

MORAVA K -THEORY AND FILTRATIONS BY POWERS

TOBIAS BARTHEL¹ AND PIOTR PSTRAĞOWSKI²

¹*Max Planck Institute for Mathematics, Vivatsgasse 7, 53111 Bonn, Germany*
(tbarthel@mpim-bonn.mpg.de)

²*Department of Mathematics, Harvard University, 1 Oxford Street, Cambridge, MA*
02139, USA
(piotr@math.harvard.edu)

(Received 11 June 2022; revised 20 May 2023; accepted 24 May 2023;
first published online 4 July 2023)

Abstract We prove the convergence of the Adams spectral sequence based on Morava K -theory and relate it to the filtration by powers of the maximal ideal in the Lubin–Tate ring through a Miller square. We use the filtration by powers to construct a spectral sequence relating the homology of the K -local sphere to derived functors of completion and express the latter as cohomology of the Morava stabiliser group. As an application, we compute the zeroth limit at all primes and heights.

Contents

1	Introduction	1656
	Part 1. Morava K-theories and Milnor modules	1661
2	Morava K-theories and their Hopf algebroids	1661
3	Digression: Minimal Morava K-theory	1668
4	Milnor modules	1669
5	Cohomology	1672
6	Milnor filtration	1676
	Part 2. The K-based Adams spectral sequence	1682
7	Convergence of the K-based Adams spectral sequence	1683
8	The finite height Miller square	1685
9	The K-based Adams spectral sequence at large primes	1690
10	Height 1 K-based Adams spectral sequence at an odd prime	1699

2020 *Mathematics subject classification*: Primary 55T15
Secondary 55N15; 55N20

© The Author(s), 2023. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<https://creativecommons.org/licenses/by/4.0>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

Part 3. Homology of inverse limits and the algebraic chromatic splitting conjecture	1702
11 The homology of inverse limits	1702
12 The Morava E -homology of inverse limits	1710
13 Digression: Cohomology of \mathbb{G}_n as Ext in comodules	1717
14 Algebraic chromatic splitting conjecture	1719
15 Cooperations at height 1	1723
References	1728

1. Introduction

In this paper, which consists of three closely related parts, we investigate the relationship between the filtration by powers of the maximal ideal in the Lubin–Tate ring and chromatic homotopy theory from several perspectives. In the first part, we focus on Morava K -theories and their associated Hopf algebroids. In particular, we give an invariant description of their cohomology and prove its finiteness. We then establish convergence of the K -based Adams spectral sequence and relate it to the K -local Adams–Novikov and filtration by powers spectral sequences through a Miller square, and describe it completely at large enough primes. In the last part, we construct Hopkins’s spectral sequence relating homology of the K -local sphere with derived functors of completion, and identify the latter with cohomology of the Morava stabiliser group. As an application, we compute the zeroth limit at all primes and heights.

Main results

A classical approach to the study of an arithmetic problem is to first consider its reduction to residue fields, and to then reassemble the local solutions. Over the p -local integers, there are just two residue fields, namely, the field \mathbb{Q} of rational numbers and the finite field \mathbb{F}_p corresponding to the closed point. Informally, these detect, respectively, the torsion-free and torsion phenomena.

The approach of reducing to residue fields also works very well in stable homotopy theory, where one is interested in classifying stable homotopy classes of maps between finite complexes. Identifying a classical field k with the corresponding Eilenberg–MacLane spectrum, we have a descent spectral sequence of signature

$$E_2^{s,t} \simeq \mathrm{Ext}_{\pi_*(k \otimes_{S^0} k)}^{s,t}(k, k) \implies \pi_{t-s}(S_k^0), \quad (1.1)$$

where S_k^0 is the appropriate Bousfield localisation. When $k = \mathbb{Q}$, this collapses immediately, recovering Serre’s calculation that $\pi_* S^0 \otimes_{\mathbb{Z}} \mathbb{Q} \simeq \mathbb{Q}$. The situation is much more complicated when $k = \mathbb{F}_p$, in which case, $\mathcal{A}_* = \pi_*(\mathbb{F}_p \otimes_{S^0} \mathbb{F}_p)$ is the dual Steenrod algebra and the above recovers the classical Adams spectral sequence. In this case, the spectral sequence converges completely, but it does not collapse at any finite page, and there is no

known algorithmic way of understanding its structure¹. It is arguably the most important tool for computing the stable homotopy groups of spheres.

A new feature in homotopy theory which is not visible in the algebraic contexts is that, even p -locally, \mathbb{Q} and \mathbb{F}_p are not the only residue fields of spectra. Instead, we have an infinite family of prime fields of ‘intermediate characteristic’, given by the Morava K -theories [HS99]. These are homotopy ring spectra K with the properties that

- (1) $\pi_*K \simeq k[u^{\pm 1}]$, where k is a perfect field of characteristic p and u is an invertible variable of degree $|u| = 2$ and
- (2) the Quillen formal group $\mathbf{G}_0 := \mathrm{Spf}(K^0(\mathbf{CP}^\infty))$ over k is of height $0 < n < \infty$.

One can show that such a homotopy ring spectrum exists for any \mathbf{G}_0 of finite height over a perfect field. By a celebrated result of Devinatz, Hopkins and Smith [DHS88], [HS98], together with \mathbb{Q} and \mathbb{F}_p , these are the only residue fields of p -local spectra.

Morava K -theories are very calculable for at least two distinct reasons:

- (1) the coefficients K_* form a graded field, so that we have an unrestricted Künneth isomorphism $K_*(X \otimes Y) \simeq K_*(X) \otimes_{K_*} K_*(Y)$ for any X, Y ;
- (2) there’s a canonical Poincaré duality isomorphism $K_*(X) \simeq K^*(X)$ whenever X is a π -finite space, in particular, a classifying space of a finite group.

The second property, known as ambidexterity, is one way in which Morava K -theories behave as if they were of characteristic zero, despite the coefficients K_* being of positive characteristic. This surprising feature makes Morava K -theories a powerful tool also in more geometric contexts, such as in the breakthrough work of Abouzaid and Blumberg on the Arnold conjecture in symplectic topology [AB21].

In the present paper, we set up and analyse the descent spectral sequence associated to the Morava K -theories. As a first result, we verify that we indeed do have convergence.

Theorem A (7.4, 7.5). *Let K be a Morava K -theory. The K -based Adams spectral sequence of signature*

$$\mathrm{Ext}_{K_*K}^{s,t}(K_*, K_*(X)) \implies \pi_{t-s}L_K X$$

is conditionally convergent for any spectrum X and converges completely whenever X is K -locally dualisable.

Note that this spectral sequence does not, in general, have a horizontal vanishing line at any finite page: while each group on the second page of this spectral sequence for the sphere is torsion, the abutment $\pi_*L_K S^0$ is known to contain torsion-free summands. In order to establish conditional convergence, we instead reduce to the case of a finite n complex, where such vanishing lines exist. Complete convergence is the consequence of the degreewise finiteness of the E_2 -term, which we prove for dualisable spectra using the Cartan–Eilenberg spectral sequence. Going back to the case of nonlocalised spectra, the utility of the classical Adams spectral sequence based

¹A common saying about the classical Adams spectral sequence is ‘*Every differential is a theorem*’.

on \mathbb{F}_p is further amplified when coupled with the Adams–Novikov spectral sequence, which is the descent spectral sequence based on the Brown–Peterson spectrum BP . As one spectacular application, Miller constructs a square relating the two spectral sequences and compares the differentials to compute the v_1 -periodic homotopy of Moore spaces, thereby proving the telescope conjecture at height 1 and for all odd primes [Mil81].

The situation is similar in the case of the K -based Adams, which has a cousin which might be more familiar to the working chromatic homotopy theorist, namely, the K -local E_n -based Adams spectral sequence. Here, E_n denotes the Lubin–Tate spectrum associated to the formal group \mathbf{G}_0 , parametrising derived deformations of the latter. We show that the relation between the two spectral sequences is again governed by a square of spectral sequences of the following explicit form.

Theorem B (8.8, 8.11). *The K -local Miller square associated to (E, K) is of the form*

$$\begin{array}{ccc}
 & \text{Ext}_{E_*^\vee E}(E_*, \bigoplus_k \mathfrak{m}^k / \mathfrak{m}^{k+1} E_*^\vee X) & \\
 \text{May} \swarrow & & \searrow \text{Mahowald} \\
 \text{Ext}_{E_*^\vee E}(E_*, E_*^\vee X) & & \text{Ext}_{K_* K}(K_*, K_* X) \\
 \searrow \text{E-Adams} & & \swarrow \text{K-Adams} \\
 & \pi_* L_K X, &
 \end{array}$$

where the May spectral sequence is obtained from the \mathfrak{m} -adic filtration of $E_*^\vee X$.

We also identify the Mahowald spectral sequence in the square above with a Cartan–Eilenberg spectral sequence of a certain extension of Hopf algebroids canonically attached to each Morava K -theory (see Section 8 for details). A theorem of Miller relates the d_2 -differentials in the K -Adams and May spectral sequences, but at large primes, we can say much more. If $2p-2 > n^2 + n$, then it is well-known that the K -local E -based Adams spectral sequence for the sphere collapses at the second page. Using a variation on the classical argument of Milnor, we equip $K_* K$ at odd primes with an additional grading which also forces the collapse of the Mahowald spectral sequence.

It follows that at sufficiently large primes, two of the spectral sequences in Miller’s square collapse, and it is thus natural to expect that the other two can be identified. This is indeed the case, as we show the following.

Theorem C (9.23). *If $2p-2 > n^2 + n + 1$, then the K -based Adams spectral sequence for S_K^0 can be given an additional grading so that it becomes isomorphic to the May spectral sequence*

$$\text{Ext}_{E_*^\vee E}(E_*, \bigoplus_k \mathfrak{m}^k / \mathfrak{m}^{k+1} E_*) \implies \text{Ext}_{E_*^\vee E}(E_*, E_*) \quad (1.2)$$

induced by the filtration of E_* by the powers of the maximal ideal.

Note that one new major phenomenon in intermediate characteristic is that Morava K -theories do depend on choices; in particular, on the choice of a formal group. By a

result of Lazard Using a variation, any two such formal groups of the same height are isomorphic over the separable closure; it follows that for our purposes, all Morava K -theories of the same height are essentially interchangeable, in particular, they determine the same Adams spectral sequence.

To be more precise, while the Hopf algebroid K_*K depends on the choice of a Morava K -theory, its category of comodules does not, by a result of Hovey and Strickland [HS05a]. In the body of the text, we describe a different derivation of this result, identifying the category of K_*K -comodules with the category Mil_{abs} of *absolute Milnor modules*, which are certain sheaves on finite spectra (see Section 4). This gives an approach to the Adams spectral sequence based on Morava K -theory, which only depends on the prime and the height but no other choices.

On a different note, the completion tower of comodules of the form

$$\dots \rightarrow E_*/\mathfrak{m}^3 \rightarrow E_*/\mathfrak{m}^2 \rightarrow E_*/\mathfrak{m}$$

appearing in Theorem C also leads to a *another* spectral sequence, first studied by Hopkins and Sadofsky². The latter spectral sequence approaches the transchromatic information contained in $L_K S^0$ through its *uncompleted* E -homology $E_*(L_K S^0)$, as opposed to the homotopy groups, as we now describe in more detail.

To provide some context, recall that it is known that at large primes there exists an equivalence $hSp_E \simeq h\mathcal{D}^{per}(E_*E)$ between the homotopy categories of E -local spectra and differential comodules. Under this equivalence, the limit $\varprojlim E_*/\mathfrak{m}^k$ in the derived ∞ -category corresponds to the K -local sphere S_K^0 [Pst18]; thus, the derived completion of E_* can be thought of as the algebraic analogue of the K -local sphere.

At smaller primes, we do not have algebraic models for the homotopy category, but we instead have a spectral sequence relating the homology groups of the derived completion to $E_*(S_K^0)$. This spectral sequence, originally due to Hopkins and Sadofsky, was subsequently worked out by Peterson [Pet20], adapting the classical construction of the Adams spectral sequence. We follow a slightly different approach, based on the notion of an adapted homology theory and Devinatz–Hopkins’s modified Adams spectral sequence [Dev97].

Our construction is closely related to the work of Hovey on derived products of comodules [Hov07], and, in fact, works in much greater generality (see Section 11). In the case of E -homology, we are able to express these derived limits as cohomology of the Morava stabiliser group, leading to the following statement.

Theorem D (11.14, 12.14, 12.12). *Let $E_*E := \pi_*(E \otimes E)$ be the uncompleted E -homology of itself, given the unique topology which restricts to the \mathfrak{m} -adic topology on each finitely generated E_* -submodule. Then, there exists a canonical isomorphism*

$$H_{\text{cts}}^s(\mathbb{G}_n, E_t E) \simeq (\varprojlim_{E_*E}^s E_*/\mathfrak{m}^k)_t$$

*between the continuous cohomology of the Morava stabiliser group and the derived functors of the limit in E_*E -comodules. Moreover, there exists a spectral sequence of E_*E -*

²The construction of Hopkins and Sadofsky is unpublished.

comodules of the form

$$E_2^{s,t} \simeq H_{\text{cts}}^s(\mathbb{G}_n, E_t E) \implies E_{t-s}(L_K S^0) \quad (1.3)$$

with differentials $d_r^{s,t}: E_r^{s,t} \rightarrow E_r^{s+r,t+r-1}$. This spectral sequence converges completely and collapses at a finite page with a horizontal vanishing line.

The subtle point in this result is the convergence of the spectral sequence, which relies crucially on the finite virtual cohomological dimension of the Morava stabiliser group. Note that here it is important to consider the derived sequential limits in the category of comodules as opposed to ordinary modules over E_* ; indeed, in positive degrees, the latter all vanish in this case, and there would be no hope of having a convergent spectral sequence.

The above spectral sequence underlies one approach towards Hopkins's chromatic splitting conjecture [Pet], [Hov95]. In a nutshell, the latter provides a precise description of the transchromatic behaviour of the K -local sphere; that is, its behaviour under applying chromatic localisations L_h for intermediate heights $0 \leq h < n$. As such, it has been verified for all heights $n \leq 2$ and all primes [SY95, GHM12, Bea17], with a minor modification to the original prediction at $n = p = 2$ ([BGH17]). Beyond height 2, the conjecture remains wide open.

The standard way of approaching the splitting conjecture is through an explicit computation of the homotopy groups of $L_K S^0$. However, as mentioned, its transchromatic information is also encoded in the *uncompleted* E -homology, and this is what the spectral sequence (11.15) abuts to.

Using the identification of derived functors of the limit with continuous cohomology of the Morava stabiliser group, we are able to compute the zeroth limit at all primes and heights.

Theorem E (14.13). *There is a canonical isomorphism*

$$\varprojlim_{E_* E} E_*/\mathfrak{m}^k E_* \simeq E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p,$$

where the limit on the left is taken in the category of $E_* E$ -comodules.

Note that $E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq E_*(S_p^0)$, the homology of the p -complete sphere. Thus, the above result can be interpreted as detecting the conjectured copy of $L_{n-1} S_p^0$ inside $L_{n-1} S_K^0$ through E -homology.

At height 1, the Morava stabiliser group is particularly simple, and we are able to compute all of the derived limits.

Theorem F (15.12). *At height $n = 1$ and any prime, we have*

$$H_{\text{cts}}^s(\mathbb{G}_1, E_* E) \simeq \begin{cases} E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p & \text{when } s = 0, \\ E_* \otimes_{\mathbb{Z}} \mathbb{Q}_p & \text{when } s = 1, \\ 0 & \text{otherwise.} \end{cases}$$

Note that the above, in particular, completely recovers the height 1 case of the chromatic splitting conjecture, which states that $L_0 L_{K(1)} S^0 \simeq L_0 S_p^0 \oplus L_0 S_p^{-1}$. The latter can be

equivalently obtained by explicitly computing $\pi_* L_K S^0$, which, if we ignore torsion, contains exactly two \mathbb{Z}_p summands, one for each sphere. However, the computation of homology gives more precise information, as the two copies of \mathbb{Z}_p are isomorphic as abelian groups, but the comodules $E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p$ and $E_* \otimes_{\mathbb{Z}} \mathbb{Q}_p$ are not.

Outline of document

We hope that the structure of the document becomes apparent from the choice of section titles. In brief, the first part of the paper, comprising Sections 2 through 6 deals with Morava K -theories, their Hopf algebroids, categories of comodules and their cohomology, through the perspective of Milnor modules. We pay special attention to the (in)dependence of our constructions on the choice of Morava K -theories, and revisit the relation to continuous cohomology.

The K -based Adams spectral sequence and the finite height Miller square are the topics of Part 2. We establish convergence properties in Section 7, then construct the finite height Miller square, and use it to relate it to the filtration by powers spectral sequence. In Section 10, the final section of this part, we illustrate our results by going through explicit computations at height 1.

The third part of the paper consists of Sections 11 to 15. Here, the focus lies on the derived category of $E_* E$ -comodules and the construction and study of the inverse limit spectral sequence. We then give our application to the algebraic chromatic splitting conjecture, based on the connection to the continuous cohomology of the Morava stabiliser group. Each of the two parts ends with some explicit computations at height 1, which we hope elucidate our methods and results.

Part 1. Morava K -theories and Milnor modules

In this part of the paper, we study Morava K -theories, which play the role of residue fields of Lubin–Tate spectra. We describe their Hopf algebroids, categories of comodules and cohomology.

2. Morava K -theories and their Hopf algebroids

Let κ be a perfect field equipped with a choice of a height n formal group \mathbf{G}_0 . Associated to these data is the Lubin–Tate ring E_0 classifying deformations [LT66]. This is a complete local $W(\kappa)$ -algebra, such that there exists a noncanonical choice of regular generators inducing an isomorphism of rings $E_0 \simeq W(\kappa)[[u_1, \dots, u_{n-1}]]$. We write $\mathfrak{m} = (p, u_1, \dots, u_{n-1})$ for the maximal ideal. The ring E_0 equipped with the universal deformation is Landweber exact and so can be lifted to a 2-periodic ring spectrum E with $E_* \simeq E_0[u^{\pm 1}]$ for some unit $u \in E_2$, and the property that the formal group $\mathbf{G} := \mathrm{Spf}(E^0(BS^1))$ is the universal deformation of \mathbf{G}_0 . It is well-known that E admits a unique \mathbf{E}_∞ -ring structure, functorial in the choice of κ and the formal group (see [GH05a]). More recently, it was proven by Lurie that E arises as a solution to a moduli problem involving formal groups over \mathbf{E}_∞ -rings, see [Lur18].

The canonical nature of the Lubin–Tate spectrum makes it a good starting point for the study of chromatic phenomena. Since E_0 is local, one would like to construct a spectrum which plays the role of the residue field of E . Following Hopkins and Lurie [HL17], we make the following definition.

Definition 2.1. An \mathbf{E}_1 - E -algebra K is a *Morava K -theory* if the unit map $E \rightarrow K$ induces an isomorphism $K_* \simeq E_*/\mathfrak{m}$.

One can show that an algebra satisfying the above conditions always exists, for any Lubin–Tate spectrum E ; in fact:

- (1) there are uncountably many Morava K -theories which are not equivalent as E -algebras,
- (2) none of which is preferred and
- (3) none of which can be promoted to an \mathbf{E}_2 - E -algebra

(see [HL17] for more information).

Warning 2.2. Large parts of the literature are written in terms of the $(2p^n - 2)$ -periodic spectrum $K(n)$ with $\pi_* K(n) \simeq \mathbb{F}_p[v_n^{\pm 1}]$; this cannot be made into a Morava K -theory according to the above definition, as it is not 2-periodic. We do not use $K(n)$ in the current work, but in the interest of completeness, we collect some results about it in Section 3 below.

Throughout the rest of this section, the letter K denotes a choice of a Morava K -theory in the sense of Definition 2.1.

Remark 2.3. While two different Morava K -theories need not be equivalent as E -algebras, one can show that they are always equivalent as E -modules [HL17, Corollary 3.6.6]. In particular, they are always equivalent as spectra.

Observe that we have $K_* \simeq E_*/\mathfrak{m}E_*$ by definition, so $K_* \simeq \kappa[u^{\pm 1}]$, which is a graded field. Note that the first isomorphism is completely canonical, while the second is not, as it depends on the choice of a unit $u \in K_2$. In any case, it follows that the ring spectrum K is even periodic, and so complex-orientable. The reduction map $E^0(BS^1) \rightarrow K^0(BS^1)$ induces a canonical isomorphism $\mathrm{Spf}(K^0(BS^1)) \simeq \mathbf{G}_0$.

Remark 2.4. It is not strictly necessary to start relative to a chosen Lubin–Tate spectrum. Instead, one could say that an \mathbf{E}_1 -algebra K in spectra is a *Morava K -theory* if there exists an isomorphism $K_* \simeq \kappa[u^{\pm 1}]$ with κ a perfect field and such that $\mathbf{G}_0 := \mathrm{Spf}(K^0(BS^1))$ is of finite height. One can show that, in this case, K can be canonically lifted to an algebra over the corresponding Lubin–Tate ring spectrum. Thus, we lose no generality by working relative to E .

In this paper, we will be interested in the K -based Adams spectral sequence. By standard arguments, the E_2 -page of this spectral sequence has a description in terms of homological algebra of comodules over the Hopf algebroid K_*K . Thus, we begin by giving a partial description of the latter.

Our strategy is to exploit the E -algebra structure on K to divide K_*K into two parts, the first of which admits a convenient interpretation in terms of formal groups and the second of which is more mysterious but manageably small. We start with the latter, for which we need to work relative to E .

Notation 2.5. If M, N are E -modules, we write

$$M_*^E N := \pi_*(M \otimes_E N)$$

for their homology relative to E and

$$M_E^* N := [N, M]_E^* \simeq \pi_{-*} F_E(N, M)$$

for their relative cohomology. Here, F_E is the internal mapping E -module; that is, the right adjoint to the tensor product of E -modules.

By usual arguments involving flatness of $K_*^E K$ over K_* , the map

$$K \otimes_E K \rightarrow K \otimes_E K \otimes_E K$$

induces a K_* -coalgebra structure on $K_*^E K$. Note that this is an honest coalgebra structure; that is, the left and right units coincide, as they are necessarily maps of E_* -algebras, of which K_* is a quotient. Together with multiplication, this makes $K_*^E K$ into a Hopf algebra, which a priori need not be either commutative nor cocommutative.

Lemma 2.6. *The coalgebra structure on $K_*^E K$ is dual to an exterior algebra on an n -dimensional vector space V in degree -1 . In particular, $K_*^E K$ is cocommutative.*

Proof. Since the coefficients of K form a field, we have an isomorphism of algebras

$$\mathrm{Hom}_{K_*}(K_*^E K, K_*) \simeq [K, K]_*^E,$$

where on the right-hand side, we have maps of E -modules. One can show that the latter is always isomorphic to an exterior algebra over a vector space of the needed dimension (see [HL17, Proposition 6.5.1]). \square

Remark 2.7. Hopkins and Lurie show that $K_*^E K$ is actually isomorphic to an exterior algebra *as a Hopf algebra*, though there is, in general, no canonical such isomorphism [HL17, Proposition 5.2.4]. In particular, it is also always commutative.

Remark 2.8. As both sides are K_* -vector spaces of dimension 2^n , the latter by Lemma 2.6, the Künneth spectral sequence

$$\mathrm{Tor}_{t,s}^{E_*}(K_*, K_*) \implies K_{s+t}^E K$$

collapses. Indeed, since E_0 is a regular ring of dimension n , the relevant Tor-groups are canonically isomorphic to an exterior algebra on n generators.

The second, ‘understandable’ part of K_*K is the image of the canonical map from E_*E , which can be identified with K_*E . The analogue of this Hopf algebroid for the minimal

Morava K -theory of Section 3 is denoted in Ravenel's book by $\Sigma(n)$ (see [Rav03, §6.2]). Notice that since E_*E is flat over E_* , we have canonical isomorphisms

$$K_*E \simeq K_* \otimes_{E_*} E_*E \simeq E_*E/\mathfrak{m},$$

which in turn have the following consequence.

Proposition 2.9. *The category of K_*E -comodules is independent of K ; more precisely, for any two choices of Morava K -theories, possibly over different Lubin–Tate spectra, these categories of comodules are canonically equivalent as symmetric monoidal categories.*

Proof. By a result of Hovey–Strickland, see [HS05a, Theorem C], the categories of E_*E -comodules for varying Lubin–Tate spectra E are canonically equivalent as locally graded symmetric monoidal categories.

The category of K_*E -comodules can be identified with K_* -modules in the symmetric monoidal category Comod_{E_*E} , and $K_* \simeq E_*/\mathfrak{m}$ itself is uniquely determined as the minimal quotient of E_* as a comodule by [HS05a, Theorem D]. Thus, the equivalence of Hovey and Strickland induces one between categories of K_*E -comodules. \square

In fact, we can give a direct algebro-geometric description of this category of comodules. By standard results about Landweber exact homology theories, we have

$$E_*E \simeq E_* \otimes_{BP_*} BP_*BP \otimes_{BP_*} E_*,$$

and by again invoking flatness, we see that

$$K_*E \simeq K_* \otimes_{BP_*} BP_*BP \otimes_{BP_*} E_*.$$

Since the ideal I_n is invariant, we can instead write

$$K_*E \simeq K_* \otimes_{BP_*} BP_*BP \otimes_{BP_*} K_*.$$

This is a familiar Hopf algebroid, commutative ring homomorphisms out of which classify pairs of homomorphisms $f_1, f_2: K_* \rightarrow A$ together with a strict isomorphism of the resulting formal groups $(f_1)^*\mathbf{G}_0 = (f_2)^*\mathbf{G}_0$. In other words, we have a pullback of algebraic stacks

$$\begin{array}{ccc} \text{Spec}(K_*E) & \longrightarrow & \text{Spec}(K_*) \\ \downarrow & & \downarrow \\ \text{Spec}(K_*) & \longrightarrow & \mathcal{M}_{fg}^{\omega=1}, \end{array}$$

where $\mathcal{M}_{fg}^{\omega=1}$ is the moduli of formal groups with a trivialised Lie algebra. The maps from $\text{Spec}(K_*)$ are faithfully flat surjections onto the height n point in this moduli stack, and we deduce that the groupoid $(\text{Spec}(K_*), \text{Spec}(K_*E))$ is its presentation.

Proposition 2.10. *The category of even graded K_*E -comodules is equivalent to the category of quasi-coherent sheaves over the moduli stack \mathcal{M}_{fg}^n of formal groups of height exactly n .*

Proof. By the discussion above, the category of ungraded K_*E -comodules can be identified with the category of quasicoherent sheaves over the moduli stack $\mathcal{M}_{fg}^{n,\omega=1}$ of formal groups of height n with trivialised Lie algebra.

The even grading of K_*E corresponds under this equivalence to the \mathbf{G}_m -action on the chosen trivialisation of the Lie algebra, so that even graded comodules can be identified with the quasicoherent sheaves over the quotient stack

$$\mathcal{M}_{fg}^{n,\omega=1} / \mathbf{G}_m \simeq \mathcal{M}_{fg}^n,$$

which is exactly the claim. \square

The above discussion identifies K_*E with familiar objects from the theory of formal groups, which is why we referred to it above as the ‘understandable’ part of K_*K . The following gives some control over how these two parts are related.

Lemma 2.11. *Consider $K \otimes E$ as an E -module with the module structure inherited only from the right factor. Then, $K \otimes E$ is equivalent as an E -module to a direct sum of K s.*

Proof. We will show something stronger, namely, that the $E \otimes E$ -modules $K \otimes E$ and $E \otimes K$ are equivalent. Since the latter has the needed property, as it admits a structure of a K -module from its right factor, this will be enough. At the level of homotopy groups, the induced maps $E_*E \rightarrow E_*K$ and $E_*E \rightarrow K_*E$ are both quotients by $\mathfrak{m}E_*E = E_*E\mathfrak{m}$, where the equality is the statement that \mathfrak{m} is an invariant ideal. Since \mathfrak{m} is generated by a regular sequence, the needed statement will follow from the following result: Let $A \in \mathrm{CAlg}(\mathcal{S}p)$ be a commutative algebra in spectra, and let $B \in \mathrm{Alg}(\mathrm{Mod}_A)$ be an algebra whose unit map induces an isomorphism, $B_* \simeq A_*/I$, where I is an ideal generated by a regular sequence x_1, \dots, x_n . Then we have an equivalence of A -modules

$$B \simeq \bigotimes_A \mathrm{cofib}(x_i: A \rightarrow A).$$

In particular, as an A -module B is determined up to equivalence by I .

To see this, note that since $1 \in B_*$ is x_i -torsion, the unit factors through a map $\mathrm{cofib}(x_i) \rightarrow A$. Then the composite

$$\bigotimes_A \mathrm{cofib}(x_i) \rightarrow \bigotimes_A B \rightarrow B,$$

where the second map is the algebra multiplication, is an isomorphism on homotopy groups and thus an equivalence. \square

Corollary 2.12. *Consider $K \otimes E$ as an E -module with the module structure inherited only from the right. Then, the Künneth spectral sequence*

$$\mathrm{Tor}^{E_*}(K_*E, K_*) \implies \pi_*((K \otimes E) \otimes_E K) \simeq K_*K$$

in E -modules collapses.

