

*Pacific
Journal of
Mathematics*

**CALABI-YAU PROPERTY UNDER MONOIDAL
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Let H and L be two Hopf algebras such that their comodule categories are monoidally equivalent. We prove that if H is a twisted Calabi–Yau (CY) Hopf algebra, then L is a twisted CY algebra when it is homologically smooth. In particular, if H is a Noetherian twisted CY Hopf algebra and L has finite global dimension, then L is a twisted CY algebra.

Introduction

In noncommutative projective algebraic geometry, what is now called an Artin–Schelter (AS) regular algebra $A = \bigoplus_{i \geq 0} A_i$ of dimension n was introduced in [Artin and Schelter 1987] as a homological analogue of a polynomial algebra with n variables. The connected graded noncommutative algebra A is considered as the homogeneous coordinate ring of some noncommutative projective space \mathbb{P}^n .

In lecture notes, Manin [1988] constructed the quantum general linear group $\mathcal{O}_A(\mathrm{GL})$ that universally coacts on an AS regular algebra A . Similarly, we can define the quantum special linear group of A , denoted by $\mathcal{O}_A(\mathrm{SL})$, by requiring the homological codeterminant of the Hopf coaction to be trivial; see [Walton and Wang 2016, Section 2.1] for details. As pointed out in that work, it is conjectured that these universal quantum groups should possess the same homological properties of A , among which the Calabi–Yau (CY) property is the most interesting, since A is always twisted CY according to [Reyes et al. 2014, Lemma 2.1] (see Section 1.2 for the definition of a twisted CY algebra). Moreover, many classical quantized coordinate rings can be realized as universal quantum groups associated to AS regular algebras via the above construction [Chirvasitu et al. 2016; Walton and Wang 2016], whose CY property and rigid dualizing complexes have been discussed in [Brown and Zhang 2008; Goodearl and Zhang 2007].

Now let us look at a nontrivial example, which is the motivation for our paper. Let \mathbb{k} be a field. AS regular algebras of global dimension 2 (not necessarily Noetherian)

MSC2010: 16E65, 16W30, 16W35.

Keywords: Morita–Takeuchi equivalence, Calabi–Yau algebra, cogroupoid.

were classified by Zhang [1998]. They are the algebras (assume they are generated in degree one)

$$A(E) = \mathbb{k}\langle x_1, x_2, \dots, x_n \rangle / \left(\sum_{1 \leq i, j \leq n} e_{ij} x_i x_j \right)$$

for $E = (e_{ij}) \in \mathrm{GL}_n(\mathbb{k})$ with $n \geq 2$. It is shown in [Walton and Wang 2016, Corollary 2.17] that $\mathcal{O}_{A(E)}(\mathrm{SL}) \cong \mathcal{B}(E^{-1})$ as Hopf algebras, where $\mathcal{B}(E^{-1})$ was defined by Dubois-Violette and Launer [1990] as the quantum automorphism group of the nondegenerate bilinear form associated to E^{-1} . In particular, when

$$E = \begin{pmatrix} 0 & -q \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad E^{-1} = E_q = \begin{pmatrix} 0 & 1 \\ -q^{-1} & 0 \end{pmatrix} \quad \text{for some } q \in \mathbb{k}^\times,$$

we have $A(E) = A_q = \mathbb{k}\langle x_1, x_2 \rangle / (x_2 x_1 + q x_1 x_2)$ is the quantum plane and $\mathcal{O}_{A_q}(\mathrm{SL}) = \mathcal{B}(E_q) = \mathcal{O}_q(\mathrm{SL}_2)$ is the quantized coordinate ring of $\mathrm{SL}_2(\mathbb{k})$.

Two Hopf algebras are called monoidally Morita–Takeuchi equivalent, if their comodule categories are monoidally equivalent. Bichon [2003, Theorem 1.1] obtained that $\mathcal{B}(E)$ (for any $E \in \mathrm{GL}_n(\mathbb{k})$ with $n \geq 2$) and $\mathcal{O}_q(\mathrm{SL}_2)$ are monoidally Morita–Takeuchi equivalent when $q^2 + \mathrm{tr}(E^t E^{-1})q + 1 = 0$. By applying this monoidal equivalence, Bichon obtained a free Yetter–Drinfeld module resolution (Definition 2.2.4) of the trivial Yetter–Drinfeld module \mathbb{k} over $\mathcal{B}(E)$. This turns out to be the key ingredient to prove the CY property of $\mathcal{B}(E)$; see that work or [Walton and Wang 2016]. Note that the quantized coordinate ring $\mathcal{O}_q(\mathrm{SL}_2)$ is well known to be twisted CY [Brown and Zhang 2008, Section 6.5 and 6.6]. Thus it is natural to ask the following question:

Question 1. *Let H and L be two Hopf algebras that are monoidally Morita–Takeuchi equivalent. Suppose H is twisted CY. Is L always twisted CY?*

The monoidal equivalence between the comodule categories of various universal quantum groups have been widely observed [Bichon 2003; 2014; Mrozinski 2014; Chirvasitu et al. 2016] by using the language of cogroupoids. In recent papers, Raedschelders and Van den Bergh [2015; 2017] proved that, for a Koszul AS regular algebra A , the monoidal structure of the comodule category of $\mathcal{O}_A(\mathrm{GL})$ only depends on the global dimension of A and not on A itself [Raedschelders and Van den Bergh 2017, Theorem 1.2.6]. We expect a positive answer to Question 1, which should play an important role in investigating the CY property of these universal quantum groups associated to AS regular algebras.

The following is our main result, showing that in order to answer Question 1, it suffices to prove that the homologically smooth condition is a monoidally Morita–Takeuchi invariant.

Theorem 2 (Theorem 2.4.5). *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. If H is twisted CY of dimension d and L is homologically smooth, then L is twisted CY of dimension d as well.*

Note that for Hopf algebras, there are several equivalent descriptions of the homological smoothness stated in Proposition A.2. Now Question 1 is reduced to the following question:

Question 3. *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. Suppose H is homologically smooth. Is L always homologically smooth?*

Though we can not fully answer Question 3, it is true in certain circumstances. We obtain the following result:

Theorem 4 (Theorem 2.4.7). *Let H be a twisted CY Hopf algebra of dimension d , and L a Hopf algebra monoidally Morita–Takeuchi equivalent to H . If one of the following conditions holds, then L is also twisted CY of dimension d .*

- (i) *H admits a finitely generated relative projective Yetter–Drinfeld module resolution for the trivial Yetter–Drinfeld module \mathbb{k} and L has finite global dimension.*
- (ii) *H admits a bounded finitely generated relative projective Yetter–Drinfeld module resolution for the trivial Yetter–Drinfeld module \mathbb{k} .*
- (iii) *H is Noetherian and L has finite global dimension.*
- (iv) *L is Noetherian and has finite global dimension.*

Relative projective Yetter–Drinfeld modules and resolutions will be explained in Section 2.2. The trivial module \mathbb{k} over $\mathcal{O}_q(\mathrm{SL}_2)$ admits a finitely generated free Yetter–Drinfeld resolution of length 3 [Bichon 2013, Theorem 5.1]. Every free Yetter–Drinfeld module resolution is a relative projective Yetter–Drinfeld module resolution. According to our result above, this immediately implies that $\mathcal{B}(E)$ is twisted CY since $\mathcal{B}(E)$ and $\mathcal{O}_q(\mathrm{SL}_2)$ are monoidally Morita–Takeuchi equivalent as mentioned above.

Twisted CY algebras, of course, have finite global dimensions. Theorem 4 leads to the last question about whether the global dimension is a monoidally Morita–Takeuchi invariant. A similar question was asked by Bichon [2016] concerning the Hochschild dimension, and the two questions are essentially the same by Proposition A.1.

Question 5. *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. Does $\mathrm{gldim}(H) = \mathrm{gldim}(L)$, or at least, $\mathrm{gldim}(H) < \infty$ if and only if $\mathrm{gldim}(L) < \infty$?*

If the answer is positive, then the finite global dimension assumptions in conditions (i), (iii), and (iv) of Theorem 4 can be dropped. This will partially answer Question 1 under the assumption that one of the Hopf algebras is Noetherian. As

a consequence of Theorem 4, we provide a partial answer to Question 5 answer under the assumption that both Hopf algebras are twisted CY.

Theorem 6 (Corollary 2.4.8). *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. If both H and L are twisted CY, then $\text{gldim}(H) = \text{gldim}(L)$.*

Monoidal Morita–Takeuchi equivalence can be described by the language of cogroupoids. If H and L are two Hopf algebras that are monoidally Morita–Takeuchi equivalent, then there exists a connected cogroupoid with 2 objects X, Y such that $H = \mathcal{C}(X, X)$ and $L = \mathcal{C}(Y, Y)$. In this case, $\mathcal{C}(X, Y)$ is just the H - L -bigois object (see Section 1.1 for details). Throughout, we will use the language of cogroupoids to discuss Hopf algebras whose comodule categories are monoidally equivalent. We generalize many definitions and results in [Brown and Zhang 2008] to the level of cogroupoids (see Section 2.4). Especially for Hopf–Galois objects, we define the left (resp. right) winding automorphisms of $\mathcal{C}(X, Y)$ using the homological integrals of $\mathcal{C}(X, X)$ (resp. $\mathcal{C}(Y, Y)$). We also generalize the famous Radford S^4 formula for finite dimensional Hopf algebras to Hopf–Galois object $\mathcal{C}(X, Y)$ by assuming both $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are AS-Gorenstein Hopf algebras.

Theorem 7 (Theorem 2.4.9 and Remark 2.4.10). *Let \mathcal{C} be a connected cogroupoid. If X and Y are two objects such that $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are both AS-Gorenstein Hopf algebras. Then for the Hopf–Galois object $\mathcal{C}(X, Y)$ we have*

$$(1) \quad (S_{Y,X} \circ S_{X,Y})^2 = \gamma \circ \phi \circ \xi^{-1},$$

where ξ and ϕ are respectively the left and right winding automorphisms given by the left integrals of $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$, and γ is an inner automorphism.

At last, we provide two examples in Section 3. One is the connected cogroupoid associated to $\mathcal{B}(E)$ and the other is the connected cogroupoid associated to a generic datum of finite Cartan type (\mathcal{D}, λ) .

1. Preliminaries

We work over a fixed field \mathbb{k} . Unless stated otherwise all algebras and vector spaces are over \mathbb{k} . The unadorned tensor \otimes means $\otimes_{\mathbb{k}}$ and Hom means $\text{Hom}_{\mathbb{k}}$.

Given an algebra A , we write A^{op} for the *opposite algebra* of A and A^e for the *enveloping algebra* $A \otimes A^{\text{op}}$. The category of left (resp. right) A -modules is denoted by $\text{Mod } A$ (resp. $\text{Mod } A^{\text{op}}$). An A -bimodule can be identified with an A^e -module, that is, an object in $\text{Mod } A^e$.

For an A -bimodule M and two algebra automorphisms μ and ν , we let ${}^{\mu}M^{\nu}$ denote the A -bimodule such that ${}^{\mu}M^{\nu} \cong M$ as vector spaces, and the bimodule

structure is given by

$$a \cdot m \cdot b = \mu(a)mv(b),$$

for all $a, b \in A$ and $m \in M$. If one of the automorphisms is the identity, we will omit it. It is well known that $A^\mu \cong A$ as A -bimodules if and only if μ is an inner automorphism of A .

For a Hopf algebra H , as usual, we use the symbols Δ, ε and S respectively for its comultiplication, counit, and antipode. We use Sweedler’s (sumless) notation for the comultiplication and coaction of H . The category of right H -comodules is denoted by \mathcal{M}^H . We write ${}_e\mathbb{k}$ (resp. \mathbb{k}_e) for the left (resp. right) trivial module defined by the counit ε of H .

