

Quantum Group Actions and Hopf Algebras

Brandon Mather

University of North Texas Master's Defense
Department of Mathematics
February 28th 2024

- (1939) Heinz Hopf works on homology of sphere groups
- (1969) Moss Sweedler writes seminal book “Hopf Algebras”
- (1986) Vladimir Drinfeld gives ICM address on quantum groups
- (1992) Susan Montgomery writes “Hopf Algebras and Their Actions on Rings”

Goal

To understand the actions of Hopf algebras on other algebras

Notation: $\mathbb{C}[v_1, \dots, v_n] = \mathbb{C} \langle v_1, \dots, v_n \mid v_j v_i = v_i v_j \rangle$

Quantum Polynomial Ring

Let $Q = (q_{ij})$ be an $n \times n$ matrix of roots of unity where

$$q_{ii} = 1 = q_{ji} q_{ij}.$$

A **quantum polynomial ring** is

$$\mathbb{C}_Q[v_1, \dots, v_n] = \mathbb{C} \langle v_1, \dots, v_n \mid v_j v_i = q_{ij} v_i v_j \rangle.$$

Example: $\mathbb{C}_{-1}[v_1, v_2] = \mathbb{C} \langle v_1, v_2 \mid v_1 v_2 = -v_2 v_1 \rangle$

Motivation

- 1 When a grp G acts on a space V over \mathbb{C} linearly, the action can be extended to $V \otimes V$ by $g \in G$ acting as

$$g \otimes g = \Delta(g).$$

Then Δ defines a coproduct map

$$\Delta : \mathbb{C}G \rightarrow \mathbb{C}G \otimes \mathbb{C}G.$$

For an arbitrary set A with a coproduct $\Delta : A \rightarrow A \otimes A$, we call $g \in A$ **grouplike** if $\Delta(g) = g \otimes g$.

Motivation

- ① When a grp G acts on a space V over \mathbb{C} linearly, the action can be extended to $V \otimes V$ by $g \in G$ acting as

$$g \otimes g = \Delta(g).$$

Then Δ defines a coproduct map

$$\Delta : \mathbb{C}G \rightarrow \mathbb{C}G \otimes \mathbb{C}G.$$

For an arbitrary set A with a coproduct $\Delta : A \rightarrow A \otimes A$, we call $g \in A$ **grouplike** if $\Delta(g) = g \otimes g$.

- ② When a Lie alg \mathfrak{g} acts on a space V over \mathbb{C} , the action can be extended to $V \otimes V$ by $x \in \mathfrak{g}$ acting as

$$x \otimes 1 + 1 \otimes x = \Delta(x).$$

Then Δ defines a coproduct map

$$\Delta : \mathfrak{g} \rightarrow \mathfrak{g} \otimes \mathfrak{g}.$$

For an arbitrary set A with a coproduct $\Delta : A \rightarrow A \otimes A$, we call $x \in A$ **primitive** if $\Delta(x) = x \otimes 1 + 1 \otimes x$.

We want an algebra that synthesizes group actions and actions by Lie algebras.

Hopf algebras combine the notions of Algebras with products and Coalgebras with coproducts.

We are looking for actions of Hopf algebras. In particular, on non-commutative algebras like Quantum Polynomial Rings.

Sweedler's Algebra

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

with operations $\Delta : H_4 \rightarrow H_4 \otimes H_4$,

$$\Delta(g) = g \otimes g, \qquad \Delta(x) = x \otimes 1 + g \otimes x$$

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

with operations $\Delta : H_4 \rightarrow H_4 \otimes H_4$, $\varepsilon : H_4 \rightarrow \mathbb{C}$,

$$\Delta(g) = g \otimes g, \quad \Delta(x) = x \otimes 1 + g \otimes x$$

$$\varepsilon(g) = 1, \quad \varepsilon(x) = 0$$

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

with operations $\Delta : H_4 \rightarrow H_4 \otimes H_4$, $\varepsilon : H_4 \rightarrow \mathbb{C}$, $S : H_4 \rightarrow H_4$

$$\Delta(g) = g \otimes g,$$

$$\Delta(x) = x \otimes 1 + g \otimes x$$

$$\varepsilon(g) = 1,$$

$$\varepsilon(x) = 0$$

$$S(g) = g^{-1},$$

$$S(x) = -x$$

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

with operations $\Delta : H_4 \rightarrow H_4 \otimes H_4$, $\varepsilon : H_4 \rightarrow \mathbb{C}$, $S : H_4 \rightarrow H_4$

