

THE ANDRÉ-QUILLEN COHOMOLOGY OF COMMUTATIVE MONOIDS

BHAVYA AGRAWALLA, NASIEF KHLAIF, AND HAYNES MILLER

ABSTRACT. We observe that Beck modules for a commutative monoid are exactly modules over a graded commutative ring associated to the monoid. Under this identification, the Quillen cohomology of commutative monoids is a special case of André-Quillen cohomology for graded commutative rings, generalizing a result of Kurdiani and Pirashvili. To verify this we develop the necessary grading formalism. The partial cochain complex developed by Pierre Grillet for computing Quillen cohomology appears as the start of a modification of the Harrison cochain complex suggested by Michael Barr.

In his book *Homotopical Algebra* [34], Daniel Quillen described a homotopy theory of simplicial objects in any of a wide class of universal algebras, and corresponding theories of homology and cohomology. Quillen homology is defined as derived functors of an abelianization functor, and in many cases can be computed using a cotriple resolution [4]. Coefficients for these theories are “Beck modules,” that is, abelian objects in a slice category. The case of commutative rings was studied at the same time by Michel André [1].

An example of such an algebraic theory, one of long standing and increasing importance, is provided by the category **ComMon** of commutative monoids. The prime exponent of the study of commutative monoids has for years been Pierre Grillet [17, 18, 19, 20, 23, 24] (but see also [10] and [28] for example). Among other things, Grillet provided the beginning of a small cochain complex, based on multilinear maps subject to certain symmetry conditions, whose cohomology he showed to be isomorphic in low dimensions to the Quillen cohomology $HQ_{CM}^*(X; M)$ of the commutative monoid X with coefficients in a Beck module M for X ; and in [22] a corresponding resolution in Beck modules was developed. These results are surprising, since Quillen cohomology is defined by means of a simplicial resolution and does not generally admit such an efficient computation.

It is well-known ([29, 17] and [38, p. 29]) and easy to see that the category of (left) Beck modules for X , **LMod** $_X$, is equivalent to the category of covariant functors from the “Leech category” L_X to the category **Ab** of abelian groups. The Leech category has object set X ; $L_X(x, y) = \{z : y =$

2010 *Mathematics Subject Classification.* 20M14, 13D03.

Key words and phrases. commutative monoid, Harrison homology, Quillen cohomology.

$z + x$ } (writing the monoid structure additively); and composition is given by addition in the commutative monoid.

In this paper, we observe that Grillet’s construction is in fact subsumed by the theory of Harrison cohomology of commutative rings, slightly augmented as suggested by Michael Barr, once this theory has been extended to the graded context. As pointed out by Bourbaki [7, Ch. 2 §11], one can speak of rings graded by a commutative monoid: an X -graded object in a category \mathbf{C} is an assignment of an object $C_x \in \mathbf{C}$ for each $x \in X$. If \mathbf{C} is the category \mathbf{Mod}_K of modules over some commutative ring K , there is a natural symmetric monoidal structure on the category \mathbf{Mod}_K^X of X -graded K -modules, and we may define X -graded K -algebras, and modules over them, accordingly.

The first observation, simple enough as to need no proof, is that there is a natural X -graded commutative K -algebra $\tilde{K}X$ in which, for each $x \in X$, $(\tilde{K}X)_x$ is the free K -module generated by an element we will write 1_x , with the evident unit and multiplication. This is the “ X -graded monoid K -algebra” of X .

The next observation, equally simple, is that the category of Beck X -modules is equivalent to the category of (X -graded) left modules over $\tilde{\mathbb{Z}}X$.

These two observations bring into play the entire highly developed homological theory of commutative rings. Our first main result 5.2 is that

$$HQ_{CM}^*(X; M) = HQ_{CA}^*(\tilde{\mathbb{Z}}X; M)$$

where the right hand term denotes the well-studied André-Quillen cohomology [35, 1, 37], extended to the graded context. This generalizes an observation of Kurdiani and Pirashvili [28], who considered the case of Beck modules pulled back from the trivial monoid, in which case one arrives at the André-Quillen cohomology of $\mathbb{Z}X$ as an ungraded commutative ring.

André-Quillen cohomology is of course hard to compute, but there are well known approximations to it. One such approximation is given by Harrison cohomology [25, 14, 2, 39] $Harr^*(A; M)$. This theory is most neatly expressed by restricting to Hochschild cochains that annihilate shuffle decomposables; or, equivalently, to cochains that satisfy appropriate “partition” symmetry conditions. This characterization was apparently suggested by Mac Lane, and was adopted in [25], but Harrison’s original invariance property involved a different characterization of the same symmetry conditions, using “monotone” permutations. The equivalence of these two definitions can be found as Corollary 4.2 in [14].

This approximation definitely breaks down in finite characteristic: The André-Quillen cohomology of a polynomial algebra vanishes in positive dimensions, but Michael Barr showed [2] that the Harrison cohomology of the polynomial algebra over a field of characteristic p is nonzero in dimension $2p$. Barr himself proposed a variant of the Harrison construction, restricting Hochschild cochains that not only by vanish on shuffle decomposables but also on divided powers. This overcomes the obstacle in dimension $2p$, but in

her thesis [39] Sarah Whitehouse proved that this variant also fails to give André-Quillen cohomology, by showing that Barr cohomology in dimension 5 does not vanish on $\mathbb{F}_2[x]$.

Our second observation is that exactly the same monotone symmetry and divided-power annihilation conditions occur in the partial complex described by Grillet; Grillet’s partial complex is precisely the beginning of the “Barr complex” for the graded monoid algebra. In later work [23], Grillet proposed that this complex correctly computes Quillen cohomology in higher dimensions as well, but Whitehouse’s counterexample shows that this conjecture fails at least in dimension 5.

Grillet’s identification of his cohomology with the Quillen cohomology of commutative monoids goes well beyond what seems to be known about the relationship between Harrison cohomology and André-Quillen cohomology in general, and suggests a variety of questions.

We note that the observation that Beck modules over a commutative monoid are just graded modules over its graded monoid algebra suggests that the description of Quillen homology for commutative monoids carried out in [28] is in fact a special case of a graded extension of Pirashvili’s earlier work [33].

We begin in §1 with a recollection of Quillen homology, along with the cotriple resolution that may be used to compute it. §2 sets out some elementary facts about X -gradings, and in §3 we explain how the grading behaves in homological algebra. Change of grading is explained in §4. The next section is the core of the work, proving the identification of Quillen homology and cohomology for commutative monoids with that of certain X -graded commutative rings. We then turn to interpreting the work of Grillet. This requires developing the Hochschild complex with its shuffle product and divided power structure (and we provide some new general information about the latter), and the various indecomposable quotients occurring in the definitions of Harrison and Barr homology. In §9, we review the motivating work of Pierre Grillet and relate it to Harrison and Barr cohomology.

Acknowledgements. We are grateful to Pierre Grillet for forwarding us, in response to a letter from us outlining the results presented here, an early copy of a paper in which a similar story is worked out. He uses somewhat different language – his “multi” objects are our graded objects – but he did not make the connection with Harrison homology that we establish here.

This work was carried out under the auspices of a program, supported by MIT’s Jameel World Education Laboratory, designed to foster collaborative research projects involving students from MIT and Palestinian universities. We acknowledge with thanks the contributions made by early participants in this program – Mohammad Damaj and Ali Tahboub of Birzeit University and Hadeel AbuTabeeh of An-Najah National University – as well as the support of Palestinian faculty – Reema Sbeih and Mohammad Saleh at Birzeit and Khalid Adarbeh and Muath Karaki at NNU. We thank Professor

Victor Kac for pointing out to us the relevance of [14]. The first author acknowledges support by the MIT UROP office.

Finally, we thank the referee for such a careful reading of the document.

1. QUILLEN HOMOLOGY AND QUILLEN COHOMOLOGY

In [35], Daniel Quillen proposed a uniform definition of the “homology” and “cohomology” of objects in a very general class of categories. The marquis example was that of commutative algebras, but his definition applies much more generally and subsumes many of the ad hoc definitions that were already in use at the time and have been considered subsequently.

Quillen proposed that the construction of “homology” should be a special case of a general procedure for deriving a functor. One of the motivations for his development of the theory of “model categories” [34, 27, 26, 16] was precisely to provide a context for defining derived functors of non-additive functors. This theory “internalizes” homological algebra, in the sense that objects playing the role of projective resolutions (called “cofibrant objects”) and maps playing the role of quasi-isomorphisms (called “weak equivalences”) exist in the category (rather than in some auxiliary category such as a category of chain complexes). One of the axioms asserts that an object admits a weak equivalence from a cofibrant object; this “cofibrant replacement” plays the role of a projective resolution.

In [34, II§4], Quillen establishes the existence of a model structure on the category of simplicial objects over any one of a very general class of categories with suitable mild properties. We refer to Quillen’s book or [13] for definitions.

