$BP^{(G)}\langle m \rangle := BP^{(G)}/(G \cdot \bar{v}_{m+1}^G, G \cdot \bar{v}_{m+2}^G, \ldots)$$

generalize the spectrum $BP_2\langle h \rangle$ in the case when $G = C_2$. In [7, Theorem 7.5], we showed that this is a spectrum of height $\leq h$, where $h = 2^{n-1}m$. Up to periodization, the $K(h)$-localization of the spectrum underlying $BP^{(G)}\langle m \rangle$ gives a model for a height $h$ Lubin–Tate theory equipped with a $G$-action coming from the Morava stabilizer group. So, the fixed points of the $BP^{(G)}\langle m \rangle$ are global models for $EO_h(G)$.

These quotients give a chromatic filtration of $(BP^{(G)})^G$ via the tower

$$\cdots \rightarrow (BP^{(G)}\langle m \rangle)^G \rightarrow (BP^{(G)}\langle m-1 \rangle)^G \rightarrow \cdots \rightarrow (BP^{(G)}\langle 1 \rangle)^G \rightarrow HZ^G.$$ 

The height increases by $2^n-1$ at each step of this tower.

Computations of the slice spectral sequence of these quotients are still few, limited to the case of $BP_2\langle m \rangle$ [29], of $BP^{(C_1)}\langle 1 \rangle$ [24], and of $BP^{(C_2)}\langle 2 \rangle$ [26].

We do not extend these computations in this paper, but rather consider the homotopy groups of the next quotient on our list, the generalization of the integral Morava $K$-theories, as a preliminary step to understanding $BP^{(G)}\langle m \rangle$ in more generality.

2. The spectra

$$BP^{(G)}\langle m, m \rangle := BP^{(G)}/(G \cdot \bar{v}_1^G, \ldots, G \cdot \bar{v}_{m-1}^G)$$

have chromatic height concentrated in degrees $rm$ for $0 \leq r \leq 2^n-1$, as shown in Theorem 3.1 below. When $n = 1$, these are the $BP_{2\langle h, h \rangle}$.

These spectra, to our knowledge, have not been considered before and are the main new example of a quotient by permutation summands studied in this paper. They serve as a computable approximation of equivariant truncated Brown–Peterson spectra $BP^{(G)}\langle m \rangle$. A key point is that their slice differentials are easier to compute than those of the $BP^{(G)}\langle m \rangle$.

1.2. Main results. We now describe the content of this paper and state our results.
Section 3. The first part of this paper is dedicated to the definition of the various equivariant quotients by permutation summands and the study of their slices. The results of this section, while not stated elsewhere, are straightforward generalizations of the work of Hill–Hopkins–Ravenel in [19].

A typical example of a permutation summand for $BP^{(G)}$ is a collection of elements of the form $G \cdot \bar{v}_j^G$ (see Definition 2.1). The main point is that the slice associated graded of quotients by permutation summands is easy to describe:

**Theorem (cf. Proposition 2.5).** The slice associated graded of the quotient

$$BP^{(G)}/(G \cdot \bar{v}_j^G \mid j \in J)$$

where $J$ is a set of natural numbers, is the generalized Eilenberg–Mac Lane spectrum

$$H\mathbb{Z}[G \cdot \bar{v}_i^G \mid i \notin J].$$

**Example.** The slice associated graded for $BP^{(G)}\langle m, m \rangle$ is $H\mathbb{Z}[G \cdot \bar{v}_m^G]$.

In fact, the results we prove do not depend on the choice of generators of the permutation summand: We can replace $\bar{v}_m$ by any element $\bar{s}_{2^m-1}$ in $\pi^{2^m-1}_{(2^m-1)\rho_2}BP^{(G)}$ that generates a permutation summand. For $\bar{S} = \{\bar{s}_{2^m-1} \mid j \in J\}$, we will write

$$G \cdot \bar{S} = \{G \cdot \bar{s}_{2^m-1} \mid j \in J\}.$$

Section 4. We determine the chromatic height of the generalized integral Morava $K$-theory spectra $BP^{(G)}\langle m, m \rangle$. Namely, we show:

**Theorem (Theorem 3.1).** The spectrum underlying $BP^{(G)}\langle m, m \rangle$ has non-trivial chromatic localizations only at heights equal to $rm$ where $0 \leq r \leq 2^{n-1}$. That is,

1. for $r = km$ where $0 \leq k \leq 2^{n-1}$, $L_{K(r)}i^*BP^{(G)}\langle m, m \rangle \not\simeq \ast$, and
2. for all other $r \geq 0$, $L_{K(r)}i^*BP^{(G)}\langle m, m \rangle \simeq \ast$.

Theorem 3.1 states that the underlying spectrum of $BP^{(G)}\langle m, m \rangle$ captures chromatic information at heights $0, m, 2m, 3m, \ldots, 2^{n-1}m$. Section 4. In this expository section, we discuss the tools needed for the computations of the rest of the paper.

To compute the homotopy groups of quotients of the form $BP^{(G)}/G \cdot \bar{S}$, we use a tool called the *localized slice spectral sequence*. This spectral sequence is developed in [36]. We briefly recall some of its highlights here, but Section 4 is dedicated to a more detailed discussion of these ideas.

Let $X$ be a $G$-spectrum and let $\{P^*\}$ denote the slice tower for $X$. For $H \subset G$ a normal subgroup, the spectral sequence associated to the tower

$$\{Q^*\} := \{\tilde{E}_rF[H] \wedge P^*\}$$

is the *localized slice spectral sequence* of $\tilde{E}_rF[H] \wedge X$, where $F[H]$ is a certain family described in Definition 4.3. By [34], it converges strongly to the $G$-equivariant homotopy groups of $\tilde{E}_rF[H] \wedge X$, which is also equal to the homotopy groups of $\Phi^H(X)^{G/H}$ (see Theorem 4.5).

**Example.** When $G = H = C_{2^n}$, the localized slice spectral sequence is the $a_\sigma$-localization of the slice spectral sequence, for $\sigma$ the sign representation. If $G = C_{2^n}$ and $H = C_2$ for $i < n$, then the localized slice spectral sequence is the $a_{\lambda_i}$-localization of the slice spectral sequence for $\lambda_i$ a rotation of the plane by an angle of $\pi/2^{n-i}$.
For $G = C_{2^n}$, the slice spectral sequence of $X$ is also divided into different regions, separated by the lines through the origin of slopes $(2^i - 1)$, $0 \leq i \leq n$. In [35] (forthcoming), the authors prove a result which they called the Slice Recovery Theorem, which we state in Theorem 4.6. It implies that for $X$ a $(-1)$-connected $G$-spectrum, the map from the slice spectral sequence of $X$ to the localized slice spectral sequence of $\tilde{E}_F[C_2^\times] \wedge X$ induces an isomorphism between all the differentials on or above the line of slope $(2^i - 1)$ for all $1 \leq i \leq n$.

Therefore, the localized slice spectral sequence serves as a bridge between the fixed points $X^G$ and the residual fixed points $(\Phi_C^G \times X)^{G/C^G \times}$. More precisely, even though the localized slice spectral sequence only computes the geometric fixed points, its $E_2$-page and differentials are closely related to the original slice spectral sequence, which computes the fixed points.

Section 4. Equipped with the tools reviewed above, we completely compute the $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$. This is the same as the localized slice spectral sequence for $\tilde{E}_F[G] \wedge BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$. This spectral sequence converges to the homotopy groups of the $G$-geometric fixed points of $BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$.

This computation, which is the content of Theorem 5.9, is done by an application of the Slice Differential Theorem of Hill–Hopkins–Ravenel [19]. The quotient map

$$BP^{(G)} \longrightarrow BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$$

induces a map of the corresponding localized slice spectral sequences. The Slice Differential Theorem produces all the differentials in the $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}BP^{(G)}$. By using the module structure and naturality, we deduce all the differentials in the $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$.

Using the Slice Recovery Theorem, the computation of the $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$ gives us a complete understanding of all the differentials above the line of slope $2^{n-1} - 1$ in the original slice spectral sequence of $BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$.

Remark 1.2. When specialized to the case $G = C_2$, the $a_\sigma$-localized slice spectral sequence of Section 5 produces all the differentials in the slice spectral sequence of $BP_{2}/\tilde{S}$. This is explained in Corollary 5.12.

The results of this section are also used to show that, in stark contrast to the non-equivariant setting, most of the quotients of $BP^{(G)}$ by permutation summands do not admit a ring structure.

Proposition (Proposition 5.16). Let $J \subseteq \mathbb{N}$ and $\tilde{S} = \{ \tilde{s}_{j-1} \mid j \in J \}$ be a set of generators for permutation summands. If there is a $k \in J$ such that $(k + 1) \notin J$, then $BP^{(G)} \langle m, m \rangle / G \cdot \tilde{S}$ does not have a ring structure in the homotopy category.

Section 6. We analyze the next region of the slice spectral sequence of $BP^{(G)} \langle m, m \rangle$, that is, the region between the lines of slopes $(2^{n-2} - 1)$ and $(2^{n-1} - 1)$. Letting $G' = C_{2n-1}$ be the subgroup of index two in $G = C_{2^n}$, the differentials in this region can be obtained by computing the localized slice spectral sequence of $\tilde{E}_F[G'] \wedge BP^{(G)} \langle m, m \rangle \cong a_{\alpha_{n-2}}^{-1}BP^{(G)} \langle m, m \rangle$, which computes the homotopy groups of the $G/G'$-fixed points of the spectrum $\Phi^{G'}(BP^{(G)} \langle m, m \rangle)$.
A useful input to computing this spectral sequence is its restriction to the group \( G' \), which computes the homotopy groups of \( \Phi^{G'} i_{\xi, \zeta}^* BP^{(G)} \langle m, m \rangle \). Then the Mackey functor structure allows us to deduce information about the \( G \)-equivariant spectral sequence from the simpler \( G' \)-equivariant spectral sequence.

This is where yet another spectral sequence comes into play, namely, the \( HF_2 \)-based Adams spectral sequence in the category of \( A \)-module spectra (as in Baker–Lazarev \([3]\)), where

\[
A := HF_2 \wedge HF_2.
\]

Here, \( HF_2 \) is given an \( A \)-module structure via the multiplication map \( A \to HF_2 \). We call this spectral sequence the \textit{relative Adams spectral sequence}.

The link between this more classical spectral sequence and this work is that, as non-equivariant spectra, there is an equivalence

\[
\Phi^{G'} i_{\xi, \zeta}^* BP^{(G)} \langle m, m \rangle \cong A/\langle \xi_i, \zeta_i : i \neq m \rangle
\]

for \( \xi_i \) and \( \zeta_i \) the usual Milnor generators and their conjugates. Furthermore, there is an intimate connection between the relative Adams spectral sequence with the \( G' \)-equivariant localized slice spectral sequence given by the following result, which we prove in Section 6.2.

**Theorem** (Theorem 6.7 and Corollary 6.10). After a reindexing of filtrations, the \( G' \)-equivariant localized slice spectral sequence of \( \mathcal{E} \mathcal{F}[G'] \wedge BP^{(G)} \langle m, m \rangle \) is isomorphic to the relative Adams spectral sequence of \( A/\langle \xi_i, \zeta_i : i \neq m \rangle \).

In Section 6.3, we compute the relative Adams spectral sequence of \( A/\langle \xi_i, \zeta_i : i \neq m \rangle \), extending our computations from \([6]\).

Combining the above theorem relating the two spectral sequences with this computation gives us the \( G' \)-equivariant localized slice spectral sequence of \( BP^{(G)} \langle m, m \rangle \).

As an example, in Section 6.4 we compute \( C_2 \)-equivariant localized slice spectral sequence of

\[
\mathcal{E} \mathcal{F}[C_2] \wedge i_{C_2}^* BP^{(C_2)} \langle 2, 2 \rangle
\]

by using the comparison of spectral sequences of Section 6.2 and the computations of Section 6.3.

**Section 7** In the final section the paper we specialize to the case \( m = 2 \) and \( G = C_4 \), letting \( a_{\lambda_0} = a_{\lambda} \). We compute the localized slice spectral sequence of \( a_{\lambda}^{-1} BP^{(C_4)} \langle 2, 2 \rangle \), converging to the \( C_4 \)-equivariant homotopy groups of

\[
a_{\lambda}^{-1} BP^{(C_4)} \langle 2, 2 \rangle \cong \mathcal{E} \mathcal{F}[C_4] \wedge BP^{(C_4)} \langle 2, 2 \rangle.
\]

**Remark** 1.3. Although we do not do this in details in this paper, the Slice Recovery Theorem 1.6 can be used to recover all the differentials in the \( C_4 \)-equivariant slice spectral sequence of \( BP^{(C_4)} \langle 2, 2 \rangle \). By Theorem 3.1 the theory \( BP^{(C_4)} \langle 2, 2 \rangle \) is of heights 0, 2 and 4. This computation is thus a height-4 computation of a spectrum that is closely related to \( BP^{(C_4)} \langle 2 \rangle \), the spectrum studied in \([26]\).

**Remark** 1.4. The slice spectral sequence of \( BP^{(C_4)} \langle 2, 2 \rangle \) is easier to compute than that of \( BP^{(C_4)} \langle 2 \rangle \) because there are less classes in the spectral sequence. We suspect these computations can be generalized to higher heights, to compute the homotopy of \( BP^{(C_4)} \langle m, m \rangle \) for any \( m \geq 1 \). This is a \( C_4 \)-equivariant theory of heights 0, \( m \) and \( 2m \). The computation of the equivariant homotopy groups of \( BP^{(C_4)} \langle m, m \rangle \) for all \( m \geq 1 \) would be a significant addition to the bank of computations at higher chromatic heights.
Remark 1.5. The computation of the $C_4$-equivariant slice spectral sequence of $BP^{((C_4)/(2,2))}$, combined with the Slice Recovery Theorem of [35] (forthcoming) determines the slice spectral sequences of $BP^{((G)/(2,2))}$ for any $G = C_2^n$ above the line of slope $2^{n-2} - 1$.

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2. Quotient modules of $MU^{((G))}$

2.1. Slices for some $MU^{((G))}$ modules. For a graded ring $R$ with augmentation ideal $I$, let $Q_n R$ denote the degree $n$ elements in $I/I^2$. One of the key computations in [19] was a convenient choice of algebra generators for the $\ast_{p_2}$-graded homotopy groups of $MU^{((G))}$. In particular, we have an isomorphism of graded $Z[G]$-modules

$$Q_{\ast_{p_2}}(\pi_{\ast_{p_2}} MU^{((G))}) \cong \bigoplus_{k \geq 1} \Sigma^{k p_2} \text{Ind}_{C_2}^G(Z_{\ast}^-),$$

where $Z_{\ast}$ is the integral sign representation.

**Definition 2.1.** Let $J \subseteq \mathbb{N}$ and

$$\tilde{S} = \{ \tilde{s}_j \in \pi_{\ast_{p_2}} MU^{((G))} \mid j \in J \}$$

be a collection of elements. Associated to $\tilde{S}$, we have a $C_2$-equivariant map

$$f_{\tilde{S}} : \bigoplus_{j \in J} \Sigma^{j p_2} Z_{\ast}^- \to \bigoplus_{j \in J} Q_{j p_2}(MU^{((G))}).$$

We say that $\tilde{S}$ generates a permutation summand if the adjoint $G$-equivariant map

$$f^*: \bigoplus_{j \in J} \Sigma^{j p_2} \text{Ind}_{C_2}^G(Z_{\ast}^-) \to \bigoplus_{j \in J} Q_{j p_2}(MU^{((G))})$$

is an isomorphism.

Given any element in the $RO(C_2)$-graded homotopy of $MU^{((G))}$, we can use the method of twisted monoid algebras from [19]. For each $j \in J$, we have a free associative algebra

$$S^0[\tilde{s}_j] := \bigvee_{i=0}^{\infty} S_{ijp_2}^0,$$

and we have a canonical associative algebra map

$$S^0[\tilde{s}_j] \to i^*_C MU^{((G))}$$

adjoint to the map defining $\tilde{s}_j$. Using the norm maps on $MU^{((G))}$ and the multiplication, we get an associative algebra map

$$S^0[G \cdot \tilde{S}] = \bigwedge_{j \in J} N^G_{C_2} S^0[\tilde{s}_j] \to MU^{((G))}.$$

**Definition 2.2.** For $J \subseteq \mathbb{N}$, let

$$MU^{((G))}/G \cdot \tilde{S} := MU^{((G))}/(G \cdot \tilde{s}_j \mid j \in J) = MU^{((G))} \wedge_{S^0[G \cdot \tilde{S}]} S^0.$$

We call $MU^{((G))}/G \cdot \tilde{S}$ a quotient by permutation summands.
The following is a slight generalization of the Slice Theorem of Hill–Hopkins–Ravenel [19 Theorem 6.1]. Recall from [19] that
\[ \pi_{\rho_2}C^j MU^{(G)} \cong \mathbb{Z}_{(2)} | G \cdot \bar{r}_1, G \cdot \bar{r}_2, \ldots \]
for generators \( \bar{r}_i \) in \( \pi_{\rho_2}C^j MU^{(G)} \) introduced in (5.39) of [19]. In fact, the conditions on the classes \( \bar{s}_j \) guarantee that we can use them instead of the \( \bar{r}_j \) for \( j \in J \). We then extend the set \( \bar{S} \) to form a set of equivariant algebra generators, as in [19 Section 5]. Any set
\[ \bar{S}' := \{ \bar{s}_j | j \notin J \} \]
of elements \( \bar{s}_j \in \pi_{\rho_2}C^j MU^{(G)} \) which generate a permutation summand will do to extend \( \bar{S} \) to a set \( \bar{S} \cup \bar{S}' \) of equivariant generators for \( \pi_{\rho_2}C^j MU^{(G)} \).

**Definition 2.3.** Let \( J \subseteq \mathbb{N} \) and \( \bar{S} \) and \( \bar{S}' \) be as above. Define
\[ H_{\mathbb{Z}}[G \cdot \bar{s}_1, G \cdot \bar{s}_2, \ldots] := H_{\mathbb{Z}} S^{0}[G \cdot \bar{s}_1, \ldots] \]
and
\[ H_{\mathbb{Z}}[G \cdot \bar{s}_1, G \cdot \bar{s}_2, \ldots] / G \cdot \bar{S} := H_{\mathbb{Z}} S^{0}[G \cdot \bar{s}_1, \ldots] \]

**Remark 2.4.** The spectrum \( H_{\mathbb{Z}}[G \cdot \bar{s}_1, G \cdot \bar{s}_2, \ldots] / G \cdot \bar{S} \) is very simple. In fact, it is equivalent to \( H_{\mathbb{Z}} S^{0}[G \cdot \bar{S}'] \), which itself is the smash product over \( j \notin J \) of the norms, in the category of \( H_{\mathbb{Z}} \)-modules, of \( H_{\mathbb{Z}}[\bar{s}_j] \cong \bigvee_{i=0}^j H_{\mathbb{Z}} S^{0} \). 

