

# MSRI: QUANTUM SYMMETRIES INTRODUCTORY WORKSHOP

ARUN DEBRAY  
JANUARY 27–31, 2020

These notes were taken at MSRI’s [introductory workshop on quantum symmetries](#) in Spring 2020. I live- $\text{\TeX}$ ed 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).

## CONTENTS

<b>Part 1. Monday, January 27</b>	1
1. Sarah Witherspoon: Hopf algebras, I	1
2. Victor Ostrik, Introduction to fusion categories, I	4
3. Eric Rowell, An introduction to modular tensor categories I	6
4. Emily Peters, Subfactors and planar algebras I	8
<b>Part 2. Tuesday, January 28</b>	11
5. Victor Ostrik, Introduction to fusion categories, II	11
6. Eric Rowell, An introduction to modular tensor categories II	13
7. Anna Beliakova, Quantum invariants of links and 3-manifolds, I	15
8. Terry Gannon, Conformal nets I	17
<b>Part 3. Wednesday, January 29</b>	20
9. Sarah Witherspoon, Hopf algebras, II	20
10. Cris Negron, Finite tensor categories and Hopf algebras: a sampling	21
<b>Part 4. Thursday, January 30</b>	23
11. Emily Peters, Subfactors and planar algebras, II	23
12. Zhenghan Wang, Topological orders I	26
13. Anna Beliakova, Quantum invariants of links and 3-manifolds, II	29
14. Colleen Delaney, Modular data and beyond	31
<b>Part 5. Friday, January 31</b>	33
15. Claudia Scheimbauer, Topological field theories and higher categories	33
16. Terry Gannon, Conformal nets II	36
17. Zhenghan Wang, Topological orders II	38
18. James Tener, Segal CFTs	40
References	42

### 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  $\mathfrak{sl}_2$ ,

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

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

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

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

(Note: the attached handout is by Chelsea Walton.)

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  $\text{Hom}$ -spaces are finite-dimensional over  $k$ ,
- $\mathcal{C}$  is semisimple,<sup>1</sup>
- $\mathcal{C}$  has only finitely many isomorphism classes of simple objects,
- $\mathbf{1}$  is indecomposable, and
- $\mathcal{C}$  is *rigid*, a condition on duals of objects.

A category satisfying all of these axioms is a *fusion category*.

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  $\text{Vec}_{\mathbb{Z}/n}^{\omega}$ , where  $n$  is a natural number and  $\omega$  is a degree-3 cocycle for  $\mathbb{Z}/n$ , valued in  $k^{\times}$ .

The objects of  $\text{Vec}_{\mathbb{Z}/n}^{\omega}$  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  $\text{Vec}_G^{\omega}$  in the same way.

With  $\omega$  as in (2.4),  $\text{Vec}_{\mathbb{Z}/2}^{\omega}$  looks like a new example, not equivalent to  $\text{Vec}_G^0$  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  $F: \text{Vec}_{\mathbb{Z}/n}^{\omega} \rightarrow \text{Vec}_{\mathbb{Z}/n}^{\omega'}$ . 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  $\omega = \omega' \cdot \partial\psi$ .*

<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.

<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  $\text{char}(k) \neq 2$ .

**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.

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.

**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)  and

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  $G$ ,  $\mathcal{R}ep_G$  is a braided fusion category. Let  $V$  and  $W$  be representations; then the braiding  $c_{V,W}(v \otimes w) := w \otimes v$ . ◀

**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  $\mathcal{R}ep_G$  is once again  $\mathcal{R}ep_G$ .

**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,  $\mathcal{C}' \simeq \mathcal{V}ect$ ), 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) 
$$\theta_{X \otimes Y} = c_{X,Y} \circ \theta_X \otimes \theta_Y.$$

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  $(\theta_X)^* = \theta_{X^*}$ .

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.

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

- 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.

**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  $\text{id } \mathcal{V}ec_G^\omega$  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

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.



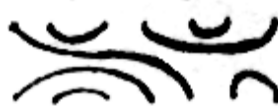


FIGURE 1. A Temperly-Lieb diagram in  $TL_7$ .

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 Temperly-Lieb diagrams which are isotopic. Let  $TL_n$  denote the complex vector space spanned by Temperly-Lieb diagrams of size  $n$ . Addition is formal.  $TL_n$  acquires an algebra structure by *stacking*: place one diagram on top of another, as illustrated in Figure 2.

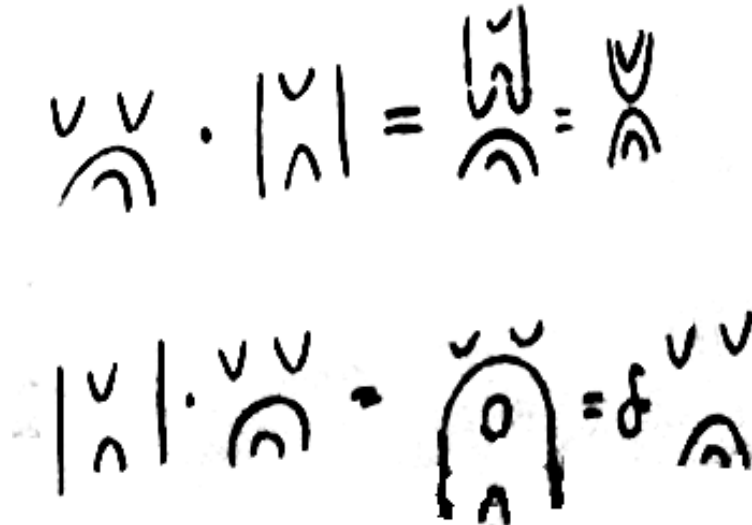


FIGURE 2. Composition of some Temperly-Lieb diagrams.

The identity operator for multiplication is the Temperly-Lieb diagram  $||| \dots |||$ .

This algebra has some additional interesting structure.

- There's a trace  $TL_n \rightarrow \mathbb{C}$ : given a Temperly-Lieb diagram, close up the embedded intervals in a process akin to a braid closure, then replace each circle with a factor of  $\delta$ .
- A  $*$ -structure, by reversing the diagram horizontally.
- This defines a Hermitian form on  $TL_n$ , by  $\langle x, y \rangle := \text{tr}(y^*x)$ . This is an inner product if  $\delta \geq 2$ .

Since the trace depends on  $\delta$ , we will write  $TL_n(\delta)$  for the Temperly-Lieb algebra with trace given by  $\delta$ .

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

**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 *planar diagrams* (which 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; the compact 1-manifolds are the spaghetti, and the holes in the annulus are the meatballs. These compose in a manner reminiscent of operator product expansion.

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

**Example 4.3.** The Temperly-Lieb algebra is a planar algebra, where the planar diagrams act by insertion.  $\blacktriangleleft$

**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  $p = p'$ . These two composition laws correspond to two planar diagrams, and these should give you the general story.

There's also a trace, where again you close off all boundaries with circles. This procedure is slightly ambiguous, so we simply sum up over all possibilities.  $\blacktriangleleft$

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.

- 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 called the *Zorro diagram* or *snake diagram* allowing us to pull taut a single strand with a cup and a cap. This allows us to freely do planar isotopy.

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  $V_n := \text{End}(X^{\otimes n})$ . The rest of the data comes from diagrammatics.

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  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$ , following work of Agustina Czenky.

