# Quantum Group Actions and Hopf Algebras

Brandon Mather

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

# History

- (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 Montogomery writes "Hopf Algebras and Their Actions on Rings"

#### Goal

To understand the actions of Hopf algebras on other algebras

### Quantum Plane

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

#### 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

$$\mathbb{C}_{Q}[v_{1},\ldots,v_{n}] = \mathbb{C}\left\langle v_{1},\ldots,v_{n} \mid v_{j}v_{i} - q_{ij}v_{i}v_{j}\right\rangle.$$

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

#### Motivation

• 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

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

Then  $\triangle$  defines a coproduct map

$$\triangle: \mathbb{C}G \to \mathbb{C}G \otimes \mathbb{C}G.$$

For arbitrary coproducts,  $\triangle: A \rightarrow A \otimes A$ , we call  $g \in A$  grouplike if  $\triangle(g) = g \otimes g$ .

#### Motivation

• 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

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

Then  $\triangle$  defines a coproduct map

$$\triangle: \mathbb{C}G \to \mathbb{C}G \otimes \mathbb{C}G.$$

For arbitrary coproducts,  $\triangle: A \rightarrow A \otimes A$ , we call  $g \in A$  grouplike if  $\triangle(g) = g \otimes g$ .

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

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

Then  $\triangle$  defines a coproduct map

$$\triangle: \mathfrak{g} \to \mathfrak{g} \otimes \mathfrak{g}.$$

For arbitrary coproducts,  $\triangle: A \rightarrow A \otimes A$ , we call  $x \in A$  **primitive** if  $\triangle(x) = x \otimes 1 + 1 \otimes x$ .

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.

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

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

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  $\triangle: H_4 \to H_4 \otimes H_4, \varepsilon: H_4 \to \mathbb{C}, S: H_4 \to H_4$ 

$$\triangle(g) = g \otimes g,$$
  $\triangle(x) = x \otimes 1 + g \otimes x$ 

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  $\triangle: H_4 \to H_4 \otimes H_4, \varepsilon: H_4 \to \mathbb{C}, S: H_4 \to H_4$ 

$$\triangle(g) = g \otimes g,$$
  $\triangle(x) = x \otimes 1 + g \otimes x$   $\varepsilon(g) = 1,$   $\varepsilon(x) = 0$ 

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  $\triangle: H_4 \to H_4 \otimes H_4, \varepsilon: H_4 \to \mathbb{C}, S: H_4 \to H_4$ 

$$\triangle(g) = g \otimes g,$$
  $\triangle(x) = x \otimes 1 + g \otimes x$ 

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

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

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  $\triangle: H_4 \to H_4 \otimes H_4, \varepsilon: H_4 \to \mathbb{C}, S: H_4 \to H_4$ 

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

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

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

$$\varepsilon(x)=0$$

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

$$S(x) = -x$$

Group-like

(1,g) — Primitive vertical spacing

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  $\triangle: H_4 \to H_4 \otimes H_4, \varepsilon: H_4 \to \mathbb{C}, S: H_4 \to H_4$ 

$$\triangle(g) = g \otimes g,$$
  $\triangle(x) = x \otimes 1 + g \otimes x$ 

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

$$S(g) = g^{-1}.$$
  $S(x) = -x$ 

Group-like

(1,g) — Primitive vertical spacing

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

### Actions of Sweedler's Algebra

$$\mathcal{H}_4$$
 acts on  $\mathbb{C}_{-1}[\mathit{v}_1,\mathit{v}_2]$  by

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

### Actions of Sweedler's Algebra

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

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

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

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

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

$$H_8 =$$

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

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

$$H_8 =$$

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

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

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

$$H_8 =$$

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

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

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

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

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

$$H_8 = \left\langle x, y, z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy) \right\rangle$$

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

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

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

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

### 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

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

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

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

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

### Actions of Kac-Paljutkin Algebra

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

with operations:

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

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

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

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

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

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

 $\mathcal{U}_q(\mathfrak{sl}_2)$  acts on  $\mathbb{C}_q[\mathit{v}_1,\mathit{v}_2]$  via the representation

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

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

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

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

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

A  $\operatorname{Hopf}$  algebra is a bialgebra H over a field with an antipode

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

 $\nabla: H \otimes H \to H$ ,

so that the following commute:

Associativity:

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

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

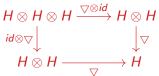
 $S: H \rightarrow H$  where the bialgebra operations are

 $\nabla: H \otimes H \to H$ ,

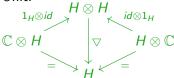
 $1_H:\mathbb{C}\to H$ ,

so that the following commute:





#### Unit:



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

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

 $\nabla: H \otimes H \to H$ ,

 $\triangle: H \to H \otimes H$ ,

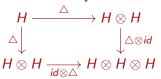
 $1_H:\mathbb{C}\to H$ ,

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:



Unit:

$$\begin{array}{c|c}
 & H \otimes H \\
 & \downarrow & \downarrow \\$$

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

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

 $\nabla: H \otimes H \to H$ ,

 $\triangle: H \to H \otimes H$ ,

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

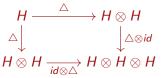
 $1_H:\mathbb{C}\to H$ ,

so that the following commute:

