

# MSRI: QUANTUM SYMMETRIES INTRODUCTORY WORKSHOP

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These notes were taken at MSRI’s [introductory workshop on quantum symmetries](#) in Spring 2020. I live-T<sub>E</sub>Xed them using `vim`, and as such there may be typos; please send questions, comments, complaints, and corrections to [a.debray@math.utexas.edu](mailto:a.debray@math.utexas.edu).

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## Part 1. Monday, January 27

### 1. SARAH WITHERSPOON: HOPF ALGEBRAS, I

Our perspective on Hopf algebras, their actions on rings and modules, and the structures on their categories of rings and modules, will be to think of them as generalizations of group actions and representations; groups actions are symmetries in the usual sense, and Hopf algebra actions are often related to “quantum symmetries.”

We’re not going to give the full definition of a Hopf algebra, because it would require drawing a lot of commutative diagrams, but we’ll say enough to give the picture.

Throughout this talk we work over a field  $k$ ; all tensor products are of  $k$ -vector spaces.

**Definition 1.1.** A *Hopf algebra* is an algebra  $A$  together with  $k$ -linear maps  $\Delta: A \rightarrow A \otimes A$ , called *comultiplication*;  $\varepsilon: A \rightarrow k$ , called the *counit*; and  $S: A \rightarrow A$ , called the *coinverse*. These maps must satisfy some properties, including that  $\varepsilon$  is an algebra homomorphism and that  $S$  is an *anti-automorphism*, i.e. that  $S(xy) = S(y)S(x)$ .

The definition is best understood through examples.

### Example 1.2.

- (1) Let  $G$  be a group. Then the group algebra  $k[G]$  is a Hopf algebra, where for all  $g \in G$ ,  $\Delta(g) := g \otimes g$ ,  $\varepsilon(g) := 1$ , and  $S(g) := g^{-1}$ . This is a key example that allows us to generalize ideas from group actions to Hopf algebra actions: whenever we define a notion for Hopf algebras, when we implement it for  $k[G]$  it should recover that notion for groups.
- (2) Let  $\mathfrak{g}$  be a Lie algebra over  $k$ . Then its universal enveloping algebra  $\mathcal{U}(\mathfrak{g})$  is a Hopf algebra, where for all  $x \in \mathfrak{g}$ ,  $\Delta(x) := x \otimes 1 + 1 \otimes x$ ,  $\varepsilon(x) := 0$ , and  $S(x) := -x$ . Since  $\varepsilon$  is an algebra homomorphism,  $\varepsilon(1_{\mathcal{U}(\mathfrak{g})}) = 1$ .

For example,

$$(1.3) \quad \mathcal{U}(\mathfrak{sl}_2) = k\langle e, f, h \mid ef - fe = h, he - eh = 2e, hf - fh = -2f \rangle,$$

given explicitly by the basis of  $\mathfrak{sl}_2$

$$(1.4) \quad e := \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad f := \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad h := \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad \blacktriangleleft$$

Both of these examples are classical, in that they've been known for a long time. But more recently, in the 1980s, people discovered new examples, coming from quantum groups.

**Example 1.5** (Quantum  $\mathfrak{sl}_2$ ). Let  $q \in k^\times \setminus \{\pm 1\}$ . Then, given a simple Lie algebra  $\mathfrak{g}$ , we can define a “quantum group,”  $\mathcal{U}_q(\mathfrak{g})$ , which is a Hopf algebra. For example, for  $\mathfrak{sl}_2$ ,

$$(1.6) \quad \mathcal{U}_q(\mathfrak{sl}_2) = k\left\langle E, F, K^{\pm 1} \mid EF - FE = \frac{K - K^{-1}}{q - q^{-1}}, KE = q^2 EK, KF = q^{-2} EK \right\rangle,$$

with comultiplication

$$(1.7a) \quad \Delta(E) := E \otimes 1 + K \otimes E$$

$$(1.7b) \quad \Delta(F) := F \otimes K^{-1} + 1 \otimes F$$

$$(1.7c) \quad \Delta(K^{\pm 1}) := K^{\pm 1} \otimes K^{\pm 1}$$

and counit  $\varepsilon(E) = \varepsilon(F) = 0$  and  $\varepsilon(K) = 1$ . This generalizes to other simple  $\mathfrak{g}$ , albeit with more elaborate data.  $\blacktriangleleft$

**Example 1.8** (Small quantum  $\mathfrak{sl}_2$ ). Let  $q$  be an  $n^{\text{th}}$  root of unity. Then, as before, given a simple Lie algebra  $\mathfrak{g}$ , we can define a Hopf algebra  $u_q(\mathfrak{g})$ , called the *small quantum group* for  $\mathfrak{g}$  and  $q$ , which is a finite-dimensional vector space over  $k$ ; for  $\mathfrak{sl}_2$ , this is

$$(1.9) \quad u_q(\mathfrak{sl}_2) = \mathcal{U}_q(\mathfrak{sl}_2) / (E^n, F^n, K^n - 1). \quad \blacktriangleleft$$

Before we continue, we need some useful notation for comultiplication, called *Sweedler notation*. Let  $A$  be a Hopf algebra and  $a \in A$ ; then we can symbolically write

$$(1.10) \quad \Delta(a) = \sum_{(a)} a_1 \otimes a_2.$$

Comultiplication in a Hopf algebra is *coassociative*, in that as maps  $A \rightarrow A \otimes A \otimes A$ ,

$$(1.11) \quad (\Delta \otimes \text{id}) \circ \Delta = (\text{id} \otimes \Delta) \circ \Delta.$$

Therefore when we iterate comultiplication, we can symbolically write

$$(1.12) \quad (\text{id} \otimes \Delta) \circ \Delta(a) = \sum_{(a)} a_1 \otimes a_2 \otimes a_3$$

without worrying about parentheses.

**Actions on rings.** Hopf algebra actions on rings generalize group actions on rings by automorphisms and actions of Lie algebras on rings by derivations. If a group  $G$  acts on a ring  $R$ , then for all  $g \in G$  and  $r, r' \in R$ ,

$$(1.13a) \quad g(rr') = (gr)(gr')$$

$$(1.13b) \quad g(1_R) = 1_R.$$

In  $k[G]$ , our Hopf algebra avatar of  $G$ ,  $\Delta(g) = g \otimes g$ , and  $\varepsilon(g) = 1$ .

If a Lie algebra  $\mathfrak{g}$  acts on a ring  $R$  by derivations, then for all  $x \in \mathfrak{g}$  and  $r, r' \in R$ ,

$$(1.14a) \quad x \cdot (rr') = (x \cdot r)r' + r(x \cdot r')$$

$$(1.14b) \quad x \cdot (1_R) = 0.$$

In  $\mathcal{U}(\mathfrak{g})$ , our Hopf algebra avatar of  $\mathfrak{g}$ ,  $\Delta(x) = x \otimes 1 + 1 \otimes x$ , and  $\varepsilon(x) = 0$ . These two examples suggest how we should implement a general Hopf algebra action on a ring: comultiplication tells us how to act on the product of two elements, and the counit tells us how to act on 1.

**Definition 1.15.** Let  $A$  be a Hopf algebra and  $R$  be a  $k$ -algebra. An  $A$ -module algebra structure on  $R$  is data of an  $A$ -module structure on  $R$  such that for all  $a \in A$  and  $r, r' \in R$ ,

$$(1.16a) \quad a \cdot (rr') = \sum_{(a)} (a_1 \cdot r)(a_2 \cdot r')$$

$$(1.16b) \quad a \cdot (1_R) = \varepsilon(a)1_R.$$

Thus a group action as in (1.13) defines an action of the Hopf algebra  $k[G]$ , and a Lie algebra action as in (1.14) defines an action of the Hopf algebra  $\mathcal{U}(\mathfrak{g})$ .

**Example 1.17.** The quantum analogue of the  $\mathfrak{sl}_2$ -action on  $k[x, y]$ , thought of as (functions on the) plane, there is an action of  $\mathcal{U}_q(\mathfrak{sl}_2)$  on the *quantum plane*

$$(1.18) \quad R := k\langle x, y \mid xy = qyx \rangle.$$

This is a deformation of  $k[x, y]$ , which is the case  $q = 1$ . The explicit data of the action is

$$(1.19) \quad E \cdot x = 0 \quad F \cdot x = y \quad K^{\pm 1} \cdot x = q^{\pm 1}x$$

$$(1.20) \quad E \cdot y = x \quad F \cdot y = 0 \quad K^{\pm 1} \cdot y = q^{\mp 1}y.$$

One has to check that this extends to an action satisfying Definition 1.15, but it does, and  $R$  is an  $A$ -module algebra. Here  $E$  and  $F$  act as *skew-derivations*, e.g.

$$(1.21) \quad E \cdot (rr') = (E \cdot r)r' + (K \cdot r)(E \cdot r')$$

for all  $r, r' \in R$ . ◀

Given a Hopf algebra action of  $A$  on  $R$  in this sense, we can construct two useful rings: the *invariant subring*

$$(1.22) \quad R^A := \{r \in R \mid a \cdot r = \varepsilon(a) \cdot r \text{ for all } a \in A\},$$

and the *smash product ring*  $R \# A$ , which as a vector space is  $R \otimes A$ , with multiplication given by

$$(1.23) \quad (r \otimes a)(r' \otimes a') := \sum_{(a)} r(a_1 \cdot r') \otimes a_2 a'.$$

The smash product ring knows the  $A$ -module algebra structure on  $R$ . Often, rings we're interested in for other reasons are smash product rings of interesting Hopf algebra actions, and identifying this structure is useful.

