

The power operation structure on Morava E -theory of height 2 at the prime 3

YIFEI ZHU

We give explicit calculations of the algebraic theory of power operations for a specific Morava E -theory spectrum and its $K(1)$ -localization. At height 2 for the prime 3, the power operations arise from the universal degree-3 isogeny of elliptic curves associated to the E -theory.

1 Introduction

The study of cohomology operations has been central to algebraic topology since the 1950s, with applications to solving problems such as the number of independent vector fields on spheres, and the non-existence of maps of Hopf invariant one. Perhaps internally cohomology operations are primarily used to cure the blindness of cohomology theories [Gre88], that is, to cure their varied degrees of inability to detect the fact that a map of spaces is essential. In other words, suppose E is a commutative S -algebra, in the sense of [EKMM97], and A is a commutative E -algebra; we want to capture the properties and underlying structure of the homotopy groups $\pi_* A = A_*$ of A , by studying operations associated to the cohomology theory that E represents.

An important family of cohomology operations, called *power operations*, is constructed via the extended powers. Specifically, consider the functor of *the m th extended power over E* from the category of E -modules to the category of commutative E -algebras

$$\mathbb{P}_E^m(-) := (-)^{\wedge_{E^m}} / \Sigma_m : \text{Mod}_E \rightarrow \text{Alg}_E$$

which sends an E -module to its m -fold smash product over E modulo the action by the symmetric group on m letters. The $\mathbb{P}_E^m(-)$'s assemble together to give the *free commutative E -algebra functor*

$$\mathbb{P}_E(-) := \bigvee_{m \geq 0} \mathbb{P}_E^m(-) : \text{Mod}_E \rightarrow \text{Alg}_E.$$

These functors descend to homotopy categories. In particular, each $\alpha \in \pi_{d+i} \mathbb{P}_E^m(\Sigma^d E)$ gives rise to a power operation

$$Q_\alpha: A_d \rightarrow A_{d+i}$$

(cf. [BMMS86, Sections I.2 and IX.1] and [Rez09, Section 3]).

Under the action of power operations, A_* is an algebra over some operad on E_* -modules involving the structure of $E_* B\Sigma_m$ for all m . This operad is traditionally called a *Dyer–Lashof algebra*, or more precisely, a *Dyer–Lashof theory* as the *algebraic theory* of power operations acting on the homotopy groups of commutative E -algebras (cf. [BMMS86, Chapters III, VIII, and IX] and [Reza, Section 9]).

A specific case is when A is $K(n)$ -local and E is a Morava E -theory of height n . Morava E -theory spectra are of crucial importance in modern stable homotopy theory, particularly in the work of Ando, Hopkins, and Strickland [AHS01]. Much of the $K(n)$ -local E -Dyer–Lashof theory has been worked out by those authors (cf. [Rez09, 1.5] for a description of the history). In [Rez09] Rezk gives a unified treatment of this Dyer–Lashof theory. He works out a congruence criterion that must hold in an algebra over the Dyer–Lashof theory ([Rez09, Theorem A]). This enables one to study the Dyer–Lashof theory, which models all the algebraic structure naturally adhering to A_* , by working with a certain associative ring Γ as the Dyer–Lashof algebra. Moreover, Rezk provides a geometric description of this congruence criterion, in terms of sheaves on the moduli problem of deformations of formal groups and Frobenius isogenies (cf. [Rez09, Theorem B]). This connects the structure of Γ to the geometry underlying E , moving one step forward from a workable object Γ to something computable. Based on these, in a companion paper [Rezb], Rezk gives explicit calculations of the Dyer–Lashof theory for a specific Morava E -theory of height $n = 2$ at the prime 2.

The purpose of this paper is to make available calculations analogous to some of the results in [Rezb], at the prime 3, together with calculations of the corresponding $K(1)$ -local power operations.

Outline of the paper

As in [Rezb], the computation of power operations in this paper follows the approach of [Ste62]: one first defines the total power operation, and then uses the computation of the cohomology of the classifying space of the symmetric group Σ_m to obtain individual power operations. These two steps are carried out in Sections 2 and 3 respectively.

In Section 2, by doing calculations with a specific elliptic curve associated to our Morava E -theory E , we give formulas of the total power operation ψ^3 on E_0 and the ring S_3 parametrizing the corresponding moduli problem ($\mathrm{Spec} S_3$ as the incidence scheme in the sense of [KM85]).

In Section 3, based on calculations of $E_*B\Sigma_m$ in [Str98], we define individual power operations, and derive the relations they satisfy. Thus in view of the general structures described in [Rez09], we get an explicit description of the Dyer–Lashof algebra Γ for $K(2)$ -local commutative E -algebras.

In Section 4, we describe the relationship between the total power operation ψ^3 , at height 2, and the corresponding $K(1)$ -local power operation. We then derive formulas of the latter from the calculations in Section 2.

In Appendices A and B, we list long formulas whose appearance in the main body might affect readability.

Remark 1 The ring S_3 mentioned above turns out to be an algebra on one generator over the base ring where our elliptic curve is defined (cf. Proposition 4). This generator appears as a parameter in the formulas of the total power operation ψ^3 , and is responsible for how the individual power operations are defined and how their formulas look like. Different choices of this parameter results in different bases of the Dyer–Lashof algebra Γ .

The parameter in this paper will be derived differently from the one used in [Rezb]; it comes intrinsically from the relative cotangent space of the elliptic curve at the identity. This choice of parameter is important for writing down Adem relations in Section 3, and it fits naturally into the treatment of gradings in [Rez09].

We should point out that our choice is by no means canonical; we do not know yet, as part of the structure of the Dyer–Lashof algebra, if there is a *canonical* basis which is both geometrically interesting and computationally convenient. Somewhat surprisingly, though it appears to come from different considerations, our choice has an analog at the prime 2 which coincides with the parameter used in [Rezb]. Our calculations follow a recipe in hope of generalizing to other Morava E -theories at height 2; we hope to address these matters and recognize more of the general patterns based on further computational evidence. \square

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Conventions

We use the symbols

$$\mathbb{F}_q, \mathbb{Z}_q, \text{ and } \mathbb{Z}/n$$

to denote a field with q elements, the ring of p -typical Witt vectors over \mathbb{F}_q (if q is a power of p with p a prime), and the additive group of integers modulo n , respectively.