**Proposition 2.5.** The slice associated graded of \( MU^{(G)} / G \cdot \bar{S} \) is the generalized Eilenberg–Mac Lane spectrum
\[ H_{\mathbb{Z}} S^{0}[G \cdot \bar{s}_1, G \cdot \bar{s}_2, \ldots] / (G \cdot \bar{S}) \]

**Proof.** We have a natural equivalence
\[ MU^{(G)} / G \cdot \bar{S} \cong MU^{(G)} S^{0}[G \cdot \bar{s}_1, \ldots] / S^{0}[G \cdot \bar{S}']. \]
The result now follows exactly as [19 Slice Theorem 6.1], using the natural degree filtration on \( S^{0}[G \cdot \bar{S}'] \). \( \square \)

Letting \( \bar{S} \) be the generators killed by the Quillen idempotent, this recovers the usual form of the slice associated graded for \( BP^{(G)} \). We could moreover always append this to any collection \( \bar{S} \) we consider, which allows us to deduce all of the analogous results for \( BP^{(G)} \). We will do so without comment moving forward.

**Remark 2.6.** The left action of \( MU^{(G)} \) on itself always endows \( MU^{(G)} / G \cdot \bar{S} \) with a canonical \( MU^{(G)} \)-module structure, and the same is true with \( BP^{(G)} \) instead.

**Notation 2.7.** In the homotopy of the spectrum \( BP^{(G)} \), let
\[ \bar{v}_k^G := \bar{v}_k^G \in \pi_{(2^k-1)\rho_2}BP^{(G)}, \]
as defined and considered in [7].

**Definition 2.8.** For each \( m \geq 0 \), let \( J_m = \{ k \mid k > m \} \). Let
\[ \bar{S}_m = \{ \bar{s}_{2^j} - 1 \in \pi_{(2^j-1)\rho_2}BP^{(G)} \mid j \in J_m \} \]
generate a permutation summand. When for each \( j \in J_m \), \( \bar{s}_{2^j} - 1 = \bar{v}_j^G \), we name the quotient
\[ BP^{(G)} / G \cdot \bar{S}_m = BP^{(G)}(m). \]
More generally, we say that the \( BP^{(G)} \)-module
\[
BP^{(G)}/G \cdot \bar{S}_m
\]
is a form of \( BP^{(G)} \langle m \rangle \).

**Notation 2.9.** Let \( v_k^G \) be the restriction to the trivial group of \( \bar{v}_k^G \).

**Remark 2.10.** Just as in [20], we note that since the underlying rings are all polynomial rings, the map
\[
\pi_*^{(e)} BP^{(G)} \rightarrow \pi_*^{(e)} B P^{(G)} \langle m \rangle = \mathbb{Z}_2[\bar{v}_1^G, \ldots, G \cdot v_m^G]
\]
has a section.

A form of \( BP^{(G)} \langle m \rangle \) is a quotient module \( M \) with the property that for any section, the composite
\[
\mathbb{Z}_2[\bar{v}_1^G, \ldots, G \cdot v_m^G] \rightarrow \pi_*^{(e)} B P^{(G)} \rightarrow \pi_*^{(e)} M
\]
is an isomorphism. The difference between the forms lies in the \( BP^{(G)} \)-module structure, not in the underlying homotopy groups.

**Corollary 2.11.** The slice associated graded for any form of \( BP^{(G)} \langle m \rangle \) is
\[
HZ[\bar{v}_1^G, \ldots, G \cdot v_m^G].
\]

**Definition 2.12.** Let \( k \) and \( m \) be natural numbers with \( 1 \leq k \leq m \). Let
\[
\bar{S}_{k,m} = \{ \bar{v}_j^G \mid 0 < j < k \text{ or } j > m \},
\]
and let
\[
BP^{(G)} \langle k, m \rangle = BP^{(G)}/G \cdot \bar{S}_{k,m}.
\]

**Remark 2.13.** As in Definition 2.8, we also define forms of \( BP^{(G)} \langle k, m \rangle \) as quotients by elements \( \bar{s}_{2j-1} \), for \( 0 < j < k \) or \( j > m \) that generate permutation summands.

**Corollary 2.14.** The slice associated graded for \( BP^{(G)} \langle k, m \rangle \) (or for any form) is
\[
HZ[\bar{v}_1^G, \ldots, G \cdot v_m^G].
\]

One of the main examples we will analyze is
\[
BP^{(G)} \langle m, m \rangle = BP^{(G)}/(G \cdot \bar{v}_1^G, \ldots, G \cdot \bar{v}_{m-1}^G, G \cdot v_m^G, \ldots)
\]
where \( m \geq 1 \).

The slice associated graded for \( BP^{(G)} \langle m, m \rangle \) is very simple, given by
\[
HZ[\bar{v}_m^G].
\]

### 3. Chromatic Height of \( BP^{(G)} \langle m, m \rangle \)

In this section, we study the underlying chromatic height of the spectra \( BP^{(G)} \langle m, m \rangle \).

**Theorem 3.1.**

1. For \( r = km \) where \( 0 \leq k \leq 2^{n-1} \), \( L_{K(r)} t^* BP^{(G)} \langle m, m \rangle \not\simeq * \);
2. For all other \( r \geq 0 \), \( L_{K(r)} t^* BP^{(G)} \langle m, m \rangle \simeq * \).
Proof. Our proof will be similar to that of Proposition 7.4 and Theorem 7.5 in [2]. In this proof, let $X = i^*_{r}BP^{(G)}(m, m)$. For any $r$, there is a cofinal sequence $J(i) = (j_0, j_1, \ldots, j_{r-1})$ of positive integers and generalized Moore spectra

$$M_{J(i)} = S^0/(v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}})$$

with maps $M_{J(i+1)} \to M_{J(i)}$ such that

$$L_{K(r)}X \cong \text{holim}, (L_{r}X \land M_{J(i)}) .$$

See [25, Prop. 7.10].

Since $X$ is a $BP$-module, it follows from [27, Cor. 1.10] that the natural map $L_{r}X \to L_{r}X$ is an equivalence (since it is a $BP$-equivalence between $BP$-local spectra). Therefore,

$$L_{r}X \land M_{J(i)} = L_{r}X \land M_{J(i)} \cong X \land L_{r}M_{J(i)} \cong X \land v_{r}^{-1}M_{J(i)} \cong v_{r}^{-1}X \land M_{J(i)} .$$

Here, we have used the fact that since $M_{J(i)}$ is a type $r$ spectrum, its finite localization is the telescope [23, Prop. 3.2]. We have also used the fact that $L_{r}X$ is smashing.

To prove (1), we assume $r$ is of the form $km$ with $0 \leq k \leq 2^{n-1}$. We will first show that under the map

$$BP \to v_{r}^{-1}X \land M_{J(i)} ,$$

the image of $v_{r} \in \pi_{a}BP$ is nonzero. Note that

$$v_{r}^{-1}X \land M_{J(i)} = v_{r}^{-1}X \land MU MU/(v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}}) = v_{r}^{-1}X/(v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}}) .$$

By an iterative application of the formula

$$v_{r}C_{n}^{2n-1} \equiv v_{r}C_{n}^{2n} + \gamma_{n} v_{r}C_{n}^{2n} + \sum_{j=1}^{r-1} \gamma_{n} v_{r}C_{n}^{2n} (v_{r}C_{n}^{2n})^{2j} \pmod{I_{r}}$$

(where $I_{r} = (2, v_{1}, \ldots, v_{r-1})$) in [27, Theorem 1.1], the images of $v_{r}^{j} = (v_{r}C_{2})^{j}$ in $(\pi_{a}X)/(v_{0}, \ldots, v_{r-1})$ are all nonzero for $j \geq 1$. This implies that their images are also nonzero in $\pi_{a}X/(v_{0}, \ldots, v_{r-1})$. Therefore, the image of $v_{r}$ in $\pi_{a}X/(v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}})$ is nonzero. After taking the homotopy limit, the image of $v_{r}$ under the map $\pi_{a}BP \to \pi_{a}L_{K(r)}X$ will also be nonzero. It follows that $\pi_{a}L_{K(r)}X \cong *$.

To prove (2), we will consider two cases, based on the divisibility of $r$ by $m$. If $r$ is not divisible by $m$, then the degree of $v_{r}$, $2(2^{r} - 1)$, is not divisible by $2(2^{m} - 1)$. However, the homotopy groups of $X$ are concentrated in degrees that are divisible by $2(2^{m} - 1)$. This implies that the multiplication by $v_{r}$ map

$$\Sigma^{[v_{r}]}X \to X$$

induces the zero map on homotopy, and

$$\pi_{a}v_{r}^{-1}X \cong v_{r}^{-1}\pi_{a}X = 0 .$$

It follows that $v_{r}^{-1}X \cong *$ and therefore $L_{K(r)}X \cong *$.

Now, suppose $m$ divides $r$. Let $r = km$ for some $k > 2^{n-1}$. The result of [7, Proposition 7.3] implies that $v_{r} \in (2, v_{1}, \ldots, v_{r-1})$ so that $v_{r}^{j} \in (v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}})$ for some $q > 0$.

Now,

$$X \land M_{J(i)} = X \land MU MU/(v_{0}^{j_0}, \ldots, v_{r-1}^{j_{r-1}}) .$$
and there is a Künneth spectral sequence [12, Theorem IV.4.1]

\[ E_2^{s,t} = \text{Tor}^{MU_*}_{s,t} (\pi_* X, \pi_0 MU/(v_0^j, \ldots, v_{r-1}^j)) \Rightarrow \pi_{t-s} (X \wedge M_{(i)}) \).

This is a cohomologically graded lower half-plane spectral sequence. As in the proof of Theorem 7.5(2) in [7], the fact that for some \( q \) multiplication by \( v_r^q \) raises filtration implies that every element in the homotopy groups of \( X \wedge M_{(i)} \) is killed by some finite power of \( v_r \). It follows that \( L_{K(r)} X = \text{holim}_i (v_r^{-1} X \wedge M_{(i)}) \approx \ast. \)

\[ \square \]

4. Localized spectral sequences

In our computations below, we will make use of various localizations of the slice spectral sequence of quotients of \( MU^{(G)} \). In this section, we recall results from [21] and [36] that we will use here. As a reminder, we continue to let \( G = C_{2^n} \).

4.1. Some notation. Here, we introduce some notation. We refer the reader to [23] for more details.

Consider 2-local homotopy equivalence classes of representation spheres \( S^V \) where \( V \) is a finite dimensional orthogonal representation. This is a semi-group with respect to the smash product. Let \( JO(G) \) be the group completion.

**Definition 4.1.** Define \( \lambda_j = \lambda_j(G) \) to be the 2-dimensional irreducible real representation of \( G \) for which the generator \( \gamma \in G \) acts on \( \mathbb{R}^2 \) by a rotation by \( 2\pi/2^{n-j} \).

We also have the one-dimensional sign representation \( \sigma_n = \sigma(G) \), for which the generator acts by multiplication by \( -1 \).

Note that \( \lambda_{n-1} = 2\sigma_n \). There is an isomorphism of underlying abelian groups

\[ JO(G) \cong \mathbb{Z}\{1, \sigma_n, \lambda_0, \ldots, \lambda_{n-2}\} \]

where the equivalence sends \( S^V \) to \( V \).

**Definition 4.2.** For each representation \( V \), there is a homotopy class

\[ a_V : S^0 \to S^V \]

which corresponds to the inclusion of \( S^0 = \{0, \infty\} \). We call this the *Euler class*. If \( V \) is an orientable representation of dimension \( d \), we also get classes

\[ u_V \in \pi_{d-V} H^2 \mathbb{Z}. \]

We call these *orientation classes*.

We have commutative diagrams

\[ \begin{array}{ccc}
S^0 & \xrightarrow{a_{\lambda_i}} & S^{\lambda_i} \\
\downarrow{a_{\lambda_{i+1}}} & & \downarrow{(-)^2} \\
S^{\lambda_{i+1}} & & \\
\end{array} \]

where the vertical arrow is a double cover. Therefore, \( a_{\lambda_i} \) divides \( a_{\lambda_{i+1}} \) for each \( 0 \leq i \leq n-2 \).
4.2. Localizations and isotropy separation.

**Definition 4.3.** For each $0 \leq i \leq n - 1$, we have families
\[ F_i = F[H_{2i+1}] = \{ H \mid H \subseteq C_{2i+1} \} \]
and $F_n = \mathbb{A}ll$ be the family of all subgroups of $G$.

These families interpolate between $F_0$ and $F_n$ be the family of all subgroups of $G$.

The universal and couniversal spaces for the family $F_i$ can be written in very algebraic terms.

**Proposition 4.4.** For $0 \leq i \leq n - 1$, we have
\[ E_{2}^{s,t} \simeq \lim_{\to} S(k\lambda_i) = S(x\lambda_i) \]
and
\[ \tilde{E}_{2}^{s,t} \simeq S^x\lambda_i = S^0[a^{-1}_{\lambda_i}] \].

**Proof.** The representation $\lambda_i$ has kernel exactly $C_{2i} \subset G$, and the residual action of $G/C_{2i}$ is faithful. The result follows.

We now state two results of Meier–Shi–Zeng that we will use later.

**Theorem 4.5 (Meier–Shi–Zeng \[36\]).** For $X$ a $G$-spectrum with regular slice tower $P^*X$, the spectral sequence associated to the tower $E_{i}F_i \wedge P^*X$, which corresponds to the $a_{\lambda_i}$-localized spectral sequence
\[ a_{\lambda_i}^{-1}E_{2}^{s,t+\alpha} = a_{\lambda_i}^{-1} \pi_{t-s+\alpha}^G P_t^i X \rightarrow \pi_{t-s+\alpha}^G(a_{\lambda_i}^{-1}X), \quad \alpha \in JO(G) \]
converges strongly.

**Theorem 4.6 (Meier–Shi–Zeng \[35\]).** Let $X$ be a $(-1)$-connected $G$-spectrum. Let $L_i$ be the line of slope $(2^i - 1)$ through the origin. The following statements hold:

1. On the integer graded page, the map from the slice spectral sequence of $X$ to the $a_{\lambda_i}$-localized slice spectral sequence of $X$ induces an isomorphism on the $E_2$-page for the classes above $L_i$, and a surjection for the classes that are on $L_i$.

2. The map of spectral sequences above induces an isomorphism between differentials that originate from classes that are on or above $L_i$.

In what follows, we will compute heavily with localized slice spectral sequences. The following remark explains the advantages of this approach.

**Remark 4.7.** It follows from Theorem 4.6 that all the differentials in the slice spectral sequence of $X$ that are on or above $L_i$ can be immediately recovered from the $a_{\lambda_i}$-localized slice spectral sequence of $X$ by truncating off the latter spectral sequence below $L_i$. In particular, all the differentials in the slice spectral sequence of $X$ can be recovered by truncating off the $a_{\sigma_n}$-inverted slice spectral sequence below the horizontal line $s = 0$.

In addition, the $a_{\lambda_i}$-localized slice spectral sequence are individually easier to compute that the non-localized spectral sequences. Of course, by localizing, we loose the information below the line $L_i$, but the approach is to work inductively, starting with the $a_{\lambda_{n-1}}$-localization (which is the same as the $a_{\sigma_n}$-localization) and ending with the $a_{\lambda_0}$-localization. As we explained above, all differentials can be recovered from the $a_{\lambda_0}$ localization so that at that stage, we have not actually lost any information at all.
One final remark on the advantage of computing with the $a_{\lambda_i}$-localized spectral sequence is that it actually records information about the slice spectral sequences

$$E_2^{s,t} = \pi_{t-s-t}^G P^t X \Rightarrow \pi_{t-s-t}^G X$$

for any $\ast = k\lambda_0$ where $k \in \mathbb{Z}$. Indeed, we can recover all the differentials in the $s + k\lambda_0$-graded spectral sequence by truncating the $a_{\lambda_i}$-localized spectral sequence below the horizontal line $s = -2k$. So, the localized spectral sequence contains much more information than simply the integer graded spectral sequence.

5. **C_{2^n}-GEOMETRIC FIXED POINTS AND QUOTIENTS OF BP^{(G)}**

As a proof-of-concept and for later computations, in this section, we will compute the homotopy of the geometric fixed points

$$\Phi^G(BP^{(G)}/G \cdot \bar{S}) \simeq (\tilde{E}\mathcal{P} \wedge BP^{(G)}/G \cdot \bar{S})^G \simeq (a^{-1}_\sigma BP^{(G)}/G \cdot \bar{S})^G$$

of quotients by permutation summands via the $a_{\lambda_i}$-localized slice spectral sequence.

On the one hand, we know the answer, since we know the homotopy type of the geometric fixed points.

**Proposition 5.1.** We have a weak-equivalence of $H\mathbb{F}_2$-modules

$$\Phi^G(BP^{(G)}/G \cdot \bar{S}) \simeq H\mathbb{F}_2 \wedge \Sigma_{\mathbb{Z}}^\infty \left( \prod_{j \in J} S^j \right).$$

**Proof.** The geometric fixed points functor is strong symmetric monoidal, and we have

$$\Phi^G(BP^{(G)}) = H\mathbb{F}_2. \quad \square$$

On the other hand, the $a_\sigma$-localization map of the slice spectral has a particular simple target, and this will tell us a great deal about any of the slice spectral sequences for these quotients.

5.1. **General quotients of BP^{(G)}**. We now consider the $a_\sigma$-localized slice spectral sequence

$$a^{-1}_\sigma E_2^{s,t} := a^{-1}_\sigma \pi_{t-s-t}^G P^t (BP^{(G)}/G \cdot \bar{S}) \Rightarrow \pi_{t-s-t}^G (BP^{(G)}/G \cdot \bar{S}).$$

Inverting $a_\sigma$ has the effect of killing the transfer from any proper subgroups. This means that the $E_2$-page of the $a_\sigma$-localized slice spectral sequence has a particular simple form:

$$a^{-1}_\sigma E_2^{s,t} \ast = \mathbb{F}_2[N^G_{C_2} \bar{s}_i | i \notin J][u_{2\sigma}, a^i_{\lambda_0}, a^i_{\lambda_1}, \ldots, a^i_{\lambda_{n-2}}].$$

**Definition 5.2.** For each $j \in \mathbb{N}$, let

$$\bar{f}_j = a^{2j-1}_{\bar{p}} N^G_{C_2} \bar{s}_j.$$  

This definition a priori depends heavily on the choices of the $\bar{s}_i$. However, from the point of view of differentials, these choices will not matter, due to a small lemma.