Proof. This is immediate from Lemma 2.11 and Remark 2.8, as the Künneth spectral sequence depends only on the E -module structure. \square

Proposition 2.13. *The map $K_*E \rightarrow K_*K$ is injective, central and presents the target as a free K_*E -module of rank 2^n .*

Proof. To see that the map is central, notice that $K \otimes K$ is canonically an $E \otimes E$ -algebra. It follows that the map $E_*E \rightarrow K_*K$ is central, and thus so must be its image $K_*E \simeq K_* \otimes_{E_*} E_*E$.

As a consequence of Corollary 2.12, the Künneth spectral sequence

$$K_*E \otimes \mathrm{Tor}^{E_*}(K_*, K_*) \simeq \mathrm{Tor}^{E_*}(K_*E, K_*) \implies K_*K$$

in E -modules collapses. Since the Tor-groups on the left form a K_* -vector space of dimension 2^n , it follows from the above collapse that K_*K has a finite filtration as a K_*E -module, such that the associated graded is free of rank 2^n . Thus, K_*K itself must be free of this rank as well. \square

Proposition 2.14. *Passing to homotopy groups in the diagram*

$$\begin{array}{ccc} K \otimes E & \longrightarrow & K \otimes K \\ \downarrow & & \downarrow \\ K \otimes_E E & \longrightarrow & K \otimes_E K \end{array}$$

induces an isomorphism

$$K_*K \otimes_{K_*E} K_* \simeq K_*^E K.$$

Proof. Both of the Künneth spectral sequences for $K \otimes K \simeq (K \otimes E) \otimes_E K$ and $K \otimes_E K$ collapse, as a consequence of Corollary 2.12 and Remark 2.8. Thus, the map $K_*K \rightarrow K_*^E K$ is surjective after passing to associated graded, and so surjective by an inductive argument. The conclusion follows by observing that $K_* \otimes_{K_*E} K_*K \rightarrow K_*^E K$ is a surjective map of K_* -vector spaces of the same dimension. \square

We are now ready to assemble the above information. By standard arguments, the pair (K_*, K_*K) acquires the structure of a Hopf algebroid. More precisely, the two maps $K \rightarrow K \otimes K$ induce left and right units, both of which are central as a consequence of Proposition 2.13, as they factor through K_*E . These make K_*K into a K_* -bimodule, and similarly, we get a suitable comultiplication and antipode.

Note that it is common in algebraic topology literature to assume in the definition of a Hopf algebroid that multiplication is commutative. However, this is not strictly necessary; in our case, as the units are central, K_*K is a Hopf algebroid in the more general sense of Maltsiniotis [Mal92]. The category of comodules can be defined in the usual way, and it will be monoidal with the tensor product lifting that of K_* -modules. It need not, in general, be symmetric monoidal.

Remark 2.15. We believe it is plausible that K_*K is, in fact, always commutative; it is a finite algebra over the commutative algebra K_*E with the relative tensor product $K_* \otimes_{K_*E} K_*K \simeq K_*^E K$ also commutative, as a consequence of Remark 2.7. We were, however, not able to resolve this question. Note that K_*K is automatically commutative

if we choose a homotopy commutative Morava K -theory, as can always be done when $p > 2$ [HL17, Proposition 3.5.2].

Theorem 2.16. *The natural maps*

$$(K_*, K_*E) \rightarrow (K_*, K_*K) \rightarrow (K_*, K_*^E K) \quad (2.17)$$

form an extension of Hopf algebroids in the sense of Ravenel.

Proof. We first recall the relevant notation and definitions from [Rav03, Section A.1]. If (A, Γ) is a Hopf algebroid, M is a right Γ -comodule and N is a left Γ -comodule, then the cotensor product is defined as the equalizer

$$N \square_{\Gamma} M := \text{eq}(N \otimes_A M \rightrightarrows N \otimes_A \Gamma \otimes_A M)$$

between the two possible comultiplications. Two particularly important cases are

$$N \square_{\Gamma} A \simeq \text{Ext}_{\text{Comod}_{\Gamma}^R}^0(A, N),$$

the coinvariants in the category of *right* comodules and

$$N \square_{\Gamma} A \simeq \text{Ext}_{\text{Comod}_{\Gamma}^L}^0(A, N),$$

the coinvariants in the category of *left* comodules. Since $K_*K \rightarrow K_*^E K$ is surjective, consulting Ravenel's definitions of a normal map of Hopf algebroids and of an extension [Rav03, A.1.1.10, A.1.1.15], we see that in our case, we have to verify that

- (1) $K_* \square_{K_*^E K} K_*K = K_*K \square_{K_*^E K} K_*$,
- (2) $K_* \square_{K_*^E K} K_* = K_*$,
- (3) $K_* \square_{K_*^E K} K_*K \square_{K_*^E K} K_* = K_*E$.

We begin with the first part. If we write

$$K_*K \simeq \pi_*(K \otimes K) \simeq \pi_*(K \otimes_E E \otimes K) \simeq K_*^E(E \otimes K),$$

then the left $K_*^E K$ -comodule structure on K_*K given by the quotient map $K_*K \rightarrow K_*^E K$ corresponds to the standard comodule structure on the relative homology $K_*^E(E \otimes K)$ relative to E . This comodule structure map is determined by the structure of $E \otimes K$ as a left E -module with module structure coming only from the left factor. By Lemma 2.11, $E \otimes K$ is equivalent as an E -module to a direct sum of K , and so admits a compatible structure of a K -module. Choosing such a K -module structure determines an isomorphism

$$K_*^E(E \otimes K) \simeq K_*^E K \otimes_{K_*} \pi_*(E \otimes K) \simeq K_*^E K \otimes_{K_*} E_*K$$

of left comodules, so that

$$K_* \square_{K_*^E K} K_*K \simeq K_* \square_{K_*^E K} K_*^E(E \otimes K) \simeq K_* \square_{K_*^E K} (K_*^E K \otimes E_*K) \simeq E_*K$$

as needed.

Using symmetry, Lemma 2.11 similarly shows that

$$K_*K \simeq K_*E \otimes_{K_*} K_*^E K$$

as right $K_*^E K$ -comodules, so that

$$K_* K \square_{K_*^E K} K_* \simeq K_* E.$$

As $K_* E$ and $E_* K$ coincide as subobjects of $K_* K$, this shows part (1) and part (3). Part (2) is an observation that $K_*^E K$ is a Hopf algebra rather than a Hopf algebroid. \square

3. Digression: Minimal Morava K -theory

Large parts of the literature on Morava K -theories are written in terms of the *minimal Morava K -theory spectrum* $K(n)$, the unique up to equivalence BP -module with $K(n)_* \simeq \mathbb{F}_p[v_n^{\pm 1}]$. Note that it is not a Morava K -theory in the sense of Definition 2.1 as it is not 2-periodic, but as a consequence of nilpotence theorem, any Morava K -theory is equivalent as a spectrum to a direct sum of $K(n)$ [HS98, Lemma 1.8].

Our focus on 2-periodic Morava K -theories stems from our preference for Lubin–Tate spectra as they admit canonical \mathbf{E}_∞ -structures, unlike the Brown–Peterson spectrum. In this short section, we collect some results about $K(n)$ to highlight similarities and differences with the E -algebra version. We do this for completeness; these results will not be used elsewhere in the current work.

It is a result of Robinson that $K(n)$ can be made into an \mathbf{E}_1 -ring spectrum, but there is no canonical way to do so [Rob89]. A surprising result of Angeltveit shows that all choices of \mathbf{E}_1 -multiplications yield equivalent \mathbf{E}_1 -algebras in spectra [Ang11].

One can also ask about less structured multiplication. By a theorem of Würdler [Wür91], in the homotopy category hSp of spectra, the spectrum $K(n)$ admits,

- (1) if $p > 2$, a unique product $K(n) \otimes K(n) \rightarrow K(n)$;
- (2) if $p = 2$, exactly two products $K(n) \otimes K(n) \rightarrow K(n)$ differing by the symmetry on $K(n) \otimes K(n)$,

which make it into an associative BP -algebra in a way compatible with its BP -module structure [Wür91, Theorem 1.5].

The ring of cooperations of $K(n)$ has been computed completely [Wür91, Theorem 2.4]. The map $K(n)_* BP \rightarrow K(n)_* K(n)$ is injective, and we have an isomorphism

$$K(n)_* BP \simeq K(n)_* [t_i] / (v_n t_i^{p^n} - v_n^{p^i} t_i),$$

where $|t_i| = 2p^i - 2$ for $i \geq 1$. At odd primes, this extends to an isomorphism

$$K(n)_* K(n) \simeq K(n)_* BP \otimes_{K(n)_*} \Lambda_{K(n)_*}(\tau_0, \dots, \tau_{n-1}),$$

where the latter factor is an exterior algebra on $|\tau_i| = 2p^i - 1$. When $p = 2$, we instead have that

$$K(n)_* K(n) \simeq K(n)_* BP \otimes_{K(n)_*} K(n)_* [\tau_0, \dots, \tau_{n-1}] / (\tau_i^2 = t_{i+1}).$$

This is analogous to the variation in the dual Steenrod algebra depending on whether p is even or odd. Note that the latter computation implies that $K(n)_* K(n)$ is commutative also at $p = 2$, despite $K(n)$ not being homotopy commutative. The corresponding question in the 2-periodic case is open (see Remark 2.15).

4. Milnor modules

As we have seen in the previous section, there are many different Morava K -theory spectra, which makes any discussion of this subject dependent on these choices. However, as in the case of Proposition 2.9, one can show that many cohomological invariants are canonical and do not depend on any choices. In this section, we make this canonical nature transparent by introducing an absolute variant of Hopkins and Lurie's categories of *Milnor modules* (see [HL17]).

Before we work in the absolute case, let us first describe the case relative to a fixed Lubin–Tate spectrum E . Note that by the uniqueness part of the Goerss–Hopkins–Miller theorem, see [GH, Corollary 7.6] or [PV22, Theorem 7.7], this is the same as choosing a perfect field equipped with a finite height formal group.

Definition 4.1. We say that an E -module is *molecular* if it is equivalent to a finite sum of shifts of Morava K -theories of E , and denote the full subcategory of E -modules on the molecular objects by $\mathrm{Mod}_E^{\mathrm{mol}}$.

Remark 4.2. Note that since any two Morava K -theories of E are equivalent as E -modules, the notion of being molecular does not depend on any choices.

Definition 4.3. The category of E -based *Milnor modules* is the category

$$\mathrm{Mil}_E := P_\Sigma(\mathrm{Mod}_E^{\mathrm{mol}}, \mathrm{Ab})$$

of additive presheaves of abelian groups on molecular E -modules.

By construction, the category of Milnor modules is a compactly generated Grothendieck abelian category. Since molecular E -modules are stable under the E -tensor product, it acquires a nonunital symmetric monoidal structure via left Kan extension. One can show this extends uniquely to a unital symmetric monoidal structure [HL17, Propositions 4.4.1 and 4.4.10].

The main property of Milnor modules is that it canonically captures cohomology of *any* Morava K -theory relative to E , in the following sense.

Proposition 4.4. *Let K be a Morava K -theory of E . Then, the left Kan extension of the functor*

$$K_*^E(-) : \mathrm{Mod}_E^{\mathrm{mol}} \rightarrow \mathrm{Comod}_{K_*^E K}$$

which associates to any molecular E -module its relative K -homology induces a monoidal equivalence

$$\mathrm{Mil}_E \simeq \mathrm{Comod}_{K_*^E K}$$

between Milnor modules and $K_^E K$ -comodules.*

Proof. This is [HL17, Corollary 6.4.13], where we replaced the category of modules over $K_*^E K$ with comodules over its linear dual. \square

Corollary 4.5. *As a monoidal category, $\mathrm{Comod}_{K_*^E K}$ does not depend on the choice of K but only on its corresponding formal group.*

Remark 4.6. Note that in the context of Corollary 4.5, the situation is somewhat better than just saying that the categories $\mathrm{Comod}_{K_*^E K}$ for fixed E and varying K are all equivalent to each other. In fact, they are all canonically equivalent to a single category which doesn't depend on any choices, namely, the category of Milnor modules of E .

Remark 4.7. The category Mil_E is not only canonical but, in a certain, sense gives the right answer even if $K_*^E K$ -comodules do not. As an example, the restricted Yoneda embedding

$$y: \mathrm{Mod}_E \rightarrow \mathrm{Mil}_E,$$

which can be thought of as a way of taking relative K -homology without choosing K , is always a symmetric monoidal functor [HL17, Variant 4.4.11].

On the other hand, even if K is not homotopy commutative, $K_*^E K$ is both commutative and cocommutative so that the category $\mathrm{Comod}_{K_*^E K}$ acquires a symmetric monoidal structure from K_* -vector spaces. However, in this case, the relative K -homology functor

$$K_*^E(-): \mathrm{Mod}_E \rightarrow \mathrm{Comod}_{K_*^E K}$$

need not be symmetric monoidal.

If K is homotopy commutative, then the above homology theory is canonically symmetric monoidal so that we have a symmetric monoidal equivalence $\mathrm{Comod}_{K_*^E K} \simeq \mathrm{Mil}_E$. Informally, any algebraic structure which one can put on $\mathrm{Comod}_{K_*^E K}$ in a way compatible with the homology functor from E -modules must already be present in the category of Milnor modules.

Let us now describe the global analogue of this situation, which describes the Adams spectral sequence in spectra rather than E -modules; alternatively, which describes comodules over $K_* K$ rather than the relative variant $K_*^E K$.

In Miller's approach to the Adams spectral sequence, the latter is determined by the class of maps, which are K -split; that is, which are split epimorphisms after applying $K \otimes -$. This only depends on the structure of K as a spectrum and does not require any coherent multiplication.

As a consequence of the nilpotence theorem, all Morava K -theories at a fixed prime and height are, as spectra, direct sums of the minimal Morava K -theory spectrum of Section 3. It follows that they all determine the same class of epimorphisms, and hence isomorphic Adams spectral sequences. In fact, the class of epimorphisms is enough to describe canonically the abelian category whose Ext-groups form the E_2 -page. To do so, we consider sheaves with respect to a certain topology, as in the construction of synthetic spectra [Pst22].

Definition 4.8. The K_* -epimorphism topology on the ∞ -category Sp^{fin} of finite spectra is the Grothendieck pretopology in which a family $\{X \rightarrow Y\}$ is covering if and only if it consists of a single map, such that $K_* X \rightarrow K_* Y$ is surjective.

Remark 4.9. A reader familiar with [Pst22] might recall that in the construction of synthetic spectra, one works with the site of those finite spectra X , such that $K_* X$ is

projective as a K_* -module [Pst22, Definition 3.12]. Since Morava K -theories are fields, this yields the class of all finite spectra, as above.

Definition 4.10. The category of *absolute Milnor modules* is the category

$$\mathrm{Mil}_{abs} := \mathrm{Shv}_{\Sigma}(\mathrm{Sp}^{fin}, \mathrm{Ab})$$

of additive sheaves of abelian groups on finite spectra with respect to the K_* -epimorphism topology.

The category of absolute Milnor modules is a compactly generated Grothendieck abelian category with a symmetric monoidal structure induced by that of the tensor product of finite spectra.

Remark 4.11. A reader familiar with synthetic spectra might immediately recognise that the category of Milnor modules can be canonically identified as $\mathrm{Mil}_{abs} \simeq \mathrm{Syn}_K^{\heartsuit}$, the heart of the stable ∞ -category of K -based synthetic spectra of [Pst22].

The following is the absolute analogue of Proposition 4.4.

Proposition 4.12. *If K is a Morava K -theory, then the left Kan extension of the functor*

$$K_* : \mathrm{Sp}^{fin} \rightarrow \mathrm{Comod}_{K_*K}$$

induces a monoidal equivalence

$$\mathrm{Mil}_{abs} \simeq \mathrm{Comod}_{K_*K}$$

*between absolute Milnor modules and K_*K -comodules.*

Proof. This is an instance of [Pst22, Remark 3.26]. □

As a consequence, we deduce the following result proven earlier by Hovey and Strickland using slightly different methods [HS05a, Section 8].

Corollary 4.13. *The monoidal category Comod_{K_*K} of K_*K -comodules does not depend on the choice of Morava K -theory but only on the prime and height.*

Remark 4.14. By the same argument as in the relative case of Remark 4.7, if K is homotopy commutative, then we have a canonical symmetric monoidal equivalence $\mathrm{Mil}_{abs} \simeq \mathrm{Comod}_{K_*K}$.

Remark 4.15 (Homological residue fields). In the terminology of Balmer, the category of Milnor modules is the *homological residue field* of the tensor-triangulated category of finite spectra at the prime ideal of spectra of type at least n (see [Bal20], [BC21]).

Remark 4.16 (Milnor modules as sheaves). The reader can observe that there is a certain asymmetry in our definitions of Milnor modules and absolute Milnor modules; namely, in the former case, we use as our indexing category only molecular E -modules, and in the

latter case, we use *all* finite spectra. Moreover, in the latter case, we use sheaves, while in the former, presheaves are already enough.

In fact, this difference is but a trick of light, as there is an alternative description of Milnor modules which is more in line with the absolute case. Namely, one can show that Mil_E is equivalent to the category of sheaves on the ∞ -category $\text{Mod}_E^{\text{perf}}$ of perfect E -modules with respect to the $K_*^E(-)$ -epimorphism topology. Under this topology, the functor

$$E \otimes - : \mathcal{S}p^{\text{fin}} \rightarrow \text{Mod}_E^{\text{perf}}$$

becomes a morphism of sites, so that left Kan extension yields a cocontinuous, symmetric monoidal functor

$$\text{Mil}_{\text{abs}} \rightarrow \text{Mil}_E.$$

In this sense, absolute Milnor modules determine a relative Milnor module, for any choice of E , justifying the terminology.

Under the equivalences of Propositions 4.4 and 4.12, the above left Kan extension corresponds to the forgetful functor

$$\text{Comod}_{K_*K} \rightarrow \text{Comod}_{K_*^E K}.$$

The image of the monoidal unit under the corresponding right adjoint can be identified with the Hopf algebroid K_*E studied previously. As the Adams spectral sequence based on K_*E in the appropriate derived ∞ -categories can be identified with the Cartan–Eilenberg spectral sequence associated to this extension of Hopf algebroids [Bel20, Theorem 1.1], we deduce that the Cartan–Eilenberg spectral sequence itself can be constructed using only the categories of Milnor modules, so it only depends on E .

5. Cohomology

In this section, we establish finiteness properties of the cohomology of K_*K -comodules using the Cartan–Eilenberg spectral sequence.

We have seen in Theorem 2.16 that we have an extension of Hopf algebroids

$$(K_*, K_*E) \rightarrow (K_*, K_*K) \rightarrow (K_*, K_*^E K)$$

which induces a Cartan–Eilenberg spectral sequence of signature

$$\text{Ext}_{K_*E}^s(K_*, \text{Ext}_{K_*^E K}^{s'}(K_*, K_*)) \implies \text{Ext}_{K_*K}^{s+s'}(K_*, K_*)$$

(see [Rav03, A.1.3.14]). This can be thought of as approximating the cohomology of K_*K using simpler pieces, namely, the cohomology of K_*E and $K_*^E K$. To make the best use of this, we need to begin by understanding the latter two. We have seen in Section 2 that the Hopf algebroid (K_*, K_*E) is an even graded presentation of the moduli of formal groups

of height exactly n (see Proposition 2.10). To identify its cohomology, it is convenient to choose a particularly small presentation of the latter moduli stack, which is what we will do.

Notation 5.1. We follow the conventions of [GHMR05, Section 2]. Let \mathbf{G}_0 be the Honda formal group law over \mathbb{F}_q , where $q = p^n$, and let E_n be the associated Lubin–Tate spectrum and K_n a Morava K -theory associated to E_n . Note that we have a noncanonical isomorphism

$$\pi_0 E_n \simeq W(\mathbb{F}_q)[[u_1, \dots, u_{n-1}]],$$

and a canonical isomorphism

$$\pi_* E_n \simeq (\pi_0 E_n)[u^{\pm 1}]$$

with $|u| = -1$. We write $\mathbb{G}_n \simeq \mathbb{S}_n \rtimes \text{Gal}(\mathbb{F}_q/\mathbb{F}_p)$ for the *extended Morava stabiliser group*, the automorphism group of the pair $(\text{Spec}(\mathbb{F}_q), \mathbf{G}_0)$; see [Hen17, Section 4.1] for an explicit description of this group. By the functoriality of the Goerss–Hopkins–Miller theorem [GH05b], the canonical action of \mathbb{G}_n on $(\text{Spec}(\mathbb{F}_q), \mathbf{G}_0)$ induces a left action on the Lubin–Tate spectrum E_n .

Lemma 5.2. *The association $\mathbb{G}_n \times (K_n)_* E_n \rightarrow (K_n)_*$ sending an element $g \in \mathbb{G}_n$ and a homotopy class $S^k \rightarrow K_n \otimes E_n$ to the homotopy class of the composite*

$$S^k \longrightarrow K_n \otimes E_n \xrightarrow{id \otimes g} K_n \otimes E_n \xrightarrow{m} K_n,$$

induces an isomorphism $\text{map}_{\text{cts}}(\mathbb{G}_n, (K_n)_) \simeq (K_n)_* E_n$ of algebras between the K_n -homology of E_n and continuous functions on the Morava stabiliser group.*

Proof. This is a result of Strickland, reduced modulo \mathfrak{m} [Str00, Theorem 12]. □

One can check that the above isomorphism is compatible with the Hopf algebroid structure, which is induced from the group structure on \mathbb{G}_n and its action on $(K_n)_* \simeq \mathbb{F}_q[u^{\pm 1}]$, which yields the following.

Corollary 5.3. *For any Morava K -theory K , there is a canonical equivalence of categories between $K_* E$ -comodules and graded $\mathbb{F}_q[u^{\pm 1}]$ -vector spaces equipped with a continuous action of the extended Morava stabiliser group \mathbb{G}_n .*

Proof. We have proven previously in Proposition 2.9 that the category of $K_* E$ -comodules is independent of the choice of K . For the particular choice of $K = K_n$ as above, this equivalence of categories is induced by Lemma 5.2. □

Remark 5.4. In terms of the equivalence $\text{Comod}_{K_* E}^{ev} \simeq \text{QCoh}(\mathcal{M}_{fg}^n)$ of Proposition 2.10, Corollary 5.3 is a consequence of the fact that the map $\mathbb{F}_q \rightarrow \mathcal{M}_{fg}^n$ classifying the Honda formal group law is a Galois covering with automorphism group \mathbb{G}_n ; we refer to [Goe08] for further details.

Corollary 5.5. *For any Morava K -theory, there is a canonical isomorphism*

$$\mathrm{Ext}_{K_*E}^{s,t}(K_*, K_*) \simeq \mathrm{H}_{\mathrm{cts}}^*(\mathbb{G}_n, \mathbb{F}_q[u^{\pm 1}])$$

between the cohomology of the Hopf algebroid (K_, K_*E) and the continuous cohomology of the Morava stabiliser group.*

The group $\mathbb{G}_n \simeq \mathbb{S}_n \rtimes \mathrm{Gal}(\mathbb{F}_q/\mathbb{F}_p)$ is a semidirect product of the automorphism group \mathbb{S}_n of \mathbf{G}_0 and the Galois group. The former is a p -adic Lie group, in fact, a group of units in the integers of the central division algebra over \mathbb{Q}_p of Hasse invariant $\frac{1}{n}$, which gives its excellent cohomological properties.

The action of the Morava stabiliser group on $\mathbb{F}_q[u^{\pm 1}]$ is easy to describe. The Galois group acts by its standard action on \mathbb{F}_q . The action of \mathbb{S}_n factors through the leading coefficient homomorphism $\rho: \mathbb{S}_n \rightarrow \mathbb{F}_q^\times$ and is determined by the formula $s \cdot u = \rho(s)u$ for $s \in \mathbb{S}_n$. The kernel of ρ is the strict Morava stabiliser group S_n ; it is a pro- p -group acting trivially. Morava [Mor85] essentially proved:

Theorem 5.6 (Morava). *We have isomorphisms of continuous cohomology groups*

$$\mathrm{H}_{\mathrm{cts}}^*(\mathbb{G}_n, \mathbb{F}_q[u^{\pm 1}]) \simeq \mathrm{H}_{\mathrm{cts}}^*(\mathbb{S}_n, \mathbb{F}_q[u^{\pm 1}])^{\mathrm{Gal}} \simeq \mathrm{H}_{\mathrm{cts}}^*(S_n, \mathbb{F}_q[u^{\pm 1}])^{\mathbb{F}_q^\times \rtimes \mathrm{Gal}}.$$

Moreover, these groups are finite in each bidegree. If $(p-1) \nmid n$, this is a Poincaré duality algebra over $\mathrm{H}_{\mathrm{cts}}^0 \simeq \mathbb{F}_p[v_n^{\pm 1}]$ of dimension n^2 , where $v_n := u^{p^n-1}$, in particular, their total dimension is finite.

Proof. These isomorphisms are induced by the collapse of the respective Lyndon–Hochschild–Serre spectral sequences, as neither Gal nor \mathbb{F}_q^\times have any higher cohomology with these coefficients, the first one by Galois theory and the second one as it is of order coprime to p .

The finiteness statements are due to Lazard, as S_n is a p -adic analytic Lie group of dimension n^2 and so has a finite index subgroup whose cohomology is isomorphic to an exterior algebra [SW00, Theorem 5.1.5] of dimension n^2 . If $(p-1) \nmid n$, then S_n has no p -torsion, see [Hen98, Theorem 3.2.1], and so it has the same cohomological dimension as all of its finite index subgroups [Ser65]. \square

Corollary 5.7. *For any finite-dimensional K_*E -comodules M, N , the groups $\mathrm{Ext}_{K_*E}^{t,s}(M, N)$ are finite in each bidegree. If $(p-1) \nmid n$, then they vanish for $s > n^2$.*

Proof. We first claim that any finite-dimensional K_*E -comodule M has an invariant element; that is, there exists a nonzero map $K_* \rightarrow M$ of comodules (possibly of nonzero internal degree). Observe that M can be considered as an E_*E -comodule using restriction along the maps $E_*E \rightarrow K_*E$ and $E_* \rightarrow K_*$. As M is finitely generated over E_* , it admits a nonzero map $E_* \rightarrow M$ of comodules by a result of Hovey and Strickland [HS05a, Theorem D]. As the target is \mathfrak{m} -torsion, the map factors through a map $K_* \rightarrow M$ of K_*E -comodules, which is what we were looking for.

We deduce that any finite-dimensional comodule M can be obtained as an iterated extension of shifts of K_* . Indeed, this is clear if M is zero-dimensional. If $\dim_{K_*}(M) > 0$, then by the above, we can find a nonzero map of comodules $K_* \rightarrow M$, which is then

necessarily injective. Then the cokernel is of lower dimension, and hence can be obtained as an iterated extension by induction.

Finally, observe that the finiteness of Ext-groups holds when $M = N = K_*$ as a combination of Corollary 5.5 and Theorem 5.6. The general case is proven by presenting M, N as iterated extensions as in the previous paragraph and using the corresponding long exact sequences of Ext-groups. \square

To get hold of the Cartan–Eilenberg spectral sequence, we also need to have some control over the cohomology of $K_*^E K$. By a result of Hopkins and Lurie, see Remark 2.7, the latter is isomorphic to an exterior algebra as a Hopf algebra, and so its cohomology is necessarily a polynomial ring. In fact, the same authors identify the generators of this polynomial ring, as we now recall.

Suppose that $x \in \mathfrak{m}$ is an element of the maximal ideal. We then have a cofibre sequence

$$E \rightarrow E/x \rightarrow \Sigma E$$

of E -modules which induces a short exact sequence

$$0 \rightarrow K_* \rightarrow K_*^E(E/x) \rightarrow K_*[1] \rightarrow 0$$

of $K_*^E K$ -comodules. Let us denote by $\psi(x)$ the corresponding element of $\text{Ext}_{K_*^E K}^{1,-1}(K_*, K_*)$.