The objects of  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega$  are all tensor products of  $1 \in \mathbb{Z}/n$ , which in diagrammatics is denoted  $\uparrow$ ; thus,  $i$  is denoted  $\uparrow \uparrow \dots \uparrow$ . To simplify notation, temporarily let  $n = 2$ . The generating morphisms are

$$(5.1) \quad \begin{array}{cc} \text{---} \curvearrowright \text{---} & \text{---} \curvearrowleft \text{---} \\ \bullet & \bullet \end{array}$$

and there are some relations:

$$(5.2) \quad \begin{array}{ccc} \text{---} \curvearrowright \text{---} & = \text{id} & \begin{array}{ccc} \text{---} \curvearrowright \text{---} & & \text{---} \curvearrowleft \text{---} \\ \bullet & & \bullet \end{array} = \begin{array}{ccc} \bullet & & \bullet \\ | & & | \\ \bullet & & \bullet \end{array} \end{array}$$

and

$$(5.3) \quad \begin{array}{ccc} \begin{array}{ccc} \bullet & & \bullet \\ \diagdown & & \diagup \\ \bullet & \curvearrowright & \bullet \end{array} & = (\pm 1) & \begin{array}{ccc} \bullet & & \bullet \\ \diagdown & & \diagup \\ \bullet & \curvearrowleft & \bullet \end{array} \end{array}$$

where the sign is  $+1$  for  $[\omega] = 0$  in  $H^3(B\mathbb{Z}/2; \mathbb{R}/\mathbb{Z})$  and  $-1$  for  $[\omega]$  nonzero. For more general  $n$ , the factor is some  $n^{\text{th}}$  root of unity  $\zeta$  determined by  $\omega$ .<sup>5</sup>

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

**Proposition 5.4.** *Let  $\mathcal{C}$  be a fusion category. Then there is a natural bijection between tensor functors  $F: \mathcal{V}ec_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{C}$  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  $\mathcal{V}ec_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{C}$  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 5.5.** Assume  $n$  is odd, so that we can use  $2 \in \mathbb{Z}/n$  as a generator. This gives two diagrams that you can compare, and one is 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  $F: \mathcal{V}ec_{\mathbb{Z}/n}^\omega \rightarrow \mathcal{B}imod_R$ , 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 5.6.** 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.

**Theorem 5.7** (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 5.8.** *There are countably many tensor equivalence classes of fusion categories over  $\mathbb{C}$ .*

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

<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.

*Remark 5.9.* 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 5.7, but is known to not vanish in characteristic  $p$  in general. ◀

**Example 5.10.** 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

$$(5.11) \quad L_i \otimes L_1 = L_1 \otimes L_i = L_{i-1} \oplus L_{i+1},$$

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  $\mathcal{V}ec_G^\omega$  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

$$(5.12a) \quad g \otimes X = X \otimes g = X$$

$$(5.12b) \quad X \otimes X = \bigoplus_{g \in G} g \oplus nX,$$

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 5.13.** 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 5.14.** 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  $\mathrm{Hom}_{\mathcal{C}}(\mathbf{1}, A) \cong k$ .

*Remark 5.15.* If we start with  $\mathcal{C} = \mathcal{V}ec_G^\omega$  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.

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  $\mathcal{V}ec_G$  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  $\mathfrak{g}$ , 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  $\text{SL}_2(\mathbb{Z})$ .

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

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  $N^{\text{th}}$  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,  $\text{Gal}(\mathbb{Q}(\theta_i)/\mathbb{Q})$  is abelian, and in particular always solvable.

---

<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.

- (2) Since we're looking at rank  $r$ , the  $T$ -matrix is  $r \times r$ , so we get an embedding  $\text{Gal}(\mathbb{K}_0/\mathbb{Q}) \hookrightarrow \text{Aut}(\text{Irr}(\mathcal{C})) \cong S_r$ .
- (3) There is some  $k$  such that  $\text{Gal}(\mathbb{Q}(\zeta_N)/\mathbb{K}_0) \cong (\mathbb{Z}/2)^k$ .

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  $\text{Gal}(\mathbb{Q}(\mathbb{K}_0/\mathbb{Q})) \cong A \subset S_r$ . 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 5.7) 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  $\psi: B_n \rightarrow \text{Aut}(X^{\otimes n})$ ; if  $\sigma_i$  denotes the braid that switches braids  $i$  and  $i + 1$ , then

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

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

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

so we get a representation  $\rho_X: B_n \rightarrow \text{GL}(\mathcal{H}_n^X)$ . 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  $\text{Irr}(\mathcal{C})$ , i.e.

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

The *Frobenius-Perron dimension* of  $X$ , denoted  $\text{FPdim}(X)$ , is the largest eigenvalue of  $N_X$ . If  $X$  is simple and  $\text{FPdim}(X)^2 \in \mathbb{Z}$ ,  $X$  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  $U_q(\mathfrak{sl}_2)$ , 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  $U_q(\mathfrak{sl}_2)$ , 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*.

More recently, these colored link invariants have been unified into a more general invariant, called the *Habiro cyclotomic invariant*, yielding a unified Witten-Reshetikhin-Turaev invariant for 3-manifolds. We’ll discuss this invariant in the second talk later this week.

Let  $L: (S^1 \times I)^{\mathbb{H}k} \hookrightarrow S^3$  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

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

where  $f$  is the identification of  $\partial(S^3 \setminus \nu(L))$  and  $(D^2 \times S^1)^{\mathbb{H}k}$  given by the framing. There are two moves K1 and K2 which change the framed link but don’t change the diffeomorphism class of the 3-manifold obtained under surgery.

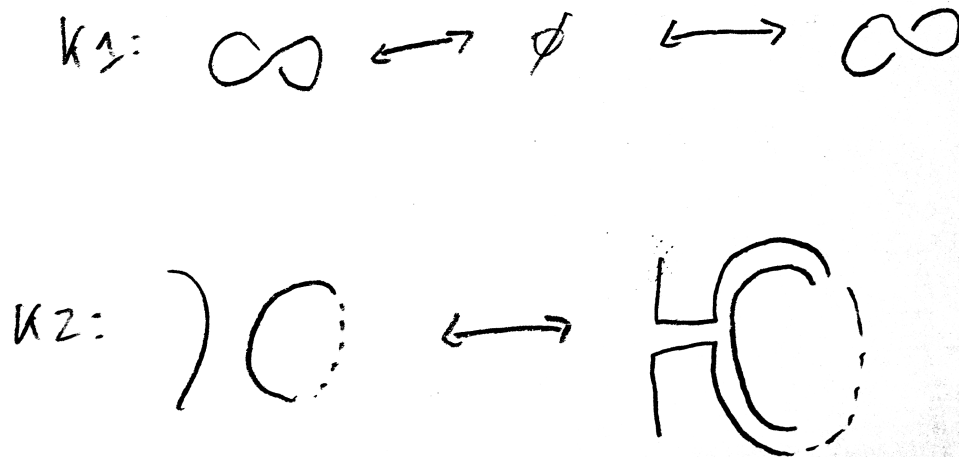


FIGURE 3. Moves on a framed link which do not change the diffeomorphism class of the 3-manifold obtained by surgery.

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

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

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

Then  $R$  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  $\bar{\beta}$  and the right with  $\bar{\alpha}$ . Label a cup (coevaluation) with  $k$  and a cap (evaluation) with  $k^{-1}$ . Call the resulting element of the universal enveloping algebra  $J_L$ . Notice that this always lands in the center of  $\mathcal{U}_k$ , which is freely generated by the *Casimir element*

$$(7.4) \quad C := \{1\}FE + \sigma K + \sigma^{-1}K^{-1}.$$

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

$$(7.6) \quad J_{K_0} = \sum_{m=0}^{\infty} a_m \sigma_m,$$

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

$$(7.7) \quad \sigma_m = \prod_{i=1}^m (c^2 - (\sigma + \sigma^{-1})^2).$$

**Example 7.8.** For the knot  $4_1$ ,  $J_{4_1} = \sum_{m=0}^{\infty} \sigma_m$ . For the knot  $3_1$ , we obtain

$$(7.9) \quad J_{3_1} = \sum_{m=0}^{\infty} (-1)^m q^{m(m-3)/2} \sigma_m. \quad \blacktriangleleft$$

In general,

$$(7.10) \quad J_{K_0}(V_n) = \sum_{m=0}^{n-1} a_m \prod_{i=1}^n (q^n + q^{-n} - q^i - q^{-i}) = \sum a_m \prod_{i=1}^m \{n+i\} \{n-i\}.$$

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

$$(7.11) \quad F_{K_a}(\xi) = \sum_{n=0}^{p-1} [n]^2 J_K(V_n)|_{q=\xi} = \sum_{n=0}^{p-1} [n]^2 q^{a(m^2-1)/4} J_{K_0}(V_n)|_{q=\xi}.$$

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 7.12.* 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  $M$ .  $\blacktriangleleft$

**Theorem 7.13** (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:

$$(7.14) \quad F_{K_a}(\xi) = \sum_{m \geq 0} a_m \sum_{n=0}^{p-1} q^{a(m^2-1)/4} \{n+m\} \cdots [n]^2 \cdots \{n-m\}.$$

This lives in  $\mathbb{Z}[q^{\pm n}, q]$ . Plugging in  $a = \pm 1$ , we see that

$$(7.15) \quad \sum_{n=0}^{p-1} q^{a(m^2-1)/4} q^{bn} = q^{-b^2/a} \gamma_a.$$

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

$$(7.16) \quad I_M = (?) \sum_{m \geq 0} a_m L_a(\{n+m\} \cdots [n]^2 \cdots \{n-m\}).$$

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

$$(7.17) \quad \widehat{\mathbb{Z}}[q] := \varprojlim_n \mathbb{Z}[q]/(q)_n,$$

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

$$(7.18) \quad f = \sum_{k=0}^{\infty} f_k(q)_k,$$

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.