**Lemma 5.3.** Let $\bar{s}_{2^{m-1}}$ be any element in degree $(2^m - 1)p_2$ that generates a permutation summand. We have

$$N^G_{C_2} \bar{s}_{2^{m-1}} \equiv N^G_{C_2} \bar{v}_m \mod (N^G_{C_2} \bar{v}_1, \ldots, N^G_{C_2} \bar{v}_{m-1}) + \text{Im}(\text{tr}),$$

where $\text{Im}(\text{tr})$ denotes the image of the transfer.

In particular, $\bar{f}_i$ is independent of the choice of $\bar{s}_i$, modulo the lower $\bar{v}_j$. 

Proof. We have

\[ \pi_{\ast\rho_2}^G(BP^{(G)})/\text{Im}(tr) \cong \mathbb{F}_2[N_{C_2}^G\tilde{v}_1^G, N_{C_2}^G\tilde{v}_2^G, \ldots], \]

and the map

\[ x \mapsto N_{C_2}^G x \]

gives a ring homomorphism

\[ \pi_{\ast\rho_2}^G(BP^{(G)}) \to \pi_{\ast\rho_2}^G(BP^{(G)})/\text{Im}(tr). \]

Additionally, Weyl equivariance of the norm shows that for any \( \gamma \in G, \)

\[ N_{C_2}^G(\gamma x) = \gamma N_{C_2}^G(x) \equiv N_{C_2}^G(x) \mod \text{Im}(tr). \]

The lemma can be restated as saying that for any generator

\[ \bar{s}_{2m-1} \in Q(2m-1)\rho_2(\pi_{\ast\rho_2}^G(BP^{(G)})), \]

we have

\[ N_{C_2}^G \bar{s}_{2m-1} = N_{C_2}^G \bar{v}_m \in Q(2m-1)\rho_2(\mathbb{F}_2[N_{C_2}^G\tilde{v}_1^G, \ldots]). \]

The above argument shows that the norm is a Weyl-equivariant ring homomorphism, and hence it induces a linear map

\[ \left(Q(2m-1)\rho_2(\pi_{\ast\rho_2}^G(BP^{(G)}))\right)_G \to Q(2m-1)\rho_2(\mathbb{F}_2[N_{C_2}^G\tilde{v}_1^G, \ldots]). \]

Both the source and target are isomorphic to \( \mathbb{F}_2, \) and choosing \( \bar{v}_m^G \) as the generator of the source shows the map to be non-zero. It is therefore non-zero on any generator for the source.

Corollary 5.4. The \( E_2 \)-term for the \( a_\sigma \)-localized slice spectral sequence for \( BP^{(G)} \)
is given by

\[ \mathbb{F}_2[a_{\sigma}^{\pm 1}, a_{\lambda_{n-2}}^{\pm 1}, \ldots, a_{\lambda_0}^{\pm 1}][b, \tilde{f}_1, \ldots], \]

where the bidegree of \( \tilde{f}_i \) is \((2^i - 1, (2^n - 1)(2^i - 1))\) and where the bidegree of

\[ b = u_{2\sigma}/a_{\sigma}^2 \]

is \((2, -2)\).

Corollary 5.5. For any \( \tilde{S} \), the \( a_\sigma \)-localized slice spectral sequence for \( BP^{(G)}/G \cdot \tilde{S} \)
is a module over that for \( BP^{(G)} \), and the \( E_2 \)-term is the quotient

\[ \mathbb{F}_2[a_{\sigma}^{\pm 1}, a_{\lambda_{n-2}}^{\pm 1}, \ldots, a_{\lambda_0}^{\pm 1}][b, \tilde{f}_1, \ldots]/(\tilde{f}_j | j \in J) \]

We start with examining the \( a_\sigma \)-localized slice spectral sequence for \( BP^{(G)} \), since all other cases are modules over this.

Proposition 5.6. Let \( \bar{s}_i \) for \( i \in \mathbb{N} \) be any choice of permutation summand generators for \( \pi_{\ast\rho_2}^G(BP^{(G)}). \)

Then in the \( a_\sigma \)-localized slice spectral sequence for \( BP^{(G)} \), the differentials are determined by

\[ d_{\ell(k)}(b^k) = \tilde{f}_{k+1}, \quad \ell(k) := 2^n(2^{k+1} - 1) + 1, \quad k \geq 0. \]

Proof. Lemma 5.3 shows that

\[ \tilde{f}_j = a_\rho^{(2^j-1)} N_{C_2}^G \tilde{v}_j^G \]

modulo the earlier generators \( \tilde{f}_i \) with \( i < j \), so the Slice Differentials Theorem of
[19] implies that we have the differentials (5.1).
Remark 5.7. The $\tilde{f}_i$ all lie on the line of slope $2^n - 1$ through the origin in the $(t-s, s)$-plane. This is a vanishing line for both the spectral sequence of $a_\sigma^{-1} BP^{(G)}$ and that of quotient by permutation summands, so the differential in $E_1^{0,1}$ is the last possible on $b^{2^n}$.

We next use this result to study the $a_\sigma$-localized slice spectral sequence of other quotients.

Definition 5.8. Let $A(J)$ be the set of non-negative integers $r$ such that the dyadic expansion $r = \varepsilon_0 + \varepsilon_1 \cdot 2 + \varepsilon_2 \cdot 4 + \ldots$ satisfies $\varepsilon_i = 0$ if $i + 1 \notin J$.

Theorem 5.9. The $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1} (BP^{(G)}/G \cdot \tilde{S})$ can be completely described as follows:

1. the only non-trivial differentials are of lengths $\ell(k) = 2^n (2^{k+1} - 1) + 1$ for some $k \geq 0$.
2. The $E_{\ell(k)}$-page is the module over

\[ \mathbb{F}_2[f_i \mid i \geq k + 1 \text{ and } i \notin J][b^{2^k}] \]

generated by the set of permanent cycles $b^r$ where $0 \leq r < 2^k$ and $r \in A(J)$.
3. If $k + 1 \notin J$, then there are non-trivial differentials are multiples of

\[ d_{\ell(k)}(b^{2^k}) = \tilde{f}_{k+1} \]

by the $d_{\ell(k)}$-cycles

\[ \mathbb{F}_2[f_i \mid i \geq k + 1 \text{ and } i \notin J][b^{2^{k+1}}][b^r \mid r < 2^k \text{ and } r \in A(J)]. \]

There are no other differentials of that length.
4. If $k + 1 \in J$, then $E_{\ell(k)} = E_{\ell(k)}$.
5. Consequently, $E_\infty \cong \mathbb{F}_2 \{b^r \mid r \in A(J)\}$.

Proof. We will prove the statements by induction on $k$. For the base case when $k = 0$, we have $\ell(0) = 2^n + 1$. The first possible non-trivial differential by sparseness is $d_{\ell(0)}(b) = \tilde{f}_1$. Therefore, $E_{\ell(0)} = E_2$ and the class $b^0$ is a permanent cycle. The claims hold.

Now, suppose that the $E_{\ell(k)}$-page is as claimed. If $k + 1 \in J$, then $b^{2^k}$ is a $d_{\ell(k)}$-cycle, and hence a permanent cycle. Any element on the $E_{\ell(k)}$-page of the form $b^r$ with $r < 2^{k+1}$ is of the form $r' + \varepsilon_k \cdot 2^k$ for $r' < 2^k$ with $r' \in A(J)$ and $\varepsilon_k \in \{0, 1\}$. Since $k + 1 \notin J$, $r \in A(J)$. Using the module structure over the $a_\sigma$-localized spectral sequence of $a_\sigma^{-1} BP^{(G)}$, the elements $b^r$ are also $d_{\ell(k)}$-cycles. By sparseness of the $E_{\ell(k)}$-page, it is impossible for $b^r$ to support a differential of length longer than $\ell(k)$ because there are no possible targets. Therefore, the elements $b^r$ are permanent cycles. This implies that $E_{\ell(k)} = E_{\ell(k+1)}$ which proves our claims when $k + 1 \in J$.

On the other hand, if $k + 1 \notin J$, we have a non-trivial differential $d_{\ell(k)}(b^{2^k}) = \tilde{f}_{k+1}$. For $\alpha \geq 1$, consider the element $\tilde{f}_i f_{k+1}^{2^t} b^{r+2^t}$ with $0 \leq r < 2^k$, $t \geq 0$ even, and $f$ a monomial in the $\tilde{f}_i$’s for $i > k + 1$ and $i \notin J$. Such an element is the target of the $d_{\ell(k)}$-differential on $f f_{k+1}^{2^t} b^{r+2^t}$. It follows that the $E_{\ell(k)+1}$-page is a polynomial algebra over

\[ \mathbb{F}_2[f_i \mid i \geq k + 2 \text{ and } i \notin J][b^{2^{k+1}}] \]

generated by the already established permanent cycles $b^r$, $r < 2^k$. Since $k + 1 \notin J$, the set $\{r \in A(J) \mid r < 2^{k+1}\}$ is equal to $\{r \in A(J) \mid r < 2^k\}$. This completes the induction step. □
Theorem 5.10. In the integer graded slice spectral sequence

\[ E_2^{t} = \pi_1^G BP^{(G)} / G \cdot \bar{S} \Rightarrow \pi_{t-s}^G BP^{(G)} / G \cdot \bar{S}, \]

we have:

1. Above the line of slope \(2^n - 1\), the \(E_2\)-page is isomorphic to the integer graded part of the \(E_2\)-page of the \(a_\sigma\)-localization of the spectral sequence, as described in Corollary 5.5.

2. The only non-trivial differentials whose sources lie on or above the line of slope \(2^n - 1\) are in one-to-one correspondence with the non-trivial differentials of the integer graded \(a_\sigma\)-localized slice spectral sequence above this line. They are of lengths \(t(k)\) for \(k \neq J\), and are generated under the module structure of the spectral sequence for \(BP^{(G)}\) by the differentials

\[ d_{t(k)}(v_k^{2^k}) = a_\sigma^{k+1} a_\rho^{k+1} - 1 a_\sigma \bar{s}_{2^{k+1} - 1} \]

for \(k + 1 \neq J\).

We will now give some examples to illustrate the results above. We start with example for the group \(G = C_2\). Since \(\bar{v}_2 \equiv \bar{v}_k - 1\) modulo the previous \(v_j\)’s, we write \(\bar{v}_k - 1 = \bar{s}_{2^k - 1}\), but any choice of permutation summand generators gives the same results.

Example 5.11. Consider \(BP_2/\bar{S}\) for \(\bar{S} = \{\bar{s}_{2^r - 1} \mid j \in J\}\). The \(E_2\)-page are the \(a_\sigma\)-localized slice spectral sequence is

\[ a_\sigma^{-1} E_2^{2,\ast} = \mathbb{F}_2[\bar{v}_i \mid i \notin J][u_{2^r}, a_\sigma^{\pm 1}], \]

the non-trivial differentials are generated by \(d_{2^k - 1}(b^k) = f_{k+1}\) and

\[ E_2^{2,\ast} \cong \mathbb{F}_2[a_\sigma^{\pm 1}][b^r \mid r \in A(J)]. \]

Figure 1 shows the example for \(BP_2(2)\).

In this case, using Theorem 4.6 as in Theorem 5.10 together with the fact that the \(a_\sigma\)-localized spectral sequence records information about many \(JO(C_2)\) degrees of the slices spectral sequence (as noted in Remark 4.7), we can easily describe a large part of the (unlocalized) \(JO(C_2)\)-graded slice spectral sequence of \(BP_2/\bar{S}\).

Corollary 5.12. Let \(JO(C_2)^+ \subseteq JO(C_2)\) be the elements of the form \(a + b\sigma\) with \(a - b \geq 0\). The \(JO(C_2)^+\) graded slice \(E_2\)-page of \(BP_2/\bar{S}\) is

\[ E_2^{2,\ast} \cong \mathbb{Z}_2[\bar{v}_i \mid i \notin J][u_{2^r}, a_\sigma]/(2a_\sigma), \quad \ast \in JO(C_2)^+. \]

1. The only non-trivial differentials are of lengths \((2^k + 2 - 1)\) for some \(k \geq 0\).
2. If \(k + 1 \neq J\), then the nontrivial differentials are multiples of

\[ d_{2^k - 1}(u_{2^r}) = \bar{v}_{k+1} u_{2^r} a_\sigma^{2^k - 1}, \quad r \in A(J) \]

by the \(d_{2^k - 1}\)-cycles \(\mathbb{F}_2[\bar{v}_i, a_\sigma \mid i \geq k + 1 \text{ and } i \notin J]\).
3. If \(k + 1 \in J\), then \(E_{2^k - 1} = E_{2^k - 1}.\)
4. Consequently, the \(E_\infty\)-page is

\[ E_\infty^{2,\ast} \cong \mathbb{Z}_2[\bar{v}_i \mid i \notin J][a_\sigma]/(2a_\sigma, \bar{v}_i a_\sigma^{2^r - 1})[u_{2^r}, 2u_{2^r} \mid r \in A(J), s \notin A(J)]. \]
The $a_{\sigma}$-localized slice spectral sequence of $a_{\sigma}^{-1}BP_{2}\langle 2 \rangle$ in integer degrees. The slice spectral sequence of $BP_{2}\langle 2 \rangle$ is obtained by removing the region below the horizontal line $s = 0$ and replacing $\bullet = \mathbb{Z}/2$ by copies of $\mathbb{Z}$, which reintroduces the transfers.

As an explicit example, we show the computation of the slice spectral sequences of $BP_{2}\langle 2, 2 \rangle$, deduced from that of $a_{\sigma}^{-1}BP_{2}\langle 2, 2 \rangle$. The computation is illustrated in Figure 2.

**Remark 5.13.** On the $E_{\infty}$-page of $BP_{2}\langle 2, 2 \rangle$ (the third picture of Figure 2), there is an exotic extension $\eta = \bar{v}_{1}a_{\sigma}$, as shown by the dashed line. This extension follows from the work in [8]. More precisely, letting $(n, k, b) = (2, 1, 0)$ in Corollary 3.11 of [8] gives the exotic $\pi_{*}MU_{2}$-multiplication $\bar{v}_{1}u_{2\sigma} = \bar{v}_{2}a_{2}^{4}$. It follows that

$$(\bar{v}_{2}a_{\sigma}u_{2\sigma}) \cdot (\bar{v}_{1}a_{\sigma}) = (\bar{v}_{2}a_{2\sigma}) \cdot (\bar{v}_{1}u_{2\sigma}) = (\bar{v}_{2}a_{2\sigma}) \cdot (\bar{v}_{2}a_{4\sigma}) = \bar{v}_{2}^{2}a_{\sigma}^{6}.$$ 

For the next two examples, the group $G = C_{4}$ with generators $\bar{s}_{2j-1} = \bar{v}_{j}^{\sigma}$, but any choice of permutation summand generators gives the same results.

**Example 5.14.** Consider $BP^{(C_{4})}\langle 2 \rangle$, so that $J = \{j \in \mathbb{N} \mid j > 2\}$. The $E_{2}$-page are the $a_{\sigma}$-localized slice spectral sequence is

$$a_{\sigma}^{-1}E_{2}^{\bullet, \bullet} \cong F_{2}[\bar{f}_{1}, \bar{f}_{2}, b].$$

The spectral sequence has two types of differentials, namely

$$d_{5}(b) = \bar{f}_{1}, \quad \text{and} \quad d_{13}(b^{2}) = \bar{f}_{2}. $$

The class $b^{4}$ is a permanent cycle, and we have

$$\pi_{*}^{C_{4}}a_{\sigma}^{-1}BP^{(C_{4})}\langle 2 \rangle \cong F_{2}[b^{4}].$$

The computation is illustrated in Figure 3.

**Example 5.15.** Consider $BP^{(C_{4})}\langle 2, 2 \rangle$. In this case, the $E_{2}$-page are the $a_{\sigma}$-localized slice spectral sequence is

$$a_{\sigma}^{-1}E_{2}^{\bullet, \bullet} = F_{2}[\bar{f}_{2}, b].$$
There is only one family of differentials, generated by
\[ d_{13}(b^2) = f_2 \]
and the answer is
\[ \pi_* a_{-1}BP_{\mathbb{R}}<2, 2> \cong \mathbb{F}_2[b^2]\{1, b\} . \]
The computation is illustrated in Figure 4.

5.2. Application: Multiplicative structure. While the left action of \( MU^{(G)}\) on itself always endows \( MU^{(G)}/G \cdot \tilde{S} \) with a canonical \( MU^{(G)}\)-module structure, and the same is true with \( BP^{(G)}\) instead, much less is known for ring structures.
We do have the following restrictive condition on quotients as a straightforward consequence of the techniques introduced above.

**Proposition 5.16.** Let \( J \subseteq \mathbb{N} \) and \( \bar{S} = \{ \hat{s}_{2j-1} \mid j \in J \} \) be a set of generators for permutation summands. If there is a \( k \in J \) such that \( (k+1) \notin J \), then \( BP^{(G)}/G \cdot \bar{S} \) does not have a ring structure in the homotopy category.

**Proof.** If there is a ring structure on \( BP^{(G)}/G \cdot \bar{S} \), then the map \( BP^{(G)}/G \cdot \bar{S} \to H\mathbb{Z} \) to the zero slice induces a map of multiplicative spectral sequences. This remains true after inverting \( a_\sigma \). Since \( \pi^G_*(a_\sigma^{-1}H\mathbb{Z}) \cong \mathbb{F}_2[b] \) and the map from \( \pi^G_*(a_\sigma^{-1}BP^{(G)}/G \cdot \bar{S}) \) to \( \pi^G_*(a_\sigma^{-1}H\mathbb{Z}) \) is the natural inclusion, the former is a subring of the latter. However, if \( k \in J \) and \( k + 1 \notin J \), then \( b^2k \) is nonzero in \( \pi^G_*(a_\sigma^{-1}BP^{(G)}/G \cdot \bar{S}) \), but its square \( b^4k \) is zero. This is a contradiction. \( \square \)

Put another way, Proposition 5.16 says that the only possible \( BP^{(G)} \)-module quotients \( BP^{(G)}/G \cdot \bar{S} \) by permutation summands which could be rings are the forms of \( BP^{(G)}(m) \). Even here, we know very little.

**Example 5.17.** For \( G = C_2 \), \( BP_{k_2}(1) = k_2 \) and \( tmf_1(3) \) is a form of \( BP_{k_2}(2) \). Both admit commutative ring structures. For \( m > 2 \) we do not know if \( BP_{k_2}(m) \) admits an associative ring structure.

For \( G = C_4 \), \( tmf_1(5) \) is a form of \( BP^{(C_4)}(1) \). For \( m > 1 \), we do not know if \( BP^{(C_4)}(m) \) admits even an associative ring structure.