**Example 1.24.** The *Borel subalgebra* of  $\mathcal{U}_q(\mathfrak{sl}_2)$  is  $k\langle E, K^{\pm 1} \mid KE = q^{-2}K \rangle$ . This is isomorphic to the smash product  $k[E] \# k\langle K \rangle$ , where  $k\langle K \rangle$  is the group algebra of the free group on the single generator  $K$ .

In fact, there's a sense in which  $\mathcal{U}_q(\mathfrak{sl}_2)$  is a deformation of  $k[E, F] \# k\langle K \rangle$ : in this smash product ring,  $E$  and  $F$  commute, and we deform this to  $\mathcal{U}_q(\mathfrak{sl}_2)$ , in which they don't commute. ◀

**Modules.** Given a Hopf algebra  $A$ , what is the structure of its category of modules? The first thing we can do is take the tensor product of  $A$ -modules  $U$  and  $V$  using comultiplication: for  $a \in A$ ,  $u \in U$ , and  $v \in V$ ,

$$(1.25) \quad a \cdot (u \otimes v) = \sum_{(a)} a_1 \cdot u \otimes a_2 \cdot v.$$

Moreover,  $k$  has a canonical  $A$ -module structure via the counit:  $a \cdot x := \varepsilon(a)x$  for  $a \in A$  and  $x \in k$ . Finally, if  $U$  is an  $A$ -module, its vector space dual  $U^* := \text{Hom}_k(U, k)$  has an  $A$ -module structure via  $S$ : for all  $a \in A$ ,  $u \in U$ , and  $f \in U^*$ ,  $(a \cdot f)(u) := f(S(a)u)$ .

The existence of tensor products, duals, and the ground field in the world of Hopf algebra modules is a nice feature: these aren't always present for a general associative algebra. Moreover, these constructions interact well with each other.

- (1) Coassociativity of  $\Delta$  implies the tensor product is associative: for  $A$ -modules  $U$ ,  $V$ , and  $W$ , we have a natural isomorphism  $U \otimes (V \otimes W) \xrightarrow{\cong} (U \otimes V) \otimes W$ .

(2) In any Hopf algebra  $A$ , we have the condition

$$(1.26) \quad \sum_{(a)} \varepsilon(a_1) a_2 = \sum_{(a)} a_1 \varepsilon(a_2)$$

for any  $a_1, a_2 \in A$ . This implies  $k$ , as an  $A$ -module, is the unit for the tensor product: we have natural isomorphisms  $k \otimes U \cong U \cong U \otimes k$  for an  $A$ -module  $U$ .

(3) Suppose  $U$  is an  $A$ -module which is a finite-dimensional  $k$ -vector space. Then it comes with data of a *coevaluation map*  $c: k \rightarrow U \otimes U^*$  sending

$$(1.27) \quad 1 \mapsto \sum_i u_i \otimes u_i^*,$$

where  $\{u_i\}$  is a basis for  $U$  over  $k$  and  $\{u_i^*\}$  is its dual basis; this map turns out to be independent of basis. We also have an *evaluation map*  $e: U^* \otimes U \rightarrow k$  sending  $f \otimes u \mapsto f(u)$ . Now, not only are these  $A$ -module homomorphisms, but the composition

$$(1.28) \quad U \xrightarrow{c \otimes \text{id}_U} U \otimes U^* \otimes U \xrightarrow{\text{id}_U \otimes e} U$$

is the identity map.

**Definition 1.29.** A *tensor category*, or *monoidal category* is a category  $\mathcal{C}$  together with a functor  $\otimes: \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ , an object  $\mathbf{1} \in \mathcal{C}$  called the *unit*, and natural isomorphisms  $U \otimes (V \otimes W) \cong (U \otimes V) \otimes W$  and  $\mathbf{1} \otimes U \cong U \cong U \otimes \mathbf{1}$  for all objects  $U, V$ , and  $W$  in  $\mathcal{C}$ , subject to some coherence conditions.

Our key examples of tensor categories are the category of modules over a Hopf algebra  $A$ , as well as the subcategory of finite-dimensional modules.

If the coinverse of  $A$  is invertible, which is always the case when  $A$  is finite-dimensional over  $k$ , then  $\mathcal{C} = \text{Mod}_A$  is a *rigid* tensor category, meaning that every object  $U$  has a *right dual*  ${}^*U := \text{Hom}_k(U, k)$ , which means the composition (1.28) is the identity.

*Remark 1.30.* Notations for left and right duals differ. We're following [EGNO15], but Bakalov-Kirillov [BK01] use a different convention; be careful!  $\blacktriangleleft$

Some Hopf algebras' categories of modules have additional structure or properties: they might be semisimple, or braided, or even symmetric. This amounts to additional information on the Hopf algebra itself.

## 2. VICTOR OSTRIK, INTRODUCTION TO FUSION CATEGORIES, I

In the world of classical symmetries, i.e. those given by group actions, there is a particularly nice subclass: finite groups. If you know your symmetry group is finite, you can take advantage of many simplifying assumptions. Likewise, in the setting of quantum symmetries, given by, say,  $\mathbb{C}$ -linear tensor categories, fusion subcategories form a very nice subclass for which many simplifying assumptions hold. And indeed, if  $G$  is a finite group, its category of finite-dimensional representations is a fusion category.

Recall that a *monoidal category* is a category  $\mathcal{C}$  together with a functor  $\otimes: \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$  and a distinguished object  $\mathbf{1} \in \mathcal{C}$  called the *unit*, together with natural isomorphisms implementing associativity of  $\otimes$ , via  $(X \otimes Y) \otimes Z \xrightarrow{\cong} X \otimes (Y \otimes Z)$ ; and unitality of  $\mathbf{1}$ , via  $\mathbf{1} \otimes X \xrightarrow{\cong} X \xrightarrow{\cong} X \otimes \mathbf{1}$ . These must satisfy some axioms which we won't discuss in detail here; the most important one is the *pentagon axiom* on the associator.

Today, we work over an algebraically closed field  $k$ , not necessarily closed. Recall that a  *$k$ -linear category*  $\mathcal{C}$  is one for which for all objects  $x, y \in \mathcal{C}$ ,  $\text{Hom}_{\mathcal{C}}(x, y)$  is a  $k$ -vector space, such that composition is bilinear. A  *$k$ -linear monoidal category* is a monoidal category that is also a  $k$ -linear category — and we also impose the consistency condition that the tensor product is a  $k$ -linear functor. we will impose a few more niceness conditions before arriving at the definition of a fusion category — in fact, as many as we can such that we still have examples!

In particular, we will only consider  $k$ -linear monoidal categories  $\mathcal{C}$  such that

- all Hom-spaces are finite-dimensional over  $k$ ,
- $\mathcal{C}$  is semisimple,<sup>1</sup>
- $\mathcal{C}$  has only finitely many isomorphism classes of simple objects,

<sup>1</sup>A  $k$ -linear category is *semisimple* if it's equivalent to the category of modules over  $k \oplus \cdots \oplus k$ , where there is a finite number of summands.

- $\mathbf{1}$  is indecomposable, and
- $\mathcal{C}$  is *rigid*, a condition on duals of objects.

A category satisfying all of these axioms is a *fusion category*. (TODO: double-check)

There are three ways we can come to an understanding of these categories: through the definition, through realizations and examples, and through diagrammatics. We will also heavily use semisimplicity, through the principle that *k-linear functors out of  $\mathcal{C}$  are determined by their values on simple objects, and all choices are allowed*.

**Example 2.1.** Our running example is  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$ , where  $n$  is a natural number and  $\omega$  is a degree-3 cocycle for  $\mathbb{Z}/n$ , valued in  $k^\times$ .

The objects of  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$  are the elements of  $\mathbb{Z}/n$ , with the tensor product  $i \otimes j := i + j$ . If  $\omega = 1$ , then we use the obvious associator, i.e. the isomorphism

$$(2.2) \quad (i \otimes j) \otimes k \xrightarrow{\cong} i \otimes (j \otimes k)$$

which corresponds to the identity under the identifications with  $i + j + k$ .<sup>2</sup> But in general, we can do something different: choose the map (2.2) which is  $\omega(i, j, k)$  times the standard one.

*A priori* you can use any function  $\mathbb{Z}/n \times \mathbb{Z}/n \times \mathbb{Z}/n \rightarrow k^\times$ , but the pentagon axiom on associativity imposes the condition that  $\omega$  is a cocycle.