If R is a ring, then R^\times denotes the group of invertible elements of R . If $I \subset R$ is an ideal, then R_I^\wedge denotes the completion of R with respect to I .

If E is an elliptic curve, then $[m]$ denotes the multiplication-by- m map on E , and $E[m]$ denotes the m -torsion subgroup of E .

The terminology for describing the structure of the Dyer–Lashof theory will follow [Rez09, Rezb]; some of the notions there are taken in turn from [BW05] and [Voe03].

2 Total power operations

The universal elliptic curve C with a choice of 4-torsion point has equation

$$Y^2Z + aXYZ + acYZ^2 = X^3 + cX^2Z,$$

over the graded ring $\mathbb{Z}[1/4][a, c]$ with $|a| = 1$ and $|c| = 2$. This equation is computed from a general affine Weierstrass equation in xy -coordinates, by requiring that the 4-torsion point P be $(0, 0)$, $2P$ be on the x -axis, and $4P$ be the identity of C at the infinity.

In the affine coordinate chart $c = 1$ of the moduli stack $\mathcal{M}(\Gamma_1(4))$, C is given by the affine Weierstrass equation

$$y^2 + axy + ay = x^3 + x^2,$$

over the ring $\mathbb{Z}[1/4][a]$, with discriminant $\Delta = a^2(a+4)(a-4)$. Let

$$S = \mathbb{Z}[1/4][a, \Delta^{-1}],$$

over which C is nonsingular. Over a finite field of characteristic 3, this nonsingular elliptic curve is supersingular precisely when the quantity

$$h := a^2 + 4$$

vanishes (cf. [Sil09, V.4.1a]), and its minimal field of definition is then \mathbb{F}_9 . Moreover the supersingular locus consists of a single closed point, as $(3, h)$ is a maximal ideal of S .

By Serre–Tate theory, 3-adically the deformation theory of C is equivalent to the deformation theory of its 3-divisible group. Let

$$\widehat{S} = \mathbb{Z}_9[[h]],$$

so that by Hensel's Lemma both a and Δ lie in \widehat{S} , and both are invertible. In fact, let i be an element generating \mathbb{Z}_9 over \mathbb{Z}_3 with $i^2 = -1$; then since $h = a^2 + 4$,

$$(1) \quad a \equiv i \pmod{(3, h)} \quad \text{and} \quad \Delta = (h-4)(h-20) \equiv -1 \pmod{(3, h)},$$

where $(3, h)$ is the maximal ideal of the complete local ring $\widehat{S} = \mathbb{Z}_9[[h]]$. Thus \widehat{S} is the completion of S with respect to $(3, h)$. Let \widehat{C} denote the formal completion of C at the identity; this defines a formal group over \widehat{S} . It is a universal deformation for its reduction to $\mathbb{F}_9 = \widehat{S}/(3, h)$ which is a formal group of height 2. Let E denote the Morava E -theory associated to this height 2 formal group, so that

$$E_* \cong \mathbb{Z}_9[[h]][u^{\pm 1}]$$

with $|u| = 2$, where u corresponds to a local uniformizer at the identity of C .

To study C at the formal neighborhood of the identity, it is convenient to make a change of variables. Let

$$u = \frac{x}{y} \quad \text{and} \quad v = \frac{1}{y}, \quad \text{so} \quad x = \frac{u}{v} \quad \text{and} \quad y = \frac{1}{v}.$$

The identity O of C is then $(u, v) = (0, 0)$, with u a local uniformizer at O . The Weierstrass equation of C becomes

$$(2) \quad v + auv + av^2 = u^3 + u^2v.$$

Proposition 2 *On the elliptic curve C over S , the uv -coordinates (d, e) of any nonzero 3-torsion point satisfy the identities*

$$f(d) = 0,$$

and

$$e = g(d),$$

where the polynomials f and g are given by

$$f(u) = u^8 + 3au^7 + 3a^2u^6 + (a^3 + 7a)u^5 + (6a^2 - 6)u^4 + 9au^3 + (-a^2 + 8)u^2 - 3au - 3,$$

$$g(u) = -\frac{1}{a(a+4)(a-4)}(au^7 + (3a^2 - 2)u^6 + (3a^3 - 6a)u^5 + (a^4 + a^2 + 2)u^4 + (4a^3 - 15a)u^3 + 18u^2 - 12au - 18).$$

Proof ¹ Given the elliptic curve

$$C: y^2 + axy + ay = x^3 + x^2,$$

a nonzero point Q of C is a 3-torsion point if and only if the division polynomial

$$\psi_3(x) := 3x^4 + (a^2 + 4)x^3 + 3a^2x^2 + 3a^2x + a^2$$

vanishes at Q (cf. [Sil09, Exercise 3.7f]). Substituting x by u/v and clearing the denominators, we have

$$\tilde{\psi}_3(u, v) := 3u^4 + (a^2 + 4)u^3v + 3a^2u^2v^2 + 3a^2uv^3 + a^2v^4,$$

so that $\tilde{\psi}_3(d, e) = 0$. In particular $d \neq 0$.

To get the polynomial f , we rewrite the equation (2) of C as a quadratic equation in v :

$$av^2 + (-u^2 + au + 1)v - u^3 = 0$$

(a is invertible in $S = \mathbb{Z}[1/4][a, \Delta^{-1}]$ as $\Delta = a^2(a + 4)(a - 4)$). Define

$$\tilde{f}(u) = \tilde{\psi}_3(u, v)\tilde{\psi}_3(u, v'),$$

where v and v' are formally the conjugate roots of the above equation so that we substitute $v + v'$ as $(u^2 - au - 1)/a$, and vv' as $-u^3/a$. We then compute \tilde{f} , and it can be factored as

$$\tilde{f}(u) = -\frac{u^4 f(u)}{a^2},$$

where $f(u)$ is as stated. Since $\tilde{f}(d) = 0$ and $d \neq 0$, we have the first stated identity

$$f(d) = 0.$$

To get the polynomial g , we note that both the quartic polynomial

$$A(v) := \tilde{\psi}_3(d, v)$$

¹See Appendix A for explicit formulas of the polynomials \tilde{f} , Q_1 , R_1 , Q_2 , R_2 , S , T , M , and N that appear below.