If we instead look only at the underlying spectrum, then work of Angeltveit and of Robinson shows that we have nice ring structures [1][41]. This has been
refined by Hahn–Wilson to show that this is still true in the category of $MU^{((G))}$ or $BP^{((G))}$-modules \[16\].

**Proposition 5.18.** For any $J \subseteq \mathbb{N}$ and for any $\tilde{S}$, the spectrum 
\[ i^*_{e}BP^{((G))}/G \cdot \tilde{S} \]

is an associative $i^*_{e}BP^{((G))}$-algebra spectrum.

**Proof.** The assumptions on $\tilde{S}$ ensure that the sequence 
\[ (\gamma^i \tilde{s}_j \mid 0 \leq i \leq 2^{n-1} - 1, j \in J) \]

forms a regular sequence in the homotopy groups of the even spectrum $i^*_{e}BP^{((G))}$. The result follows from [16, Theorem A].

**Remark 5.19.** The Hahn–Shi Real orientation shows the restriction to $C_2$ of the spectrum $BP^{((G))}/G \cdot \tilde{S}$ always admits an $E_{\sigma}$-algebra structure \[15\].

6. The $C_{2n-1}$-geometric fixed points

Let $G' = C_{2n-1}$, the subgroup of index two in $G = C_{2n}$. We extend the results of the previous section slightly, considering the $a_{\lambda_{n-2}}$-localized slice spectral sequence for permutation quotients. This is again a spectral sequence of Mackey functors, now essentially for $C_4 \cong G/C_{2n-2}$. In this section, we study the $C_2 \cong G'/C_{2n-2}$-equivariant level, since we can tell an increasingly complete story here. The $C_4$-fixed points are more subtle, as we will see in Section \[7\].

---

**Figure 4.** The $a_\sigma$-localized slice spectral sequence of $a^{-1}_\sigma BP^{((C_4))}/(2,2)$.
Note that since
\[ i_G^* \lambda_{n-2} = \lambda_{(n-1)-1} = 2\sigma, \]
the restriction to \( G' \) of the \( a_{n-2} \)-localized slice spectral sequence for \( BP^{(G)}/G \cdot \tilde{S} \)
is the \( a_{\sigma} \)-localized slice spectral sequence for
\[ i_G^* BP^{(G)}/G \cdot \tilde{S}. \]
Just as for the \( G \)-geometric fixed points, we start by identifying the homotopy type.
In this case, since
\[ i_G^* \lambda_{n-2} = \lambda_{2} \]
we have
\[ \Phi^G BP^{(G)} \cong BP^{((G'))} \land BP^{((G'))}, \]
and all of the geometric fixed points we consider will take place in the category of modules over
\[ A = HF_2 \land HF_2. \]
Composing with the localization map
\[ i_G^* BP^{(G)} \to \tilde{E}P \land i_G^* BP^{(G)}, \]
the element \( N_{C_2} \hat{s}_i \) gives us a polynomial in the dual Steenrod algebra.

**Definition 6.1.** Let \( g_i \in \pi_i A \) be the image of \( N_{C_2} \hat{g}_i \).

Note that the residual \( C_2 \cong G'/C_{2n-2} \)-action interchanges
\[ N_{C_2} \hat{s}_i \text{ and } \gamma N_{C_2} \hat{s}_i, \]
while acting as the conjugation in the dual Steenrod algebra.

**Lemma 6.2.** The \( G' \)-geometric fixed points of \( BP^{(G)}/G \cdot \tilde{S} \) are the \( A \)-module
\[ A/(g_i, \hat{g}_i \mid i \in J). \]

In general, the homotopy type of this module very heavily depends on the choices of generators. We have several cases where we can explicitly identify the images, however. Using [19 Proposition 2.57] and [36 Proposition 6.2], we see that for Hill–Hopkins–Ravenel generators \( v^G_i \) of \( BP^{(G)} \), the \( G' \)-geometric fixed points of their norms satisfies
\[ \xi_i = \Phi^G N_{C_2} v^G_i \]
\[ \zeta_i = \Phi^G N_{C_2} \gamma v^G_i, \]
where \( \xi_i \) are the Milnor generators of the mod 2 dual Steenrod algebra, and \( \zeta_i \) are their dual.

**6.1. Forms of \( BP^{(G)}\langle k, m \rangle \).** We can get much more explicit answers for the geometric fixed points with certain forms of \( BP^{(G)}\langle k, m \rangle \), since here we can identify the geometric fixed points of the norms exactly.

**Corollary 6.3.** The \( G' \)-geometric fixed points of \( BP^{(G)}\langle k, m \rangle \) are given by the \( A \)-module
\[ A/(\xi_i, \zeta_i \mid i < k \text{ or } i > m) \cong A/(\xi_i, \zeta_i \mid i < k) \land A/(\xi_j, \zeta_j \mid j > m). \]

Writing this module in several ways makes working with this easier, as we can connect this with a series of modules and computations studied in [6].
Definition 6.4. For any subset $I$ of the natural numbers, let

$$M_I = \bigcap_{i \in I} A/(\xi_i)$$

and

$$\overline{M}_I = \bigcap_{i \in I} A/(\xi_i).$$

Let

$$R_k = \text{End}_A(M_{\{1,...,k-1\}})$$

and let

$$A\langle m \rangle = M_{\{m+1,m+2,...\}}.$$

As the endomorphisms of a module, $R_k$ is always an associative algebra. By [6], for any $m$, $A\langle m \rangle$ and $\overline{A}\langle m \rangle$ are associative algebras as well. More surprisingly, by [6, ], we have

$$R_k \simeq \Sigma M_{\{1,...,k-1\}} \wedge \overline{M}_{\{1,...,k-1\}},$$

which allows us to rewrite $\Phi^G BP^{(G)}\langle k, m \rangle$.

Corollary 6.5. For any $k \leq m$, we have

$$\Phi^G BP^{(G)}\langle k, m \rangle \simeq \Sigma R_k \wedge A\langle m \rangle \wedge \overline{A}\langle m \rangle,$$

the suspension of an associative $A$-algebra.

The extreme case of this is $BP^{(G)}\langle m, m \rangle$.

Corollary 6.6. The $G'$-geometric fixed points of $BP^{(G)}\langle m, m \rangle$ are given by the $A$-module

$$\Sigma R_m \wedge A\langle m \rangle \wedge \overline{A}\langle m \rangle.$$

The homotopy of this $A$-module is more complicated than one might have initially expected. These kinds of modules were studied by the authors [6], where we used a Baker–Lazarev style Adams spectral sequence based on $HF_2$-homology, but in the category of $A$-modules [3]. A remarkable feature of the case of $BP^{(G)}\langle m, m \rangle$ is that this relative Adams spectral sequence completely determines the $a_\sigma$-localized slice spectral sequence.

6.2. A comparison of spectral sequences. Let $P_* = P_* BP^{(G)}\langle m, m \rangle$ be the slice covering tower of $BP^{(G)}\langle m, m \rangle$. That is, $P_t$ is the homotopy fibre of the canonical map

$$BP^{(G)}\langle m, m \rangle \to P_{t-1}BP^{(G)}\langle m, m \rangle$$

where $P_* = P_* BP^{(G)}\langle m, m \rangle$ is the regular slice tower.

The slices $P_t BP^{(G)}\langle m, m \rangle$ are non-trivial only in dimensions of the form $t = 2i(2^m - 1)$. Therefore we can “speed-up” the slice tower without losing any information. Define

$$\tilde{P}_t = P_{2i(2^m - 1)}.$$

This re-indexes the slice tower, so that

$$\tilde{P}_t = P_{2i(2^m - 1)} BP^{(G)}\langle m, m \rangle.$$

Since there is an equivalence

$$\Phi^G BP^{(G)} \simeq HF_2 \wedge HF_2 = A,$$

$\Phi^G \tilde{P}_*$ is a covering tower converging to $\Phi^G BP^{(G)}\langle m, m \rangle$ in the category of $A$-modules.
Theorem 6.7. The tower \( \Phi G \hat{P} \Phi G^n BP^{(G)} \langle m, m \rangle \) is an \( HF_2 \)-Adams resolution of \( \Phi G^n BP^{(G)} \langle m, m \rangle \) in the category of \( A \)-modules.

Proof. Let \( Q_i = \Phi G^n \hat{P} \Phi G^n BP^{(G)} \langle m, m \rangle \) for convenience. Then \( Q_i \) is an \( HF_2 \)-Adams resolution of \( Q_0 = \Phi G^n BP^{(G)} \langle m, m \rangle \) in \( A \)-modules if the following conditions are met for each \( i \geq 0 \) [19, Def. 2.2.1.3]:

1. \( Q_i \) is a wedge of suspensions of \( HF_2 \)-s, and
2. the map \( Q_i \to Q_i' \) is monomorphic in \( HF_2 \)-homology.

We now verify the first condition. By definition,

\[
Q_0^0 = \Phi G^n P_0^n BP^{(G)} \langle m, m \rangle = \Phi G^n H^m = HF_2 \langle b \rangle,
\]

with \( A \)-module structure defined by the geometric fixed points of the reduction map \( BP^{(G)} \to H^m \). By [19, Prop. 7.6], for each \( i, \pi^G_i, \) and its conjugate \( \gamma \pi^G_i \) act trivially on \( H^m \), thus the geometric fixed points of \( N_{G_2} \pi^G_i \) and \( N_{G_2} \gamma \pi^G_i \), which are \( \xi_i \) and \( \zeta_i \), act trivially on \( HF_2 \langle b \rangle \). Therefore, as an \( A \)-module, \( Q_0^0 \cong \bigvee_{j=0}^{\infty} \Sigma^{2j} HF_2 \). The Slice Theorem [19, Thm. 6.1] implies that for \( i > 0 \), \( Q_i^0 \) is a wedge of suspensions of \( Q_0^0 \), thus the first condition is met.

We verify the second condition by an alternative construction of the slice covering tower of \( BP^{(G)} \langle m, m \rangle \). As in [19, §6], let \( R = \mathbb{S}[G : \pi^G_m] \) be the homotopy refinement of \( BP^{(G)} \langle m, m \rangle \), and \( M_i \) be the subcomplex of \( R \) consisting of spheres of dimension \( \geq 2(2m - 1) \). The arguments in [19, §6.1] tell us that

\[
\hat{P}_i \cong \Phi G^n BP^{(G)} \langle m, m \rangle \wedge_R M_i.
\]

Notice that \( G' \)-equivariantly, \( M_{i+1} \subset M_i \) is the sub \( R \)-module \( \langle \pi^G_m, \gamma \pi^G_m \rangle M_i \), thus the quotient \( M_i/M_{i+1} \) is equivalent to \( M_i/(\pi^G_m, \gamma \pi^G_m)M_i \). Taking the \( G' \)-geometric fixed points on the cofibration

\[
BP^{(G)} \langle m, m \rangle \wedge_R M_{i+1} \to BP^{(G)} \langle m, m \rangle \wedge_R M_i \to BP^{(G)} \langle m, m \rangle \wedge_R M_i/M_{i+1},
\]

we obtain the cofibration

\[
Q_{i+1} \to Q_i \to Q_i' \cong Q_i/(\xi_m, \zeta_m)Q_i
\]

because \( \Phi G^n N_{G_2} \pi^G_m = \xi_m \) and \( \Phi G^n N_{G_2} \gamma \pi^G_m = \zeta_m \). Since \( \xi_m \) and \( \zeta_m \) have trivial image under \( A \to HF_2 \), the map \( Q_i \to Q_i' \) induces a monomorphism in \( HF_2 \)-homology. \( \square \)

Corollary 6.8. We have an isomorphism of spectral sequences between the relative Adams spectral sequence for \( A/\langle \xi_i, n \rangle | i \neq m \rangle \) and the speeded-up \( a_{\sigma} \)-localized slice spectral sequence for \( i^*_{G} BP^{(G)} \langle m, m \rangle \).

The dictionary here can be a little confusing, due to the scaling in the slice filtration. We record the un-scaled version here:

Remark 6.9. A relative Adams \( d_r \) corresponds to an ordinary \( a_{\sigma} \)-localized slice differential \( d_{2(2m-1)r+1} \).

Corollary 6.10. The integer graded \( E_{2m+1} \)-page of the \( G' \)-equivariant \( a_{\sigma} \)-localized slice spectral sequence of \( i^*_{G} BP^{(G)} \langle m, m \rangle \) computing \( \pi^G_{m} a_{\sigma}^{-1} i^*_{G} BP^{(G)} \langle m, m \rangle \) is isomorphic to the \( E_2 \)-page of the relative Adams spectral sequence of the spectrum \( \Phi G^n i^*_{G} BP^{(G)} \langle m, m \rangle \).
6.3. The Relative Adams spectral sequence for $\Phi^{G'}\iota^*_G BP^{[G]}\langle m, m \rangle$. By Corollary 6.6, the $G'$-geometric fixed points of $BP^{[G]}\langle m, m \rangle$ are a suspension of an associative ring spectrum. Because of this, we instead work with the associative algebra, since then the spectral sequence will be one of associative algebras.

One of the most surprising results from [6] was a decomposition of $A\langle m \rangle$, and hence of further quotients, into simpler, finite pieces. This makes our computations even easier.

**Definition 6.11.** For each $m \geq 1$, let

$$\tilde{A}(m) = A(m) \wedge A_{m+1, \ldots, 2m}.$$  

**Proposition 6.12 ([6 Corollary 5.6]).** For each $m$, we have a decomposition of $A(m)$ such that the projection map

$$A(m) \wedge \overline{A}(m) \to \tilde{A}(m)$$

is a map of associative algebras.

This reduces the study of modules of the form

$$M \wedge A(m) \wedge \overline{A}(m)$$

to the study of $\tilde{A}(m)$-modules of the form

$$M \wedge \tilde{A}(m).$$

We apply this in the case of $M = R_m$, where we again have an associative algebra structure.

**Definition 6.14.** Let

$$R(m) = R_m \wedge \tilde{A}(m).$$

By [6], the $E_2$-page of the relative Adams spectral sequence of $R(m)$ is given by

$$\mathbb{F}_2[\xi_1, \ldots, \xi_m, e]/e^{2m} \otimes E(\beta_2, \beta_4, \ldots, \beta_{2m-1})/(\xi_i + \xi_{i+1} \beta_2 | 1 \leq i \leq m - 1),$$

where the bidegrees are given by:

$$|e| = (2^{m+1}, 0)$$

$$|\xi_m| = (2^m - 1, 1)$$

$$|\beta_k| = (-k, 0).$$

Since for $1 \leq i < m$, we have the relation

$$\xi_i = \xi_{i+1} \beta_2,$$

this simplifies as an algebra to

$$\mathbb{F}_2[\xi_m] \otimes E(\beta_2, \beta_4, \ldots, \beta_{2m-1}) \otimes \mathbb{F}_2[e_{2m+1}]/(e_{2m+1}^{2m}).$$
Then

\[ \text{Proof.} \]

Let

for some

and we do not include the proof here.

It follows that

is divisible by

This simplifies to

(6.3)

If

Lemma 6.17. We start with two useful lemmas.

We get elements,

\[ \beta(0), \beta(2), \ldots, \beta(2^m - 2) \]

where \( \beta(\ell) \) has degree \( -\ell \). Note that, as element on the \( E_2 \)-page for \( R\langle m \rangle \), for \( 0 \leq \ell \leq \ell' \)

(6.1)

\[ \beta(\ell) \beta(\ell') = \begin{cases} \beta(\ell') & \ell = 0 \\ \left( (\ell') - 1 \right) \beta(\ell + \ell') & \ell > 0 \end{cases} \]

In [6], we determined a number of differentials in these kinds of relative Adams spectral sequences.

**Proposition 6.16** ([6, Corollary 7.5]). In the relative Adams spectral sequence for \( \tilde{A}\langle m \rangle \), for each \( 1 \leq i \leq m \) and \( n \geq 0 \), we have differentials

\[ d_{1+2^i+1}(e^{2^i+2^{i+1}n}) = \xi_m^{2^i+1} \xi_{i+1} \cdot e^{2^{i+1}n}. \]

The spectrum \( R\langle m \rangle \) is an \( \tilde{A}\langle m \rangle \)-algebra. Therefore, by naturality and the relations on the \( E_2 \)-page, in the relative Adams spectral sequence of \( R\langle m \rangle \) there are differentials

(6.2)

\[ d_{1+2^i+1}(e^{2^i+2^{i+1}n}) = \xi_m^{1+2^i+1} \xi_{i+1} \cdot e^{2^{i+1}n} \beta(2^m - 2^{i+1}) \]

for \( 0 \leq i \leq m - 1 \) and \( 0 \leq n < 2^{m-(i+1)} \), provided that the target survives to the \( E_{1+2^i+1} \)-page. We will see that all other differentials will be determined by these and the multiplicative structure of the spectral sequence.

We start with two useful lemmas.

**Lemma 6.17.** If \( d_{1+2^r}(\beta(\ell)e^k) \) is non-zero, then

\[ d_{1+2^r}(\beta(\ell)e^k) = \xi_m^{1+2^r} \beta(\ell + 2^m - 2r)e^{k-r} \]

for some \( 1 \leq r \leq k \).

**Proof.** Let

\[ d_{1+2^r}(\beta(\ell)e^k) = \xi_m^{1+2^r} \beta(\ell)e^{k'}. \]

Then \( k' \leq k \) so we let \( s \) be a number such that \( k' = k - s \). Note that \( 0 \leq s < 2^m \) and \( 0 < r < 2^m \). Computing degrees, we obtain the equation

(6.3)

\[ 2^{m+1}k - \ell - 1 = (2^m - 1)(1 + 2r) + 2^{m+1}(k - s) - \ell' \]

This simplifies to

\[ -2^m + (\ell' - \ell) + 2r = 2^{m+1}(r - s). \]

Since \( 0 \leq \ell, \ell' \leq 2^m - 2 \), we have

\[ 2 - 2^m \leq \ell' - \ell \leq 2^m - 2. \]

Furthermore, since \( 0 < r < 2^m \), \( 0 < 2r < 2^{m+1} \). Therefore the absolute value of \( -2^m + (\ell' - \ell) + 2r \) is less than \( 2^{m+1} \). The equation above implies that this quantity is divisible by \( 2^{m+1} \). This implies that both sides of the equation must be zero. It follows that \( r = s \) and \( \ell' = \ell + 2^m - 2r \).