$$\Delta(g) = g \otimes g,$$

$$\Delta(x) = x \otimes 1 + g \otimes x$$

$$\varepsilon(g) = 1,$$

$$\varepsilon(x) = 0$$

$$S(g) = g^{-1},$$

$$S(x) = -x$$

Group-like

$(1, g)$ – Primitive

The unique 4-dim'l non-commutative, non-cocommutative Hopf alg given by M. Sweedler (1969):

$$H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$$

with operations $\Delta : H_4 \rightarrow H_4 \otimes H_4$, $\varepsilon : H_4 \rightarrow \mathbb{C}$, $S : H_4 \rightarrow H_4$

$$\Delta(g) = g \otimes g,$$

$$\Delta(x) = x \otimes 1 + g \otimes x$$

$$\varepsilon(g) = 1,$$

$$\varepsilon(x) = 0$$

$$S(g) = g^{-1},$$

$$S(x) = -x$$

Group-like

$(1, g)$ – Primitive

Let τ be the 'flip' over the tensor product, so $\tau(u \otimes v) = v \otimes u$.
Note that $\tau \circ \Delta(x) \neq \Delta(x)$, so H is non-cocommutative.

Actions of Sweedler's Algebra

H_4 acts on $\mathbb{C}_{-1}[v_1, v_2]$ by

$$g \cdot v_1 = v_1, \quad g \cdot v_2 = -v_2, \quad x \cdot v_1 = 0, \quad x \cdot v_2 = v_1.$$

H_4 acts on $\mathbb{C}_{-1}[v_1, v_2]$ by

$$g \cdot v_1 = v_1, \quad g \cdot v_2 = -v_2, \quad x \cdot v_1 = 0, \quad x \cdot v_2 = v_1.$$

We can express this action on the generators v_1, v_2 as

$$g \mapsto \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad x \mapsto \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}.$$

Kac-Paljutkin Algebra

The unique 8-dim'l non-comm., non-cocomm. Hopf alg given by G. Kac and V. Paljutkin in "Finite Ring Groups" (1966):

$$H_8 =$$

$$\left\langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy) \right\rangle$$

Kac-Paljutkin Algebra

The unique 8-dim'l non-comm., non-cocomm. Hopf alg given by G. Kac and V. Paljutkin in "Finite Ring Groups" (1966):

$$H_8 =$$

$$\left\langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy) \right\rangle$$

with operations

$$\Delta(x) = x \otimes x, \quad \Delta(y) = y \otimes y,$$

$$\Delta(z) = \frac{1}{2}(1 \otimes 1 + 1 \otimes x + y \otimes 1 - y \otimes x)(z \otimes z),$$

Kac-Paljutkin Algebra

The unique 8-dim'l non-comm., non-cocomm. Hopf alg given by G. Kac and V. Paljutkin in "Finite Ring Groups" (1966):

$$H_8 =$$

$$\langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy) \rangle$$

with operations

$$\Delta(x) = x \otimes x, \quad \Delta(y) = y \otimes y,$$

$$\Delta(z) = \frac{1}{2}(1 \otimes 1 + 1 \otimes x + y \otimes 1 - y \otimes x)(z \otimes z),$$

$$\varepsilon(x) = \varepsilon(y) = \varepsilon(z) = 1,$$

The unique 8-dim'l non-comm., non-cocomm. Hopf alg given by G. Kac and V. Paljutkin in "Finite Ring Groups" (1966):

$$H_8 =$$

$$\left\langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy) \right\rangle$$

with operations

$$\Delta(x) = x \otimes x, \Delta(y) = y \otimes y,$$

$$\Delta(z) = \frac{1}{2}(1 \otimes 1 + 1 \otimes x + y \otimes 1 - y \otimes x)(z \otimes z),$$

$$\varepsilon(x) = \varepsilon(y) = \varepsilon(z) = 1,$$

$$S(x) = x, S(y) = y, S(z) = z.$$

Actions of Kac-Paljutkin Algebra

H_8 acts on $\mathbb{C}_q[v_1, v_2]$ where $q^2 = -1$ via the representation

$$x \mapsto \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Actions of Kac-Paljutkin Algebra