and the quadratic polynomial

$$B(v) := av^2 + (-d^2 + ad + 1)v - d^3$$

vanish at e , and thus so does their greatest common divisor (gcd). By the Euclidean algorithm, we have

$$A(v) = Q_1(v)B(v) + R_1(v),$$

$$B(v) = Q_2(v)R_1(v) + R_2,$$

where

$$R_1(v) = S(d)v + T(d)$$

for some polynomials S and T , and $R_2 = 0$ as a result of $f(d) = 0$. Thus $R_1(v)$ is the gcd of $A(v)$ and $B(v)$, and hence

$$S(d)e + T(d) = R_1(e) = 0.$$

To write e in terms of d from the above identity, we apply the Euclidean algorithm to the polynomials f and S . Their gcd turns out to be 1, and thus there are polynomials M and N such that

$$M(u)f(u) + N(u)S(u) = 1.$$

Since $f(d) = 0$, we then have $N(d)S(d) = 1$, and thus

$$e = -N(d)T(d) = g(d),$$

where g is as stated. □

Remark 3 We have

$$f(u) \equiv u^2(u + a)^6 \pmod{3},$$

where a is invertible in $\mathbb{F}_9 = \widehat{S}/(3, h)$ as in (1). The two roots (counted with multiplicity) of $f(u)$ which reduce to zero modulo 3 correspond to the two nonzero elements of the unique order-3 subgroup of C in the formal neighborhood of the identity. □

Proposition 4 *The universal degree-3 isogeny ψ with domain C is defined over the ring*

$$S_3 := S[\alpha]/(w(\alpha))$$

where

$$w(\alpha) = \alpha^4 - 6\alpha^2 + (a^2 - 8)\alpha - 3,$$

and has range the elliptic curve

$$C': v + r(a)uv + r(a)v^2 = u^3 + u^2v,$$

where

$$r(a) = a^3 + (\alpha^3 - 6\alpha - 12)a - 4(\alpha + 1)^2(\alpha - 3)a^{-1}.$$

The kernel of this isogeny is generated by a 3-torsion point with coordinates (d, e) satisfying

$$\alpha = -\frac{1}{(a+4)(a-4)}(ad^7 + (3a^2 - 2)d^6 + (3a^3 - 6a)d^5 + (a^4 + a^2 + 2)d^4 + (4a^3 - 15a)d^3 + (a^2 + 2)d^2 - 12ad - 18) = ae - d^2.$$

The induced map on relative cotangent spaces at the identity sends du to αdu .

Proof ² Let $P = (u, v)$ be a general point on C , and $Q = (d, e)$ be a nonzero 3-torsion point. Rewriting the equation (2) of C as

$$v = u^3 + u^2v - auv - av^2,$$

we can then express v in terms of a power series in u by recursive substitution. For the purpose of our calculations, we take this power series up to u^9 as an expression of v , and write $e = g(d)$ as in Proposition 2.

Define the isogeny $\psi: C \rightarrow C'$ by

$$(3) \quad \begin{aligned} u' &:= u(\psi(P)) = u(P) \cdot u(P - Q) \cdot u(P + Q), \\ v' &:= v(\psi(P)) = v(P) \cdot v(P - Q) \cdot v(P + Q), \end{aligned}$$

whose kernel is precisely the order-3 subgroup generated by Q . By computing the group law on C , we can write down formal expansions in terms of the local uniformizer u at the identity:

$$(4) \quad \begin{aligned} u' &= \alpha u + \cdots, \\ v' &= \beta u^3 + \cdots, \end{aligned}$$

where the coefficients $(\alpha, \beta, \text{etc.})$ involve a and d .

We then solve for the Weierstrass equation that u' and v' satisfy. For the equation to be in the form of (2), we adjust the definition of v' as

$$v' = \frac{\alpha^3}{\beta} \cdot v(P) \cdot v(P - Q) \cdot v(P + Q).$$

Using this and (4), we determine the coefficients of a general Weierstrass equation and get the stated equation of C' .

²See Appendix B for explicit formulas of power series expansion of v and calculations involving the group law on C that appear below.

For the remaining statements in the proposition, the first formula of α in terms of a and d is computed above in the process of expressing u' in terms of u . The second formula of α in terms of a , d , and e can be checked by comparing the previous one with the formula of g in Proposition 2. In view of $f(d) = 0$ as in Proposition 2, we further compute that α satisfies $w(\alpha) = 0$ where w is as stated. The last statement follows by definition of α in (4). \square

Remark 5 The definition (3) of ψ in the proof above follows Lubin's construction in [Lub67, proof of Theorem 1.4], so that the kernel of ψ is a *canonical subgroup* of C and ψ is a *lift of Frobenius* (cf. [Lub79]).

Remark 6 The parameter α is invariant under change of coordinates: if

$$w := \sum_{i=1}^{\infty} a_i u^i \quad \text{and} \quad w' := \sum_{i=1}^{\infty} a_i (u')^i,$$

where $a_i \in S$ and $a_1 \in S^\times$, then

$$w' = \alpha w + \dots.$$

We also note that the analog of α at the prime 2 coincides with d which is the u -coordinate of a nonzero 2-torsion point on the universal elliptic curve with a choice of 3-torsion point (cf. [Rezb, Section 3]). \square

Let

$$(5) \quad \widehat{S}_3 = S_3 \otimes_S \widehat{S} = (S_3)_{(3,h)}^\wedge,$$

where S_3 is the ring parametrizing the moduli problem as in Proposition 4. In [Str98] Strickland shows that

$$\widehat{S}_3 \cong E^0 B\Sigma_3 / I,$$

where $I := \sum_{0 < i < 3} \text{Image}(E^0 B(\Sigma_i \times \Sigma_{3-i}) \xrightarrow{\text{transfer}} E^0 B\Sigma_3)$ is the *transfer ideal*. In view of this and the construction of *total power operations* for Morava E -theories in [Rez09, 3.23], we have the following corollary.