The next lemma is a straightforward but annoying exercise analyzing inequalities and we do not include the proof here.
Lemma 6.18. Consider pairs $(\ell, k)$, where $\ell$ is even and $0 \leq \ell, k \leq 2^m - 1$. Define subsets of such pairs by

$$S = \{(\ell, k) : k \leq \ell\}, \quad \text{and} \quad S' = \{(\ell, k) : \ell < k\}$$

as follows. Let $k \leq \ell$. Set

$$j = \max \left\{ 0 \leq r \leq m - 1 : \left( \frac{\ell}{2^r} \right) \equiv 0 \mod 2 \right\},$$

$$i = \min \left\{ j \leq r \leq m - 1 : \left( \frac{k}{2^r} \right) \equiv 0 \mod 2 \right\}.$$

Then letting

$$\phi(\ell, k) = (\ell - (2^m - 2^{i+1}), k + 2^i)$$

gives a bijection $\phi : S \to S'$.

Remark 6.19. If $\ell < k$ and we fix $i \geq 0$, then for $2^i \leq k < 2^{i+1}$ and $\ell - 2^i \leq k < \ell$, if $k$ can be written in the form $k = \kappa + 2^{i+1}n$, then $\phi^{-1}(\ell, k) = (\ell + 2^m - 2^{i+1}, k - 2^i)$. This formulation of the above bijection will be useful for proving the next result.

Theorem 6.20. In the relative Adams spectral sequence of $R(\langle m \rangle)$, for

$$0 \leq k, \ell \leq 2^m - 1$$

with $\ell$ even, we have the following:

1. the class $\beta(\ell)e^k$ is a permanent cycle if and only if $k \leq \ell$;
2. if $\ell < k$, the class $\beta(\ell)e^k$ supports a non-trivial differential, determined as follows. Fix $i \geq 0$. For $2^i \leq k < 2^{i+1}$ and $\ell - 2^i \leq k < \ell$, if $k = \kappa + 2^{i+1}n$, then there is a differential

$$d_{1+2^{i+1}}(\beta(\ell)e^k) = \xi_m^{1+2^{i+1}} \beta(\ell + 2^m - 2^{i+1})e^{k - 2^i}.$$  

These are the only non-trivial differentials.

Proof. This is a multiplicative spectral sequence. At $E_2$-page, there is a vanishing line of slope $1/(2^m - 1)$ with intercept on the $(t-s)$-axis at $2^m - 2$ (the vanishing line is formed by the $\xi_m$-multiples on $\beta(2^m - 2)$). Furthermore, looking at the map of spectral sequences from $\hat{A}(n)$, we see that the class $e^2$ survives to the $E_{1+2^{i+1}}$-page for $1 \leq i \leq m - 1$. Therefore, the differentials $d_r$ are $e^2$-linear for $r < 2^{i+1} + 1$. The first non-zero class in positive filtration is $\xi_m\beta(2^m - 2)$ which has topological degree $(2^m - 1) - (2^m - 2) = 1$. Therefore, every element of $E(\beta)$ is a permanent cycle and the spectral sequence is one of modules over this exterior algebra.

We will prove the following statements inductively on $0 \leq j \leq m - 1$:

1. For $2^j \leq k < 2^{j+1}$, if $k - 2^j \leq \ell < k$, then

$$d_{1+2^{j+1}}(\beta(\ell)e^{k+2^{j+1}n}) = \xi_m^{1+2^{j+1}} \beta(\ell + 2^m - 2^{j+1})e^{k - 2^j + 2^{j+1}n}.$$  

2. For $2^j \leq k < 2^{j+1}$ and $k \leq \ell$, the class $\beta(\ell)e^k$ is a permanent cycle.

3. There are no other non-trivial differentials until the $E_{1+2^{j+2}}$-page.

We note that (1) and (2) inductively imply that any class $\beta(\ell)e^k$ with $k < 2^{j+1}$ either supports a differential $d_r$ for $r \leq 1 + 2^{j+1}$, or is a permanent cycle.

To prove the inductive claim, we start with $j = 0$, so that $k = 1$ in (1). Using that $\ell$ is even, in (1), the range forces $\ell = 0$. The first possible non-trivial differential for degree reasons is on $e$, and this differential is forced by the $d_3$-differential

$$d_3(e) = \xi_m^3 \beta(2^m - 2)$$
in $\bar{A}(n)$. All $d_3$-s are then determined by $c^2$-linearity and given by
\[ d_3(e^{1+2n}) = \xi_m^3 \beta(2^m - 2)e^{2n}. \]
Here, we have used the fact that the differentials are linear over $F_2[\xi_m] \otimes E(\beta)$. For degree reasons, the classes $\beta(\ell)e$ for $\ell \geq 2$ are permanent cycles, proving (2). The differentials are $c^2$-linear and all other classes that could support a $d_3$ are the product of $c^2$ with permanent cycles. So they survive to the $E_5$-page.

Let $i > 0$ and assume that (1), (2), (3) hold for smaller values of $0 \leq j < i$. As noted above, the differentials in the spectral sequence of $\bar{A}(m)$ implies the differentials
\[ d_{1+2i+1}(e^{2^i+2^{i+1}n}) = \xi_m^{1+2^{i+1}} \beta(2^m - 2^{i+1})e^{2^{i+1}n}, \]
provided that the targets survive to the $E_{1+2i+1}$-page. By the induction hypothesis and Lemma [6.18] this is the case. This proves the differential of (1) for $k = 2^i$ and $\ell = 0$.

Now, choose $k$ and $\ell$ so that $2^i \leq k < 2^{i+1}$ and $k - 2^i \leq \ell < k$ as in (1). In particular, $\ell > 0$. The class $[\beta(\ell)e^{k-2^i}]$ is a permanent cycle by the induction hypothesis. Therefore,
\[ d_{1+2i+1}(\beta(\ell)e^{k+2^{i+1}n}) = d_{1+2i+1}([\beta(\ell)e^{k-2^i}]e^{2^{i+1}n}) = \xi_m^{1+2^{i+1}} \beta(2^m - 2^{i+1})e^{2^{i+1}n}. \]
The binomial expansion of $2^m - 2^{i+1}$ is
\[ 2^{m-1} + \ldots + 2^{i+2} + 2^{i+1}. \]
The bounds on $\ell$ give $0 < \ell < 2^{i+1}$, which guarantees that $\binom{2^m - 2^{i+1}}{\ell}$ is $0$ since $\ell > 0$. So, by [6.1],
\[ \beta(\ell) \beta(2^m - 2^{i+1}) = \beta(\ell + 2^m - 2^{i+1}). \]
We get a non-trivial differential as long as the target is non-zero, which is the case by the induction hypothesis and Lemma [6.18]. This proves (1).

We next show that the classes $\beta(\ell)e^k$ for $k \leq \ell$ and $2^i \leq k < 2^{i+1}$ are permanent cycles. Suppose that for $2^i \leq r \leq k$,
\[ d_{1+2r}(\beta(\ell)e^k) = \xi_m^{1+2r} \beta(\ell + 2^m - 2r)e^{k-r}. \]
The form of the differential comes from Lemma [6.17]. Note that
\[ k - r \leq \ell - r \leq \ell - r + 2^m - r = \ell + 2^m - 2r. \]
This shows that the target is a permanent cycle by the induction hypothesis. We will now show that this target is actually killed by a shorter differential.

Since
\[ \ell + 2^m - 2r - (2^m - 2^{i+1}) = 2^{i+1} + \ell - 2r \geq 2^{i+1} + k - 2k = 2^{i+1} - k > 0, \]
Therefore, $\ell + 2^m - 2r > 2^m - 2^{i+1}$ and so we can write
\[ \ell + 2^m - 2r = 2^m - 2^{i+1} + \bar{\ell}, \quad \bar{\ell} < 2^j, \quad 0 \leq j \leq i \]
\[ k - r = \bar{k} + 2^h - 2^j + 2^{h+1}n, \quad j \leq h, \quad \bar{k} < 2^j, \quad 0 \leq n \]
Let

$$\ell' = \ell + 2^m - 2r - (2^n - 2^h + 1) = \ell + 2^h + 1 - 2^i + 1$$

and

$$k' = k - r - 2^{h+1}n + 2^h = k + 2^h + 1 - 2^j.$$

Then, $k' - 2^h \leq \ell' < k'$ and $2^h \leq k' < 2^{h+1}$. So by the induction hypothesis,

$$d_{1+2^h+1}(\xi_m^{2r-2^{h+1}} \beta(\ell') e^{k' + 2^{h+1}n}) = \xi_m^{2r-2^{h+1}} \left( \xi_m^{1+2^{h+1}} \beta(\ell' + 2^m - 2^{k+1}) e^{k' - 2^h + 2^{h+1}n} \right) = \xi_m^{1+2r} \beta(\ell + 2^m - 2r) e^{k-r}.$$

Therefore, the target was killed by a shorter differential. This proves (2).

Finally, (3) holds by the linearity of the differentials with respect to the $d_{2^{m}+2}$-cycle $e^{2^{m}+1}$.

Finally, the correspondence between the $a_\sigma$-localized slice spectral sequence of $i_*^G BP^{[G]}(m,m)$ and the relative Adams spectral sequence is as follows:

**Summary 6.21.** The $E_2$-page of the relative Adams spectral sequence of the geometric fixed points $\Phi^G BP^{[G]}(m,m)$ is, additively,

$$E_2^{\alpha,\beta} \cong \Sigma^{2^m-2} \mathbb{F}_2[\xi_m] \otimes E(\beta) \otimes \mathbb{F}_2[\epsilon_{2^m+1}]$$

where the shift preserves the filtration and adds $2^m - 2$ to the topological degree.

The correspondence between the slice spectral sequence and the relative Adams spectral sequence is as follows:

1. The elements $b^k$ for $0 \leq k \leq 2^m - 1 - 1$ correspond to $\beta(2^m - 2(k + 1))$. Note that $b^{2^m-1}$ corresponds to $\beta(0) = 1$, the multiplicative unit in the relative Adams spectral sequence of $R(m)$.

2. For $\ell = 2^{m-1}(2^n - 1) + 1$, $0 \leq k < 2^{m-1}$ and $r \geq 0$, the element $b^k + 2^{m-1}$ in the localized sliced spectral sequence supports the differential

$$d_{\ell}(b^k + 2^{m-1}) = b^k (\bar{f}_m + \gamma f_m),$$

forced by the slice differential

$$d_{\ell}(u^{2^{m-1}}_{2\sigma}) = a^{2^{m-1}+1}_{\sigma} (\bar{v}^G_m + \gamma \bar{v}^G_m).$$

These differentials are $b^{2^m}$-linear, leaving behind $b^k$ where the dyadic expansion of $k = \epsilon_0 + \epsilon_1 2 + ...$ satisfies $\epsilon_{m-1} = 0$. This family of differentials identifies $\bar{f}_m$ with $\gamma \bar{f}_m$ in the whole slice spectral sequence.

3. After the slice differentials above, multiplication by either $\bar{f}_m$ or $\gamma \bar{f}_m$ corresponds to multiplication by $\xi_m$ in the relative Adams spectral sequence.

4. The remaining elements $b^k$ are in one-to-one correspondence with the elements in filtration $s = 0$ in the relative Adams spectral sequence, shifted by a degree $2^m - 2$. In particular, the element $b^{2^m+2^{m-1}-1}$ corresponds to $\epsilon\ell_{2^m+1}$.

### 6.4 The $C_2$-slice spectral sequence of $BP^{[C_4]}(2,2)$

As an application, we illustrate the above correspondence of spectral sequences by computing the $C_2$-slice spectral sequence of $BP^{[C_4]}(2,2)$.

The $C_2$-slice spectral sequence of $BP^{[C_4]}(2,2)$ is determined by the relative Adams spectral sequence for

$$R(2) = \mathbb{A}(2)/((\zeta_0, \ldots)) \wedge A \text{End}_A(M_1),$$
whose computation follows from Section 6.3 above. The essential features were also completely computed in Section 7.3 of [3]. The $E_2$-page is

$$F_2[e] \otimes E(\beta, 2) \otimes F_2[e].$$

There are only $d_3$- and $d_5$-differentials. The $d_3$-differentials are generated by

$$d_3(e_8^{1+2*}) = e_8^2 \xi_2^3 \beta_2,$$

and the $d_5$-differentials are generated by

$$d_5(e_8^{2+4*}) = e_8^4 \xi_2^5,$$

$$d_5(e_8^{3+4*} \beta_2) = e_8^{1+4*} \xi_2^3 \beta_2.$$

The $E_2$-term of the $a_\sigma$-localized slice spectral sequence for $a_\sigma^{-1}i_C^* BP^{(C_4)}(2, 2)$ is

$$F_2[u_{2\sigma}, q_{2\sigma}^{-1}, t_2, \gamma t_2].$$

As before, let $b = u_{2\sigma}/a_2$. The shortest differentials in this spectral sequence are the $d_7$-differentials, whose effects are to identify $t_2$ with $\gamma t_2$. The $d_7$-differentials are generated by

$$d_7(b^{2+4*}) = b^{4*}(t_2 + \gamma t_2)a_\sigma^3,$$

$$d_7(t^{3+4*}) = b^{1+4*}(t_2 + \gamma t_2)a_\sigma^3.$$

After the $d_7$-differentials, we can then import the differentials from the relative Adams spectral sequence as explained in Summary 6.21. As a result, the Adams $d_3$-differentials become the slice $d_{19}$-differentials, generated by

$$d_{19}(b^{5+8*}) = b^{1+8*}t_2^3 a_\sigma^9.$$

The Adams $d_5$-differentials become the slice $d_{31}$-differentials, generated by

$$d_{31}(b^{9+16*}) = b^{1+16*}t_2^9 a_\sigma^{15},$$

$$d_{31}(b^{12+16*}) = b^{4+16*}t_2^5 a_\sigma^{15}.$$

Figure 7 shows the $a_\sigma$-localized slice spectral sequence for $a_\sigma^{-1}i_C^* BP^{(C_4)}(2, 2)$. At $E_2$, the classes $\bullet$ denote families of monomials formed by the classes $a_\sigma^3 t_2$ and $a_\sigma^3 \gamma t_2$ on the various powers of $b$. At $E_3$, a $\bullet$ depicted as the target of a $d_7$-differential becomes a copy of $\mathbb{Z}/2$, represented by a class of the form $a_\sigma^3 t_2^k b^l$ for $k \neq 2, 3 \mod 4$. Each $\bullet$ depicted as the source of a $d_7$-differential is completely gone as the $d_7$-differentials are injective.

As in Theorem 4.6, to obtain the differentials in the $C_2$-slice spectral sequence of $BP^{(C_4)}(2, 2)$, we truncate at the horizontal line of filtration $s = 0$ and remove the region below this line.

7. The $C_4$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}(2, 2)$

In this section, we compute the integer-graded $C_4$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}(2, 2)$, using all the tools that we have developed in the previous sections. This computation serves to demonstrate the robustness of our techniques as well as providing insights to higher differentials phenomena when generalized to higher heights.
Figure 5. The $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}C_2 BP^{(C_4)}(2, 2)$.

Remark 7.1. Just like the integer-graded spectral sequence, the full $RO(C_4)$-graded spectral sequence can be computed by the exact same method. We have opted to only compute the integer-graded slice spectral sequence because it is more convenient to present its diagrams.

Remark 7.2. By the discussion in Section 4, the slice spectral sequence of the unlocalized spectrum $BP^{(C_4)}(2, 2)$ is completely determined by the $a_\lambda$-localized slice spectral sequence by truncating away the region below the line of filtration $s = 0$.

Remark 7.3. The following facts are good to keep in mind while doing the computation:

1. The differentials with source on or above the line of slope 1 in the $C_4$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}(2, 2)$ are determined by the $C_4$-localized slice spectral sequence of $a_\sigma^{-1}BP^{(C_4)}(2, 2)$ computed in Example 5.15. These are all $d_{13}$ differentials.
(2) Many of the differentials $d_{i\leq 31}$ are determined using the $C_2$-slice differentials computed in Section 6.4 and the Mackey functor structure (i.e. restriction and transfer).

(3) The $C_1$-localized slice spectral sequence of $a^{-1}_\lambda BP^{(C_4)}(2,2)$ is a module over the spectral sequence of $a^{-1}_\lambda MU^{(C_4)}$, but very little of that structure is needed for the computation (see Section 7.3). Multiplication with respect to two key classes gives rise to periodicity of differentials and a vanishing line (Theorem 7.20). These phenomena determine all higher differentials ($d_{\geq 31}$).

7.1. Organization of the slice associated graded. For the rest of this section, we let

$$\bar{t}_1 = \bar{v}^{C_4}$$

and

$$\bar{t}_2 = \bar{v}^{C_4}_{2}.$$ 

From Corollary 2.14, the slice associated graded for $BP^{(C_4)}(2,2)$ is $H_\mathbb{Z} [\bar{t}_2, \gamma \bar{t}_2]$, so the $E_2$-page of our spectral sequence is obtained by $a_\lambda$-localization of the homotopy of this slice associated graded.

We organize the slice cells by powers of

$$\bar{d}_{t_2} := N_{C_2}^{C_4}(\bar{t}_2).$$

Remark 7.4. This mirrors the approach taken by Hill–Hopkins–Ravenel in [24] to compute the slice spectral sequence of $BP^{(C_4)}(1,1) = BP^{(C_4)}(1,1)$, where they organized the slice cells by powers of $\bar{d}_{t_1} := N_{C_2}^{C_4}(\bar{t}_1)$.

The slice cells are organized according to the following matrix:

$$
\begin{pmatrix}
\bar{d}_{t_2}^0(t_2, \gamma t_2) & \bar{d}_{t_2}^1(t_2, \gamma t_2) & \bar{d}_{t_2}^2(t_2, \gamma t_2) & \cdots \\
\bar{d}_{t_2}^0(t_2, \gamma t_2) & \bar{d}_{t_2}^1(t_2, \gamma t_2) & \bar{d}_{t_2}^2(t_2, \gamma t_2) & \cdots \\
\bar{d}_{t_2}^0(t_2, \gamma t_2) & \bar{d}_{t_2}^1(t_2, \gamma t_2) & \bar{d}_{t_2}^2(t_2, \gamma t_2) & \cdots \\
\vdots & \vdots & \vdots & \ddots
\end{pmatrix}
$$

To read this, note that $\bar{d}_{t_2}^\rho \cdot \bar{d}_{t_2} = \bar{t}_2 \gamma \bar{t}_2$ so that every monomial in $\bar{t}_2, \gamma \bar{t}_2$ appears in some entry of the matrix.

Entries $\bar{d}_{t_2}^\rho$ in the matrix represent slice cells of the form

$$H_{\mathbb{Z}} \wedge S^{3j \rho_4},$$

where $\rho_4$ is the regular representation of $C_4$. These are the regular (or non-induced) cells. Entries of the form $\bar{d}_{t_2}^0(\bar{t}_2^\rho, \gamma \bar{t}_2)$ represent slice cells of the form

$$H_{\mathbb{Z}} \wedge (C_4 \wedge C_2 S^{8j \rho_2}(3j \rho_4 + 3 \rho_2)) \cong H_{\mathbb{Z}} \wedge (C_4 \wedge C_2 S^{6j + 3 \rho_2}).$$

These are the induced cells.