**Exercise 2.3.** If you have not seen this before, verify that the pentagon axiom forces  $\partial\omega = 1$ .

The simplest nontrivial example<sup>3</sup> is for  $n = 2$  and

$$(2.4) \quad \omega(i, j, k) := \begin{cases} 1, & \text{if } i = 0, j = 0, \text{ or } k = 0 \\ -1, & \text{otherwise.} \end{cases} \quad \blacktriangleleft$$

$\mathbb{Z}/n$  was not special here — given any finite group  $G$  and a cocycle  $\omega \in Z^3(G; k^\times)$ , we obtain a fusion category  $\mathcal{V}ec_G^\omega$  in the same way.

With  $\omega$  as in (2.4),  $\mathcal{V}ec_{\mathbb{Z}/2}^\omega$  looks like a new example, not equivalent to  $\mathcal{V}ec_G^0$  for any  $G$  — but in order to understand that precisely, we need to discuss when two tensor categories are equivalent.

**Definition 2.5.** A *tensor equivalence* of tensor categories  $\mathcal{C}$  and  $\mathcal{D}$  is a monoidal functor  $F: \mathcal{C} \rightarrow \mathcal{D}$ , i.e. a functor together with data of natural isomorphisms  $F(X \otimes Y) \xrightarrow{\cong} F(X) \otimes F(Y)$  satisfying some axioms.

Choose cocycles  $\omega$  and  $\omega'$  for  $\mathbb{Z}/n$ , and let's consider tensor functors  $F: \mathcal{V}ec_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{V}ec_{\mathbb{Z}/n}^{\omega'}$ . Furthermore, let's assume  $F$  is the identity on objects, so the data of  $F$  is the natural isomorphism  $F(X \otimes Y) \cong F(X) \otimes F(Y)$ . This is a choice of an element of  $k^\times$  for every pair of objects, subject to some additional conditions:

**Proposition 2.6.**  $F$  is a tensor functor iff  $\omega = \omega' \cdot \partial\psi$ .

**Corollary 2.7.**  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega \simeq \mathcal{V}ec_{\mathbb{Z}/n}^{\omega'}$  if  $\omega$  and  $\omega'$  are cohomologous.

Recall that  $H^3(\mathbb{Z}/n; k^\times) \cong \mathbb{Z}/n$ , so we have  $n$  possibilities, some of which might coincide. If  $F$  isn't the identity on objects, it's fairly easy to see that as a function on objects, identified with a function  $\mathbb{Z}/n \rightarrow \mathbb{Z}/n$ , we must get a group homomorphism; if  $F$  is to be an equivalence, this homomorphism must be an isomorphism. One can run a similar argument as above and obtain a nice classification result.

**Proposition 2.8.** The tensor equivalence classes of tensor categories  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$  are in bijection with the orbits  $H^3(\mathbb{Z}/n; k^\times) / \text{Aut}(\mathbb{Z}/n)$ , via the map sending  $\omega$  to its class in cohomology.

The action of  $\text{Aut}(\mathbb{Z}/n) = (\mathbb{Z}/n)^\times$  on  $H^3(\mathbb{Z}/n; k^\times) \cong \mathbb{Z}/n$  is not the first action you might write down! Given  $a \in (\mathbb{Z}/n)^\times$  and  $s \in H^3(\mathbb{Z}/n; k^\times)$ , the action is

$$(2.9) \quad a \cdot s = a^2 s.$$

This is a standard fact from group cohomology.

<sup>2</sup>These multiplication rules are really special, in that we were able to just write down an associator. This is generally not true; for general multiplication rules you're interested in, you'll have to work a little harder.

<sup>3</sup>This is nontrivial provided  $\text{char}(k) \neq 2$ .

Now let's discuss some realizations of fusion categories. If  $H$  is a semisimple Hopf algebra, then  $\mathcal{C} := \mathcal{R}ep_H^{fd}$  is a fusion category. Let  $F: \mathcal{C} \rightarrow \mathcal{V}ec$  denote the forgetful functor to finite-dimensional vector spaces. It turns out that one can reconstruct  $\mathcal{C}$  as a fusion category from  $F$ , and in fact any fusion category  $\mathcal{C}$  with a tensor functor to  $\mathcal{V}ec$  is equivalent to  $\mathcal{R}ep_H^{fd}$  for some Hopf algebra  $H$ . The data of the tensor functor to  $\mathcal{V}ec$  is crucial!

**Example 2.10.** For example,  $\mathcal{V}ec_{\mathbb{Z}/n} \simeq \mathcal{R}ep_{\mathbb{Z}/n}^{fd}$ ; we saw in the previous lecture that representations of  $\mathbb{Z}/n$  are equivalent to modules over the Hopf algebra  $k[\mathbb{Z}/n] := k[x]/(x^n - 1)$ , with comultiplication  $\Delta(x) := x \otimes x$ .

However, if  $\omega$  is nontrivial,  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$  admits no tensor functor to  $\mathcal{V}ec$ , and therefore cannot be seen using Hopf algebras. One can try to generalize the reconstruction program, using quasi-Hopf algebras, weak Hopf algebras, etc.  $\blacktriangleleft$

Bimodules provide another approach to realizations: we look for a ring  $R$  and a tensor functor  $F: \mathcal{C} \rightarrow \mathcal{B}imod_R$ . Applying this to  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$ , we get  $(R, R)$ -bimodules  $F(i)$  for each  $i \in \mathbb{Z}/n$  and isomorphisms  $F(i) \otimes_R F(j) \xrightarrow{\cong} F(i+j)$ . In particular, each  $F(i)$  is (tensor-)invertible.

**Example 2.11.** An *inner automorphism* of a ring  $R$  is conjugation by some  $r \in R^\times$ . Inner automorphisms form a normal subgroup of  $\text{Aut}(R)$ , and the quotient is called the *outer automorphism group* of  $R$  and denoted  $\text{Out}(R)$ . An *outer action* of a group  $G$  on a ring  $R$  is a group homomorphism  $\varphi: G \rightarrow \text{Out}(R)$ .

Given an outer automorphism  $\theta$  of  $R$ , one obtains an  $(R, R)$ -bimodule  $R_\theta$ , whose left action is the  $R$ -action on  $R$  by left multiplication, and whose right action is  $r \cdot x = r\theta(x)$ . We need to choose an element in  $\text{Aut}(R)$  mapping to  $\theta$  to make this definition, but different choices lead to isomorphic bimodules.

Anyways, given an outer action of  $\mathbb{Z}/n$  on  $R$ , we obtain  $(R, R)$ -bimodules  $R_{\varphi(i)}$  indexed by the objects  $i \in \mathcal{V}ec_{\mathbb{Z}/n}$  and isomorphisms between  $R_{\varphi(i)} \otimes R_{\varphi(j)} \xrightarrow{\cong} R_{\varphi(i+j)}$ . This data stitches together into a tensor functor  $\mathcal{V}ec_{\mathbb{Z}/n} \rightarrow \mathcal{B}imod_R$ .  $\blacktriangleleft$

Diagrammatics represents the objects of a fusion category  $\mathcal{C}$  as points, and morphisms as lines. One can then impose relations on certain morphisms, and therefore diagrammatics provide a generators-and-relations approach to the structure of a given fusion category. Next time, we'll see how to do this for  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$ , and see more examples.

### 3. ERIC ROWELL, AN INTRODUCTION TO MODULAR TENSOR CATEGORIES I

In this lecture, we'll begin with definitions and basic examples of modular tensor categories, and then use them in the next lecture. But first, let's discuss the whys of modular tensor categories.

We're often interested in knot and link invariants which are pictorial in nature, e.g. computed using a diagram. Another seemingly unrelated application is to study statistical-mechanical systems. Witten introduced TQFT into this story, extending the Jones polynomial to 3-manifold invariants using physics. Lately, there are interesting condensed-matter phenomena in topological phases. All of these are governed by modular tensor categories in different ways, and in related ones.

(TODO: list of references, via handout)

**Definition 3.1.** Let  $\mathcal{C}$  be a fusion category. A *braiding* on  $\mathcal{C}$  (after which it's called a *braided fusion category*) is data of a natural transformation  $c_{X,Y}: X \otimes Y \xrightarrow{\cong} Y \otimes X$  satisfying some relations called the *hexagon identities*.

You can think of  $c_{X,Y}$  as taking strands labeled by the objects  $X$  and  $Y$ , and laying the  $X$  strand over the  $Y$  strand. The hexagon identities arise by comparing the two strands

$$(3.2) \quad \begin{array}{c} \text{Diagram 1: Two strands crossing, with the left strand (X) over the right strand (Y).} \end{array} \quad \text{and} \quad \begin{array}{c} \text{Diagram 2: Two strands crossing, with the right strand (Y) over the left strand (X).} \end{array}$$

Because the braiding is implemented via a natural transformation, it is functorial: we can braid morphisms as well as objects.

**Example 3.3.** Given a finite group  $G$ ,  $\mathcal{Rep}_G$  is a braided fusion category. Let  $V$  and  $W$  be representations; then the braiding  $c_{V,W}(v \otimes w) := w \otimes v$ .  $\blacktriangleleft$

**Definition 3.4.** Let  $\mathcal{C}$  be a braided fusion category. The *symmetric center* or *Müger center* of  $\mathcal{C}$  is the subcategory  $\mathcal{C}'$  of  $x \in \mathcal{C}$  such that  $c_{X,Y}c_{Y,X} = \text{id}_X$  for all  $Y \in \mathcal{C}$ .