Proposition 5.8. *The association $x \mapsto \psi(x)$ induces a map*

$$\mathfrak{m}/\mathfrak{m}^2 \rightarrow \text{Ext}_{K_*^E K}^{1,-1}(K_*, K_*)$$

which extends to an isomorphism of bigraded rings

$$K_* \otimes_{\kappa} \text{Sym}_{\kappa}^*(\mathfrak{m}/\mathfrak{m}^2) \simeq \text{Ext}_{K_*^E K}(K_*, K_*).$$

Proof. As we show in Proposition 4.4, the category of $K_*^E K$ -comodules can be identified, as a monoidal category, with the category of Milnor modules associated to E . It follows that we have

$$\text{Ext}_{K_*^E K}^*(K_*, K_*) \simeq \text{Ext}_{\text{Mil}_E}^*(y(E), y(E)),$$

the cohomology in Milnor modules, where $y(E)$ is the Milnor module associated to E . For the right-hand side, the needed isomorphism is proven in [HL17, Proposition 7.2.7]. \square

Remark 5.9. If we again let K_n be any Morava K -theory associated to the Honda formal group over \mathbb{F}_q , it follows that the Cartan–Eilenberg spectral sequence for cohomology of the unit has signature

$$H_{\text{cts}}^{s_0}(\mathbb{G}_n, \mathbb{F}_q[u^{\pm 1}] \otimes_{\mathbb{F}_q} \text{Sym}_{\mathbb{F}_q}^{s_1}(\mathfrak{m}/\mathfrak{m}^2)) \implies \text{Ext}_{K_*^E K}^{s_0+s_1}(K_*, K_*).$$

To determine the action on the symmetric algebra, it is convenient to work in the context of Milnor modules, as in the proof of Proposition 5.8. The category of Milnor modules Mil_E is by construction functorial in automorphisms of E , and it is clear that the association $x \mapsto \psi(x)$ is natural with respect to the action of the Morava stabiliser group. It follows that the action of \mathbb{G}_n on this symmetric algebra is the one induced by its action on the cotangent space $\mathfrak{m}/\mathfrak{m}^2$ of the Lubin–Tate ring.

Using the Cartan–Eilenberg spectral sequence, we can prove the following finiteness statement.

Theorem 5.10. *Let M, N be finite-dimensional K_*K -comodules. Then, the group $\text{Ext}_{K_*K}^{s,t}(M, N)$ is finite in each bidegree.*

Proof. By replacing N by $N \otimes M^\vee$, where $M^\vee := \text{Hom}_{K_*}(M, K_*)$ is the linear dual, we can assume that $M = K_*$. We have a Cartan–Eilenberg spectral sequence of signature

$$\text{Ext}_{K_*E}^{s_0}(K_*, \text{Ext}_{K_*^EK}^{s_1}(K_*, N)) \implies \text{Ext}_{K_*K}^{s_0+s_1}(K_*, N).$$

The groups contributing to $\text{Ext}_{K_*K}^s(K_*, N)$ are those indexed by s_0, s_1 with $s_0 + s_1 = s$, of which there are finitely many. For a fixed s_1 , the group $\text{Ext}_{K_*^EK}^{s_1}(K_*, N)$ is finite-dimensional over K_* since both M and K_*^EK are, and we can compute this Ext-group using the cobar complex. The finiteness of $\text{Ext}_{K_*E}^{s_0}(K_*, -)$ applied to these groups follows from Corollary 5.7. \square

6. Milnor filtration

In this section, we describe a filtration on K_*K , which arises from its module structure over E , which we call the *Milnor filtration*. We show that at odd primes, this filtration can be canonically refined to a grading which forces the Cartan–Eilenberg spectral sequence associated to the extension $K_*E \rightarrow K_*K \rightarrow K_*^EK$ to collapse.

Remark 6.1. This existence of an additional grading at $p > 2$ is a finite height analogue of the classical argument involving the Cartan–Eilenberg spectral sequence associated to $H\mathbb{F}_p$ (see [Rav03, Theorem 4.3.3]).

The Milnor filtration will be induced by a suitable filtration of the spectrum $K \otimes K$. Before we work with such objects, we first recall some standard definitions and establish terminology.

A nonnegatively *filtered spectrum* is a functor $P_\bullet: \mathbb{N} \rightarrow \mathcal{S}p$, where we consider the natural numbers as a partially ordered set. If X is a spectrum, then a *filtration* on X is a filtered spectrum P_\bullet together with an equivalence $\varinjlim P_\bullet \simeq X$.

Remark 6.2. Note that according to our terminology, any filtered spectrum is canonically a filtration of its colimit.

To any filtration P_\bullet , we can attach an associated nonnegatively graded spectrum

$$\text{gr}(P_\bullet) = \bigoplus_s \text{gr}_s(P_\bullet)$$

with the degree s part defined by

$$\text{gr}_s(P_\bullet) := \text{cofib}(P_{s-1} \rightarrow P_s),$$

where $P_{-1} = 0$ by convention. The boundary maps

$$\Sigma^{-1}\text{gr}_s(P_\bullet) \rightarrow P_{s-1} \rightarrow \text{gr}_{s-1}(P_\bullet)$$

make $\Sigma^{-s}\mathrm{gr}_s(P_\bullet)$ into a chain complex in the homotopy category of spectra. Any filtration has a corresponding spectral sequence of signature

$$E_{s,t}^1 := \pi_t \Sigma^{-s} \mathrm{gr}_s(P_\bullet) \implies \pi_{s+t} X,$$

where the first differential is induced by the chain complex structure on the associated graded [Lur16, Section 1.2.2]. The increasing filtration on $\pi_* X$ associated to this spectral sequence is given by the images of the maps $\pi_* P_s \rightarrow \pi_* X$.

There is a natural tensor product on the ∞ -category of filtered spectra, given by Day convolution. This has the properties that

- (1) if P_\bullet and S_\bullet are filtrations of X, Y , then $P_\bullet \otimes S_\bullet$ is a filtration of $X \otimes Y$ and
- (2) $\mathrm{gr}(P_\bullet \otimes S_\bullet) \simeq \mathrm{gr}(P_\bullet) \otimes \mathrm{gr}(S_\bullet)$, where the latter is the tensor product of graded objects.

In fact, the latter equivalence can be upgraded to an isomorphism in the category of chain complexes in the homotopy category of spectra, where we consider the latter as symmetric monoidal with the differential on the tensor product given by the usual Leibniz rule [Rak20, Remark 3.2.15].

Example 6.3. We will need certain special filtrations of E -modules, the main reference here being Lurie [Lur16, Section 7.2.1], who works with simplicial objects. By the stable Dold–Kan correspondence of [Lur16, Section 1.2.4], this is equivalent to working with filtered objects as we do.

If P_\bullet is an E -module filtration of some M , then we say P_\bullet is E -free if the associated simplicial object is S -free with respect to the set $S = \{ \Sigma^n E \mid n \in \mathbb{Z} \}$. We say it is an E -resolution if it is E -free and an S -hypercov. For precise definitions of these terms, see [Lur16, Definition 7.2.1.2]. The two main facts we need are that:

- (1) if P_\bullet is E -free, then the associated graded E -module is levelwise free,
- (2) if it is a resolution, then $\pi_* \Sigma^{-n} \mathrm{gr}_n(P_\bullet)$ is a projective resolution of M_* in E -modules.

Lurie shows that any E -module M admits a resolution, which is unique (as an augmented simplicial object) up to simplicial homotopy.

If P_\bullet is an E -module resolution of M and X is an arbitrary spectrum, then $P_\bullet \otimes X$ is a filtration of $M \otimes X$, and so we get a spectral sequence whose signature is readily shown to be

$$E_{t,s}^2 := \mathrm{Tor}_{s,t}^{E_*}(M_*, E_* X) \implies M_* X.$$

This is the Künneth spectral sequence which we previously mentioned in Corollary 2.12. Note that in the particular case of $X = S^0$, this spectral sequence is concentrated on the $s = 0$ line, as E_* is flat over itself, so that the filtration on the homotopy groups M_* induced by P_\bullet is trivial.

We are now ready to make the key definition of this section.

Definition 6.4. The *Milnor filtration* on $K_*K \simeq \pi_*(K \otimes K)$ is the filtration induced by the filtration $P_\bullet \otimes P_\bullet$ of $K \otimes K$, where P_\bullet is an E -free resolution of K as an E -module.

In fact, the above filtration is readily identified with a familiar one.

Lemma 6.5. *The Milnor filtration coincides with the filtration induced by the Künneth spectral sequence of signature*

$$\mathrm{Tor}_{s,t}^{E_*}(K_*, E_*K) \implies K_{t+s}K.$$

Proof. The Künneth spectral sequence is induced by the filtration $P_\bullet \otimes K$, and the obvious map $P_\bullet \rightarrow K$ into the constant filtration of the latter induces a comparison map $P_\bullet \otimes P_\bullet \rightarrow P_\bullet \otimes K$ of filtrations of $K \otimes K$. We claim this induces an isomorphism of spectral sequences starting from the second page onwards, and hence an isomorphism of filtrations of K_*K .

On the first pages of the corresponding spectral sequences, we are looking at the map

$$\pi_*(\mathrm{gr}(P_\bullet) \otimes \mathrm{gr}(P_\bullet)) \rightarrow \pi_*(\mathrm{gr}(P_\bullet \otimes K)),$$

where we have suppressed the suspensions needed to make the above into chain complexes of graded abelian groups.

Note that if M is an arbitrary E -module, then $E_*M \simeq E_*E \otimes_{E_*} M$ as E_*E is flat over E_* so that the corresponding Künneth spectral sequence collapses. It follows that since each $\mathrm{gr}(P_\bullet)$ is levelwise free as an E -module, we can rewrite the above map on first pages of the corresponding spectral sequences as

$$\pi_*\mathrm{gr}(P_\bullet) \otimes_{E_*} E_*E \otimes_{E_*} \pi_*\mathrm{gr}(P_\bullet) \rightarrow \pi_*\mathrm{gr}(P_\bullet) \otimes_{E_*} E_*E \otimes_{E_*} K_*.$$

The tensor product of the first two factors is a nonnegatively graded complex of flat E_* -modules, so that tensoring with it preserves quasi-isomorphism. As $\mathrm{gr}_*(P_\bullet) \rightarrow K_*$ is a quasi-isomorphism, we deduce that so is the map on first pages, ending the argument. \square

Corollary 6.6. *The Milnor filtration does not depend on the choice of the E -free resolution.*

Proof. This is immediate from Lemma 6.5, as any two E -free filtrations P_\bullet^1, P_\bullet^2 induce the same Künneth filtration, as $P_\bullet^1 \otimes K$ and $P_\bullet^2 \otimes K$ are simplicially homotopic. \square

Remark 6.7. By symmetry, Lemma 6.5 implies that the Milnor filtration also coincides with the filtration induced by the other Künneth spectral sequence, namely, that of signature

$$\mathrm{Tor}_{s,t}^{E_*}(K_*E, K_*) \implies K_{t+s}K.$$

The main advantage of using the Milnor filtration is that its definition is manifestly symmetric, so that it is easier to work with.

Note that since the Milnor filtration coincides with the Künneth one, we immediately deduce that the associated graded object is given by

$$\mathrm{Tor}_{*,*}^{E_*}(K_*, E_*K) \simeq \mathrm{Tor}_{*,*}^{E_*}(K_*, K_*) \otimes E_*K,$$

where the additional grading comes from the external Tor-grading. In particular, the elements of filtration zero are given by

$$F_0^{Mil}(K_*K) = E_*K,$$

the image of the canonical map $E_*E \rightarrow K_*K$. As the latter is a sub-Hopf algebroid, this suggests that the Milnor filtration is compatible with the Hopf algebroid structure. This is indeed the case, as we now show.

Lemma 6.8. *The Milnor filtration on K_*K is multiplicative.*

Proof. We first claim that the multiplication map $K \otimes K \rightarrow K$ lifts to a morphism $P_\bullet \otimes P_\bullet \rightarrow P_\bullet$ of filtrations.

Observe that since K is an E -algebra, the multiplication factors canonically through a map $K \otimes_E K \rightarrow K$. Observe that $P_\bullet \otimes_E P_\bullet$ is an E -free filtration of $K \otimes_E K$ (although not a resolution, but this is not needed). Then, since P_\bullet is an E -module resolution of K , it follows from [Lur16, Proposition 7.2.1.5] (where $C = K$) that the map $K \otimes_E K \rightarrow K$ of E -modules lifts to a map $P_\bullet \otimes_E P_\bullet \rightarrow P_\bullet$ of filtrations. The needed lift of $K \otimes K \rightarrow K$ is then given as composition

$$P_\bullet \otimes P_\bullet \rightarrow P_\bullet \otimes_E P_\bullet \rightarrow P_\bullet,$$

where the first map is the canonical one to the relative tensor product.

We now claim that the multiplication on $K \otimes K$ also lifts to a map of corresponding filtrations of spectra, showing that it respects filtrations on homotopy groups. This product map is given up to homotopy by the composite

$$K \otimes K \otimes K \otimes K \xrightarrow{K \otimes \sigma \otimes K} K \otimes K \otimes K \otimes K \xrightarrow{m \otimes m} K \otimes K,$$

where σ is the twist in the symmetric monoidal structure. This is lifted to a map of filtrations by

$$(P_\bullet \otimes P_\bullet) \otimes (P_\bullet \otimes P_\bullet) \xrightarrow{P_\bullet \otimes \sigma \otimes P_\bullet} P_\bullet \otimes P_\bullet \otimes P_\bullet \otimes P_\bullet \xrightarrow{\tilde{m} \otimes \tilde{m}} P_\bullet \otimes P_\bullet,$$

where \tilde{m} is the lift of the multiplication map constructed above. This ends the argument. \square

Theorem 6.9. *The Milnor filtration makes K_*K into a filtered Hopf algebroid over K_* .*

Proof. We have already checked that the Milnor filtration is preserved by multiplication on K_*K in Lemma 6.8. Thus, we are left with comultiplication and antipode. The latter is induced by the twist map $K \otimes K$, which can be lifted to a map of filtration by the twist on $P_\bullet \otimes P_\bullet$, hence it preserves the filtration on homotopy groups.

We move on to comultiplication $\Delta: K_*K \rightarrow K_*K \otimes_{K_*} K_*K$. This is induced by the map

$$K \otimes K \simeq K \otimes S^0 \otimes K \xrightarrow{K \otimes u \otimes K} K \otimes K \otimes K \simeq (K \otimes K) \otimes_K (K \otimes K),$$

where $u: S^0 \rightarrow K$ is the unit and we implicitly use the Künneth isomorphism

$$\pi_*((K \otimes K) \otimes_K (K \otimes K)) \simeq K_*K \otimes_{K_*} K_*K,$$

which holds in full generality since K_* is a field.

As P_\bullet is an E -free filtration of K , it induces a trivial filtration on K_* , so that the unit factors through some map $S^0 \rightarrow P_0$. The latter induces a map $\tilde{u}: S^0 \rightarrow P_\bullet$ of filtrations, where we equip the sphere with the trivial filtration, which makes it into the monoidal unit of filtered spectra.

Consider the composite

$$P_\bullet \otimes P_\bullet \xrightarrow{P_\bullet \otimes \tilde{u} \otimes P_\bullet} P_\bullet \otimes P_\bullet \otimes P_\bullet \longrightarrow P_\bullet \otimes K \otimes P_\bullet \simeq (P_\bullet \otimes K) \otimes_K (K \otimes P_\bullet)$$

which by construction lifts the map, inducing comultiplication. As the filtrations of K_*K induced by $P_\bullet \otimes K$ and $K \otimes P_\bullet$ coincide with the Milnor filtration by Lemma 6.5 and Remark 6.7, we deduce that comultiplication preserves the Milnor filtration as needed. \square

We now show that if $p > 2$ and K_*K is commutative—for example, if K is homotopy commutative—then the Milnor filtration can be canonically promoted to a grading. We will prove that the existence of this grading implies that the Cartan–Eilenberg spectral sequence associated to the extension $K_*E \rightarrow K_*K \rightarrow K_*^E K$ collapses.

Assume that $p > 2$ and K_*K is commutative. We first use the Milnor filtration to describe K_*K completely as an algebra. By Lemma 6.5, the associated graded to the Milnor filtration is given by

$$\mathrm{Tor}_{*,*}^{E*}(K_*, E_*K) \simeq \mathrm{Tor}_{*,*}^{E*}(K_*, K_*) \otimes E_*K.$$

Observe that since $F_0^{\mathrm{Mil}}(K_*K) \simeq E_*K$ is concentrated in even internal degrees, the canonical projection

$$F_1^{\mathrm{Mil}}(K_*K) \rightarrow \mathrm{gr}_1^{\mathrm{Mil}}(K_*K) \simeq \mathrm{Tor}_1^{E*}(K_*, K_*) \otimes E_*K$$

is an isomorphism in odd internal degrees. It follows that the inclusion

$$i: \mathrm{Tor}_1^{E*}(K_*, K_*) \hookrightarrow \mathrm{Tor}_1^{E*}(K_*, K_*) \otimes E_*K$$

can be uniquely lifted to a map

$$j: \mathrm{Tor}_1^{E*}(K_*, K_*) \rightarrow F_1^{\mathrm{Mil}} K_*K.$$

Since $\mathrm{Tor}_{*,*}^{E*}(K_*, K_*)$ is an exterior algebra on elements of external degree one, when $p > 2$, this Tor-algebra is a free commutative K_* -algebra on the vector space $\mathrm{Tor}_{1,*}$. If K_*K is commutative, it follows that the above lift j uniquely extends to a map of K_* -algebras

$$\mathrm{Tor}_{*,*}^{E*}(K_*, K_*) \rightarrow K_*K$$

with the following property:

Proposition 6.10. *Let $p > 2$, and assume that K_*K is commutative. Then, the induced map of E_*K -algebras*

$$\mathrm{Tor}_{*,*}^{E_*}(K_*, K_*) \otimes_{K_*} E_*K \rightarrow K_*K \quad (6.11)$$

is an isomorphism.

Proof. By construction, the above map is surjective on the associated graded of K_*K with respect to the Milnor filtration. Thus, it is surjective by an inductive argument, and as a surjective map of free E_*K -modules of the same rank, it must be an isomorphism. \square

As a consequence of Proposition 6.10, K_*K inherits an additional external grading from the grading of Tor-groups. This grading can be made explicit, as in the following definition.

Definition 6.12. Let $p > 2$, and assume that K_*K is commutative. Then, the *Milnor grading* on K_*K is the unique algebra grading, such that

- (1) elements of Milnor filtration zero are of Milnor degree zero and
- (2) odd internal degree elements of Milnor filtration at most one are of Milnor degree one.

Lemma 6.13. *The Milnor grading is well-defined.*

Proof. This is immediate from Proposition 6.10, as the external grading on the algebra tensor product on $\mathrm{Tor}_{*,*}^{E_*}(K_*, K_*) \otimes_{K_*} E_*K$ is uniquely determined by which elements are of degrees zero and one. \square

Remark 6.14. The increasing filtration associated to the Milnor grading is exactly the Milnor filtration. Thus, this grading can be considered as a refinement of the latter canonical filtration, which exists at all primes and with no assumptions on commutativity.

Theorem 6.15. *Let $p > 2$, and assume that K_*K is commutative. Then, the Milnor grading on K_*K is compatible with comultiplication and antipode, making it into a bigraded Hopf algebroid.*

Proof. As K_*K is generated as an algebra by elements in Milnor degrees zero and one, it is enough to check that these two degrees are preserved. The subspace of elements of Milnor degree at most one coincides with elements of filtration at most one, which get preserved by comultiplication and antipode by Theorem 6.9.

Since the ones in Milnor degree zero are precisely those of even internal degree, and the ones in Milnor degree one are exactly the ones of odd internal degree, we deduce that each degree gets preserved separately by both comultiplication and antipode. \square

Remark 6.16. To see what goes wrong if $p = 2$, observe that even if K_*K were commutative, odd degree elements do not have to square to zero, and so there need not be a multiplicative extension of the canonical map $\mathrm{Tor}_1^{E_*}(K_*, K_*) \rightarrow K_*K$ to a map on the whole Tor-algebra.

One can try to define the Milnor grading at $p = 2$ directly similarly to Definition 6.12, by declaring that elements in Milnor degree s are the s -fold products of those in Milnor degree one. This is bound to fail; the calculations of Würigler in the case of the minimal Morava K -theory given in Section 3 show that the elements τ_i of Milnor degree one square to nonzero elements of Milnor degree zero.

Theorem 6.17. *Suppose that $p > 2$ and that K_*K is commutative. Then, the Cartan–Eilenberg spectral sequence associated to the extension*

$$K_*E \rightarrow K_*K \rightarrow K_*^E K$$

collapses on the second page, inducing a canonical isomorphism

$$\mathrm{Ext}_{K_*K}(K_*, K_*) \simeq \mathrm{Ext}_{K_*E}(K_*, \mathrm{Ext}_{K_*^E K}(K_*, K_*)).$$

Proof. Under the given assumptions, K_*K is bigraded using its internal grading and the Milnor grading of Definition 6.12. This grading is compatible with the above extension, with all of K_*E of Milnor degree zero.

As $K_*^E K \simeq \Lambda_{K_*}(V)$ as Hopf algebras, where V is the K_* -vector subspace of primitive elements, we have

$$\mathrm{Ext}_{K_*^E K}^{*,*,*}(K_*, K_*) \simeq \mathrm{Sym}_{K_*}(V^\vee),$$

an isomorphism with the symmetric algebra. Here, V^\vee is of homological degree one and Milnor degree one, and so the whole above Ext-algebra is concentrated on the plane of elements for which the Milnor degree is equal to the homological one.

Since the Cartan–Eilenberg differentials lower the homological degree and preserve the Milnor degree, we deduce that they are all zero. This gives an isomorphism as above up to passing to associated graded to the homological filtration, as the extension problems all get trivialised by the additional grading. \square

Part 2. The K -based Adams spectral sequence

In this part, we study the Adams spectral sequence based on a Morava K -theory K at arbitrary height n and prime p , constructed as part of a finite height analogue of Miller’s square of spectral sequences. In particular, we establish its (perhaps surprisingly) good convergence properties and identify it with the filtration by powers spectral sequence, at least for sufficiently large primes p . We then conclude this part with an illustration of the spectral sequence at heights 1 and odd primes, already exhibiting the existence of arbitrary long differentials.

Remark 6.18 (Adams spectral sequence based on Milnor modules). We do not proceed in this way, but one can phrase the K -based Adams spectral sequence entirely in terms of absolute Milnor modules, following Miller’s observation that the Adams spectral sequence is determined by the class of K_* -injective maps.

To see this, notice that the restricted Yoneda embedding, followed by a sheafification, gives a symmetric monoidal functor

$$y: \mathrm{Sp} \rightarrow \mathrm{Mil}_{abs}$$

which can be considered a Milnor modules-valued homology theory. That is, the functor y takes cofibre sequences to exact sequences, preserves arbitrary direct sums and takes the suspension in spectra to the distinguished autoequivalence of Milnor modules induced by the suspension functor on Sp^{fin} .

By construction, any injective object in Milnor modules can be lifted to a representing object in spectra, and this allows one to construct a ‘ y -based’ Adams spectral sequence based on injectives, where the E_2 -terms are canonically given by Ext-groups in absolute Milnor modules [PP21]. Through the equivalence of Proposition 4.12, this spectral sequence is canonically isomorphic to the K -based Adams spectral sequence for any choice of Morava K -theory.

7. Convergence of the K -based Adams spectral sequence

In this short section, we prove that the K -based Adams spectral sequence is conditionally convergent for any K -local spectrum, and it converges completely in the dualisable case.

Remark 7.1. As observed in Remark 6.18, the K -based Adams spectral sequence depends only on the choice of the prime and the height. However, this independence from choices will not be needed in this section, as the arguments we use apply equally well to any Morava K -theory.

By standard arguments, the K -based Adams spectral sequence is isomorphic to the totalisation spectral sequence obtained by mapping into the *canonical K -Adams resolution*

$$X \rightarrow K \otimes X \rightrightarrows K \otimes K \otimes X \rightrightarrows \dots$$

Thus, it follows that the K -based Adams spectral sequence converges to the homotopy of the *K -nilpotent completion of X* :

$$\mathrm{Tot}(K^{\otimes \bullet + 1} \otimes X) := \varprojlim_{s \in \Delta} K^{\otimes \bullet + 1} \otimes X.$$

Since the totalisation is K -local as a limit of K -local spectra, there is a canonical comparison map from the K -localisation of X . Our first task is to determine when this map is an equivalence.

Proposition 7.2. *For any spectrum X , the K -nilpotent completion of X is equivalent to the K -localisation of X ; that is, the canonical map*

$$L_K X \rightarrow \mathrm{Tot}(K^{\otimes \bullet + 1} \otimes X) \tag{7.3}$$

is an equivalence.

Proof. Since both sides are K -local, it is enough to show that this map is a K_* -isomorphism. The latter can be checked after tensoring with any non- K -acyclic spectrum as K_* is a field, so that we have the Künneth isomorphism, and tensoring with a nonzero K_* -vector space reflects isomorphisms.

After tensoring with a finite spectrum $F(n)$ of type n , the above map becomes

$$L_K(X \otimes F(n)) \rightarrow \text{Tot}(K^{\otimes \bullet + 1} \otimes X \otimes F(n)),$$

as both sides of (7.3) define exact functors in X and so commute with tensoring with a finite spectrum. Thus, it is enough to check the result holds for $X \otimes F(n)$.

The proof of the smash product theorem in [Rav92, Chapter 8] shows that S^0 is E -prenilpotent; that is, $L_E S^0 \in \text{Thick}^{\otimes}(E)$, where $\text{Thick}^{\otimes}(Y)$ denotes the smallest full subcategory of $\mathcal{S}p$ which contains Y , is thick and is closed under smashing with arbitrary objects in $\mathcal{S}p$. It follows that

$$L_K F(n) \simeq L_E F(n) \in \text{Thick}^{\otimes}(E \otimes F(n)) \subseteq \text{Thick}^{\otimes}(K).$$

In other words, $F(n)$ is K -prenilpotent. By definition, $X \otimes F(n)$ is thus also K -prenilpotent for all $X \in \mathcal{S}p$. Therefore, Bousfield's theorem [Bou79, Theorem 6.10] applies to provide an equivalence $L_K(X \otimes F(n)) \simeq \text{Tot}(K^{\otimes \bullet + 1} \otimes X \otimes F(n))$, which is what we wanted. \square

If X, Y are spectra, then by applying $[Y, -]$ to the canonical K -Adams resolution of X , we obtain the Adams spectral sequence as the totalisation spectral sequence. Since K_* is a field, $K_* Y$ is projective over the base ring, so that by standard arguments, the resulting spectral sequence has signature

$$E_2^{s,t}(Y, X) \simeq \text{Ext}_{K_* K}^{s,t}(K_* Y, K_* X) \implies [Y, L_K X]^{t-s}.$$

Indeed, if we use the canonical Adams resolution, then the first page of the Adams spectral sequence is given by the cobar complex, which in the projective case computes the Ext-groups in comodules [Rav03, Corollary A.1.2.12].

Corollary 7.4. *For any K -local spectrum X and any Y , the K -based Adams spectral sequence converges conditionally in the sense of Boardman to $[Y, L_K X]$.*

Proof. The totalisation spectral sequence is the spectral sequence induced by the tower of partial totalisations. Conditional convergence to $[-, L_K X]$ in the sense of Boardman is equivalent to the natural map from $L_K X$ into the limit of this tower being an equivalence, so that the statement follows from Proposition 7.2. \square

Let us write $E_r^{*,*}(Y, X)$ for the r -th page of the K -based Adams spectral sequence converging conditionally to $[Y, L_K X]$, so that we have $E_2^{s,t}(Y, X) \simeq \text{Ext}_{K_* K}^{s,t}(K_* Y, K_* X)$. The differentials in this spectral sequence are of the form

$$d_r: E_r^{s,t}(Y, X) \rightarrow E_r^{s+r, t+r-1}(Y, X).$$

In particular, for $r > s$, there are inclusions $E_{r+1}^{s,t}(Y, X) \subseteq E_r^{s,t}(Y, X)$, and we write

$$E_{\infty}^{s,t}(Y, X) = \lim_r E_r^{s,t}(Y, X).$$

Let $F^*[Y, L_K X]_*$ denote the filtration on $[Y, L_K X]_*$ induced by the spectral sequence. Following Bousfield [Bou79, Section 6], we say that the K -based Adams spectral sequence

for X converges completely if the canonical maps

$$[Y, L_K X]_* \twoheadrightarrow \lim_s [Y, L_K X]_* / F^s [Y, L_K X]_*$$

and

$$F^s [Y, L_K X]_* / F^{s+1} [Y, L_K X]_* \hookrightarrow E_\infty^{s, s+*} (Y, X)$$

are isomorphisms. By the work of Bousfield, see [Bou79, Proposition 6.3], this is equivalent to the condition that $\lim_{r>s}^1 E_r^{s,t} (Y, X)$ vanishes.

Proposition 7.5. *The K -based Adams spectral sequence of signature*

$$\mathrm{Ext}_{K_* K}^{s,t} (K_* Y, K_* X) \implies [Y, L_K X]^{t-s}$$

converges completely for any spectra X and Y with $K_ X$ and $K_* Y$ finite-dimensional.*

Proof. By Theorem 5.10, the groups in the E_2 -term are all finite. Therefore, the system

$$(E_r^{s,t} (Y, X))_{r>s}$$

is Mittag-Leffler, so that Bousfield's convergence criterion [Bou79, Proposition 6.3] applies. \square

Remark 7.6. For a spectrum X , the homology $K_* X$ being finite-dimensional is equivalent to X being K -locally dualisable (see [HS99, Theorem 8.6]).