1.1. Cogroupoid. We first recall the definition of a cogroupoid.

Definition 1.1.1. A cocategory \mathcal{C} consists of:

- A set of objects $\text{ob}(\mathcal{C})$,
- For any $X, Y \in \text{ob}(\mathcal{C})$, an algebra $\mathcal{C}(X, Y)$,
- For any $X, Y, Z \in \text{ob}(\mathcal{C})$, algebra homomorphisms

$$\Delta_{XY}^Z : \mathcal{C}(X, Y) \rightarrow \mathcal{C}(X, Z) \otimes \mathcal{C}(Z, Y) \text{ and } \varepsilon_X : \mathcal{C}(X, X) \rightarrow \mathbb{k}$$

such that for any $X, Y, Z, T \in \text{ob}(\mathcal{C})$, the following diagrams commute:

$$\begin{array}{ccc} \mathcal{C}(X, Y) & \xrightarrow{\Delta_{X,Y}^Z} & \mathcal{C}(X, Z) \otimes \mathcal{C}(Z, Y) \\ \Delta_{X,Y}^T \downarrow & & \Delta_{X,Z}^T \otimes 1 \downarrow \\ \mathcal{C}(X, T) \otimes \mathcal{C}(T, Y) & \xrightarrow{1 \otimes \Delta_{T,Y}^Z} & \mathcal{C}(X, T) \otimes \mathcal{C}(T, Z) \otimes \mathcal{C}(Z, Y) \end{array}$$

$$\begin{array}{ccc} \mathcal{C}(X, Y) & & \mathcal{C}(X, Y) \\ \downarrow \Delta_{X,Y}^Y & \searrow & \downarrow \Delta_{X,Y}^X \\ \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, Y) & \xrightarrow{1 \otimes \varepsilon_Y} & \mathcal{C}(X, Y) \quad \mathcal{C}(X, X) \otimes \mathcal{C}(X, Y) \xrightarrow{\varepsilon_X \otimes 1} \mathcal{C}(X, Y) \end{array}$$

Thus a cocategory with one object is just a bialgebra.

A cocategory \mathcal{C} is said to be *connected* if $\mathcal{C}(X, Y)$ is a nonzero algebra for any $X, Y \in \text{ob}(\mathcal{C})$.

Definition 1.1.2. A cogroupoid \mathcal{C} consists of a cocategory \mathcal{C} together with, for any $X, Y \in \text{ob}(\mathcal{C})$, linear maps

$$S_{X,Y} : \mathcal{C}(X, Y) \rightarrow \mathcal{C}(Y, X)$$

such that for any $X, Y \in \mathcal{C}$, the following diagrams commute:

$$\begin{array}{ccccc}
 \mathcal{C}(X, X) & \xrightarrow{\varepsilon_X} & \mathbb{k} & \xrightarrow{u} & \mathcal{C}(X, Y) \\
 \Delta_{X,X}^Y \downarrow & & & & \uparrow \cdot \\
 \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, X) & \xrightarrow{1 \otimes S_{Y,X}} & & & \mathcal{C}(X, Y) \otimes \mathcal{C}(X, Y) \\
 \\
 \mathcal{C}(X, X) & \xrightarrow{\varepsilon_X} & \mathbb{k} & \xrightarrow{u} & \mathcal{C}(Y, Y) \\
 \Delta_{X,X}^Y \downarrow & & & & \uparrow \cdot \\
 \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, X) & \xrightarrow{S_{X,Y} \otimes 1} & & & \mathcal{C}(Y, X) \otimes \mathcal{C}(Y, X).
 \end{array}$$

From the definition, we can see $\mathcal{C}(X, X)$ is a Hopf algebra for each object $X \in \mathcal{C}$.

We use Sweedler’s notation for cogroupoids. Let \mathcal{C} be a cogroupoid. For any $a^{X,Y} \in \mathcal{C}(X, Y)$, we write

$$\Delta_{X,Y}^Z(a^{X,Y}) = a_1^{X,Z} \otimes a_2^{Z,Y}.$$

The following lemma describes properties of the “antipodes”:

Lemma 1.1.3 [Bichon 2014, Proposition 2.13]. *Let \mathcal{C} be a cogroupoid and let $X, Y \in \text{ob}(\mathcal{C})$.*

- (i) $S_{Y,X} : \mathcal{C}(Y, X) \rightarrow \mathcal{C}(X, Y)^{\text{op}}$ is an algebra homomorphism.
- (ii) For any $Z \in \text{ob}(\mathcal{C})$ and $a^{Y,X} \in \mathcal{C}(Y, X)$,

$$\Delta_{X,Y}^Z(S_{Y,X}(a^{Y,X})) = S_{Z,X}(a_2^{Z,X}) \otimes S_{Y,Z}(a_1^{Y,Z}).$$

For other basic properties of cogroupoids, we refer to the same work.

Bichon [2014] reformulated Schauenburg’s [1996] results by cogroupoids. This theorem shows that discussing two Hopf algebras with monoidally equivalent comodule categories is equivalent discussing connected cogroupoids. In what follows, unless otherwise stated, we assume that the cogroupoids mentioned are *connected*.

Theorem 1.1.4 [Bichon 2014, Theorem 2.10, 2.12]. *If \mathcal{C} is a connected cogroupoid, then for any $X, Y \in \mathcal{C}$, we have equivalences of monoidal categories that are inverse to each other*

$$\begin{aligned}
 \mathcal{M}^{\mathcal{C}(X,X)} \cong^{\otimes} \mathcal{M}^{\mathcal{C}(Y,Y)} & \qquad \mathcal{M}^{\mathcal{C}(Y,Y)} \cong^{\otimes} \mathcal{M}^{\mathcal{C}(X,X)} \\
 V \mapsto V \square_{\mathcal{C}(X,X)} \mathcal{C}(X, Y) & \qquad V \mapsto V \square_{\mathcal{C}(Y,Y)} \mathcal{C}(Y, X).
 \end{aligned}$$

Conversely, if H and L are Hopf algebras such that $\mathcal{M}^H \cong^{\otimes} \mathcal{M}^L$, then there exists a connected cogroupoid with 2 objects X, Y such that $H = \mathcal{C}(X, X)$ and $L = \mathcal{C}(Y, Y)$.

This monoidal equivalence can be extended to categories of Yetter–Drinfeld modules.

Lemma 1.1.5 [Bichon 2014, Proposition 6.2]. *Let \mathcal{C} be a cogroupoid, $X, Y \in \text{ob}(\mathcal{C})$ and V a right $\mathcal{C}(X, X)$ -module.*

- (i) $V \otimes \mathcal{C}(X, Y)$ has a right $\mathcal{C}(Y, Y)$ -module structure defined by

$$(v \otimes a^{X,Y}) \leftarrow b^{Y,Y} = v \cdot b_2^{X,X} \otimes S_{Y,X}(b_1^{Y,X})a^{X,Y}b_3^{X,Y}.$$

Together with the right $\mathcal{C}(Y, Y)$ -comodule structure defined by $1 \otimes \Delta_{X,Y}^Y$, $V \otimes \mathcal{C}(X, Y)$ is a Yetter–Drinfeld module over $\mathcal{C}(Y, Y)$.

- (ii) *If moreover V is a Yetter–Drinfeld module, then $V \square_{\mathcal{C}(X,X)} \mathcal{C}(X, Y)$ is a Yetter–Drinfeld submodule of $V \otimes \mathcal{C}(X, Y)$.*

Theorem 1.1.6 [Bichon 2014, Theorem 6.3]. *Let \mathcal{C} be a connected cogroupoid. Then for any $X, Y \in \text{ob}(\mathcal{C})$, the functor*

$$\mathcal{YD}_{\mathcal{C}(X,X)}^{\mathcal{C}(X,X)} \rightarrow \mathcal{YD}_{\mathcal{C}(Y,Y)}^{\mathcal{C}(Y,Y)} \quad V \mapsto V \square_{\mathcal{C}(X,X)} \mathcal{C}(X, Y)$$

is a monoidal equivalence.

1.2. Calabi–Yau algebras. In this subsection, we recall the definition of (twisted) Calabi–Yau algebras.

Definition 1.2.1. An algebra A is a *twisted Calabi–Yau algebra of dimension d* if

- (i) A is *homologically smooth*, that is, A has a bounded resolution by finitely generated projective A^e -modules;
- (ii) There is an automorphism μ of A such that

$$(2) \quad \text{Ext}_{A^e}^i(A, A^e) \cong \begin{cases} 0, & i \neq d, \\ A^\mu, & i = d, \end{cases}$$

as A^e -modules.

If such an automorphism μ exists, it is unique up to an inner automorphism and is called the *Nakayama automorphism* of A . In the definition, the dimension d is usually called the Calabi–Yau dimension of A . A *Calabi–Yau algebra* in the sense of Ginzburg [2007] is a twisted Calabi–Yau algebra whose Nakayama automorphism is an inner automorphism. In what follows, Calabi–Yau is abbreviated to CY.

Twisted CY algebras include CY algebras as a subclass. They are the natural algebraic analogues of Bieri and Eckmann’s [1973] duality groups. The twisted CY property of noncommutative algebras has been studied under other names for many years, even before the definition of a CY algebra. Rigid dualizing complexes of noncommutative algebras were studied in [Van den Bergh 1997]. The twisted CY property was called “rigid Gorenstein” in [Brown and Zhang 2008] and was called “skew Calabi–Yau” in a recent paper [Reyes et al. 2014].

2. Calabi–Yau property

2.1. Artin–Schelter Gorenstein Hopf algebras. Let H be a Hopf algebra. We denote the Hochschild dimension of H by $\text{Hdim}(H)$. In the Appendix, it is shown that the left global dimension and the right global dimension of H are always equal. We denote the global dimension of H by $\text{gldim}(H)$. The left adjoint functor $L : \text{Mod } H^e \rightarrow \text{Mod } H$ is defined by the algebra homomorphism $(\text{id} \otimes S) \circ \Delta : H \rightarrow H^e$. Similarly, the algebra homomorphism $\tau \circ (S \otimes \text{id}) \circ \Delta : H \rightarrow (H^e)^{\text{op}} = H^e$ defines the right adjoint functor $R : \text{Mod } (H^e)^{\text{op}} \rightarrow \text{Mod } H^{\text{op}}$, where $\tau : H^{\text{op}} \otimes H \rightarrow H \otimes H^{\text{op}}$ is the flip map. Let M be an H -bimodule. Then $L(M)$ is a left H -module defined by the action

$$x \rightarrow m = x_1 m S(x_2) \quad \text{for any } x \in H,$$

while $R(M)$ is a right H -module defined by the action

$$m \leftarrow x = S(x_1) m x_2 \quad \text{for any } x \in H.$$

The algebra H^e is a left and right H^e -module with left action

$$(3) \quad (a \otimes b) \rightarrow (x \otimes y) = ax \otimes yb,$$

and right action

$$(4) \quad (x \otimes y) \leftarrow (a \otimes b) = xa \otimes by.$$

for any $x \otimes y$ and $a \otimes b \in H^e$. So $L(H^e)$ and $R(H^e)$ are H - H^e and H^e - H -bimodules, where the corresponding H -module structures are given by

$$a \rightarrow (x \otimes y) = a_1 x \otimes y S(a_2) \quad \text{and} \quad (x \otimes y) \leftarrow a = x a_2 \otimes S(a_1) y$$

for any $a \in H$ and $x \otimes y \in H^e$, respectively.

Let ${}_*H \otimes H$ be the free left H -module, where the structure is given by the left multiplication of the first factor H . Similarly, let $H_* \otimes H$ be the free right H -module defined by the right multiplication of the first factor H . Moreover, we give ${}_*H \otimes H$ a right H^e -module structure such that

$$(5) \quad (x \otimes y) \leftarrow (a \otimes b) = x a_1 \otimes b y S^2(a_2)$$

and $H_* \otimes H$ a left H^e -module structure via

$$(6) \quad (a \otimes b) \rightarrow (x \otimes y) = a_2 x \otimes S^2(a_1) y b$$

for any $x \otimes y \in {}_*H \otimes H$ or $H_* \otimes H$ and $a \otimes b \in H^e$.

Lemma 2.1.1. *Retain the above notation. Then we have:*

- (i) $L(H^e) \cong {}_*H \otimes H$ as H - H^e -bimodules.
- (ii) $R(H^e) \cong H_* \otimes H$ as H^e - H -bimodules.