For the non-induced cells, the homotopy groups of $H_{\mathbb{Z}} \wedge S^{* \rho_4}$ are computed in [24] and depicted in Figure 3 of that reference. For the induced cells, we get the induced Mackey functors

$$H_{\mathbb{Z}}(C_4 \wedge S^{* \rho_2}) \cong \Gamma_{C_2} H_{\mathbb{Z}}(S^{* \rho_2}),$$

(see Definition 2.6 of [24]) whose values are also known. After inverting $a_\lambda$, we obtain the $E_2$-page depicted in Figure 6.

We use the same notation as in Table 1 of [24] for the Mackey functors. Blue Mackey functors are supported on induced cells and represent multiple copies of
the Mackey functor \(\hat{\cdot}\) of [24], supported on the various monomials in the matrix (7.1) that are not in the first row.

We name the classes that do not come from induced cells. First, there are classes of order four (which have non-trivial restrictions):

- \(\delta^{2i}_{2j}u_{(6i-j)\lambda}u_{6i\sigma}a_{j\lambda}\) in degree \((24i - 2j, 2j)\) for \(0 \leq i\) and \(0 \leq j \leq 6i\).

Next, the classes of order two which do not come from induced cells are:

- \(\delta^{i}_{2j}u_{2k\sigma}a_{3i\lambda}a_{(3i-2k)\sigma}\) in degree \((3i + 2k, 9i - 2k)\) for \(0 \leq i\) and \(0 \leq 2k < 3i\).
  These are above the line of slope one.
- \(\delta^{i}_{2j}u_{j\lambda}u_{(3i-1)\sigma}a_{(3i-j)\lambda}a_{\sigma}\) in degree \((6i + 2j - 1, 6i - 2j + 1)\) for \(i\) odd, \(0 \leq i\) and \(0 \leq j\).

The induced cells are named by treating them as images of the transfer map from the corresponding classes in the \(C_2\)-slice spectral sequence.
7.2. The $d_7$-differentials. The first differentials are the $d_7$-differentials. They occur between classes supported on slice cells that are in the same column of the matrix \( \text{[7.1]} \). The $d_7$-differentials are all proven by restricting to the $a_\sigma$-localized slice spectral sequence of $a_\sigma^{-1}i^*_\sigma BP^{(C_4)}(2,2)$. More specifically, the restriction of certain classes to the $C_2$-spectral sequence support the $d_7$-differentials discussed in Section \( \text{[6.4]} \) and therefore by naturality and degree reasons their preimages must also support $d_7$-differentials in the $C_4$-spectral sequence. By naturality and degree reasons, these are all the $d_7$-differentials that can occur, after which we obtain the $E_8$-page.

Let $b = \frac{u_{24}}{2}$. The restriction of this class is the class $b = \frac{u_{24}}{2}$ in the $C_2$-spectral sequence. We have $d_7$-differentials
\[
d_7 \left( b^{2+4*} \right) = tr_{C_2^*}(i_2a_{3\sigma})b^{4*} \\
d_7 \left( b^{3+4*} \right) = tr_{C_2^*}(i_2a_{3\sigma})b^{1+4*}.
\]

Figure \( \text{[7]} \) depicts the $E_7$-page. The $\circ$ classes are $\mathbb{Z}/4$'s coming from non-induced cells. The black $\bullet$ classes are $\mathbb{Z}/2$'s coming from the non-induced cells, while the blue $\bullet$ classes are direct sums of $\mathbb{Z}/2$'s coming from the induced cells.

Figure \( \text{[8]} \) depicts the $E_8$-page. In that figure, all dots represent a copy of $\mathbb{Z}/2$, with the exception of the white $\circ$ classes which represent $\mathbb{Z}/4$'s. The pink denotes a degree where, on a previous page, there was a $\mathbb{Z}/4$ but the generator supported a non-zero differential and is no longer present. As before, blue classes come from induced cells.

7.3. Strategy for computing higher differentials. Before computing the higher differentials (those of lengths $\geq 13$), we describe our strategy. There are two classes that will be very important for our computation. They are the classes
\[
\alpha = \bar{\delta}_{12}^8u_{24\sigma}a_{24\lambda} \text{ at } (48,48), \\
b^{32} = u_{32\lambda}/a_{32\lambda} \text{ at } (64,-64).
\]

We will use the following crucial facts about the spectral sequence of $a_\lambda^{-1}MU^{(C_4)}$. These results are the only significant computational inputs from the localized slice spectral sequence for $a_\lambda^{-1}MU^{(C_4)}$ and the much harder computations of \([25]\).

**Proposition 7.5.** The class $\alpha = \bar{\delta}_{12}^8u_{24\sigma}a_{24\lambda}$ is a permanent cycle in the localized slice spectral sequence for $a_\lambda^{-1}MU^{(C_4)}$. Consequently, the differentials are linear with respect to multiplication by $\alpha$.

**Proof.** This is a direct consequence of the Slice Differential Theorem of Hill–Hopkins–Ravenel \([19\text{ Theorem 9.9]}\). More precisely, all the differentials in the region on or above the line of slope 1 in the $C_4$ localized slice spectral sequence for $a_\lambda^{-1}MU^{(C_4)}$ can be completely computed. \( \square \)

**Proposition 7.6.** In the localized slice spectral sequence for $a_\lambda^{-1}MU^{(C_4)}$, we have the following facts:

1. The class $b^8 = u_{6\lambda}/a_{8\lambda}$ supports a $d_{15}$-differential.
2. The class $b^{16} = u_{16\lambda}/a_{16\lambda}$ supports a $d_{31}$-differential.
3. The class $b^{32} = u_{32\lambda}/a_{32\lambda}$ is a $d_{61}$-cycle.
Figure 7. The $E_7$-page of the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP((C_4)/(2,2))$.

Proof. All the claims are direct consequences of the computations for the $C_4$ slice spectral sequence of $BP((C_4)/(2))$ (see Table 1 in [26]). We will elaborate on each of them below.

For (1), the restriction of the class $u_{8\lambda}$ is $u_{16\sigma_2}$, which supports the $d_{31}$-differential

$$d_{31}(u_{16\sigma_2}) = v_4^2 a_{31\sigma_2}$$

in the $C_2$-spectral sequence of $MU((C_4))$. Therefore by naturality of the restriction map, the class $u_{8\lambda}$ must support a differential of length at most 31. By a stemwise computation, it is impossible for the class $u_{8\lambda}$ to support a differential of length $\leq 13$, as there are no possible targets. We will not carry out the details of this computation here, as [26, Section 7.3] already contains the arguments and results to show that $u_{8\lambda}$ supports a $d_{15}$-differential in the slice spectral sequence of $MU((C_4))$. It follows that the class $\frac{u_{8\lambda}}{a_{8\lambda}}$ must also support a $d_{15}$-differential in the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}MU((C_4))$. This proves (1).
Figure 8. The $E_8$-page of the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}\langle 2,2 \rangle$.

For (2), the restriction of the class $u_{16\lambda}$ is $u_{32\sigma_2}$, which supports the $d_{63}$-differential

$$d_{63}(u_{32\sigma_2}) = \pi_3 a_{63\sigma_2}$$

in the $C_2$-spectral sequence of $MU^{(C_4)}$. Therefore by naturality of the restriction map, the class $u_{16\lambda}$ must support a differential of length at most 63. By a stem-wise computation, it is impossible for the class $u_{16\lambda}$ to support a differential of length $\leq 19$, as there are no possible targets. Again, we do not write down the details here, as the computation in [26] already shows that $u_{16\lambda}$ supports a $d_{31}$-differential in the slice spectral sequence of $MU^{(C_4)}$ (see the discussion in Section 11.2 and the chart in Section 13 of [26]). It follows that the class $\frac{u_{16\lambda}}{a_{16\lambda}}$ must also support a $d_{31}$-differential in the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}MU^{(C_4)}$. This proves (2).

For (3), it is a consequence of the computation of $a_\lambda^{-1}BP^{(C_4)}\langle 2,2 \rangle$ that $u_{32\lambda}$ is a $d_{61}$-cycle in the slice spectral sequence of $MU^{(C_4)}$ (in fact, it can be shown that
it supports the $d_{61}$-differential $d_{61}(u_{32}\lambda) = N(v_5a_{61}\sigma_2)u_{16}\lambda$, but we will not prove it here). □

Multiplication by the classes $\alpha$ and $b^{32}$ give the spectral sequence a large amount of structure which we will exploit in our computation. We describe this below, focusing on each class at a time.

7.3.1. Multiplication by $\alpha$. The class $\alpha$ is extremely important for this computation. A key consequence of the behavior we describe here is that this allows us to compute differentials out of order, flipping back and forth between different pages of the spectral sequence without losing the thread of its story. We make this precise now, starting with the following straightforward lemma.

Lemma 7.7. In the $C_4$-localized slice spectral sequence of $a^{-1}_\lambda BP[[C_4]]/(2,2)$, on the $E_{13}$-page, we have:

1. Multiplication by $\alpha$ is injective.
2. Let $x$ be a class in bidegree $(t-s,s)$. If $s - 48 \geq -(t-s-48)$ and $s - 48 \leq 3(t-s-48)$

then $x$ is $\alpha$ divisible.

See Figure 7

The key result is then the following:

Proposition 7.8. Let $r \geq 13$. Suppose that $d_r(x) = y$ is a non-trivial differential on the $E_r$-page of the localized slice spectral sequence of $a^{-1}_\lambda BP[[C_4]]/(2,2)$. Then $y$ is $\alpha$-free in the sense that no multiple $\alpha^i y$ is zero at $E_r$. Consequently, $x$ is also $\alpha$-free.

Proof. First, note that if $y$ is $\alpha$-free, the linearity of the differentials with respect to multiplication by $\alpha$ implies that $x$ must also be $\alpha$-free.

We prove that $y$ is $\alpha$-free by induction on $r$. If $r = 13$, the claim follows immediately from the fact that all classes are $\alpha$-free at $E_{13}$ (Lemma 7.7). Suppose that the claim holds for all $r' < r$, that $d_r(x) = y$ is a non-trivial differential and that $y$ is $\alpha$-torsion. Then there exists $i > 0$, $r' < r$ and $z$ such that

$$d_{r'}(z) = \alpha^i y.$$ Choose a minimal such $i$, so that $\alpha^{i-1} y$ is non-zero at $E_r$. A comparison of degrees then implies that the bidegree of $z$ satisfies the conditions of Lemma 7.7, so that $z$ is $\alpha$-divisible. It cannot be the case that $d_{r'}(z/\alpha) = \alpha^{i-1} y$ since this contradicts the minimality of $i$. So we must have that $d_{r'}(z/\alpha) = v \neq 0$ for some $r'' < r' < r$. But by the induction hypothesis, $v$ is then $\alpha$-free which means that $d_{r''}(z) = \alpha v \neq 0$, which is also a contradiction. □

Remark 7.9. We will show in Section 7.4.3 that $\alpha$ is killed by a $d_{61}$-differential. This will imply that for any permanent cycle $x$, the class $\alpha x$ must be hit by a differential of length at most 61.

We now explain the upshot of Proposition 7.8. Given any class $y$ at $E_{13}$, there is a unique class $x$ which is not $\alpha$-divisible (so is in the complement of the region of Lemma 7.7, 3) and such that $y = \alpha^i x$ for some $i \geq 0$. We say that $x$ generates an $\alpha$-free family, where the family is the collection of classes $\{\alpha^i x \mid i \geq 0\}$. 
Now, Proposition 7.8 implies that $\alpha$-free families come in pairs: one family in the pair, generated by $x$ say, supports differentials which truncate the second family in the pair, generated by $y$ say. (In fact, by Remark 7.9, the differentials must be of the form $d_r(\alpha^i x) = \alpha^{i+1} y$.) All classes in the $\alpha$-free family generated by $x$ are then gone at the $E_{r+1}$-page, having supported a no-trivial differential. The class $y$ is now $\alpha$-torsion, and by Proposition 7.8, it cannot support any further differential. This allows us to discard $y$ from the rest of the computation, making the spectral sequence effectively sparser. Furthermore, we may now run differentials out of order if we find a unique possibility for pairing $\alpha$-free families, even if this is through very long differentials.

Remark 7.10. This is in fact a common behavior for spectral sequences. For example, what we have here is very similar to the situation explained in a certain elliptic spectral sequence [5, Section 6], where there the role of $\alpha$ is played by the class $\bar{\kappa}$.

7.3.2. Multiplication by $b^{32}$. Multiplication by the permanent cycle $b^{32}$ acts as a periodicity generator for most of the spectral sequence. More precisely, we have:

Lemma 7.11. Let $r \geq 13$. Multiplication by $b^{32}$ is injective on the $E_r$-page for classes on or below the line of slope 1 through the origin.

It follows that if a differential has both source and target on or below the line of slope 1 through the origin, then $d_r(x) = y$ occurs if and only if $d_r(b^{32} x) = b^{32} y$ occurs. Differentials whose source and target are above the line of slope 1 through the origin are determined by the $a_{\sigma}$-localized spectral sequence. Some differentials, fall in neither category in the sense that they cross the line of slope one. That is, the source is on or below the line of slope one and the target is above. For these differentials, the target may be $b^{32}$-torsion while the source is not.

As one does the computation however, one sees that the target of such differentials have bidegree $(t - s, s)$ such that

$$s \leq (t - s) + 14.$$  

This can be seen from the $d_{13}$-differentials that are obtained from the $a_{\sigma}$-localized spectral sequence and the structure of the $E_{14}$-page. Since the longest differential is a $d_{61}$ and classes are concentrated in degrees with $t - s$ even, classes strictly below the line

$$s = (t - s) - 60$$

cannot support differentials that cross the line of slope 1 through the origin. Therefore, to completely determine the differentials of the spectral sequence using $b^{32}$-linearity and $\alpha$-linearity, it is sufficient to determine:

- The $d_{13}$'s with source on or above the line of slope 1 through the origin, all obtained from the $a_{\sigma}$-localized spectral sequence.
- The differentials on classes with source of bidegree $(t - s, s)$ where is in the rectangular region:

$$s \leq (t - s) \quad s \geq -(t - s)$$

$$s \geq (t - s) - 188 \quad s < -(t - s) + 96$$

This region is larger than what is needed in practice, but the goal of this discussion is simply to illustrate the strategy and make a rough estimate on what differentials need to be determined. As we go through the computation, we learn that the region that determines all differentials is in fact smaller but, a priori, this is not clear.
7.3.3. Summary. To summarize, we just have to focus on the classes in the shaded rectangular region of Figure 9 which is the union of a cone and a rectangle. Once we have figured out the fate of all the classes in this region, we can propagate by the classes $\alpha$ and $b_{32}$ to obtain the rest of the differentials. Furthermore, once an $\alpha$-multiple of a class gets truncated by a differential, that class can no longer support differentials and can be disregarded from future arguments.

7.4. Differentials of length at most 13.

7.4.1. $d_{13}$-differentials. By degree reasons, the next possible differentials are the $d_{13}$-differentials.
The differentials on or above the line of slope 1 are all obtained by computing the $a_\sigma$-localized spectral sequence, as explained in Section 5.1. This spectral sequence is depicted in Figure 4. The differentials are summarized in the following proposition.

**Proposition 7.12.** The $d_{13}$-differentials that are on or above the line of slope 1 are generated by

$$(1) \quad d_{13}\left(\bar{d}_{12}^3 u_{6\sigma} a_{6\lambda}\right)^{i+1+4k} = \bar{d}_{12}^3 u_{2\sigma} a_{9\lambda} a_{7\sigma} \cdot \left(\bar{d}_{12}^3 u_{6\sigma} a_{6\lambda}\right)^{i-1+4k}$$

$$i = 1, 2, k \geq 0.$$

$$(2) \quad d_{13}\left(\bar{d}_{12}^2 u_{4\sigma} a_{6\lambda} a_{2\sigma} \cdot \left(\bar{d}_{12}^2 u_{6\sigma} a_{6\lambda}\right)^{i+4k}\right) = \bar{d}_{12}^3 a_{9\lambda} a_{9\sigma} \cdot \left(\bar{d}_{12}^2 u_{6\sigma} a_{6\lambda}\right)^{i+4k}$$

$$i = 0, 3, k \geq 0.$$

$$(3) \quad d_{13}\left(\bar{d}_{12}^5 u_{14\sigma} a_{15\lambda} a_{\sigma} \cdot \left(\bar{d}_{12}^2 u_{6\sigma} a_{6\lambda}\right)^{i+4k}\right) = \bar{d}_{12}^6 u_{10\sigma} a_{18\lambda} a_{\sigma} \cdot \left(\bar{d}_{12}^2 u_{6\sigma} a_{6\lambda}\right)^{i+4k}$$

$$i = 0, 1, k \geq 0.$$

To prove the $d_{13}$-differentials that are under the line of slope 1, we would like to first point out that the class $\bar{d}_{12}^4 u_{12\sigma} a_{12\lambda}$ in bidegree $(7, 5)$ is a permanent-cycle by degree reasons.

The class $\bar{d}_{12}^4 u_{12\sigma} a_{12\lambda}$ in bidegree $(24, 24)$ will also be important. By the Hill–Hopkins–Ravenel Slice differential theorem [19 Theorem 9.9]. This class supports the $d_{13}$-differential

$$d_{13}(\bar{d}_{12}^4 u_{12\sigma} a_{12\lambda}) = \bar{d}_{12}^5 u_{8\sigma} a_{15\lambda} a_{7\sigma}$$

in the slice spectral sequence of $BP^\ell(C_4)$. By naturality, this differential also appears in the slice spectral sequence of $BP^\ell(C_4) \cap 2$. When applying the Leibniz rule, the class $\bar{d}_{12}^4 u_{12\sigma} a_{12\lambda}$ acts as if it is a $d_{13}$-cycle for differentials whose sources are below the line of slope 1. More specifically, the target of the $d_{13}$-differential on this class multiplied with the source of another $d_{13}$-differential below the line of slope 1 is always 0.