Theorem 1.1. [34, II§4, Theorem 4] *Let \mathbf{C} be any cocomplete category admitting a set \mathcal{P} of small projective generators (a “quasi-algebraic category” in the language of [13]). Then there is a model structure on the category of simplicial objects over \mathbf{C} in which the weak equivalences are the morphisms f such that $\mathbf{C}(P, f)$ is a weak equivalence of simplicial sets for all $P \in \mathcal{P}$.*

All normally occurring categories of universal algebras satisfy these assumptions.

This model structure on $s\mathbf{C}$ allows us to define derived functors for any functor $E : \mathbf{C} \rightarrow \mathbf{A}$, where \mathbf{A} is an abelian category: For any X in \mathbf{C} , let $P_\bullet \rightarrow X$ be a cofibrant replacement and define

$$L_n E(X) = \pi_n(EP_\bullet).$$

See [13] for an elaboration of the naturality of this construction. The fact that any cofibrant replacement can be used is contained, for example, in [13, Proposition 3.9].

Explicit cofibrant replacements can often be constructed as a “cotriple resolution” [4]. An adjoint pair

$$\mathbf{C} \rightleftarrows \mathbf{D}$$

defines a triple F on \mathbf{C} and a cotriple G on \mathbf{D} ; see [12, 5]. For example the free commutative monoid functor \mathbb{N} is left adjoint to the forgetful functor –

$$\mathbb{N} : \mathbf{Set} \rightleftarrows \mathbf{ComMon} : u$$

– and this adjoint pair defines triple $u\mathbb{N}$ on \mathbf{Set} and a cotriple $\mathbb{N}u$ on \mathbf{ComMon} . The commutative monoid of natural numbers (also denoted by \mathbb{N}) is a small projective generator for \mathbf{ComMon} , and $u(S) = \mathbf{ComMon}(\mathbb{N}, S)$.

A cotriple G on \mathbf{C} determines a functor G_\bullet to the category $s\mathbf{C}$ of simplicial objects over \mathbf{C} , augmented to the identity functor: this is the “cotriple resolution”: see [4] or [37, Chapter 8]. To relate it to the model category structure we need a further restriction: A category \mathbf{C} is *algebraic* (in Franland’s sense) if it is quasi-algebraic and Barr-exact ([3, p. 35],[13, p. 91]).

Proposition 1.2. [35, p. 69] *Let \mathbf{C} be an algebraic category and \mathcal{P} a set of small projective generators. When the cotriple G is associated to the adjoint pair $\mathbf{C} \rightleftarrows \mathbf{Set}^{\mathcal{P}}$, the cotriple resolution $G_\bullet A \rightarrow A$ serves as a cofibrant replacement of A (regarded as a constant simplicial object) in the Quillen model structure on $s\mathbf{C}$.*

This allows one to calculate the derived functors for any functor $E : \mathbf{C} \rightarrow \mathbf{A}$ to an abelian category:

$$L_n E(C) = \pi_n(E(G_\bullet C)) = H_n(\text{ch } E(G_\bullet C))$$

where ch denote formation of the chain complex associated to a simplicial object in an abelian category; see [37, Theorem 8.4.1], for example.

Quillen’s definition [35] of homology and cohomology of an object in a category \mathbf{C} involves the notion of Beck modules.

Definition 1.3. [5, Definition 5] *A Beck module over an object A in \mathbf{C} is an abelian object in the slice category \mathbf{C}/A .*

With the evident morphisms, Beck A -modules form a category \mathbf{LMod}_A . The terminal object in \mathbf{LMod}_A is the identity map $\text{id}_A : A \downarrow A$ with its unique abelian structure. If \mathbf{C} is quasi-algebraic, so is $\text{Ab}(\mathbf{C}/A)$ [13, 3.40]. Under mild additional conditions $\text{Ab}(\mathbf{C}/A)$ is an abelian category:

Proposition 1.4. [35, p. 69]¹, [3, Chapter 2, Theorem 2.4] *Let \mathbf{C} be an algebraic category and $A \in \mathbf{C}$. Then both \mathbf{C}/A and $\text{Ab}(\mathbf{C}/A)$ are algebraic; $\text{Ab}(\mathbf{C}/A)$ is abelian; and the forgetful functor $\text{Ab}(\mathbf{C}/A) \rightarrow \mathbf{C}/A$ has a left adjoint $\text{Ab}_A : \mathbf{C}/A \rightarrow \text{Ab}(\mathbf{C}/A)$.*

We are now in position to recall the following definition.

Definition 1.5. [34] *Let \mathbf{C} be an algebraic category. The Quillen homology of an object A in \mathbf{C} is the sequence of Beck A -modules given by*

$$HQ_n(A) = L_n \text{Ab}_A(\text{id}_A) = \pi_n(\text{Ab}_A(P_\bullet))$$

¹But Quillen inadvertently omits the exactness condition.

where $P_\bullet \rightarrow A$ is a cofibrant replacement regarded as an object in $s\mathbf{C}/A$. The Quillen cohomology of A with coefficients in a Beck A -module is the sequence of abelian groups

$$HQ^n(A; M) = H^n(\mathrm{Hom}_A(\mathrm{ch} P_\bullet, M)).$$

In terms of the cotriple resolution,

$$\begin{aligned} HQ_n(A) &= \pi_n(\mathrm{Ab}_A(G_\bullet A)) \\ HQ^n(A; M) &= H^n(\mathrm{Hom}_A(\mathrm{Ab}_A(G_\bullet A), M)). \end{aligned}$$

For example [35, §4], when \mathbf{C} is the category \mathbf{ComAlg}_K of commutative K -algebras, the category of Beck A -modules is equivalent to the category of left A -modules: An abelian object over A , $p : B \downarrow A$, first of all has a section, the “zero-section,” which provides an identification of K -modules $B \cong A \oplus M$ where M is the kernel of p as an A -module. The abelian structure forces the multiplication on $A \oplus M$ to be given by $(a, m)(b, n) = (ab, an + bm)$. Under this identification, a section of $A \oplus M \downarrow A$ in \mathbf{ComAlg}_K is given by $a \mapsto (a, da)$ where $d \in \mathrm{Der}_K(A, M)$. The abelianization of $\mathrm{id} : A \downarrow A$ is the A -module such that $\mathrm{Hom}_A(\mathrm{Ab}_A(A), M) = \mathrm{Der}_K(A, M)$; that is, $\mathrm{Ab}_A(A)$ is the usual module $\Omega_{A/K}$ of Kähler differentials. More generally, for $B \downarrow A$ in \mathbf{ComAlg}_K/A

$$\mathrm{Ab}_A(B) = A \otimes_B \Omega_{B/K}.$$

So in that case we have the “cotangent complex”

$$\mathbf{L}_{A/K} = A \otimes_{G_\bullet A} \Omega_{G_\bullet A/K}.$$

The André-Quillen homology is its homotopy –

$$HQ_n(A) = \pi_n(\mathbf{L}_{A/K})$$

– and the André-Quillen cohomology is

$$HQ^n(A; M) = H^n(\mathrm{Hom}_A(\mathrm{ch} \mathbf{L}_{A/K}, M)).$$

In this case we can also define homology with coefficients in an A -module M :

$$HQ_n(A; M) = \pi_n(\mathbf{L}_{A/K} \otimes_A M).$$

2. GRADINGS

We begin by setting up some structure on categories of objects graded over a commutative monoid.

Let X be a commutative monoid, which we will write additively. Following Bourbaki [7, Ch. 2 §11], we say that an X -graded object C_\bullet in a category \mathbf{C} is a choice of object C_x of \mathbf{C} for each $x \in X$. Write \mathbf{C}^X for the category of X -graded objects in \mathbf{C} . A morphism $C_\bullet \rightarrow C'_\bullet$ is a morphism $C_x \rightarrow C'_x$ for each $x \in X$. A functor $F : \mathbf{C} \rightarrow \mathbf{D}$ induces $F^X : \mathbf{C}^X \rightarrow \mathbf{D}^X$, and an adjunction between E and F induces a canonical adjunction between E^X and F^X .

Structure on \mathbf{C} often induces structure on \mathbf{C}^X . For example suppose that $(\mathbf{C}, \mathbf{1}, \otimes, c)$ is a closed symmetric monoidal category [6, §6.1]. Assuming that \mathbf{C} has coproducts of large enough sets of objects, there is then a canonical symmetric monoidal structure on \mathbf{C}^X , which is also closed if \mathbf{C} has products of large enough sets of objects, in which

$$\mathbf{1}_x = \begin{cases} \mathbf{1} & \text{for } x = 0 \\ \mathbf{0} & \text{for } x \neq 0 \end{cases}$$

$$(C_\bullet \otimes D_\bullet)_z = \coprod_{x+y=z} C_x \otimes D_y.$$

The symmetry $c : (C_\bullet \otimes D_\bullet)_z \rightarrow (D_\bullet \otimes C_\bullet)_z$ is such that for all x, y with $x + y = z$,

$$c \circ \text{in}_{x,y} = \text{in}_{y,x} \circ c_{C_x, D_y}$$

where $c_{C,D} : C \otimes D \rightarrow D \otimes C$ is the symmetry in \mathbf{C} .