Remark 7.7. In general, the K -based Adams spectral sequence may fail to converge completely in the sense of Bousfield (see Example 10.7).

8. The finite height Miller square

In his seminal paper [Mil81] on relations between Adams spectral sequences, Miller uses the relationship between the Adams–Novikov and classical Adams spectral sequences to prove the telescope conjecture at height 1 and odd primes. In this section, we apply his axiomatic framework to the case of Lubin–Tate and Morava K -theory spectra.

In Miller's framework, one starts with a map $A \rightarrow B$ of homotopy ring spectra; that is, an arrow in the category $\mathrm{Alg}(\mathrm{ho}(\mathrm{Sp}))$. In this context, it is not hard to show that a map $X \rightarrow Y$ of spectra which is A -*monic*, in the sense that $A \otimes X \rightarrow A \otimes Y$ is a split inclusion, is also B -*monic*. Thus, any B -injective spectrum is also A -injective (see [Mil81, Lemma 2.1]).

Definition 8.1 (Miller). A spectrum X is (A, B) -*primary* if there exists an A -Adams resolution $X \rightarrow I^\bullet$, such that for each m , the B -Adams spectral sequence computing $\pi_* I^m$ converges and collapses on the second page.

When X is (A, B) -primary, Miller constructs a square of spectral sequences

$$\begin{array}{ccc}
 & E_{A,B}^2(X) & \\
 \swarrow \text{May} & & \searrow \text{Mahowald} \\
 E_A^2(X) & & E_B^2(X) \\
 \searrow \text{A-Adams} & & \swarrow \text{B-Adams} \\
 & \pi_* X &
 \end{array}$$

which we now explain. The terms $E_A^2(X), E_B^2(X)$ form the second pages of the relevant Adams spectral sequences, and the bottom two arrows are the corresponding Adams spectral sequences.

The construction of the other two spectral sequences is more involved, but let us briefly recall the arguments of Miller. Observe that $E_A^2(X)$ arises as homology of the cochain complex $\pi_* I^\bullet$, where I^\bullet is an A -Adams resolution as in Definition 8.1. As this cochain complex is given by homotopy groups, it has an additional filtration given by the B -Adams filtration. By definition, the term $E_{A,B}^2(X)$ is the cohomology of the associated graded of $\pi_* I^\bullet$ with respect to this filtration, and the top left arrow is the associated cohomology of filtered complex spectral sequence, which Miller calls the *May spectral sequence*.

If X is primary in the sense of Definition 8.1, the cohomology $E_{A,B}^2(X)$ of the associated graded of $\pi_* I^\bullet$ is the same as the cohomology of the complex $E_B^2(I^\bullet)$ consisting of the B -Adams E_2 -pages of the spectra I^\bullet . As all A -split maps are B -split, these E_2 -pages are related by long exact sequences and can be collected into an E_1 of an exact couple using that I^\bullet is a resolution of X , yielding a spectral sequence computing $E_B^2(X)$. This is the spectral sequence in the top right corner, which Miller calls the *Mahowald spectral sequence*.

Remark 8.2. Miller proves that the above diagram of spectral sequences is commutative in the sense that, after making appropriate choices, the d_2 -differentials in the May spectral sequence can be identified with d_2 -differentials in the B -Adams spectral sequence [Mil81, Theorem 4.2]. In the case of Morava K -theory and under the assumption that the prime is large enough compared to the height, we generalise this result to higher differentials in Proposition 9.13.

Let us give an explicit description of these spectral sequences for Lubin–Tate spectra and Morava K -theories. Note that in this case, the E -based Adams spectral sequence computes the E -local homotopy groups, which are quite different from the K -local ones. Thus, to get a commutative square, we should work internally to K -local spectra.

Our first goal is to show that the K -based Adams spectral sequence has a particularly simple form for E -modules with flat homotopy groups. To do so, we will reduce to the profree case using the work of Hovey [Hov04c].

Before we proceed, let us recall that the completion functor $M_* \mapsto (M_*)_{\mathfrak{m}}^\vee := \varprojlim M_*/\mathfrak{m}^n M_*$ is neither left nor right exact, but it has left derived functors $L_s: \text{Mod}_{E_*} \rightarrow$

Mod_{E_*} . For more properties of these functors, see [HS99, Appendix B] or [BF15, Appendix A].

Lemma 8.3. *Let M_* be an E_* -module, such that $\mathrm{Tor}_{s^*}^{E_*}(M_*, K_*) = 0$ for $s > 0$; for example, M_* can be flat over E_* . Then, the completion $(M_*)_{\mathfrak{m}}^{\vee}$ is profree.*

Proof. This is proven by Hovey in [Hov04c, Proposition 1.2]. \square

Lemma 8.4. *Let M be an E -module such that M_* is flat over E_* . Then, the K -localisation map $M \rightarrow L_K M$ induces an isomorphism $\pi_* L_K M \simeq (M_*)_{\mathfrak{m}}^{\vee}$ with the completion.*

Proof. Hovey constructs for any E -module M a strongly convergent spectral sequence of signature

$$L_s M_t \rightarrow \pi_{t+s} L_K M.$$

In the present case, the spectral is concentrated on the zero line by Lemma 8.3, hence, the spectral sequence collapses, inducing the needed isomorphism. \square

Corollary 8.5. *Let M be an E -module, such that M_* is flat over E_* . Then, $L_K M$ is equivalent as an E -module to the K -localisation of a direct sum of copies of E .*

Proof. We have $\pi_* L_K M \simeq (M_*)_{\mathfrak{m}}^{\vee}$ by Lemma 8.4 and $(M_*)_{\mathfrak{m}}^{\vee}$ is profree by Lemma 8.3. Choosing pro-generators of the latter induces a map $L_K(\bigoplus E) \rightarrow L_K M$ from a direct sum of shifts of E which is an equivalence by inspection of homotopy groups. \square

Proposition 8.6. *If M is an E -module, such that M_* is E_* -flat, then the K -Adams filtration on M_* is the \mathfrak{m} -adic one and the K -based Adams spectral sequence for M converges completely to $\pi_* L_K M := (M_*)_{\mathfrak{m}}^{\vee}$ and collapses on the second page.*

Proof. By flatness, we have $\pi_* L_K M \simeq (M_*)_{\mathfrak{m}}^{\vee}$. Since the \mathfrak{m} -adic filtration on M_* is induced by that of completion, we can replace M by its K -localisation. In this case, M is K -locally equivalent to a direct sum of E by Corollary 8.5. As the Adams spectral sequence of a direct sum is a direct sum of spectral sequences, we can assume that $M = E$.

We have a base-change isomorphism

$$\mathrm{Ext}_{K_* K}(K_* E, K_*) \simeq \mathrm{Ext}_{K_*^E K}(K_*, K_*)$$

and, by Proposition 5.8, a further isomorphism

$$\mathrm{Ext}_{K_*^E K}(K_*, K_*) \simeq K_* \otimes_{\kappa} \mathrm{Sym}_{\kappa}^*(\mathfrak{m}/\mathfrak{m}^2).$$

Since E_0 is regular, $\mathrm{Sym}_{\kappa}^*(\mathfrak{m}/\mathfrak{m}^2)$ can be identified with the associated graded to the \mathfrak{m} -adic filtration on E_0 .

We deduce from the above that the E_2 -term of the K -based Adams for E is abstractly isomorphic to the associated graded of the \mathfrak{m} -adic filtration on E_* . Moreover, since the E_2 -term is concentrated in even Adams degree, we deduce that the Adams spectral sequence collapses.

We are left with showing that the K -based Adams filtration on E_* coincides with the \mathfrak{m} -adic one. Observe that since $E \rightarrow K$ is a K_* -monomorphism by Proposition 2.13, the elements of positive Adams filtration are precisely given by $\mathfrak{m}E_* = \ker(E_* \rightarrow K_*)$.

Using compatibility of the Adams filtration with products, we deduce that any element of $\mathfrak{m}^n E_*$ is of Adams filtration at least n . Thus, one filtration is contained in the other. As their associated gradeds have the same dimension over K_* by what was said above, we deduce that the two filtrations must coincide, as needed. \square

Proposition 8.7. *Let X be a spectrum, such that $E_*^\vee(X) := \pi_* L_K(E \otimes X)$ is profree; for example, such that $E_* X$ is flat. Then, X is (E, K) -primary in the K -local category.*

Proof. The implication that $E_* X$ flat implies $E_*^\vee X$ profree is a combination of Lemma 8.3 and Proposition 8.6.

Since $E_* E$ is flat over E_* , this, in particular, implies that $E_*^\vee E$ is profree, which can be also proven directly using evenness (see [HS99, Theorem 8.6]). It follows (as in [BH16, Corollary 1.24], for example) that

$$\pi_* L_K(E^\bullet \otimes X) \simeq (E_*^\vee E)^{\otimes_{E_*}^\vee \bullet - 1} \otimes_{E_*}^\vee E_*^\vee X,$$

where on the right-hand side we have the completed tensor products, which are again profree. This together with Proposition 8.6 implies that the standard K -local E -based Adams resolution

$$\begin{array}{ccccccc} L_K X & \longrightarrow & L_K(E \otimes X) & \longrightarrow & L_K(E \otimes \overline{E} \otimes X) & \longrightarrow & \dots \\ & & \downarrow & & \downarrow & & \\ & \swarrow \text{dashed} & L_K(\overline{E} \otimes M) & \swarrow \text{dashed} & L_K(\overline{E} \otimes \overline{E} \otimes X) & & \end{array}$$

satisfies the primarity condition. \square

If $E_*^\vee X$ is profree, then the E_1 -page of the K -local E -based Adams spectral sequence is given by the cobar complex

$$\pi_* L_K(E^\bullet \otimes X) \simeq (E_*^\vee E)^{\otimes_{E_*}^\vee \bullet - 1} \otimes_{E_*}^\vee E_*^\vee X.$$

It follows from Proposition 8.6 that the K -Adams filtration on these homotopy groups coincides with the filtration by powers of the maximal ideal \mathfrak{m} ; this is the ‘filtration by powers’ appearing in the title. This has the following consequence.

Corollary 8.8. *If $E_*^\vee X$ is profree, then Miller’s May spectral sequence associated to (E, K) coincides with the spectral sequence of signature*

$$\mathrm{Ext}_{E_*^\vee E}^{s,t}(E_*, \bigoplus \mathfrak{m}^n / \mathfrak{m}^{n+1} E_*^\vee X) \implies \mathrm{Ext}_{E_*^\vee E}^{s,t}(E_*, E_*^\vee X)$$

obtained by filtering $E_^\vee X$ by powers of the maximal ideal; that is, by $\mathfrak{m}^n E_*^\vee X$.*

Proof. Since Miller’s May spectral sequence is induced by the K -Adams filtration on the homotopy groups of the K -local E -Adams resolution, this is a consequence of Proposition 8.6, as under the above assumption all of the spectra in the resolution are profree. \square

Remark 8.9. The identification of the E_2 -page of the K -local E -based Adams spectral sequence is somewhat subtle. However, in the case where $E_*^\vee X$ is profree, it follows from [BH16] that it acquires a structure of a suitably complete comodule over $E_*^\vee E$ and that the E_2 -page is given by the Ext-groups in comodules as above.

We deduce that the K -local Miller square associated to (E, K) is of the form

$$\begin{array}{ccc}
 & \text{Ext}_{E_*^\vee E}(E_*, \bigoplus \mathfrak{m}^n / \mathfrak{m}^{n+1} E_*^\vee X) & \\
 \swarrow \text{May} & & \searrow \text{Mahowald} \\
 \text{Ext}_{E_*^\vee E}(E_*, E_*^\vee X) & & \text{Ext}_{K_* K}(K_*, K_* X) \\
 \searrow E\text{-Adams} & \pi_* L_K X, & \swarrow K\text{-Adams}
 \end{array} \tag{8.10}$$

whenever $E_*^\vee X$ is profree. This leaves the question of identifying the Mahowald spectral sequence, which is not too difficult.

Proposition 8.11. *If $E_*^\vee X$ is profree, then Miller's Mahowald spectral sequence based on (E, K) can be identified with the Cartan–Eilenberg spectral sequence associated to the extension of Hopf algebroids*

$$K_* E \rightarrow K_* K \rightarrow K_*^E K.$$

Proof. Taking the standard K -local E -Adams resolution

$$X \rightarrow L_K(E \otimes X) \rightarrow L_K(E \otimes \overline{E} \otimes X) \rightarrow \dots$$

and applying K -homology gives the long exact sequence of comodules of the form

$$K_* X \rightarrow K_* E \otimes K_* X \rightarrow K_* E \otimes_{K_*} \overline{K_* E} \otimes_{K_*} K_* X \rightarrow \dots$$

Applying $\text{Ext}_{K_* K}(K_*, -)$ to the above leads to an exact couple which yields the Mahowald spectral sequence.

Note that from the description of the E_1 -term, we see that this is just the $K_* E$ -based Adams spectral sequence in the derived category of $K_* K$ -comodules, sometimes called the Margolis–Palmieri spectral sequence. This is known to be isomorphic to the Cartan–Eilenberg spectral sequence associated to the extension (see [Bel20, Theorem 4.2]). \square

Remark 8.12. We have shown in Theorem 6.17 that if $p > 2$, then the Cartan–Eilenberg spectral sequence computing $\text{Ext}_{K_* K}(K_*, K_*)$ collapses on the second page. It follows from the isomorphism of Proposition 8.11 that the same is true for Miller's (E, K) -Mahowald spectral sequence associated to $X = S^0$.

Remark 8.13. Note that applying Proposition 8.11 to the starting terms of the respective spectral sequences implies, in particular, that

$$\text{Ext}_{E_*^\vee E}(E_*, \bigoplus \mathfrak{m}^n / \mathfrak{m}^{n+1} E_*) \simeq \text{Ext}_{E_* K}(K_*, \text{Ext}_{K_*^E K}(K_*, K_*)).$$

This can be proven directly, without resorting to Miller's work, using Hopkins and Lurie's calculation of the cohomology of $K_*^E K$, which we stated as Proposition 5.8. The key is that since E_0 is regular, we have $\mathrm{Sym}_\kappa(\mathfrak{m}/\mathfrak{m}^2) \simeq \bigoplus \mathfrak{m}^n/\mathfrak{m}^{n+1}$.

Remark 8.14. If we again pick $E = E_n$, the Lubin–Tate spectrum associated to the Honda formal group law of height n over \mathbb{F}_{p^n} , then the relevant Ext-groups appearing in the Miller square can be described in terms of the cohomology of the Morava stabiliser group (see [BH16, Theorem 4.3]). Keeping this choice of E in mind, we can rewrite the Miller square as

$$\begin{array}{ccc}
 & H^*(\mathbb{G}_n, \bigoplus \mathfrak{m}^n/\mathfrak{m}^{n+1} E_*^\vee X) & \\
 \swarrow \text{May} & & \searrow \text{Mahowald} \\
 H^*(\mathbb{G}_n, E_*^\vee X) & & \mathrm{Ext}_{K_*K}(K_*, K_*X) \\
 \searrow \text{E-Adams} & & \swarrow \text{K-Adams} \\
 & \pi_* L_K X &
 \end{array}$$

Remark 8.15. In the important case of $(MU, H\mathbb{F}_p)$, the Miller square can also be described explicitly (see, for example [GWX21]). In this context, the Miller square foreshadows the later development of the $C\tau$ -philosophy of Gheorghe, Isaksen, Wang and Xu which applied motivic methods to breakthrough results in stable homotopy groups of spheres [IWX20].

9. The K -based Adams spectral sequence at large primes

It is well-known that if p is large compared to the height, then the E -based Adams–Novikov spectral sequence for the K -local sphere collapses. As the same is true for the Mahowald spectral sequence, as we have shown in Remark 8.12, we deduce that under these assumptions, two of the sides of the Miller square of (8.10) represent collapsing spectral sequences.

It is then only natural to expect that the other two sides can be identified up to regrading; in this section, we show that this is indeed the case. More precisely, we show that if $2p - 2 > n^2 + n + 1$, then the K -based Adams spectral sequence for the sphere is isomorphic to the filtration by powers spectral sequence

$$H^*(\mathbb{G}_n, \bigoplus \mathfrak{m}^n/\mathfrak{m}^{n+1}) \implies H^*(\mathbb{G}_n, E_*),$$

which we can identify with Miller's May spectral sequence by Corollary 8.8.

Remark 9.1. Note that a result of Miller [Mil81, Theorem 4.2] relates the d_2 -s in the May and K -based Adams spectral sequence, at all primes and heights. Our first approach to this problem was to try to push Miller's methods further into higher differentials, hoping that the collapses of the other two spectral sequences in the square would simplify the situation. This approach was unsuccessful, and below we use quite different methods.

Remark 9.2. While we show in this section that at large primes the K -based Adams spectral sequence admits an algebraic description, it *never* collapses for $n > 0$, unlike the

Adams–Novikov spectral sequence. Indeed, the element $v_n = u^{p^n-1} \in \text{Ext}_{K_*K}^{0,2p^n-2}(K_*, K_*)$ is never a permanent cycle, as the K -local sphere is of type 0 and so cannot admit a v_n -periodic map.

To prove our comparison result, we use an algebraicity result for homotopy categories of E -local spectra at large primes due to the second author, strengthened in recent work with Patchkoria [PP21], which compares it to the following algebraic construction.

Notation 9.3. Let us write $\mathcal{D}(E_*E)$ for the derived ∞ -category of the abelian category of comodules. This is a symmetric monoidal stable ∞ -category, with monoidal unit given by E_* itself, considered as a chain complex concentrated in degree zero. The unit defines for any $X \in \mathcal{D}(E_*E)$ its *homotopy groups*

$$\text{Ext}_{\mathcal{D}(E_*E)}^{s,t}(X) := [\Sigma^s E_*[t], X]_{\mathcal{D}(E_*E)}.$$

Notice that the homotopy groups are bigraded, since the abelian category of E_*E -comodules has an internal grading. This endows the derived ∞ -category with *two* gradings,

- (1) the *homological* one given by the suspension and corresponding above to s and
- (2) the *internal one* induced from the grading shift functor on Comod_{E_*E} and corresponding above to t .

In the special case of X being a comodule, considered as an object of the heart, these homotopy groups encode the E_2 -term of the E -based Adams spectral sequence in the ∞ -category of spectra.

Definition 9.4. The *periodicity algebra* $P(E_*)$ is the \mathbf{E}_∞ -algebra in $\mathcal{D}(E_*E)$ determined by the commutative algebra

$$E_*[\tau^{\pm 1}], \text{ where } |\tau| = (1, -1)$$

in chain complexes of comodules, equipped with the zero differential.

Notation 9.5. For brevity, let us write

$$\text{Mod}_{P(E_*)} := \text{Mod}_{P(E_*)}(\mathcal{D}(E_*E)).$$

The following result shows that modules over the periodicity algebra give an algebraic model for the homotopy category of E -local spectra.

Theorem 9.6. *If $2p - 2 > n^2 + n$, there exists an equivalence*

$$\phi: h\mathcal{S}p_E \simeq h\text{Mod}_{P(E_*)} \mathcal{D}(E_*E)$$

of homotopy categories of E -local spectra and $P(E_*)$ -modules which is moreover compatible with homology functors in the sense that the following diagram commutes

$$\begin{array}{ccc} hSp_E & \xrightarrow{\phi} & h\mathrm{Mod}_{P(E_*)}\mathcal{D}(E_*E) \\ & \searrow E_*(-) & \swarrow H_0 \\ & \mathrm{Comod}_{E_*E} & \end{array}$$

Proof. This is proven under the assumption $2p-2 > 2(n^2+n)$ in the second author's thesis [Pst18]. The bound was improved to the one given above in joint work with Patchkoria [PP21]. \square

Remark 9.7. Note that as an \mathbf{E}_1 -algebra in $\mathcal{D}(E_*E)$, the connective cover of the periodicity algebra $P(E_*)$ can be identified with the free \mathbf{E}_1 -algebra on the object $\Sigma E_*[-1]$, and so is uniquely determined by its homology groups.

The category of modules over $P(E_*)$ (considered only as a stable ∞ -category) can be identified with the subcategory of modules over the connective cover spanned by those modules on which τ acts invertibly. Thus, to define the target of the equivalence of Theorem 9.6, it is not strictly necessary to work with algebras in chain complexes as in Definition 9.4, but we do so out of convenience.

Remark 9.8. For any $M, N \in \mathrm{Mod}_{P(E_*)}$, we have an Adams spectral sequence of signature

$$\mathrm{Ext}^{s,t}(H_0(M), H_0(N)) \implies [M, N]_{t-s},$$

where on the right-hand side, we have homotopy classes of maps of $P(E_*)$ -modules.

This observation, due to Franke [Fra], is the starting point for the comparison of $\mathrm{Mod}_{P(E_*)}$ to the E -local category. The general form of Franke's conjecture implies that all stable ∞ -categories admitting a suitably convergent Adams-type spectral sequence of this signature must have equivalent homotopy categories [PP21].

One of the advantages of $P(E_*)$ -modules over E -local spectra is the existence of the free module functor

$$P(E_*) \otimes -: \mathcal{D}(E_*E) \rightarrow \mathrm{Mod}_{P(E_*)}$$

(also called the *periodicisation*) which is cocontinuous and symmetric monoidal. The homotopy groups of free modules can be understood explicitly, as the following shows.

Remark 9.9. Since the periodicity algebra is a sum of shifts of a unit as an object of the derived ∞ -category, the homotopy groups of the free module are simple to understand. More precisely, for any $M \in \mathcal{D}(E_*E)$, we have

$$[P(E_*), P(E_*) \otimes_{E_*} M]_{P(E_*)}^t \simeq [E_*, P(E_*) \otimes_{E_*} M]_{\mathcal{D}(E_*E)}^t \simeq \bigoplus_s \mathrm{Ext}_{E_*E}^{s, t-s}(E_*, M).$$

As a consequence, whenever a $P(E_*)$ -module can be written as a periodicisation of some M as above, its homotopy groups acquire an additional grading. Note that any given

module can be written as a periodicisation in many different ways, and this additional grading depends on that choice.

Our plan is to use Theorem 9.6 to compare the K -based Adams spectral sequence in E -local spectra to the one in its algebraic model, and subsequently give an explicit description of the latter in terms of filtration by powers.

Lemma 9.10. *Let X be either the E -local sphere or a Morava K -theory; that is, $X = S_E^0$ or $X = K$. Then, there exists a canonical isomorphism*

$$\phi(X) \simeq P(E_*) \otimes_{E_*} E_* X,$$

in $h\mathrm{Mod}_{P(E_*)}$, where ϕ is the algebraicity equivalence of Theorem 9.6.

Proof. It will be convenient to work here with the Johnson-Wilson homology, the p -local Landweber exact homology theory with

$$\pi_* E(n) \simeq \mathbb{Z}_{(p)}[v_1, \dots, v_{n-1}, v_n^{\pm 1}].$$

Both this ring and $E(n)_* E(n)$ are concentrated in degrees divisible by $2p-2$, which is a key ingredient in the construction of the equivalence ϕ [Pst18, Section 2].

Choosing coordinates for the Quillen formal group over E_* , such that $v_i = 0$ for $i > n$, we obtain a classifying map $E(n)_* \rightarrow E_*$ which is faithfully flat, and hence

$$E_* X \simeq E_* \otimes_{E(n)_*} E(n)_* X.$$

The induced functor $\mathrm{Comod}_{E(n)_* E(n)} \rightarrow \mathrm{Comod}_{E_* E}$ is an equivalence of categories by a result of Hovey and Strickland [HS05a].

Now suppose that X is a spectrum with $E(n)_* X$ concentrated in degrees divisible by $2p-2$. Since ϕ is compatible with taking homology, we have

$$H_0(\phi(X)) \simeq E_* X \simeq E_* \otimes_{E(n)_*} E(n)_* X$$

as comodules. By Remark 9.8, we have an Adams spectral sequence

$$\mathrm{Ext}^{s,t}(E_* X, E_* X) \implies [\phi(X), P(E_*) \otimes_{E_*} E_* X]^{t-s}.$$

Using the equivalence of categories of comodules, we can rewrite the E_2 -page as

$$\mathrm{Ext}^{s,t}(E(n)_* X, E(n)_* X) \simeq \mathrm{Ext}^{s,t}(E_* X, E_* X).$$

This vanishes above $n^2 + n$ by [Pst18, Remark 2.5] and is concentrated in degrees t divisible by $2p-2$. Since $2p-2 > n^2 + n$ by assumption, we deduce that the spectral sequence collapses on the second page, so that the identity of $E_* X$ descends to an equivalence $\phi(X) \simeq P(E_*) \otimes_{E_*} E_* X$.

This establishes the result for $X = S_E^0$, which has $E(n)_* X$ homology concentrated in degrees divisible by $2p-2$. If K is a Morava K -theory, then as a consequence of the nilpotence theorem, it is a module over the minimal Morava K -theory $K(n)$ of

Section 3 and so equivalent as a spectrum to a direct sum of $K(n)$ s. As ϕ preserves direct sums and

$$E(n)_*K(n) \simeq K(n)_* \otimes_{E(n)_*} E(n)_*E(n)$$

is concentrated in degrees divisible by $2p-2$, the result follows also for $X = K$. \square

Remark 9.11. The detour into Johnson-Wilson homology Lemma 9.10 can be avoided, by directly defining a splitting of order $(2p-2)$ on the category Comod_{E_*E} by using the equivalence with quasicoherent sheaves on the moduli of formal groups of height at most n . We decided against it, as the degree divisibility argument involving $E(n)$ is classical and well-known.

Let us write $K_{alg} := P(E_*) \otimes_{E_*} E_*K$ for the algebraic model for the Morava K -theory spectrum. Note that its homotopy groups satisfy

$$\pi_s K_{alg} := [P(E_*), K_{alg}]_s^{P(E_*)} \simeq K_s,$$

so that K_{alg} is a field object in $P(E_*)$. Consequently, for a map $M \rightarrow N$ of $P(E_*)$ -modules, the following two conditions are equivalent:

- (1) $K_{alg} \otimes_{P(E_*)} M \rightarrow K_{alg} \otimes_{P(E_*)} N$ is a split monomorphism of $P(E_*)$ -modules or
- (2) $[N, K_{alg}]_* \rightarrow [M, K_{alg}]_*$ is an epimorphism of graded abelian groups.

This forms a class of monomorphisms and so determines an Adams spectral sequence [PP21, Section 3.1].

Definition 9.12. We call the Adams spectral sequence in $P(E_*)$ -modules determined by the above class of monomorphisms the *K_{alg} -based Adams spectral sequence*.

We are now ready to verify the correspondence between the topological and algebraic Adams spectral sequences; we learned the following elegant argument from Robert Burklund.

Proposition 9.13. *If $2p-2 > n^2 + n + 1$, then the K -based Adams spectral sequence in Sp_E for S_E^0 is isomorphic to the K_{alg} -based Adams spectral sequence for $P(E_*)$ in $P(E_*)$ -modules.*

Proof. We claim that the equivalence ϕ of Theorem 9.6 induces an isomorphism of exact couples leading to these spectral sequences. Both of these are obtained by mapping into suitable towers, so we have to verify that ϕ takes a K -Adams resolution of S_E^0 to a K_{alg} -Adams resolution of $\phi(S_E^0) \simeq P(E_*)$. If $2p-2 > n^2 + n + 1$, the equivalence ϕ is compatible with triangulated structures [Pst21, Corollary B.8], so it remains to show that it identifies K -injectives with K_{alg} -injectives, as the corresponding class of monomorphism is then uniquely determined. This follows immediately from Lemma 9.10, as on both sides each injective is a direct sum of shifts of, respectively, K and K_{alg} . \square

In our case, in Proposition 9.13, we considered a $K_{alg} = P(E_*) \otimes_{E_*} E_*K$ -based Adams spectral sequence for the monoidal unit $P(E_*)$. Both objects arise through periodicisation, giving us additional information, which we now make explicit.

Proposition 9.14. *If $2p-2 > n^2 + n + 1$, then the K -based Adams spectral sequence for S_E^0 can be given an additional grading, so that it becomes isomorphic to the E_*K -based Adams spectral sequence in $\mathcal{D}(E_*E)$.*

Proof. By Proposition 9.13, the K -Adams spectral sequence in Sp_E is isomorphic to the K_{alg} -based Adams spectral sequence in $P(E_*)$ -modules. The latter is isomorphic to the spectral sequence induced by the Amitsur resolution

$$P(E_*) \rightarrow K_{alg} \rightrightarrows K_{alg} \otimes_{P(E_*)} K_{alg} \rightrightarrows \dots$$

which is an image of the E_*K -Adams resolution of E_* in $\mathcal{D}(E_*E)$ under the periodicisation functor. The statement follows from the isomorphism of homotopy groups of Remark 9.9 applied to the exact couple giving rise to the spectral sequence. \square

The above result reduces the study of the K -based Adams spectral sequence at large primes to the study of the algebraic E_*K -based in the derived ∞ -category of comodules. The latter can be described explicitly in terms of the cohomology of the Morava stabiliser group, with no assumptions on the prime, which is our next step.