Proof. It is straightforward to check the corresponding isomorphisms of bimodules are given by the following four homomorphisms:

$$L(H^e) \rightarrow {}_*H \otimes H, \quad x \otimes y \mapsto x_1 \otimes yS^2(x_2)$$

with inverse

$${}_*H \otimes H \rightarrow L(H^e), \quad x \otimes y \mapsto x_1 \otimes yS(x_2),$$

and

$$R(H^e) \rightarrow H_* \otimes H, \quad x \otimes y \mapsto x_2 \otimes S^2(x_1)y$$

with inverse

$$H_* \otimes H \rightarrow R(H^e), \quad x \otimes y \mapsto x_2 \otimes S(x_1)y. \quad \square$$

Lemma 2.1.2. *Let H be a Hopf algebra and B an algebra.*

- (i) *Let M be an H^e - B -bimodule. Then $\text{Ext}_{H^e}^i(H, M) \cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, L(M))$ as right B -modules for all $i \geq 0$.*
- (ii) *Let M be an B - H^e -bimodule. Then $\text{Ext}_{H^e}^i(H, M) \cong \text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, R(M))$ as left B -modules for all $i \geq 0$.*

Proof. We only prove (i); the proof of (ii) is quite similar. With Lemma 2.4 in [Brown and Zhang 2008], we only need to prove that for an H^e - B -bimodule N , there is an H^e - B -bimodule monomorphism $0 \rightarrow N \rightarrow I$, such that I is injective as an H^e -module. The H^e - B -bimodule N can be viewed as an $H^e \otimes B^{\text{op}}$ -module. It can be embedded into an injective $H^e \otimes B^{\text{op}}$ -module I . We have

$$\begin{aligned} \text{Hom}_{H^e}(-, I) &\cong \text{Hom}_{H^e}(-, \text{Hom}_{H^e \otimes B^{\text{op}}}((H^e \otimes B^{\text{op}})_{H^e}, I)) \\ &\cong \text{Hom}_{H^e \otimes B^{\text{op}}}((H^e \otimes B^{\text{op}})_{H^e} \otimes -, I). \end{aligned}$$

$H^e \otimes B^{\text{op}}$ is clearly free as an H^e -module. Therefore, the functor $\text{Hom}_{H^e}(-, I)$ is exact. That is, I is injective as an H^e -module. This completes the proof. \square

It is well known that there is an equivalence of categories between the category of left H^e -modules and the category of right H^e -modules for $(H^e)^{\text{op}} = H^e$. As a consequence, $\text{Ext}_{H^e}^i(H, H^e)$ can be computed both by using the left and the right H^e -module structures on H^e defined in (3) and (4).

Proposition 2.1.3. *Let H be a Hopf algebra such that it is homologically smooth. We have*

$$\text{Ext}_{H^e}^i(H, H^e) \cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) \otimes H \cong \text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) \otimes H$$

as H^e -modules for all $i \geq 0$, where the H^e -module structures on $\text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) \otimes H$ and on $\text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) \otimes H$ are induced by (5) and (6), respectively.

Proof. We prove the isomorphism $\text{Ext}_{H^e}^i(H, H^e) \cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) \otimes H$. The proof of the isomorphism $\text{Ext}_{H^e}^i(H, H^e) \cong \text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) \otimes H$ is quite similar.

Since H is homologically smooth, the trivial module ${}_\varepsilon\mathbb{k}$ admits a bounded projective resolution $\mathbf{P}_\bullet \rightarrow {}_\varepsilon\mathbb{k} \rightarrow 0$, with each term finitely generated (Proposition A.2). Now we have the following H^e -module isomorphisms:

$$\begin{aligned} \text{Ext}_{H^e}^i(H, H^e) &\cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, L(H^e)) \cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, {}_*H \otimes H) \\ &\cong H^i(\mathbf{P}_\bullet, {}_*H \otimes H) \cong H^i(\mathbf{P}_\bullet, H) \otimes H \\ &\cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) \otimes H. \end{aligned}$$

The first and the second isomorphism follows from Lemma 2.1.2 and 2.1.1, respectively. The fourth isomorphism holds since $\mathbf{P}_\bullet \rightarrow {}_\varepsilon\mathbb{k} \rightarrow 0$ is a bounded projective resolution with each term finitely generated. \square

Now we recall the definition of an Artin–Schelter (AS) Gorenstein algebra.

Definition 2.1.4 (cf. [Brown and Zhang 2008, Definition 1.2]). Let H be a Hopf algebra.

- (i) The Hopf algebra H is said to be *left AS-Gorenstein* if
 - (a) $\text{injdim}_H H = d < \infty$,
 - (b) $\text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) = 0$ for $i \neq d$ and $\text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) = \mathbb{k}$.
- (ii) The Hopf algebra H is said to be *right AS-Gorenstein* if
 - (c) $\text{injdim} H_H = d < \infty$,
 - (d) $\text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) = 0$ for $i \neq d$ and $\text{Ext}_{H^{\text{op}}}^d(\mathbb{k}_\varepsilon, H) = \mathbb{k}$.
- (iii) If H is both left and right AS-Gorenstein (relative to the same augmentation map ε), then H is called *AS-Gorenstein*.
- (iv) If, in addition, the global dimension of H is finite, then H is called *AS-regular*.

Remark 2.1.5. In above definitions, we do not require the Hopf algebra H to be Noetherian. For AS-regularity, the right global dimension always equals the left global dimension by Proposition A.1. Moreover, when H is AS-Gorenstein and homologically smooth, the right injective dimension always equals the left injective dimension, which are both given by the integer d such that $\text{Ext}_{H^e}^d(H, H^e) \neq 0$ by Proposition 2.1.3.

Homological integrals for an AS-Gorenstein Hopf algebra introduced in [Lu et al. 2007] are a generalization of integrals for finite dimensional Hopf algebras [Sweedler 1969]. The concept was further extended to any AS-Gorenstein algebra in [Brown and Zhang 2008].

Let A be a left AS-Gorenstein algebra of injective dimension d with augmentation $\varepsilon : A \rightarrow \mathbb{k}$. One sees that $\text{Ext}_A^d({}_\varepsilon\mathbb{k}, A)$ is a one-dimensional right A -module. Any nonzero element in $\text{Ext}_A^d({}_\varepsilon\mathbb{k}, A)$ is called a *left homological integral* of A . Usually,

$\text{Ext}_A^d({}_\varepsilon\mathbb{k}, A)$ is denoted by \int_A^l . Similarly, if A is a right AS-Gorenstein algebra of injective dimension d , any nonzero element in $\text{Ext}_{A^{\text{op}}}^d(\mathbb{k}_\varepsilon, A)$ is called a *right homological integral*. And $\text{Ext}_{A^{\text{op}}}^d(\mathbb{k}_\varepsilon, A)$ is denoted by \int_A^r . Abusing the language slightly, \int_A^l (resp. \int_A^r) is also called the left (resp. right) homological integral.

A Noetherian Hopf algebra H with bijective antipode is AS-regular in the sense of [Brown and Zhang 2008, Definition 1.2] if and only if H is twisted CY [Reyes et al. 2014, Lemma 1.3]. If H is not necessarily Noetherian, we have the following result:

Proposition 2.1.6. *Let H be a Hopf algebra with bijective antipode such that it is homologically smooth. Then the following are equivalent:*

- (i) H is a twisted CY algebra of dimension d .
- (ii) There is an integer d such that

$$\text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) = 0 \quad \text{for } i \neq d \quad \text{and} \quad \dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) = 1.$$

- (iii) There is an integer d such that

$$\text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) = 0 \quad \text{for } i \neq d \quad \text{and} \quad \dim \text{Ext}_{H^{\text{op}}}^d(\mathbb{k}_\varepsilon, H) = 1.$$

- (iv) $\text{Ext}_H^i({}_\varepsilon\mathbb{k}, H)$ and $\text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H)$ are finite dimensional for $i \geq 0$ and there is an integer d such that $\dim \text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) = \dim \text{Ext}_{H^{\text{op}}}^i(\mathbb{k}_\varepsilon, H) = 0$ for $i > d$, and $\dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) \neq 0$ or $\dim \text{Ext}_{H^{\text{op}}}^d(\mathbb{k}_\varepsilon, H) \neq 0$.

In these cases, we have $\text{gldim}(H) = \text{injdim } H_H = \text{injdim } {}_H H = d$.

Proof. (i) \Rightarrow (ii), (iii) This proof can be found for example in [Yu et al. 2016, Lemma 2.15].

(ii) \Rightarrow (i) By Proposition 2.1.3, $\text{Ext}_{H^e}^i(H, H^e) \cong \text{Ext}_H^i({}_\varepsilon\mathbb{k}, H) \otimes H$ for all $i \geq 1$ as H^e -modules. Since $\text{Ext}_H^d({}_\varepsilon\mathbb{k}, H)$ is a one-dimensional right H -module, we simply write it as \mathbb{k}_ξ , for some algebra homomorphism $\xi : H \rightarrow \mathbb{k}$. Therefore,

$$\text{Ext}_{H^e}^i(H, H^e) = 0 \quad \text{for } i \neq d \quad \text{and} \quad \text{Ext}_{H^e}^d(H, H^e) \cong \mathbb{k}_\xi \otimes H \stackrel{(a)}{\cong} H^\mu,$$

where μ is defined by $\mu(h) = \xi(h_1)S^2(h_2)$ for any $h \in H$. The isomorphism (a) holds because the H^e -module structure on $\mathbb{k}_\xi \otimes H$ is induced by the equation (5) according to Proposition 2.1.3. Moreover, it is easy to check that μ is an algebra automorphism of H with inverse given by $\mu^{-1}(h) = \xi(S(h_1))S^{-2}(h_2)$ for any $h \in H$.

(iii) \Rightarrow (i) The proof is similar to that of (ii) \Rightarrow (i).

(ii), (iii) \Rightarrow (iv) This is obvious.

(iv) \Rightarrow (ii), (iii) The proof of [Brown and Zhang 2008, Lemma 3.2] works generally for this case. Suppose $\dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) \neq 0$; the case for $\dim \text{Ext}_{H^{\text{op}}}^d(\mathbb{k}_\varepsilon, H) \neq 0$

is similar. Since H is homologically smooth, by Proposition A.2 and [Brown and Goodearl 1997, Lemma 1.11], we can apply Ischebeck’s spectral sequence

$$\text{Ext}_{H^{\text{op}}}^p(\text{Ext}_H^{-q}({}_\varepsilon\mathbb{k}, H), H) \implies \text{Tor}_{-p-q}^H(H, {}_\varepsilon\mathbb{k})$$

to obtain $\dim \text{Ext}_{H^{\text{op}}}^i({}_\varepsilon\mathbb{k}, H) = 0$ for $i \neq d$. From the proof of [Brown and Goodearl 1997, Lemma 1.11], $\dim \text{Ext}_H^d(M, H) = \dim M \cdot \dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H)$ for any finite dimensional left H -module M . Thus by the finite dimensional assumption,

$$\dim \text{Ext}_H^d(\text{Ext}_{H^{\text{op}}}^d({}_\varepsilon\mathbb{k}, H), H) = \dim \text{Ext}_{H^{\text{op}}}^d({}_\varepsilon\mathbb{k}, H) \cdot \dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H).$$

Again by the Ischebeck’s spectral sequence, $\text{Ext}_H^d(\text{Ext}_{H^{\text{op}}}^d({}_\varepsilon\mathbb{k}, H), H) \cong \mathbb{k}$. Hence,

$$\dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) = \dim \text{Ext}_{H^{\text{op}}}^d({}_\varepsilon\mathbb{k}, H) = 1.$$

Now (ii) and (iii) are proved.

Finally, we can apply the same proof of [Berger and Taillefer 2007, Proposition 2.2] to show that for a twisted CY Hopf algebra H of dimension d , we have $\text{Hdim}(H) = d$. Hence $\text{gldim}(H) = d$ by Proposition A.1. The equality of the injective dimension of H is easy to see since it is always bounded by $\text{gldim}(H) = d$ and we have $\dim \text{Ext}_H^d({}_\varepsilon\mathbb{k}, H) \neq 0$ or $\dim \text{Ext}_{H^{\text{op}}}^d({}_\varepsilon\mathbb{k}, H) \neq 0$. \square

Corollary 2.1.7. *Let H be a Hopf algebra with bijective antipode. Then the following are equivalent:*

- H is twisted CY.
- H is left AS-Gorenstein and the left trivial module ${}_\varepsilon\mathbb{k}$ admits a bounded projective resolution with each term finitely generated.
- H is right AS-Gorenstein and the right trivial module \mathbb{k}_ε admits a bounded projective resolution with each term finitely generated.

Proof. It follows from Proposition A.2 and Proposition 2.1.6. \square

2.2. Yetter–Drinfeld modules. In this subsection, we recall some definitions related to Yetter–Drinfeld modules.

Definition 2.2.1. Let H be a Hopf algebra. A (right-right) Yetter–Drinfeld module V over H is simultaneously a right H -module and a right H -comodule satisfying the compatibility condition

$$\delta(v \cdot h) = v_{(0)} \cdot h_2 \otimes S(h_1)v_{(1)}h_3 \quad \text{for any } v \in V, h \in H.$$

We denote by \mathcal{YD}_H^H the category of Yetter–Drinfeld modules over H with morphisms given by H -linear and H -collinear maps. Endowed with the usual tensor product of modules and comodules, \mathcal{YD}_H^H is a monoidal category, with unit the trivial Yetter–Drinfeld module \mathbb{k} .