One may consider commutative monoids with respect to this commutative monoid structure. For example, a commutative monoid in the symmetric monoidal category \mathbf{Set}^X consists of a set T_x for each $x \in X$ together with an element $1 \in T_0$ and maps $\mu : T_x \times T_y \rightarrow T_{x+y}$ satisfying evident conditions. This is to be distinguished from an X -graded commutative monoid, an object of \mathbf{ComMon}^X !

We can then describe the free commutative \otimes -monoid generated by an X -graded set T , denoted $\mathbb{N}_X T$, by the following sequence of observations.

(1) The free commutative \otimes -monoid $\mathbb{N}_X t$ with a single generator t in degree x has

$$(\mathbb{N}_X t)_y = \{k \in \mathbb{N} : kx = y\},$$

and the product of $k \in (\mathbb{N}_X t)_y$ with $k' \in (\mathbb{N}_X t)_{y'}$ is $k + k' \in (\mathbb{N}_X t)_{y+y'}$.

(2) An X -graded set T is *finite* if $\sum_x |T_x| < \infty$. The free commutative \otimes -monoid generated by a finite X -graded set T is the tensor product of $\mathbb{N}_X t$'s as t runs over T_x , $x \in X$.

(3) Any X -graded set is the direct limit of a filtered family of finite X -graded sets, and the free commutative \otimes -monoid functor commutes with filtered colimits.

Let K be a commutative ring. The category of X -graded K -modules \mathbf{Mod}_K^X admits a symmetric monoidal structure given by the “graded tensor product,” with

$$(A_\bullet \otimes_K B_\bullet)_z = \bigoplus_{x+y=z} A_x \otimes_K B_y$$

and unit given by the X -graded K -module with K in degree 0 and 0 in all other degrees. The symmetry sends $x \otimes y$ to $y \otimes x$. An X -graded K -algebra is a monoid for this tensor product. Once again, beware of this use of language; this is not an X -graded object in \mathbf{ComAlg}_K . Write $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$ for this category. A Beck module for the commutative X -graded K -algebra A_\bullet is an action of this monoid.

For $T \in \mathbf{Set}^X$ the free commutative X -graded K -algebra generated by $T \in \mathbf{Set}^X$ is given in degree x by the free K -module generated by $(\mathbb{N}_X T)_x$. This provides us with an adjoint pair

$$F_X : \mathbf{Set}^X \rightleftarrows \mathbf{ComAlg}(\mathbf{Mod}_K^X) : u_X.$$

The relationship with the Leech category (section 5 below) suggests that rather than defining a right A_\bullet -module as a right action, we should say this:

Definition 2.1. *A right A_\bullet -module is an X -graded K -module M^\bullet together with homomorphisms*

$$\varphi_{x,y} : M^{x+y} \otimes A_y \rightarrow M^x$$

such that $\varphi_{x,0}(m \otimes 1) = m$ and

$$\begin{array}{ccc} M^{x+y+z} \otimes A_z \otimes A_y & \xrightarrow{1 \otimes \mu_{z,y}} & M^{x+y+z} \otimes A_{z+y=y+z} \\ \downarrow \varphi_{x+y,z} \otimes 1 & & \downarrow \varphi_{x,y+z} \\ M^{x+y} \otimes A_y & \xrightarrow{\varphi_{x,y}} & M^x \end{array}$$

commutes.

Write $\mathbf{RMod}_{A_\bullet}$ for the category of right A_\bullet -modules. If X has inverses, so is in fact an abelian group, the category $\mathbf{RMod}_{A_\bullet}$ is equivalent to the category of a right A_\bullet -modules in the usual sense, using “lower indexing” $M_x = M^{-x}$.

Let N_\bullet be a left A_\bullet -module and M^\bullet a right A_\bullet module. Their *tensor product* over A_\bullet , $M^\bullet \otimes_{A_\bullet} N_\bullet$, is the K -module defined as the coequalizer of the two maps

$$f, g : P = \bigoplus_{x,y} M^{x+y} \otimes A_y \otimes N_x \rightrightarrows \bigoplus_z M^z \otimes N_z.$$

Each of these maps is defined by giving the composite with an inclusion $\text{in}_{x,y} : M^{x+y} \otimes A_y \otimes N_x \rightarrow P$:

$$\begin{aligned} f \circ \text{in}_{x,y} &= \text{in}_{x+y} \circ (1 \otimes \varphi_{y,x}), \\ g \circ \text{in}_{x,y} &= \text{in}_x \circ (\varphi_{x,y} \otimes 1). \end{aligned}$$

3. GRADED HOMOLOGICAL ALGEBRA

From now on we will write just A rather than A_\bullet and so on. Let A be an X -graded K -algebra. For each $x \in X$, there is a left A -module P^x together with $\iota \in P_x^x$ such that for any left A -module N the map

$$\text{Hom}_A(P^x, N) \rightarrow N_x, \quad f \mapsto f(\iota)$$

is an isomorphism. Explicitly,

$$(1) \quad P_y^x = \bigoplus_{x+z=y} A_z$$

and ι is the image of $1 \in A_0$ under $\text{in}_0 : A_0 \rightarrow P_x^x$. Given $n \in N_x$, the corresponding map $\widehat{n} : P^x \rightarrow N$ is defined by

$$\widehat{n} \circ \text{in}_z(a) = an, \quad a \in A_z.$$

Lemma 3.1. *The set $\{P^x : x \in X\}$ is a generating set of small projective A -modules.*

Proof. For each $x \in X$, the A -module P^x is projective since $N \mapsto N_x$ is an exact functor. An object is small if the functor it co-represents preserves filtered colimits. For P^x this is clear since colimits in \mathbf{LMod}_A are computed component-wise. For any A -module N , the map

$$\bigoplus_{x \in X} \bigoplus_{n \in N_x} P^x \rightarrow N,$$

given by \widehat{n} on the component indexed by (x, n) , is an epimorphism; this shows that $\{P^x : x \in X\}$ is a generating set. \square

It follows that any projective A -module is a retract of a direct sum of P^x 's.

The account of Quillen homology and cohomology given above goes through in the graded context without essential change. For an X -graded K -algebra A we have identified the category \mathbf{LMod}_A with the category of left actions of A . A left A module N corresponding to the abelian object in \mathbf{ComAlg}_K/A given by $\text{pr}_1 : A \oplus N \downarrow A$ with unit section $a \mapsto (a, 0)$ and product given by $(a, x)(b, y) = (ab, ay + xb)$. A section of this object of \mathbf{ComAlg}_K/A is a (degree-preserving) derivation, that is, an X -graded K -module map $d : A \rightarrow N$ such that $d(ab) = a db + b da$, as usual. The functor $N \mapsto \text{Der}_K(A, N)$ is co-represented by the (graded) A -module of Kähler differentials: $\Omega_{A/K} \in \mathbf{LMod}_A$. Expressed in terms of generators and relations, this A -module is the cokernel of the map

$$d : \bigoplus_{x, y} P^{x+y} \rightarrow \bigoplus_z P^z$$

determined by

$$d \circ \text{in}_{x, y} = \text{in}_x \circ y^* - \text{in}_{x+y} + \text{in}_y \circ x^*.$$

This is $\text{Ab}_A A$. To describe $\text{Ab}_A B$, for $p : B \rightarrow A$ in $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$, notice that for each $x \in X$ the right A -module P_x can be regarded as a right B -module through the map p . Then

$$(\text{Ab}_A B)_x = P_x \otimes_B \Omega_{B/K}.$$

The left A -module structure on $\text{Ab}_A B$ arises from the A -bimodule structure of P .

The (F_X, u) adjoint pair of Section 2 produces a cotriple on $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$ which we denote by Sym_K^X . Following [4], this in turn leads to a natural simplicial object $\text{Sym}_{K^\bullet}^X A$ augmented to A , with $\text{Sym}_{K^n}^X A = (\text{Sym}_K^X)^{n+1} A$, the simplicial cotriple resolution, which can be used to derive functors on

$\mathbf{ComAlg}(\mathbf{Mod}_K^X)/A$. The Quillen homology of $A \in \mathbf{ComAlg}(\mathbf{Mod}_K^X)$ is defined as the derived functors of $\mathrm{Ab}_A : \mathbf{ComAlg}(\mathbf{Mod}_K^X)/A \rightarrow \mathbf{LMod}_A$, evaluated at the object $\mathrm{id}_A : A \downarrow A$.