We will need to recall some results on décalage, following Deligne and Levine [Lev15].

Construction 9.15. If X^\bullet is a cosimplicial spectrum, we have an associated conditionally convergent spectral sequence

$$\mathrm{Tot} E_{s,t}^2 := H^s \pi_t X^\bullet \implies \pi_{t-s} \mathrm{Tot}(X^\bullet).$$

The *décalage* of this cosimplicial object is the tower

$$\mathrm{Dec}_n := \mathrm{Tot}(\tau_{\leq n} X^\bullet)$$

obtained by totalising the Postnikov truncations of X . Since limits commute with limits, we have

$$\varprojlim \mathrm{Dec}_n \simeq \varprojlim \mathrm{Tot}(\tau_{\leq n} X^\bullet) \simeq \mathrm{Tot}(\varprojlim \tau_{\leq n} X^\bullet) \simeq \mathrm{Tot}(X^\bullet).$$

The above equivalence induces a spectral sequence associated to the tower on the left, which is conditionally convergent and of signature

$$\mathrm{Dec} E_{s,t}^1 := H^s \pi_t X^\bullet \implies \pi_{t-s} \mathrm{Tot}(X^\bullet).$$

Levine proves that the evident isomorphisms between the E^2 -term of the Tot-spectral sequence and the E_1 -term of the spectral sequence associated to the décalage extends to an isomorphism of spectral sequences [Lev15].

In our case, we will be working with cosimplicial objects in $\mathcal{D}(E_*E)$, rather than in spectra. Thus, the role of the Postnikov towers will be played by the truncations in the standard t -structure on the derived category.

Definition 9.16. Let $X^\bullet: \Delta \rightarrow \mathcal{D}(E_*E)$ be a cosimplicial object in the derived ∞ -category of comodules. The *homological décalage* of X^\bullet is the tower

$$h\mathrm{Dec}_n := \mathrm{Tot}(\tau_{\leq n} X^\bullet),$$

where $\tau_{\leq n}$ denotes the truncation in the standard t -structure on the derived ∞ -category.

Warning 9.17. Note that if X^\bullet is a cosimplicial object in $\mathcal{D}(E_*E)$, then the homological décalage tower induces a spectral sequence obtained by applying $\mathrm{Ext}(E_*, -)$. Since Postnikov towers converge in $\mathcal{D}(E_*E)$, this is conditionally convergent to $\mathrm{Ext}(E_*, \mathrm{Tot}(X^\bullet))$.

The layers of the tower are given, up to a shift, by $\mathrm{Tot}(H_k(X^\bullet))$, so that this spectral sequence has signature

$$\mathrm{Ext}(E_*, \mathrm{Tot}(H_k(X^\bullet))) \implies \mathrm{Ext}(E_*, \mathrm{Tot}(X^\bullet)).$$

This spectral sequence is usually not the same as the one obtained by applying $\mathrm{Ext}(E_*, -)$ to X^\bullet itself, because the homological t -structure does not interact in an easy way with E_* -homotopy groups, unlike in the case of the standard t -structure on the ∞ -category of spectra.

Despite the above warning, for a certain restricted class of cosimplicial objects, we do have an isomorphism between the spectral sequence of a cosimplicial object and its homological décalage.

Lemma 9.18. Let $X^\bullet: \Delta \rightarrow \mathcal{D}(E_*E)$ be a cosimplicial object, and assume that each X^m is a direct sum of shifts of objects in the heart, each of which is a cofree E_*E -comodule. Then

$$F(E_*[t], h\mathrm{Dec}_n X^\bullet) \simeq \mathrm{Dec}_n F(E_*, X^\bullet),$$

where $F(E_*[t], -)$ is the internal mapping spectrum in $\mathcal{D}(E_*E)$. That is, for such cosimplicial objects, mapping out of $E_*[t]$ takes homological décalage to the spectral one.

Proof. Since $F(E_*, -)$ preserves totalisations, it is enough to check that $F(E_*, -)$ takes homological truncations to Postnikov truncations. Since X^\bullet is levelwise a direct sum of shifts of cofree comodules, it is enough to check this in the latter case, where it is clear since $\mathrm{Ext}^s(E_*[t], C) = 0$ for $s > 0$ whenever C is cofree. \square

Corollary 9.19. The E_*K -based Adams spectral sequence in $\mathcal{D}(E_*E)$ has a second page isomorphic to the first page of the spectral sequence associated to the homological décalage $h\mathrm{Dec}_n(E_*K)^{\otimes \bullet}$ of the Amitsur resolution.

Proof. Both the Adams spectral sequence and the spectral sequence of the tower are obtained by applying $F(E_*[t], -)$ (for all t at once) and using the relevant spectral sequence in spectra. Thus, the result then follows from Levine's work and Lemma 9.18, since

$$E_*K^{\otimes n} \simeq (E_*E)^{\otimes n} \otimes_{E_*} K_*^{\otimes_{E_*} n}$$

and

$$K_*^{\otimes_{E_*} n} \simeq \mathrm{Tor}^{E_*}(K_*, K_*) \otimes_{K_*} \dots \otimes_{K_*} \mathrm{Tor}^{E_*}(K_*, K_*),$$

where the right-hand side has $(n-1)$ factors and the unadorned tensor products are the derived tensor products over E_* . This is a direct sum of shifts of K_* , as needed. \square

The idea is now to relate the homological décalage of E_*K to that of K_* .

Lemma 9.20. *The morphism $K_* \rightarrow E_*E \otimes K_* \simeq E_*K$ of algebras in the derived category of E_*E -comodules induces an isomorphism of spectral sequences associated to the homological décalage of Amitsur resolutions.*

Proof. Since E_*E is flat, for any $X \in \mathcal{D}(E_*E)$, we have $H_n(E_*E \otimes X) \simeq E_*E \otimes H_n(X)$. Thus, the map between the layers of the homological décalage towers is given by applying totalisation to the map

$$H_n(K_*^{\otimes \bullet}) \rightarrow E_*E^{\otimes \bullet} \otimes H_n(K_*^{\otimes \bullet}).$$

The map is obtained by tensoring the map

$$E_*^{\otimes \bullet} \rightarrow E_*E^{\otimes \bullet},$$

which is a quasi-isomorphism of levelwise flat cosimplicial comodules, with $H_n(K_*^{\otimes \bullet})$, so it is a quasi-isomorphism again. It follows that it is an equivalence after taking totalisations. \square

Proposition 9.21. *From the second page on, the Adams spectral sequence associated to E_*K is isomorphic to the spectral sequence obtained from the tower*

$$\dots \rightarrow E_*/\mathfrak{m}^2 \rightarrow E_*/\mathfrak{m},$$

that is, it is the filtration by powers spectral sequence.

Proof. We know from Corollary 9.19 that this Adams spectral sequence has second page isomorphic to the spectral sequence of the homological décalage tower, which is in turn equivalent to the homological décalage tower associated to the K_* -Adams resolution by Lemma 9.20. Thus, it is enough to identify the latter.

We're interested in the cosimplicial object

$$K_* \rightrightarrows K_* \otimes_{E_*} K_* \rightrightarrows \dots,$$

all tensor products being implicitly derived. Everything here is 2-periodic and concentrated in even degrees in the internal grading, so that we can instead focus on the cosimplicial object

$$K_0 \rightrightarrows K_0 \otimes_{E_0} K_0 \rightrightarrows \dots,$$

working in the derived category of E_0 -modules. As an object of the latter, $K_0 \otimes_{E_0} K_0$ is a direct sum of its homology groups, and we have

$$H_*(K_0 \otimes_{E_0} K_0) \simeq \mathrm{Tor}_*^{E_0}(K_0, K_0)$$

and more generally

$$H_*(K_0^{\otimes_{E_0} n}) \simeq \mathrm{Tor}_*^{E_0}(K_0, K_0)^{\otimes_{K_0} n-1}, \quad (9.22)$$

where on the left we have the derived tensor product of E_0 -modules and on the right the ordinary tensor product of graded K_0 -modules.

Using that E_0 is a regular ring with residue field K_0 , the canonical isomorphism

$$\mathrm{Tor}_1^{E_0}(K_0, K_0) \simeq (\mathfrak{m}/\mathfrak{m}^2)^\vee$$

with the tangent space extends to a grading-preserving isomorphism

$$\mathrm{Tor}_*^{E_0}(K_0, K_0) \simeq \Lambda_{K_0}((\mathfrak{m}/\mathfrak{m}^2)^\vee)$$

with the exterior algebra. This is flat over K_0 , which is a field, so by standard arguments, the cosimplicial object $K_0^{\otimes \bullet}$ on the right of (9.22) encodes the cobar complex computing

$$\mathrm{Cotor}_{\Lambda_{K_0}((\mathfrak{m}/\mathfrak{m}^2)^\vee)}(K_0, K_0) \simeq \mathrm{Sym}_{K_0}(\mathfrak{m}/\mathfrak{m}^2) \simeq \bigoplus_{n \geq 0} \mathfrak{m}^n / \mathfrak{m}^{n+1}.$$

Note that this is bigraded using the internal grading of the exterior algebra and the Cotor-grading, with the summand $\mathfrak{m}^n / \mathfrak{m}^{n+1}$ being concentrated in degrees (n, n) .

Using the isomorphism in Equation (9.22) and passing to cohomology, we deduce that

$$H^s(H_n(K_0^{\otimes_{E_0} \bullet})) \simeq \begin{cases} \mathfrak{m}^n / \mathfrak{m}^{n+1} & \text{when } s = n, \\ 0 & \text{otherwise,} \end{cases}$$

where H^s is the cohomology of the given cosimplicial abelian group. Thus, the totalisation spectral sequence for $H_n(K_0^{\otimes_{E_0} \bullet})$, which we consider as a cosimplicial object of the heart of the derived ∞ -category of E_0 -modules, collapses, and we deduce that

$$\mathrm{Tot}(H_n(K_0^{\otimes \bullet})) \simeq \Sigma^{-n} \mathfrak{m}^n / \mathfrak{m}^{n+1},$$

It follows that the graded pieces of the homological décalage filtration of E_* are given by

$$\mathrm{fib}(\mathrm{Dec}_n \rightarrow \mathrm{Dec}_{n-1}) \simeq \mathrm{Tot}(\Sigma^n H_n(K_*^{\otimes \bullet})) \simeq \mathfrak{m}^n / \mathfrak{m}^{n+1} \otimes_{E_0} E_*,$$

and so by induction, the tower itself must be of the claimed form. \square

Theorem 9.23. *If $2p-2 > n^2 + n + 1$, the K -based Adams spectral sequence can be given an additional grading so that it becomes isomorphic to the spectral sequence induced by applying $\mathrm{Ext}_{E_*E}(E_*, -)$ to the filtration of E_* given by powers $\mathfrak{m}^n E_*$ of the maximal ideal.*

Proof. This is a combination of Propositions 9.14 and 9.21. \square

We believe the following question related to the above result is interesting, but we do not pursue it in this paper.

Definition 9.24. The additional grading guaranteed by Theorem 9.23 should provide certain restrictions on the possible differentials in the K -based Adams spectral sequence at large primes. Can one find out explicitly what are these restrictions?

Remark 9.25. If we pick $E = E_n$ to be the Morava E -theory of the Honda formal group law over \mathbb{F}_{p^n} , then since $\mathfrak{m}^n/\mathfrak{m}^{n+1}E_*$ is \mathfrak{m} -torsion, we have

$$\mathrm{Ext}_{E_*E}^*(E_*, \mathfrak{m}^n/\mathfrak{m}^{n+1}E_*) \simeq H_{\mathrm{cts}}^*(\mathbb{G}_n, \mathfrak{m}^n/\mathfrak{m}^{n+1}E_*).$$

Thus, the spectral sequence of Theorem 9.23 is isomorphic to the conditionally convergent spectral sequence

$$H_{\mathrm{cts}}^*(\mathbb{G}_n, \mathfrak{m}^n/\mathfrak{m}^{n+1}E_*) \implies H_{\mathrm{cts}}^*(\mathbb{G}_n, E_*)$$

obtained by the same filtration of E_* but in continuous \mathbb{G}_n -modules.

10. Height 1 K -based Adams spectral sequence at an odd prime

Let us describe how, using our methods, one obtains an explicit description of the K -based Adams spectral sequence at $n = 1$ and p odd. Since in this case

$$2p - 2 \geq 4 > 3 = n^2 + n + 1.$$

Theorem 9.23 and Remark 9.25 imply that the relevant spectral sequence is isomorphic to the one computing the cohomology $H_{\mathrm{cts}}^*(\mathbb{G}_n, E_*)$ using the filtration by powers of the maximal ideal, where E_0 is the Lubin–Tate ring of the Honda formal group law.

Notation 10.1. We again follow the conventions of [GHMR05, Section 2]. We have $E_* \simeq \mathbb{Z}_p[u^{\pm 1}]$ with $|u| = -2$, $\mathfrak{m} = (p)$ and $\mathbb{G}_1 \simeq \mathbb{Z}_p^\times$ with the action determined by $\lambda_*(u) = \lambda^{-1}u$ for $\lambda \in \mathbb{Z}_p^\times$. We denote the associated graded of E_* by

$$A_* \simeq \mathbb{F}_p[b][u^{\pm 1}],$$

with $|b| = (0, 1)$ the equivalence class of $p \in E_0$, and $|u| = (-2, 0)$, where the first degree is internal, and the second one is coming from the filtration.

The p -adic group \mathbb{Z}_p^\times is topologically cyclic at odd primes, generated by $\psi = \sigma(1 + p)$ for σ a primitive $(p - 1)$ -th root of unity. It follows that for a profinite \mathbb{Z}_p^\times -module M , its cohomology can be computed using the 2-term complex

$$\partial: M \rightarrow M, \tag{10.2}$$

where $\partial = id_M - \psi_*$.

The complex of (10.2) is a quasiisomorphism quotient of the standard group cohomology cochain complex

$$M \rightarrow \mathrm{Map}_{\mathrm{cts}}(\mathbb{Z}_p^\times, M) \rightarrow \mathrm{Map}_{\mathrm{cts}}(\mathbb{Z}_p^\times \times \mathbb{Z}_p^\times, M) \rightarrow \dots, \tag{10.3}$$

the quotient map being given by the identity in degree zero and evaluation at the generator $\psi \in \mathbb{Z}_p^\times$ in degree one.

From this explicit description, we see that if we equip M with a filtration, the above quotient map is a quasi-isomorphism of filtered complexes, where we consider both (10.2) and (10.3) with the filtration induced from that of M . In particular, both filtrations induced isomorphic spectral sequences.

Remark 10.4. The 2-term complex of (10.2) can be used to directly compute the cohomology groups $H_{\text{cts}}^*(\mathbb{Z}_p^\times, \mathbb{Z}_p[u^{\pm 1}])$, recovering the classical image of J pattern [Lur10, Lecture 35]. Our goal is not to compute the above groups, which are well-known, but rather analyse the structure of the spectral sequence associated to filtration by powers of p .

We first determine the cohomology groups of the associated graded A_* . We have $\psi_*b = b$, because the latter can be represented by $p \in E_0$ which is necessarily acted on trivially, and since $\psi_*u \equiv \sigma^{-1}u \pmod{p}$, we have $\psi_*u = [\sigma]^{-1}u$ in the associated graded, where $[\sigma] \in \mathbb{F}_p$ is the image of σ . Thus, in the associated graded, we have that $\partial(b) = 0$ and $\partial(u^k)$ is a unit multiple of u^k for $(p-1) \nmid k$ and zero otherwise. We deduce the following.

Proposition 10.5. *The E_2 -term of the K -based Adams for S^0 at $n = 1$ and $p > 2$ is given by*

$$\text{Ext}_{K_*K}^*(K_*, K_*) \simeq H_{\text{cts}}^*(\mathbb{G}_1, A_*) \simeq H_{\text{cts}}^*(\mathbb{Z}_p^\times, \mathbb{F}_p[b][u^{\pm 1}]) \simeq \mathbb{F}_p[b][v_1^{\pm 1}] \otimes \Lambda(\zeta),$$

where $v_1 = u^{1-p}$ is of degree $(2p-2, 0, 0)$ and ζ is the class of 1 of degree $(0, 0, 1)$, where the three degrees are, respectively, the internal degree, the degree of the associated graded and the cohomological degree.

By Remark 9.25, if the K -based Adams is isomorphic to the spectral sequence computing $H_{\text{cts}}^*(\mathbb{Z}_p^\times, \mathbb{Z}_p[u^{\pm 1}])$ induced by the filtration of (10.2) by powers of p , with E_2 -term as above and with differentials $d_r: E_r \rightarrow E_r$ of degree $(0, r, 1)$. We now analyse this spectral sequence.

We know that $\partial(p) = 0$ in E_0 , so that b is a permanent cycle. The same is true for ζ , for degree reasons, and we deduce that all of the differentials are both b and ζ -linear, and so the structure of the spectral sequence is completely determined by what it does on v_1^k . If we write $k = p^n m$, where $p \nmid m$, then one can calculate

$$\partial(u^{(1-p)k}) \equiv \text{unit} \cdot p^{n+1} u^{(1-p)k} \pmod{p^{n+2}}$$

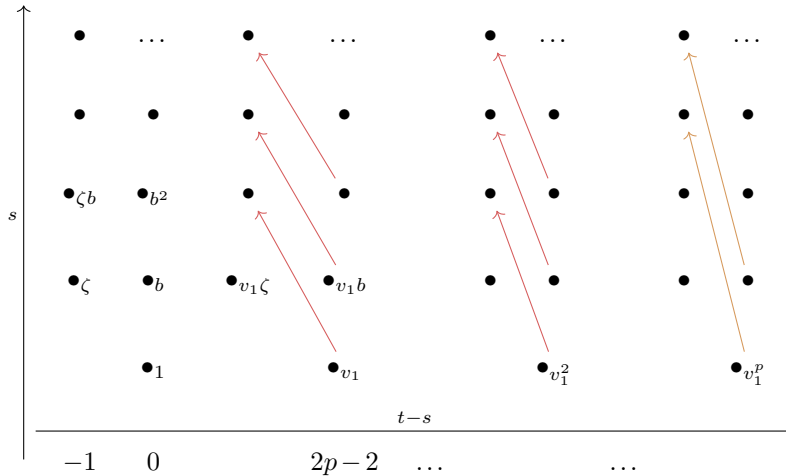
from which we deduce that

$$d_i(v_1^k) = \begin{cases} 0 & \text{for } i < n+1 \\ \zeta b^{n+1} v_1^k & \text{for } i = n+1. \end{cases} \quad (10.6)$$

Note that the first computation is also implied by the Leibniz rule for p -th powers. The extension problems are resolved using multiplication by b , recovering the classical answer that

$$H_{\text{cts}}^{s,t}(\mathbb{Z}_p^\times, \mathbb{Z}_p[u^{\pm 1}]) = \begin{cases} \mathbb{Z}_p & \text{if } (s, t) = (0, 0), \\ \mathbb{Z}_p\{\zeta\} & \text{if } (s, t) = (1, 0), \\ \mathbb{Z}/p^{n+1}\{\zeta u^{(p-1)p^n m}\} & \text{if } (s, t) = (1, (2p-2)p^n m), \text{ where } p \nmid m, \\ 0 & \text{otherwise,} \end{cases}$$

where $\{-\}$ denotes a generator of the given group. Thus, the spectral sequence is as in the following familiar ‘image of J ’ pattern



with even longer differentials supported on $v_1^{p^k}$ for $k \geq 1$. The above picture is made in the Adams grading $(t-s, s)$, with t the internal degree and s the cohomological one, while the one inherited from passing to the associated graded not visible.

It is interesting to observe that this shows that already at height one, the K -based Adams spectral sequence has nonzero differentials of arbitrary length.

Example 10.7 (Noncompletely convergent K -Adams). Using the above calculation, we can give an example of a K -local spectrum for which its K -based Adams spectral sequence is not completely convergent. Note that we know that it is always conditionally convergent by Proposition 7.2.

To this end, we construct a spectrum X for which $\lim_r^1 E_r^{0,0}(X)$ does not vanish at height $n = 1$ and $p > 2$. Set $\lambda_k = 2(p-1)p^k$, and consider the spectrum

$$X = L_K \bigoplus_{k \geq 0} S^{-\lambda_k}.$$

In bidegree $(s, t) = (0, 0)$, the E_2 -page is given by

$$E_2^{0,0}(X) \simeq \bigoplus_{k \geq 0} \mathbb{F}_p \{v_1^{p^k}\},$$

where the generators correspond to the maps $v_1^{p^k} : K_* \rightarrow K_* S^{\lambda_k}$. The formulas for the differentials of Equation (10.6) show that (up to reindexing) the filtration on $E_2^{0,0}(X)$ is given by

$$\dots \subset \bigoplus_{k \geq 2} \mathbb{F}_p \{v_1^{p^k}\} \subset \bigoplus_{k \geq 1} \mathbb{F}_p \{v_1^{p^k}\} \subset \bigoplus_{k \geq 0} \mathbb{F}_p \{v_1^{p^k}\} = E_2^{0,0}(X).$$

Therefore, we obtain an exact sequence

$$0 \rightarrow \lim_r E_r^{s,t}(X) \rightarrow E_2^{0,0}(X) = \bigoplus_{k \geq 0} \mathbb{F}_p\{v_1^{p^k}\} \rightarrow \prod_{k \geq 0} \mathbb{F}_p\{v_1^{p^k}\} \rightarrow \lim_r^1 E_r^{s,t}(X) \rightarrow 0.$$

In particular, we see that $\lim_r E_r^{s,t}(X) = 0$, while $\lim_r^1 E_r^{s,t}(X) \neq 0$.

Part 3. Homology of inverse limits and the algebraic chromatic splitting conjecture

In the third part of the work, we largely move away from Morava K -theory, and we focus on homology of K -local spectra. From the perspective of E -local category, K -localisation is a form of completion, and so we first focus on homology of inverse limits, constructing a spectral sequence computing these in the generality of an arbitrary adapted homology theory.

In the case of K -localisation, the E_2 -page of this spectral sequence is given by derived functors of limits in E_*E -comodules. We describe the latter in terms of cohomology of the Morava stabiliser group, and use it to compute the zeroth one at all heights and primes. At height 1, we compute these derived functors completely.

11. The homology of inverse limits

We begin with a general review of the context for the construction of the modified Adams spectral sequence, following the approach of Devinatz and Hopkins [Dev97]. This approach will then be employed to construct a spectral sequence that computes the homology of inverse limits in a presentable stable ∞ -category.

In particular, this gives rise to a spectral sequence for computing the E -homology of the inverse limit of a tower of spectra (X_α) from the derived functors of inverse limits of the tower of E_*E -comodules (E_*X_α) , for suitable ring spectra E . The question of when this spectral sequence converges is subtle, and will be studied in detail in the case of Morava E -theory. The material in this section is based on unpublished work of Mike Hopkins and Hal Sadofsky.

11.1. Adapted homology theories

In this short section, we recall basic facts about adapted homology theories. Informally, these are exactly those homology theories which admit an Adams spectral sequence based on injectives. Everything here is classical, although our presentation is most close to [PP21, Section 2].

A locally graded ∞ -category is an ∞ -category equipped with a distinguished autoequivalence $[1]_{\mathcal{C}}: \mathcal{C} \rightarrow \mathcal{C}$. A locally graded functor $f: \mathcal{C} \rightarrow \mathcal{D}$ is functor equipped with a natural isomorphism $f \circ [1]_{\mathcal{C}} \simeq [1]_{\mathcal{D}} \circ f$.

Definition 11.1. Let \mathcal{C} be a stable ∞ -category, considered as a locally graded ∞ -category using the suspension functor, and \mathcal{A} an arbitrary locally graded abelian category. We say a locally graded functor $H: \mathcal{C} \rightarrow \mathcal{A}$ is a *homology theory* if, for any cofibre sequence

$$X \rightarrow Y \rightarrow Z$$

in \mathcal{C} , the induced diagram

$$H(X) \rightarrow H(Y) \rightarrow H(Z)$$

in \mathcal{A} is exact in the middle.

Remark 11.2. The requirement that H is locally graded amounts to specifying an isomorphism

$$H(\Sigma X) \simeq H(X)[1]$$

natural in $X \in \mathcal{C}$.

In cases of interest to us, H is *Grothendieck* in the sense that

- (1) \mathcal{C} is presentable,
- (2) \mathcal{A} is Grothendieck abelian and
- (3) H preserves arbitrary direct sums.

In particular, this means that \mathcal{A} has enough injectives. Any injective object I of \mathcal{A} gives rise to a cohomological functor

$$\mathrm{Hom}_{\mathcal{A}}(H(-), I): \mathcal{C}^{\mathrm{op}} \rightarrow \mathcal{A}.$$

Since \mathcal{C} is presentable and stable, Brown's representability theorem holds [PP21, Proposition 2.15], so that there exists some $D(I) \in \mathrm{Ho}\mathcal{C}$ representing $\mathrm{Hom}_{\mathcal{A}}(H(-), I)$. It follows that, for any object $X \in \mathcal{C}$, there is a natural equivalence

$$\mathrm{Hom}_{\mathcal{A}}(H(X), I) \simeq \pi_0 \mathrm{Hom}_{\mathcal{C}}(X, D(I)).$$

Note that the object $D(I)$ is H -local, in the sense that for any object $Y \in \mathcal{C}$ with $H(Y) = 0$, we have $\mathrm{Hom}(Y, D(I)) = 0$. Moreover, the identity map on $D(I)$ corresponds under this isomorphism to a natural counit map $H(D(I)) \rightarrow I$.

Definition 11.3. We say $H: \mathcal{C} \rightarrow \mathcal{A}$ is *adapted* if the counit map $H(D(I)) \rightarrow I$ is an equivalence for any injective $I \in \mathcal{A}$.

Example 11.4. Rational homology, viewed as a functor from spectra to graded rational vector spaces, is an adapted homology theory. In this case, the lift $D(V)$ of a (graded) \mathbb{Q} -vector space V is the (generalised) Eilenberg–MacLane spectrum HV .

Example 11.5. In contrast to the previous example, mod p homology is not adapted for any p ; indeed, the lift of \mathbb{F}_p is $H\mathbb{F}_p$, but its mod p -cohomology is the mod p Steenrod algebra \mathcal{A}_p which is larger than \mathbb{F}_p .

However, $H_*(-, \mathbb{F}_p)$ has more structure: it takes values in the category $\mathrm{Comod}_{\mathcal{A}_p}$ of graded \mathcal{A}_p -comodules. It turns out that the homology theory

$$H_*(-; \mathbb{F}_p): \mathrm{Sp} \rightarrow \mathrm{Comod}_{\mathcal{A}_p}$$

is adapted.

Remark 11.6. The phenomena visible in Example 11.5 is typical in the sense that asking for H to be adapted is to ask for \mathcal{A} to encode all available homological information. This generalises considerably: one can show that any homology theory factors uniquely through an adapted one followed by an exact comonadic functor of abelian categories [PP21, Section 3.3]

Let R be a homotopy commutative ring spectrum which satisfies the Adams condition, that is, it can be written as a filtered colimit of finite spectra X_α with the properties that

- (1) R_*X_α is a finitely generated projective R_* -module and
- (2) the Künneth map $R^*X_\alpha \rightarrow \mathrm{Hom}_{R^*}(R_*X_\alpha, R_*)$ is an isomorphism.

Note that the second condition follows from the first, whenever R can be made \mathbf{E}_1 .

For example, $H\mathbb{F}_p$ or any Landweber exact homology theory satisfy the Adams condition [Hov04a, Theorems 1.4.7–1.4.9], but $H\mathbb{Z}$ does not [GH, Page 17]. This condition guarantees that the associated Hopf algebroid (R_*, R_*R) is Adams and thus has a well-behaved category of comodules Comod_{R_*R} (see [Hov04a, Section 1.4] for details).

One way in which the Adams-type condition implies that the category Comod_{R_*R} is well-behaved also in the topological sense is the following result of Devinatz.

Lemma 11.7 [Dev97, Theorem 1.5 and Section 2]. *Let R be a topologically flat commutative ring spectrum. For any injective R_*R -comodule I , the identity map on $D(I)$ corresponds (in the sense explained above) to an isomorphism $R_*D(I) \simeq I$. In other words, the functor*

$$R_0: Sp \rightarrow \mathrm{Comod}_{R_*R}$$

is an adapted homology theory.