**Theorem 7.19** (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,

$$(7.20) \quad I_M = \frac{q}{1-q} \sum (-1)^k q^{k(k+1)/2} (q^{k+1})_{k+1}.$$

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 7.19 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.

## 8. TERRY GANNON, CONFORMAL NETS I

Why care about conformal nets? Well, conformal field theory (CFT) is implicitly tied to most of the subjects in this conference, e.g. to a few talks explicitly about CFTs later this week, but also relationships with modular tensor categories. Conformal nets are our current best understanding of CFT, and as such are closely related to many other topics present in this conference.

In the last three centuries, physics has given back a great deal to mathematics, first via classical mechanics leading to the study of differential equations (ordinary and partial), and then symplectic geometry; then quantum mechanics and its ramifications in functional analysis; and recently, the still ongoing mathematical understanding of quantum field theory (QFT). We are barely scratching the surface, and the mathematical understanding of quantum field theory is promising to be a much deeper gift to mathematics than classical mechanics. Witten wrote around the turn of the century that understanding QFT will be a distinguished feature of 21<sup>st</sup>-century mathematics.

Quantum field theory is very general. We will study a very special, simple case: quantum field theories in dimension  $1+1$  (i.e. one dimension each of space and time) which are conformally invariant. Conformal invariance is a strong condition to impose on a QFT, and we will be rewarded with nice properties and interesting examples.

The Wightman axioms lead to a focus on quantum fields, which when applied to  $(1+1)$ -dimensional CFT lead to an axiomatization of CFTs through vertex operator algebras. This is different, almost rival, to the perspective of conformal nets we will discuss today. Heisenberg argued that, since quantum fields aren't physically observable objects, we shouldn't focus on them, and instead we should axiomatize the observables, those things that one can actually (in principle) measure in a physical theory of the universe. This leads to the Haag-Kastler axioms for QFT, and when we implement this for CFT, we will see conformal nets.

In classical mechanics, the state of a system is a point in a phase space, which is a symplectic manifold. Observable data, such as the position, momentum, etc., of particles, are functions on phase space. Quantum mechanics is different. The state of a system is a ray in the phase space, which is a Hilbert space  $H$ . Observables are Hermitian operators on  $H$ , such as  $(i/\hbar)\frac{\partial}{\partial x}$ . Measurements amount to projecting down onto eigenspaces for different operators, and these projections tell you the different probabilities.

To discuss conformal field theories, let's first discuss conformal symmetries, which are symmetries which preserve angles infinitesimally, but might not preserve distances. For example,  $z \mapsto z^{-1}$  is a conformal transformation on the Riemann sphere — one says there's a *conformal compactification* of  $\mathbb{C}$ , which is the Riemann sphere. The story is similar on  $\mathbb{R}^{m,n}$ , leading to a conformal symmetry group  $\text{SO}(m+1, n+1)/\{\pm 1\}$ , provided that  $m, n \geq 1$  and  $m+n \geq 3$ .

But we care about  $m=n=1$ , in which things change drastically. The conformal compactification of  $\mathbb{R}^{1,1}$  is  $S^1 \times S^1$ ; we add all possible light rays. The conformal transformations of  $S^1 \times S^1$  are huge — this group is  $\text{Diff}^+(S^1) \times \text{Diff}^+(S^1)$ : two copies of the orientation-preserving diffeomorphisms of the circle!  $\text{Diff}^+(S^1)$  is a Lie group in a suitable infinite-dimensional sense, and its Lie algebra is  $\text{Vect}(S^1)$ , the Lie algebra of vector fields on the circle.

Quantum field theory is all about representation theory; this is how it relates to tensor categories. So we will be interested in representations of the groups and Lie algebras we've seen so far — but since states are rays in  $H$ , rather than points, the correct notion of representation in this setting is projective representations. The best way to handle these is to pass to a central extension and obtain a *bona fide* representation, and therefore we will see central extensions of  $\text{Diff}^+(S^1)$  and  $\text{Vect}(S^1)$ . This might make contact with familiar mathematics: complexify the Lie algebra and centrally extend, and what you obtain is the *Virasoro algebra*. So the representation theory of the Virasoro algebra, and those representations which lift to representations of a central extension of  $\text{Diff}^+(S^1)$ , are important in  $(1+1)$ -dimensional CFT.

Inside  $\text{Diff}^+(S^1) \times \text{Diff}^+(S^1)$ , we could consider the somewhat special, finite-dimensional subgroup  $\text{SO}(2,2)/\{\pm 1\} \cong \text{PSL}_2(\mathbb{R}) \times \text{PSL}_2(\mathbb{R})$ . Another fairly obvious subgroup is the subgroup of rotations, the diagonals in  $\text{SO}(2,2)$ .

The Virasoro algebra has a nice basis, which is the standard basis that people use when discussing it: there are elements  $L_n$  for each  $n \geq 0$ , and a central element  $k$ . The Lie bracket is

$$(8.1) \quad [L_m, L_n] = (m-n)L_{m+n} + \delta_{m,-n}ck,$$

where  $c$  is some constant, in fact  $(m^3 - m)/12$ . Since  $k$  is central, all other brackets of basis elements vanish.

There is a standard trick in conformal field theory: focus on the two factors of  $\text{Diff}^+(S^1)$  separately. This leads to a significant simplification — a *chiral conformal field theory* is a CFT restricted to each factor of  $S^1$ . This isn't the full story: we'd have to fit the two pieces together into one, in order to understand the full story, but there are reasonable scenarios in which this works well. It doesn't work for everything, but it will work for the examples we focus on.

**Definition 8.2.** A *conformal net* is data of

- a Hilbert space  $H$ , called the *state space*; and
- for every interval<sup>7</sup>  $I \subset S^1$ , a von Neumann algebra  $A(I)$  of bounded linear operators on  $H$ , called the *algebra of observables* on  $I$ ,

such that the algebra generated by all  $A(I)$ s is  $B(H)$ , and satisfying a crucial axiom called *locality*: if  $I_1$  and  $I_2$  are disjoint intervals, with  $O_1 \in A(I_1)$  and  $O_2 \in A(I_2)$ , then  $[O_1, O_2] = 0$ .

For a conformal field theory, we need a projective representation  $U$  of  $\text{Diff}^+(S^1)$ . This will enforce the condition of conformal invariance (well, really covariance): for every  $\gamma \in \text{Diff}^+(S^1)$ , we get a unitary operator  $U(\gamma)$ , and we impose as part of the definition of a conformal net that

$$(8.3) \quad U(\gamma)A(I)U(\gamma)^* = A(\gamma(I)).$$

<sup>7</sup>By an *interval* in  $S^1$ , we mean an open, connected subset.

By differentiating, we obtain a representation of the Virasoro algebra. The *Hamiltonian* of the theory is  $L_0$ . We ask that in the Virasoro representation,  $L_0$  is diagonalizable and has nonnegative eigenvalues. These are the possible energies in this theories, so we want these to be nonnegative. There's a final axiom, involving the vacuum.

The easiest way to get your hands on von Neumann algebras is: pick your favorite group  $G$ , which can be infinite, and a unitary representation  $V$ , maybe infinite-dimensional. Then you get lots of unitary operators; single out those which commute with the group action, the symmetries of the representation. These form a von Neumann algebra, and, up to isomorphism, all von Neumann algebras arise in this way. If you'd prefer, there's a list of axioms on a  $*$ -algebra giving the definition of a von Neumann algebra, but it does not get the idea across as effectively.