For each $n \geq 0$ the Quillen homology $HQ_n(A)$ is itself an A -module, and $HQ_0(A) = \Omega_{A/K}$. We can endow the Quillen homology with coefficients in a right A -module M :

$$HQ_n(A; M) = \pi_n(M \otimes_A \mathrm{Ab}_A \mathrm{Sym}_{K^\bullet}^X A).$$

For any $x \in X$, we can recover $HQ_n(A)_x$ by using the right A -module P_x for coefficients:

$$HQ_n(A)_x = HQ_n(A; P_x).$$

For $N \in \mathbf{LMod}_A$ we can define the André-Quillen cohomology as follows:

$$HQ^n(A; N) = H^n(\mathrm{Hom}_A(\mathrm{ch} \mathrm{Sym}_{K^\bullet}^X A, N)).$$

4. CHANGE OF GRADING MONOID

Let $\alpha : Y \rightarrow X$ be a map of commutative monoids. An X -graded object C in \mathbf{C} determines a Y -graded object α^*C by

$$(\alpha^*C)_y = C_{\alpha(y)}.$$

If \mathbf{C} has coproducts, the functor $\alpha^* : \mathbf{C}^X \rightarrow \mathbf{C}^Y$ has a left adjoint given by

$$(\alpha_*C)_x = \coprod_{\alpha(y)=x} C_y.$$

Let K be a commutative ring. The functor $\alpha_* : \mathbf{Mod}_K^Y \rightarrow \mathbf{Mod}_K^X$ is symmetric monoidal –

$$\alpha_*(M \otimes N) = \alpha_*M \otimes \alpha_*N$$

– so α_* sends Y -graded commutative K -algebras to X -graded commutative K -algebras. Then for any $A \in \mathbf{ComAlg}(\mathbf{Mod}_K^Y)$ the map α induces adjoint pairs

$$\alpha_* : \mathbf{LMod}_A \rightleftarrows \mathbf{LMod}_{\alpha_*A} : \alpha^*$$

and

$$\alpha_* : \mathbf{RMod}_A \rightleftarrows \mathbf{RMod}_{\alpha_*A} : \alpha^*$$

Let N be an α_*A -module. It is straightforward to construct a natural isomorphism

$$\mathrm{Der}_K(A, \alpha^*N) = \mathrm{Der}_K(\alpha_*A, N)$$

and thus a natural isomorphism of α_*A -modules

$$\Omega_{\alpha_*A/K} = \alpha_*\Omega_{A/K}.$$

The adjoint pairs (F_X, u_X) are compatible under change of grading monoid: A monoid homomorphism $\alpha : Y \rightarrow X$ determines the following squares.

$$\begin{array}{ccc}
 \mathbf{Set}^Y & \xleftarrow{u_X} & \mathbf{ComAlg}(\mathbf{Mod}_K^Y) & & \mathbf{Set}^Y & \xrightarrow{F_Y} & \mathbf{ComAlg}(\mathbf{Mod}_K^Y) \\
 \uparrow \alpha^* & & \uparrow \alpha^* & & \downarrow \alpha_* & & \downarrow \alpha_* \\
 \mathbf{Set}^X & \xleftarrow{u_X} & \mathbf{ComAlg}(\mathbf{Mod}_K^X) & & \mathbf{Set}^X & \xrightarrow{F_X} & \mathbf{ComAlg}(\mathbf{Mod}_K^X)
 \end{array}$$

The diagram of right adjoints clearly commutes, so the diagram of left adjoints does too:

$$\alpha_* F_Y(T) = F_X(\alpha_* T) \in \mathbf{ComAlg}(\mathbf{Mod}_K^X).$$

Passing to the cotriples,

$$\alpha_* \mathbf{Sym}_K^Y(A) = \alpha_* F_Y u_X(A) = F_X \alpha_* u_Y(A) = F_X u_X(\alpha_* A) = \mathbf{Sym}_K^X(\alpha_* A)$$

and thus to simplicial resolutions:

$$\alpha_* \mathbf{Sym}_{K_\bullet}^Y(A) = \mathbf{Sym}_{K_\bullet}^X(\alpha_* A).$$

Assembling all this, along with the fact that α_* is exact, we find:

Proposition 4.1. *Let $\alpha : Y \rightarrow X$ be a homomorphism of commutative monoids. There are isomorphisms of $\alpha_* A$ -modules natural in $A \in \mathbf{ComAlg}(\mathbf{Mod}_K^Y)$*

$$\alpha_* H Q_n(A) = H Q_n(\alpha_* A)$$

as well as isomorphisms of K -modules

$$H Q_n(A; \alpha^* M) = H Q_n(\alpha_* A; M)$$

natural in $M \in \mathbf{RMod}_{\alpha_* A}$ and

$$H Q^n(A; \alpha^* N) = H Q^n(\alpha_* A; N)$$

natural in $N \in \mathbf{LMod}_{\alpha_* A}$.

An important example is provided by taking X to be the one-element monoid, e , and $\alpha : Y \rightarrow e$ the unique map. Then $\alpha_* A$ is the “degrading” of A , an ungraded commutative K -algebra, and N is a module for it; $\alpha^* N$ is the “constant” Y -graded K -module with $(\alpha^* N)_y = N$ for all $y \in Y$, and A acting among them in the obvious way; and $H Q_*(\alpha_* A)$, $H Q_*(\alpha_* A; M)$, and $H Q^*(\alpha_* A; N)$ are the usual André-Quillen groups.

5. COMMUTATIVE MONOIDS

We now regard commutative monoids as the category of homological interest, rather than as a source of gradings.

Let $X \in \mathbf{ComMon}$. It is easy [29, 17] to identify the category of Beck modules over X in terms of the *Leech category*, L_X , with object set X and $L_X(x, z) = \{y \in X : x + y = z\}$ with unit and composition determined by the commutative monoid structure on X . Write $y_* : x \rightarrow (x + y)$ for a morphism in this category. The category of Beck modules over X is

canonically equivalent to the category of functors from L_X to the category \mathbf{Ab} of abelian groups.

A map $\alpha : Y \rightarrow X$ of commutative monoids induces a functor

$$\alpha^* : \mathbf{LMod}_X \rightarrow \mathbf{LMod}_Y$$

which, under the equivalence with functors from the Leech categories, may be regarded as induced by pre-composition with the induced functor $\alpha : L_Y \rightarrow L_X$. The left adjoint α_* is then induced by left Kan extension [30, Chapter X] along α .

A section of an abelian object over X is a “derivation,” and under the identification of abelian objects over X with functors on L_X a derivation with values in $N : L_X \rightarrow \mathbf{Ab}$ is an assignment of an element $s(x) \in N_x$ for each $x \in X$ such that

$$s(x + y) = x_*s(y) + y_*s(x)$$

There is a universal example, the Beck module of “Kähler differentials” Ω_X^{CM} , which provides a distinguished object of \mathbf{LMod}_X . For any $\alpha : Y \rightarrow X$,

$$\mathbf{Ab}_X Y = \alpha_* \Omega_Y^{CM}.$$

A commutative monoid X defines a canonical commutative X -graded K -algebra $\tilde{K}X$ in which $(\tilde{K}X)_x = K$ for each $x \in X$, with generator 1_x , $1 = 1_0 \in (\tilde{K}X)_0$, and

$$\mu_{x,y}(a_x \otimes b_y) = (ab)_{x+y} = ab1_{x+y}, \quad a, b \in K.$$

This object of \mathbf{ComAlg}_K^X co-represents the functor sending an object A to the set of sections a of the grading function $A \rightarrow X$ such that $a_x a_y = a_{x+y}$.

For a Beck K -module N over X we may define a left module over $\tilde{K}X$, which we will also denote by N . The K -module in degree x is N_x and the multiplication by $\tilde{K}X$ is given by the action of elements of X , regarded as morphisms in L_X . The following lemma is simply a change in perspective.

Lemma 5.1. *The category of covariant functors $L_X \rightarrow \mathbf{Mod}_K$ is canonically equivalent to the category of $\tilde{K}X$ -modules. The category of contravariant functors $L_X \rightarrow \mathbf{Mod}_K$ is canonically equivalent to the category of right $\tilde{K}X$ -modules.*

Of course, the usual monoid-algebra is obtained from $\tilde{K}X$ as

$$KX = \alpha_* \tilde{K}X, \quad \alpha : X \rightarrow e.$$

These isomorphisms are compatible with attendant structure: the functors induced by a map $\alpha : Y \rightarrow X$ of commutative monoids agree with the functors induced by $\tilde{Z}\alpha : \tilde{Z}Y \rightarrow \tilde{Z}X$. Under this identification the Kähler differential objects match up:

$$\Omega_Y^{CM} = \Omega_{\tilde{Z}Y}^{CA}$$

and more generally $\alpha_*\tilde{\mathbb{Z}}Y \in \mathbf{ComAlg}(\mathbf{Mod}_K^X)/\tilde{\mathbb{Z}}X$ and

$$\mathrm{Ab}_X(Y) = \mathrm{Ab}_{\tilde{\mathbb{Z}}X}(\alpha_*\tilde{\mathbb{Z}}Y)$$

in $\mathbf{LMod}_X = \mathbf{LMod}_{\tilde{\mathbb{Z}}X}$. As a further example, given a contravariant functor $M : L_X \rightarrow \mathbf{Mod}_K$ and a covariant functor $N : L_X \rightarrow \mathbf{Mod}_K$,

$$M \otimes_{\tilde{\mathbb{Z}}X} N = M \otimes_{L_X} N$$

where the right hand side is the usual tensor product over the category L_X , as considered by Kurdiani and Pirashvili in [28].