We can always construct a Yetter–Drinfeld module from a right comodule.

Lemma-Definition 2.2.2 [Bichon 2013, Proposion 3.1, Definition 3.2]. Let H be a Hopf algebra and V a right H -comodule. Endow $V \otimes H$ with the right H -module structure defined by multiplication on the right. Then the linear map

$$V \otimes H \rightarrow V \otimes H \otimes H, \quad v \otimes h \mapsto v_{(0)} \otimes h_2 \otimes S(h_1)v_{(1)}h_3$$

endows $V \otimes H$ with a right H -comodule structure, and with a right-right Yetter–Drinfeld module structure. We denote by $V \boxtimes H$ the resulting Yetter–Drinfeld module.

A Yetter–Drinfeld module over H is said to be *free* if it is isomorphic to $V \boxtimes H$ for some right H -comodule V .

A free Yetter–Drinfeld module is obviously free as a right H -module. We call a free Yetter–Drinfeld module $V \boxtimes H$ *finitely generated* if V is finite dimensional.

Bichon [2016] introduced the notion of relative projective Yetter–Drinfeld module, corresponding to the notion of relative projective Hopf bimodule considered in [Shnider and Sternberg 1993] via the monoidal equivalence between Yetter–Drinfeld modules and Hopf bimodules.

Lemma-Definition 2.2.3 [Bichon 2016, Definition 4.1, Proposition 4.2]. Let P be a Yetter–Drinfeld module over a Hopf algebra H . The following are equivalent:

- (1) The functor $\text{Hom}_{\mathcal{YD}_H^H}(P, -)$ transforms exact sequences of Yetter–Drinfeld modules that splits as sequences of comodules to exact sequences of vector spaces.
- (2) Any epimorphism of Yetter–Drinfeld modules $f : M \rightarrow P$ that admits a comodule section admits a Yetter–Drinfeld module section.
- (3) P is a direct summand of a free Yetter–Drinfeld module.

A Yetter–Drinfeld module is said to be *relative projective* if it satisfies one of the above equivalent conditions.

It is clear that a relative projective Yetter–Drinfeld module is a projective module. We call a relative projective Yetter–Drinfeld module *finitely generated* if it is a direct summand of a finitely generated free Yetter–Drinfeld module.

Definition 2.2.4. Let H be a Hopf algebra and let $M \in \mathcal{YD}_H^H$. A *free (resp. relative projective) Yetter–Drinfeld module resolution* of M consists of a complex of free (resp. relative projective) Yetter–Drinfeld modules

$$P_\bullet : \cdots \rightarrow P_{i+1} \rightarrow P_i \rightarrow \cdots \rightarrow P_1 \rightarrow P_0 \rightarrow 0$$

for which there exists a Yetter–Drinfeld module morphism $\epsilon : P_0 \rightarrow M$ such that

$$\cdots \rightarrow P_{i+1} \rightarrow P_i \rightarrow \cdots \rightarrow P_1 \rightarrow P_0 \xrightarrow{\epsilon} M \rightarrow 0$$

is an exact sequence in \mathcal{YD}_H^H .

If each $P_i, i \geq 0$, is a finitely generated free (resp. relative projective) Yetter–Drinfeld module, we call this complex \mathbf{P}_\bullet a finitely generated free (resp. relative projective) Yetter–Drinfeld module resolution.

Of course each free Yetter–Drinfeld module resolution is a free resolution and each relative projective Yetter–Drinfeld module resolution is a projective resolution.

Lemma 2.2.5. *Let \mathcal{C} be a cogroupoid and $X, Y \in \text{ob}(\mathcal{C})$. The equivalence functor $-\square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ sends any relative projective Yetter–Drinfeld module resolution \mathbf{P}_\bullet of the trivial Yetter–Drinfeld module \mathbb{k} over $\mathcal{C}(X, X)$ to a relative projective Yetter–Drinfeld module resolution $\mathbf{P}_\bullet \square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ of the trivial Yetter–Drinfeld module \mathbb{k} over $\mathcal{C}(Y, Y)$. In particular, if \mathbf{P}_\bullet is finitely generated (resp. bounded), then $\mathbf{P}_\bullet \square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ is also finite generated (resp. bounded).*

Proof. Following from Lemma-Definition 2.2.3 and Section 4 in [Bichon 2013], we see that the functor $-\square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ is exact and sends a relative projective Yetter–Drinfeld module over $\mathcal{C}(X, X)$ to a relative projective Yetter–Drinfeld module over $\mathcal{C}(Y, Y)$. So $\mathbf{P}_\bullet \square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ is a relative projective Yetter–Drinfeld module resolution.

Lemma-Definition 2.2.3 and [Bichon 2014, Proposition 1.16] guarantee that if \mathbf{P}_\bullet is finitely generated, then $\mathbf{P}_\bullet \square_{\mathcal{C}(X,X)}\mathcal{C}(X, Y)$ is also finite generated. The argument for boundedness is clear. □

2.3. Homological properties of cogroupoids. From now on we assume that the Hopf algebras mentioned have *bijective* antipodes. We also assume that any cogroupoid \mathcal{C} mentioned satisfies that $S_{X,Y}$ is *bijective* for any $X, Y \in \text{ob}(\mathcal{C})$. This assumption is to make sure that $S_{Y,X} \circ S_{X,Y}$ is an algebra automorphism of $\mathcal{C}(X, Y)$. Actually, if \mathcal{C} is a connected cogroupoid such that for some object $X, \mathcal{C}(X, X)$ is a Hopf algebra with bijective antipode, then $S_{X,Y}$ is bijective for any objects X, Y (see Remark 2.6 in [Yu 2016]).

Let \mathcal{C} be a cogroupoid and $X, Y \in \text{ob}(\mathcal{C})$. Both the morphisms $\Delta_{X,X}^Y : \mathcal{C}(X, X) \rightarrow \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, X)$ and $S_{Y,X} : \mathcal{C}(Y, X) \rightarrow \mathcal{C}(X, Y)^{\text{op}}$ are algebra homomorphisms (Lemma 1.1.3), so the composition of the morphisms

$$(7) \quad \mathcal{C}(X, X) \xrightarrow{\Delta_{X,X}^Y} \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, X) \xrightarrow{\text{id} \otimes S_{Y,X}} \mathcal{C}(X, Y) \otimes \mathcal{C}(Y, X)^{\text{op}} (= \mathcal{C}(X, Y)^\epsilon)$$

is an algebra homomorphism. This induces a functor

$$\mathcal{L}_X : \text{Mod } \mathcal{C}(X, Y)^\epsilon \rightarrow \text{Mod } \mathcal{C}(X, X).$$

The functor \mathcal{L}_X is just the functor \mathcal{L} defined in [Yu 2016]. Let M be a $\mathcal{C}(X, Y)$ -bimodule. The left $\mathcal{C}(X, X)$ -module structure of $\mathcal{L}_X(M)$ is given by

$$x \rightarrow m = x_1^{X,Y} m S_{Y,X}(x_2^{Y,X}) \quad \text{for any } m \in M, x \in \mathcal{C}(X, X).$$

From the cogroupoid \mathcal{C} , we define a coopposite cogroupoid \mathcal{C}' as follows:

- $\text{ob}(\mathcal{C}') = \text{ob}(\mathcal{C})$.
- For any objects Y, X , the algebra $\mathcal{C}'(Y, X)$ is the algebra $\mathcal{C}(X, Y)$.
- For any objects Y, X and Z , the algebra homomorphism $\Delta'_{YX}{}^Z : \mathcal{C}'(Y, X) \rightarrow \mathcal{C}'(Y, Z) \otimes \mathcal{C}'(Z, X)$ is the algebra homomorphism $\tau \circ \Delta_{XY}{}^Z : \mathcal{C}(X, Y) \rightarrow \mathcal{C}(Z, Y) \otimes \mathcal{C}(X, Z)$ in \mathcal{C} , where $\tau : \mathcal{C}(X, Z) \otimes \mathcal{C}(Z, Y) \rightarrow \mathcal{C}(Z, Y) \otimes \mathcal{C}(X, Z)$ is the flip map.
- For any object X , $\varepsilon'_X : \mathcal{C}'(X, X) \rightarrow \mathbb{k}$ is the same as $\varepsilon_X : \mathcal{C}(X, X) \rightarrow \mathbb{k}$ in \mathcal{C} .
- For any objects Y, X , the morphism $S'_{Y,X} : \mathcal{C}'(Y, X) \rightarrow \mathcal{C}'(X, Y)$ is the morphism $S_{Y,X}^{-1} : \mathcal{C}(X, Y) \rightarrow \mathcal{C}(Y, X)$.

It is easy to check that this indeed defines a cogroupoid.

For any objects $X, Y \in \text{ob}(\mathcal{C}) = \text{ob}(\mathcal{C}')$, the algebras $\mathcal{C}(X, Y)$ and $\mathcal{C}(Y, Y)$ in \mathcal{C} are just the algebras $\mathcal{C}'(Y, X)$ and $\mathcal{C}'(Y, Y)$ in \mathcal{C}' . So we have a functor

$$\mathcal{L}'_Y : \text{Mod } \mathcal{C}(X, Y)^e \rightarrow \text{Mod } \mathcal{C}(Y, Y).$$

If M is a $\mathcal{C}(X, Y)$ -bimodule, the left $\mathcal{C}(Y, Y)$ -module structure of $\mathcal{L}'_Y(M)$ is given by

$$y \rightarrow m = y_2^{X,Y} m S_{X,Y}^{-1}(y_1^{Y,X}) \quad \text{for any } m \in M \quad \text{and} \quad y \in \mathcal{C}(Y, Y).$$

As usual, we view $\mathcal{C}(X, Y)^e$ as a left and a right $\mathcal{C}(X, Y)^e$ -module respectively in the following ways:

$$(8) \quad (a \otimes b) \rightarrow (x \otimes y) = ax \otimes yb,$$

and

$$(9) \quad (x \otimes y) \leftarrow (a \otimes b) = xa \otimes by,$$

for any $x \otimes y$ and $a \otimes b \in \mathcal{C}(X, Y)^e$. Then we have the modules $\mathcal{L}_X(\mathcal{C}(X, Y)^e)$ and $\mathcal{L}'_Y(\mathcal{C}(X, Y)^e)$. They are all free modules.

Let ${}_*\mathcal{C}(X, X) \otimes \mathcal{C}(X, Y)$ be the left $\mathcal{C}(X, X)$ -module defined by the left multiplication of the factor $\mathcal{C}(X, X)$, and ${}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y)$ be the left $\mathcal{C}(Y, Y)$ -module defined by the left multiplication of the factor $\mathcal{C}(Y, Y)$. Then we have the following:

Lemma 2.3.1. (i) $\mathcal{L}_X(\mathcal{C}(X, Y)^e) \cong {}_*\mathcal{C}(X, X) \otimes \mathcal{C}(X, Y)$ as left $\mathcal{C}(X, X)$ -modules.

The isomorphism is given by

$$\mathcal{L}_X(\mathcal{C}(X, Y)^e) \rightarrow {}_*\mathcal{C}(X, X) \otimes \mathcal{C}(X, Y), \quad x \otimes y \mapsto x_1^{X,X} \otimes y S_{Y,X}(S_{X,Y}(x_2^{X,Y})).$$

(ii) $\mathcal{L}'_Y(\mathcal{C}(X, Y)^e) \cong {}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y)$ as left $\mathcal{C}(Y, Y)$ -modules. The isomorphism is given by

$$\mathcal{L}'_Y(\mathcal{C}(X, Y)^e) \rightarrow {}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y), \quad x \otimes y \mapsto x_2^{Y,Y} \otimes y S_{X,Y}^{-1}(S_{Y,X}^{-1}(x_1^{X,Y})).$$

Proof. (i) is Lemma 2.1 in [Yu 2016]. (ii) can be obtained by applying (i) to the coopposite cogroupoid \mathcal{C}' . □

Lemma 2.3.2. *Let \mathcal{C} be a cogroupoid, $X, Y \in \text{ob}(\mathcal{C})$ and B another algebra. Let M be a $\mathcal{C}(X, Y)^e$ - B -bimodule.*

- (i) $\text{Ext}_{\mathcal{C}(X,Y)^e}^i(\mathcal{C}(X,Y), M) \cong \text{Ext}_{\mathcal{C}(X,X)(\varepsilon\mathbb{k}, \mathcal{L}_X(M))}^i$ as right B -bimodules for all $i \geq 0$.
- (ii) $\text{Ext}_{\mathcal{C}(X,Y)^e}^i(\mathcal{C}(X,Y), M) \cong \text{Ext}_{\mathcal{C}(Y,Y)(\varepsilon\mathbb{k}, \mathcal{L}'_Y(M))}^i$ as right B -bimodules for all $i \geq 0$.