Corollary 7 *The total power operation*

$$\psi^3: E^0 \rightarrow E^0 B\Sigma_3 / I \cong E^0[\alpha] / (w(\alpha))$$

is given by

$$\psi^3(h) = h^3 + (\alpha^3 - 6\alpha - 36)h^2 + 3(-8\alpha^3 + \alpha^2 + 48\alpha + 130)h + 4(30\alpha^3 - 9\alpha^2 - 178\alpha - 303),$$

$$\psi^3(a) = a^3 + (\alpha^3 - 6\alpha - 12)a - 4(\alpha + 1)^2(\alpha - 3)a^{-1}.$$

Proof By [Rez09, Theorem B], there is a correspondence between the universal degree-3 isogeny ψ with domain C and the total power operation ψ^3 with domain E^0 . In particular $\psi^3(a)$ is given by the polynomial $r(a)$ in Proposition 4. As ψ^3 is a ring homomorphism, we then get the formula of $\psi^3(h) = \psi^3(a^2 + 4)$. \square

3 Individual power operations

To understand the power operation structure on E_0 , we need to consider composition of power operations. Given the correspondence between power operations and Frobenius isogenies (cf. [Rez09, Theorem B] and Corollary 7), we first look at what happens on the geometric side and consider the composite of two degree-3 isogenies.

By Proposition 4, as the kernel of the degree-3 isogeny ψ , the universal example G of an order-3 subgroup of C is defined over $S_3 = S[\alpha]/(w(\alpha))$. Similarly, consider the universal degree-3 isogeny ψ' with domain $C' \cong C/G$, and denote its kernel by G' . Analogous to S and S_3 , let

$$(6) \quad S' = \mathbb{Z}[1/4][a', (\Delta')^{-1}] \quad \text{and} \quad S'_3 = S'[\alpha']/(w'(\alpha')),$$

where

$$\Delta' = (a')^2(a' + 4)(a' - 4) \quad \text{and} \quad w'(\alpha') = (\alpha')^4 - 6(\alpha')^2 + ((a')^2 - 8)\alpha' - 3.$$

Let $S_{3,3}$ be the pushout in the diagram

$$\begin{array}{ccc} S' & \xrightarrow{t^*} & S_3 \\ s^* \downarrow & & \downarrow \sigma^* \\ S'_3 & \xrightarrow{\tau^*} & S_{3,3}, \end{array} \quad \sqcap$$

where s^* is the inclusion, and t^* sends a' to $r(a)$ (cf. Proposition 4; the image of Δ' is automatically invertible in S_3 by construction of C'). Then σ^* and τ^* classify the subgroup G of C , and the subgroup G' of C' , respectively. Let $C[3]$ be the group of 3-torsion points of C . Thus, as

$$\frac{C'}{G'} \cong \frac{C/G}{C[3]/G},$$

the ring

$$S_{3,3} \cong S[\alpha, \alpha'] / \left(\alpha^4 - 6\alpha^2 + (a^2 - 8)\alpha - 3, (\alpha')^4 - 6(\alpha')^2 + (r(a)^2 - 8)\alpha' - 3 \right)$$

carries the universal example of a chain $G < C[3]$ of subgroups of C with $|G| = |C[3]/G| = 3$ (Spec $S_{3,3}$ as the incidence scheme for the relation of such a chain of subgroups, in the sense of [KM85, Section 1.3]).

By base change we then have a commutative diagram of elliptic curves over $S_{3,3}$:

$$\begin{array}{ccc} C & \xrightarrow{\psi} & C/G \cong C' \\ & \searrow [3] & \downarrow \hat{\psi} \cong [-1]\psi' \\ & & C \cong C/C[3] \cong \frac{C/G}{C[3]/G} \cong \frac{C'}{G'} \end{array}$$

where $\hat{\psi}$ is the isogeny dual to ψ . Note that both ψ and ψ' restrict to the supersingular locus over \mathbb{F}_9 as the third-power Frobenius endomorphism ψ_0 (cf. Remark 5). Since $\psi_0^2 + 3 = 0$ in the endomorphism ring of the supersingular elliptic curve³, we have $\hat{\psi} \cong [-1]\psi'$.

The isogenies in the above diagram induce maps on relative cotangent spaces at the identity, and by Proposition 4 we have a commutative diagram

$$(7) \quad \begin{array}{ccc} 3du = -\alpha\alpha' du & \xleftarrow{\psi^*} & -\alpha' du \\ & \searrow [3]^* & \uparrow -(\psi')^* \\ & du & \equiv du \end{array}$$

Lemma 8 *The following relations hold in $S_{3,3}$:*

$$\alpha\alpha' + 3 = 0,$$

and

$$\alpha' = -\alpha^3 + 6\alpha + (-a^2 + 8).$$

³By Honda–Tate theory, ψ_0 satisfies either $\psi_0^2 + 3 = 0$, or $\psi_0^2 + 3\psi_0 + 3 = 0$, or $\psi_0^2 - 3\psi_0 + 3 = 0$. By checking the action of ψ_0 at a specific 2-torsion point with xy -coordinates $(-1, 0)$, we exclude the latter two possibilities.

Proof The first relation is read off from (7). From this and $w(\alpha) = 0$, we then get the second relation. \square

Remark 9 As noted in Remark 6, the analog of α at the prime 2 coincides with the parameter d used in [Rez1, Section 3]. Thus, with the notations there, d and d' satisfy an analogous relation $dd' + 2 = 0$ in the ring $S_{2,2}$. \square

Let S_9 be the pullback in the diagram

$$(8) \quad \begin{array}{ccc} S_9 & \longrightarrow & S_{3,3} \\ \downarrow \lrcorner & & \downarrow \pi^* \\ S & \xrightarrow{s^*} & S_3 \end{array},$$

where s^* is again the inclusion, and π^* sends a to a , α to α , a' to $r(a)$, and α' to $-\alpha^3 + 6\alpha + (-a^2 + 8)$ as in Lemma 8. The map π^* classifies the chain of subgroups $G < C[3]$ in C . Thus the universal example of an order-9 subgroup of C is defined over S_9 , and the map $S_9 \rightarrow S$ classifies $C[3]$.

Equipped with the geometry above, we now turn to power operations.

Let A be a $K(2)$ -local commutative E -algebra. From the total power operation on E_0 in Section 2, we have total power operations

$$\psi^3: A_0 \rightarrow A_0 \otimes_{E_0} (E^0 B\Sigma_3/I) \cong A_0[\alpha]/(w(\alpha)),$$

and, with the notations in (6),

$$\begin{aligned} \psi^3 \circ \psi^3: A_0 &\rightarrow (A_0 \otimes_{E_0} (E^0 B\Sigma_3/I))^{\psi^3} \otimes_{E_0} (E^0 B\Sigma_3/I) \\ &\cong (A_0[\alpha']/(w'(\alpha')))^{\psi^3} \otimes_{E_0} (E^0[\alpha]/(w(\alpha))), \end{aligned}$$

where $\alpha' = \psi^3(\alpha) = -\alpha^3 + 6\alpha + (-h + 12)$ by Lemma 8.