**Proposition 7.13.** We have the following $d_{13}$-differentials:

$$(1) \quad d_{13}(b^4) = \bar{d}_{12} u_{\lambda} u_{2\sigma} a_{2\lambda} a_{\sigma}$$

$$(2) \quad d_{13}(b^5) = \bar{d}_{12} u_{2\lambda} u_{2\sigma} a_{2\lambda} a_{\sigma}$$

$$(3) \quad d_{13}(\bar{d}_{12} u_{4\lambda} u_{2\sigma} a_{\lambda} a_{\sigma}) = 2\bar{d}_{12} u_{6\sigma} a_{6\lambda}$$

$$(4) \quad d_{13}(\bar{d}_{12} u_{4\lambda} u_{2\sigma} a_{\lambda} a_{\sigma} \cdot b) = 2\bar{d}_{12} u_{6\sigma} a_{6\lambda} \cdot b$$

$$(5) \quad d_{13}(\bar{d}_{12} u_{4\lambda} u_{2\sigma} a_{\lambda} a_{\sigma} \cdot b^2) = 2\bar{d}_{12} u_{6\sigma} a_{6\lambda} \cdot b^2$$

$$(6) \quad d_{13}(\bar{d}_{12} u_{4\lambda} u_{2\sigma} a_{\lambda} a_{\sigma} \cdot b^3) = 2\bar{d}_{12} u_{6\sigma} a_{6\lambda} \cdot b^3$$

**Proof.** To prove (1), we will first prove the differential

$$d_{13}(b^{12}) = \bar{d}_{12} u_{9\lambda} u_{2\sigma} a_{6\lambda} a_{\sigma} \quad (d_{13}(24, -24) = (23, -11))$$

The source of this differential restricts to a class in the $C_2$-spectral sequence that supports a $d_{31}$-differential. By naturality and degree reasons, we must have the $d_{13}$-differential claimed above. Applying Leibniz with the class $b^8$ in degree $(16, -16)$ proves (1).

The source of (2) restricts to a class that supports a $d_{19}$-differential in the $C_2$-spectral sequence. Therefore the source class must support either a $d_{13}$- or a $d_{19}$-differential. By naturality, it cannot be a $d_{19}$-differential because the target does not restrict to the target of the $d_{19}$-differential in the $C_2$-spectral sequence.
The targets of (3) is in the image of the transfer. The preimage is killed by a $d_{19}$-differential. Therefore by naturality and degree reasons, we have the $d_{13}$-differential claimed in (3).

Differentials (4) and (5) are obtained by applying the Leibniz rule using the class $\delta_{t_2} u_{\lambda_2} u_{2\sigma_2} a_2 \lambda_{a_\sigma}$ (7, 5) with differentials (1) and (2) (and also using the gold relation).

It remains to prove differential (6). Consider the class $\delta_{t_2} u_{7\lambda} u_{2\sigma_2} a_{-4\lambda}$. The restriction of this class is $\delta_{t_2} u_{7\lambda} u_{2\sigma_2} a_{-8\sigma_2}$, which supports a $d_7$-differential in the $C_2$-spectral sequence. Therefore, the class $\delta_{t_2} u_{7\lambda} u_{2\sigma_2} a_{-4\lambda}$ also supports a $d_7$-differential in the $C_4$-spectral sequence. The existence of this $d_7$-differential shows that there is an exotic restriction of filtration 6 for the class $\delta_{t_2} u_{7\lambda} u_{2\sigma_2} a_{-4\lambda}$ (19, 7). It must have nonzero restriction, restricting to the class $\delta_{t_2} u_{10\sigma_2} a_{-\sigma_2}$ (19, 1) after the $E_2$-page.

Since the class $\delta_{t_2} u_{10\sigma_2} a_{-\sigma_2}$ (19, 1) supports a $d_{13}$-differential in the $C_2$-spectral sequence, the class $\delta_{t_2} u_{7\lambda} u_{2\sigma_2} a_{-4\lambda}$ (19, 7) cannot survive past the $E_{25}$-page. The only possibility is for it to support the $d_{13}$-differential claimed by (6).

The same proof for differentials (1)–(6) can be used to prove six more differentials that are obtained by multiplying both the source and the target of each differential by (12, 12): $\delta_{t_2} u_{6\lambda} a_{6\lambda}$ (note that we can’t just directly propagate by this class using the Leibniz rule because it supports a $d_5$-differential in SliceSS($BP^{(C_1)}$)).

**Proposition 7.14.** The following classes are $d_{13}$-cycles:

1. $2b^5 (12, -12)$;
2. $2\delta_{t_2} u_{6\lambda} u_{6\sigma} (24, 0)$;
3. $\delta_{t_2} u_{6\lambda} u_{6\sigma} a_{\lambda} a_{\sigma}$ (33, 3).

**Proof.** For (1), the class $2\delta_{t_2} u_{6\lambda} u_{12\sigma_2} a_{6\lambda}$ (36, 12) is a $d_{13}$-cycle by using the class $\delta_{t_2} u_{6\lambda} u_{2\sigma_2} a_{2\lambda} a_{\sigma}$ (7, 5) to apply the Leibniz rule to the $d_{13}$-differential

$$d_{13}(\delta_{t_2} u_{6\lambda} u_{6\sigma} a_{3\lambda} a_{\sigma}) = 2\delta_{t_2} u_{2\lambda} u_{12\sigma_2} a_{10\lambda} \quad (d_{13}(29, 7) = (28, 20)).$$

Therefore, by Leibniz with the class $\delta_{t_2} u_{12\sigma_2} a_{12\lambda}$ (24, 24), the class $2b^5 (12, -12)$ is also a $d_{13}$-cycle.

(2) is proven by the exact same method, by using the class $\delta_{t_2} u_{2\lambda} u_{12\sigma_2} a_{2\lambda} a_{\sigma}$ (7, 5) to apply the Leibniz rule to the $d_{13}$-differential

$$d_{13}(\delta_{t_2} u_{6\lambda} u_{2\sigma_2} a_{-4\lambda} a_{\sigma}) = 2\delta_{t_2} u_{2\lambda} u_{6\sigma} a_{4\lambda} \quad (d_{13}(17, -5) = (16, 8)).$$

For (3), the class $\delta_{t_2} u_{6\lambda} u_{6\sigma} a_{\lambda} a_{\sigma}$ is a $d_{13}$-cycle in SliceSS($BP^{(C_4)}$). Therefore by naturality it is a $d_{13}$-cycle in SliceSS($BP^{(C_1)}(2, 2)$).

Now, we can propagate all the differentials by the classes $\delta_{t_2} u_{12\sigma_2} a_{12\lambda}$ (24, 24) and $b^5 (16, -16)$. The $d_{13}$-differentials under the line of slope 1 are summarized in the following proposition.

**Proposition 7.15.** The $d_{13}$-differentials that are under the line of slope 1 are

1. $d_{13}\left( b^{4+i+8j} \cdot (\delta_{t_2} u_{6\sigma} a_{6\lambda})^k \right) = \delta_{t_2} u_{6\lambda} u_{2\sigma_2} a_{\lambda} a_{\sigma} \cdot b^{i+8j} (\delta_{t_2} u_{6\sigma} a_{6\lambda})^k$, $0 \leq i \leq 1$, $j, k \geq 0$.
2. $d_{13}\left( \delta_{t_2} u_{4\lambda} u_{2\sigma_2} a_{-4\lambda} a_{\sigma} \cdot b^{i+8j} (\delta_{t_2} u_{6\sigma} a_{6\lambda})^k \right) = 2\delta_{t_2} u_{6\lambda} a_{6\lambda} \cdot b^{i+8j} (\delta_{t_2} u_{6\sigma} a_{6\lambda})^k$, $0 \leq i \leq 3$, $j, k \geq 0$.

They are shown in Figure 10.
Remark 7.16. We will see that these are the last non-trivial $d_{13}$ differentials. However, at this point in the computation, there are possibilities for other non-trivial $d_{13}$ differentials. Later, (in Lemmas 7.21 and 7.24) we will show that these do not occur.

7.4.2. $d_{19}$-differentials.

Proposition 7.17. The following $d_{19}$-differentials exist:

1. $d_{19}(2b^5) = \text{tr}(\bar{f}_2 a_9 a_{\sigma_2})$ ($d_{19}(10, -10) = (9, 9)$)
2. $d_{19}(2b^6) = \text{tr}(\bar{f}_2 a_{2\sigma_2} a_{\sigma_2})$ ($d_{19}(12, -12) = (11, 7)$)
3. $d_{19}(b^9) = \text{tr}(\bar{f}_2 a_{8\sigma_2} a_{\sigma_2})$ ($d_{19}(18, -18) = (17, 1)$)
4. $d_{19}(2b^{13}) = \text{tr}(\bar{f}_2 a_{16\sigma_2} a_{-7\sigma_2})$ ($d_{19}(26, -26) = (25, -7)$)
Proof. Differential (1) is obtained by applying transfer to the $d_{19}$-differential

$$d_{19} \left( \frac{u_{10\sigma_2}}{a_{10\sigma_2}} \right) = \bar{r}_2^{3} a_{9\sigma_2}$$

in the $C_2$-spectral sequence.

For differentials (2) and (3), the classes $\bar{r}_2^{3} u_{2\sigma_2} a_{7\sigma_2}$ and $\bar{r}_2^{3} u_{8\sigma_2} a_{\sigma_2}$ are killed by $d_{31}$-differentials in the $C_2$-spectral sequence. Therefore their images under the transfer map must also be killed by differentials of lengths at most 31. The only possibilities are the differentials claimed.

Differential (4) is obtained by applying the transfer to the $d_{19}$-differential

$$d_{19} \left( \frac{u_{26\sigma_2}}{a_{26\sigma_2}} \right) = \bar{r}_2^{3} u_{16\sigma_2} a_{-7\sigma_2}$$

in the $C_2$-spectral sequence. \hfill \square

The same arguments in the proof above can be used to prove twelve more $d_{19}$-differentials, obtained by multiplying the four $d_{19}$-differentials in Proposition 7.17 by $\bar{d}_2^{7} u_{6\sigma_2} a_{6\lambda}$ (12, 12), $\bar{d}_2^{7} u_{12\sigma_2} a_{12\lambda}$ (24, 24), and $\bar{d}_2^{6} u_{18\sigma_2} a_{18\lambda}$ (36, 36).

**Proposition 7.18.** The following $d_{19}$-differentials exist:

1. $d_{19}(2b^{14}) = tr(\bar{r}_2^{3} u_{18\sigma_2} a_{-9\sigma_2})$ ($d_{19}(28, -28) = (27, -9)$)

2. $d_{19} \left( 2b^{14} \cdot (\bar{d}_2^{7} u_{6\sigma_2} a_{6\lambda}) \right) = tr(\bar{r}_2^{3} u_{18\sigma_2} a_{3\sigma_2})$ ($d_{19}(40, -16) = (39, 3)$)

3. $d_{19} \left( 2b^{14} \cdot (\bar{d}_2^{7} u_{6\sigma_2} a_{6\lambda})^2 \right) = tr(\bar{r}_2^{3} u_{18\sigma_2} a_{15\sigma_2})$ ($d_{19}(52, -4) = (51, 15)$)

4. $d_{19} \left( 2b^{14} \cdot (\bar{d}_2^{7} u_{6\sigma_2} a_{6\lambda})^3 \right) = tr(\bar{r}_2^{3} u_{18\sigma_2} a_{27\sigma_2})$ ($d_{19}(64, 8) = (63, 27)$)

Proof. We will prove differential (1) first. Consider the class $tr(\bar{r}_2^{3} u_{18\sigma_2} a_{3\sigma_2})$ (75, 39). This class must die on or before the $E_{61}$-page. There are three possible ways for this class to die. It can support a $d_{31}$-differential hitting the class $\bar{d}_2^{12} u_{1\lambda} u_{36\sigma_2} a_{35\lambda}$ (74, 70): it can be the target of a $d_{19}$-differential from the class $2\bar{d}_2^{8} u_{14\lambda} u_{24\sigma_2} a_{10\lambda}$ (76, 20); or it can be the target of a $d_{43}$-differential from the class $2\bar{d}_2^{6} u_{20\lambda} u_{18\sigma_2} a_{-2\lambda}$ (76, -4).

It is impossible for this class to support a $d_{31}$-differential because it is the transfer of a class that supports a $d_{31}$-differential in the $C_2$-slice spectral sequence, and the target does not transfer to the class $\bar{d}_2^{12} u_{1\lambda} u_{36\sigma_2} a_{35\lambda}$ (74, 70).

The $d_{43}$-differential also cannot happen because the class $2\bar{d}_2^{8} u_{20\lambda} u_{18\sigma_2} a_{-2\lambda}$ (76, -4) is the transfer of $\bar{r}_2^{3} u_{4\sigma_2} a_{-4\sigma_2}$, which is the target of a $d_{41}$-differential in the $C_2$-spectral sequence. Therefore it must be killed by a differential of length at most 31.

It follows that the $d_{19}$-differential

$$d_{19}(2b^{8} u_{14\lambda} u_{24\sigma_2} a_{10\lambda}) = tr(\bar{r}_2^{3} u_{18\sigma_2} a_{3\sigma_2})$$

exists. Applying Leibniz with respect to the class $\bar{d}_2^{4} u_{24\sigma_2} a_{24\lambda}$ (48, 48) proves (1).

Differentials (2), (3), (4) are proven by the exact same method. \hfill \square

Now, we can propagate the $d_{19}$-differentials that we have proven by the classes $b^{16}$ (32, -32) and $\bar{d}_2^{4} u_{24\sigma_2} a_{24\lambda}$ (48, 48) to obtain the rest of the $d_{19}$-differentials.

**Proposition 7.19.** The $d_{19}$-differentials are
Figure 11. The $E_{19}$-page of the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}(2,2)$.

1. \[ d_{19} \left( 2b^{i+8j} \cdot (\tilde{\delta}_{t_2}^3 u_{6\sigma} a_{6\lambda})^k \right) = tr(E_3^2 a_{8\sigma_2}) \cdot b^{i-5+8j} (\tilde{\delta}_{t_2}^7 u_{6\sigma} a_{6\lambda})^k \]
   \[ i = 5, 6, j, k \geq 0 \]

2. \[ d_{19} \left( b^{9+16i} \cdot (\tilde{\delta}_{t_2}^2 u_{6\sigma} a_{6\lambda})^k \right) = tr(E_3^3 u_{8\sigma_2} a_{4\sigma_2}) \cdot b^{16i} (\tilde{\delta}_{t_2}^4 u_{6\sigma} a_{6\lambda})^k \]
   \[ i, k \geq 0. \]

They are shown in Figure 11.

7.4.3. The vanishing theorem.

**Theorem 7.20** (Vanishing Theorem). In the $a_\lambda$-localized slice spectral sequence for $a_\lambda^{-1}BP^{(C_4)}(2,2)$, we have the $d_{61}$-differential

\[ d_{61}(\tilde{\delta}_{t_2}^3 u_{16\lambda} u_{8\sigma} a_{-7\lambda a_\sigma}) = \tilde{\delta}_{t_2}^8 u_{24\sigma} a_{24\lambda} \quad (d_{61}(49, -13) = (48, 48)). \]

Furthermore, any class of the form $(\tilde{\delta}_{t_2}^8 u_{24\sigma} a_{24\lambda}) \cdot x$ must die on or before the $E_{61}$-page.
In the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}$, the class $N(\bar{v}_4)u_{16\sigma}a_{31\lambda}$ must die on or before the $E_{61}$-page because it is the target of the predicted $d_{61}$-differential

$$d_{61}(u_{16\lambda}a_{\sigma}) = N(\bar{v}_4)u_{16\sigma}a_{31\lambda},$$

obtained by norming up the $d_{31}$-differential $d_{31}(u_{16\sigma}) = \bar{v}_4a_{31\sigma}$ in the $C_2$-spectral sequence. Therefore, if we multiply the target by $\delta_{t_2}^{11}u_{32\sigma}a_{32\lambda}$, the class $\delta_{t_2}^{11}N(\bar{v}_4)u_{48\sigma}a_{48\lambda}$ (96, 96) must die on or before the $E_{61}$-page.

Under the map

$$a_\lambda^{-1}\text{SliceSS}(BP^{(C_4)}) \longrightarrow a_\lambda^{-1}\text{SliceSS}(BP^{(C_4)})(2, 2),$$

the class $\delta_{t_2}^{11}N(\bar{v}_4)u_{48\sigma}a_{48\lambda}$ is sent to $\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}$ (96, 96). By naturality and degree reasons, the only possibility is for it to be killed by a $d_{61}$-differential. This implies that the original class must also be killed by a $d_{61}$-differential in the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}$. Furthermore, by the module structure, any class in the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(C_4)}(2, 2)$ of the form $(\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}) \cdot x$ must die on or before the $E_{61}$-page.

The class $\delta_{t_2}^{8}u_{24\sigma}a_{24\lambda}$ (48, 48) is also the target of a $d_{61}$-differential because after multiplying it by $\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}$ (96, 96), it must die on or before the $E_{61}$-page. By degree reasons, the only possibility is for it to be killed by a $d_{61}$-differential. Since multiplication by $\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}$ (96, 96) induces an injection on the $E_2$-page, and all the classes above the line of slope $-1$ with this class as the origin are all divisible by it, the claimed $d_{61}$-differential must occur.

Similarly, for any class of the form $(\delta_{t_2}^{8}u_{24\sigma}a_{24\lambda}) \cdot x$, we can multiply it by $\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}$ (96, 96) to deduce that the product must die on or before the $E_{61}$-page. It follows from the same reasoning as the previous paragraph that the original class must also die on or before the $E_{61}$-page. $\square$

7.4.4. $d_{31}$-differentials. To prove the $d_{31}$-differentials, we will first prove the nonexistence of certain $d_{13}$-differentials.

**Lemma 7.21.** At the $E_{13}$-page, we have

\[(1) \quad d_{13}(\delta_{t_3}^{2}u_{8\lambda}u_{23\sigma}a_{-5\lambda}a_{\sigma}) \neq 2\delta_{t_2}^{6}u_{41\sigma}u_{6\sigma}a_{23\lambda} \quad (d_{13}(21, -9) \neq (20, 4)).\]

\[(2) \quad d_{13}(\delta_{t_3}^{2}u_{8\lambda}u_{38\sigma}a_{\lambda}a_{\sigma}) \neq 2\delta_{t_2}^{6}u_{12\lambda}u_{a\sigma}a_{48\lambda} \quad (d_{13}(33, 3) \neq (32, 16)).\]

**Proof.** Suppose (1) exists. By applying the Leibniz rule with respect to the classes $\delta_{t_3}^{2}u_{2\sigma}a_{12\lambda}$ (24, 24) and $b^8$ (16, -16), the $d_{13}$-differential

$$d_{13}(\delta_{t_3}^{2}u_{16\lambda}u_{23\sigma}a_{-\lambda}a_{\sigma}) = 2\delta_{t_2}^{6}u_{12\lambda}u_{18\sigma}a_{6\lambda} \quad (d_{13}(61, -1) = (60, 12))$$

must also exist. Consider the class $\delta_{t_2}^{2}u_{33\lambda}u_{26\sigma}a_{24\lambda}a_{\sigma}$ in (59, 49). By Theorem 7.20, this class must die on or before the $E_{61}$-page. However, with the class $2\delta_{t_2}^{6}u_{12\lambda}u_{18\sigma}a_{6\lambda}$ (60, 12) gone, there are no classes that could kill it or be killed by this class on or before the $E_{61}$-page. Contradiction.