Proof. By applying Lemma 2.2 in [Yu 2016] to the cogroupoid \mathcal{C} and its coopposite cogroupoid \mathcal{C}' , we obtain vector space isomorphisms

$$\text{Ext}_{\mathcal{C}(X,Y)^e}^i(\mathcal{C}(X, Y), M) \cong \text{Ext}_{\mathcal{C}(X,X)(\varepsilon\mathbb{k}, \mathcal{L}_X(M))}^i$$

and

$$\text{Ext}_{\mathcal{C}(X,Y)^e}^i(\mathcal{C}(X, Y), M) \cong \text{Ext}_{\mathcal{C}(Y,Y)(\varepsilon\mathbb{k}, \mathcal{L}'_Y(M))}^i$$

for all $i \geq 0$. By a quite similar discussion to that in the proof of Lemma 2.1.2, we can see that the isomorphisms above are B -linear. □

2.4. Main results. In order to state our main results we need to define winding automorphisms of cogroupoids.

Let \mathcal{C} be a cogroupoid and $X, Y \in \text{ob}(\mathcal{C})$. Let $\xi : \mathcal{C}(X, X) \rightarrow \mathbb{k}$ be an algebra homomorphism. The *left winding automorphism* $[\xi]_{X,Y}^l$ of $\mathcal{C}(X, Y)$ associated to ξ is defined to be

$$[\xi]_{X,Y}^l(a^{X,Y}) = \xi(a_1^{X,X})a_2^{X,Y} \quad \text{for any } a \in \mathcal{C}(X, Y).$$

Let $\eta : \mathcal{C}(Y, Y) \rightarrow \mathbb{k}$ be an algebra homomorphism. Similarly, the *right winding automorphism* of $\mathcal{C}(X, Y)$ associated to η is defined to be

$$[\eta]_{X,Y}^r(a^{X,Y}) = a_1^{X,Y}\eta(a_2^{Y,Y}) \quad \text{for any } a \in \mathcal{C}(X, Y).$$

Lemma 2.4.1. *Let \mathcal{C} be a cogroupoid and $X, Y \in \text{ob}(\mathcal{C})$, let $\xi : \mathcal{C}(X, X) \rightarrow \mathbb{k}$, and $\eta : \mathcal{C}(Y, Y) \rightarrow \mathbb{k}$ be algebra homomorphisms. Then*

- (i) $([\xi]_{X,Y}^l)^{-1} = [\xi S_{X,X}]_{X,Y}^l$.
- (ii) $\xi S_{X,X}^2 = \xi$, so $[\xi]_{X,Y}^l = [\xi S_{X,X}^2]_{X,Y}^l$.
- (iii) $[\xi]_{X,Y}^l \circ S_{Y,X} \circ S_{X,Y} = S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l$.
- (i') $([\eta]_{X,Y}^r)^{-1} = [\eta S_{Y,Y}]_{X,Y}^r$.
- (ii') $\eta S_{Y,Y}^2 = \eta$, so $[\eta]_{X,Y}^r = [\eta S_{Y,Y}^2]_{X,Y}^r$.
- (iii') $[\eta]_{X,Y}^r \circ S_{Y,X} \circ S_{X,Y} = S_{Y,X} \circ S_{X,Y} \circ [\eta]_{X,Y}^r$.

Proof. (i) can be proved directly and (ii) is just Lemma 2.5 (c) in [Brown and Zhang 2008]. Now, we give a proof of (iii). For $x \in \mathcal{C}(X, Y)$,

$$S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l(a^{X,Y}) = \xi(a_1^{X,X})S_{Y,X}(S_{X,Y}(a_2^{X,Y})).$$

Since $\Delta_{X,Y}^X(S_{Y,X}(S_{X,Y}(a^{X,Y}))) = S_{X,X}^2(a_1^{X,X}) \otimes S_{Y,X}(S_{X,Y}(a_2^{X,Y}))$,

$$[\xi]_{X,Y}^l \circ S_{Y,X} \circ S_{X,Y}(a^{X,Y}) = \xi S_{X,X}^2(a_1^{X,X})S_{Y,X}(S_{X,Y}(a_2^{X,Y})).$$

By (ii), $\xi S_{X,X}^2 = \xi$, so

$$S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l(a^{X,Y}) = [\xi]_{X,Y}^l \circ S_{Y,X} \circ S_{X,Y}(a^{X,Y}).$$

Therefore, $S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l = [\xi]_{X,Y}^l \circ S_{Y,X} \circ S_{X,Y}$.

(i'), (ii') and (iii') hold symmetrically to (i), (ii) and (iii), respectively. □

The following is the main result of [Yu 2016]:

Theorem 2.4.2. *Let \mathcal{C} be a connected cogroupoid and let $X \in \text{ob}(\mathcal{C})$ such that $\mathcal{C}(X, X)$ is a twisted CY algebra of dimension d with left homological integral $\int_{\mathcal{C}(X,X)}^l = \mathbb{k}_\xi$, where $\xi : \mathcal{C}(X, X) \rightarrow \mathbb{k}$ is an algebra homomorphism. Then for any $Y \in \text{ob}(\mathcal{C})$, $\mathcal{C}(X, Y)$ is a twisted CY algebra of dimension d with Nakayama automorphism μ defined as $\mu = S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l$. That is,*

$$\mu(a) = \xi(a_1^{X,X})S_{Y,X}(S_{X,Y}(a_2^{X,Y}))$$

for any $x \in \mathcal{C}(X, Y)$.

Though we do not say that the CY-dimension of $\mathcal{C}(X, X)$ and $\mathcal{C}(X, Y)$ are the same in the statement of [Yu 2016, Theorem 2.5], it is easy to see from its proof. Applying Theorem 2.4.2 to the coopposite cogroupoid \mathcal{C}' , we obtain the following corollary:

Corollary 2.4.3. *Let \mathcal{C} be a connected cogroupoid and let $Y \in \text{ob}(\mathcal{C})$ such that $\mathcal{C}(Y, Y)$ is a twisted CY algebra of dimension d with left homological integral $\int_{\mathcal{C}(Y,Y)}^l = \mathbb{k}_\eta$, where $\eta : \mathcal{C}(Y, Y) \rightarrow \mathbb{k}$ is an algebra homomorphism. Then for any $X \in \text{ob}(\mathcal{C})$, $\mathcal{C}(X, Y)$ is a twisted CY algebra of dimension d with Nakayama automorphism μ' defined as $\mu' = S_{X,Y}^{-1} \circ S_{Y,X}^{-1} \circ [\eta]_{X,Y}^r$. That is,*

$$\mu'(a) = S_{X,Y}^{-1}(S_{Y,X}^{-1}(a_1^{X,Y}))\eta(a_2^{Y,Y})$$

for any $x \in \mathcal{C}(X, Y)$.

Theorem 2.4.4. *Let \mathcal{C} be a connected cogroupoid and let X be an object in \mathcal{C} such that $\mathcal{C}(X, X)$ is a twisted CY Hopf algebra of dimension d . Then for any $Y \in \text{ob}(\mathcal{C})$ such that $\mathcal{C}(Y, Y)$ is homologically smooth, $\mathcal{C}(Y, Y)$ is a twisted CY algebra of dimension d as well.*

Proof. Let Y be an object in \mathcal{C} such that $\mathcal{C}(Y, Y)$ is homologically smooth. We need to compute the Hochschild cohomology of $\mathcal{C}(Y, Y)$. By Lemma 2.3.2,

$$\mathrm{Ext}_{\mathcal{C}(X, Y)^e}^i(\mathcal{C}(X, Y), \mathcal{C}(X, Y)^e) \cong \mathrm{Ext}_{\mathcal{C}(Y, Y)^{\mathrm{op}}}^i({}_\varepsilon\mathbb{k}, \mathcal{L}'_Y(\mathcal{C}(X, Y)^e))$$

for all $i \geq 0$. $\mathcal{L}'_Y(\mathcal{C}(X, Y)^e)$ is a $\mathcal{C}(Y, Y)$ - $\mathcal{C}(X, Y)^e$ -bimodule. The left $\mathcal{C}(Y, Y)$ -module isomorphism

$$\mathcal{L}'_Y(\mathcal{C}(X, Y)^e) \rightarrow {}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y), \quad x \otimes y \mapsto x_2^{Y, Y} \otimes y S_{X, Y}^{-1}(S_{Y, X}^{-1}(x_1^{X, Y}))$$

in Lemma 2.3.1 is also an isomorphism of left $\mathcal{C}(X, Y)^e$ -modules if we endow a right $\mathcal{C}(X, Y)^e$ -module structure on ${}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y)$ as follows:

$$(x \otimes y) \leftarrow (a \otimes b) = x a_2^{Y, Y} \otimes b y S_{X, Y}^{-1}(S_{Y, X}^{-1}(a_1^{X, Y}))$$

for any $x \otimes y \in {}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y)$ and $a \otimes b \in \mathcal{C}(X, Y)^e$. Therefore, we obtain the following left $\mathcal{C}(X, Y)^e$ -module isomorphisms:

$$\begin{aligned} \mathrm{Ext}_{\mathcal{C}(X, Y)^e}^i(\mathcal{C}(X, Y), \mathcal{C}(X, Y)^e) &\cong \mathrm{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{L}'_Y(\mathcal{C}(X, Y)^e)) \\ &\cong \mathrm{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, {}_*\mathcal{C}(Y, Y) \otimes \mathcal{C}(X, Y)) \\ &\cong \mathrm{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y) \end{aligned}$$

for $i \geq 0$. The third isomorphism follows from the fact that $\mathcal{C}(Y, Y)$ is homologically smooth, the trivial module ${}_\varepsilon\mathbb{k}$ admits a bounded projective resolution with each term finitely generated (Proposition A.2). The right $\mathcal{C}(X, Y)^e$ -module structure on $\mathrm{Ext}_{\mathcal{C}(Y, Y)^{\mathrm{op}}}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y)$ induced by the isomorphisms above is given by

$$(x \otimes y) \leftarrow (a \otimes b) = x a_2^{Y, Y} \otimes b y S_{X, Y}^{-1}(S_{Y, X}^{-1}(a_1^{X, Y}))$$

for any $x \otimes y \in \mathrm{Ext}_{\mathcal{C}(Y, Y)^{\mathrm{op}}}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y)$ and $a \otimes b \in \mathcal{C}(X, Y)^e$. Note that the right $\mathcal{C}(Y, Y)$ -module structure of $\mathcal{C}(Y, Y)$ induces a right $\mathcal{C}(Y, Y)$ -module structure on $\mathrm{Ext}_{\mathcal{C}(Y, Y)^{\mathrm{op}}}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y))$.