You might have guessed from the notation that these  $A(I)$  form a net: whenever  $I_1 \subset I_2$ ,  $A(I_1) \subset A(I_2)$ : if you can measure something inside a smaller space(time), you can measure it inside the bigger space(time).

Locality is asking that nothing can travel faster than the speed of light. Two regions which are separated from each other cannot influence each other infinitely fast; you can think of simultaneously performing two experiments in the different regions.

Plenty of thought went into the axioms of a conformal net, but it's clear that there's still a lot of work to do before we get to the level of mathematical comfort with this definition that we're at in, say, symplectic geometry.

**Example 8.4.** The silliest example involves  $H = \mathbb{C}$ . ◀

**Example 8.5.** A better example is to begin with a vertex operator algebra  $A$ . The quantum fields in this model of the CFT are the vertex operators, which are operator-valued distributions; hit them with some test function  $f(\theta)$  which is supposed inside an interval  $I$ . After some difficult functional analysis, this gives operators which make up  $A(I)$ . This is beginning to be understood, thanks to work of Carpi, Kawahigashi, Longo, and Wiener [CKLW18]. ◀

**Example 8.6.** Let  $LSU(n)$  denote the *loop group* of  $SU(n)$ , i.e. the infinite-dimensional Lie group of maps  $S^1 \rightarrow SU(n)$ . If one chooses a good representation of the loop group (this is related to the conditions needed to obtain a modular tensor category of such representations). Then, in a similar way, one can build a conformal net, which was a difficult undertaking by Wasserman and others. ◀

The axioms of a conformal net are rich enough to produce some interesting phenomena. For example, if  $I$  is an interval, the interior of  $S^1 \setminus I$ , called  $I'$ , is also an interval, and these two intervals don't overlap.  *Haag duality* tells us that these two must commute, and we end up with  $A(I) = (A(I'))'$ . We also see that  $A(I)$  is always a particular kind of irreducible von Neumann algebra (called a *factor*), type III<sub>1</sub>. This is a very special type of von Neumann algebra, and we will see some consequences of this next time.

Conformal nets exist so that we can study their representation theory, so let's discuss what a representation is. The definition might not be surprising: a representation  $\pi$  of a conformal net  $A$  is data of, for each interval  $I \subset S^1$ , an algebra map  $\pi(I): A(I) \rightarrow B(K)$ , where  $K$  is some Hilbert space not necessarily related to  $H$ . This is required to satisfy some axioms: notably, when  $I_1 \subset I_2$ , we require  $\pi(I_2)|_{I_1} = \pi(I_1)$ .

The tautological representation of  $A$  acting on itself by the identity map is called the *vacuum representation*. Later, when we see that representations of a conformal net form a tensor category, the vacuum representation will be the tensor unit.

Any representation of a conformal net is automatically compatible with  $\text{Diff}^+(S^1)$  in the following sense: given  $x \in A(I)$  and  $\gamma \in \text{Diff}^+(S^1)$ ,

$$(8.7) \quad \pi(\gamma(I))(U(\gamma)xU(\gamma)^*) = U_\pi(\gamma)\pi(I)(x)U_\pi(\gamma)^*.$$

Next, we'll discuss how to build a tensor category on the category of such representations; if the CFT has a finiteness condition called *rationality*, it will be a modular tensor category. So a conformal net is a very complicated way to obtain a modular tensor category, and we will discuss this and related questions.

**Part 3. Wednesday, January 29**

9. SARAH WITHERSPOON, HOPF ALGEBRAS, II

Today, we will spend some time discussing non-semisimple Hopf algebras and tensor categories. This makes the classification question more complicated; there can be algebras or categories of wild type, where classifying all modules or objects, even the indecomposables, is just unrealistic.

So what can you do, then? It's still possible to make coarser classifications of objects and use techniques to gain partial information. Cohomology is particularly useful.

**Definition 9.1.** Let  $A$  be a Hopf algebra and  $n > 0$ . An  $n$ -extension of  $A$ -modules  $U$  and  $V$  is an exact sequence of  $A$ -modules

$$(9.2) \quad 0 \longrightarrow V \longrightarrow M_n \longrightarrow \cdots \longrightarrow M_2 \longrightarrow M_1 \longrightarrow U \longrightarrow 0.$$

A morphism of  $n$ -extensions is a commutative diagram

$$(9.3) \quad \begin{array}{ccccccccccccccc} 0 & \longrightarrow & V & \longrightarrow & M_n & \longrightarrow & \cdots & \longrightarrow & M_n & \longrightarrow & M_1 & \longrightarrow & U & \longrightarrow & 0 \\ & & \parallel & & \downarrow & & & & \downarrow & & \downarrow & & \parallel & & \\ 0 & \longrightarrow & V & \longrightarrow & M'_n & \longrightarrow & \cdots & \longrightarrow & M'_2 & \longrightarrow & M'_1 & \longrightarrow & U & \longrightarrow & 0, \end{array}$$

i.e. the maps on  $U$  and  $V$  are the identity. This does not define a symmetric relation on  $n$ -extensions, so define  $\text{Ext}_A^n(U, V)$  to be the set of  $n$ -extensions, modulo the smallest equivalence relation generated by morphisms.

There is an abelian group structure on  $\text{Ext}_A^n(U, V)$  induced by *Baer sum* of extensions.

**Definition 9.4.** The *Hopf algebra cohomology* of a Hopf algebra  $A$  over  $k$  is  $H^n(A, k) := \text{Ext}_A^n(k, k)$ .

Hopf algebra cohomology carries a graded product structure.

**Definition 9.5.** Consider an  $m$ -extension and an  $n$ -extension of  $k$  by  $k$ , given respectively by

$$(9.6a) \quad 0 \longrightarrow k \longrightarrow M_n \longrightarrow \cdots \longrightarrow M_1 \xrightarrow{\alpha} k \longrightarrow 0$$

$$(9.6b) \quad 0 \longrightarrow k \xrightarrow{\beta} N_n \longrightarrow \cdots \longrightarrow N_1 \longrightarrow k \longrightarrow 0.$$

The *Yoneda splice* of these two extensions is the  $(m+n)$ -extension

$$(9.7) \quad 0 \longrightarrow k \longrightarrow M_m \longrightarrow \cdots \longrightarrow M_1 \xrightarrow{\beta \circ \alpha} N_n \longrightarrow \cdots \longrightarrow N_1 \longrightarrow k \longrightarrow 0.$$

Yoneda splice defines a bilinear map  $H^m(A, k) \times H^n(A, k) \rightarrow H^{m+n}(A, k)$ , called the *Yoneda product* or *cup product*; this makes  $H^*(A, k) := \bigoplus_n H^n(A, k)$  into a graded ring.

We haven't used the Hopf algebra structure yet, and this cohomology ring exists for a general algebra.

**Theorem 9.8.** *If  $A$  is a bialgebra, then  $H^*(A, k)$  is graded commutative.*

That is, this theorem uses comultiplication, but not the antipode.

More generally, given a tensor category  $\mathcal{C}$ , one can define a graded commutative  $k$ -algebra  $H^*(\mathcal{C}, \mathbf{1})$ .

**Conjecture 9.9** (Friedlander-Suslin, Etingof-Ostrik). If  $A$  is a finite-dimensional Hopf algebra, then  $H^*(A, k)$  is finitely generated, and moreover, if  $U$  and  $V$  are finite-dimensional  $A$ -modules,  $\text{Ext}_A^*(U, V)$  is a finitely generated module over  $H^*(A, k)$ .<sup>8</sup>

Correspondingly, if  $\mathcal{C}$  is a finite tensor category,<sup>9</sup>  $H^*(\mathcal{C}, \mathbf{1})$  is finitely generated, and for any  $X, Y \in \mathcal{C}$ ,  $\text{Ext}_{\mathcal{C}}(X, Y)$  is a finitely generated  $H^*(\mathcal{C}, \mathbf{1})$ -module.

Somehow this conjecture needs the fact that there *is* a comultiplication, but doesn't need the specific comultiplication, which is a little surprising.