Associativity:

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

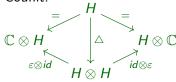
Coassociativity:



Unit:



Counit:



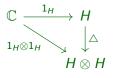
### Hopf Algebra Diagrams

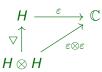
Product and Coproduct compatibility:

### Hopf Algebra Diagrams

Product and Coproduct compatibility:

Unit and Counit compatibility:



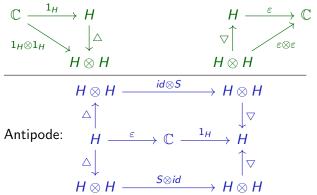


# Hopf Algebra Diagrams

Product and Coproduct compatibility:

$$\begin{array}{ccc} H \otimes H & \stackrel{\nabla}{\longrightarrow} & H & \stackrel{\triangle}{\longrightarrow} & H \otimes H \\ & & & & \uparrow_{\nabla \otimes \nabla} \\ H \otimes H \otimes H \otimes H & \stackrel{id \otimes \tau \otimes id}{\longrightarrow} & H \otimes H \otimes H \otimes H \end{array}$$

Unit and Counit compatibility:



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

(1) 
$$R\left(\sum h_{(1)} \otimes h_{(2)}\right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$
  
(2)  $\triangle \otimes id(R) = R_{1,3}R_{2,3}$ 

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

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

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

(1) 
$$R\left(\sum h_{(1)} \otimes h_{(2)}\right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$
  
(2)  $\triangle \otimes id(R) = R_{1,3}R_{2,3}$   
(3)  $id \otimes \triangle(R) = R_{1,3}R_{1,2}$   
where  $R = \sum R_{(1)} \otimes R_{(2)}$  and  $R_{1,2} = \sum R_{(1)} \otimes R_{(2)} \otimes 1$   
 $R_{1,3} = \sum R_{(1)} \otimes 1 \otimes R_{(2)}$   
 $R_{2,3} = \sum 1 \otimes R_{(1)} \otimes R_{(2)}$ .

Common philosophy: A **quantum group** is a Hopf alg H with a bijective antipode, and some invertible  $R \in H \otimes H$  witnessing how close H is to being cocommutative and satisfying:

(1) 
$$R\left(\sum h_{(1)} \otimes h_{(2)}\right) R^{-1} = \sum h_{(2)} \otimes h_{(1)}$$
  
(2)  $\triangle \otimes id(R) = R_{1,3}R_{2,3}$   
(3)  $id \otimes \triangle(R) = R_{1,3}R_{1,2}$   
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 algs examples above are all quantum groups.

And the ambiguity of what is a quantum group can be best seen with  $\mathcal{U}_q(\mathfrak{sl}_2)$ . This is 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.

# Quantum Group Examples

The three Hopf algs 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

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

And the ambiguity of what is a quantum group can be best seen with  $\mathcal{U}_q(\mathfrak{sl}_2)$ . This is 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.

# Quantum Group Examples

The three Hopf algs examples above are all quantum groups.

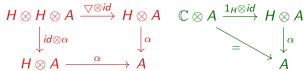
• Sweedler's algebra,  $H_4 = \langle g, x \mid g^2 = 1, x^2 = 0, gx = -xg \rangle$ , has the univ R-matrix

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

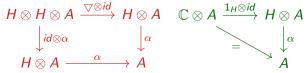
• The Kac-Paljutkin algebra,  $H_8 = \langle x,y,z \mid x^2 = y^2 = 1, xy = yx, zx = yz, zy = xz, z^2 = \frac{1}{2}(1+x+y-xy)\rangle$ , has 6 non-iso quasitriangular structures. And the ambiguity of what is a quantum group can be best seen with  $\mathcal{U}_q(\mathfrak{sl}_2)$ . This is undoubtedly 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.

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

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



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



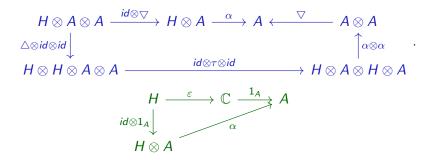
A is called an H-module algebra if the following also commute:

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

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

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

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



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  $\forall h \in H, \forall a, a' \in A$ 

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

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

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

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

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

# Smash Product Algebra

#### "Group-like" and "Lie-like"

For Hopf alg H, define

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

which forms a group, and define

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

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? If the action does not factor through a group action, it is said to have "quantum symmetry".

- Which actions on algebras by Hopf algebras factor through a group action? If the action does not factor through a group action, it is said to have "quantum symmetry".
- Which Hopf Algebras act on pther noncommutative algebras?

- Which actions on algebras by Hopf algebras factor through a group action? If the action does not factor through a group action, it is said to have "quantum symmetry".
- Which Hopf Algebras act on pther noncommutative algebras?

- Which actions on algebras by Hopf algebras factor through a group action? If the action does not factor through a group action, it is said to have "quantum symmetry".
- Which Hopf Algebras act on pther 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? If the action does not factor through a group action, it is said to have "quantum symmetry".
- Which Hopf Algebras act on pther 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  $B\#\mathcal{U}_q(\mathfrak{sl}_2)$ ?