It follows from Theorem 2.4.2 that $\mathcal{C}(X, Y)$ is a twisted CY algebra of dimension d with Nakayama automorphism $\mu = S_{Y, X} \circ S_{X, Y} \circ [\xi]_{X, Y}^l$. So

$$\mathrm{Ext}_{\mathcal{C}(X, Y)^e}^i(\mathcal{C}(X, Y), \mathcal{C}(X, Y)^e) = \begin{cases} 0, & i \neq d, \\ \mathcal{C}(X, Y)^\mu, & i = d. \end{cases}$$

Now we arrive at the isomorphism of left $\mathcal{C}(X, Y)^e$ -modules

$$\mathrm{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y) \cong \begin{cases} 0, & i \neq d, \\ \mathcal{C}(X, Y)^\mu, & i = d. \end{cases}$$

A right $\mathcal{C}(X, Y)^e$ -module can be viewed as a $\mathcal{C}(X, Y)$ -bimodule. The left module structure of $\mathrm{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y)$ is just the left multiplication to the

factor $\mathcal{C}(X, Y)$. So especially, as left $\mathcal{C}(X, Y)$ -modules,

$$\text{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) \otimes \mathcal{C}(X, Y) \cong \begin{cases} 0, & i \neq d, \\ \mathcal{C}(X, Y), & i = d. \end{cases}$$

This shows that $\text{Ext}_{\mathcal{C}(Y, Y)}^i({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y)) = 0$ for $i \neq d$. Moreover, for degree d , we denote $V = \text{Ext}_{\mathcal{C}(Y, Y)}^d({}_\varepsilon\mathbb{k}, \mathcal{C}(Y, Y))$. Then $V \otimes \mathcal{C}(X, Y) \cong \mathcal{C}(X, Y)$ as free left $\mathcal{C}(X, Y)$ -modules. Hence $0 < \dim V < \infty$ (note that we do not know whether $\mathcal{C}(X, Y)$ has the FBN property). Similarly, $\text{Ext}_{\mathcal{C}(Y, Y)^{\text{op}}}^i(\mathbb{k}_\varepsilon, \mathcal{C}(Y, Y)) = 0$ for $i \neq d$ and $\text{Ext}_{\mathcal{C}(Y, Y)^{\text{op}}}^d(\mathbb{k}_\varepsilon, \mathcal{C}(Y, Y))$ is finite dimensional as well. Hence $\mathcal{C}(Y, Y)$ is twisted CY of dimension d by Proposition 2.1.6. \square

Theorem 2.4.5. *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. If H is twisted CY of dimension d and L is homologically smooth, then L is twisted CY of dimension d as well.*

Proof. This directly follows from Theorem 1.1.4 and Theorem 2.4.4. \square

Before we present our next theorem, we need the following lemma:

Lemma 2.4.6. *If H be a Noetherian Hopf algebra, then the trivial Yetter–Drinfeld module \mathbb{k} admits a finitely generated free Yetter–Drinfeld module resolution.*

Proof. First we have an epimorphism $\epsilon : \mathbb{k} \boxtimes H \rightarrow \mathbb{k}$, $1 \otimes h \mapsto \varepsilon(h)$ of Yetter–Drinfeld modules. Set $P_0 = \mathbb{k} \boxtimes H$. Since H is Noetherian, $\text{Ker } \epsilon$ is finitely generated as a module over H . Say it is generated by a finite dimensional subspace V_1 of P_0 . That is, there exists an epimorphism $V_1 \otimes H \rightarrow \text{Ker } \epsilon \rightarrow 0$ given by $v \otimes h \mapsto vh$ for any $v \in V_1$ and $h \in H$. Let C_1 be the subcomodule of $\text{Ker } \epsilon$ generated by V_1 . We know C_1 is finite dimensional since V_1 is finite dimensional by the fundamental theory of comodules. Construct the epimorphism $C_1 \boxtimes H \rightarrow \text{Ker } \epsilon \rightarrow 0$ via $c \otimes h \mapsto ch$ for any $c \in C_1$ and $h \in H$. It is easy to check that it is a morphism of Yetter–Drinfeld modules. Set $P_1 = C_1 \boxtimes H$, we have the exact sequence $P_1 \rightarrow P_0 \rightarrow \mathbb{k} \rightarrow 0$. Note that P_1 is again a Noetherian H -module. Hence we can do the procedure recursively to obtain a finitely generated free Yetter–Drinfeld module resolution of \mathbb{k} . \square

Theorem 2.4.7. *Let H be a twisted CY Hopf algebra of dimension d , and L a Hopf algebra monoidally Morita–Takeuchi equivalent to H . If one of the following conditions holds, then L is also twisted CY of dimension d .*

- (i) *H admits a finitely generated relative projective Yetter–Drinfeld module resolution for the trivial Yetter–Drinfeld module \mathbb{k} and L has finite global dimension.*
- (ii) *H admits a bounded finitely generated relative projective Yetter–Drinfeld module resolution for the trivial Yetter–Drinfeld module \mathbb{k} .*
- (iii) *H is Noetherian and L has finite global dimension.*
- (iv) *L is Noetherian and has finite global dimension.*

Proof. By Theorem 2.4.4, we only need to prove that if one of the conditions listed in the theorem holds, then L is homologically smooth.

In case (i) We use the language of cogroupoids. Since H and L are monoidally Morita–Takeuchi equivalent, there exists a connected cogroupoid with 2 objects X, Y such that $H = \mathcal{C}(X, X)$ and $L = \mathcal{C}(Y, Y)$ (Theorem 1.1.4). By Proposition A.2, to show $L = \mathcal{C}(Y, Y)$ is homologically smooth, we only need to show that the trivial module \mathbb{k}_ε admits a bounded projective resolution with each term finitely generated. By assumption, the trivial Yetter–Drinfeld module \mathbb{k} over the Hopf algebra $H = \mathcal{C}(X, X)$ admits a finitely generated relative projective Yetter–Drinfeld module resolution

$$(10) \quad \cdots \rightarrow P_i \xrightarrow{\delta_i} P_{i-1} \rightarrow \cdots \rightarrow P_1 \rightarrow P_0 \rightarrow \mathbb{k} \rightarrow 0.$$

By Lemma 2.2.5,

$$(11) \quad \cdots \rightarrow P_i \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \xrightarrow{\delta_i \square_{\mathcal{C}(X, X)}} P_{i-1} \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow \cdots \\ \cdots \rightarrow P_1 \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow P_0 \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow \mathbb{k} \rightarrow 0.$$

is a finitely generated relative projective Yetter–Drinfeld module resolution of the trivial Yetter–Drinfeld module \mathbb{k} over $\mathcal{C}(Y, Y)$. So each $P_i \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y)$ is a finite generated projective $\mathcal{C}(Y, Y)$ -module. By assumption, the global dimension of $\mathcal{C}(Y, Y)$ is finite, say n . Set $K_n = \text{Ker}(\delta_{n-1} \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y))$. Following from Lemma 4.1.6 in [Weibel 1994], K_n is projective, so it is a direct summand of $P_n \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y)$. Since $P_n \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y)$ is finitely generated, K_n is finitely generated as well. Therefore,

$$0 \rightarrow K_n \rightarrow P_{n-1} \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow \cdots \\ \cdots \rightarrow P_1 \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow P_0 \square_{\mathcal{C}(X, X)} \mathcal{C}(X, Y) \rightarrow \mathbb{k} \rightarrow 0$$

is a bounded projective resolution with each term finitely generated. Hence, $L = \mathcal{C}(Y, Y)$ is homologically smooth.

The proof in case (ii) uses a similar argument as in case (i) since equations (10) and (11) now are bounded finitely generated projective resolutions for \mathbb{k} .

Case (iii) is a direct consequence of Lemma 2.4.6 and (i).

That the Hopf algebra L is homologically smooth in case (iv) follows from [Brown and Zhang 2008, Lemma 5.2]. \square

Corollary 2.4.8. *Let H and L be two monoidally Morita–Takeuchi equivalent Hopf algebras. If both H and L are twisted CY, then $\text{gldim}(H) = \text{gldim}(L)$.*

Proof. It follows from Theorem 2.4.7 and the fact that for twisted CY Hopf algebras the CY dimension always equals the global dimension by Proposition 2.1.6. \square

Now we discuss the relation between the homological integrals of $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ when both of them are twisted CY.

Theorem 2.4.9. *Let \mathcal{C} be a connected cogroupoid. If X and Y are two objects such that $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are both twisted CY algebras, then we have*

$$(12) \quad (S_{Y,X} \circ S_{X,Y})^2 = [\eta]_{X,Y}^r \circ ([\xi]_{X,Y}^l)^{-1} \circ \gamma,$$

where $\xi : \mathcal{C}(X, X) \rightarrow \mathbb{k}$ and $\eta : \mathcal{C}(Y, Y) \rightarrow \mathbb{k}$ are algebra homomorphisms given by the left homological integrals of $\mathcal{C}(X, X) : \int_{\mathcal{C}(X,X)}^l = \mathbb{k}_\xi$ and $\mathcal{C}(Y, Y) : \int_{\mathcal{C}(Y,Y)}^l = \mathbb{k}_\eta$ respectively, and γ is an inner automorphism of $\mathcal{C}(X, Y)$.

Proof. From Theorem 2.4.2 and Corollary 2.4.3, it is easy to see that the CY-dimensions of $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are equal. Moreover, $\mu = S_{Y,X} \circ S_{X,Y} \circ [\xi]^l$ and $\mu' = S_{X,Y}^{-1} \circ S_{Y,X}^{-1} \circ [\eta]^r$ are the Nakayama automorphisms of $\mathcal{C}(X, Y)$. Since Nakayama automorphisms are unique up to inner automorphisms,

$$S_{Y,X} \circ S_{X,Y} \circ [\xi]_{X,Y}^l = S_{X,Y}^{-1} \circ S_{Y,X}^{-1} \circ [\eta]_{X,Y}^r \circ \gamma,$$

for some inner automorphism γ of $\mathcal{C}(X, Y)$. The automorphism $[\xi]_{X,Y}^l$ commutes with $S_{Y,X} \circ S_{X,Y}$ (Lemma 2.4.1), we obtain that

$$(S_{Y,X} \circ S_{X,Y})^2 = ([\xi]_{X,Y}^l)^{-1} \circ [\eta]_{X,Y}^r \circ \gamma. \quad \square$$

Remark 2.4.10. The three maps composed to give $(S_{Y,X} \circ S_{X,Y})^2$ in (12) commute with each other. This can be proved as in [Brown and Zhang 2008, Proposition 4.6] with the help of Lemma 2.4.1. It is not hard to see that Theorem 2.4.9 holds when $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are both AS-Gorenstein. The equation (12) is just (4.6.1) in the same work when $X = Y$. Since the inner automorphism $\gamma = (S_{Y,X} \circ S_{X,Y})^2 \circ ([\eta]_{X,Y}^r)^{-1} \circ [\xi]_{X,Y}^l$ is intrinsic in $\mathcal{C}(X, Y)$, it prompts us to generalize their Question 4.6 to the Hopf-bigalois object $\mathcal{C}(X, Y)$ when both $\mathcal{C}(X, X)$ and $\mathcal{C}(Y, Y)$ are AS-Gorenstein.

Question 2.4.11. What is the inner automorphism in Theorem 2.4.9?

3. Examples

In this section, we provide some examples.

3.1. Example 1. We take the field \mathbb{k} to be \mathbb{C} in this subsection. Let $E \in \text{GL}_m(\mathbb{C})$ with $m \geq 2$ and let $\mathcal{B}(E)$ be the algebra presented by generators $(u_{ij})_{1 \leq i, j \leq m}$ and relations

$$E^{-1}u^tEu = I_m = uE^{-1}u^tE,$$

where u is the matrix $(u_{ij})_{1 \leq i, j \leq m}$, u^t is the transpose of u and I_m is the identity matrix. The algebra $\mathcal{B}(E)$ is a Hopf algebra and was defined by Dubois-Violette and

Launer [1990] as the quantum automorphism group of the nondegenerate bilinear form associated to E . When

$$E = E_q = \begin{pmatrix} 0 & 1 \\ -q^{-1} & 0 \end{pmatrix},$$

$\mathcal{B}(E_q)$ is just the algebra $\mathcal{O}_q(\mathrm{SL}_2(\mathbb{C}))$, the quantized coordinate algebra of $\mathrm{SL}_2(\mathbb{C})$.

In order to describe Hopf algebras whose comodule categories are monoidally equivalent to the one of $\mathcal{B}(E)$, we recall the cogroupoid \mathcal{B} .

Let $E \in \mathrm{GL}_m(\mathbb{C})$ and let $F \in \mathrm{GL}_n(\mathbb{C})$. The algebra $\mathcal{B}(E, F)$ is defined to be the algebra with generators u_{ij} , $1 \leq i \leq m$, $1 \leq j \leq n$, subject to the relations:

$$(13) \quad F^{-1}u^t E u = I_n; \quad u F^{-1}u^t E = I_m.$$

The generators u_{ij} in $\mathcal{B}(E, F)$ is denoted by u_{ij}^{EF} to express the dependence on E and F when needed. It is clear that $\mathcal{B}(E) = \mathcal{B}(E, E)$.

For any $E \in \mathrm{GL}_m(\mathbb{C})$, $F \in \mathrm{GL}_n(\mathbb{C})$ and $G \in \mathrm{GL}_p(\mathbb{C})$, define the following maps:

$$(14) \quad \Delta_{E,F}^G: \mathcal{B}(E, F) \rightarrow \mathcal{B}(E, G) \otimes \mathcal{B}(G, F), \quad u_{ij} \mapsto \sum_{k=1}^p u_{ik} \otimes u_{kj},$$

$$(15) \quad \varepsilon_E: \mathcal{B}(E) \rightarrow \mathbb{C}, \quad u_{ij} \mapsto \delta_{ij},$$

$$(16) \quad S_{E,F}: \mathcal{B}(E, F) \rightarrow \mathcal{B}(F, E)^{\mathrm{op}}, \quad u \mapsto E^{-1}u^t F.$$

It is clear that $S_{E,F}$ is bijective.