*Remark 9.10.* There is another cohomology theory for algebras, called *Hochschild cohomology*. However, the analogue of Conjecture 9.9 for Hochschild cohomology is false!  $\blacktriangleleft$

<sup>8</sup>We haven't specified how to make this module structure; one way is to write  $\text{Ext}_A^*(U, V) \cong \text{Ext}_A^*(k, U^* \otimes V)$  and form a Yoneda splice on the left.

<sup>9</sup>A *finite* tensor category is one satisfying a few niceness conditions, including that it has only finitely many simple objects.

Why care about Conjecture 9.9? There is a theory of “varieties for modules” which is most useful in settings where the conjecture is true. The idea is to realize modules over noncommutative objects in terms of modules over commutative objects, and then take advantage of commutativity. Recent work of Bergh-Plavnik-Witherspoon [BPW19] works out a lot of this theory for general finite tensor categories.

Conjecture 9.9 is still open, but is known in a number of cases. Here are some established results.

- For  $A = k[G]$  or  $\mathcal{C} = \text{Rep}_G$ ,  $G$  a finite group, this has been known for a long time. This is only interesting in modular characteristic (i.e.  $\text{char}(k) = p$  divides the order of  $G$ ); otherwise,  $k[G]$  is semisimple and its cohomology is concentrated in degree zero. This was established in the 1960s by Golodi, Venkov, and Evans; the theory of varieties for modules in this setting followed soon after.
- In positive characteristic, if  $A$  is a *restricted enveloping algebra*, i.e. a finite-dimensional quotient of  $U(\mathfrak{g})$ , Conjecture 9.9 was established by Friedlander-Parshall [FP86, FP87].
- In characteristic zero, Conjecture 9.9 is true for the small quantum group  $u_q(\mathfrak{g})$ , as shown by Ginzburg-Kumar [GK93].
- In positive characteristic, if  $A$  is a finite-dimensional cocommutative Hopf algebra, Conjecture 9.9 was shown by Friedlander-Suslin [FS97]. This was a significant breakthrough.

Some of these papers go beyond Conjecture 9.9, establishing structural results rather than just size.

The obstruction to understanding the general case is that we don’t really understand finite-dimensional Hopf algebras and finite tensor categories well enough. But there has been recent progress, including work of Gordon (2000), Mastnak-Pevtsova-Schauenburg-Witherspoon [MPSW10], Bendel-Nukana-Parshall-Pillen (2014), Nguyen-Witherspoon [NW14] for twisted group algebras, Drupieski (2016) for supergroup schemes, Vay-Stefan (2016), Friedlander-Negron (2018) on Drinfeld doubles of cocommutative algebras, Nguyen-Wang-Witherspoon [NWW17, NWW19] in positive characteristic and a few general results; Erdmann-Silberg-Wang, Negron-Plavnik [NP18] recently on some general results on finite tensor categories; and more. There’s been a lot of recent progress, but finishing off the conjecture will probably require new ideas.

Ongoing work of Andruskiewitsch-Angimo-Pevtsova-Witherspoon tackles the conjecture in characteristic zero for finite-dimensional pointed Hopf algebra whose grouplike elements form an abelian group — you always get a group, but the nonabelian case is wilder and a lot harder! This relies on previous results of Nicholas and Ivan on the structure theory of pointed Hopf algebras.

Yetter-Drinfeld modules are an important tool in the proof.

**Definition 9.11.** A *Yetter-Drinfeld  $k[G]$ -module* is a  $k[G]$ -module  $V$  together with a  $G$ -grading  $V = \bigoplus_{g \in G} V_g$ , such that for all  $g, h \in G$ ,  $h \cdot V_g = V_{hgh^{-1}}$ . The category of Yetter-Drinfeld  $k[G]$ -modules is denoted  ${}^{k[G]}_{k[G]}\mathcal{YD}$ .

In the finite-dimensional case, these are equivalent to modules over the Drinfeld double of  $G$ .

Given a Yetter-Drinfeld module  $V$ , its tensor algebra  $T(V)$  is a *braided Hopf algebra*, i.e. a Hopf algebra object in  ${}^{k[G]}_{k[G]}\mathcal{YD}$ . There is a largest ideal  $J \subset T(V)$  that is also a *coideal*, i.e.

$$(9.12) \quad \Delta(J) = J \otimes T(V) + T(V) \otimes J.$$

This ideal  $J$  is concentrated in degrees greater than 1.

**Definition 9.13.** The *Nichols algebra* is  $T(V)/J$ .

**Example 9.14.** If  $q$  is an  $n^{\text{th}}$  root of unity, then  $u_q(\mathfrak{sl}_2)^+ := k\langle E \mid E^n = 0 \rangle$  is a Nichols algebra, and we can obtain

$$(9.15) \quad u_q(\mathfrak{sl}_2)^{\geq 0} = \langle E, K \mid E^n = 0, K^n = 1, KE = q^2EK \rangle$$

as a smash product  $u_q(\mathfrak{sl}_2)^+ \# k\langle K \rangle$ ; in this setting, the smash product is also called the *bosonization* of  $u_q(\mathfrak{sl}_2)^+$ . ◀

More generally, finite-dimensional pointed Hopf algebras whose group of grouplike elements are abelian arise not necessarily as bosonizations of Nichols algebras, but aren’t far off; they’re what’s called *cocycle deformations*. This uses the classification of Nichols algebras, in terms of Dynkin and related diagrams.

## 10. CRIS NEGRON, FINITE TENSOR CATEGORIES AND HOPF ALGEBRAS: A SAMPLING

Today, we work over an algebraically closed field  $k$ .

**Example 10.1** (Small quantum groups). Small quantum groups are important examples of Hopf algebras. Let  $k = \mathbb{C}$  and let  $\mathfrak{g}$  be a simple Lie algebra. Choose Cartan data for  $\mathfrak{g}$ , so that we have a set  $\Delta$  of positive roots, and choose  $q \in \mathbb{C}^\times$  of order  $p$ . The *small quantum group* associated to this data is the algebra generated by  $E_\alpha, F_\alpha, K_\alpha$  for  $\alpha \in \Delta$  subject to the *q-Serre relations*

$$(10.2a) \quad E_\alpha^p = F_\alpha^p = K_\alpha^p - 1 = 0$$

$$(10.2b) \quad K_\alpha E_\beta K_\alpha^{-1} = q^{\langle \alpha, \beta \rangle} E_\beta$$

$$(10.2c) \quad K_\alpha F_\beta K_\alpha^{-1} = q^{-\langle \alpha, \beta \rangle} F_\beta.$$

This is a finite-dimensional, non-semisimple Hopf algebra.

Let  $u_q(\mathfrak{b})$ , called the *quantum Borel*, denote the subalgebra of  $u_q(\mathfrak{g})$  generated by the  $K_\alpha$  and  $E_\alpha$  elements; this is also finite-dimensional and non-semisimple. Let  $G \subseteq u_q(\mathfrak{b})$  be the subgroup generated by the  $K_\alpha$  elements.  $\blacktriangleleft$

One might ask: how much information is lost when we move from a Hopf algebra to its tensor category of representations?

Recall that a tensor category is an abelian,  $k$ -linear, rigid monoidal category  $\mathcal{C}$  whose objects all have finite length, whose Hom spaces are finite-dimensional over  $k$ , and whose unit is simple.

**Definition 10.3.** Call  $\mathcal{C}$  *finite* if it has finitely many simple objects and enough projectives.

This implies  $\mathcal{C}$  is tensor equivalent to a category of representations of a finite-dimensional algebra. For example, the representation categories of  $u_q(\mathfrak{g})$  and  $u_q(\mathfrak{b})$  are finite tensor categories.

**Definition 10.4.** If  $\mathcal{C}$  is semisimple and has finitely many simple objects, call  $\mathcal{C}$  *fusion*.

There's a sequence of nested inclusions

$$(10.5) \quad \begin{aligned} \{\text{representations of finite groups over } \mathbb{C}\} &\subseteq \{\text{fusion categories}\} \\ &\subseteq \{\text{finite tensor categories}\} \\ &\subseteq \{\text{tensor categories}\}. \end{aligned}$$

For example,  $\mathcal{R}ep_{\text{SL}_n}$  is a tensor category that is not finite.