Define the *individual power operations*

$$Q_i: A_0 \rightarrow A_0,$$

for $i = 0, 1, 2, 3$, by

$$\psi^3(x) = Q_0(x) + Q_1(x)\alpha + Q_2(x)\alpha^2 + Q_3(x)\alpha^3.$$

Proposition 10 *The following relations hold among the individual power operations Q_0, Q_1, Q_2 , and Q_3 :*

(i) *Additivity*

$$Q_i(x + y) = Q_i(x) + Q_i(y);$$

(ii) *Action on scalars*

$$\begin{aligned} Q_0(1) &= 1, \\ Q_1(1) &= Q_2(1) = Q_3(1) = 0, \\ Q_0(h) &= h^3 - 36h^2 + 390h - 1212, \\ Q_1(h) &= -6h^2 + 144h - 712, \\ Q_2(h) &= 3h - 36, \\ Q_3(h) &= h^2 - 24h + 120, \\ Q_0(a) &= a^3 - 12a + 12a^{-1}, \\ Q_1(a) &= -6a + 20a^{-1}, \\ Q_2(a) &= 4a^{-1}, \\ Q_3(a) &= a - 4a^{-1}; \end{aligned}$$

(iii) *Commutation relations*

$$\begin{aligned} Q_0(hx) &= (h^3 - 36h^2 + 390h - 1212)Q_0(x) + (3h^2 - 72h + 360)Q_1(x) + (9h - 108)Q_2(x) + 24Q_3(x), \\ Q_1(hx) &= (-6h^2 + 144h - 712)Q_0(x) + (-18h + 228)Q_1(x) + (-72)Q_2(x) + (h - 12)Q_3(x), \\ Q_2(hx) &= (3h - 36)Q_0(x) + 8Q_1(x) + 12Q_2(x) + (-24)Q_3(x), \\ Q_3(hx) &= (h^2 - 24h + 120)Q_0(x) + (3h - 36)Q_1(x) + 8Q_2(x) + 12Q_3(x), \\ Q_0(ax) &= (a^3 - 12a + 12a^{-1})Q_0(x) + (3a - 12a^{-1})Q_1(x) + (12a^{-1})Q_2(x) + (-12a^{-1})Q_3(x), \\ Q_1(ax) &= (-6a + 20a^{-1})Q_0(x) + (-20a^{-1})Q_1(x) + (-a + 20a^{-1})Q_2(x) + (4a - 20a^{-1})Q_3(x), \\ Q_2(ax) &= (4a^{-1})Q_0(x) + (-4a^{-1})Q_1(x) + (4a^{-1})Q_2(x) + (-a - 4a^{-1})Q_3(x), \\ Q_3(ax) &= (a - 4a^{-1})Q_0(x) + (4a^{-1})Q_1(x) + (-4a^{-1})Q_2(x) + (4a^{-1})Q_3(x); \end{aligned}$$

(iv) *Adem relations*

$$\begin{aligned} Q_1Q_0(x) &= (-6)Q_0Q_1(x) + (6h - 72)Q_0Q_2(x) + (-6h^2 + 144h - 747)Q_0Q_3(x) + 18Q_1Q_2(x) + 3Q_2Q_1(x) + (-18h + 216)Q_1Q_3(x) + (-54)Q_2Q_3(x) + (-9)Q_3Q_2(x), \\ Q_2Q_0(x) &= (-3)Q_0Q_2(x) + (3h - 36)Q_0Q_3(x) + 9Q_1Q_3(x) + 3Q_3Q_1(x), \\ Q_3Q_0(x) &= Q_0Q_1(x) + (-h + 12)Q_0Q_2(x) + (h^2 - 24h + 126)Q_0Q_3(x) + (-3)Q_1Q_2(x) + (3h - 36)Q_1Q_3(x) + 9Q_2Q_3(x); \end{aligned}$$

(v) *Cartan formulas*

$$\begin{aligned} Q_0(xy) &= Q_0(x)Q_0(y) + 3(Q_1(x)Q_3(y) + Q_2(x)Q_2(y) + Q_3(x)Q_1(y)) + 18Q_3(x)Q_3(y), \\ Q_1(xy) &= (Q_0(x)Q_1(y) + Q_1(x)Q_0(y)) + (-h + 12)(Q_1(x)Q_3(y) + Q_2(x)Q_2(y) + Q_3(x)Q_1(y)) + 3(Q_2(x)Q_3(y) + Q_3(x)Q_2(y)) + (-6h + 72)Q_3(x)Q_3(y), \end{aligned}$$

$$\begin{aligned}
Q_2(xy) &= (Q_0(x)Q_2(y) + Q_1(x)Q_1(y) + Q_2(x)Q_0(y)) + 6(Q_1(x)Q_3(y) + Q_2(x)Q_2(y) + \\
&\quad Q_3(x)Q_1(y)) + (-h + 12)(Q_2(x)Q_3(y) + Q_3(x)Q_2(y)) + 39Q_3(x)Q_3(y), \\
Q_3(xy) &= (Q_0(x)Q_3(y) + Q_1(x)Q_2(y) + Q_2(x)Q_1(y) + Q_3(x)Q_0(y)) + 6(Q_2(x)Q_3(y) + \\
&\quad Q_3(x)Q_2(y)) + (-h + 12)Q_3(x)Q_3(y);
\end{aligned}$$

(vi) *Frobenius congruence*

$$Q_0(x) \equiv x^3 \pmod{3}, \text{ with } \theta: A_0 \rightarrow A_0 \text{ such that } Q_0(x) = x^3 + 3\theta(x).$$

Proof Except for (iv), all the relations can be derived directly from the formulas in Corollary 7 and the fact that ψ^3 is a ring homomorphism.