In order to express the functoriality of \tilde{K} , we need a category of graded algebras in which the grading commutative monoid can vary. So let \mathbf{ComAlg}_K^* be the category whose objects are pairs (X, A) where X is a commutative monoid and A is a commutative X -graded K -algebra. A morphism $(X, A) \rightarrow (Y, B)$ consists of a monoid homomorphism $\alpha : X \rightarrow Y$ together with a morphism $f : \alpha_*A \rightarrow B$ in $\mathbf{ComAlg}(\mathbf{Mod}_K^Y)$ (or equivalently a morphism $\hat{f} : A \rightarrow \alpha^*B$ in $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$). Given a second morphism $(\beta, g) : (Y, B) \rightarrow (Z, C)$, the composite is defined as $(\beta \circ \alpha, g \circ \beta_*f)$, (or equivalently as $(\beta \circ \alpha, \alpha^*\hat{g} \circ \hat{f})$). Then the construction \tilde{K} provides a functor

$$\tilde{K} : \mathbf{ComMon} \rightarrow \mathbf{ComAlg}_K^* .$$

Here is the main theorem of the paper.

Theorem 5.2. *There are isomorphisms, natural in the commutative monoid X ,*

$$HQ_n^{CM}(X) = HQ_n^{CA}(\tilde{\mathbb{Z}}X) ,$$

where we have identified Beck modules over X with modules over $\tilde{\mathbb{Z}}X$. For any right Beck module M over X ,

$$HQ_n^{CM}(X; M) = HQ_n^{CA}(\tilde{\mathbb{Z}}X; M)$$

and for any left Beck module N

$$HQ_{CM}^n(X; N) = HQ_{CA}^n(\tilde{\mathbb{Z}}X; N) .$$

Proof. Let $\alpha : Y_\bullet \rightarrow X$ be a cofibrant replacement of $X \in \mathbf{ComMon}$ regarded as a constant simplicial object. We could take the cotriple resolution $\mathbb{N}_\bullet X$ for example, and for definiteness we will do so. We claim that the induced map $\alpha_*\tilde{K}\mathbb{N}_\bullet X \rightarrow \tilde{K}X$ is a cofibrant replacement for $\tilde{K}X$ in $s\mathbf{ComAlg}(\mathbf{Mod}_K^X)$.

The augmentation $\alpha : \mathbb{N}_\bullet X \rightarrow X$ is a weak equivalence in $s\mathbf{ComMon}$, which is to say a weak equivalence of simplicial sets. The entire simplicial set $\mathbb{N}_\bullet X$ splits into a disjoint union of the pre-images under α of the elements of X , and each of these components is a weakly contractible simplicial set.

Now apply the functor \tilde{K} to $\mathbb{N}_\bullet X$, to get a simplicial object in \mathbf{ComAlg}_K^* with an augmentation $\tilde{K}\mathbb{N}_\bullet X \rightarrow \tilde{K}X$; that is, a map

$$\alpha_*\tilde{K}\mathbb{N}_\bullet X \rightarrow \tilde{K}X$$

in $s\mathbf{ComAlg}(\mathbf{Mod}_K^X)$. The object $\alpha_*\tilde{K}\mathbb{N}_\bullet X$ of $s\mathbf{Mod}_K^X$ splits as a direct sum of the free K -module functor applied to the components of $\mathbb{N}_\bullet X$ above the elements of X . But a weak equivalence $Z_\bullet \rightarrow Y_\bullet$ of simplicial sets induces a weak equivalence $KZ_\bullet \rightarrow KY_\bullet$ [16, III, Prop. 2.16], so the map $\alpha_*\tilde{K}\mathbb{N}_\bullet X \rightarrow \tilde{K}X$ is a weak equivalence.

The second observation is that $\alpha_*\tilde{K}\mathbb{N}_\bullet X$ is cofibrant in the model category of simplicial objects in $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$. Indeed, it is almost free in the sense of [31], and hence, as observed there, is cofibrant. A simplicial object $Z_\bullet \in s\mathbf{ComMon}$ is “almost free” if there are subsets $G_s \subseteq Z_s$, for each s , that are respected by all face and degeneracy maps except for d_0 , and such that Z_s is freely generated by G_s . A cotriple resolution, such as $\mathbb{N}_\bullet X$, is easily seen to be almost free. If we then apply the functor $\alpha_*\tilde{K}$ to it, the same generating sets again generate as objects in $\mathbf{ComAlg}(\mathbf{Mod}_K^X)$; it is an almost free object in $s\mathbf{ComAlg}(\mathbf{Mod}_K^X)$.

The map $\alpha_*\tilde{K}\mathbb{N}_\bullet X \rightarrow \tilde{K}X$ thus joins $\mathrm{Sym}_{K_\bullet}^X(\tilde{K}X) \rightarrow \tilde{K}X$ as a cofibrant replacement, and so (e.g. [13, Proposition 3.9]) can be used to compute Quillen homology. Thus (finally taking $K = \mathbb{Z}$)

$$\mathrm{Ab}_X \mathbb{N}_\bullet X = \mathrm{Ab}_{\tilde{\mathbb{Z}}X}(\alpha_*\tilde{\mathbb{Z}}\mathbb{N}_\bullet X) \simeq \mathrm{Ab}_{\tilde{\mathbb{Z}}X}(\mathrm{Sym}_{\tilde{\mathbb{Z}}_\bullet}^X(\tilde{\mathbb{Z}}X))$$

as simplicial objects in $\mathbf{LMod}_X = \mathbf{LMod}_{\tilde{\mathbb{Z}}X}$. Applying the functors $\pi_*(-) = H_*(\mathrm{ch}(-))$, $\pi_*(M \otimes_{\tilde{\mathbb{Z}}X} -) = H_*(M \otimes_{\tilde{\mathbb{Z}}X} \mathrm{ch}(-))$, and $H^*(\mathrm{Hom}_{\tilde{\mathbb{Z}}X}(\mathrm{ch}(-), N))$ gives us the results. \square

Corollary 5.3 ([28]). *Let X be a commutative monoid and let $\alpha : X \rightarrow e$ be the unique monoid map to the trivial monoid. There are isomorphisms*

$$\alpha_* H_n^{CM}(X; \alpha^* M) = H_n^{CA}(\mathbb{Z}X; M)$$

natural in the right X -module M , and

$$\alpha_* H_{CM}^n(X; \alpha^* N) = H_{CA}^n(\mathbb{Z}X; N)$$

natural in the left X -module N .

6. THE HOCHSCHILD COMPLEX

This section reviews well known material (e.g. [37, 40]) in the graded setting.

Let A be an associative X -graded K -algebra. There is a canonical simplicial A -bimodule (so each level is an X -graded K -module with grade-preserving left and right actions of A) $B_\bullet(A)$ over K with

$$B_n(A) = A^{\otimes(n+2)}$$

for $n \geq 0$, augmented to A , and

$$d_i = 1^{\otimes i} \otimes \mu \otimes 1^{\otimes(n-i)} : A^{\otimes(n+2)} \rightarrow A^{\otimes(n+1)}, \quad 0 \leq i \leq n$$

$$s_i = 1^{\otimes(i+1)} \otimes \eta \otimes 1^{\otimes(n-i)} : A^{\otimes(n+1)} \rightarrow A^{\otimes(n+2)}, \quad 0 \leq i \leq n-1$$

where $\mu : A \otimes A \rightarrow A$ is the multiplication and $\eta : K \rightarrow A$ includes the unit.

There are also maps

$$s_{-1} = \eta \otimes 1^{\otimes(n+1)}, \quad s_n = 1^{\otimes(n+1)} \otimes \eta : A^{\otimes(n+1)} \rightarrow A^{\otimes(n+2)}.$$

The first is a right A -module map and the second is a left A -module map, and they provide contracting homotopies of the simplicial object regarded as either a simplicial right A -module or a simplicial left A -module. In fact it is just the simplicial bar resolution of A as a left or right A -module. Thus the chain complex associated to $B_\bullet(A)$, $\text{ch } B_\bullet(A)$, is a relative projective resolution of A as an A -bimodule, the *Hochschild resolution*. If A is projective as a K -module, it is an absolute projective resolution.