For example, the symmetric center of  $\mathcal{Rep}_G$  is once again  $\mathcal{Rep}_G$ .

**Exercise 3.5.** Why is the symmetric center of  $\mathcal{C}$  a braided fusion category? In particular, why is it closed under tensor products?

**Definition 3.6.** If the symmetric center of  $\mathcal{C}$  is itself, we call  $\mathcal{C}$  *symmetric*.<sup>4</sup> If the symmetric center of  $\mathcal{C}$  is generated by the unit object (equivalently,  $\mathcal{C}' \simeq \mathcal{Vect}$ ), we call  $\mathcal{C}$  *nondegenerate*.

Here, “generated by the unit object” means every object is isomorphic to a direct sum of copies of the unit.

Now let’s put some more adjectives in front of these structures. These will make the structure nicer, as usual, but are interesting enough to have examples.

**Definition 3.7.** Let  $\mathcal{C}$  be a braided fusion category. A *twist* on  $\mathcal{C}$  is a choice of  $\theta \in \text{Aut}(\text{id}_{\mathcal{C}})$ .

Diagrammatically, we think of the twist as acting by the diagram in the first Reidemeister move, except we place right over left, not left over right. By looking at a picture of the twist on  $X \otimes Y$ , and untangling the picture, you can prove the *balancing equation*

$$(3.8) \quad \theta_{X \otimes Y} = c_{X,Y} \circ \theta_X \otimes \theta_Y.$$

Diagrams make it easier to picture these relations, but aren’t strictly necessary. For example, the evaluation map  $d_X: X^* \otimes X \rightarrow \mathbf{1}$  is represented by a diagram  $\frown$  labeled by  $X$ , and coevaluation  $b_X: \mathbf{1} \rightarrow X^* \otimes X$  is represented by a diagram  $\smile$  labeled by  $X$ . Since braided categories aren’t necessarily symmetric, one must be careful with left versus right duals.

**Definition 3.9.** A *ribbon structure* on a braided fusion category  $\mathcal{C}$  is a twist such that  $(\theta_X)^* = \theta_{X^*}$ .

**TODO:** picture goes here. Here’s where it’s useful to use ribbon diagrams rather than string diagrams: really we want to keep track of the normal framings of the strings in our diagrams (thought of as embedded in  $\mathbb{R}^3$ ), and ribbons provide a clean way to understand that.

Let  $\text{Irr}(\mathcal{C})$  denote the set of isomorphism classes of irreducible objects in  $\mathcal{C}$ . This is always a finite set; the *rank* of  $\mathcal{C}$  is  $\#\text{Irr}(\mathcal{C})$ . Choose representatives  $x_1, \dots, x_r$  of the isomorphism classes of simple objects; then, by Schur’s lemma,  $\text{Aut}(X_i) \cong \mathbb{C}^\times$ . Let  $\theta_i \in \mathbb{C}^\times$  denote the twist of  $X_i$ .

Now we have all the words we need to define modular tensor categories.

**Definition 3.10.** A *modular tensor category* is a nondegenerate ribbon fusion category.

There are other, equivalent definitions.

**Definition 3.11.** A *pivotal structure* on a fusion category  $\mathcal{C}$  is a natural isomorphism  $j: X \xrightarrow{\cong} X^{**}$ .

If a pivotal structure satisfies a certain niceness condition, it’s called *spherical*. Then:

- A braided fusion category with a pivotal structure automatically has a twist.
- If that pivotal structure is spherical, the twist defines a ribbon structure.
- A nondegenerate braided fusion category with a spherical structure is a modular tensor category.

This still hasn’t quite made contact with the usual definition.

If  $\mathcal{C}$  is a ribbon fusion category, it has a canonical trace on  $\text{End}(X)$ , valued in  $\text{End}(\mathbf{1}) \cong \mathbb{C}$ . The *dimension* of an object  $X \in \mathcal{C}$  is  $\text{tr}(\text{id}_X)$ .

**Definition 3.12.** The *S-matrix* of a ribbon fusion category is the matrix with entries  $S_{ij} := \text{tr}(c_{X_i, X_j} \circ c_{X_j, X_i})$  for  $X_i, X_j \in \text{Irr}(\mathcal{C})$ .

**Theorem 3.13** (Brugières-Müger). *A ribbon tensor category  $\mathcal{C}$  is modular if and only if the S-matrix is invertible.*

Now let’s turn to examples.

<sup>4</sup>Notice that being symmetric is a property of braided fusion categories.



**Example 3.14.** Let  $G$  be a finite abelian group and  $\mathcal{V}ec_G$  be the category of  $G$ -graded vector spaces. These were discussed previously in Example 2.1, albeit in a slightly different way.

Let  $c: G \times G \rightarrow \mathbb{C}^\times$  be a *bicharacter* of  $G$ , i.e. for all  $g, h, k \in G$ ,

$$(3.15) \quad c(gh, k) = c(g, k)c(h, k).$$

Then we obtain a braiding on  $\mathcal{V}ec_G$  by  $c: g \otimes h \rightarrow h \otimes g$  by

$$(3.16) \quad \theta_g(v \otimes w) = c(g, h)w \otimes v.$$

For the twist, use  $\theta_g := c(g, g)$ . This defines a ribbon tensor category, and it is modular iff  $\det((c(g, h)c(h, g))_{g, h}) \neq 0$ .

**Exercise 3.17.** In particular, let  $G := \mathbb{Z}/3$  and  $w$  be a generator. Show that  $c(w, w) = \exp(2\pi i/3)$  extends to a bicharacter that defines a modular tensor structure on  $\mathcal{C} := \mathcal{V}ec_G$ . Show that we cannot obtain a modular structure on  $\mathcal{V}ec_{\mathbb{Z}/2}$  in this way, however.

We can produce a modular structure on  $\mathcal{V}ec_{\mathbb{Z}/2}$  in a different way: let  $z$  be a generator, and define  $c(z, z) := i$  and  $c(1, z) = c(z, 1) = c(1, 1) = 1$ . This defines a modular tensor category structure on  $\mathcal{V}ec_{\mathbb{Z}/2}^\omega$  whenever  $\omega$  is cohomologically nontrivial; this category is of considerable interest in physics, where it's known as the *semion category*. ◀

If you tried to generalize this to  $G$  nonabelian, you would not be able to write down a braiding, because  $g \otimes h \not\cong h \otimes g$ .

If all simple objects in  $\mathcal{C}$  are invertible,  $\mathcal{C}$  is called a *pointed fusion category*. It turns out these have been classified, and the underlying monoidal tensor category is  $\mathcal{V}ec_G^\omega$  for some finite group  $G$  and some cocycle  $\omega$ . If in addition  $\mathcal{C}$  is braided, then  $G$  is abelian, and we can ask about the converse.

**Theorem 3.18.** *If  $|G|$  is odd,  $\mathcal{V}ec_G^\omega$  admits a braiding iff  $\omega$  is cohomologically trivial.*

When  $|G|$  is even, things are more complicated, as we saw above, but the answers are known. For  $\mathbb{Z}/2$ , we can get  $\mathcal{R}ep_{\mathbb{Z}/2}$ , and for  $c(z, z) = -1$ , we obtain  $s\mathcal{V}ec$ . Both of these are symmetric. One can generalize: Deligne [Del02] classified symmetric fusion categories, showing they're all equivalent to  $\mathcal{R}ep_G$  or  $\mathcal{R}ep_G(z)$ , where  $z \in G$  is central and order 2 (giving a super-vector space structure on  $G$ -representations). Symmetric fusion categories equivalent to  $\mathcal{R}ep_G$  are called *Tannakian*; those equivalent to  $\mathcal{R}ep_G(z)$  are called *super-Tannakian*.

#### 4. EMILY PETERS, SUBFACTORS AND PLANAR ALGEBRAS I

Note: I (Arun) didn't fully understand this talk, and there are a lot of **TODOs**. Hopefully I can fix some of them soon. I'm sorry about that.

In the subject of planar algebra, one can do a lot of math by drawing pictures and reasoning carefully about them. So these talks will have plenty of pictures.

References for today's talk:

- Jones, "Planar algebras I," [Jon99] the original reference.
- The speaker's thesis.
- Heunen and Vicary, "Categories for quantum theory."

**Definition 4.1.** A *Temperley-Lieb diagram* of size  $n$  is an embedding of  $n$  disjoint copies of  $[0, 1]$  into  $[0, n] \times [0, 1]$ , such that the boundaries of the embedded intervals lie on integer-valued points.

That is, we take an  $n \times 2$  rectangle of points, and draw lines pairing them, such that no two lines cross. We identify two Temperley-Lieb diagrams which are isotopic.

Let  $\mathcal{TL}_n$  denote the complex vector space spanned by Temperley-Lieb diagrams of size  $n$ . Addition is formal.  $\mathcal{TL}_n$  acquires an algebra structure by *stacking*: place one diagram on top of another.