Write \widehat{S}' , \widehat{S}_3' , $\widehat{S}_{3,3}$, and \widehat{S}_9 , analogous to \widehat{S}_3 in (5), to denote the completions of rings. In view of (8) and the moduli interpretations of $S_{3,3}$ and S_9 , we note that the composite

$$A_0 \xrightarrow{\psi^3} A_0 \otimes_{\widehat{S}}^{s*} \widehat{S}_3 \xrightarrow{\psi^3} A_0 \otimes_{\widehat{S}'}^{s*} \widehat{S}_3' \xrightarrow{t^*} A_0 \otimes_{\widehat{S}}^{s*} \widehat{S}_3 \cong A_0 \otimes_{\widehat{S}}^{s*} \widehat{S}_{3,3}$$

factors through $A_0 \otimes_{\widehat{S}} \widehat{S}_9$. In terms of formulas, we have

$$\begin{aligned}
\psi^3(\psi^3(x)) &= \psi^3(Q_0(x) + Q_1(x)\alpha + Q_2(x)\alpha^2 + Q_3(x)\alpha^3) \\
&= \psi^3(Q_0(x)) + \psi^3(Q_1(x))\alpha' + \psi^3(Q_2(x))(\alpha')^2 + \psi^3(Q_3(x))(\alpha')^3 \\
&= \sum_{i,j=0}^3 Q_i Q_j(x) \alpha^i (-\alpha^3 + 6\alpha + (-h + 12))^j,
\end{aligned}$$

where the last expression is the projection to \widehat{S}_3 from $\widehat{S}_{3,3}$ along π^* . Factoring through $A_0 \otimes_{\widehat{S}} \widehat{S}_9$ then means that the coefficients of α , α^2 , and α^3 in this last expression must be 0 (α satisfies a quartic equation in \widehat{S}_3). This gives the three relations in (iv). \square

Definition 11 We define an associative ring Γ equipped with a ring homomorphism $\eta: \widehat{S} \rightarrow \Gamma$ as follows⁴. The ring Γ is generated over \widehat{S} via η by elements Q_0 , Q_1 , Q_2 , and Q_3 , subject to *commutation relations* and *Adem relations*. The commutation relations state that the Q_i 's commute with elements of $\mathbb{Z}_9 \subset \widehat{S}$, and that

$$Q_0 h = (h^3 - 36h^2 + 390h - 1212)Q_0 + (3h^2 - 72h + 360)Q_1 + (9h - 108)Q_2 + 24Q_3,$$

$$Q_1 h = (-6h^2 + 144h - 712)Q_0 + (-18h + 228)Q_1 + (-72)Q_2 + (h - 12)Q_3,$$

$$Q_2 h = (3h - 36)Q_0 + 8Q_1 + 12Q_2 + (-24)Q_3,$$

$$Q_3 h = (h^2 - 24h + 120)Q_0 + (3h - 36)Q_1 + 8Q_2 + 12Q_3.$$

⁴For any element $s \in \widehat{S} = E_0$, $\eta(s)$ corresponds to the multiplication-by- s operation on the E_0 -algebra A_0 (cf. [Rez09, Section 6]).

The Adem relations are

$$Q_1 Q_0 = (-6)Q_0 Q_1 + (6h - 72)Q_0 Q_2 + (-6h^2 + 144h - 747)Q_0 Q_3 + 18Q_1 Q_2 + 3Q_2 Q_1 + (-18h + 216)Q_1 Q_3 + (-54)Q_2 Q_3 + (-9)Q_3 Q_2,$$

$$Q_2 Q_0 = (-3)Q_0 Q_2 + (3h - 36)Q_0 Q_3 + 9Q_1 Q_3 + 3Q_3 Q_1,$$

$$Q_3 Q_0 = Q_0 Q_1 + (-h + 12)Q_0 Q_2 + (h^2 - 24h + 126)Q_0 Q_3 + (-3)Q_1 Q_2 + (3h - 36)Q_1 Q_3 + 9Q_2 Q_3. \quad \square$$

Remark 12 Proposition 10 describes explicitly the structure of Γ as a *graded twisted bialgebra* over $E_0 = \widehat{S}$ (cf. [Rez09, Section 5] and [Rezb, 2.1]). In particular it follows using commutation relations and Adem relations that Γ has an *admissible basis*, that is, it is free as a left \widehat{S} -module on the elements of the form

$$Q_0^i Q_{k_1} \cdots Q_{k_r},$$

where $i, r \geq 0$, and $k_j = 1, 2$, or 3 . Note that if we write $\Gamma[d]$ for the degree- d part of Γ , then $\Gamma[d]$ is of rank $1 + 3 + \cdots + 3^d$. \square

Example 13 We have $E^0 S^2 \cong \mathbb{Z}_9[[h]][u]/(u^2)$. By definition of α in (4), the Q_i 's act canonically on $E^0 S^2$:

$$Q_i \cdot u = \begin{cases} u, & \text{if } i = 1, \\ 0, & \text{if } i \neq 1. \end{cases}$$

Let ω be the kernel of $E^0 S^2 \rightarrow E^0$. It is a Γ -module (cf. [Rezb, 2.2]) on one generator u , and its Γ -module structure is canonical as above. \square

Following the terminology in [Rez09, Section 2] and [Rezb, 2.5 and 2.6], we can now describe the power operation structure on $K(2)$ -local commutative E -algebras.

Theorem 14 Let A be a $K(2)$ -local commutative E -algebra. Let Γ be the graded twisted bialgebra over E_0 given in Definition 11, and let ω be the Γ -module given in Example 13. Then A_* is an ω -twisted $\mathbb{Z}/2$ -graded amplified Γ -ring. In particular,

$$\pi_* L_{K(2)} \mathbb{P}_E(\Sigma^d E) \cong (F_d)_{(3,h)}^\wedge,$$

where F_d is the free ω -twisted $\mathbb{Z}/2$ -graded amplified Γ -ring on one generator in degree d .

Formulas of Γ aside, this result is essentially due to Rezk [Rez09, Rezb].