For Hopf algebras, taking the category of representations lands in tensor categories, and we can study how tensor equivalences of representation categories can be thought of in the language of Hopf algebras. This is sort of asking, what happens as the boundary of this map from Hopf algebras to tensor categories?

**Definition 10.6.** A *Drinfeld twist* of a Hopf algebra  $A$  is a unit  $J \in A \otimes A$  satisfying

$$(10.7) \quad (\varepsilon \otimes 1)H = (1 \otimes \varepsilon)J = 1$$

and the *cocycle condition*

$$(10.8) \quad (\Delta \otimes 1)(J)(J \otimes 1) = (1 \otimes \Delta)(J)(1 \otimes J).$$

Given a Drinfeld twist  $J$ , we can build some new things.

- First, a new Hopf algebra denoted  $A^J$ , which is the same as  $A$  except the comultiplication is modified to  $\Delta^J := J\Delta(-)J$ .
- We also get a new fiber functor  $F_J: \mathcal{R}ep_A \rightarrow \mathcal{V}ect$ , which is the usual forgetful functor on objects and morphisms, but whose monoidal structure is modified: when defining the map

$$(10.9) \quad F_J(V) \otimes F_J(W) \rightarrow F_J(V \otimes W),$$

take the usual map, then apply  $J$ .

**Theorem 10.10.** When  $A$  is a finite-dimensional Hopf algebra, all fiber functors  $\mathcal{R}ep_A \rightarrow \mathcal{V}ect$  arise from Drinfeld twists in this way.

**Theorem 10.11** (Ng-Schauenberg). Let  $A$  and  $B$  be finite-dimensional Hopf algebras such that  $\mathcal{R}ep_A \simeq \mathcal{R}ep_B$  as tensor categories. Then there is a Drinfeld twist  $J$  of  $A$  such that, as Hopf algebras,  $B \cong A^J$ .

**Example 10.12** (Negron [Neg18]). Specializing to  $A = u_q(\mathfrak{b})$ , an equivalence  $\mathcal{R}ep_B \simeq \mathcal{R}ep_{u_q(\mathfrak{b})}$  leads to an alternating bicharacter  $J \in \text{Alt}(G^\vee) \subset T_w(u_q(\mathfrak{b}))$ , such that  $B \cong u_q(\mathfrak{b})^J$ . Since  $\text{Alt}(G^\vee)$  is a finite set, this is particularly nice.  $\blacktriangleleft$

As we heard in Rowell’s talk, the notion of being the category of representations of a Hopf algebra is not invariant under tensor equivalence, and more generally, Hopf algebra representation categories are not closed under reasonable operations on the class of tensor categories.

For example, if a group  $G$  acts on a tensor category  $\mathcal{C}$ , then we can *equivariantize*, building a new tensor category  $\mathcal{C}^G$ , the category of objects  $V \in \mathcal{C}$  with compatible structural isomorphisms  $g \cdot V \xrightarrow{\cong} V$  for all  $g \in G$ . An embedding  $\mathcal{Vect} \hookrightarrow \mathcal{C}$  induces an embedding  $\mathcal{Rep}_G \hookrightarrow \mathcal{C}^G$ .

**Theorem 10.13** (Drinfeld-Gilyaki-Nikshych-Ostrik [DGNO10]). *Equivariantization defines a bijection between tensor equivalence classes of tensor categories with a  $G$ -action and tensor categories with a specified embedding of  $\mathcal{Rep}_G$ .*

This ultimately implies that even if  $\mathcal{C}$  admits a fiber functor (as representation categories of Hopf algebras must),  $\mathcal{C}^G$  might not, because there are categories containing  $\mathcal{Rep}_G$  but not admitting a fiber functor.

Tensor categories have connections with 2d conformal field theory, hence vertex operator algebras.

- Given a *rational conformal field theory* (equivalently, a rational vertex operator algebra), Y. Huang shows how to extract a modular fusion category.
- Given a *logarithmic conformal field theory*, a series of papers by Huang-Lepowski-Zhang construct a modular tensor category, maybe with some additional assumptions. See in particular [HLZ11].

The upshot is that given an *finite* logarithmic vertex operator algebra  $V$ , its category of representations is a finite, braided tensor category which is nondegenerate and pivotal (hence ribbon).<sup>10</sup>

**Example 10.14.** Given a simple Lie algebra  $\mathfrak{g}$  over  $\mathbb{C}$  and  $p \in \mathbb{Z}_+$ , one can construct a non-rational vertex operator algebra denoted  $W_p(\mathfrak{g})$ , which is cut out of a lattice model by an action of  $u_q(\mathfrak{n})$  by something called short-screening operations. This was studied by Lentner and others.

These are understood in type  $A_1$  and, at  $p = 2$ , type  $B_n$ :  $W_p(\mathfrak{sl}_2)$  is the *triplet model* of Kausch (1991), and  $W_2(B_n)$  is the *symplectic fermion model* of Kausch [Kau00]. As established by Flandoli-Lentner [FL18], these have non-semisimple, modular representation theories. ◀

**Conjecture 10.15.** There is a modular equivalence  $F_\otimes$  from the category of representations of  $u_q(\mathfrak{g})$  to the category of representations of  $W_p(\mathfrak{g})$ , where  $q := \exp(i\pi/p)$ .

This is mostly done for  $\mathfrak{g} = \mathfrak{sl}_2$ , but is completely open in general.

*Remark 10.16.* You should be careful with what’s precisely meant by  $u_q(\mathfrak{g})$ . See work of Negron and several others. ◀

To finish, let’s talk a little bit about cohomology. Suppose  $\mathcal{C}$  is a finite, but not semisimple, tensor category. Then let  $\text{Proj } \mathcal{C}$  denote the subcategory of projective objects in  $\mathcal{C}$ ; this has finitely many indecomposables  $P_1, \dots, P_n$ , canonically labeled by the isomorphism classes of simple objects.  $\text{Proj } \mathcal{C}$  has a *strong* fusion rule, with

$$(10.17) \quad P_i \otimes P_j \cong \bigoplus_k P_k^{\oplus N_{ij}^k}$$

for some natural numbers  $N_{ij}^k$ . In fact, something stronger is true:  $\text{Proj } \mathcal{C}$  can be described by discrete/number-theoretic data. But what happens on the rest of  $\mathcal{C}$ ?

The *stable category* of  $\mathcal{C}$  is  $\text{Stab } \mathcal{C} := \mathcal{C}/\text{Proj } \mathcal{C}$ . This is not an abelian category, though it is triangulated — in particular, it has a shift functor  $\Sigma: \text{Stab } \mathcal{C} \rightarrow \text{Stab } \mathcal{C}$ . This data is regulated by geometry and continuous invariants, called *support theory* or *tensor-triangulated geometry*, related to the Proj variety of  $\text{End}_{\text{Stab } \mathcal{C}}^*(\mathbf{1})$ . There’s a lot more that could be said about this approach to the stable category, but that is a story for another day.

## Part 4. Thursday, January 30

### 11. EMILY PETERS, SUBFACTORS AND PLANAR ALGEBRAS, II

Last time we dove into planar algebras; today we’ll get to subfactors too.

<sup>10</sup>NOTE by the notetaker: I missed a few of the references starting at this point of the talk. Sorry about that.

**Definition 11.1.** A *von Neumann algebra*  $A$  is a unital,  $*$ -closed subalgebra of  $B(\mathcal{H})$ , the algebra of bounded operators on some Hilbert space, such that the *double commutant*  $A''$  of  $A$  is again  $A$ . (The double commutant is the space of operators which commute with the things which commute with  $A$ .) A *factor* is a von Neumann algebra  $A$  such that  $Z(A) = A \cap A' = \mathbb{C} \cdot \text{id}$ . A *subfactor* is a unital inclusion of factors.

Why care about subfactors? Well, if you want to understand maps between von Neumann algebras, you can begin by trying to decompose your algebras into smaller pieces, and subfactors are the basic building blocks of maps.

Let  $S_\infty$  denote the *finitary symmetric group*, i.e. the group of permutations of a countable set which leave all but finitely many elements fixed. Alternatively,  $S_\infty = \text{colim}_n S_n$ . In  $S_\infty$ , cycle types are conjugacy classes, as with finite symmetric groups, and therefore there are infinitely many conjugacy classes.