(**TODO**: some pictures)

The identity operator for multiplication is (**TODO**: diagram that looks like  $||||$ ).

This algebra has some additional interesting structure.

- There's a trace  $\mathcal{TL}_n \rightarrow \mathbb{C}$ : given a Temperley-Lieb diagram, close up the embedded intervals in a process akin to a braid closure. Then **TODO**. (Also, **TODO**: a picture) I think there is a parameter  $\delta$ , and if the result has  $n$  circles, we get  $\delta^n$ .



- A  $*$ -structure, by reversing the diagram horizontally.
- This defines a Hermitian form on  $\mathrm{TL}_n$ , by  $\langle x, y \rangle := \mathrm{tr}(y^* x)$ . This is an inner product if  $\delta \geq 2$ .

Since the trace depends on  $\delta$ , we will write  $\mathrm{TL}_n(\delta)$  for the Temperley-Lieb algebra with trace given by  $\delta$ .

There is an embedding  $\mathrm{TL}_n \hookrightarrow \mathrm{TL}_{n+1}$ , given by adding a single vertical interval on the right-hand side of a diagram. Call the colimit  $\mathrm{TL}(\delta)$ .

**Exercise 4.2.** Check that this inclusion respects multiplication, the identity, and the trace, assuming we use the same value of  $\delta$  in both cases.

This is the basic example of a *planar algebra*. In general, a planar algebra is a collection of vector spaces  $V_0, V_1, V_2, \dots$ , together with an action by something called the *planar operad*. Fortunately, you don't need to know what an operad is to understand the planar operad. This operad is given by (TODO: in what sense?) *planar diagrams* (which TODO: I think are also called “spaghetti-and-meatballs diagrams”). These are diagrams of embeddings of compact 1-manifolds inside many-holed annuli, together with marked points on the boundaries of the annuli. These compose in a manner reminiscent of operator product expansion. TODO: a picture is more useful than a description here.

An action of the planar operad means, for each planar diagram, a multilinear map  $\bigotimes V_i \rightarrow V_0$ ; we also ask for these maps to be compatible with compositions.

**Example 4.3.** The Temperley-Lieb algebra is a planar algebra, where the planar diagrams act by insertion. ◀

**Example 4.4.** The *graph planar algebra* on a simply laced graph  $\Gamma$  takes as its  $V_n$  the complex vector space spanned by the set of loops on  $\Gamma$  of length  $n$ .

There are a few different ways we can compose loops. Of course, we can concatenate loops with the same origin, as in algebraic topology; but there's another option. Assume both loops are of even length, and let  $p$  and  $p'$  be their respective halfway points; then, we can define their composition to be 0 if  $p \neq p'$ , and to be the first half of the first loop, then the second half of the second loop, if  $p = p'$ . TODO: I think that these two composition laws correspond to two planar diagrams, and these should give you the general story, so double-check this and then include those pictures.

TODO: planar diagrams enter this story somehow?

There's also a trace (TODO: picture goes here). This procedure is slightly ambiguous, so we simply sum up over all possibilities. ◀

We've seen in a few different talks so far the idea of a monoidal category, along with many variations of their definition.

**Definition 4.5.** A *monoidal category* is a category  $\mathcal{C}$  together with a functor  $\otimes: \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$  and a distinguished object  $\mathbf{1} \in \mathcal{C}$  called the *unit*, together with data of an *associator*, a natural isomorphism  $(-\otimes-) \otimes - \xrightarrow{\cong} - \otimes (-\otimes-)$  and *left and right unitors*, natural isomorphisms  $\mathbf{1} \otimes - \xrightarrow{\cong} -$  and  $- \otimes \mathbf{1} \xrightarrow{\cong} -$ ; these are subject to some coherence conditions.

The point of recalling this definition is that we'll relate it to all the pictures in not just this lecture, but also the other ones this week. This is a point that is often unclear to people — if you already know why you can do diagrammatics for various kinds of categories, it might feel not worth reviewing, but if not, it's certainly confusing.

The idea is, we can draw objects, morphisms, and equations in a monoidal category as diagrams in 2d. TODO: those diagrams.

- A morphism  $f: A \rightarrow B$  is a box from a strand labeled by  $B$  to a strand labeled by  $A$ .
- Composition is stacking vertically.
- The tensor product is stacking horizontally, both of objects and of morphisms.
- The monoidal unit is the empty diagram.

Two diagrams which are related under planar isotopy are considered equal.

**Theorem 4.6.** A well-typed equation between morphisms in a monoidal category follows from the axioms of a monoidal category iff it holds true in the graphical language described above.

As a simple example, how do vertical and horizontal composition (namely, composition of morphisms, resp. tensor product) interact? If you do vertical, then horizontal, or horizontal, then vertical, you get the same

diagrams, and therefore they must be equal: given maps  $f: A \rightarrow B$ ,  $g: B \rightarrow C$ ,  $h: D \rightarrow E$ , and  $k: E \rightarrow F$ ,

$$(4.7) \quad (f \circ g) \otimes (h \circ k) = (f \otimes h) \circ (g \otimes k)$$

as maps  $A \otimes D \rightarrow C \otimes F$ .

A monoidal category is *rigid* if it has left and right duals for all objects. Evaluation and coevaluation correspond to cups and caps; thus we obtain an identity (TODO: Zorro diagram, also called snake diagram). This allows us to freely do planar isotopy. (TODO: so do we need rigidity in order for Theorem 4.6 to hold?)

Now let  $\mathcal{C}$  be a rigid monoidal category and  $X \in \mathcal{C}$ ; we will obtain a planar algebra by “zooming in” on this object  $X$ . Specifically, take  $V_n := \text{End}(X^{\otimes n})$ . (TODO: rest of data comes from diagrammatics, I think?)

Why care? Well, the formalism of planar algebras is different enough from that of monoidal categories to lend different tools to the study of things in their intersections. For example, monoidal categories and planar algebras have different notions of smallness. For example, in a semisimple rigid monoidal category, you might measure the number of simple objects. In a planar algebra generated by  $X$  as above, smallness is more traditionally measured with the *Frobenius-Perron dimension*. This can be understood in general semisimple rigid monoidal categories  $\mathcal{C}$ ; it is a map  $K_0(\mathcal{C}) \rightarrow \mathbb{R}$  which is positive on simple eigenvalues. Specifically, suppose

$$(4.8) \quad X \otimes Y = \sum c_{XY}^Z Z,$$

where the sum is over isomorphism classes of simple objects  $Z$  of  $\mathcal{C}$ ; this defines a matrix in the entries  $X$  and  $Y$ ; its Frobenius-Perron eigenvalue is the Frobenius-Perron dimension of  $X$ .

## Part 2. Tuesday, January 28

### 5. VICTOR OSTRIK, INTRODUCTION TO FUSION CATEGORIES, II

We begin by discussing diagrammatics for  $\text{Vec}_{\mathbb{Z}/n}^\omega$ , following work of Agustina Czenky.

The objects of  $\text{Vec}_{\mathbb{Z}/n}^\omega$  are all tensor products of  $1 \in \mathbb{Z}/n$ , which in diagrammatics is denoted  $\uparrow$ ; thus,  $i$  is denoted  $\uparrow\uparrow \dots \uparrow$ . The generating morphisms are (TODO: two of them), and there are some relations: (TODO: and (TODO: are the identity, and (TODO: is  $\zeta$  times (TODO: where  $\zeta$  is some  $n^{\text{th}}$  root of unity determined by  $\omega$ .<sup>5</sup>

This generators-and-relations description of  $\text{Vec}_{\mathbb{Z}/n}^\omega$  allows us to uncover a universal property.

**Proposition 5.1.** *Let  $\mathcal{C}$  be a fusion category. Then there is a natural bijection between tensor functors  $F: \text{Vec}_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{C}$  and isomorphism classes of data of an object  $X \in \mathcal{C}$  and an isomorphism  $\theta: X^{\otimes n} \xrightarrow{\cong} \mathbf{1}$ .*

The idea is that, looking at the diagrammatics of  $X := F(1)$ , we have two different isomorphisms  $X^{\otimes(n+1)} \xrightarrow{\cong} X$ , and one must be  $\zeta$  times the other.

The slightly more sophisticated way to say this is that functors  $\text{Vec}_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{C}$  form a category, and the data  $(X, \phi)$  as above forms a category, and the above bijection can be promoted to an equivalence of categories.

**Example 5.2.** Assume  $n$  is odd, so that we can use  $2 \in \mathbb{Z}/n$  as a generator. Now you can compare (TODO: two diagrams), and one should be a multiple of another. It turns out the factor is  $\zeta^4$ , and this gives the action of  $\text{Aut}(\mathbb{Z}/n)$  on  $H^3(\mathbb{Z}/n; k^\times)$  from last time.  $\blacktriangleleft$

Now let us use this to study tensor functors  $F: \text{Vec}_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{B}imod_R$ , where  $R$  is a  $k$ -algebra. These are classified by  $(R, R)$ -bimodules  $X$  together with an isomorphism  $X^{\otimes n} \xrightarrow{\cong} R$ ; in particular,  $X$  is invertible. Hence we can restrict our search to  $\text{Pic}(R) \subset \mathcal{B}imod_R$ , the subcategory of invertible bimodules. Inside  $\text{Pic}(R)$ , we also have  $\text{Out}(R)$ ; as described last time, an outer automorphism defines an (isomorphism class of)  $(R, R)$ -bimodules.