Proof Let $\tilde{\Gamma}$ be the graded twisted bialgebra of power operations on E described in [Rez09, Section 6]. It suffices to identify $\tilde{\Gamma}$ with Γ . There is a direct sum decomposition $\tilde{\Gamma} = \bigoplus_{d \geq 0} \tilde{\Gamma}[d]$, where the pieces come from the E -homology of $B\Sigma_{3^d}$ (cf. [Rez09, 6.2]). There is a degree-preserving ring homomorphism $\phi: \Gamma \rightarrow \tilde{\Gamma}$ which is an isomorphism in degrees 0 and 1 (cf. Corollary 7). Since $\tilde{\Gamma}$ is generated in degree 1 by transfer argument, ϕ is surjective. Since $\Gamma[d]$ and $\tilde{\Gamma}[d]$ are of the same rank $1 + 3 + \cdots + 3^d$ as free modules over E_0 by Remark 12 and [Str98, Theorem 1.1]), ϕ is also injective. \square

4 $K(1)$ -local power operations

Let $F = L_{K(1)}E$. The general pattern of the relationship between $K(1)$ -local power operations (cf. [Hop]) and the power operations in Section 2 is as follows:

$$\begin{array}{ccc} E^0 & \xrightarrow{\psi^3} & E^0 B\Sigma_3/I \\ \downarrow & & \downarrow \\ F^0 & \xrightarrow{\psi_F^3} & F^0 B\Sigma_3/I \xleftarrow{\cong} F^0. \end{array}$$

Recall Proposition 4 and Corollary 7 that ψ^3 arises from the universal degree-3 isogeny which is parametrized by the ring S_3 with

$$\widehat{S}_3 = (S_3)_{(3,h)}^\wedge \cong E^0 B\Sigma_3/I.$$

The vertical maps are induced by the $K(1)$ -localization $E \rightarrow F$. In terms of homotopy groups, this is obtained by inverting the generator h (so that the resulting formal group is of height at most 1) and completing at the ideal (3) , i.e.

$$E_* = \mathbb{Z}_9[[h]][u^{\pm 1}] \quad \text{and} \quad F_* = \mathbb{Z}_9[[h]][h^{-1}]_3^\wedge[u^{\pm 1}].$$

Explicitly,

$$(9) \quad F_0 = \mathbb{Z}_9((h))_3^\wedge = \varprojlim_k \mathbb{Z}_9((h))/(3^k) = \left\{ \sum_{n=-\infty}^{\infty} c_n h^n \mid c_n \in \mathbb{Z}_9, \lim_{n \rightarrow -\infty} c_n = 0 \right\}.$$

The formal group \widehat{C} over E^0 has a unique order-3 subgroup after being pulled back to F^0 (cf. Remark 3), and the composite map

$$E^0 B\Sigma_3/I \rightarrow F^0 B\Sigma_3/I \cong F^0$$

classifies this subgroup. The map

$$E^0 B\Sigma_3/I \rightarrow F^0 B\Sigma_3/I$$

factors through $F^0 \otimes_{E^0} E^0 B\Sigma_3/I$; along the base change

$$E^0 B\Sigma_3/I \rightarrow F^0 \otimes_{E^0} E^0 B\Sigma_3/I,$$

the special fiber of the 3-divisible group \widehat{C} which consists solely of a formal component may split into formal and étale components. We want to take the formal component so as to keep track of the unique order-3 subgroup of the formal group over F^0 which gives rise to the $K(1)$ -local power operation ψ_F^3 .

As in Proposition 4, the ring

$$S_3 = S[\alpha]/(w(\alpha))$$

parametrizes order-3 subgroups of C . Since

$$w(\alpha) = \alpha^4 - 6\alpha^2 + (h - 12)\alpha - 3 \equiv \alpha(\alpha^3 + h) \pmod{3},$$

the equation $w(\alpha) = 0$ has a unique root $\alpha = 0$ in $\mathbb{F}_3((h))$ (in view of (9), $\alpha^3 + h$ cannot be zero). By Hensel's Lemma this unique root lifts to a root in $\mathbb{Z}_9((h))_3^\wedge$; it corresponds to the unique order-3 subgroup of \widehat{C} over $F^0 = \mathbb{Z}_9((h))_3^\wedge$. Plugging this specific value of α into the formulas of

$$\psi^3: E^0 \rightarrow E^0[\alpha]/(w(\alpha))$$

given in Corollary 7, we then get an endomorphism of the ring F^0 . This endomorphism is the $K(1)$ -local power operation ψ_F^3 .

Explicitly, with h invertible in F^0 , we can solve for α from the equation $w(\alpha) = 0$ by first writing

$$\alpha = \frac{1}{h-12}(3 + 6\alpha^2 - \alpha^4) = (3 + 6\alpha^2 - \alpha^4) \cdot \sum_{n=1}^{\infty} 12^{n-1} h^{-n}$$

and then substituting α recursively. We plug this into $\psi^3(h)$ and get

$$\psi_F^3(h) = h^3 - 36h^2 + 372h - 996 + 186h^{-1} + 2232h^{-2} + \dots$$

Similarly we have

$$\psi_F^3(a) = a^3 - 12a - 6a^{-1} - 84a^{-3} - 933a^{-5} - 10956a^{-7} + \dots$$

Appendices

The calculations in this paper involve power series expansions and basic manipulations of long polynomials with large coefficients, namely division, factorization, and finding greatest common divisors. These are done using the software *Wolfram Mathematica* 8. In particular the commands `Reduce` and `Solve` are used to extract relations out of given identities.

A List of formulas in the proof of Proposition 2

$$\tilde{f}(u) = -u^4(-3 - 3au + 8u^2 - a^2u^2 + 9au^3 - 6u^4 + 6a^2u^4 + 7au^5 + a^3u^5 + 3a^2u^6 + 3au^7 + u^8)/a^2$$

$$Q_1(v) = \frac{1}{a} - d - \frac{2d^2}{a} + ad^2 + 2d^3 + \frac{d^4}{a} + (-1 + 2ad + d^2)v + av^2$$

$$R_1(v) = \frac{d^3}{a} + 2d^4 - \frac{2d^5}{a} + ad^5 + 2d^6 + \frac{d^7}{a} + (-\frac{1}{a} + \frac{3d^2}{a} + 2d^3 - \frac{3d^4}{a} + ad^4 + 2d^5 + \frac{d^6}{a})v$$

$$Q_2(v) = -a(1 + ad - 4d^2 - 4ad^3 + 6d^4 - a^2d^4 + ad^5 - 4d^6 + a^2d^6 + 2ad^7 + d^8 + av - 3ad^2v - 2a^2d^3v + 3ad^4v - a^3d^4v - 2a^2d^5v - ad^6v)/(-1 + 3d^2 + 2ad^3 - 3d^4 + a^2d^4 + 2ad^5 + d^6)^2$$