Let  $\mathcal{H} := \ell^2(S_\infty)$ , which carries the left regular representation  $\lambda: S_\infty \rightarrow B(\mathcal{H})$  by

$$(11.2) \quad (\lambda(g))\xi(h) = \xi(g^{-1}h).$$

Define the *group von Neumann algebra* to be  $L(S_\infty) := \mathbb{C}[\lambda(S_\infty)]''$ . Taking the double commutant is called the *von Neumann closure*;  $L(S_\infty)$  is a von Neumann algebra, and even a factor, though there is an argument to make here. This factor is called the *hyperfinite type II<sub>1</sub> factor*.

*Remark 11.3.* You can make this construction for any group with an infinite number of conjugacy classes (in fact, even if not, you still get a von Neumann algebra, but not a factor). For the free groups  $F_2$  and  $F_3$  on two, respectively three, elements,  $\mathbb{C}[\lambda(F_2)] \not\cong \mathbb{C}[\lambda(F_3)]$ , but it is a longstanding open question whether the group von Neumann algebras are isomorphic (i.e. after von Neumann closure).

On the other hand, if  $G$  is profinite (i.e. a colimit of finite groups, as with  $S_\infty$ ),  $L(G) \cong L(S_\infty)$ . ◀

Let  $G$  be any finite subgroup of  $S_\infty$ . Then we can build a subfactor:  $G$  acts on  $L(S_\infty)$ , and the invariants  $L(S_\infty)^G \hookrightarrow L(S_\infty)$  are a subfactor.

Given a subfactor  $A \subset B$ , we will build a planar algebra, at least assuming  $A$  is finite-index and irreducible. Let  $X := {}_A B_B$ , i.e.  $B$  as an  $(A, B)$ -bimodule, with  $A$ -action implemented through the inclusion. Correspondingly, let  $\bar{X} := {}_B B_A$ .

Associated to this data we have some diagrammatics. We represent  $X$  by a vertical line shaded to the right, and  $\bar{X}$  by a vertical line shaded to the left.

$$(11.4) \quad \begin{array}{c} \text{shaded right} \\ | \\ X \end{array} \quad \begin{array}{c} \text{shaded left} \\ | \\ \bar{X} \end{array}$$

There is an evaluation map

$$(11.5) \quad \text{shaded right} \cap \text{shaded left} : X \otimes \bar{X} = {}_A B \otimes_B B_A = {}_A B_A \longrightarrow {}_A A_A.$$

In the theory of von Neumann algebras, this map is called *conditional expectation*, and has been well-studied. Correspondingly, the inclusion map  ${}_A A_A \hookrightarrow {}_A B_A$  is denoted  $\text{shaded left} \cup$ .

Two more diagrams: a map

$$(11.6) \quad \text{shaded left} \cup : {}_B B_B \longrightarrow \bar{X} \otimes X = {}_B B \otimes_A B_B,$$

which arises from the basic construction  $A \subset B \subset B \otimes_A B$ ; and the multiplication map

$$(11.7) \quad \text{shaded right} \cap : {}_B B \otimes_A B \longrightarrow {}_B B_B.$$

Let  $V_n := \text{End}(X \otimes \bar{X} \otimes \cdots)$ , where there are  $n$  factors of  $X$  or  $\bar{X}$ . You can represent  $V_n$  by a box with  $n$  input and output wires.

From these diagrams we have a planar algebra. But the planar algebras which come from subfactors have extra structure. Because  $A$  and  $B$  are factors, the diagrams corresponding to the circle (two diagrams: shaded inside, or shaded outside) are constants. We adopt the convention to normalize such that both of them are the number  $\text{FPdim}(X)$ .



There are two flavors of box, depending on whether you shade on the inside or outside; call them  $V_{n,+}$  and  $V_{n,-}$ , depending on which of  $X$  or  $\bar{X}$  is the first factor in the tensor product. These are all finite-dimensional, which follows from our assumption that  $A \hookrightarrow B$  is finite index; and  $\dim(V_{0,\pm}) = 1$ . Moreover, we can take isotopies in  $S^2$ , rather than  $\mathbb{R}^2$  — we can move strands through the point at infinity, as in Figure 4.

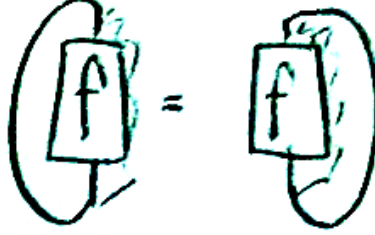


FIGURE 4. Moving a strand through the point at infinity on  $S^2$ .

Finally, we have a positivity constraint: if  $a, b \in V_{n,\pm}$ ,  $\langle a, b \rangle := \text{tr}(b^*a)$  is positive (provided  $a, b \neq 0$ ). As before,  $*$  is reflection across a horizontal line.

Call a planar algebra satisfying these three additional constraints a *subfactor planar algebra*.

**Theorem 11.8** (Jones). *The planar algebras coming from subfactors are subfactor planar algebras.*

**Theorem 11.9** (Popa). *All subfactor planar algebras arise from subfactors.*

However, both constructions are sadly non-functorial.

The subfactor planar algebra associated to a subfactor is a nice invariant of a subfactor, but is not the only interesting one. The first invariant associated to a subfactor is Jones' *index*,

$$(11.10) \quad [B : A] := \dim_A B.$$

This is equal to  $\text{FPdim}(X)^2$ . Actually making sense of this dimension can be a little funny, and you may have to dip into some analysis, but it can be done.

Jones proved a theorem characterizing the possible indices which made people sit up and take notice.

**Theorem 11.11** (Jones [Jon83]). *The index is either of the form  $4 \cos^2(\pi/n)$ , for  $n = 3, 4, 5, \dots$ , or is an element of  $[4, \infty]$ , and all of these can arise.*

The indices of the form  $4 \cos^2(\pi/n)$  are “classical,” less surprising, but the new, continuous ones are stranger.

The principal graph of a subfactor is another useful invariant — in fact, its ability to remember important information but not too much has led some people to think of it as the “Goldilocks invariant.” It encodes the fusion rules of a tensor category. Consider a decomposition of  $X \otimes \bar{X} \otimes X \otimes \dots \otimes X$  into irreducible bimodules, then build a graph depicting  $\otimes X^\pm$ . For example, if we had the rules

$$(11.12a) \quad X \otimes \bar{X} = Z_1 \oplus \mathbf{1}$$

$$(11.12b) \quad Z_1 \otimes X = X \oplus Z_2 \oplus Z_2$$

$$(11.12c) \quad Z_2 \otimes \bar{X} = Z_3 \otimes \bar{X} = Z_1,$$

we would obtain the graph

$$(11.13) \quad \begin{array}{c} \bullet \\ \diagup \\ \mathbf{1} \text{ --- } X \text{ --- } Z_1 \\ \diagdown \\ \bullet \\ Z_2 \\ \bullet \\ Z_3 \end{array}$$

Using this, we can build a unitary tensor category from a subfactor/subfactor planar algebra. Unitarity means that each Hom space has a positive Hermitian form, and consequently all dimensions are positive. The objects of this category are the irreducible bimodules obtained from  $X \otimes \bar{X} \otimes \dots \otimes X^\pm$ , the morphisms are the relevant planar diagrams, and the tensor product is disjoint union of diagrams.