H_8 acts on $\mathbb{C}_q[v_1, v_2]$ where $q^2 = -1$ via the representation

$$x \mapsto \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

And on $\mathbb{C}_Q[v_1, v_2, v_3, v_4]$ for

$q_{12} = q_{34}^{-1}$, $q_{13} = q_{24}^{-1}$, $q_{14}^2 = 1$, $q_{23}^2 = -1$ via the representation

$$x \mapsto \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}.$$

Actions of Kac-Paljutkin Algebra

H_8 acts on $\mathbb{C}_q[v_1, v_2]$ where $q^2 = -1$ via the representation

$$x \mapsto \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

And on $\mathbb{C}_Q[v_1, v_2, v_3, v_4]$ for

$q_{12} = q_{34}^{-1}$, $q_{13} = q_{24}^{-1}$, $q_{14}^2 = 1$, $q_{23}^2 = -1$ via the representation

$$x \mapsto \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}.$$

And on $\mathbb{C}_{-1}[v_1, v_2]$ via the rep

$$x \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad y \mapsto \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}, \quad z \mapsto \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}.$$

Quantized Universal Enveloping Algebra

Described by P. Kulish and N. Reshetikhin in “Quantum linear problem...” (1983), leading Vladimir Drinfeld to quantum groups:

$$\mathcal{U}_q(\mathfrak{sl}_2) =$$

$$\left\langle E, F, K, K^{-1} \mid EF - FE = (q - q^{-1})^{-1} (K - K^{-1}), KEK^{-1} = q^2 E, \right. \\ \left. KFK^{-1} = q^{-2} F, KK^{-1} = K^{-1}K = 1 \right\rangle$$

Quantized Universal Enveloping Algebra

Described by P. Kulish and N. Reshetikhin in “Quantum linear problem...” (1983), leading Vladimir Drinfeld to quantum groups:
 $\mathcal{U}_q(\mathfrak{sl}_2) =$

$$\left\langle E, F, K, K^{-1} \mid EF - FE = (q - q^{-1})^{-1} (K - K^{-1}), KEK^{-1} = q^2 E, \right. \\ \left. KFK^{-1} = q^{-2} F, KK^{-1} = K^{-1}K = 1 \right\rangle$$

with operations:

$$\Delta(E) = E \otimes 1 + K \otimes E, \Delta(F) = F \otimes K^{-1} + 1 \otimes F,$$

$$\Delta(K) = K \otimes K, \Delta(K^{-1}) = K^{-1} \otimes K^{-1},$$

Quantized Universal Enveloping Algebra

Described by P. Kulish and N. Reshetikhin in “Quantum linear problem...” (1983), leading Vladimir Drinfeld to quantum groups:
 $\mathcal{U}_q(\mathfrak{sl}_2) =$

$$\left\langle E, F, K, K^{-1} \mid EF - FE = (q - q^{-1})^{-1} (K - K^{-1}), KEK^{-1} = q^2 E, \right. \\ \left. KFK^{-1} = q^{-2} F, KK^{-1} = K^{-1}K = 1 \right\rangle$$

with operations:

$$\Delta(E) = E \otimes 1 + K \otimes E, \Delta(F) = F \otimes K^{-1} + 1 \otimes F,$$

$$\Delta(K) = K \otimes K, \Delta(K^{-1}) = K^{-1} \otimes K^{-1},$$

$$\varepsilon(E) = \varepsilon(F) = 0, \varepsilon(K) = \varepsilon(K^{-1}) = 1,$$

Quantized Universal Enveloping Algebra

Described by P. Kulish and N. Reshetikhin in “Quantum linear problem...” (1983), leading Vladimir Drinfeld to quantum groups:
 $\mathcal{U}_q(\mathfrak{sl}_2) =$

$$\left\langle E, F, K, K^{-1} \mid EF - FE = (q - q^{-1})^{-1} (K - K^{-1}), KEK^{-1} = q^2 E, \right. \\ \left. KFK^{-1} = q^{-2} F, KK^{-1} = K^{-1}K = 1 \right\rangle$$

with operations:

$$\Delta(E) = E \otimes 1 + K \otimes E, \Delta(F) = F \otimes K^{-1} + 1 \otimes F,$$

$$\Delta(K) = K \otimes K, \Delta(K^{-1}) = K^{-1} \otimes K^{-1},$$

$$\varepsilon(E) = \varepsilon(F) = 0, \varepsilon(K) = \varepsilon(K^{-1}) = 1,$$