Lemma 3.2 in [Bichon 2014] ensures that with these morphisms we have a cogroupoid. The cogroupoid \mathcal{B} is defined as follows:

- (i) $\mathrm{ob}(\mathcal{B}) = \{E \in \mathrm{GL}_m(\mathbb{C}), m \geq 1\}$.
- (ii) For $E, F \in \mathrm{ob}(\mathcal{B})$, the algebra $\mathcal{B}(E, F)$ is the algebra defined as in (13).
- (iii) The structural maps $\Delta_{\bullet, \bullet}^{\bullet}$, ε_{\bullet} and $S_{\bullet, \bullet}$ are defined in (14), (15) and (16), respectively.

Lemma 3.1.1 [Bichon 2014, Lemma 3.4, Corollary 3.5]. *Let $E \in \mathrm{GL}_m(\mathbb{C})$, $F \in \mathrm{GL}_n(\mathbb{C})$ with $m, n \geq 2$. Then $\mathcal{B}(E, F) \neq (0)$ if and only if $\mathrm{tr}(E^{-1}E^t) = \mathrm{tr}(F^{-1}F^t)$. Consequently, let $\lambda \in \mathbb{C}$, and \mathcal{B}^λ the full subgroupoid of \mathcal{B} with objects*

$$\mathrm{ob}(\mathcal{B}^\lambda) = \{E \in \mathrm{GL}_n(\mathbb{C}), m \geq 2, \mathrm{tr}(E^{-1}E^t) = \lambda\}.$$

Then \mathcal{B}^λ is a connected cogroupoid.

Thus, if $E \in \mathrm{GL}_m(\mathbb{C})$, $F \in \mathrm{GL}_n(\mathbb{C})$ with $m, n \geq 2$ satisfy $\mathrm{tr}(E^{-1}E^t) = \mathrm{tr}(F^{-1}F^t)$, then the comodule categories of $\mathcal{B}(E)$ and $\mathcal{B}(F)$ are monoidally equivalent.

The Calabi–Yau property of the algebras $\mathcal{B}(E)$ was discussed in [Bichon 2013, Section 6] (see also [Walton and Wang 2016] and [Yu 2016]). Theorem 2.4.7 provides a more simplified way to prove that the algebras $\mathcal{B}(E)$ are twisted CY algebras.

Actually, by Lemma 5.6 in [Bichon 2013], the trivial Yetter–Drinfeld module over the algebra $\mathcal{B}(E_q)$ admits a bounded finitely generated free Yetter–Drinfeld module resolution and $\mathcal{B}(E_q)$ twisted CY of dimension 3 with left homological integral $\int_{\mathcal{B}(E_q)}^l = \mathbb{C}_\eta$ given by

$$\eta(u) = \begin{pmatrix} q^{-2} & 0 \\ 0 & q^2 \end{pmatrix}.$$

For any $E \in \text{GL}_m(\mathbb{C})$ ($m \geq 2$), there is a $q \in \mathbb{C}^\times$ such that

$$\text{tr}(E^{-1}E^t) = -q - q^{-1} = \text{tr}(E_q^{-1}E_q^t),$$

so $\mathcal{B}(E)$ and $\mathcal{B}(E_q)$ are monoidally Morita–Takeuchi equivalent. Therefore, the algebra $\mathcal{B}(E)$ is twisted CY by Theorem 2.4.7. Let $\int_{\mathcal{B}(E)}^l = \mathbb{C}_\xi$ be the left homological integral of $\mathcal{B}(E)$, where $\xi : \mathcal{B}(E) \rightarrow \mathbb{C}$ is an algebra homomorphism. Since there are no nontrivial units in $\mathcal{B}(E, E_q)$. Then ξ and η satisfy the equation

$$(S_{E_q, E} \circ S_{E, E_q})^2 = [\eta]_{E, E_q}^t \circ ([\xi]_{E, E_q}^l)^{-1}$$

by Theorem 2.4.9. So ξ is defined by $\xi(u^E) = (E^t)^{-1}E(E^t)^{-1}E$. Hence, the Nakayama automorphism of $\mathcal{B}(E)$ is defined by $\mu(u) = (E^t)^{-1}Eu(E^t)^{-1}E$ [Reyes et al. 2014, Lemma 1.3].

3.2. Example 2. In this subsection, we want to present a class of Hopf algebras such that the inner automorphism in Theorem 2.4.9 can be calculated. We first recall the definition of the 2-cycle cogroupoid.

Let H be a Hopf algebra with bijective antipode. A (right) 2-cocycle on H is a convolution invertible linear map $\sigma : H \otimes H \rightarrow \mathbb{k}$ satisfying

$$\sigma(h_1, k_1)\sigma(h_2k_2, l) = \sigma(k_1, l_1)\sigma(h, k_2l_2), \quad \sigma(h, 1) = \sigma(1, h) = \varepsilon(h)$$

for all $h, k, l \in H$. The set of 2-cocycles on H is denoted $Z^2(H)$. They define the 2-cocycle cogroupoid of H .

Let $\sigma, \tau \in Z^2(H)$. The algebra $H(\sigma, \tau)$ is defined to be the vector space H together with the multiplication given by

$$(17) \quad x \cdot y = \sigma(x_1, y_1)x_2y_2\tau^{-1}(x_3, y_3) \quad \text{for any } x, y \in H.$$

The Hopf algebra $H(\sigma, \sigma)$ is just the cocycle deformation H^σ of H defined by Doi [1993]. The comultiplication of H^σ is the same as the comultiplication of H . However, the multiplication and the antipode are deformed:

$$h \cdot k = \sigma(h_1, k_1)h_2k_2\sigma^{-1}(h_3, k_3), \quad S_{\sigma, \sigma}(h) = \sigma(h_1, S(h_2))S(h_3)\sigma^{-1}(S(h_4), h_5)$$

for any $h, k \in H^\sigma$.

Now we recall the necessary structural maps for the 2-cocycle cogroupoid of H . For any $\sigma, \tau, \omega \in Z^2(H)$, define the following maps:

$$(18) \quad \Delta_{\sigma, \tau}^{\omega} = \Delta: H(\sigma, \tau) \rightarrow H(\sigma, \omega) \otimes H(\omega, \tau), \quad x \mapsto x_1 \otimes x_2.$$

$$(19) \quad \varepsilon_{\sigma} = \varepsilon: H(\sigma, \sigma) \rightarrow \mathbb{k}.$$

$$(20) \quad S_{\sigma, \tau}: H(\sigma, \tau) \rightarrow H(\tau, \sigma), \quad x \mapsto \sigma(x_1, S(x_2))S(x_3)\tau^{-1}(S(x_4), x_5).$$

It is routine to check that the inverse of $S_{\sigma, \tau}$ is given as follows:

$$(21) \quad S_{\sigma, \tau}^{-1}: H(\tau, \sigma) \rightarrow H(\sigma, \tau), \quad x \mapsto \sigma^{-1}(x_5, S^{-1}(x_4))S^{-1}(x_3)\tau(S^{-1}(x_2), x_1).$$

The 2-cocycle cogroupoid of H , denoted \underline{H} , is the cogroupoid defined as follows:

- (i) $\text{ob}(\underline{H}) = Z^2(H)$.
- (ii) For $\sigma, \tau \in Z^2(H)$, the algebra $\underline{H}(\sigma, \tau)$ is the algebra $H(\sigma, \tau)$ defined in (17).
- (iii) The structural maps $\Delta_{\bullet, \bullet}^{\bullet}$, ε_{\bullet} and $S_{\bullet, \bullet}$ are defined in (18), (19) and (20) respectively.

Following [Bichon 2014, Lemma 3.13], the morphisms $\Delta_{\bullet, \bullet}^{\bullet}$, ε_{\bullet} and $S_{\bullet, \bullet}$ indeed satisfy the conditions required for a cogroupoid. It is clear that a 2-cocycle cogroupoid is connected.

Now we recall the definition of the pointed Hopf algebras $U(\mathcal{D}, \lambda)$. For a group Γ , we denote by ${}^{\Gamma}\mathcal{YD}$ the category of Yetter–Drinfeld modules over the group algebra $\mathbb{k}\Gamma$. If Γ is an abelian group, then it is well known that a Yetter–Drinfeld module over the algebra $\mathbb{k}\Gamma$ is just a Γ -graded Γ -module.

We fix the following terminology.

- a free abelian group Γ of finite rank s ;
- a Cartan matrix $\mathbb{A} = (a_{ij}) \in \mathbb{Z}^{\theta \times \theta}$ of finite type, where $\theta \in \mathbb{N}$. Let (d_1, \dots, d_{θ}) be a diagonal matrix of positive integers such that $d_i a_{ij} = d_j a_{ji}$, which is minimal with this property;
- a set \mathcal{X} of connected components of the Dynkin diagram corresponding to the Cartan matrix \mathbb{A} . If $1 \leq i, j \leq \theta$, then $i \sim j$ means that they belong to the same connected component;
- a family $(q_I)_{I \in \mathcal{X}}$ of elements in \mathbb{k} which are *not* roots of unity;
- elements $g_1, \dots, g_{\theta} \in \Gamma$ and characters $\chi_1, \dots, \chi_{\theta} \in \hat{\Gamma}$ such that

$$(22) \quad \chi_j(g_i)\chi_i(g_j) = q_I^{d_i a_{ij}}, \quad \chi_i(g_i) = q_I^{d_i} \quad \text{for all } 1 \leq i, j \leq \theta, I \in \mathcal{X}.$$

For simplicity, we write $q_{ji} = \chi_i(g_j)$. Then equation (22) reads as follows:

$$(23) \quad q_{ii} = q_I^{d_i} \quad \text{and} \quad q_{ij}q_{ji} = q_I^{d_i a_{ij}} \quad \text{for all } 1 \leq i, j \leq \theta, I \in \mathcal{X}.$$

Let \mathcal{D} be the collection $\mathcal{D}(\Gamma, (a_{ij})_{1 \leq i, j \leq \theta}, (q_l)_{l \in \mathcal{X}}, (g_i)_{1 \leq i \leq \theta}, (\chi_i)_{1 \leq i \leq \theta})$. A *linking datum* $\lambda = (\lambda_{ij})$ for \mathcal{D} is a collection of elements $(\lambda_{ij})_{1 \leq i < j \leq \theta, i \approx j} \in \mathbb{k}$ such that $\lambda_{ij} = 0$ if $g_i g_j = 1$ or $\chi_i \chi_j \neq \varepsilon$. We write the datum $\lambda = 0$, if $\lambda_{ij} = 0$ for all $1 \leq i < j \leq \theta$. The datum $(\mathcal{D}, \lambda) = (\Gamma, (a_{ij}), q_l, (g_i), (\chi_i), (\lambda_{ij}))$ is called a *generic datum of finite Cartan type* for group Γ .

A generic datum of finite Cartan type for a group Γ defines a Yetter–Drinfeld module over the group algebra $\mathbb{k}\Gamma$. Let V be a vector space with basis $\{x_1, x_2, \dots, x_\theta\}$. We set

$$|x_i| = g_i, \quad g(x_i) = \chi_i(g)x_i, \quad 1 \leq i \leq \theta, g \in \Gamma,$$

where $|x_i|$ denotes the degree of x_i . This makes V a Yetter–Drinfeld module over the group algebra $\mathbb{k}\Gamma$. We write $V = \{x_i, g_i, \chi_i\}_{1 \leq i \leq \theta} \in {}_\Gamma^{\Gamma}\mathcal{YD}$. The braiding is given by

$$c(x_i \otimes x_j) = q_{ij} x_j \otimes x_i, \quad 1 \leq i, j \leq \theta.$$

The tensor algebra $T(V)$ on V is a natural graded braided Hopf algebra in ${}_\Gamma^{\Gamma}\mathcal{YD}$. The smash product $T(V) \# \mathbb{k}\Gamma$ is a usual Hopf algebra. It is also called a bosonization of $T(V)$ by $\mathbb{k}\Gamma$.