11.2. Construction of the spectral sequence

The starting point of our construction is the existence of modified Adams towers for any homology theory $H: \mathcal{C} \rightarrow \mathcal{A}$. We collect its properties in the next result:

Lemma 11.8. *Consider an adapted homology theory $H: \mathcal{C} \rightarrow \mathcal{A}$. Let $X \in \mathcal{C}$, and suppose*

$$\begin{array}{ccccccc} 0 & \longrightarrow & H(X) = C_0 & \xrightarrow{\eta_0} & I_0 & \xrightarrow{\tau_0} & I_1 \xrightarrow{\tau_1} \dots \\ & & & & \uparrow \eta_0 & & \uparrow \eta_1 \\ & & & & C_0 & & C_1 \quad \dots \end{array}$$

is an injective resolution of $H(X)$ in \mathcal{A} , where $C_i = \ker(\tau_i)$ for all i . There exists a tower of objects in \mathcal{C} over X of the form

$$\begin{array}{ccccccc} X = X_0 & \xleftarrow{g_0} & X_1 & \xleftarrow{g_1} & X_2 & \xleftarrow{g_2} & \dots \\ \downarrow f_0 & \nearrow \delta_0 & \downarrow f_1 & \nearrow \delta_1 & \downarrow f_2 & \nearrow \delta_2 & \\ \Sigma^0 D(I_0) & & \Sigma^{-1} D(I_1) & & \Sigma^{-2} D(I_2) & & \dots, \end{array}$$

where the dotted maps are the boundary maps shifting degree by 1, and such that the following properties are satisfied for all i :

- (1) $X_{i+1} \simeq \text{fib}(f_i)$;
- (2) $H(X_i) \simeq C_i[-i]$;
- (3) $H(f_i) = \eta_i[-i]$;
- (4) $H(g_i) = 0$;
- (5) $H(\delta_i)$ is the surjection $I_i[-i] \rightarrow C_{i+1}[-i]$.

If X is H -local, then X_i and $D(I_i)$ are H -local for all i . Moreover, this tower is weakly functorial; that is, a map $X \rightarrow Y$ can be extended to a (noncanonical) map of towers $(X_i) \rightarrow (Y_i)$.

Proof. This lemma is an axiomatisation of the results proven in [Dev97, Section 1]. The tower so constructed consists of H -local spectra as noticed in Section 11.1, while naturality follows from the naturality of injective resolutions. \square

Notation 11.9. We refer to the tower (X_i) constructed in Lemma 11.8 as the modified Adams tower of X with respect to the adapted homology theory $H: \mathcal{C} \rightarrow \mathcal{A}$.

Since the limit $\varprojlim I_\alpha$ of an injective tower of injectives in \mathcal{A} is injective, the construction of the previous subsection yields an object $D(\varprojlim I_\alpha)$ of \mathcal{C} . In order to proceed, we need an auxiliary characterisation of injective towers of objects in a Grothendieck abelian category \mathcal{A} .

Lemma 11.10. Let \mathcal{A} be a Grothendieck abelian category. An object $I = (I_\alpha) \in \mathcal{A}^{\mathbb{N}}$ is injective if and only if I_α is injective for all $\alpha \in J$ and all structure maps in I are split epimorphisms.

Proof. This is proven in [Jan88, Proposition 1.1]. We sketch the argument of the implication we need. Let $j: \mathbb{N}^\delta \rightarrow \mathbb{N}$ be the inclusion of the discrete set of natural numbers into the poset of natural numbers. This induces an adjunction (j^*, j_*) between diagram categories. If I is injective, then the natural monomorphism $I \rightarrow j_* j^* I$ is split. By construction, the structure maps of $j_* j^* I$ are projections, so I also has split surjective structure maps, and the claim follows. \square

Proposition 11.11. If $I = (I_\alpha) \in \text{Inj}(\mathcal{A}^{\mathbb{N}})$ is an injective tower in \mathcal{A} , then there is a preferred equivalence

$$D(\varprojlim_{\mathcal{A}} I_\alpha) \xrightarrow{\sim} \varprojlim_{\mathcal{C}} D(I_\alpha),$$

of objects in \mathcal{C} , well-defined up to homotopy.

Proof. For brevity, let us write $I_\infty := \varprojlim_{\mathcal{A}} I_\alpha$; note that this is an injective object of \mathcal{A} . The canonical structure maps $\varprojlim_{\mathcal{A}} I_\alpha \rightarrow I_\alpha$ give arrows

$$D(I_\infty) \rightarrow D(I_\alpha),$$

well-defined and compatible up to homotopy. By the Milnor exact sequence, these can be lifted to a homotopy class of maps

$$\phi: D(I_\infty) \longrightarrow \varprojlim D(I_\alpha),$$

in \mathcal{C} . We claim this is an equivalence, which we will check by verifying that both sides represent the same functor in the homotopy category.

Indeed, for any $X \in \mathcal{C}$, there are isomorphisms

$$\begin{aligned} [X, D(I_\infty)]_* &\simeq \mathrm{Hom}_{\mathcal{A}}^*(H(X), I_\infty) \\ &\simeq \varprojlim \mathrm{Hom}_{\mathcal{A}}^*(H(X), I_\alpha) \\ &\simeq \varprojlim [X, D(I_\alpha)]_*. \end{aligned}$$

The Milnor sequence associated to the limit $\varprojlim D(I_n)$ takes the form

$$0 \longrightarrow \varprojlim^1 [X, D(I_n)]_{*+1} \longrightarrow [X, \varprojlim D(I_\alpha)]_* \longrightarrow \varprojlim [X, D(I_\alpha)]_* \longrightarrow 0. \quad (11.12)$$

It follows from Lemma 11.10 that the structure maps in the tower

$$([X, D(I_\alpha)]_{*+1}) \simeq (\mathrm{Hom}_{\mathcal{A}}^{*+1}(H(X), I_\alpha))$$

are split epimorphisms, so the \varprojlim^1 -term in (11.12) vanishes. Thus, the Yoneda lemma implies that ϕ is an equivalence, as claimed. \square

The spectral sequence we construct involves derived functors of the limit, and so we first establish a consistent notation for these.

Notation 11.13. If \mathcal{A} is a Grothendieck abelian category and $F: J \rightarrow \mathcal{A}$ is a diagram, then we write $\varprojlim_{\mathcal{A}} F$ for the limit taken in \mathcal{A} itself. Formation of limits defines a functor

$$\varprojlim_{\mathcal{A}}: \mathrm{Fun}(J, \mathcal{A}) \rightarrow \mathcal{A},$$

and we denote its right derived functors by

$$\varprojlim_{\mathcal{A}}^s F.$$

Alternatively, \mathcal{A} has an associated derived ∞ -category, and we write

$$\varprojlim_{\mathcal{D}(\mathcal{A})} F$$

for the limit of the composite of F with the inclusion with the heart. These two different notions of limits, one in \mathcal{A} and the other in the derived ∞ -category, are related by the formula

$$\varprojlim_{\mathcal{A}}^s F \simeq H_{-s}(\varprojlim_{\mathcal{D}(\mathcal{A})} F),$$

where on the right-hand side, we have the homology of an object of the derived ∞ -category. Thus, $\varprojlim_{\mathcal{D}(\mathcal{A})} F$ can be thought of as the total derived functor of the limit.

Theorem 11.14. *Let $H: \mathcal{C} \rightarrow \mathcal{A}$ be an adapted homology theory. If $(X^\alpha) \in \mathcal{C}^\mathbb{N}$ is a tower in \mathcal{C} , then there exists a natural spectral sequence in \mathcal{A} of the form*

$$E_2^{s,t} \simeq \varprojlim_{\mathcal{A}}^s H(X^\alpha)[-t]_{\mathcal{A}} \implies H(\varprojlim_{\mathcal{A}} X^\alpha)[s-t]_{\mathcal{A}} \quad (11.15)$$

with differentials $d_r^{s,t}: E_r^{s,t} \rightarrow E_r^{s+r,t+r-1}$.

Proof. If H is adapted, then so is the induced homology theory

$$H: \mathcal{C}^\mathbb{N} \rightarrow \mathcal{A}^\mathbb{N}$$

between the ∞ -categories of towers [PP21, Example 8.24]. Thus, we have Adams resolutions of towers, and we let $(X_i^\alpha)_{i \geq 0}$ be a modified Adams tower of (X^α) as in Lemma 11.8.

Taking limits in the Adams resolution of X^α yields a tower in \mathcal{C} of the form

$$\begin{array}{ccccccc} \varprojlim X_0^\alpha & \xleftarrow{g_0} & \varprojlim X_1^\alpha & \xleftarrow{g_1} & \varprojlim X_2^\alpha & \xleftarrow{g_2} & \dots \\ f_0 \downarrow & \nearrow \delta_0 & f_1 \downarrow & \nearrow \delta_1 & f_2 \downarrow & \nearrow \delta_2 & \\ \varprojlim \Sigma^0 D(I_0^\alpha) & & \varprojlim \Sigma^{-1} D(I_1^\alpha) & & \varprojlim \Sigma^{-2} D(I_2^\alpha) & & \dots \end{array}$$

For brevity, let us write $[k] := [k]_{\mathcal{A}}: \mathcal{A} \rightarrow \mathcal{A}$ for the internal degree shift. Setting $D_1^{s,t} = H(\varprojlim X_s^\alpha)[s-t]$ and $E_1^{s,t} = H(\varprojlim \Sigma^{-s} D(I_s^\alpha))[s-t]$, this induces an exact couple of bigraded objects in \mathcal{A} of the form

$$\begin{array}{ccc} D & \xrightarrow{i_1=H(g_i)[s-t]} & D \\ & \searrow k_1=H(\delta_i)[s-t] \quad \swarrow j_1=H(f_i)[s-t] & \\ & E, & \end{array}$$

where the maps have bidegree $|i_1| = (-1, -1)$, $|j_1| = (0, 0)$ and $|k_1| = (1, 0)$. The E_1 -term can be identified using Proposition 11.11 and Lemma 11.7 as

$$E_1^{s,t} = \varprojlim \Sigma^{-s} D(I_s^\alpha)[s-t] \simeq D(\varprojlim_{\mathcal{A}} I_s^\alpha)[-t] = (\varprojlim_{\mathcal{A}} I_s^\alpha)[-t]$$

and $d_1 = \varprojlim_{\mathcal{A}} \tau_s^\alpha$. This gives the E_2 -term

$$E_2^{s,t} \simeq \varprojlim_{\mathcal{A}}^s (H_* X^\alpha)[-t],$$

as needed. It is clear from this construction and Lemma 11.8 that the resulting spectral sequence is natural in the tower X^α and that all pages and differentials are in \mathcal{A} . \square

Warning 11.16. Note that since the local grading $[1]_{\mathcal{A}}: \mathcal{A} \rightarrow \mathcal{A}$ is an equivalence, it commutes with derived functors of the limit, and in the spectral sequence of Theorem 11.14, we have

$$E_2^{s,t} := \varprojlim_{\mathcal{A}}^s H(X^\alpha)[-t]_{\mathcal{A}} \simeq (\varprojlim_{\mathcal{A}}^s H(x^\alpha))[-t]_{\mathcal{A}} \simeq E_2^s[-t]_{\mathcal{A}}.$$

Thus, the $t = 0$ line in the spectral sequence already determines the whole E_2 -page. This is similar to the case of the Bockstein spectral sequence, which also has a periodic E_2 -page.

Remark 11.17. Suppose that (X^α) is a tower under X . Then, the image

$$\mathrm{im}(H(X)) \subseteq \varprojlim_{\mathcal{A}}^0 H(X^\alpha)$$

consists of permanent cycles; that is, it is in the kernel of all the differentials in the spectral sequence of Theorem 11.14.

To see this, note that the assumption gives a map from the constant tower on X to (X^α) , inducing a map of spectral sequences

$$\begin{array}{ccc} \varprojlim_{\mathcal{A}}^s H(X) & \Longrightarrow & H(X) \\ \downarrow & & \downarrow \\ \varprojlim_{\mathcal{A}}^s H(X^\alpha) & \Longrightarrow & H(\varprojlim_{\mathcal{A}} X^\alpha). \end{array}$$

The E_2 -page of the top spectral sequence is concentrated in

$$E_2^{0,t} \simeq \varprojlim_{\mathcal{A}}^0 H(X)[-t]_{\mathcal{A}} \simeq H(X)[-t]_{\mathcal{A}},$$

so that the spectral sequence collapses. The comparison map is readily identified with the induced morphism $H(X) \rightarrow \varprojlim_{\mathcal{A}} H(X^\alpha)$, so the claim follows.

11.3. Derived limits of comodules

We now specialise the above to the case of a homology theory on spectra corresponding to a ring spectrum of Adams type. In order to study the E_2 -term of the spectral sequence of Theorem 11.14, we begin with a general discussion of inverse limits of comodules over suitable flat Hopf algebroids. Let (A, Ψ) be an Adams Hopf algebroid in the sense of [Hov04a][Definition 1.4.3], so that Ψ is a filtered colimit of dualisable comodules. We now describe an approach to computing limits in the derived ∞ -category $\mathcal{D}(\Psi) = \mathcal{D}(\mathrm{Comod}_{\Psi})$ of comodules by reducing to the case of modules. The forgetful functor $\epsilon_*: \mathrm{Comod}_{\Psi} \rightarrow \mathrm{Mod}(A)$ is *left* adjoint to the extended (or cofree) comodule functor ϵ^* which sends an A -module M to $\Psi \otimes_A M$. These functors are exact and thus give rise to an adjunction:

$$\epsilon_* \dashv \epsilon^*: \mathcal{D}(\Psi) \rightleftarrows \mathcal{D}(A).$$

In terms of chain complexes, both can be computed levelwise.

The corresponding monad $\epsilon^* \epsilon_*$ can be used to construct a resolution of any comodule. Concretely, if M is a Ψ -comodule, then we have the associated cobar complex

$$0 \rightarrow M \rightarrow \Psi \otimes_A M \rightarrow \Psi \otimes_A \Psi \otimes_A M \rightarrow \dots,$$

which is a resolution of M by extended comodules, that is, those of the form $\epsilon^* N = \Psi \otimes_A N$ for an A -module N .

One way to phrase that the cobar complex is exact is to say that the augmented cosimplicial object from which it arises, namely

$$M \rightarrow \Psi \otimes_A M \rightrightarrows \Psi \otimes_A \Psi \otimes_A M \rightrightarrows \dots, \quad (11.18)$$

is a limit diagram in the derived ∞ -category $\mathcal{D}(\Psi)$. Now, since limit diagrams are stable under levelwise limits, it follows that if (M_i) is a diagram of comodules, then the diagram

$$\varprojlim_{\mathcal{D}(\Psi)} M_i \rightarrow \varprojlim_{\mathcal{D}(\Psi)} \Psi \otimes_A M_i \rightrightarrows \varprojlim_{\mathcal{D}(\Psi)} \Psi \otimes_A \Psi \otimes_A M_i \rightrightarrows \dots,$$

is also a limit, giving an approach to computing $\varprojlim_{\mathcal{D}(\Psi)} M_i$. To see this, notice that since ϵ^* is a right adjoint and thus preserves limits, we have

$$\varprojlim_{\mathcal{D}(\Psi)} \Psi \otimes_A N_i \simeq \varprojlim_{\mathcal{D}(\Psi)} \epsilon^* N_i \simeq \epsilon^* (\varprojlim_{\mathcal{D}(A)} N_i) \simeq \Psi \otimes_A (\varprojlim_{\mathcal{D}(A)} N_i).$$

Applying this to the cosimplicial diagram (11.18), we see that we get a limit diagram of the form

$$\varprojlim_{\mathcal{D}(\Psi)} M_i \rightarrow \Psi \otimes_A (\varprojlim_{\mathcal{D}(A)} M_i) \rightrightarrows \Psi \otimes_A (\varprojlim_{\mathcal{D}(A)} \Psi \otimes_A M_i) \rightrightarrows \dots$$

which expresses the limit in the derived category of comodules using only limits taken in the category of modules. Passing to homology, which encodes the derived functors of the limit in the categories of A -modules and Ψ -comodules, we deduce the following.

Proposition 11.19. *If M_i is a diagram of comodules, then there exists a spectral sequence of comodules of signature*

$$E_1^{s,t} := \Psi \otimes_A \varprojlim_A^s (\Psi^{\otimes_A t} \otimes_A M_i) \implies \varprojlim_{\Psi}^{s+t} M_i,$$

computing the derived functors of the limit in comodules.

Remark 11.20. Note that in the particular case of sequential inverse limits, that is, diagrams of the form

$$\dots \rightarrow M_2 \rightarrow M_1 \rightarrow M_0,$$

this spectral sequence collapses after at most two pages, since, in this case, we have $\varprojlim_A^s N_i = 0$ for $s \neq 0, -1$ and any diagram N_i of A -modules.

Remark 11.21. In an even more specific case, let us assume that we work with sequential inverse limits and that the maps $M_{n+1} \rightarrow M_n$ are all epimorphisms. If that is the case, the same is true for $\Psi \otimes_A \dots \otimes_A M_{n+1} \rightarrow \Psi \otimes_A \dots \otimes_A M_n$, and we deduce using the Mittag-Leffler condition that all of the \varprojlim_A^1 -terms vanish. In this case, the spectral sequence of Proposition 11.19 has only one potentially nonzero differential.

Phrasing it without the use of spectral sequences, we see that the diagram of comodules

$$\Psi \otimes_A (\varprojlim_A M_i) \rightarrow \Psi \otimes_A (\varprojlim_A \Psi \otimes_A M_i) \rightarrow \dots,$$

is an explicit presentation of the derived limit $\varprojlim_{\mathcal{D}(\Psi)} M_i$ as a chain complex.

Example 11.22. Suppose that R is a homotopy commutative ring spectrum of Adams-type. As $R_* : \mathcal{S}p \rightarrow \text{Comod}_{R_*R}$ is an adapted homology theory by Lemma 11.7, Theorem 11.14 specialises to give a spectral sequence

$$E_2^{s,t} \simeq \varprojlim_{R_*R}^s (R_{*+t} X^\alpha) \implies R_{*+s+t} (\lim_\alpha X^\alpha)$$

for a tower of spectra (X^α) , where the derived functors of the limit are taken in R_*R -comodules.

This is a spectral sequence in R_*R -comodules, so that, in particular, the E_2 -page is *trigraded*. Passing to internal degree zero, we obtain a more-pleasant looking bigraded spectral sequence

$$E_2^{s,t} \simeq (\varprojlim_{R_*R}^s R_*X^\alpha)_t \implies R_{s+t}(\lim_\alpha X^\alpha).$$

Note that, in general, we cannot rewrite the E_2 -page as “ $\varprojlim_{R_*R}^s (R_t X^\alpha)$ ”, as the derived functors of the limit are computed in R_*R -comodules, a structure which cannot be restricted to a single degree.

Warning 11.23. Even for quite reasonable R , such as $R = H\mathbb{Q}$, convergence of the spectral sequence of Example 11.22 is a subtle problem. For example, let (M_{p^i}) be the tower of mod p^i Moore spectra with the canonical structure maps, and suppose $R = H\mathbb{Q}$. Since

$$\lim(\dots \longrightarrow M_{p^2} \longrightarrow M_p) \simeq S_p^0,$$

the p -complete sphere, the abutment of the spectral sequence is nontrivial, while the E_2 -term is zero. We study this question in more detail in the next section in the case of Morava E -theory.

Remark 11.24. The same methods as those leading to Example 11.22 have been employed by Hovey to set up a spectral sequence computing the R -homology of a product of spectra (see [Hov07]). In [Pet20, Appendix A], a different construction of the spectral sequence of Example 11.22 is given, based on Adams resolutions rather than modified Adams resolutions.

12. The Morava E -homology of inverse limits

The goal of this section is to study the spectral sequence constructed in Theorem 11.14 in the special case of (uncompleted) Morava E -homology. In particular, we identify the E_2 -page for the sphere spectrum in terms of the continuous cohomology of the Morava stabiliser group and exhibit conditions on the tower that ensure convergence.

We will work with a particular form of Morava E -theory, which we used previously in Section 5. For convenience of the reader, let us fix our notation for the remainder of the current work.

We fix a prime p and a height $n > 0$, and we let \mathbf{G}_0 be the Honda formal group law over $\mathbb{F}_q := \mathbb{F}_{p^n}$. We write E for the associated Lubin-Tate spectrum, so that we have a noncanonical isomorphism

$$E_* \simeq W(\mathbb{F}_{p^n})[[u_1, \dots, u_{n-1}]] [u^{\pm 1}].$$

We write $\mathfrak{m} = (p, u_1, \dots, u_{n-1})$ for the maximal ideal of E_0 . By Goerss-Hopkins-Miller, the spectrum E is acted on by the extended Morava stabiliser group $\mathbb{G}_n := \text{Aut}(\mathbf{G}_0/\mathbb{F}_q) \rtimes \text{Gal}(\mathbb{F}_q/\mathbb{F}_p)$.

Warning 12.1. We remind the reader that, unless otherwise noted, we work with uncompleted E -homology, the uncompleted homology cooperations $E_*E := \pi_*(E \otimes E)$ and uncompleted E_*E -comodules.

12.1. Continuous cohomology of filtered colimits

In this subsection, we prove that continuous cohomology groups of \mathbb{G}_n commute with certain filtered colimits. To this end, it will be useful for us to consider the following variant on the \mathfrak{m} -adic topology on an E_0 -module.

Definition 12.2. Let M be an E_0 -module. The *local \mathfrak{m} -adic* topology on M is the linear topology in which a submodule $U \subseteq M$ is open if for every finitely generated E_0 -submodule $M' \subseteq M$,

$$U \cap M' \subseteq M'$$

is open in the usual \mathfrak{m} -adic topology on M' ; that is, we have $\mathfrak{m}^n M' \subseteq U \cap M'$ for some n depending on M' .

Example 12.3. Suppose that M is finitely generated over E_0 . Then, the local \mathfrak{m} -adic topology on M coincides with the usual \mathfrak{m} -adic topology.

Example 12.4. Suppose that M is an arbitrary E_0 -module. Then, we can write $M \simeq \varinjlim M_\alpha$ as a filtered colimit of finitely generated E_0 -modules. The local \mathfrak{m} -adic topology coincides with the colimit topology if we equip each M_α with its usual \mathfrak{m} -adic topology.

The importance of the local \mathfrak{m} -adic topology in our context comes down to the following observation.

Remark 12.5. Let X be a spectrum. Then, E_0X is a continuous \mathbb{G}_n -module with respect to its local \mathfrak{m} -adic topology. To see this, observe that we can write $X \simeq \varinjlim X_\alpha$ as a filtered colimit of finite spectra, so that

$$E_0X \simeq \varinjlim E_0X_\alpha. \quad (12.6)$$

Each of E_0X_α is a continuous \mathbb{G}_n -module when considered with its \mathfrak{m} -adic topology, and E_0X becomes a topological \mathbb{G}_n -module since it has the colimit topology with respect to (12.6).

We will be interested in the continuous cohomology of \mathbb{G}_n with coefficients in an E_0 -module equipped with its local \mathfrak{m} -adic topology. As we will see, this has an elegant description in terms of cohomologies of its finitely generated submodules. The key is the following lemma.

Lemma 12.7. *Let K be a compact Hausdorff topological space and M be an E_0 -module equipped with its local \mathfrak{m} -adic topology. Then, any continuous map $f: K \rightarrow M$ factors through a finitely generated submodule. In other words, we have*

$$\mathrm{map}_{\mathrm{cts}}(K, M) \simeq \varinjlim \mathrm{map}_{\mathrm{cts}}(K, M_\alpha),$$

where M_α is the poset of finitely generated submodules of M .

Proof. Suppose for the sake of contradiction that for every finitely generated submodule M' , there exists a $k \in K$, such that $f(k) \notin M'$. Proceeding inductively, we produce an increasing sequence

$$M_0 \subseteq M_1 \subseteq M_2 \subseteq \dots$$

of finitely generated submodules and points $k_n \in K$, such that $f(k_n) \in M_{n+1}$, but $f(k_n) \notin M_n$. We claim that an arbitrary finitely generated submodule N contains at most finitely many of the $f(k_n)$. To see this, let us write $M_\infty = \bigcup M_n$ and consider $N \cap M_\infty$; the latter is again finitely generated, as E_0 is Noetherian, and its intersection with $\{f(k_n)\}$ is the same as that of N . By finite generation, we have $N \cap M_\infty = N \cap M_n$ for sufficiently large n , proving the claim, as the latter contains at most n of the $f(k_n)$.

Since each finitely generated submodule is Hausdorff, its finite subspaces are closed and discrete, and we deduce that $T = \{f(k_n)\}$ is closed and discrete as a subspace of M , as this is true for its intersection with each finitely generated submodule. This is a contradiction, as $T = f(f^{-1}(T))$ must be compact Hausdorff as an image of a closed subspace of K , so it cannot be both infinite and discrete. \square

Proposition 12.8. *Let $M \simeq \varinjlim M_\alpha$ be a filtered colimit diagram of E_0 -modules equipped with their local \mathfrak{m} -adic topologies, and let K be compact Hausdorff. Then, the induced map*

$$\theta: \varinjlim \mathrm{map}_{\mathrm{cts}}(K, M_\alpha) \rightarrow \mathrm{map}_{\mathrm{cts}}(K, M)$$

is an isomorphism of abelian groups.

Proof. We first show surjectivity of θ . Suppose that $f: K \rightarrow M$ is a continuous map, by Lemma 12.7, it factors through a finitely generated submodule $N \subseteq M$. If we write $N_\alpha = N \times_M M_\alpha$, then since filtered colimits are exact, we have

$$N \simeq \varinjlim N_\alpha.$$

As N is finitely generated and E_0 is Noetherian, it is finitely presented, and we deduce that there exists a section $N \rightarrow N_\alpha$ for some α . Then, the composite

$$K \rightarrow N \rightarrow N_\alpha \rightarrow M_\alpha$$

determines the needed element of the filtered colimit.

For injectivity, suppose that we have a continuous map $f: K \rightarrow M_\alpha$, such that the composite $s_\alpha \circ f: K \rightarrow M$, where $s_\alpha: M_\alpha \rightarrow M$ is the canonical map, is zero. By another application of Lemma 12.7, K factors through a finitely generated submodule $N_\alpha \subseteq M_\alpha$, and we necessarily have $N_\alpha \subseteq \ker(s_\alpha)$. As N_α is finitely generated, the second condition implies that we can find a larger index β , such that the composite

$$N_\alpha \rightarrow M_\alpha \rightarrow M_\beta$$

is zero. It follows that f determines the zero element of the filtered colimit, as needed. \square

Corollary 12.9. *Let $M \simeq \varinjlim M_\alpha$ be a filtered colimit of E_0 -modules equipped with their local \mathfrak{m} -adic topology and compatible continuous \mathbb{G}_n -actions. Then,*

$$H_{\mathrm{cts}}^*(\mathbb{G}_n, M) \simeq \varinjlim H_{\mathrm{cts}}^*(\mathbb{G}_n, M_\alpha).$$

In particular, for any E_0 -module N , we have

$$H_{\text{cts}}^*(\mathbb{G}_n, N) \simeq \varinjlim H_{\text{cts}}^*(\mathbb{G}_n, N_\alpha),$$

where the colimit is taken over the poset N_α of finitely generated submodules.

Proof. The continuous cohomology is computed by the standard cochain complex

$$M \rightarrow \text{map}_{\text{cts}}(\mathbb{G}_n, M) \rightarrow \text{map}_{\text{cts}}(\mathbb{G}_n \times \mathbb{G}_n, M) \rightarrow \dots$$

of continuous cochains. The statement follows from an application of Proposition 12.8 to each term separately, as $\mathbb{G}_n \times \dots \times \mathbb{G}_n$ is compact Hausdorff and taking cohomology of cochain complexes commutes with filtered colimits. \square

12.2. Inverse limits of E_*E -comodules and continuous cohomology

In this section, we give a description of derived functors of the limit

$$\varprojlim_{E_*E}^s M/\mathfrak{m}^k M \simeq H_{-s}(\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M)$$

in E_*E -comodules as cohomology of the Morava stabiliser group. The importance of these derived functors stems from the fact that they form the E_2 -page of the spectral sequence constructed in Section 11.2.

Lemma 12.10. *If M is a dualisable E_*E -comodule, then we have a canonical isomorphism*

$$\begin{aligned} & \text{Ext}_{\mathcal{D}(E_*E)}^s(E_*, \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \\ & := \pi_{-s} \text{Hom}_{\mathcal{D}(E_*E)}(E_*, \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \simeq H_{\text{cts}}^s(\mathbb{G}_n, M) \end{aligned}$$

for any $s \geq 0$, where E_*/\mathfrak{m}^k is the \mathfrak{m} -adic tower of E_* .

Proof. For brevity, if $X \in \mathcal{D}(E_*E)$, let us write

$$\text{Ext}^s(X) := \text{Ext}_{\mathcal{D}(E_*E)}^s(E_*, X) \simeq \pi_{-s} \text{Hom}_{\mathcal{D}(E_*E)}(E_*, X).$$

Since we have

$$\text{Hom}_{\mathcal{D}(E_*E)}(E, \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \simeq \varprojlim \text{Hom}_{\mathcal{D}(E_*E)}(E, M/\mathfrak{m}^k M),$$

there is a Milnor sequence

$$0 \rightarrow \varprojlim^1 \text{Ext}^{s-1}(M/\mathfrak{m}^k M) \rightarrow \text{Ext}^s(\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \rightarrow \varprojlim \text{Ext}^s(M/\mathfrak{m}^k M) \rightarrow 0,$$

where we have omitted subscripts for simplicity and the derived functors of the limit are taken in abelian groups.