$$S(E) = -K^{-1}E, S(F) = -FK, S(K) = K^{-1}, S(K^{-1}) = K.$$

Quantized Universal Enveloping Algebra

Described by P. Kulish and N. Reshetikhin in “Quantum linear problem...” (1983), leading Vladimir Drinfeld to quantum groups:

$$\mathcal{U}_q(\mathfrak{sl}_2) =$$

$$\left\langle E, F, K, K^{-1} \mid EF - FE = (q - q^{-1})^{-1} (K - K^{-1}), KEK^{-1} = q^2 E, \right. \\ \left. KFK^{-1} = q^{-2} F, KK^{-1} = K^{-1}K = 1 \right\rangle$$

with operations:

$$\Delta(E) = E \otimes 1 + K \otimes E, \Delta(F) = F \otimes K^{-1} + 1 \otimes F,$$

$$\Delta(K) = K \otimes K, \Delta(K^{-1}) = K^{-1} \otimes K^{-1},$$

$$\varepsilon(E) = \varepsilon(F) = 0, \varepsilon(K) = \varepsilon(K^{-1}) = 1,$$

$$S(E) = -K^{-1}E, S(F) = -FK, S(K) = K^{-1}, S(K^{-1}) = K.$$

Note: You can recover $\mathcal{U}(\mathfrak{sl}_2)$ by limiting $q \rightarrow 1$.

Actions of $\mathcal{U}_q(\mathfrak{sl}_2)$

$\mathcal{U}_q(\mathfrak{sl}_2)$ acts on $\mathbb{C}_q[v_1, v_2]$, where $q^2 \neq 1$, via the representation

Actions of $\mathcal{U}_q(\mathfrak{sl}_2)$

$\mathcal{U}_q(\mathfrak{sl}_2)$ acts on $\mathbb{C}_q[v_1, v_2]$, where $q^2 \neq 1$, via the representation

$$E \mapsto \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

$$F \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

Actions of $\mathcal{U}_q(\mathfrak{sl}_2)$

$\mathcal{U}_q(\mathfrak{sl}_2)$ acts on $\mathbb{C}_q[v_1, v_2]$, where $q^2 \neq 1$, via the representation

$$E \mapsto \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

$$K \mapsto \begin{bmatrix} q & 0 \\ 0 & q^{-1} \end{bmatrix}$$

$$F \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

$$K^{-1} \mapsto \begin{bmatrix} q^{-1} & 0 \\ 0 & q \end{bmatrix}$$

Hopf Algebra

A **Hopf algebra** is a bialgebra H over a field with an antipode $S : H \rightarrow H$ where the bialgebra operations are

Hopf Algebra

A **Hopf algebra** is a bialgebra H over a field with an antipode

$S : H \rightarrow H$ where the bialgebra operations are

$$\nabla : H \otimes H \rightarrow H,$$

so that the following commute:

Associativity:

$$\begin{array}{ccc} H \otimes H \otimes H & \xrightarrow{\nabla \otimes id} & H \otimes H \\ id \otimes \nabla \downarrow & & \downarrow \nabla \\ H \otimes H & \xrightarrow{\nabla} & H \end{array}$$

Hopf Algebra

A **Hopf algebra** is a bialgebra H over a field with an antipode

$S : H \rightarrow H$ where the bialgebra operations are

$$\nabla : H \otimes H \rightarrow H,$$

$$1_H : \mathbb{C} \rightarrow H,$$

so that the following commute:

Associativity:

$$\begin{array}{ccc} H \otimes H \otimes H & \xrightarrow{\nabla \otimes id} & H \otimes H \\ id \otimes \nabla \downarrow & & \downarrow \nabla \\ H \otimes H & \xrightarrow{\nabla} & H \end{array}$$

Unit:

$$\begin{array}{ccccc} & & H \otimes H & & \\ 1_H \otimes id \nearrow & & \downarrow \nabla & \nwarrow id \otimes 1_H & \\ \mathbb{C} \otimes H & & H & & H \otimes \mathbb{C} \\ \searrow = & & & \swarrow = & \\ & & H & & \end{array}$$

Hopf Algebra

A **Hopf algebra** is a bialgebra H over a field with an antipode

$S : H \rightarrow H$ where the bialgebra operations are

$$\nabla : H \otimes H \rightarrow H,$$

$$\Delta : H \rightarrow H \otimes H,$$

$$1_H : \mathbb{C} \rightarrow H,$$

so that the following commute:

Associativity:

$$\begin{array}{ccc} H \otimes H \otimes H & \xrightarrow{\nabla \otimes id} & H \otimes H \\ id \otimes \nabla \downarrow & & \downarrow \nabla \\ H \otimes H & \xrightarrow{\nabla} & H \end{array}$$

Coassociativity:

$$\begin{array}{ccc} H & \xrightarrow{\Delta} & H \otimes H \\ \Delta \downarrow & & \downarrow \Delta \otimes id \\ H \otimes H & \xrightarrow{id \otimes \Delta} & H \otimes H \otimes H \end{array}$$

Unit:

$$\begin{array}{ccccc} & & H \otimes H & & \\ 1_H \otimes id \nearrow & & \downarrow \nabla & \nwarrow id \otimes 1_H & \\ \mathbb{C} \otimes H & & H & & H \otimes \mathbb{C} \\ \searrow = & & & \swarrow = & \\ & & H & & \end{array}$$

Hopf Algebra

A **Hopf algebra** is a bialgebra H over a field with an antipode

$S : H \rightarrow H$ where the bialgebra operations are

$$\nabla : H \otimes H \rightarrow H,$$

$$1_H : \mathbb{C} \rightarrow H,$$

$$\Delta : H \rightarrow H \otimes H,$$

$$\varepsilon : H \rightarrow \mathbb{C}$$

so that the following commute:

Associativity:

$$\begin{array}{ccc} H \otimes H \otimes H & \xrightarrow{\nabla \otimes id} & H \otimes H \\ id \otimes \nabla \downarrow & & \downarrow \nabla \\ H \otimes H & \xrightarrow{\nabla} & H \end{array}$$

Coassociativity:

$$\begin{array}{ccc} H & \xrightarrow{\Delta} & H \otimes H \\ \Delta \downarrow & & \downarrow \Delta \otimes id \\ H \otimes H & \xrightarrow{id \otimes \Delta} & H \otimes H \otimes H \end{array}$$

Unit:

$$\begin{array}{ccccc} & & H \otimes H & & \\ 1_H \otimes id \nearrow & & \downarrow \nabla & \nwarrow id \otimes 1_H & \\ \mathbb{C} \otimes H & & H & & H \otimes \mathbb{C} \\ & \searrow = & & \swarrow = & \\ & & H & & \end{array}$$

Counit:

$$\begin{array}{ccccc} & & H & & \\ \varepsilon \otimes id \nwarrow & & \downarrow \Delta & \nearrow id \otimes \varepsilon & \\ \mathbb{C} \otimes H & & H \otimes H & & H \otimes \mathbb{C} \\ & \nwarrow = & & \swarrow = & \\ & & H & & \end{array}$$

Hopf Algebra Diagrams

Product and Coproduct compatibility:

$$\begin{array}{ccccc}
 H \otimes H & \xrightarrow{\quad \nabla \quad} & H & \xrightarrow{\quad \Delta \quad} & H \otimes H \\
 \Delta \otimes \Delta \downarrow & & & & \uparrow \nabla \otimes \nabla \\
 H \otimes H \otimes H \otimes H & \xrightarrow{\quad id \otimes \tau \otimes id \quad} & H \otimes H \otimes H \otimes H & &
 \end{array}$$

Hopf Algebra Diagrams

Product and Coproduct compatibility:

$$\begin{array}{ccccc}
 H \otimes H & \xrightarrow{\nabla} & H & \xrightarrow{\Delta} & H \otimes H \\
 \Delta \otimes \Delta \downarrow & & & & \uparrow \nabla \otimes \nabla \\
 H \otimes H \otimes H \otimes H & \xrightarrow{id \otimes \tau \otimes id} & H \otimes H \otimes H \otimes H & &
 \end{array}$$

Unit and Counit compatibility:

$$\begin{array}{ccc}
 \mathbb{C} & \xrightarrow{1_H} & H \\
 1_H \otimes 1_H \searrow & & \downarrow \Delta \\
 & & H \otimes H
 \end{array}
 \qquad
 \begin{array}{ccc}
 H & \xrightarrow{\epsilon} & \mathbb{C} \\
 \nabla \uparrow & \nearrow \epsilon \otimes \epsilon & \\
 H \otimes H & &
 \end{array}$$