Let Q_A be the functor from A -bimodules to X -graded K -modules with

$$Q_A(M)_z = M/K\{am - ma : a \in A_x, m \in M_w, w + x = z\}.$$

More generally, given an A -bimodule N , define the functor Q_N^A , or Q_N if A is understood, from A -bimodules to X -graded K -modules

$$Q_N(M)_z = (M \otimes N)_z / R$$

where R is the sub- K -module generated by

$$\{am \otimes n - m \otimes na, ma \otimes n - m \otimes an : m \in M_w, a \in A_x, n \in N_y, w + x + y = z\}.$$

We recover Q_A by regarding A as a bimodule over itself using left and right multiplication. A bimodule is the same thing as a module over $A^e = A \otimes A^{op}$, and under this equivalence

$$Q_N(M) = M \otimes_{A^e} N.$$

In general, this is just an X -graded K -module, but if A is commutative then $Q_A(M)$ is naturally an A -module, since A is then an (A, A^e) -bimodule.

Apply this functor to $B_\bullet(A)$ to obtain a simplicial object in \mathbf{Mod}_K^X , $Q_N B_\bullet(A)$, equipped with an augmentation to $Q_N A$. This is the *Hochschild complex* with coefficients in N ,

$$C_\bullet(A/K; N) = \text{ch } Q_N B_\bullet(A)$$

and by definition

$$\text{Hoch}_n(A/K; N) = H_n(C_\bullet(A/K; N)).$$

When the ground ring K is understood we may drop it from the notation. When $N = A$ with its natural A -bimodule structure, we may drop it from the notation as well:

$$C_\bullet(A) = C_\bullet(A/K; A) \quad \text{and} \quad \text{Hoch}_\bullet(A) = \text{Hoch}_\bullet(A/K; A).$$

To understand this better, notice the isomorphism

$$Q_N(A \otimes V \otimes A) \rightarrow V \otimes N$$

for $V \in \mathbf{Mod}_K^X$, given by factoring

$$a \otimes v \otimes b \otimes n \mapsto v \otimes bna$$

through $Q_N(A \otimes V \otimes A)$. The inverse sends $v \otimes n$ to $[1 \otimes v \otimes 1 \otimes n]$.

This isomorphism breaks symmetry. But using it we may write the augmented simplicial K -module $Q_N B_\bullet(A)$ as

$$Q_N(A) \leftarrow N \leftarrow A \otimes_K N \leftarrow \cdots,$$

so

$$C_n(A; N) = A^{\otimes n} \otimes_K N.$$

If A and Z are two X -graded K -algebras and M and N bimodules for them, there is a natural isomorphism

$$Q_A(M) \otimes Q_Z(N) \rightarrow Q_{A \otimes Z}(M \otimes N)$$

under the identity map on $M \otimes N$. The fact that it is an isomorphism follows from the identity

$$(a \otimes z)(m \otimes n) - (m \otimes n)(a \otimes z) = am \otimes (zn - nz) + (am - ma) \otimes nz$$

We get natural isomorphisms of simplicial objects

$$\begin{aligned} B_\bullet(A) \otimes B_\bullet(Z) &\rightarrow B_\bullet(A \otimes Z) \\ Q_A B_\bullet(A) \otimes Q_Z B_\bullet(Z) &\rightarrow Q_{A \otimes Z} B_\bullet(A \otimes Z) \end{aligned}$$

If A is commutative, we may take $A = Z$ and compose with the K -algebra map $\mu : A \otimes A \rightarrow A$ to obtain a simplicial commutative A -algebra structure on $Q_A B_\bullet(A)$, and $Q_N B_\bullet(A)$ becomes a module over $Q_A B_\bullet(A)$.

Passing to associated chain complexes, the Eilenberg-Zilber or shuffle map ([11, p. 64] or [32, p. 39]) results in the structure of a commutative (in the signed sense) differential graded A -algebra on $C_\bullet(A)$ and hence a graded commutative A -algebra structure on its homology $Hoch_\bullet(A)$.

Dually, the Hochschild cochain complex with coefficients in and A -bimodule N is $\text{Hom}_{A \otimes A^{op}}(B_\bullet(A), N)$, and its homology is the Hochschild cohomology $Hoch^\bullet(A; N)$.

It is well known and easy to verify that

$$Hoch_1(A) = \Omega_{A/K} = HQ_0^{CA}(A)$$

and

$$Hoch^1(A; M) = \text{Der}_K(A; M) = HQ_{CA}^0(A; M).$$

7. HARRISON HOMOLOGY AND COHOMOLOGY

Now suppose that A is a commutative K -algebra. Then $Q_A A = A$; the Hochschild complex $C_\bullet(A)$ is augmented to A . Let $I_\bullet(A)$ denote the kernel of this augmentation; this is the ideal of positive-dimensional elements in the commutative differential graded A -algebra $C_\bullet(A)$. The *Harrison complex* [25] is the differential graded module of indecomposables in $C_\bullet(A)$, $I_\bullet(A)/I_\bullet(A)^2$. The *Harrison homology* of A is the homology of this chain complex of A -modules:

$$Harr_n(A) = H_n(I_\bullet(A)/I_\bullet(A)^2).$$

We can equip it with coefficients in an A -module M :

$$Harr_n(A; M) = H_n((I_\bullet(A)/I_\bullet(A)^2) \otimes_A M).$$

The Harrison cohomology with coefficients in an A -module M is

$$Harr^n(A; M) = H^n(\text{Hom}_A(I_\bullet(A)/I_\bullet(A)^2, M)).$$

Clearly

$$Harr_0(A) = 0 \quad \text{and} \quad Harr_1(A) = Hoch_1(A)$$

The shuffle product defines a sign-commutative graded K -algebra structure on the \mathbb{N} -graded K -module $\overline{C}_\bullet(A)$ with

$$\overline{C}_n(A) = A^{\otimes n}.$$

As graded A -algebras

$$C_\bullet(A) = A \otimes \overline{C}_\bullet(A).$$

Only the differential depends on the algebra structure, and it is not the A -linear extension of a differential on $\overline{C}_\bullet(A)$.

The K -module of Harrison cochains can be re-expressed in terms of the graded K -algebra $\overline{C}_\bullet(A)$. Let $\overline{I}_\bullet(A)$ be its augmentation ideal; then

$$I_\bullet = A \otimes \overline{I}_\bullet, \quad I_\bullet^2 = A \otimes \overline{I}_\bullet^2,$$

and so

$$I_\bullet(A)/I_\bullet(A)^2 = A \otimes (\overline{I}_\bullet(A)/\overline{I}_\bullet(A)^2).$$

A Harrison n -cochain (for $n > 0$) with coefficients in M is thus a K -linear map

$$s : A^{\otimes n} \rightarrow M$$

that annihilates decomposables. This may be phrased as a symmetry condition on the cochain: given i, j , both positive and summing to n , let $\Sigma(i, j)$ be the set (i, j) -shuffles; that is, the set of elements of Σ_n that preserve the order of $\{1, \dots, i\}$ and of $\{i+1, \dots, n\}$. The symmetry condition (i, j) on a Hochschild cochain $s : A^{\otimes n} \rightarrow M$ is

$$\sum_{\sigma \in \Sigma(i, j)} \text{sgn}(\sigma) s \circ \sigma = 0.$$

Since the shuffle product is commutative, we may assume that $i \leq j$; there are $\lfloor n/2 \rfloor$ independent conditions.

An alternative symmetry condition (apparently the one originally conceived of by Harrison; the shuffle description is said to be due to Mac Lane) is described in [14]. Think of an element of Σ_n as an ordering of $\{1, 2, \dots, n\}$. Let $1 \leq k \leq n$. An element $\sigma \in \Sigma_n$ is a k -monotone permutation if the lead element is k , the numbers $1, 2, \dots, k$ occur in decreasing order, and the numbers $k+1, \dots, n$ occur in increasing order. There are $\binom{n-1}{k-1}$ of them. For example there is only one n -monotone permutation in Σ_n , corresponding to the sequence $n, n-1, \dots, 2, 1$, and the 4-monotone permutations in Σ_6 are 432156, 432516, 432561, 435216, 435261, 435621, 453216, 453261, 453621, 456321

Let $M_k(n)$ be the set of k -monotone permutations in Σ_n . Let $dr(\sigma)$ be the sum of the positions occupied by $1, 2, \dots, k-1$ in the permutation $\sigma \in M_k(n)$.