**Exercise 5.3.** Assuming  $Z(R) \cong k$ , let  $\theta \in \text{Out}(R)$ . Show that  $\theta(g) = \zeta g$  for  $g \in R^\times$  and some root of unity  $\zeta$ . If this is too difficult at first, take a look at some examples; see if you can give an example for any  $\zeta$ .

One big open problem in this field is to classify all fusion categories. This is of course way too hard, given that it's more difficult than the classification of finite groups, but as with the classification of finite groups, intermediate results are interesting, possible, and useful.

<sup>5</sup>Conversely, any choice of  $\zeta$  is given by some  $\omega$ , though it's not always easy to work this out in practice.

**Theorem 5.4** (Ocneanu rigidity (Etingof-Nikshych-Ostrik [ENO05])). *Fusion categories over  $\mathbb{C}$  have no deformations.*

This was originally conjectured by Ocneanu. We won't say precisely what a deformation of a fusion category is, but the data of associativity in a fusion category is matrices satisfying some equations, modulo the action of some symmetry group. Ocneanu rigidity amounts to there being only finitely many orbits of solutions under this group action.

**Corollary 5.5.** *There are countably many tensor equivalence classes of fusion categories over  $\mathbb{C}$ .*

For example,  $\text{Vec}_G^\omega$  is classified by  $H^3(G; \mathbb{C}^\times)$ , which is a finite group.

*Remark 5.6.* Ocneanu rigidity is open in positive characteristic; the speaker expects it to be true, but for different reasons. The proof in characteristic zero uses a tool called *Davydov-Yetter cohomology* for fusion categories — this vanishes in characteristic zero, which implies Theorem 5.4, but is known to not vanish in characteristic  $p$  in general. ◀

**Example 5.7.** Another rich source of interesting examples of fusion categories are quantum groups at roots of unity. The construction is quite complicated. For example, fix an integer  $\lambda$ , called the *level*; then, one can build a fusion category  $\mathcal{C}(\mathfrak{sl}_2, \lambda)$  as follows. There are  $\lambda + 1$  simple objects  $L_0, \dots, L_\lambda$ , and the fusion rules are determined by

$$(5.8) \quad L_i \otimes L_1 = L_1 \otimes L_i = L_{i-1} \oplus L_{i+1},$$

where  $L_{-1} = L_{\lambda+1} = 0$ ; this suffices to determine the rest of the fusion rules. This looks reminiscent of the representation theory of  $\mathfrak{sl}_2$ , but “cut off” at  $\lambda$ . ◀

Any fusion category not equivalent to  $\text{Vec}_G^\omega$  or a quantum group is called *exotic*. Examples of exotic fusion categories are constructed using subfactor theory; many are related to something called *near group categories*. Such a category has as its set of simple objects  $G \amalg \{X\}$ , where  $G$  is a finite group. The tensor product on elements of  $G$  is just multiplication, and the remaining rules are

$$(5.9a) \quad g \otimes X = X \otimes g = X$$

$$(5.9b) \quad X \otimes X = \bigoplus_{g \in G} g \oplus nX,$$

for some  $n \in \mathbb{N}$ .

It's not necessarily true that one can find an associator compatible with this data, but often one can. For  $n = 0$ , these are *Tambara-Yamagami categories*, which are relatively well-studied. For  $n > 0$ , Evans-Gannon [EG14] showed that either  $n = \#G - 1$  or  $\#G \mid n$ . Moreover, if  $n \geq \#G$ , then  $G$  must be abelian, which is a nice simplification! Izumi-Tucker [IT19] considered the cases where  $n = \#G - 1$  and  $n = \#G$  — in the latter case, there are only finitely many examples, and for  $n = 2\#G$ , there's a single example with  $G = \mathbb{Z}/3$ . In general, it's open whether there are a finite number of examples for a fixed  $n$  as a function of  $\#G$ .

There are also various useful constructions which, given some fusion categories, produce more. One example is Deligne's tensor product  $\mathcal{C} \boxtimes \mathcal{D}$  of fusion categories, which is again a fusion category.

**Definition 5.10.** An *associative algebra* in a fusion category  $\mathcal{C}$  is an object  $A \in \mathcal{C}$  together with  $\mathcal{C}$ -morphisms  $m: A \otimes A \rightarrow A$  and a unit  $i: \mathbf{1} \rightarrow A$ , subject to axioms guaranteeing associativity of  $m$  and that  $i$  is a unit for  $m$ .

Given an associative algebra  $A$  in  $\mathcal{C}$ , we can define  $A$ -module and  $(A, A)$ -bimodule objects in  $\mathcal{C}$ , analogous to the usual case.

**Exercise 5.11.** Write these definitions down.

The upshot is, given an associative algebra  $A$  in  $\mathcal{C}$ , the category of  $(A, A)$ -bimodule objects, denoted  ${}_A\mathcal{C}_A$ , is a tensor category. The monoidal product is  $\otimes_A$ , and the unit is  $A$ . This is generally not a fusion category — and indeed, even if  $A$  is just an algebra in vector spaces, its category of bimodules generally isn't fusion! But if  $A$  satisfies an assumption called *separability*, then  ${}_A\mathcal{C}_A$  is semisimple and rigid, which is pretty close to being fusion — all we need is that  $\mathbf{1} \in {}_A\mathcal{C}_A$  is indecomposable. A sufficient (but not necessary) condition for this is  $\text{Hom}_{\mathcal{C}}(\mathbf{1}, A) \cong k$ .

*Remark 5.12.* If we start with  $\mathcal{C} = \text{Vec}_G^\omega$  and look for bimodule categories for algebras in  $\mathcal{C}$ , the fusion categories we obtain are called *group-theoretical fusion categories*. ◀

Another procedure to obtain fusion categories is called *graded extensions*, building a  $G$ -graded fusion category, where  $G$  is a finite group, out of an ungraded fusion category.

Here are two extremely useful tools for classifying fusion categories.

- (1) The Drinfeld center of a fusion category is a modular tensor category. Modular tensor categories have a lot of structure, and this is helpful for learning about fusion categories.
- (2) Diagrammatic methods are helpful, as we saw at the beginning of today's lecture.

## 6. ERIC ROWELL, AN INTRODUCTION TO MODULAR TENSOR CATEGORIES II

Last time, we discussed a few different kinds of tensor categories, in particular pointed ribbon fusion categories and pointed modular tensor categories. Both of these have been classified; the classification amounts to finding compatible twists on  $\text{Vec}_G$  with various braidings.

**Theorem 6.1** ([EGNO15]).

- (1) *Pointed ribbon fusion categories up to equivalence are classified by data of a finite abelian group  $G$  and a quadratic form  $q: G \times G \rightarrow \mathbb{C}^\times$ .*
- (2) *Pointed modular tensor categories are classified by  $(G, q)$  as above, subject to the condition that  $q$  is nondegenerate.*

The data of  $(G, q)$  is often called a *pre-metric group*, and if  $q$  is nondegenerate, it's called a *metric group*. The quadratic form determines the 2-cocycle that specified the braiding, via

$$(6.2) \quad B(g, h) := \frac{q(g)q(h)}{q(gh)}.$$

This is all very nice, but we would like some more interesting examples, so we turn to quantum groups  $\mathcal{C}(\mathfrak{g}, \ell)$ . Here  $\mathfrak{g}$  is a simple Lie algebra and  $\mathcal{C}$  is the category of modules over  $\mathcal{U}_q(\mathfrak{g})$ , where  $q := \exp(\pi i/m \ll)$ . For  $m = 1$ ,  $\mathfrak{g}$  can be ADE type; for  $m = 2$ , of BCF type; and for  $m = 3$ ,  $\mathfrak{g} = \mathfrak{g}_2$ . Setting up the category involves some technical details, but can be done, and we obtain modular categories!<sup>6</sup>

**Example 6.3.** Let's take  $\mathfrak{g} = \mathfrak{so}_5$  and  $\ell = 5$ , so  $q = e^{i\pi/10}$ . The objects in  $\mathcal{C}$  are described by a Weyl chamber for  $\mathfrak{g}$  (TODO: it was not at all clear to me why), but  $\ell = 5$  imposes that we kill all objects above a certain line. In this we have the standard representation  $V$ , the adjoint representation  $A$ , and an object at coordinates  $(1/2, 1/2)$  with quantum dimension  $\sqrt{5}$ . The level (in the notation of the previous talk) of this category is 2, so sometimes it's also denoted  $\text{SO}(5)_2$ . ◀

**Example 6.4.** Let's consider  $\mathcal{C}(\mathfrak{sl}_2, 5)$ . Now we look at a ray within the one-dimensional root space, and only keep the first three objects,  $S$  at 1,  $A$  at  $\tau$ , and the unit. The fusion rules are  $A^{\otimes 2} = \mathbf{1} \oplus A$ , and  $S^{\otimes 2} \cong \mathbf{1}$ . Thus this category actually splits as a Deligne tensor product of the subcategory generated by  $S$ , which is called the *semion category*, and the subcategory generated by  $A$ , which is called the *Fibonacci category*. Both of these are fundamental examples. ◀