Now, suppose (2) exists. By applying the Leibniz rule with respect to the classes $\delta_{t_2}^{2}u_{2\sigma}a_{12\lambda}$ (24, 24) and $b^8$ (16, -16), the $d_{13}$-differential

$$d_{13}(\delta_{t_3}^{2}u_{16\lambda}u_{20\sigma}a_{5\lambda}a_{\sigma}) = 2\delta_{t_2}^{6}u_{12\lambda}u_{24\sigma}a_{12\lambda} \quad (d_{13}(73, 11) = (72, 24))$$

must also exist. Consider the class $\delta_{t_2}^{11}u_{33\lambda}u_{32\sigma}a_{30\lambda}a_{\sigma}$ (71, 61). By Theorem 7.20, this class must die on or before the $E_{61}$-page. Just like the previous case, there is no
class that could kill it or be killed by it on or before the $E_{61}$-page. Contradiction. □

**Proposition 7.22.** We have the following $d_{31}$-differentials:

1. $d_{31}(tr(t_{12}^{11}u_{10\sigma_2}a_{23\sigma_2})) = \delta_{t_2}^6u_{18\sigma}a_{24\lambda}a_{6\sigma}$;
2. $d_{31}(tr(t_{12}^{11}u_{10\sigma_2}a_{23\sigma_2}) \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})) = \delta_{t_2}^6u_{18\sigma}a_{24\lambda}a_{6\sigma} \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})$;
3. $d_{31}(tr(t_{12}^{11}u_{24\sigma_2}a_{9\sigma_2}) \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})) = 2\delta_{t_2}^8u_{4\lambda}a_{24\sigma}a_{20\lambda} \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})^j$,
   $0 \leq i \leq 3$;
4. $d_{31}(tr(t_{12}^{11}u_{24\sigma_2}a_{9\sigma_2}) \cdot b^{16}(\delta^2_{t_2}u_{6\sigma}a_{6\lambda})) = 2\delta_{t_2}^8u_{4\lambda}a_{24\sigma}a_{20\lambda}b^{16}(\delta^2_{t_2}u_{6\sigma}a_{6\lambda})^j$,
   $0 \leq i \leq 3$.

**Proof.** To prove (1), first multiply the predicted target, $\delta_{t_2}^6u_{18\sigma}a_{24\lambda}a_{6\sigma}$ (42, 54), by $\delta_{t_2}^{16}u_{48\sigma}a_{48\lambda}$ (96, 96). By Theorem 7.20 and degree reasons, the product must be killed by a differential of length 61. It follows that (1) must hold.

By Theorem 7.20 and degree reasons, the target of (2) must be killed by a differential of length at most 61. The only possible differential is the ones claimed.

To prove (3), note that in the $a_{\sigma_2}$-localized slice spectral sequence of $i_{t_2}^*BP(C_3)\langle 2, 2 \rangle$, we have the differential

$$d_{31}(t_{12}^{11}u_{24\sigma_2}a_{9\sigma_2}) = t_{12}^{16}u_{8\sigma_2}a_{40\sigma_2} \cdot (d_{31}(57, 9) = (56, 40)).$$

Applying transfer to the target shows that the image of the target under the transfer map must be killed on or after the $E_{31}$-page. There are only two possibilities. Either the claimed $d_{31}$-differential exists, or it is killed by a $d_{13}$-differential from $\delta_{t_2}^7u_{8\lambda}a_{20\sigma}a_{13\lambda}a_{6\sigma}$. By Lemma 7.21, the $d_{13}$-differential does not exist. Therefore the claimed $d_{31}$-differential happens for $i = 0$. The rest of the differentials in (3) and all the differentials in (4) are proven by the same method. □

We can propagate the differentials in Proposition 7.22 with respect to the classes $\delta_{t_2}^8u_{24\sigma}a_{24\lambda}$ (48, 48) and $b^{12}(64, -64)$ to obtain the rest of the $d_{31}$-differentials.

**Proposition 7.23.** The $d_{31}$-differentials are

1. $d_{31}(tr(t_{12}^{11}u_{10\sigma_2}a_{23\sigma_2}) \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})) = \delta_{t_2}^6u_{18\sigma}a_{24\lambda}a_{6\sigma} \cdot (\delta^2_{t_2}u_{6\sigma}a_{6\lambda})^j$,
   $i = 0, 1, j \geq 0$;
2. $d_{31}(tr(t_{12}^{11}u_{24\sigma_2}a_{15\sigma_2}) \cdot b^{16}(\delta^2_{t_2}u_{6\sigma}a_{6\lambda})) = 2\delta_{t_2}^8u_{4\lambda}a_{24\sigma}a_{20\lambda}b^{16}(\delta^2_{t_2}u_{6\sigma}a_{6\lambda})^j$,
   $i, j \geq 0$.

They are shown in Figure 13.

7.4.5. $d_{37}$-differentials. To prove the $d_{37}$-differentials, we will first prove the nonexistence of certain $d_{13}$-differentials.

**Lemma 7.24.** At the $E_{13}$-page, we have

1. $d_{13}(\delta_{t_2}^{13}u_{34\sigma}a_{30\lambda}a_{5\sigma}) \neq \delta_{t_2}^{13}u_{34\sigma}a_{30\lambda}a_{5\sigma}$;
2. $d_{13}(\delta_{t_2}^{12}u_{34\sigma}a_{30\lambda} \cdot (\delta_{t_2}^2u_{6\sigma}a_{6\lambda})) \neq \delta_{t_2}^{13}u_{34\sigma}a_{30\lambda}a_{5\sigma} \cdot (\delta_{t_2}^2u_{6\sigma}a_{6\lambda})$;
3. $d_{13}(\delta_{t_2}^{11}u_{33\sigma}a_{32\sigma}a_{30\lambda}a_{\sigma}) \neq \delta_{t_2}^{12}u_{34\sigma}a_{36\lambda}a_{2\sigma}$;
4. $d_{13}(\delta_{t_2}^{11}u_{33\sigma}a_{32\sigma}a_{30\lambda}a_{\sigma} \cdot (\delta_{t_2}^2u_{6\sigma}a_{6\lambda})) \neq \delta_{t_2}^{12}u_{34\sigma}a_{36\lambda}a_{2\sigma} \cdot (\delta_{t_2}^2u_{6\sigma}a_{6\lambda})$. 
\begin{proof}
To prove (1), note that if the class $\bar{d}_{8}^{} t_{2} u_{17}^{\lambda} u_{24} a_{12} a_{12} a_{12}$ \text{(54, 70)} supports a $d_{13}$-differential, then applying the Leibniz rule with respect to the class $\bar{d}_{2}^{} t_{2} u_{18} a_{12} a_{12} a_{12}$ (24, 24) would show that the class $\bar{d}_{3}^{} t_{2} u_{24} a_{13} a_{13} a_{13} (50, 46)$ must support a differential of length at most 13. This is a contradiction because there are no possible targets. The nonexistence of differentials (2), (3), and (4) can be proven by the same method. The differentials in (5) follows from (1)-(4) by applying the Leibniz rule with respect to $\bar{d}_{3}^{} t_{2} u_{12} a_{12} a_{12} (24, 24)$ and $b_{16}^{16} (32, -32)$. \end{proof}

\begin{proposition}
We have the following $d_{37}$-differentials for $i = 0, 1$:
\[ d_{37}(\bar{d}_{6}^{} t_{2} u_{27} a_{14} a_{14} a_{14}) = \bar{d}_{6}^{} t_{2} u_{17} a_{14} a_{14} a_{14} \cdot \bar{d}_{2}^{} t_{2} u_{6} a_{6} a_{6}, \]
\[ d_{37}(\bar{d}_{6}^{} t_{2} u_{27} a_{14} a_{14} a_{14} \cdot \bar{d}_{2}^{} t_{2} u_{6} a_{6} a_{6}) = \bar{d}_{6}^{} t_{2} u_{17} a_{14} a_{14} a_{14} \cdot \bar{d}_{2}^{} t_{2} u_{6} a_{6} a_{6}. \]
\end{proposition}

\begin{proof}
To prove the differential when $i = 0$, we will show that the $d_{37}$-differential
\[ d_{37}(\bar{d}_{6}^{} t_{2} u_{27} a_{14} a_{14} a_{14} a_{14}) = \bar{d}_{6}^{} t_{2} u_{17} a_{14} a_{14} a_{14} \cdot \bar{d}_{2}^{} t_{2} u_{6} a_{6} a_{6} \cdot \bar{d}_{2}^{} t_{2} u_{6} a_{6} a_{6}. \]

\end{proof}
exists. Propagating with respect to the class $\delta^8_{t_2} u_{24} a_{24\lambda}$ (48, 48) would then prove the desired differential. Note that by Theorem 7.20, the class $\delta^{15}_{t_2} u_{17\lambda} u_{56\sigma} a_{31\lambda}$ (130, 62) must die on or before the $E_{61}$-page. There are two possibilities: either it supports a $d_{37}$-differential hitting $\delta^{15}_{t_2} u_{8\lambda} u_{56\sigma} a_{49\lambda} a_{\sigma}$ (129, 99), or the claimed differential exists. Suppose the first case happens, then we claim there is no possibility for the class $\delta^{13}_{t_2} u_{27\lambda} u_{38\sigma} a_{12\lambda} a_{\sigma}$ (131, 25) to die on or before the $E_{61}$-page. This is because if the class does die, then the only possibility is for it to support a $d_{13}$-differential hitting $2\delta^7_{t_2} u_{23\lambda} u_{42\sigma} a_{19\lambda}$ (130, 38). However, if this $d_{13}$-differential exists, then by applying the Leibniz rule with respect to the class $\delta^4_{t_2} u_{12\sigma} a_{12\lambda}$ (24, 24), the class $\delta^9_{t_2} u_{27\lambda} u_{26\sigma} a_{\sigma}$ (107, 1) must also support a differential of length at most 13. This is a contradiction because we must have the $d_{37}$-differential
\[
d_{37}(\delta^9_{t_2} u_{27\lambda} u_{26\sigma} a_{\sigma}) = \delta^{12}_{t_2} u_{17\lambda} u_{36\sigma} a_{19\lambda} \quad (d_{37}(107, 1) = (106, 38))
\]
by the Vanishing Theorem and degree reasons (Theorem 7.20). It follows that the class $\delta^9_{t_2} u_{27\lambda} u_{26\sigma} a_{\sigma}$ (107, 1) supports a $d_{37}$-differential.

The second differential, when $i = 1$, is proven by the same method. \square

**Proposition 7.26.** The $d_{37}$-differentials are

1. $d_{37}(\delta^7_{t_2} u_{8\lambda} u_{21\sigma} a_{12\lambda} a_{3\sigma} \cdot (\delta^{13}_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}) = \delta^7_{t_2} u_{18\sigma} a_{21\lambda} a_{3\sigma} \cdot (\delta^{13}_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}$, $i = 0, 1, j \geq 0$;
2. $d_{37}(\delta^8_{t_2} u_{22\sigma} a_{-5\lambda} a_{\sigma} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}) = \delta^8_{t_2} u_{8\sigma} a_{12\lambda} a_{4\sigma} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}$, $i = 0, 3, j \geq 0$;
3. $d_{37}(\delta^7_{t_2} u_{10\sigma} a_{15\lambda} a_{5\sigma} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}) = \delta^7_{t_2} u_{10\lambda} u_{8\sigma} a_{15\lambda} a_{5\sigma} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}$, $i = 0, 1, j \geq 0$;
4. $d_{37}(2b^{12+16\iota} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}) = \delta^7_{t_2} u_{12\lambda} u_{8\sigma} a_{11\lambda} b^{16\iota} (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}$, $i, j \geq 0$;
5. $d_{37}(\delta^7_{t_2} u_{11\lambda} u_{21\sigma} a_{-8\lambda} a_{\sigma} \cdot b^{16\iota} (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}) = \delta^7_{t_2} u_{12\sigma} a_{11\lambda} b^{16\iota} (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i+j}$, $i, j \geq 0$.

They are shown in Figure I3.

**Proof.** All the differentials can be proven immediately from the Vanishing Theorem and degree reasons (Theorem 7.20 and Lemma 7.24), Proposition 7.25, and propagation with respect to the classes $\delta^8_{t_2} u_{24\sigma} a_{24\lambda}$ (48, 48) and $b^{32}$ (64, −64). \square

### 7.4.6. $d_{43}$-differentials

**Proposition 7.27.** The following $d_{43}$-differentials exist for $i = 0, 1$: $d_{43}(\delta^{12}_{t_2} u_{40\lambda} u_{36\sigma} a_{-4\lambda} \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i}) = tr(F^{21}_{t_2} u_{58\sigma} a_{35\sigma} a_{35\sigma}) \cdot (\delta^7_{t_2} u_{6\sigma} a_{6\lambda})^{i}$.

**Proof.** When $i = 0$, note that by the Vanishing Theorem (Theorem 7.20), the class $tr(F^{31}_{t_2} u_{58\sigma} a_{35\sigma} a_{35\sigma})$ (151, 35) must die on or before the $E_{61}$-page. There are two possibilities. Either the claimed differential occurs, or it supports a $d_{43}$-differential hitting $2\delta^{20}_{t_2} u_{15\lambda} u_{60\sigma} a_{45\lambda}$ (150, 90). The second case does not occur because the class $2\delta^{20}_{t_2} u_{15\lambda} u_{60\sigma} a_{45\lambda}$ (150, 90) needs to support a $d_{61}$-differential killing the class $\delta^{25}_{t_2} u_{74\sigma} a_{75\lambda} a_{\sigma}$ (149, 151), or else no class would be able to kill $\delta^{25}_{t_2} u_{74\sigma} a_{75\lambda} a_{\sigma}$.
Figure 13. The $E_{37}$-page of the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP(C_4)(2, 2)$.  

(149, 151) on or before the $E_{61}$-page and we would reach a contradiction with Theorem 7.20. The second differential is proven by the same method. \[\square\]

**Proposition 7.28**. The $d_{43}$-differentials are

1. $d_{43}(b^{16+32i} \cdot (\delta^2_{t_2} u_{6a6a})^{j+4k}) = \text{tr}(I_{t_2} u_{10a22} a_{11a2}) \cdot b^{32i}(\delta^2_{t_2} u_{6a6a})^{j+4k}$,  
   $i, k \geq 0$, $j = 0, 3$;

2. $d_{43}(b^{24+32i} \cdot (\delta^2_{t_2} u_{6a6a})^{j+4k} (\delta^2_{t_2} u_{5a6a6a})^\ell) = \text{tr}(I_{t_2} u_{26a22} a_{5-5a2}) \cdot b^{32i}(\delta^2_{t_2} u_{6a6a})^{j+4k}(\delta^2_{t_2} u_{5a6a6a})^\ell$,  
   $i, k \geq 0$, $j = 0, 1$, $\ell = 0, 1, 2$.

They are shown in Figure 14.
Proof. All the differentials can be proven immediately from the Vanishing Theorem and degree reasons (Theorem 7.20, Proposition 7.27) and propagation with respect to the classes \( \delta_t^8 u_{24\sigma}a_{24\lambda} \) (48, 48) and \( b^{32} \) (64, –64).

7.4.7. \( d_{55} \)-differentials.

**Proposition 7.29.** The \( d_{55} \)-differentials are

\[
\begin{align*}
(1) & \quad d_{55} \left( \text{tr}(r_{3}^2 u_{26 \sigma} a_{-17 \sigma}) \cdot b^{32i}(\delta_t^2 u_{6\sigma} a_{6\lambda})^j 4k \right) = \delta_t^6 u_{16\sigma} a_{18\sigma} b^{32i}(\delta_t^2 u_{6\sigma} a_{6\lambda})^j 4k, \\
& \quad i, k \geq 0, j = 0, 3; \\
(2) & \quad d_{55} \left( \text{tr}(r_{3}^2 u_{26 \sigma} a_{-17 \sigma}) \cdot b^{32i}(\delta_t^2 u_{6\sigma} a_{6\lambda})^j 4k(\delta_t^2 u_{8\lambda} a_{6\sigma} a_{-2\lambda})^\ell \right) \\
& \quad = \delta_t^6 u_{16\sigma} a_{18\sigma} b^{32i}(\delta_t^2 u_{6\sigma} a_{6\lambda})^j 4k(\delta_t^2 u_{8\lambda} a_{6\sigma} a_{-2\lambda})^\ell, \\
& \quad i, k \geq 0, j = 0, 1, \ell = 0, 1, 2.
\end{align*}
\]

They are shown in Figure 14.

Proof. All the differentials can be deduced from the Vanishing Theorem and degree reasons (Theorem 7.20), and propagation with respect to the classes \( \delta_t^8 u_{24\sigma}a_{24\lambda} \) (48, 48) and \( b^{32} \) (64, –64).

7.4.8. \( d_{61} \)-differentials.

**Proposition 7.30.** We have the following \( d_{61} \)-differentials:

\[
\begin{align*}
(1) & \quad d_{61} \left( \delta_t^2 u_{16 \lambda} a_{18 \sigma} a_{-13 \lambda} \delta_t^2 u_{8 \lambda} a_{6 \sigma} a_{-2 \lambda} \right) \cdot \delta_t^2 u_{6 \sigma} a_{6 \lambda}^j 4k b^{32 \ell}, \\
& \quad i, j = (0, 0), (0, 1), (1, 0), (1, 1), (2, 0), (2, 1), (3, -3), (3, 0), k, \ell \geq 0; \\
(2) & \quad d_{61} \left( \delta_t^2 u_{15 \lambda} a_{12 \sigma} a_{-2 \lambda} \delta_t^2 u_{8 \lambda} a_{6 \sigma} a_{-2 \lambda} \right) \cdot \delta_t^2 u_{6 \sigma} a_{6 \lambda}^j 4k b^{32 \ell}, \\
& \quad i, j = (0, 0), (0, 1), (1, -3), (1, 0), (2, -4), (2, -3), (3, -4), (3, -3), k, \ell \geq 0.
\end{align*}
\]

They are shown in Figure 14.

Proof. All the differentials can be deduced from the Vanishing Theorem and degree reasons (Theorem 7.20), and propagation with respect to the classes \( \delta_t^8 u_{24\sigma}a_{24\lambda} \) (48, 48) and \( b^{32} \) (64, –64).
Figure 14. The $d_{43}$ (blue), $d_{55}$ (magenta), and $d_{61}$-differentials (black) in the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{(2)}(2,2)$. 
Figure 15. The $E_\infty$-page of the $a_\lambda$-localized slice spectral sequence of $a_\lambda^{-1}BP^{\langle \mathcal{C}_4 \rangle}(2,2)$. 
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