Definition 3.2.1. Given a generic datum of finite Cartan type (\mathcal{D}, λ) for a group Γ , define $U(\mathcal{D}, \lambda)$ as the quotient Hopf algebra of the smash product $T(V) \# \mathbb{k}\Gamma$ modulo the ideal generated by

$$\begin{aligned} (\text{ad}_c x_i)^{1-a_{ij}}(x_j) &= 0, & 1 \leq i \neq j \leq \theta, \quad i \sim j, \\ x_i x_j - \chi_j(g_i) x_j x_i &= \lambda_{ij}(g_i g_j - 1), & 1 \leq i < j \leq \theta, \quad i \approx j, \end{aligned}$$

where ad_c is the braided adjoint representation defined in [Andruskiewitsch and Schneider 2004, Sec. 1].

To present the CY property of the algebras $U(\mathcal{D}, \lambda)$, we recall the concept of root vectors. Let Φ be the root system corresponding to the Cartan matrix \mathbb{A} with $\{\alpha_1, \dots, \alpha_\theta\}$ a set of fixed simple roots, and \mathcal{W} the Weyl group. We fix a reduced decomposition of the longest element $w_0 = s_{i_1} \cdots s_{i_p}$ of \mathcal{W} in terms of the simple reflections. Then the positive roots are precisely the following:

$$\beta_1 = \alpha_{i_1}, \quad \beta_2 = s_{i_1}(\alpha_{i_2}), \dots, \beta_p = s_{i_1} \cdots s_{i_{p-1}}(\alpha_{i_p}).$$

For $\beta_i = \sum_{a=1}^\theta m_a \alpha_a$, we write $g_{\beta_i} = g_1^{m_1} \cdots g_\theta^{m_\theta}$ and $\chi_{\beta_i} = \chi_1^{m_1} \cdots \chi_\theta^{m_\theta}$.

Lusztig [1993] defined the root vectors for a quantum group $U_q(\mathfrak{g})$. Up to a nonzero scalar, each root vector can be expressed as an iterated braided commutator. In [Andruskiewitsch and Schneider 2002, Sec. 4.1], the root vectors were generalized on a pointed Hopf algebras $U(\mathcal{D}, \lambda)$. For each positive root β_i , $1 \leq i \leq p$, the root vector x_{β_i} is defined by the same iterated braided commutator of the elements x_1, \dots, x_θ , but with respect to the general braiding.

Remark 3.2.2. If $\beta_j = \alpha_l$, then we have $x_{\beta_j} = x_l$. That is, x_1, \dots, x_θ are the simple root vectors.

Lemma 3.2.3 [Yu et al. 2016, Lemma 3.3]. *Let (\mathcal{D}, λ) be a generic datum of finite Cartan type for a group Γ , and H the Hopf algebra $U(\mathcal{D}, \lambda)$. Let s be the rank of Γ and p the number of the positive roots of the Cartan matrix.*

- (i) *The algebra H is Noetherian AS-regular of global dimension $p + s$. The left homological integral module \int_H^l of H is isomorphic to \mathbb{k}_ξ , where $\xi : H \rightarrow \mathbb{k}$ is an algebra homomorphism defined by $\xi(g) = (\prod_{i=1}^p \chi_{\beta_i})(g)$ for all $g \in \Gamma$ and $\xi(x_k) = 0$ for all $1 \leq k \leq \theta$.*
- (ii) *The algebra H is twisted CY with Nakayama automorphism μ defined by $\mu(x_k) = q_{kk}x_k$ for all $1 \leq k \leq \theta$, and $\mu(g) = (\prod_{i=1}^p \chi_{\beta_i})(g)$ for all $g \in \Gamma$.*

Let (\mathcal{D}, λ) be a generic datum of finite Cartan type for a group Γ . The algebra $U(\mathcal{D}, \lambda)$ is a cocycle deformation of $U(\mathcal{D}, 0)$. That is $U(\mathcal{D}, \lambda) = U(\mathcal{D}, 0)^\sigma$, where σ is the cocycle defined by

$$(24) \quad \begin{aligned} \sigma(g, g') &= 1, \\ \sigma(g, x_i) &= \sigma(x_i, g) = 0, \quad 1 \leq i \leq \theta, g, g' \in \Gamma, \\ \sigma(x_i, x_j) &= \begin{cases} \lambda_{ij}, & i < j, i \not\approx j, \\ 0, & \text{otherwise.} \end{cases} \end{aligned}$$

Lemma 3.2.3 shows that both $U(\mathcal{D}, 0)$ and its cocycle deformation $U(\mathcal{D}, \lambda)$ are twisted CY. The algebras $U(\mathcal{D}, \lambda)$ are Noetherian with finite global dimension by Lemma 2.1 in [Yu and Zhang 2013]. Therefore, Theorem 2.4.7 explains why for this class of Hopf algebras, cocycle deformation preserves the CY property.

With Lemma 3.2.3, we can write the inner automorphism in Theorem 2.4.9 explicitly.

Proposition 3.2.4. *Let H be $U(\mathcal{D}, 0)$, then $U(\mathcal{D}, \lambda) = H^\sigma$, where σ is the cocycle as defined in (24). Let $\int_H^l = \mathbb{k}_\xi$ and $\int_{H^\sigma}^r = \mathbb{k}_\eta$ be left homological integral of H and H^σ respectively, where $\xi : H \rightarrow \mathbb{k}$ and $\eta : H^\sigma \rightarrow \mathbb{k}$ are algebra homomorphisms. Then the following equation holds.*

$$(S_{\sigma,1} \circ S_{1,\sigma})^2 = [\eta]_{1,\sigma}^r \circ ([\xi]_{1,\sigma}^l)^{-1} \circ \gamma,$$

where γ is the inner automorphism defined by $\gamma(x_k) = [\prod_{i=1}^p g_{\beta_i}]^{-1}(x_k)[\prod_{i=1}^p g_{\beta_i}]$ for $1 \leq k \leq \theta$ and $\gamma(g) = g$ for any $g \in \Gamma$.

Appendix

We list two basic homological properties of Hopf algebras. They are well known, but due to a lack of convenient references, we provide in most cases their proofs. We do not require bijectivity of antipode or Noetherianity of a Hopf algebra.

First we want to show that for a Hopf algebra, the left global dimension always equals the right global dimension.

Let H be a Hopf algebra. We denote the left global dimension, the right global dimension and the Hochschild dimension of H by $\text{lgldim}(H)$, $\text{rgldim}(H)$ and $\text{Hdim}(H)$, respectively. We have the left adjoint functor $L : \text{Mod } H^e \rightarrow \text{Mod } H$ and the right adjoint functor $R : \text{Mod}(H^e)^{\text{op}} \rightarrow \text{Mod } H^{\text{op}}$. Let M be an H -bimodule. Then $L(M)$ is a left H -module defined by the action

$$x \rightarrow m = x_1 m S(x_2) \quad \text{for any } x \in H.$$

While $R(M)$ is a right H -module defined by the action

$$m \leftarrow x = S(x_1) m x_2 \quad \text{for any } x \in H.$$

Proposition A.1. *Let H be a Hopf algebra. Then*

$$\text{projdim } \mathbb{k}_\varepsilon = \text{projdim } {}_\varepsilon \mathbb{k} = \text{rgldim}(H) = \text{lgldim}(H) = \text{Hdim}(H).$$

Proof. That $\text{projdim } \mathbb{k}_\varepsilon = \text{rgldim}(H)$ and $\text{projdim } {}_\varepsilon \mathbb{k} = \text{lgldim}(H)$ follows from [Lorenz and Lorenz 1995, Section 2.4]. We know from [Cartan and Eilenberg 1956, IX.7.6] that $\text{rgldim}(H)$ and $\text{lgldim}(H)$ are bounded by $\text{Hdim}(H)$. Let M be any H -bimodule. By Lemma 2.4 in [Brown and Zhang 2008], there are isomorphisms $\text{Ext}_{H^e}^i(H, M) \cong \text{Ext}_H^i({}_\varepsilon \mathbb{k}, L(M))$ for $i \geq 0$. This shows that $\text{Hdim}(H) \leq \text{lgldim}(H)$. Similarly, for $i \geq 0$, the isomorphisms $\text{Ext}_{H^e}^i(H, M) \cong \text{Ext}_H^i(\mathbb{k}_\varepsilon, R(M))$ hold. So $\text{Hdim}(H) \leq \text{rgldim}(H)$. Therefore, we have $\text{rgldim}(H) = \text{lgldim}(H) = \text{Hdim}(H)$. In conclusion, we obtain that

$$\text{projdim } \mathbb{k}_\varepsilon = \text{projdim } {}_\varepsilon \mathbb{k} = \text{rgldim}(H) = \text{lgldim}(H) = \text{Hdim}(H). \quad \square$$

Next we want to show that to see whether a Hopf algebra H is homologically smooth it is enough to investigate the projective resolution of the trivial module.

Proposition A.2. *Let H be a Hopf algebra. The following are equivalent:*

- (i) *The algebra H is homologically smooth.*
- (ii) *The left trivial module ${}_\varepsilon \mathbb{k}$ admits a bounded projective resolution with each term finitely generated.*
- (iii) *The right trivial module \mathbb{k}_ε admits a bounded projective resolution with each term finitely generated.*

Proof. We only need to show that (i) and (ii) are equivalent. (i) \iff (iii) can be proved symmetrically.

(i) \implies (ii) Suppose that H is homologically smooth. That is, H has a resolution

$$0 \rightarrow P_n \rightarrow P_{n-1} \rightarrow \cdots \rightarrow P_1 \rightarrow P_0 \rightarrow H \rightarrow 0$$

such that each term is a finitely generated projective H^e -module. Following from Lemma 2.4 in [Berger and Taillefer 2007],

$$0 \rightarrow P_n \otimes_H \varepsilon\mathbb{k} \rightarrow P_{n-1} \otimes_H \varepsilon\mathbb{k} \rightarrow \cdots \rightarrow P_1 \otimes_H \varepsilon\mathbb{k} \rightarrow P_0 \otimes_H \varepsilon\mathbb{k} \rightarrow \varepsilon\mathbb{k} \rightarrow 0$$

is a projective resolution of $\varepsilon\mathbb{k}$. Clearly, it is a bounded projective resolution with each term finitely generated as left H -module.

(ii) \Rightarrow (i) View H^e as an H^e - H -bimodule via

$$a \otimes b \rightarrow x \otimes y = ax \otimes yb, \quad (x \otimes y) \leftarrow a = xa_1 \otimes S(a_2)y$$

for any $a \otimes b, x \otimes y \in H^e$ and $a \in H$. Let $H \otimes H_*$ be the free right H -module defined by multiplication to the second factor H . The morphism

$$H^e \rightarrow H \otimes H_*, \quad x \otimes y \mapsto x_2y \otimes x_1$$

is an isomorphism of right H -modules with inverse

$$H \otimes H_* \rightarrow H^e, \quad x \otimes y \mapsto y_1 \otimes S(y_2)x.$$

That is, $H^e \cong H \otimes H_*$ as right H -modules. So the functor $H^e \otimes_H - : \text{Mod } H \rightarrow \text{Mod } H^e$ is exact. This functor clearly sends projective H -modules to projective H^e -modules. Moreover, $H^e \otimes_H \varepsilon\mathbb{k} \cong H$ as left H^e -modules. The isomorphism $H^e \otimes_H \varepsilon\mathbb{k} \rightarrow H$ is defined by $x \otimes y \mapsto xy$. Therefore, if the left trivial module $\varepsilon\mathbb{k}$ admits a bounded projective resolution \mathbf{Q} , with each term finitely generated, then $H^e \otimes_H \mathbf{Q}$ is a bounded projective resolution of H over H^e with each term finitely generated. That is, H is homologically smooth. \square

Acknowledgement

The authors sincerely thank the referee for his/her valuable comments and suggestions that helped them to improve the paper quite a lot. Wang and Yu are grateful to the Department of Mathematics of Zhejiang Normal University for the hospitality they received during a visit in summer 2016. Wang is supported by AMS-Simons travel grant. Yu is supported by grants from NSFC (No. 11301126, No. 11571316, No. 11671351).

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Received October 12, 2016. Revised February 17, 2017.

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The Pacific Journal of Mathematics (ISSN 0030-8730) at the University of California, c/o Department of Mathematics, 798 Evans Hall #3840, Berkeley, CA 94720-3840, is published twelve times a year. Periodical rate postage paid at Berkeley, CA 94704, and additional mailing offices. POSTMASTER: send address changes to Pacific Journal of Mathematics, P.O. Box 4163, Berkeley, CA 94704-0163.

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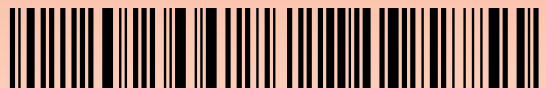
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