**Example 6.5.**  $\mathcal{C}(\mathfrak{sl}_2, 4)$  is an *Ising category*. Its simple objects are  $\mathbf{1}$ ,  $\sigma$ , and  $\psi$ . Here  $\dim(\sigma) = \sqrt{2}$ ,  $\dim(\psi) = 1$ ,  $\theta_\sigma = e^{3\pi i/8}$ , and  $\theta_\psi = -1$ . This  $\sigma$  particle was the first nonabelian anyon discovered, and it's reminiscent (though not the same as) to a Majorana fermion. The  $S$ -matrix is

$$(6.6) \quad S = \begin{pmatrix} 1 & \sqrt{2} & 1 \\ \sqrt{2} & 0 & -\sqrt{2} \\ 1 & -\sqrt{2} & 1 \end{pmatrix}. \quad \blacktriangleleft$$

We've described examples of modular categories via their *modular data*: the  $S$ -matrix and also the  $T$ -matrix  $T_{ij} = \delta_{ij}\theta_i$ . Stay tuned for a talk later this weey by Colleen Delaney with more details.

The modular group  $\text{SL}_2(\mathbb{Z})$  is generated by two matrices  $S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$  and  $T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ . The  $S$ - and  $T$ -matrices appearing in the data of a modular category satisfy relations that imply they define a projective representation  $\Phi$  of  $\text{SL}_2(\mathbb{Z})$ .

<sup>6</sup>Here  $m$  is important; if you leave it out, you'll always get a ribbon category, but not necessarily a modular one.

**Theorem 6.7** (Ng-Schauenburg [NS10]). *The image of such a representation  $\Phi$  is finite. In fact, if  $N$  is the order of  $T$ , then  $\Phi$  factors over  $\mathrm{SL}_2(\mathbb{Z}/n)$ .*

Classifying fusion categories is too difficult in general, but modular categories have more adjectives in front of them. Maybe we can classify them, at least for a fixed rank  $r$  that's not too large. Or even, how many of them are there?

A good first step is to consider the field  $\mathbb{K}_0 := \mathbb{Q}(s_{ij})$ , which sits inside  $\mathbb{Q}(\theta_i)$ . Since  $T$  has finite order,  $\mathbb{Q}(\theta_i)$  is a cyclotomic extension  $\mathbb{Q}(\zeta_N)$  for some primitive  $N^{\mathrm{th}}$  root of unity  $\zeta_N$ . These are particularly nice Galois extensions in that:

- (1) Since  $\mathbb{Q} \hookrightarrow \mathbb{Q}(\theta_i)$  is a cyclotomic extension,  $\mathrm{Gal}(\mathbb{Q}(\theta_i)/\mathbb{Q})$  is abelian, and in particular always solvable.
- (2) Since we're looking at rank  $r$ , the  $T$ -matrix is  $r \times r$ , so we get an embedding  $\mathrm{Gal}(\mathbb{K}_0/\mathbb{Q}) \hookrightarrow \mathrm{Aut}(\mathrm{Irr}(\mathcal{C})) \cong S_r$ .
- (3) There is some  $k$  such that  $\mathrm{Gal}(\mathbb{Q}(\zeta_N)/\mathbb{K}_0) \cong (\mathbb{Z}/2)^k$ .

Thus we have a recipe for classifying modular categories of rank  $r$ .

- (1) Choose an abelian subgroup  $A$  of  $S_r$ . Then, using the above facts, classify all possible  $S$ -matrices which yield the Galois group  $\mathrm{Gal}(\mathbb{Q}(\mathbb{K}_0/\mathbb{Q}) \cong A \subset S_r$ . For many choices of  $A$ , there are no possible  $S$ -matrices.
- (2) The *Verlinde formula* determines the fusion rules from the  $S$ -matrix.
- (3) Finally, an analogue of Ocneanu rigidity (Theorem 5.4) informs us that there are finitely many modular tensor categories with fixed fusion rules.

This has worked completely up to rank 5 so far, and is also effective in rank 6. One general question, which is still open, is *if you fix a fusion category, how do you classify its possible modular structures?* We know there can only be finitely many, but that theorem is nonconstructive. In special cases, things are known; for example, a result of Kazhdan-Wenzl [KW93] allows us to solve this for  $\mathcal{C}(\mathfrak{sl}_n, \ell)$ . More recent work of Nikshych [Nik19] establishes how to classify the possible braidings given fixed fusion rules. And spherical structures on a modular tensor categories are understood: they're given by invertible objects with order at most 2.

**Theorem 6.8** (Rank-finiteness (Bruillard-Ng-Rowell-Wang [BNRW16])). *There are finitely many modular tensor categories of a fixed rank  $r$ .*

The proof ultimately relies on results in analytic number theory, which is interesting.

Moving on, let  $\mathcal{C}$  be a braided fusion category and  $B_n$  denote the braid group on  $n$  strands. Given an object  $X \in \mathcal{C}$ , the braiding defines a map  $\psi: B_n \rightarrow \mathrm{Aut}(X^{\otimes n})$ ; if  $\sigma_i$  denotes the braid that switches braids  $i$  and  $i+1$ , then

$$(6.9) \quad \psi(\sigma_i) := \mathrm{id}_X^{\otimes(i-1)} \otimes c_{X,X} \otimes \mathrm{id}_X^{\otimes(n-i-1)}.$$

$\mathrm{Aut}(X^{\otimes n})$  acts on

$$(6.10) \quad \mathcal{H}_n^X := \bigoplus_{Y \in \mathrm{Irr}(\mathcal{C})} \mathrm{Hom}(Y, X^{\otimes n}),$$

so we get a representation  $\rho_X: B_n \rightarrow \mathrm{GL}(\mathcal{H}_n^X)$ . In addition to being an interesting braid group representation on its own, this representation is important for implementing gates in topological quantum computation.

It's natural to ask whether the image of  $\rho_X$  is finite.

**Definition 6.11.** We say that  $X \in \mathcal{C}$  has *property F* if the image of  $\rho_X$  is finite.

The Ising category (or rather, its nontrivial simple object) has property F, but the Fibonacci category does not.

**Definition 6.12.** Let  $X$  be an object in a fusion category  $\mathcal{C}$  and  $N_X$  be the matrix of fusion with  $X$  on  $\mathrm{Irr}(\mathcal{C})$ , i.e.

$$(6.13) \quad (N_X)_{ij} = \dim \mathrm{Hom}_{\mathcal{C}}(X \otimes X_j, X_i).$$

The *Frobenius-Perron dimension* of  $X$ , denoted  $\mathrm{FPdim}(X)$ , is the largest eigenvalue of  $N_X$ . If  $X$  is simple and  $\mathrm{FPdim}(X)^2 \in \mathbb{Z}$ ,  $X$  is called *weakly integral*.

Over 10 years ago, the speaker conjectured that  $X$  is weakly integral iff it has property F. This is known in special cases.

- For pointed fusion categories, this is essentially an exercise.
- For group-theoretical braided fusion categories (e.g.  $\text{Rep}(D^\omega G)$ ), this is due to Etingof-Rowell-Witherspoon [ERW08].
- For quantum groups  $\mathcal{C}(\mathfrak{g}, \ell)$ , this is known, thanks to work of Jones, Freedman, Larsen, Wang, Rowell, and Wenzl.
- Recently, this conjecture has been verified for weakly group-theoretical braided fusion categories by Green-Nikshych [GN19]. There is a different conjecture that weakly group-theoretical is equivalent to weakly integral.

This veracity of this conjecture is closed under taking Deligne tensor products, Drinfeld doubles, and a few other useful operations.

There are still many interesting open questions! For example, from a nondegenerate braided fusion category, one can extract an invariant called the *Witt group*, and this seems to be a rich and interesting invariant that we are still in the process of understanding.

## 7. ANNA BELIAKOVA, QUANTUM INVARIANTS OF LINKS AND 3-MANIFOLDS, I

The title of this talk is inspired from Turaev's talk, but we have a different aim in mind: Turaev studies things from a very general perspective, but we're going to focus on specific examples in detail.

There is a procedure called surgery which associates to a framed link in  $S^3$  a closed, oriented 3-manifold. A famous theorem of Lickorish-Wallace asserts that every closed, oriented 3-manifold can be realized in this way, and conversely, two framed links yield diffeomorphic 3-manifolds iff they differ by a series of known moves.

Given a ribbon Hopf algebra, one can build an invariant of framed links; for  $\mathcal{U}_q(\mathfrak{sl}_2)$ , for example, this is the colored Jones polynomial. Using a procedure called integration, we obtain 3-manifold invariants, in this case the Witten-Reshetikhin-Turaev invariants. And there's a way to build them directly from 3-manifolds, which uses finiteness.