Hopf Algebra Diagrams

Product and Coproduct compatibility:

$$\begin{array}{ccccc}
 H \otimes H & \xrightarrow{\quad \nabla \quad} & H & \xrightarrow{\quad \Delta \quad} & H \otimes H \\
 \Delta \otimes \Delta \downarrow & & & & \uparrow \nabla \otimes \nabla \\
 H \otimes H \otimes H \otimes H & \xrightarrow{\quad id \otimes \tau \otimes id \quad} & H \otimes H \otimes H \otimes H & &
 \end{array}$$

Unit and Counit compatibility:

$$\begin{array}{ccc}
 \mathbb{C} & \xrightarrow{1_H} & H \\
 1_H \otimes 1_H \searrow & & \downarrow \Delta \\
 & & H \otimes H
 \end{array}
 \qquad
 \begin{array}{ccc}
 H & \xrightarrow{\epsilon} & \mathbb{C} \\
 \nabla \uparrow & & \nearrow \epsilon \otimes \epsilon \\
 H \otimes H & &
 \end{array}$$

Antipode:

$$\begin{array}{ccccc}
 H \otimes H & \xrightarrow{\quad id \otimes S \quad} & H \otimes H & & \\
 \Delta \uparrow & & & & \downarrow \nabla \\
 H & \xrightarrow{\quad \epsilon \quad} & \mathbb{C} & \xrightarrow{1_H} & H \\
 \Delta \downarrow & & & & \uparrow \nabla \\
 H \otimes H & \xrightarrow{\quad S \otimes id \quad} & H \otimes H & &
 \end{array}$$

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

$$(1) \ R \left(\sum h_{(1)} \otimes h_{(2)} \right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

$$(1) R \left(\sum h_{(1)} \otimes h_{(2)} \right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$

$$(2) \Delta \otimes id(R) = R_{1,3} R_{2,3}$$

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

$$(1) R \left(\sum h_{(1)} \otimes h_{(2)} \right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$

$$(2) \Delta \otimes id(R) = R_{1,3} R_{2,3}$$

$$(3) id \otimes \Delta(R) = R_{1,3} R_{1,2}$$

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

$$(1) R \left(\sum h_{(1)} \otimes h_{(2)} \right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$

$$(2) \Delta \otimes id(R) = R_{1,3} R_{2,3}$$

$$(3) id \otimes \Delta(R) = R_{1,3} R_{1,2}$$

where $R = \sum R_{(1)} \otimes R_{(2)}$ and

$$R_{1,2} = \sum R_{(1)} \otimes R_{(2)} \otimes 1$$

$$R_{1,3} = \sum R_{(1)} \otimes 1 \otimes R_{(2)}$$

$$R_{2,3} = \sum 1 \otimes R_{(1)} \otimes R_{(2)}.$$

Quantum Group

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode and some invertible $R \in H \otimes H$ satisfying:

$$(1) R \left(\sum h_{(1)} \otimes h_{(2)} \right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$

$$(2) \Delta \otimes id(R) = R_{1,3} R_{2,3}$$

$$(3) id \otimes \Delta(R) = R_{1,3} R_{1,2}$$

where $R = \sum R_{(1)} \otimes R_{(2)}$ and

$$R_{1,2} = \sum R_{(1)} \otimes R_{(2)} \otimes 1$$

$$R_{1,3} = \sum R_{(1)} \otimes 1 \otimes R_{(2)}$$

$$R_{2,3} = \sum 1 \otimes R_{(1)} \otimes R_{(2)}.$$

Hence, R is a solution to the quantum Yang-Baxter equation, and so is often called a **universal R-matrix**.

$$R_{1,2} R_{1,3} R_{2,3} = R_{2,3} R_{1,3} R_{1,2}.$$

Quantum Group Examples

The three Hopf alg examples above are all quantum groups.

Quantum Group Examples

The three Hopf alg examples above are all quantum groups.

- Sweedler's algebra, $H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$, has the univ R-matrix

$$R = 1 \otimes 1 - 2\frac{1-g}{2} \otimes \frac{1-g}{2} + x \otimes x + 2x\frac{1-g}{2} \otimes x\frac{1-g}{2} - 2x \otimes x\frac{1-g}{2}.$$

Quantum Group Examples

The three Hopf alg examples above are all quantum groups.