We first claim that the \varprojlim^1 -term above vanishes. Note that since $M/\mathfrak{m}^k M$ is finitely generated and \mathfrak{m} -torsion for any $k \geq 1$, we have a canonical isomorphism

$$\text{Ext}(M/\mathfrak{m}^k M) \simeq H_{\text{cts}}^s(\mathbb{G}_n, M/\mathfrak{m}^k M)$$

with the cohomology of the Morava stabiliser group. For $k = 1$, we have a further isomorphism

$$\mathrm{Ext}(M/\mathfrak{m}M) \simeq \mathrm{Ext}_{E_*E}(E_*, K_* \otimes_{E_*} M) \simeq \mathrm{Ext}_{E_*K}(K_*, K_* \otimes_{E_*} M)$$

and the group on the right is degreewise finite by Corollary 5.7. It follows by induction that $\mathrm{Ext}(M_*/\mathfrak{m}^k M)$ is degreewise finite for each $k \geq 1$. Therefore, the groups $\mathrm{Ext}(M/\mathfrak{m}^k M)$ satisfy the Mittag-Leffler condition as k varies, so that the corresponding \varprojlim^1 -term vanishes as claimed.

Consequently, we get a string of isomorphisms

$$\begin{aligned} \mathrm{Ext}^s(\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) &\simeq \varprojlim \mathrm{Ext}^s(E_*, M/\mathfrak{m}^k M) \\ &\simeq \varprojlim H_{\mathrm{cts}}^s(\mathbb{G}_n, M/\mathfrak{m}^k M) \\ &\simeq H_{\mathrm{cts}}^s(\mathbb{G}_n, M). \end{aligned}$$

Here, the last isomorphism uses that M is \mathfrak{m} -adically complete as a finitely generated E_* -module, and that taking continuous cohomology of a finitely generated profinite group commutes with taking countable inverse limits of finite modules [NSW13, Section 7]. \square

In order to pass from Lemma 12.10 to a description of the derived functors $\varprojlim_{E_*E}^s E_*/\mathfrak{m}^k$, we have to understand the homology groups of $\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M$, rather than its homotopy. To do so, we will make use of the Adams condition, which involves certain filtered colimits. To commute past the latter, we will need a technical lemma stating that homotopy groups

$$\mathrm{Ext}^s(E_*, -) := \pi_{-s} \mathrm{Hom}_{\mathcal{D}(E_*E)}(E_*, -)$$

preserve certain filtered colimits of bounded complexes. If $p > n + 1$, then the monoidal unit of $\mathcal{D}(E_*E)$ is compact, so no boundedness hypotheses are required, but this can fail for general n . In general, we still have the following result.

Lemma 12.11. *Suppose $(L_\alpha)_\alpha$ is a filtered system of complexes of E_*E -comodules which are uniformly bounded above in the standard t -structure on $\mathcal{D}(E_*E)$; that is, there exists an N , such that, for all $s > N$ and all α , we have $H_s(L_\alpha) = 0$. Then the canonical comparison map*

$$\phi: \varinjlim_\alpha \mathrm{Ext}^s(L_\alpha) \longrightarrow \mathrm{Ext}^s(\varinjlim_\alpha L_\alpha)$$

is an isomorphism for any $s \in \mathbb{Z}$.

Proof. By shifting the system $(L_\alpha)_\alpha$ if necessary, we may reduce to the case of $s = 0$. In other words, we have to show that the canonical map

$$\varinjlim_\alpha [E_*, L_\alpha] \longrightarrow [E_*, \varinjlim_\alpha L_\alpha]$$

between homotopy classes of maps in the derived ∞ -category, is an isomorphism.

Since E_* is connective in the standard t -structure, we can then replace L_α by its connective cover $\tau_{\geq 0} L_\alpha$; that is, reduce to the case in which there exists a nonnegative

integer N , such that L_α has homology concentrated in degrees $[0, N]$ for all α . By induction and the five-lemma, we can reduce further to the case that L_α is concentrated in a single nonnegative degree $[s, s]$ for all α .

Summarising these reduction steps, it remains to prove that the canonical map

$$\varprojlim_{\alpha} \mathrm{Ext}_{E_*E}^s(E_*, L_\alpha) \longrightarrow \mathrm{Ext}_{E_*E}^s(E_*, \varprojlim_{\alpha} L_\alpha)$$

is an isomorphism for any filtered system of comodules $L_\alpha \in \mathrm{Comod}_{E_*E}$. This is clear, these Ext -groups can be computed by the cobar complex, formation of which commutes with filtered colimits. \square

Proposition 12.12. *For any dualisable E_*E -comodule M , there exists a canonical isomorphism*

$$\varprojlim_{E_*E}^s M/\mathfrak{m}^k M \simeq H_{\mathrm{cts}}^s(\mathbb{G}_n, E_*E \otimes_{E_*} M)$$

between the derived functors of the limit in comodules and the continuous cohomology of the Morava stabiliser group with coefficients in $E_*E \otimes_{E_*} M$ equipped with its local \mathfrak{m} -adic topology.

Proof. We have

$$\varprojlim_{E_*E}^s M/\mathfrak{m}^k M \simeq H_{-s}(\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M)$$

which we can further rewrite as

$$H_{-s}(\varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \simeq \mathrm{Ext}^s(E_*E \otimes_{E_*} \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M),$$

where the tensor product is the derived one. Writing $E_*E \simeq \varinjlim N_\alpha$ as a filtered colimit of dualisable comodules, we have

$$\begin{aligned} \mathrm{Ext}^s(E_*E \otimes_{E_*} \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) &\simeq \mathrm{Ext}^s(\varinjlim (N \otimes_{E_*} \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M)) \\ &\simeq \varinjlim \mathrm{Ext}^s(N \otimes_{E_*} \varprojlim_{\mathcal{D}(E_*E)} M/\mathfrak{m}^k M) \\ &\simeq \varinjlim \mathrm{Ext}^s(\varprojlim_{\mathcal{D}(E_*E)} N \otimes_{E_*} M/\mathfrak{m}^k (N \otimes_{E_*} M)) \\ &\simeq \varinjlim H_{\mathrm{cts}}^s(\mathbb{G}_n, N \otimes_{E_*} M) \\ &\simeq H_{\mathrm{cts}}^s(\mathbb{G}_n, \varinjlim N \otimes_{E_*} M) \\ &\simeq H_{\mathrm{cts}}^s(\mathbb{G}_n, E_*E \otimes_{E_*} M). \end{aligned}$$

Here, the first isomorphism uses that the derived tensor product commutes with filtered colimits and the second one is Lemma 12.11. The third isomorphism uses that tensoring with a dualisable object commutes with limit, the fourth one is Lemma 12.10, while the fifth one is Corollary 12.9. \square

Remark 12.13. The relationship between derived functors of the limit and derived completion in the context of comodules over a flat Hopf algebroid is studied further in [BHV20].

12.3. The inverse limit spectral sequence and its convergence

In this subsection, we study the convergence of the inverse limit spectral sequence based on Morava E -theory and combine the previous results in a spectral sequence computing the (uncompleted) E -homology of the K -local sphere spectrum from continuous group cohomology with coefficients in the (uncompleted) cooperations E_*E .

Proposition 12.14. *If $R = E$ is Morava E -theory and $(X^\alpha) \in \mathrm{Sp}_E^{\mathbb{N}}$ is a tower of E -local spectra, then the spectral sequence of Example 11.22 converges conditionally and strongly, and has a horizontal vanishing line at the E_r -page for some $r \geq 2$.*

Proof. By Lemma 11.8 and assumption on X^α , the modified Adams tower (X_i^α) is E -local for all i . Therefore, the proof of the smash product theorem due to Hopkins and Ravenel [Rav92, Theorem 7.5.6] yields a constant N independent of α , such that

$$g_s^\alpha \circ \dots \circ g_{s+N-1}^\alpha : X_{s+N}^\alpha \longrightarrow X_s^\alpha$$

is null for all α (see [HS05b, Theorem 5.10]). Consequently,

$$g_s \circ \dots \circ g_{s+N-1} : \varprojlim X_{s+N}^\alpha \longrightarrow \varprojlim X_s^\alpha \quad (12.15)$$

is null as well, so [Boa99] shows that the spectral sequence is conditionally convergent. Similarly, we obtain the horizontal vanishing line from (12.15), which in turn gives strong convergence. \square

Theorem 12.16. *If $(X^\alpha) \in \mathrm{Sp}_E^{\mathbb{N}}$ is a tower of E -local spectra, then there is a strongly convergent spectral sequence*

$$E_2^{s,t} \simeq (\varprojlim_{E_*E}^s E_*X^\alpha)_t \implies E_{t-s}(\varprojlim X^\alpha),$$

with a horizontal vanishing line at the E_r -page for some $r \geq 2$. In particular, this spectral sequence specialises to:

$$H_{\mathrm{cts}}^s(\mathbb{G}_n, E_t E) \simeq (\varprojlim_{E_*E}^s E_*/\mathfrak{m}^k)_t \implies E_{t-s}(L_K S^0). \quad (12.17)$$

Proof. The spectral sequence was constructed in Theorem 11.14, see also Example 11.22, while the convergence properties were established in Proposition 12.14. The final statement follows by applying this spectral sequence to a cofinal tower of E -local generalised type n Moore spectra, as in [HS99, Section 4]. The identification of the E_2 -page in terms of continuous cohomology was proven in Proposition 12.12. \square

Remark 12.18. The spectral sequence (12.17) may be thought of as an E_* -homology version of the K -local E -based Adams spectral sequence for the sphere, which has signature

$$H_{\mathrm{cts}}^s(\mathbb{G}_n, E_*)_t \implies \pi_* L_K S^0$$

and is also strongly convergent. In contrast, working with completed E_* -homology would result in an isomorphism $E_* \simeq E_*^\vee L_K S^0 \simeq H_{\mathrm{cts}}^*(\mathbb{G}_n, E_*^\vee E_*)$. This amply highlights the extra information contained in the terms $H_{\mathrm{cts}}^*(\mathbb{G}_n, E_* E)$.

13. Digression: Cohomology of \mathbb{G}_n as Ext in comodules

In Lemma 12.10, we have expressed the continuous cohomology of the Morava stabiliser group with coefficients in a dualisable E_*E -comodule M in terms of the homotopy groups of a derived completion. In this short section, we use a form of local duality in the context of comodules to express it as an Ext-groups between actual comodules, rather than objects of the derived ∞ -category. Using this calculation, we define a comparison map between Ext-groups and continuous cohomology.

Let $I_k = (p, v_1, \dots, v_{k-1})$ be the k -th invariant chromatic ideal in E_* ; in particular, $I_n = \mathfrak{m}$. We define $E_* = E_*/I_0^\infty$ and then iteratively construct E_*E -comodules via the cofibre sequences

$$E_*/I_k^\infty \rightarrow v_k^{-1}E_*/I_k^\infty \rightarrow E_*/I_{k+1}^\infty \quad (13.1)$$

in $\mathcal{D}(E_*E)$. Note that $E_*/I_k^\infty \simeq \varinjlim E_*/v_0^{l_0}, \dots, v_{k-1}^{l_{k-1}}$, where the colimit is taken over a set of indices with $l_i \rightarrow \infty$. For the constituent pieces, we have the following self-duality result:

Lemma 13.2. *In the derived category of E_*E -comodules, the comodule $E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k}$ is self-dual with a shift in the sense that there exists an equivalence*

$$D(E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k}) \simeq \Sigma^{-k} E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k},$$

where $DX = F(X, E_*)$ denotes the monoidal dual.

Proof. We prove this by induction on k , where $k = -1$ is clear, since E_* is the monoidal unit.

Now assume that the statement is known for $E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}}$. Multiplication by $v_k^{i_k}$ induces a cofibre sequence

$$E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}} \rightarrow E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}} \rightarrow E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k}$$

which after taking duals yields a cofibre sequence

$$D(E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k}) \rightarrow D(E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}}) \rightarrow D(E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}}).$$

By the inductive assumption, this sequence can be rewritten as

$$D(E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_k^{i_k}) \rightarrow \Sigma^{k-1} E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}} \rightarrow \Sigma^{k-1} E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}}.$$

The self-map of $\Sigma^{k-1} E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}} \rightarrow \Sigma^{k-1} E_*/v_0^{i_0}, v_1^{i_1}, \dots, v_{k-1}^{i_{k-1}}$ appearing on the right cannot be nonzero, since it is a dual to the nonzero class $v_k^{i_k}$. It follows that it must be itself a unit times $v_k^{i_k}$ since there is nothing else in this degree (see, for example [Rav03, Theorem 4.3.2(b)]). The assertion then follows. \square

Lemma 13.3. *If M is a finitely generated E_*E -comodule, then its derived comodule completion of M is given by*

$$\varprojlim_{\mathcal{D}(E_*E)} (M \otimes_{E_*} E_*/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}) \simeq \varprojlim_{\mathcal{D}(E_*E)} M/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}},$$

where on the left-hand side we have used the derived tensor product of comodules.

Proof. This is proven in [BHV20, Proposition 2.25] \square

The next result is an incarnation of local duality for comodules [BHV18, Section 5], relating local cohomology (derived torsion) and local homology (derived completion), combined with Lemma 12.10.

Theorem 13.4. *Let M be a finitely generated E_*E -comodule. Then, there exists an isomorphism*

$$\mathrm{Ext}_{E_*E}^{n+s}(E_*/I_n^\infty, M) \simeq \mathrm{H}_{\mathrm{cts}}^s(\mathbb{G}_n, M)$$

between Ext-groups in comodules and the cohomology of \mathbb{G}_n , for any $s \geq 0$.

Proof. As noted before, we have $E_*/I_n^\infty \simeq \varinjlim E_*/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}$, where the colimit is taken over a set of indices with $k_i \rightarrow \infty$. By the duality equivalence of Lemma 13.2, we have

$$\begin{aligned} & \mathrm{Hom}_{\mathcal{D}(E_*E)}(\varinjlim \Sigma^{-n} E_*/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}, M) \\ & \simeq \mathrm{Hom}_{\mathcal{D}(E_*E)}(E_*, \varprojlim_{\mathcal{D}(E_*E)} M \otimes E_*/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}). \end{aligned}$$

In light of Lemma 13.3, the latter term is equivalent to $\mathrm{Hom}_{\mathcal{D}(E_*E)}(E_*, \varprojlim M/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}})$. It follows that

$$\mathrm{Ext}_{E_*E}^{n+s}(E_*/I_n^\infty, M) \simeq \varprojlim \mathrm{Ext}_{E_*E}^s(E_*, M/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}),$$

up to possible \varprojlim^1 -terms. However, all of the Ext groups on the right are finite, since M is finitely generated, so these \varprojlim^1 -terms vanish. We then deduce as in Lemma 12.10 that

$$\mathrm{Ext}_{E_*E}^{n+s}(E_*/I_n^\infty, M) \simeq \varprojlim \mathrm{Ext}_{E_*E}^s(E_*, M/v_0^{k_0}, \dots, v_{n-1}^{k_{n-1}}) \simeq \mathrm{H}_{\mathrm{cts}}^s(\mathbb{G}_n, M),$$

which is what we wanted to show. \square

The boundary maps $\delta_k: E_*/I_{k+1}^\infty \rightarrow \Sigma E_*/I_k^\infty$ associated with the cofibre sequences (13.1) compose to give a ‘residue map’ in the derived category:

$$\delta := \delta_{n-1} \circ \dots \circ \delta_0: E_*/I_n^\infty \rightarrow \Sigma^n E_*.$$

For any finitely generated E_*E -comodule N , the map δ induces a natural map on Ext-groups that fits, for any s , into a commutative square

$$\begin{array}{ccc} \mathrm{Ext}_{E_*E}^s(E_*, N) & \xrightarrow{\mathrm{Ext}(\delta, N)} & \mathrm{Ext}_{E_*E}^{s+n}(E_*/I_n^\infty, N) \\ \simeq \downarrow & & \downarrow \simeq \\ [N^{\mathrm{dual}}, E_*]^{-s} & \longrightarrow & [N^{\mathrm{dual}}, \varprojlim_{\mathcal{D}(E_*E)} E_*/I_n^k]^{-s}. \end{array} \quad (13.5)$$

Here, the left vertical isomorphism is by duality, while the right vertical isomorphism is established as in the proof of the previous theorem. Unwinding the construction,

the bottom horizontal map is then induced by the canonical completion map $E_* \rightarrow \varprojlim_{\mathcal{D}(E_*E)} E_*/I_n^k$.

Definition 13.6. For a finitely generated E_*E -comodule N , we define the comparison map α_N as the composite

$$\alpha_N: \mathrm{Ext}_{E_*E}^s(E_*, N) \rightarrow \mathrm{Ext}_{E_*E}^{n+s}(E_*/I_n^\infty, N) \simeq H_{\mathrm{cts}}^s(\mathbb{G}_n, N)$$

of the map in (13.5) and the isomorphism of Theorem 13.4.

Note that, by construction, the maps α_N are natural and compatible with the long exact sequences of Ext-groups and cohomology.

Remark 13.7. Alternatively, it is possible to define the comparison map α_M directly using the cobar complex. More precisely, one can show that if M is a finitely generated E_*E -comodule, then the differentials in the cobar complex

$$M \rightarrow E_*E \otimes_{E_*} M \rightarrow E_*E \otimes_{E_*} E_*E \otimes_{E_*} M \rightarrow \dots$$

respect the \mathfrak{m} -adic filtration (even though they are not E_* -linear). The completion of the cobar complex is exactly the cochain complex computing continuous \mathbb{G}_n -cohomology, and the induced map on homology can be shown to be exactly α_M .

14. Algebraic chromatic splitting conjecture

In this penultimate section, we use the comparison map of the previous section to compute the zeroth derived limit as $\varprojlim_{E_*E}^0 E_*/\mathfrak{m}^k \simeq E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p$. This result should be viewed in light of Hopkins's algebraic chromatic splitting conjecture, see [Pet, Section 14], which we briefly review for context.

Notation 14.1. To simplify notation, if N is a finitely generated E_*E -comodule, we sometimes use abbreviations $\mathrm{Ext}^s(N) := \mathrm{Ext}_{E_*E}^s(E_*, N)$ and $H^s(N) := H_{\mathrm{cts}}^s(\mathbb{G}_n, N)$.

14.1. The algebraic chromatic splitting conjecture

Motivated by computations in height 2, this conjecture was formulated by Hopkins and recorded later in [Pet, Conjecture 134]³ as well as [BSS20, Conjecture 6.10], and studied further in [BH18]. To state it, we first recall the construction of the class $\zeta \in \pi_{-1}L_K S^0$ due to Devinatz and Hopkins [DH04, Section 8].

If we write \mathbb{G}_n^1 for the kernel of the reduced determinant map $\det: \mathbb{G}_n \rightarrow \mathbb{Z}_p$, there is a residual action of \mathbb{Z}_p on $E_n^{h\mathbb{G}_n^1}$. For t is a topological generator of \mathbb{Z}_p , we then obtain a fibre sequence of spectra

$$L_K S^0 \longrightarrow E_n^{h\mathbb{G}_n^1} \xrightarrow{\mathrm{id}-t} E_n^{h\mathbb{G}_n^1} \xrightarrow{\delta} L_K S^1.$$

³We note that the statement given there contains a typo: the left-hand side of the equation should have v_{n-1} inverted.

The composition $\delta \circ \eta: S^0 \rightarrow L_K S^0$ of the unit map with the boundary map gives rise to an element $\zeta \in \pi_{-1} L_K S^0$. In [DH04, Proposition 8.2], Devinatz and Hopkins prove a result originally due to Hopkins and Miller, saying that ζ is nontrivial as long as the height $n > 0$.

Conjecture 14.2 (Algebraic chromatic splitting conjecture). *For all heights $n \geq 2$ and sufficiently large p , there are isomorphisms of E_*E -comodules*

$$\varprojlim_{E_*E}^s E_*/(p, \dots, v_{n-2}, v_{n-1}^i) \simeq \begin{cases} E_*/(p, \dots, v_{n-2}) & s = 0 \\ v_{n-1}^{-1} E_*/(p, \dots, v_{n-2}) & s = 1 \\ 0 & \text{otherwise.} \end{cases}$$

Moreover, these isomorphisms are topologically realised by the unit map $\iota: S^0 \rightarrow L_K S^0$ and the map $\zeta: S^{-1} \rightarrow L_K S^0$, respectively.

Remark 14.3. As the name suggests, the algebraic chromatic splitting conjecture provides an algebraic counterpart to Hopkins's chromatic splitting conjecture [Hov95, Conjecture 4.2] in the edge case: If the algebraic chromatic splitting conjecture holds at height n and prime p , then the maps ι and ζ induce a splitting

$$(\iota, \zeta): L_{n-1}F \oplus \Sigma^{-1} L_{n-1}F \simeq L_{n-1} L_K F$$

for any finite spectrum F of type $n-1$. Indeed, the conclusion of the algebraic chromatic splitting conjecture forces the inverse limit sequence (11.15) for $L_K F$ to collapse at the E_2 -page, thereby showing (ι, ζ) is an E_* -isomorphism, and hence an E -local equivalence.

Example 14.4. In Section 15, we verify a height 1 variant of the algebraic chromatic splitting conjecture at any prime (see, in particular, Theorem 15.12 and also [Pet, Section 14]). The appearance of the additional tensor factors is the only reason we excluded the case of height 1 from the statement of the algebraic chromatic splitting conjecture above.

14.2. The comparison map in degree 0

We work with Notation 14.1. Our goal is to study the comparison map $\text{Ext}^s(M) \rightarrow H^s(M)$, constructed in Definition 13.6. We focus on the particular case when $s = 0$; note that in this case, this map is always injective, as both the source and target are abelian subgroups of M .

Thus, the real question is how far this comparison map is from being surjective. When M is the monoidal unit, we have the following folklore result of Hopkins.

Lemma 14.5 (Hopkins). *We have $H^0(E_*) \simeq \mathbb{Z}_p$ and the map $\text{Ext}^0(E_*) \rightarrow H^0(E_*)$ is a p -completion; that is, it induces an isomorphism $\mathbb{Z}_p \otimes_{\mathbb{Z}} \text{Ext}^0(E_*) \simeq H^0(E_*)$.*

Proof. The first part is [BG18, Lemma 1.33]. The second part follows from the fact that $\text{Ext}^0(E_*) \simeq \mathbb{Z}_{(p)}$, as in both cases, the relevant invariants are generated by the unit of the Lubin–Tate ring. \square

Lemma 14.6. *The map $\text{Ext}^1(E_*) \rightarrow H^1(E_*)$ is a monomorphism.*

Proof. Since it vanishes rationally, the source of this map is p -torsion. For a given $x \in \text{Ext}^1(E_*)$, we can thus find a k and $y \in \text{Ext}^0(E_*/p^k)$ so that x can be written as $x = \delta(y)$, where δ denotes the boundary homomorphism. We have a commutative diagram

$$\begin{array}{ccccccc} \text{Ext}^0(E_*) & \longrightarrow & \text{Ext}^0(E_*) & \longrightarrow & \text{Ext}^0(E_*/p^k) & \xrightarrow{\delta} & \text{Ext}^1(E_*) \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \text{H}^0(E_*) & \xrightarrow{p^k} & \text{H}^0(E_*) & \longrightarrow & \text{H}^0(E_*/p^k) & \xrightarrow{\delta} & \text{H}^1(E_*) \end{array}$$

with exact rows. Thus, it is enough to show that if the image $\tilde{y} \in \text{H}^0(E_*/p^k)$ of y can be lifted to $\text{H}^0(E_*)$, then y can be lifted to $\text{Ext}^0(E_*)$. By Lemma 14.5, the latter two groups are isomorphic to, respectively, \mathbb{Z}_p and $\mathbb{Z}_{(p)}$.

By multiplying by an appropriate unit σ in the p -adics congruent to 1 modulo p^k , and replacing the chosen lift $\tilde{z} \in \text{H}^0(E_*) \simeq \mathbb{Z}_p$ of \tilde{y} by $\sigma\tilde{z}$, we can assume that $\tilde{z} \in \mathbb{Z}_{(p)}$. It follows that y can be lifted to $\text{Ext}^0(E_*)$, which is what we wanted. \square

Our goal is to use an inductive argument, building on the calculation of invariants of E_* due to Hopkins and extending it to a larger class of comodules. The starting point is the following class.

Definition 14.7. We say a finitely generated E_*E -comodule M is *pure* if it belongs to the smallest class of comodules closed under extensions and containing all shifts of E_* .

Remark 14.8. Any pure M is finitely generated and projective over E_* , and so dualisable. It follows that if

$$0 \rightarrow K \rightarrow M \rightarrow N \rightarrow 0$$

is a short exact sequence of pure comodules, then it is split over E_* , so that the induced sequence

$$0 \rightarrow N^{\text{dual}} \rightarrow M^{\text{dual}} \rightarrow K^{\text{dual}} \rightarrow 0$$

of linear duals is again exact. We deduce that the class of pure comodules is closed under taking duals.

Remark 14.9. It is plausible that it follows from the arguments of Hovey and Strickland, who establish an analogue of the Landweber filtration for E_*E -comodules [HS05a], that all comodules finitely generated and projective over E_* are pure in the sense of Definition 14.7. We did not check whether this is true, as we do not need this fact in our arguments.

Lemma 14.10. *The category of E_*E -comodules is generated under colimits by pure comodules.*

Proof. Since $E \simeq \varinjlim E_\alpha$ is a filtered colimit of finite spectra, it follows formally that the category of E_*E -comodules is generated under colimits by shifts of comodules of the form E_*E_α [Hov04a, Proposition 1.4.4].

Furthermore, we claim that since the E_α only have even cells, the resulting comodules E_*E_α are pure. Using a cell decomposition of E_α and the associated long exact sequences in homology, which is short exact here, we deduce that each E_*E_α is a comodule which can be obtained using iterated extensions of shifts of E_* and so is pure. \square

Recall that a E_*E -comodule is dualisable if and only if the underlying E_* -module is finitely generated and projective.

Theorem 14.11. *If N is a dualisable E_*E -comodule, then*

- (1) $\text{Ext}^0(N)$ is a finitely generated $\mathbb{Z}_{(p)}$ -module and
- (2) the map $\alpha_N: \text{Ext}^0(N) \rightarrow H^0(N)$ is a p -completion, that is, it induces an isomorphism $\text{Ext}^0(N) \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq H^0(N)$.

Proof. For $N = E_*$ or its shifts, this is Lemma 14.5.

We first claim that the result is true for comodules C which are pure in the sense of Definition 14.7. By induction on rank, we can assume that we have a short exact sequence

$$0 \rightarrow E_* \rightarrow C \rightarrow C' \rightarrow 0$$

and that the result already holds for C' . The long exact sequence of Ext-groups implies that $\text{Ext}^0(C)$ is a finitely generated module over $\mathbb{Z}_{(p)}$. Thus, we have a commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(E_*) & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(C) & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(C') \longrightarrow \mathbb{Z}_p \otimes \text{Ext}^1(E_*) \\ & & \downarrow & & \downarrow & & \downarrow & \downarrow \\ 0 & \longrightarrow & H^0(E_*) & \longrightarrow & H^0(C) & \longrightarrow & H^0(C') \longrightarrow H^1(E_*), \end{array}$$

where the top row is again exact, since \mathbb{Z}_p is flat. By induction on rank, counting from the left, the first and third vertical maps are isomorphisms. By Lemma 14.6, the fourth one is a monomorphism, as $\mathbb{Z}_p \otimes \text{Ext}^1(E_*) \simeq \text{Ext}^1(E_*)$ because the latter group is p -torsion. We deduce that the second one is an isomorphism using the five-lemma, which was our claim.

Now suppose that N is an arbitrary dualisable comodule; by Lemma 14.10, we can find a surjection $C \rightarrow N$ from a pure comodule. By taking duals, we can assume that we instead have a monomorphism $N \hookrightarrow C$, where C is again pure by Remark 14.8. Since we already know $\text{Ext}^0(C)$ and $H^0(C)$ are free finitely generated over, respectively, $\mathbb{Z}_{(p)}$ and \mathbb{Z}_p , we deduce that the same is true for their submodules $\text{Ext}^0(N)$ and $H^0(N)$, proving (1).

Let us denote the cokernel of $N \hookrightarrow C$ by C' . We then have another commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(N) & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(C) & \longrightarrow & \mathbb{Z}_p \otimes \text{Ext}^0(C') \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & H^0(N) & \longrightarrow & H^0(C) & \longrightarrow & H^0(C'). \end{array}$$

By what we have proven above, the middle map is an isomorphism as well. Since the right one is injective, we deduce from the four-lemma that the left one is surjective, ending the argument. \square

Remark 14.12. One would like to prove that Theorem 14.11 holds for all finitely generated comodules, rather than only the finitely generated projective ones. It is possible this more general result can be deduced formally from the projective case, but we were not able to do so.

The key ingredient in the above proof is the calculation of $H_{\text{cts}}^0(\mathbb{G}_n, E_*)$; it seems likely that the version for arbitrary comodules would follow from a more general calculation of $H_{\text{cts}}^0(\mathbb{G}_n, E_*/I_k)$ by Landweber filtration arguments.