Lemma 7.1 ([14], Theorem 4.1). *A map $s : A^{\otimes n} \rightarrow M$ is a Harrison cochain if and only if*

$$s = \sum_{\sigma \in M_k(n)} (-1)^{dr(\sigma)} s \circ \sigma, \quad 2 \leq k \leq n.$$

So for example a Hochschild 4-cochain s is a Harrison cochain if and only if

$$\begin{aligned} s(a_1, a_2, a_3, a_4) &= s(a_2, a_1, a_3, a_4) - s(a_2, a_3, a_1, a_4) + s(a_2, a_3, a_4, a_1) \\ &= -s(a_3, a_2, a_1, a_4) + s(a_3, a_2, a_4, a_1) - s(a_3, a_4, a_2, a_1) \\ &= -s(a_4, a_3, a_2, a_1) \end{aligned}$$

The 4-monotone and 2-monotone symmetries combine to give

$$s(a_4, a_3, a_2, a_1) = -s(a_2, a_1, a_3, a_4) + s(a_2, a_3, a_1, a_4) - s(a_2, a_3, a_4, a_1)$$

which is the same as the 3-monotone condition (after rearranging the labels); so we can dispense with either one of the first two conditions in this list. The same argument shows that one need only assume the n -monotone condition together with one condition from each pair $\{2, n-1\}, \{3, n-2\}, \dots$: so $\lfloor n/2 \rfloor$ conditions suffice. This matches with the number of independent shuffle conditions.

8. DIVIDED POWERS AND BARR HOMOLOGY

Michael Barr suggested possible variations on Harrison's symmetry conditions, in an attempt to come closer to Quillen homology. As explained by Sarah Whitehouse [39], these variations still fail, though they may give better approximations.

Gerstenhaber and Schack [14, Remark, p. 232] (see also [39]) suggest that one of Barr's ideas was to divide the Hochschild complex not just by shuffle decomposables but by the divided power structure as well. While a divided power structure on the even homotopy groups of a simplicial commutative algebra was implicit in the works of Eilenberg and Mac Lane [11] and Henri Cartan [9, Exp. 8], its construction on the level of the Hochschild complex was at best a folk result at the time of Barr's question, and even when Gerstenhaber and Schack were writing. It seems to have first been set out, in the associated chain complex of a simplicial commutative algebra B_\bullet , by Siegfried Brüderle and Ernst Kunz [8] in 1994; see also [36] and [15]. The result is a natural family of maps

$$\gamma_k : B_{2n} \rightarrow B_{2kn}$$

such that $k! \gamma_k x = x^k$.

From these sources one obtains the following formula for the divided power structure on $\overline{C}_{even}(A)$, where A is a commutative K -algebra. Let $S_k(kn)$ be

the set of shuffles associated to the partition of $\{1, 2, \dots, kn\}$ into k intervals of length n . Let $S'_k(kn)$ be the subset of these such that the leading terms of the k sequences occur in order. Then, for n even,

$$\gamma_k[a_1 | \cdots | a_n] = \sum_{\sigma \in S'_k(kn)} \text{sgn}(\sigma) [a_1 | \cdots | a_n | a_1 | \cdots | a_n | \cdots | a_1 | \cdots | a_n] \circ \sigma$$

where the sequence $a_1 | \cdots | a_n$ is repeated k times. For example

$$\begin{aligned} \gamma_2[a|b] &= [a|b|a|b], \quad \gamma_3[a|b] = [a|b|a|b|a|b], \\ \gamma_2[a|b|c|d] &= [a|b|c|d|a|b|c|d] - [a|b|c|a|d|b|c|d] + [a|b|c|a|b|d|c|d] \\ &\quad + [a|b|a|c|d|b|c|d] - [a|b|a|c|b|d|c|d] + 2[a|b|a|b|c|d|c|d]. \end{aligned}$$

We can put at least one restriction on the tensors occurring in the expression for the divided powers. To express it, notice that there is a universal Hochschild n -chain, $[a_1 | \cdots | a_n] \in K[a_1, \dots, a_n]^{\otimes n}$.

Lemma 8.1. *No decomposable tensor with entries chosen from $\{a_1, \dots, a_n\}$ occurring with nonzero coefficient in $\gamma_k[a_1 | \cdots | a_n]$ has consecutive occurrences of any a_i .*

Proof. We show how such terms cancel in pairs in the expression for the divided power, by defining a free involution on the set of terms with neighboring repeated letters such that the elements of each orbit occur with opposite signs. The involution will leave unchanged all the letters up to and including the left-most neighboring repeated pair.

If the repeated pair is $a_1|a_1$, swap the positions of the remaining letters in the two blocks initiated by these letters. We get an identical word, but since n is even this is an odd number of transpositions, so the terms cancel.

If the repeated pair is $a_i|a_i$ for $i > 1$, just swap those two entries. This is allowed since the leading term of both blocks precedes both entries in the repeated pair. \square

Since every term in the expression for $\gamma_k[a_1 | \cdots | a_n]$ has leading entry a_1 , we obtain:

Corollary 8.2. $\gamma_k[a|b] = [a|b|a|b] \cdots [a|b]$.

In general the expression for γ_k seems very complicated. For example, a computer calculation shows that $\gamma_3[a|b|c|d]$ has 53 terms, with coefficients ranging from -4 to 6 .

Write $Barr_*(A)$ for the homology of the chain complex of A -modules obtained from $C_\bullet(A)$ quotienting out by decomposables and the image of divided powers. Since $k! \gamma_k(\omega)$ is decomposable, we have an exact sequence $0 \rightarrow Harr_{2k+1}(A) \rightarrow Barr_{2k+1}(A) \rightarrow T_{2k} \rightarrow Harr_{2k}(A) \rightarrow Barr_{2k}(A) \rightarrow 0$ where $k!T_{2k} = 0$. Thus

$$\begin{aligned} Harr_{2k+1}(A) \rightarrow Barr_{2k+1}(A) &\text{ is injective with cokernel killed by } k!, \\ Harr_{2k}(A) \rightarrow Barr_{2k}(A) &\text{ is surjective with kernel killed by } k!. \end{aligned}$$

We can also form the ‘‘Barr cohomology’’ with coefficients in an A -module. Its cochains are the Hochschild cochains s satisfying the Harrison symmetry conditions with the additional conditions

$$s(\gamma_k(\omega)) = 0, \quad k > 0,$$

for $|\omega|$ even; for example $s(a, b, a, b) = 0$ in dimension 4; $s(a, b, a, b, a, b) = 0$ in dimension 6; and in dimension 8 there are two additional symmetries,

$$s(a, b, a, b, a, b, a, b) = 0$$

guaranteeing annihilation of $\gamma_4[a|b]$, and

$$\begin{aligned} & s(a, b, c, d, a, b, c, d) - s(a, b, c, a, d, b, c, d) + s(a, b, c, a, b, d, c, d) \\ & + s(a, b, a, c, d, b, c, d) - s(a, b, a, c, b, d, c, d) + 2s(a, b, a, b, c, d, c, d) = 0 \end{aligned}$$

to annihilate $\gamma_2[a|b|c|d]$.

Remark 8.3. It is natural to hope that the natural map of A -modules $Hoch_n(A) \rightarrow HQ_{n-1}(A)$ factors as

$$Hoch_n(A) \rightarrow Harr_n(A) \rightarrow Barr_n(A) \rightarrow HQ_{n-1}(A),$$

but this seems unlikely to us except in low dimensions.

9. GRILLET’S WORK

In a series of papers, Pierre Grillet associated to a commutative monoid X and a Beck module M over it the beginning of a cochain complex and proves or conjectures that it computes the low-dimensional components of the Quillen cohomology $HQ_{CM}^*(X; M)$. We observe that the symmetry conditions he imposed are precisely the monotone conditions, with two variations corresponding to Barr’s variation on the Harrison complex. We will not attempt a complete survey of Grillet’s work on this subject, but merely note the occurrence of symmetry conditions that we now see as Harrison or Barr symmetry conditions on Hochschild cochains, and where in Grillet’s work they are proved to yield cohomology groups isomorphic to Quillen’s.

To begin with, for any X graded K -algebra and A -module M ,

$$Harr^1(A; M) = Hoch^1(A; M) = HQ_{CA}^0(A; M) = Der_K(A, M)$$

so

$$Harr^1(\tilde{\mathbb{Z}}X; M) = HQ_{CM}^0(X; M).$$

In 1974 [17] Grillet used 2-cocycles s with the symmetry

$$s(a, b) = s(b, a)$$

to classify extensions of commutative monoids. This is of course the 2-monotone symmetry. Twenty years later, in [18], he returned to this by invoking Quillen cohomology as an intermediary, thus showing that

$$Harr^2(\tilde{\mathbb{Z}}X; M) = HQ_{CM}^1(X; M).$$

(Grillet chooses to index Quillen homology following the Hochschild convention, so he would write $HQ_{CM}^2(X; M)$.)

This study was supplemented by [19], which confirmed this result by direct computation and extended it to dimension 3 using the symmetry conditions

$$\begin{aligned} s(a, b, c) + s(c, b, a) &= 0 \\ s(a, b, c) + s(b, c, a) + s(c, a, b) &= 0. \end{aligned}$$

Taken together, these are equivalent to the k -monotone symmetries for $k = 2$ and 3. With a remarkable calculation Grillet then verified that

$$\text{Harr}^3(\tilde{\mathbb{Z}}X; M) = \text{HQ}_{CM}^2(X; M)$$

This work was consolidated and summarized in his book [20].