There is another way to obtain framed link invariants from  $\mathcal{U}_q(\mathfrak{sl}_2)$ , yielding *Kashaev invariants*, which are of quantum dimension zero. These are sometimes also called *logarithmic invariants*. The corresponding 3-manifold invariants are called *Hennings CGP invariants*. (TODO: double-check this.)

More recently, these colored link invariants have been unified into a more general invariant called (TODO: double check) Hashiro's cyclotomic extension, yielding a unified Witten-Reshetikhin-Turaev invariant for 3-manifolds. We'll discuss this invariant in the second talk later this week.

Let  $L: (S^1 \times I)^{\text{II}k} \hookrightarrow S^3$  be a framed link, and let  $\nu(L)$  denote its normal bundle, embedded in  $S^3$  via the tubular neighborhood theorem. Given this data, *surgery on  $L$*  is the closed, oriented 3-manifold

$$(7.1) \quad S^3(K_f) := S^3 \setminus \nu(L) \cup_f (D^2 \times S^1)^{\text{II}k},$$

where  $f$  is the identification of  $\partial(S^3 \setminus \nu(L))$  and  $(D^2 \times S^1)^{\text{II}k}$  given by the framing. There are two moves which change the framed link but don't change the diffeomorphism class of the 3-manifold obtained under surgery.

- The simpler move, denoted K1, exchanges a figure-8 with an empty set.
- K2 is a little more elaborate. TODO: picture.

We will define a universal  $\mathfrak{sl}_2$  framed link invariant. Given  $n \in \mathbb{N}$ , let  $\{n\} := \sigma^n - \sigma^{-n}$ , where  $\sigma$  is a formal variable, and let  $[n] = \{n\}/\{1\}$ . Now, we define the quantum group

$$(7.2) \quad \mathcal{U}_q(\mathfrak{sl}_2) = \langle e, F^{(n)}, K \rangle,$$

where  $F^{(n)} := F^n/[n]!$ ,  $e = \{1\}E$ , and  $\sigma^H = K = \exp((h/2)H)$ . Let

$$(7.3) \quad E = \sigma^{H \otimes H} 2 \sum_{n=0}^{\infty} \sigma^{\frac{n(n-1)}{2}} F^{(n)} \otimes e^n \subset \mathcal{U}_k \hat{\otimes} \mathcal{U}_k.$$

Then (TODO: not sure)  $R$  is a simple tensor: write  $R = \alpha \otimes \beta$ . Now we label pieces of a framed link: if, traveling upwards, left travels over right, label the left with  $\beta$  and the right with  $\alpha$ ; if right travels over left,



label the left with  $\overline{\beta}$  and the right with  $\overline{\alpha}$ . Label a cup (coevaluation) with  $k$  and a cap (evaluation) with  $k^{-1}$ . Call the resulting element of the universal enveloping algebra  $J_L$ .

**Example 7.4.** TODO: example computed from a diagram. ◀

Notice that this always lands in the center of  $\mathcal{U}_k$ , which is freely generated by the *Casimir element*

$$(7.5) \quad C := \{1\}FE + \sigma K + \sigma^{-1}K^{-1}.$$

Let  $V_n$  be the  $n$ -dimensional irreducible representation of  $\mathcal{U}_q(\mathfrak{sl}_2)$ . Then let  $J_L(V_n)$  denote the action of  $J_L$  on  $V_n$ . For example, the Casimir acts on  $V_n$  by  $\sigma^n + \sigma^{-n}$ .

**Theorem 7.6** (Habiro [Hab08]). *Let  $K_0$  be a 0-framed knot. Then*

$$(7.7) \quad J_{K_0} = \sum_{m=0}^{\infty} a_m \sigma_m,$$

where  $a_m \in \mathbb{Z}[q^{\pm 1}]$  and

$$(7.8) \quad \sigma_m = \prod_{i=1}^m (c^2 - (\sigma + \sigma^{-1})^2).$$

**Example 7.9.** For the knot  $4_1$ ,  $J_{4_1} = \sum_{m=0}^{\infty} \sigma_m$ . For the knot  $3_1$ , we obtain

$$(7.10) \quad J_{3_1} = \sum_{m=0}^{\infty} (-1)^m q^{m(m-3)/2} \sigma_m. \quad \text{◀}$$

In general,

$$(7.11) \quad J_{K_0}(V_n) = \sum_{m=0}^{n-1} a_m \prod_{i=1}^n (q^n + q^{-n} - q^i - q^{-i}) = \sum a_m \prod_{i=1}^m \{n+i\} \{n-i\}.$$

This recovers the Witten-Reshetikhin-Turaev invariant as follows: let  $\xi$  be a  $p^{\text{th}}$  root of unity and plug in  $q = \xi$ . Then define

$$(7.12) \quad F_{K_a}(\xi) = \sum_{n=0}^{p-1} [n]^2 J_K(V_n)|_{q=\xi} = \sum_{n=0}^{p-1} [n]^2 q^{a(m^2-1)/4} J_{K_0}(V_n)|_{q=\xi}.$$

Then, the Witten-Reshetikhin-Turaev invariant of  $S^3(K_a)$  at  $\xi$  is  $F_{K_a}(\xi)/F_{\text{unknot}}(\xi)$ , where the unknot has framing given by the sign of  $a$ .

*Remark 7.13.* There is another invariant of 3-manifolds given similar-looking data, called the *Turaev-Viro invariant*, computed by triangulating the 3-manifold and labeling tetrahedra by  $6j$ -symbols. Beliakova-Durhuus [BD96], Walker, and Turaev showed that the Turaev-Viro invariant of  $M$  is equal to the Reshetikhin-Turaev invariant of  $M \# (-M)$ , i.e. the square of the Reshetikhin-Turaev invariant of  $M$ . ◀

**Theorem 7.14** (Beliakova-Chen-Lê [BCL14]). *For all closed, oriented 3-manifolds  $M$  and all  $\xi$ , the Witten-Reshetikhin-Turaev invariant of  $M$  at  $\xi$  is in  $\mathbb{Z}[\xi]$ .*

That is, we can write the Witten-Reshetikhin-Turaev invariant of  $M$  as a polynomial in  $\xi$  of degree at most  $p-1$ , and this is telling us that the coefficients are integers.

Now, let's write  $F_{K_a}(\xi)$  using a Gauss sum:

$$(7.15) \quad F_{K_a}(\xi) = \sum_{m \geq 0} a_m \sum_{n=0}^{p-1} q^{a(m^2-1)/4} \{n+m\} \cdots [n]^2 \cdots \{n-m\}.$$

This lives in  $\mathbb{Z}[q^{\pm n}, q]$ . Plugging in  $a = \pm 1$  (TODO: I think?), we see that

$$(7.16) \quad \sum_{n=0}^{p-1} q^{a(m^2-1)/4} q^{bn} = q^{-b^2/a} \gamma_a.$$



Let  $L_a(q^{bn} := q^{-b^2/a}$  and

$$(7.17) \quad I_M = (?) \sum_{m \geq 0} a_m L_a(\{n+m\} \cdots [n]^2 \cdots \{n-m\}).$$

Let  $(q)_n := (1-q) \cdots (1-q^n) \in \mathbb{Z}[q]$  and  $\tilde{I}_n \subset \mathbb{Z}[q]$  denote the ideal spanned by  $(q)_n$ . Then  $\tilde{I}_n \subset \tilde{I}_{n+1} \subset \tilde{I}_{n+2} \subset \dots$ , and we can complete to

$$(7.18) \quad \widehat{\mathbb{Z}}[q] := \varprojlim_n \mathbb{Z}[q]/(q)_n,$$

which is the ring of analytic functions on the roots of unity, and is called the *Habiro ring*. An element of  $\widehat{\mathbb{Z}}[q]$  can be represented as

$$(7.19) \quad f = \sum_{k=0}^{\infty} f_k(q)_k,$$

where  $f_k \in \mathbb{Z}[q]$ . This defines an embedding  $\widehat{\mathbb{Z}}[q] \hookrightarrow \mathbb{Z}[[1-q]]$ , and  $f \in \widehat{\mathbb{Z}}[q]$  is determined uniquely by its values at roots of unity. The value  $\omega_\xi f$  is well-defined (TODO: figure out what this means).

**Theorem 7.20** (Habiro [Hab08]). *If  $M$  is an integral homology sphere, there is a unique  $I_M \in \widehat{\mathbb{Z}}[q]$  such that for any  $\xi$ ,  $\omega_\xi I_M$  is the Witten-Reshetikhin-Turaev invariant for  $\xi$  and  $M$ .*

For example, if  $M$  is the Poincaré homology sphere,

$$(7.21) \quad I_M = \frac{q}{1-q} \sum (-1)^k q^{k(k+1)/2} (q^{k+1})_{k+1}.$$

If  $M$  is a rational homology sphere with  $b_1(M) > 0$  the theorem, proven by Beliakova-Bühler-Lê [BBL11], is not quite as simple. Recently, Habiro-Lê [HL16] have generalized Theorem 7.20 to the analogues of these invariants defined using an arbitrary simple Lie algebra.

Next time, we'll see how even non-semisimple invariants are determined by Witten-Reshetikhin-Turaev invariants.

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