14.3. The comodule completion of Morava E -theory

We now come to the main theorem of this section. One may view the computation of this inverse limit at all heights and primes as uniform evidence for the validity for the algebraic chromatic splitting conjecture, and hence of the chromatic splitting conjecture itself.

Theorem 14.13. *We have*

$$\varprojlim_{E_*E} E_*/\mathfrak{m}^k \simeq H_{\text{cts}}^0(\mathbb{G}_n, E_*E) \simeq E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p,$$

where the left-hand side is the limit in the category of E_*E -comodules.

Proof. The first isomorphism is an instance of Proposition 12.12. By Corollary 12.9, if M_α is a filtered diagram of dualisable E_*E -comodules, such that $\varinjlim M_\alpha \simeq E_*E$, then

$$H_{\text{cts}}^0(\mathbb{G}_n, E_*E) \simeq \varinjlim H_{\text{cts}}^0(\mathbb{G}_n, M_\alpha) \simeq \varinjlim \text{Ext}_{E_*E}^0(E_*, M_\alpha) \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p$$

where the second isomorphism is Theorem 14.11. This ends the argument. \square

Remark 14.14. Since $E_*S_p^0 \simeq E_* \otimes_{MU_*} MU_*S_p^0 \simeq E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p$, one can rephrase Theorem 14.13 as saying that $\varprojlim^0 E_*/\mathfrak{m}^k \simeq E_*S_p^0$, which relates this result to the topological chromatic splitting conjecture.

Remark 14.15. There is a short exact sequence of E_*E -modules

$$0 \longrightarrow \Sigma^{|v_{n-1}|} E_*/I_{n-1} \xrightarrow{v_{n-1}} E_*/I_{n-1} \longrightarrow E_*/I_n \longrightarrow 0.$$

Applying the functor $\varprojlim_{\mathcal{D}(E_*E)} E_*/I_n^k \otimes -$ and considering the induced long exact sequence in cohomology, we deduce that v_{n-1} acts on $\varprojlim_{\mathcal{D}(E_*E)}^s E_*/(p, \dots, v_{n-2}, v_{n-1}^i)$ injectively for $s = 0$ and bijectively for $s > 0$. This provides further evidence for Conjecture 14.2.

15. Cooperations at height 1

In the previous section, we discussed the importance of the derived functors of the limit in the category of comodules and its relation to the chromatic splitting conjecture. In

Proposition 12.12, we gave an explicit formula for these in the form of an isomorphism

$$\varprojlim_{E_*E}^s E_*/\mathfrak{m}^k E_* \simeq H_{\text{cts}}^s(\mathbb{G}_n, E_*E),$$

where on the left-hand side we have the s -th derived functor of the limit in E_*E -comodules and the right-hand side we have continuous cohomology of the Morava stabiliser group. To make use of this, we would like to understand E_*E as a \mathbb{G}_n -representation; in this section, we do so for $n = 1$.

Warning 15.1. Let us warn the reader again that we are interested in the uncompleted cooperations; that is, $E_*E = \pi_*(E \otimes E)$. The description of the completed cooperations

$$E_*^\vee E := \pi_*(L_K(E \otimes E)) \simeq (E_*E)_{\mathfrak{m}}^\vee$$

is well-known, as we have $E_*^\vee E \simeq \text{map}_{\text{cts}}(\mathbb{G}_n, E_*)$ at any height by a result of Strickland [Str00] or [Hov04b].

Notation 15.2. Instead of the Honda formal group law, it will be convenient to work with the multiplicative formal group law over \mathbb{F}_p , which we denote by Γ . This is of height 1, so that the Lubin–Tate ring is isomorphic to the p -adics, with the universal deformation the multiplicative formal group law over \mathbb{Z}_p . By the uniqueness part of the Goerss–Hopkins–Miller theorem, the Lubin–Tate spectrum associated to this universal deformation is given by

$$E := KU_p^\vee,$$

the p -complete complex K -theory. The action of \mathbb{G}_1 is given by Adams operations.

Lemma 15.3. *There is an isomorphism*

$$E_*E \simeq E_*KU \otimes_{\mathbb{Z}} \mathbb{Z}_p$$

of \mathbb{G}_1 -representations, where on the right-hand side the action is trivial on the \mathbb{Z}_p -factor.

Proof. We have $KU_* \simeq \mathbb{Z}[u^{\pm 1}]$ and $E_* \simeq KU_* \otimes \mathbb{Z}_p$, which is flat over KU_* . It then follows from flatness that we have an isomorphism

$$E_*E \simeq E_*KU \otimes_{\mathbb{Z}} \mathbb{Z}_p$$

induced by the multiplication map

$$(E \otimes KU) \otimes_{KU} E \rightarrow E \otimes E.$$

Since this multiplication map is \mathbb{G}_1 -equivariant with respect to the action on the left E factor, this is, in fact, an isomorphism of representations. \square

Corollary 15.4. *There is an isomorphism*

$$H_{\text{cts}}^s(\mathbb{G}_1, E_*E) \simeq H_{\text{cts}}^s(\mathbb{G}_1, E_*KU) \otimes_{\mathbb{Z}} \mathbb{Z}_p.$$

Proof. Let us write $H^*(M) := H_{\text{cts}}^*(\mathbb{G}_1, M)$ for brevity. As \mathbb{Z}_p is flat, it can be written as a filtered colimit $\mathbb{Z}_p \simeq F_\alpha$ of finitely generated, free abelian groups by Lazard’s theorem.

We then have

$$H^s(E_*E) \simeq H^s(E_*KU \otimes_{\mathbb{Z}} \mathbb{Z}_p) \simeq H^s(\varinjlim E_*KU \otimes_{\mathbb{Z}} F_\alpha) \simeq \varinjlim H^s(E_*KU \otimes_{\mathbb{Z}} F_\alpha),$$

where the last equivalence used Corollary 12.9, and further

$$\varinjlim H^s(E_*KU \otimes_{\mathbb{Z}} F_\alpha) \simeq \varinjlim H^s(E_*KU) \otimes_{\mathbb{Z}} F_\alpha \simeq H^s(E_*KU) \otimes_{\mathbb{Z}} \mathbb{Z}_p,$$

where the first equivalence used additivity of cohomology. \square

It follows from Corollary 15.4 that to understand the cohomology with coefficients in E_*E , it is enough to understand E_*KU . As we are working with coefficients in the homology of a spectrum rather than an arbitrary \mathbb{G}_1 -module, we have a canonical family of invariants. To be more precise, we have a Hurewicz homomorphism

$$KU_* \rightarrow E_*KU$$

whose image necessarily consists of \mathbb{G}_1 -invariants. It follows that the cohomology groups

$$H_{\text{cts}}^*(\mathbb{G}_1, E_*KU)$$

are 2-periodic. As they're also even, as E_*KU is, it is enough to determine the cohomology with coefficients in E_0KU .

Lemma 15.5. *The composite*

$$E_0KU \rightarrow E_0^\vee KU \simeq E_0^\vee E \simeq \text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$$

is injective.

Proof. Note that by Landweber exactness, we have

$$E_0KU \simeq \mathbb{Z}_p \otimes_{\mathbb{Z}} KU_0KU.$$

This is flat over \mathbb{Z}_p , and we deduce from Proposition 8.6 that the above composite can be identified with a p -completion map. By a result of Adams, Harris and Switzer, KU_0KU is free as an abelian group [AHS71]. It follows that the p -completion map

$$\mathbb{Z}_p \otimes_{\mathbb{Z}} KU_0KU \rightarrow (\mathbb{Z}_p \otimes_{\mathbb{Z}} KU_0KU)_p^\vee \simeq (KU_0KU)_p^\vee \simeq E_0^\vee E$$

is injective as needed. \square

The completion map of Lemma 15.5 is \mathbb{G}_1 -equivariant, and we deduce that E_0KU is naturally a subrepresentation of $\text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$. On the latter, \mathbb{G}_1 acts by right multiplication on the source. Our goal is to describe the given subrepresentation.

By unwrapping the definitions, the map of Lemma 15.5 can be described explicitly. By standard results about weakly periodic Landweber exact homology theories, KU_0KU is the algebra classifying automorphisms of the multiplicative formal group law. If $g \in \mathbb{G}_1$ is an automorphism over the p -adics, then we can write

$$g(x) = \sum_i b_i(g)x^i,$$

where the b_i depend continuously on g . The above expression defines an automorphism of the multiplicative formal group law over $\text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$; this is the automorphism classified by the injective map

$$KU_0KU \rightarrow \text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p).$$

Combined with Lemma 15.5, this proves the following.

Proposition 15.6. *The ring E_0KU is the \mathbb{Z}_p -subalgebra of $\text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$ generated by the functions $b_i: \mathbb{G}_1 \rightarrow \mathbb{Z}_p$ for $i \geq 1$ as well as b_1^{-1} .*

As we work with the multiplicative formal group law, these functions b_i can be made explicit. Assume first that $a \in \mathbb{Z}$, so that the corresponding multiple of the identity of the multiplicative formal group law is given by

$$[a](x) = (1+x)^a - 1 = \sum_{k>0} \binom{a}{k} x^k.$$

The last expression makes sense even if a is a p -adic integer, where we take

$$\binom{a}{k} = \frac{a(a-1)\dots(a-k+1)}{k!},$$

and the sum is now possibly infinite. One can check that these are automorphisms of the multiplicative formal group law even if a is p -adic, so that the identification

$$\mathbb{Z}_p^\times \simeq \mathbb{G}_1$$

is given by $a \mapsto [a](x) = \sum_{k>0} \binom{a}{k} x^k$. Thus, Proposition 15.6 can be stated in the following more explicit form.

Proposition 15.7. *The algebra E_0KU is the \mathbb{Z}_p -subalgebra of $\text{map}_{\text{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$ generated by the functions $b_i(a) = \binom{a}{i}$ for $i \geq 1$ as well as $b_1^{-1}(a) = \frac{1}{a}$.*

Remark 15.8. The functions b_i appearing in Proposition 15.7 are well-known to p -adic analysts. By a fundamental theorem of Mahler, any continuous p -adic function on \mathbb{Z}_p can be written as an infinite convergent sum of the b_i -s in a unique way [Mah58].

This immediately implies the following calculation.

Proposition 15.9. *We have $H_{\text{cts}}^0(\mathbb{G}_1, E_0KU) \simeq \mathbb{Z}_p$.*

Proof. This is immediate from Proposition 15.7, as the only functions $\mathbb{G}_1 \rightarrow \mathbb{Z}_p$ invariant under translation are the constants. \square

To compute higher cohomology groups, it is convenient to observe that they are necessarily rational.

Lemma 15.10. *The groups $H_{\text{cts}}^i(\mathbb{G}_1, E_0KU)$ are rational vector spaces for $i > 0$.*

Proof. Since the inclusion $E_0KU \hookrightarrow \mathrm{map}_{\mathrm{cts}}(\mathbb{G}_1, \mathbb{Z}_p)$ is an isomorphism after p -completion, as we observed in the proof of Lemma 15.5, we deduce that it is an isomorphism modulo p . It follows that

$$H_{\mathrm{cts}}^i(\mathbb{G}_1, E_0KU \otimes_{\mathbb{Z}_p} \mathbb{F}_p) \simeq H_{\mathrm{cts}}^i(\mathbb{G}_1, \mathrm{map}_{\mathrm{cts}}(\mathbb{G}_1, \mathbb{F}_p))$$

and the right-hand side vanishes for $i > 0$. The long exact sequence of cohomology associated to

$$0 \rightarrow E_0KU \rightarrow E_0KU \rightarrow E_0KU \otimes_{\mathbb{Z}_p} \mathbb{F}_p \rightarrow 0,$$

where the first map is multiplication by p , gives the required result. \square

Proposition 15.11. *We have*

$$H_{\mathrm{cts}}^1(\mathbb{G}_1, E_0KU) \simeq \mathbb{Q}_p$$

and the higher cohomology groups vanish.

Proof. By Lemma 15.10, all cohomology groups of positive degree are rational, so that we can replace E_0KU by $\mathbb{Q}_p \otimes_{\mathbb{Z}_p} E_0KU$ without changing these. The cohomology with the coefficients in the latter can be computed directly.

As each binomial coefficient $b_i(a) = \binom{a}{i}$ is a polynomial in a with rational coefficients, we deduce from Proposition 15.7 that $\mathbb{Q}_p \otimes_{\mathbb{Z}_p} E_0KU$ can be identified with the \mathbb{Q}_p -subalgebra of $\mathrm{map}_{\mathrm{cts}}(\mathbb{G}_1, \mathbb{Q}_p)$ generated by $b_1(a) = a$ and its inverse.

It follows that there is an isomorphism of representations

$$\mathbb{Q}_p \otimes_{\mathbb{Z}_p} E_0KU \simeq \mathbb{Q}_p[b^{\pm 1}],$$

where $b = b_1$ and the action is determined by $g \cdot b = gb$ for $g \in \mathbb{G}_1$. This decomposes as a direct sum of character representations

$$\mathbb{Q}_p[b^{\pm 1}] \simeq \bigoplus_{k \in \mathbb{Z}} \mathbb{Q}_p(k),$$

where we identify $\mathbb{Q}_p(k)$ with the subrepresentation generated by b^k . It follows that

$$H_{\mathrm{cts}}^i(\mathbb{G}_1, \mathbb{Q}_p[b^{\pm 1}]) \simeq \bigoplus_{k \in \mathbb{Z}} H_{\mathrm{cts}}^i(\mathbb{G}_1, \mathbb{Q}_p(k)).$$

Let $U \subseteq \mathbb{G}_1 \simeq \mathbb{Z}_p^\times$ be a normal subgroup of finite index, such that $U \simeq \mathbb{Z}_p$. As finite groups have no rational cohomology, Lyndon–Hochschild–Serre spectral sequence collapses and gives an isomorphism

$$H^i(\mathbb{G}_1, \mathbb{Q}_p(k)) \simeq H^i(U, \mathbb{Q}_p(k))^{\mathbb{G}_1/U}.$$

It follows that the cohomology groups vanish above degree 1, as $U \simeq \mathbb{Z}_p$ is of cohomological dimension one.

As $U \simeq \mathbb{Z}_p$ is cyclic as a profinite group, its cohomology can be computed using a two-step cochain complex, as we did in Section 10. It follows that the only one-dimensional representation of U over \mathbb{Q}_p with nontrivial cohomology is the trivial one.

As the characters $\mathbb{Q}_p(k)$ restrict to nontrivial representations for $k \neq 0$, we deduce that

$$H_{\text{cts}}^1(\mathbb{G}_1, \mathbb{Q}_p[b^{\pm 1}]) \simeq H_{\text{cts}}^1(\mathbb{G}_1, \mathbb{Q}_p) \simeq \mathbb{Q}_p$$

as claimed. \square

Theorem 15.12. *At height $n = 1$ and any prime, we have*

$$H_{\text{cts}}^s(\mathbb{G}_1, E_*E) \simeq \begin{cases} E_* \otimes_{\mathbb{Z}} \mathbb{Z}_p & \text{when } s = 0; \\ E_* \otimes_{\mathbb{Z}} \mathbb{Q}_p & \text{when } s = 1; \\ 0 & \text{otherwise.} \end{cases}$$

Proof. As we observed previously that the cohomology with coefficients in E_*E is concentrated in even internal degrees and 2-periodic, it is enough to establish this in internal degree zero, where this is a combination of Corollary 15.4 and Propositions 15.9 and 15.11. \square

Remark 15.13. As we observed at the beginning, the cohomology groups of Theorem 15.12 coincide with derived functors of completion in comodules by Proposition 12.12. Using the latter perspective, a sketch of the calculation of the rationalisation of the above groups at $p > 2$ appears in a talk by Hopkins, recorded in [Pet, Talk 14]. We were independently informed by Hopkins that he first made this calculation in the 1990s and that it was part of the motivation towards the algebraic chromatic splitting conjecture.

Acknowledgments. We would like to thank Agnès Beaudry, Robert Burklund, Mike Hopkins, Eric Peterson and Hal Sadofsky for useful conversations related to this work. We acknowledge the hospitality of the Max Planck Institute for Mathematics in Bonn.

Competing Interest. None.

References

- [AB21] M. ABOUZAID AND A. J. BLUMBERG, Arnold conjecture and Morava k-theory, Preprint, 2021, [arXiv:2103.01507](https://arxiv.org/abs/2103.01507).
- [AHS71] J. F. ADAMS, A. S. HARRIS AND R. M. SWITZER, Hopf algebras of cooperations for real and complex k-theory, *Proc. Lond. Math. Soc.* **3**(3) (1971), 385–408.
- [Ang11] V. ANGELTVEIT, Uniqueness of Morava k-theory, *Compos. Math.* **147**(2) (2011), 633–648.
- [Bal20] P. BALMER, Nilpotence theorems via homological residue fields, *Tunis. J. Math.* **2**(2) (2020), 359–378.
- [BC21] P. BALMER AND J. C. CAMERON, Computing homological residue fields in algebra and topology, *Proc. Amer. Math. Soc.* **149**(8) (2021), 3177–3185.
- [Bea17] A. BEAUDRY, The chromatic splitting conjecture at $n = p = 2$, *Geom. Topolo.* **21**(6) (2017), 3213–3230.
- [Bel20] E. BELMONT, A Cartan-Eilenberg spectral sequence for non-normal extensions, *J. Pure Appl. Algebra* **224**(4) (2020), 106216, 21.
- [BF15] T. BARTHEL AND M. FRANKLAND, Completed power operations for Morava E-theory, *Algebr. Geom. Topol.* **15**(4) (2015), 2065–2131.

- [BG18] I. BOBKOVA AND P. G. GOERSS, Topological resolutions in $K(2)$ -local homotopy theory at the prime 2, *J. Topol.* **11**(4) (2018), 918–957.
- [BGH17] A. BEAUDRY, P. G. GOERSS AND H.-W. HENN, Chromatic splitting for the $K(2)$ -local sphere at $p = 2$, Preprint, 2017, [arXiv:1712.08182](https://arxiv.org/abs/1712.08182).
- [BH16] T. BARTHEL AND D. HEARD, The E_2 -term of the $K(n)$ -local E_n -Adams spectral sequence, *Topol. Its Appl.* **206** (2016), 190–214.
- [BH18] T. BARTHEL AND D. HEARD, Algebraic chromatic homotopy theory for BP_*BP -comodules. *Proc. Lond. Math. Soc. (3)* **117**(6) (2018), 1135–1180.
- [BHV18] T. BARTHEL, D. HEARD AND G. VALENZUELA, Local duality in algebra and topology, *Adv. Math.* **335** (2018), 563–663.
- [BHV20] T. BARTHEL, D. HEARD AND G. VALENZUELA, Derived completion for comodules, *Manuscripta Math.* **161**(3–4) (2020), 409–438.
- [Boa99] J. M. BOARDMAN, Conditionally convergent spectral sequences, in Homotopy invariant algebraic structures (Baltimore, MD, 1998), vol. 239, pp. 49–84, *Contemporary Mathematics* (American Mathematical Society, Providence, RI, 1999).
- [Bou79] A. K. BOUSFIELD, The localization of spectra with respect to homology, *Topology*, **18**(4) (1979), 257–281.
- [BSS20] T. BARTHEL, T. M. SCHLANK AND N. STAPLETON, Chromatic homotopy theory is asymptotically algebraic, *Invent. Math.* **220** (2020), 737–845.
- [Dev97] E. S. DEVINATZ, Morava modules and Brown-Comenetz duality, *Amer. J. Math.* **119**(4) (1997), 741–770.
- [DH04] E. S. DEVINATZ AND M. J. HOPKINS, Homotopy fixed point spectra for closed subgroups of the Morava stabilizer groups, *Topology* **43**(1) (2004), 1–47.
- [DHS88] E. S. DEVINATZ, M. J. HOPKINS AND J. H. SMITH, Nilpotence and stable homotopy theory I, *Ann. Math.* **128**(2) (1988), 207–241.
- [Fra] J. FRANKE, Uniqueness theorems for certain triangulated categories with an Adams spectral sequence, 1996, <http://www.math.uiuc.edu/K-theory/0139/>.
- [GH] P. G. GOERSS AND M. J. HOPKINS, Moduli Spaces of Commutative Ring Spectra, *Unpublished manuscript*.
- [GH05a] P. G. GOERSS AND M. J. HOPKINS, Moduli problems for structured ring spectra, Preprint, 2005a, <https://sites.math.northwestern.edu/~pgoerss/spectra/obstruct.pdf>.
- [GH05b] P. GOERSS AND M. HOPKINS, Moduli spaces of commutative ring spectra, in London Mathematical Society, vol. **315**, p. 151, *Lecture Note Series* (2005b).
- [GHM12] P. G. GOERSS, H.-W. HENN AND M. MAHOWALD, The rational homotopy of the $k(2)$ -local sphere and the chromatic splitting conjecture for the prime 3 and level 2, Preprint, 2012, [arXiv:1210.7031](https://arxiv.org/abs/1210.7031).
- [GHMR05] P. GOERSS, H.-W. HENN, M. MAHOWALD AND C. REZK, A resolution of the $k(2)$ -local sphere at the prime 3, *Ann. Math.* **162**(2) (2005), 777–822.
- [Goe08] P. GOERSS, Quasi-coherent sheaves on the moduli stack of formal groups, Preprint, 2008, [arXiv:0802.0996](https://arxiv.org/abs/0802.0996).
- [GWX21] B. GHEORGHE, G. WANG AND Z. XU, The special fiber of the motivic deformation of the stable homotopy category is algebraic, *Acta Math.* **226**(2) (2021), 319–407.
- [Hen98] H.-W. HENN, Centralizers of elementary abelian p -subgroups and mod- p cohomology of profinite groups, *Duke Math. J.* **91**(3) (1998), 561–585.
- [Hen17] H.-W. HENN, A mini-course on Morava stabilizer groups and their cohomology, in Algebraic Topology: VIASM 2012–2015, vol. 2194, pp. 149–178, *Lecture Notes in Mathematics* (Springer, 2017).
- [HL17] M. J. HOPKINS AND J. LURIE, On Brauer groups of Lubin-Tate spectra I, Preprint, 2017, available at <https://www.math.ias.edu/~lurie/>.

- [Hov95] M. HOVEY, Bousfield localization functors and Hopkins' chromatic splitting conjecture, in *The Čech centennial* (Boston, MA, 1993), vol. 181, pp. 225–250, *Contemporary Mathematics* (American Mathematical Society, Providence, RI, 1995).
- [Hov04a] M. HOVEY, Homotopy theory of comodules over a Hopf algebroid, in *Homotopy theory: Relations with algebraic geometry, group cohomology, and algebraic K-theory*, vol. **346**, pp. 261–304, *Contemporary Mathematics* (American Mathematical Society, Providence, RI, 2004).
- [Hov04b] M. HOVEY, Operations and co-operations in Morava E -theory, *Homol. Homotopy Appl.* **6**(1) (2004), 201–236.
- [Hov04c] M. HOVEY, Some spectral sequences in Morava E -theory, Preprint, 29, 2004, available at https://folk.ntnu.no/drewkh/hovey_ss.pdf.
- [Hov07] M. HOVEY, The generalized homology of products, *Glasg. Math. J.* **49**(1) (2007), 1–10.
- [HS98] M. J. HOPKINS AND J. H. SMITH, Nilpotence and stable homotopy theory. II, *Ann. of Math.* **148**(1) (1998), 1–49.
- [HS99] M. A. HOVEY AND N. P. STRICKLAND, Morava K -theories and localization, *Mem. Am. Math. Soc.* **139**(666) (1999), viii+100–100.
- [HS05a] M. HOVEY AND N. STRICKLAND, Comodules and Landweber exact homology theories, *Adv. Math.* **192**(2) (2005), 427–456.
- [HS05b] M. HOVEY AND N. STRICKLAND, Local cohomology of BP_*BP -comodules, *Proc. London Math. Soc.* (3) **90**(2) (2005), 521–544.
- [IWX20] D. C. ISAKSEN, G. WANG AND Z. XU, Stable homotopy groups of spheres, *Proc. Natl. Acad. Sci. U.S.A.* **117**(40) (2020), 24757–24763.
- [Jan88] U. JANNSEN, Continuous étale cohomology, *Math. Ann.* **280**(2) (1988), 207–245.
- [Laz06] M. P. LAZARD, Commutative formal groups, vol. **443** (Springer, 2006).
- [Lev15] M. LEVINE, The Adams-Novikov spectral sequence and Voevodsky's slice tower, *Geom. Topol.* **19**(5) (2015), 2691–2740.
- [LT66] J. LUBIN AND J. TATE, Formal moduli for one-parameter formal Lie groups, *Bull. Soc. Math. France*, **94** (1966), 49–59.
- [Lur10] J. LURIE, Chromatic homotopy theory, *Lecture notes online*, 2010.
- [Lur16] J. LURIE, Higher algebra, Preprint, 2016, available at <https://www.math.ias.edu/~lurie/>.
- [Lur18] J. LURIE, Elliptic cohomology II: Orientations, Preprint, 2018, available from the author's website.
- [Mah58] K. MAHLER, An interpolation series for continuous functions of a p -adic variable, *Journal für die reine und angewandte Mathematik*, **199** (1958), 23–34.
- [Mal92] G. MALTSINIOTIS, Groupoïdes quantiques, *C. R. Acad. Sci. Paris Sér. I Math.* **314**(4) (1992), 249–252.
- [Mil81] H. R. MILLER, On relations between Adams spectral sequences, with an application to the stable homotopy of a Moore space, *J. Pure Appl. Algebra* **20**(3) (1981), 287–312.
- [Mor85] J. MORAVA, Noetherian localisations of categories of cobordism comodules, *Ann. Math.* (2), **121**(1) (1985), 1–39.
- [NSW13] J. NEUKIRCH, A. SCHMIDT AND K. WINGBERG, Cohomology of number fields, in vol. 323, *Grundlehren der Mathematischen Wissenschaften* (Springer Science & Business Media, 2013).
- [Pet] E. PETERSON, Report on E -theory conjectures seminar, <https://web.math.rochester.edu/people/faculty/doug/otherpapers/peterson-mit-ettheory.pdf>.

- [Pet20] E. PETERSON, Coalgebraic formal curve spectra and spectral jet spaces, *Geom. Topol.* **24**(1) (2020), 1–47.
- [PP21] I. PATCHKORIA AND P. PSTRAGOWSKI, Adams spectral sequences and Franke’s algebraicity conjecture, Preprint, 2021, [arXiv:2110.03669](https://arxiv.org/abs/2110.03669).
- [Pst18] P. PSTRAGOWSKI, Chromatic homotopy is algebraic when $p > n^2 + n + 1$, Preprint, 2018, [arXiv:1810.12250](https://arxiv.org/abs/1810.12250).
- [Pst21] P. PSTRAGOWSKI, Chromatic homotopy theory is algebraic when $p > n^2 + n + 1$. *Adv. Math.* **391** (2021), 107958.
- [Pst22] P. PSTRAGOWSKI, Synthetic spectra and the cellular motivic category, *Invent. Math.* **232** (2023), 553–681.
- [PV22] P. PSTRAGOWSKI AND P. VANKOUGHNETT, Abstract Goerss-Hopkins theory, *Adv. Math.* **395** (2022), 108098.
- [Rak20] A. RAKSIT, Hochschild homology and the derived de Rham complex revisited, Preprint, 2020, [arXiv:2007.02576](https://arxiv.org/abs/2007.02576).
- [Rav92] D. C. RAVENEL, Nilpotence and periodicity in stable homotopy theory, in vol. 128, *Annals of Mathematics Studies* (Princeton University Press, Princeton, NJ, 1992). Appendix C by Jeff Smith.
- [Rav03] D. C. RAVENEL, *Complex Cobordism and Stable Homotopy Groups of Spheres* (American Mathematical Society, Providence, RI, 2003).
- [Rob89] A. ROBINSON, Obstruction theory and the strict associativity of Morava k -theories, in *Advances in homotopy theory: Papers in Honour of I M James, Cortona 1988*, *London Mathematical Society Lecture Notes*, vol. 139, pp. 143–152 (Cambridge University Press, Cambridge, 1989).
- [Ser65] J.-P. SERRE, Sur la dimension cohomologique des groupes profinis, *Topology* **3** (1965), 413–420.
- [Str00] N. P. STRICKLAND, Gross-Hopkins duality, *Topology* **39**(5) (2000), 1021–1033.
- [SW00] P. SYMONDS AND T. WEIGEL, Cohomology of p -adic analytic groups, in *New horizons in pro- p groups*, vol. 184, pp. 349–410, *Progress in Mathematics* (Birkhäuser Boston, Boston, MA, 2000).
- [SY95] K. SHIMOMURA AND A. YABE, The homotopy groups $\pi_*(l_2 s^0)$, *Topology* **34**(2) (1995), 261–289.
- [Wür91] U. WÜRLER, Morava K -theories: A survey, in *Algebraic topology Poznań 1989*, vol. 1474, pp. 111–138, *Lecture Notes in Mathematics* (Springer, Berlin, 1991).