After another twenty years, Grillet returned again to this project, in [21], extending his calculation to dimension 4 using cochains satisfying the symmetry conditions simplified in [22] to

$$\begin{aligned} s(a, b, c, d) - s(b, a, c, d) + s(b, c, a, d) - s(b, d, d, a) &= 0, \\ s(a, b, c, d) + s(d, c, b, a) &= 0, \\ s(a, b, b, a) &= 0. \end{aligned}$$

The reader will recognize the first two as the 2-monotone and 4-monotone symmetries. The first equation implies $s(a, b, a, b) = s(b, a, a, b)$, so the third condition is equivalent to the Barr variant $s(a, b, a, b) = 0$. Here again, Grillet obtained the surprising result

$$\text{Barr}^4(\tilde{\mathbb{Z}}X; M) = \text{HQ}_{CM}^3(X; M).$$

This work was quickly followed by [23], in which Grillet proposed symmetric conditions on Hochschild cocycles extending into dimensions 5 and 6. In dimension 5, he proposed

$$\begin{aligned} s(a, b, c, d, e) - s(b, a, c, d, e) + s(b, c, a, d, e) - s(b, c, d, a, e) + s(b, c, d, e, a) &= 0 \\ s(a, b, c, d, e) + s(e, d, c, b, a) &= 0. \end{aligned}$$

We recognize these as the 2-monotone and 5-monotone conditions, which suffice to determine Harrison cohomology. In dimension 6, his proposed symmetries are precisely the k -monotone conditions for $k = 2, 3$, and 6, augmented by the Barr variant $s(a, b, a, b, a, b) = 0$.

In these higher dimensions the identifications with Quillen cohomology are left as conjectures. We can now see that at least the 5-dimensional case was too optimistic. Write α for the unique map of commutative monoids $\mathbb{N} \rightarrow e$. Then

$$\text{Barr}^\bullet(\tilde{\mathbb{Z}}\mathbb{N}; \alpha^*\mathbb{F}_p) = \text{Barr}^\bullet(\mathbb{Z}[x]; \mathbb{F}_p).$$

Let $c : \mathbb{F}_2[x]^{\otimes 5} \rightarrow \mathbb{F}_2$ be the non-bounding Barr cocycle described by Whitehouse [39]. Its composite with $\mathbb{Z}[x]^{\otimes 5} \rightarrow \mathbb{F}_2[x]^{\otimes 5}$ is again a cocycle and satisfies the same invariance properties, and if this composite were a coboundary then c would be too. So $\text{Barr}^5(\mathbb{Z}[x]; \mathbb{F}_2)$, which is the cohomology in degree 5 of Grillet's complex for the free commutative monoid \mathbb{N} with coefficients in $\alpha^*\mathbb{F}_2$, is nontrivial.

REFERENCES

- [1] M. André, *Méthode simpliciale en algèbre homologique et algèbre commutative*, Springer Lecture Notes in Mathematics 32 (1967).
- [2] M. Barr, Harrison homology, Hochschild homology, and triples, *Journal of Algebra* 8 (1968) 324–323.
- [3] M. Barr, *Acyclic models*, Centre de Recherches Mathématiques Monograph Series 17, 2002.
- [4] M. Barr and J. Beck, Homology and standard constructions, *1969 Seminar on Triples and Categorical Homology Theory*, Springer Lecture Notes in Mathematics 80 (1969) 245–335.
- [5] J. Beck, *Triples, algebras, and cohomology*, Reprints in Theory and Applications of Categories, No. 2, 2003.
- [6] F. Borceaux, *Handbook of Categorical Algebra 2: Categories and Structures*, Encyclopedia of Mathematics and its Applications 51, 2008.
- [7] N. Bourbaki, *Elements of Mathematics: Algebra I, Chapters 1–3*, Hermann, 1971.
- [8] S. Brüderle and E. Kunz, Divided powers and Hochschild homology of complete intersections, *Mathematische Annalen* 299 (1994) 57–76.
- [9] H. Cartan et al., *Algèbres d’Eilenberg Mac Lane et Homotopie*, Séminaire Henri Cartan 1954/1955.
- [10] M. Calvo-Cervera, A. M. Cegarra, and B. A. Heredia, On the third cohomology group of commutative monoids, *Semigroup Forum* 92 (2016) 511–533.
- [11] S. Eilenberg and S. Mac Lane, On the groups $H(\Pi, n)$, I, *Annals of Mathematics* 58:1 (1953) 55–106.
- [12] S. Eilenberg and J. C. Moore, Adjoint functors and triples, *Illinois Journal of Mathematics* 9 (1965) 381–398.
- [13] M. Frankland, Behavior of Quillen (co)homology with respect to adjunctions, *Homology, Homotopy and Applications* 17:1 (2015) 67–109.
- [14] M. Gerstenhaber and S. D. Schack, A Hodge-type decomposition for commutative algebra cohomology, *Journal of Pure and Applied Algebra* 48 (1987) 229–247.
- [15] W. D. Gillam, *Simplicial Methods in Algebra and Algebraic Geometry*, preprint.
- [16] P. G. Goerss and J. F. Jardine, *Simplicial Homotopy Theory*, Progress in Mathematics 174, Birkhäuser, 1999.
- [17] P. A. Grillet, Left coset extensions, *Semigroup Forum* 7 (1974) 200–263.
- [18] P. A. Grillet, Commutative semigroup cohomology, *Communications in Algebra* 23:10 (1995) 3573–3587.
- [19] P. A. Grillet, Cocycles in commutative semigroup cohomology, *Communications in Algebra* 25:11 (1997) 3427–3462.
- [20] P. A. Grillet, *Commutative Semigroups*, Springer, 2001.
- [21] P. A. Grillet, Four-cocycles in commutative semigroup cohomology, *Semigroup Forum* 100:1 (2020) 180–282.
- [22] P. A. Grillet, Commutative monoid homology, *Semigroup Forum* 103:2 (2021) 495–549.
- [23] P. A. Grillet, The inheritance of symmetry conditions in commutative semigroup cohomology, *Semigroup Forum* 104 (2022) 72–87.
- [24] P. A. Grillet, *The Cohomology of Commutative Semigroups: An overview*, Springer Lecture Notes in Mathematics 2307, 2022.
- [25] D. K. Harrison, Commutative algebras and cohomology, *Transactions of the American Mathematical Society* 104 (1962) 191–204.
- [26] P. S. Hirschhorn, *Model categories and their localizations*, *Mathematical Surveys and Monographs* 99 (2003).
- [27] M. Hovey, *Model Categories*, *Mathematical Surveys and Monographs* 63, American Mathematical Society, 1999.

- [28] R. Kurdiani and T. Pirashvili, Functor homology and homology of commutative monoids, *Semigroup Forum* 92:1 (2016) 102–120.
- [29] J. Leech, \mathcal{H} -coextensions of monoids, *Memoirs of the American Mathematical Association* 157 (1975) 1–66.
- [30] S. Mac Lane, *Categories for the Working Mathematician*, Springer Graduate Texts in Mathematics, 1971.
- [31] H. Miller, Correction to “The Sullivan conjecture on maps from classifying spaces,” *Annals of Mathematics* 121:3 (1985) 605–609.
- [32] H. Miller, *Lectures on Algebraic Topology*, World Scientific, 2021.
- [33] T. Pirashvili, André-Quillen homology via functor homology, *Proceedings of the American Mathematical Society* 131:6 (2002) 1687–1694.
- [34] D. G. Quillen, *Homotopical Algebra*, Springer Lecture Notes in Mathematics 43, 1967.
- [35] D. G. Quillen, On the (co-)homology of commutative rings, *Proceedings of Symposia on Pure Mathematics XVII* (1970) 65–87, American Mathematical Society.
- [36] B. Richter, Divided power structures and chain complexes, *Alpine perspectives on algebraic topology*, *Contemporary Mathematics* 504 (2009) 237–254.
- [37] C. A. Weibel, *An Introduction to Homological Algebra*, Cambridge Studies in Advanced Mathematics 38, Cambridge University Press, 1994.
- [38] C. Wells, Extension theories for monoids, *Semigroup Forum* 16 (1978) 13–35.
- [39] S. A. Whitehouse, A counterexample to a conjecture of Barr, *Theory and Applications of Categories* 3 (1996) 36–39.
- [40] S. J. Witherspoon, *Hochschild Cohomology for Algebras*, Graduate Studies in Mathematics 204, American Mathematical Society, 2019.

DEPARTMENT OF MATHEMATICS, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MA 02139

E-mail address: bhavya@mit.edu

DEPARTMENT OF MATHEMATICS, BIRZEIT UNIVERSITY, RAMALLAH, PALESTINE

E-mail address: nkhlai@birzeit.edu

DEPARTMENT OF MATHEMATICS, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MA 02139

E-mail address: hrm@math.mit.edu