- Sweedler's algebra, $H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$, has the univ R-matrix

$$R = 1 \otimes 1 - 2\frac{1-g}{2} \otimes \frac{1-g}{2} + x \otimes x + 2x\frac{1-g}{2} \otimes x\frac{1-g}{2} - 2x \otimes x\frac{1-g}{2}.$$

- The Kac-Paljutkin algebra, $H_8 = \langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1 + x + y - xy) \rangle$, has 6 non-iso quasitriangular structures.

Quantum Group Examples

The three Hopf alg examples above are all quantum groups.

- Sweedler's algebra, $H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$, has the univ R-matrix

$$R = 1 \otimes 1 - 2 \frac{1-g}{2} \otimes \frac{1-g}{2} + x \otimes x + 2x \frac{1-g}{2} \otimes x \frac{1-g}{2} - 2x \otimes x \frac{1-g}{2}.$$

- The Kac-Paljutkin algebra, $H_8 = \langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1 + x + y - xy) \rangle$, has 6 non-iso quasitriangular structures.
- The ambiguity of what is a quantum group can be best seen with $\mathcal{U}_q(\mathfrak{sl}_2)$. Undoubtedly a quantum group, as it was the inspiration for the concept. But its univ R-matrix exists only in a completion of the tensor product $\mathcal{U}_q(\mathfrak{sl}_2) \otimes \mathcal{U}_q(\mathfrak{sl}_2)$, and so is a formal power series of pure tensors.

Hopf Algebra Actions

Let H be a Hopf alg and A an alg with a map $\alpha : H \otimes A \rightarrow A$.

Then we say H **acts** on A by α if the following diagrams commute:

Hopf Algebra Actions

Let H be a Hopf alg and A an alg with a map $\alpha : H \otimes A \rightarrow A$.

Then we say H **acts** on A by α if the following diagrams commute:

$$\begin{array}{ccc} H \otimes H \otimes A & \xrightarrow{\nabla \otimes id} & H \otimes A \\ \downarrow id \otimes \alpha & & \downarrow \alpha \\ H \otimes A & \xrightarrow{\alpha} & A \end{array} \quad \begin{array}{ccc} \mathbb{C} \otimes A & \xrightarrow{1_H \otimes id} & H \otimes A \\ & \searrow = & \downarrow \alpha \\ & & A \end{array}$$

Hopf Algebra Actions

Let H be a Hopf alg and A an alg with a map $\alpha : H \otimes A \rightarrow A$.
Then we say H **acts** on A by α if the following diagrams commute:

$$\begin{array}{ccc}
 H \otimes H \otimes A & \xrightarrow{\nabla \otimes id} & H \otimes A \\
 \downarrow id \otimes \alpha & & \downarrow \alpha \\
 H \otimes A & \xrightarrow{\alpha} & A
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathbb{C} \otimes A & \xrightarrow{1_H \otimes id} & H \otimes A \\
 \searrow = & & \downarrow \alpha \\
 & & A
 \end{array}$$

A is called an H -**module algebra** if the following also commute:

Hopf Algebra Actions

Let H be a Hopf alg and A an alg with a map $\alpha : H \otimes A \rightarrow A$.
Then we say H **acts** on A by α if the following diagrams commute:

$$\begin{array}{ccc}
 H \otimes H \otimes A & \xrightarrow{\nabla \otimes id} & H \otimes A \\
 \downarrow id \otimes \alpha & & \downarrow \alpha \\
 H \otimes A & \xrightarrow{\alpha} & A
 \end{array}
 \qquad
 \begin{array}{ccc}
 C \otimes A & \xrightarrow{1_H \otimes id} & H \otimes A \\
 & \searrow = & \downarrow \alpha \\
 & & A
 \end{array}$$

A is called an **H -module algebra** if the following also commute:

$$\begin{array}{ccccc}
 H \otimes A \otimes A & \xrightarrow{id \otimes \nabla} & H \otimes A & \xrightarrow{\alpha} & A \xleftarrow{\nabla} A \otimes A \\
 \Delta \otimes id \otimes id \downarrow & & & & \uparrow \alpha \otimes \alpha \\
 H \otimes H \otimes A \otimes A & \xrightarrow{id \otimes \tau \otimes id} & & & H \otimes A \otimes H \otimes A
 \end{array}$$