$$R_2 = -ad^4(-3 - 3ad + 8d^2 - a^2d^2 + 9ad^3 - 6d^4 + 6a^2d^4 + 7ad^5 + a^3d^5 + 3a^2d^6 + 3ad^7 + d^8)/(-1 + 3d^2 + 2ad^3 - 3d^4 + a^2d^4 + 2ad^5 + d^6)^2$$

$$S(d) = \frac{d^3}{a} + 2d^4 - \frac{2d^5}{a} + ad^5 + 2d^6 + \frac{d^7}{a}$$

$$T(d) = -\frac{1}{a} + \frac{3d^2}{a} + 2d^3 - \frac{3d^4}{a} + ad^4 + 2d^5 + \frac{d^6}{a}$$

$$M(u) = (-4096a^6 + 13568a^8 - 2672a^{10} + 179a^{12} - 4a^{14} - 98304a^7u + 19456a^9u - 1280a^{11}u + 28a^{13}u + 8192a^6u^2 - 69120a^8u^2 + 17248a^{10}u^2 - 1610a^{12}u^2 + 66a^{14}u^2 - a^{16}u^2 + 77824a^7u^3 - 41984a^9u^3 + 6384a^{11}u^3 - 382a^{13}u^3 + 8a^{15}u^3 - 4096a^6u^4 - 55040a^8u^4 + 11792a^{10}u^4 - 825a^{12}u^4 + 19a^{14}u^4 - 28672a^7u^5 + 6144a^9u^5 - 432a^{11}u^5 + 10a^{13}u^5)/(65536a^8 - 16384a^{10} + 1536a^{12} - 64a^{14} + a^{16})$$

$$N(u) = a(12288a^6 - 106240a^8 + 24400a^{10} - 2073a^{12} + 76a^{14} - a^{16} + 307200a^7u - 99072a^9u + 11856a^{11}u - 621a^{13}u + 12a^{15}u - 20480a^6u^2 + 296192a^8u^2 - 71856a^{10}u^2 + 6555a^{12}u^2 - 265a^{14}u^2 + 4a^{16}u^2 - 135168a^7u^3 + 199680a^9u^3 - 40272a^{11}u^3 + 3082a^{13}u^3 - 98a^{15}u^3 + a^{17}u^3 + 4096a^6u^4 + 213760a^8u^4 - 22928a^{10}u^4 - 1435a^{12}u^4 + 239a^{14}u^4 - 7a^{16}u^4 + 12288a^7u^5 + 78592a^9u^5 - 16880a^{11}u^5 + 1177a^{13}u^5 - 27a^{15}u^5 + 4096a^6u^6 +$$

$$\frac{83712a^8u^6 - 17936a^{10}u^6 + 1257a^{12}u^6 - 29a^{14}u^6 + 28672a^7u^7 - 6144a^9u^7 + 432a^{11}u^7 - 10a^{13}u^7}{(65536a^8 - 16384a^{10} + 1536a^{12} - 64a^{14} + a^{16})}$$

B List of formulas in the proof of Proposition 4

$$v = u^3 - au^4 + (1 + a^2)u^5 - a(3 + a^2)u^6 + (1 + 6a^2 + a^4)u^7 - a(6 + 10a^2 + a^4)u^8 + (1 + 20a^2 + 15a^4 + a^6)u^9 + O(u^{10})$$

The group law on C (cf. [Sil09, III.2]) satisfies:

- given $P(u, v)$, the coordinates of $-P$ are

$$u_0 = -\frac{v}{u(u+v)} \quad \text{and} \quad v_0 = -\frac{v^2}{u^2(u+v)};$$

- given $P_1(u_1, v_1)$ and $P_2(u_2, v_2)$, the coordinates of $-(P_1 + P_2)$ are

$$u_3 = ak - \frac{b}{1+k} - u_1 - u_2 \quad \text{and} \quad v_3 = ku_3 + b,$$

where $k = \frac{v_1 - v_2}{u_1 - u_2}$ is the slope and $b = \frac{u_1 v_2 - u_2 v_1}{u_1 - u_2}$ is the v -intercept of the line through P_1 and P_2 .

Thus, given $P(u, v)$ and $Q(d, e)$, to compute formulas of u' and v' ,

- set

$$(u_1, v_1) = \left(-\frac{v}{u(u+v)}, -\frac{v^2}{u^2(u+v)} \right) \quad \text{and} \quad (u_2, v_2) = (d, e),$$

and take

$$P - Q = (u_3, v_3);$$

- set

$$(u_1, v_1) = (u, v) \quad \text{and} \quad (u_2, v_2) = (d, e),$$

and take

$$P + Q = \left(-\frac{v_3}{u_3(u_3 + v_3)}, -\frac{v_3^2}{u_3^2(u_3 + v_3)} \right).$$

Plugging the coordinates of $P - Q$ and $P + Q$ into (3), and in view of $f(d) = 0$ as in Proposition 2, we have in (4), among coefficients of higher powers of u ,

$$\alpha = -(-18 - 12ad + 2d^2 + a^2d^2 - 15ad^3 + 4a^3d^3 + 2d^4 + a^2d^4 + a^4d^4 - 6ad^5 + 3a^3d^5 - 2d^6 + 3a^2d^6 + ad^7) / ((-4 + a)(4 + a)),$$

$$\beta = -(-12 - 6a^2 - 117ad + 3a^3d + 20d^2 - 153a^2d^2 + 10a^4d^2 + 31ad^3 - 80a^3d^3 + 6a^5d^3 - 4d^4 - 96a^2d^4 - 4a^4d^4 + a^6d^4 - 15ad^5 - 33a^3d^5 + 3a^5d^5 - 4d^6 - 33a^2d^6 + 3a^4d^6 - 11ad^7 + a^3d^7) / ((-4 + a)a^2(4 + a)).$$

$$\alpha^3/\beta = -(4 - 4a^2 + 9ad - 3a^3d - 12d^2 + 21a^2d^2 - a^4d^2 - 15ad^3 + 11a^3d^3 + 12d^4 + 6a^2d^4 + 3a^4d^4 - 13ad^5 + 9a^3d^5 - 4d^6 + 9a^2d^6 + 3ad^7) / ((-4 + a)(4 + a))$$

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Department of Mathematics, University of Minnesota, Minneapolis, MN 55455, USA

zyf@math.umn.edu