Hopf Algebra Actions

Let H be a Hopf alg and A an alg with a map $\alpha : H \otimes A \rightarrow A$.
Then we say H **acts** on A by α if the following diagrams commute:

$$\begin{array}{ccc}
 H \otimes H \otimes A & \xrightarrow{\nabla \otimes id} & H \otimes A \\
 \downarrow id \otimes \alpha & & \downarrow \alpha \\
 H \otimes A & \xrightarrow{\alpha} & A
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathbb{C} \otimes A & \xrightarrow{1_H \otimes id} & H \otimes A \\
 & \searrow = & \downarrow \alpha \\
 & & A
 \end{array}$$

A is called an H -**module algebra** if the following also commute:

$$\begin{array}{ccccc}
 H \otimes A \otimes A & \xrightarrow{id \otimes \nabla} & H \otimes A & \xrightarrow{\alpha} & A \xleftarrow{\nabla} A \otimes A \\
 \Delta \otimes id \otimes id \downarrow & & & & \uparrow \alpha \otimes \alpha \\
 H \otimes H \otimes A \otimes A & \xrightarrow{id \otimes \tau \otimes id} & H \otimes A \otimes H \otimes A & &
 \end{array}$$

$$\begin{array}{ccc}
 H & \xrightarrow{\varepsilon} & \mathbb{C} \xrightarrow{1_A} A \\
 id \otimes 1_A \downarrow & & \nearrow \alpha \\
 H \otimes A & &
 \end{array}$$

Hopf Algebra Actions

In words, H **acts on** A iff you can multiply in H and then act on A or act on A consecutively, $\forall h, h' \in H, \forall a \in A$

$$(hh')(a) = h(h'(a)), \quad 1_H(a) = a.$$

And A is an H -**module alg** iff H acts on A and $\forall h \in H, \forall a, a' \in A$

$$h(aa') = \sum h_{(1)}(a) \cdot h_{(2)}(a'), \quad h(1_A) = \varepsilon(h)1_A$$

where $\Delta(h) = \sum h_{(1)} \otimes h_{(2)}$.

This generalizes the notion of acting by automorphisms.

Semidirect Product

Let G and G' be groups where G' acts on G by automorphisms, giving the semidirect product group, $G \rtimes G'$.

The action can be extended to the group algebras:

$$\mathbb{C}(G \rtimes G') = \mathbb{C}G \# \mathbb{C}G'$$

with product $g'g = g'(g)g'$.

Smash Product Algebra

If H is a Hopf algebra and A an H -module algebra, then $A \# H$ is defined as $A \otimes H$ as a vector space and with product

$$(a' \otimes h)(a \otimes h') = \sum a' h_{(1)}(a) \otimes h_{(2)} h'$$

where $a, a' \in A$, $h, h' \in H$ and $\Delta(h) = \sum h_{(1)} \otimes h_{(2)}$.

Smash Product Algebra

"Group-like" and "Lie-like"

For Hopf alg H , define

$$G(H) = \{h \in H \mid \Delta(h) = h \otimes h\} = \text{grouplike elements}$$

which forms a group, and define

$$P(H) = \{h \in H \mid \Delta(h) = h \otimes 1 + 1 \otimes h\} = \text{primitive elements}$$

which forms a Lie alg.

Cartier-Kostant-Milnor-Moore Theorem

Let H be a cocommutative Hopf algebra over \mathbb{C} , then as Hopf alg,

$$H \cong \mathcal{U}(P(H)) \# \mathbb{C}G(H)$$

Cor: Any cocomm, finite-dim'l Hopf alg over \mathbb{C} is iso to a grp alg.

- Which actions on algebras by Hopf algebras factor through a group action?

- Which actions on algebras by Hopf algebras factor through a group action?
- Which Hopf Algebras act on other noncommutative algebras?

- Which actions on algebras by Hopf algebras factor through a group action?
- Which Hopf Algebras act on other noncommutative algebras?
- If H is semisimple and finite-dimensional, and A is semiprime, is $A \# H$ semiprime?

- Which actions on algebras by Hopf algebras factor through a group action?
- Which Hopf Algebras act on other noncommutative algebras?
- If H is semisimple and finite-dimensional, and A is semiprime, is $A \# H$ semiprime?
- If B is a Koszul algebra, are there nontrivial PBW deformations of $B \# \mathcal{U}_q(\mathfrak{sl}_2)$?

Thank you!