And this is a helpful tool for studying these tensor categories. For small subfactor planar algebras,  $\text{FPdim}(X) = \sqrt{[B:A]}$  tells you about the growth rate of  $\{V_{n,\pm}\}$  (assuming here that the subfactor is finite-depth or amenable). Under these assumptions, the principal graph is of ADE type, but — and a lot of work went into this — the ADE graphs that arise are  $D_n$  for  $n$  even,  $E_6$ , and  $E_8$ . One can also get extended Dynkin diagrams. These are the cases where the index is  $4 \cos^2(\pi/n)$  for some  $n$ , so Haagerup asked what nontrivial principal graphs can arise in the next simplest setting, where the index is above 4, but not by much. Figure 5 delineates the possible graphs. Bisch [Bis98] showed  $B_i$  doesn't work: its

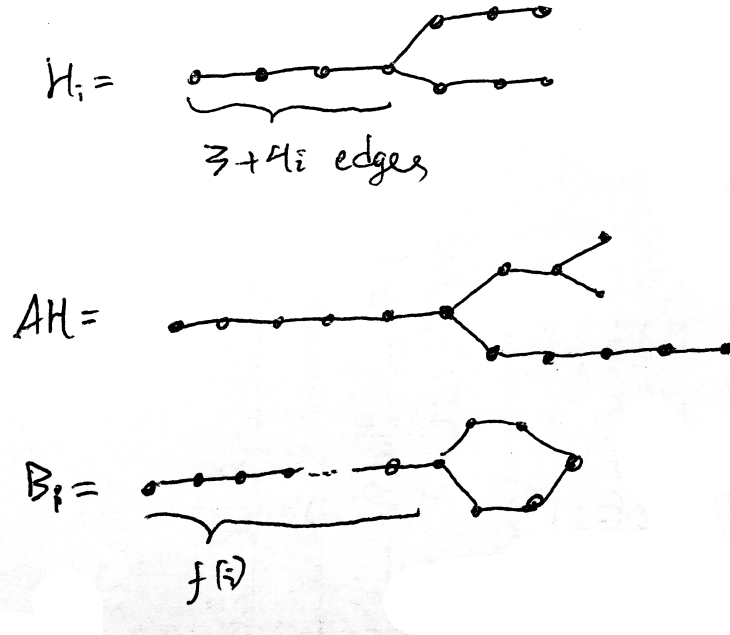


FIGURE 5. Haagerup's graphs for the case when the index is a little more than 4.

fusion rules are nonassociative. Asaeda-Haagerup [AH99] constructed subfactors realizing  $H_0$  and  $AH$ ; then Asaeda-Yasuda [AY09] showed that  $H_i$  for  $i \geq 2$  cannot be realized.

This leaves one case,  $H_1$ .

**Theorem 11.14** (Bigelow-Morrison-Peters-Snyder [BMPS12]). *There is a planar algebra realizing the graph  $H_1$ .*

This algebra is called the *extended Haagerup planar algebra*. It is a positive planar algebra generated, as a planar algebra, by  $S \in V_8$  with some relations. It has Frobenius-Perron dimension about equal to 2.09218, which indicates we're just barely in the region of continuous index. The relations are described by pictures, as in Figure 6.

You can write down any random set of relations, and will probably get something zero or infinite. The work that went into Theorem 11.14 was showing that this is finite, and interesting.

## 12. ZHENGHAN WANG, TOPOLOGICAL ORDERS I

This talk will be a mathematics talk about topological order (in topological phases of matter), which is a subject close to physics. For a general reference for this talk, see [RW18]. We will focus on bosonic/spin intrinsic order, as opposed to fermionic order or SPT phases; if this doesn't mean anything to you, that's OK.

When we consider topological orders in dimension  $2 + 1$ , we mean two dimensions of space, and one of time, so we will usually think about surfaces, and sometimes 3-manifolds. A  $(2 + 1)$ -dimensional topological order is equivalent to a unitary topological modular functor, which is equivalent to a unitary modular tensor category (sometimes called an *anyon model* in physics). There are several reasons to care about these phases.

- (1) At least in theory, the ability to build topological phases of matter would allow one to build a quantum computer, which has numerous applications to the real world, including making money.

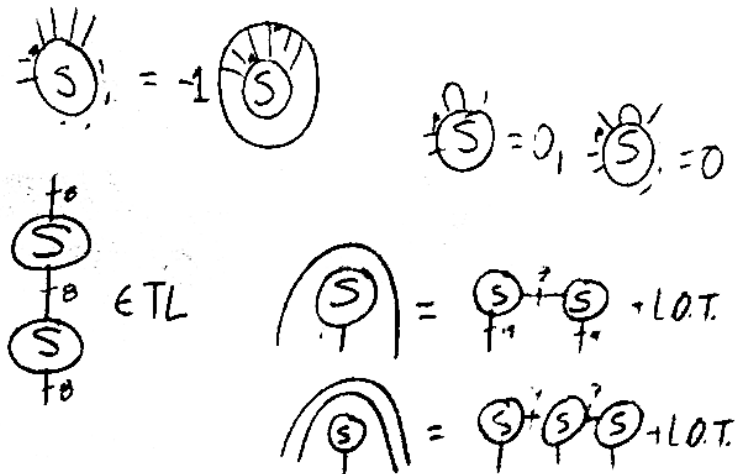


FIGURE 6. Diagrammatics for relations in the extended Haagerup planar algebra.

This is being pursued in industry, e.g. by Microsoft. However, there is still much to do, in both theory and engineering, before this can be a reality.

- (2) From a theoretical physics perspective, topological phases are very interesting. These are in the subfield of condensed-matter physics, which historically understood phases of matter via Landau's group symmetry-breaking paradigm; for example, crystals are understood via discrete translation symmetries, but liquids have continuous symmetries. Phase transitions correspond to symmetry breaking. But topological phases do not follow these rules, leading to a paradigm shift in physicists' perspectives on phases, to the perspective of quantum symmetries.
- (3) Finally, these are interesting objects in their own mathematical right.

Analogously to the relationship between Riemann sums and definite integrals, there are two perspectives on quantum field theory that shed mathematical insight into it: one can work in the continuum (akin to the integral) or on the lattice, which is more discrete, akin to a Riemann sum. Sometimes we use integrals to approximate Riemann sums, even though that wasn't the original way information flowed; likewise, these topological phases are QFTs on the lattice, but we can study them with continuum limits. This is a part of the general mathematical goal of understanding quantum field theory.

We will focus on two examples: the toric code and Haah's code. The toric code is very, very well-studied — almost any question you might ask about it has been answered. Haah's code is newer, and poorly understood: it's an example of a fracton model, and we think that a proper understanding of such models will lie beyond quantum field theory.

We will first study the toric code via its robust ground state degeneracy, which is a TQFT, and which is a mathematically satisfying perspective even if it's still not completely understood. In the next lecture, we'll study the elementary excitations, which lead to unitary modular tensor categories, a different perspective. But there is a mathematical theorem relating unitary TQFTs in dimension  $2 + 1$  and unitary modular tensor categories.

You should not just accept these definitions as final — this field is still in the process of being mathematically codified. Some of these definitions are matters of convenience, so that we can actually get somewhere, even if we don't have the most correct definitions.

**Definition 12.1.** A *quantum theory* is a triple  $(L, B, H)$ , where  $L$  is a finite-dimensional Hilbert space,  $B$  is a basis of  $L$ , and  $H: L \rightarrow L$  is a Hermitian operator, which thanks to  $B$  we can think of as a matrix.

The basis is an unusual ingredient when one studies QFTs, but is important in the story of quantum information: it's how you represent classical information.

Many quantum theories satisfying Definition 12.1 aren't related to physics, and are therefore somewhat useless. We focus on the examples which come from physics; after all, Definition 12.1 is trying to (partially) axiomatize things physicists are interested in, right?

**Definition 12.2.** An  $n$ -dimensional quantum schema is a rule assigning to every  $n$ -dimensional manifold with a triangulation and a finite-dimensional Hilbert space, a quantum theory.

**Example 12.3.** The 1-dimensional Ising chain is a 1-dimensional quantum schema. Given a circle with a triangulation, the Hilbert space is the tensor product of copies of  $\mathbb{C}^2$  indexed by the vertices. Assume there are  $N$  vertices, and orient the circle so we can identify them with  $1, \dots, N$  in order, and call the Hilbert space  $L_N$ . Inside  $\mathbb{C}^2$ , let  $|0\rangle$  and  $|1\rangle$  be the standard basis vectors (i.e.  $(1, 0)$  and  $(0, 1)$ , respectively). The Hamiltonian has the form

$$(12.4) \quad H = - \sum_{i=1}^{n-1} \sigma_i^z \sigma_{i+1}^z.$$

This is physicists' notation: let's explain what's going on. The *Pauli matrices* are the standard basis of  $\mathfrak{su}_2$ :

$$(12.5) \quad \sigma^x = \sigma_1 := \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma^z = \sigma_3 := \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \sigma^y = \sigma_2 := i\sigma^x\sigma^z.$$

These are Hermitian matrices which square to the identity.

The notation  $\sigma_i^z$  means that  $\sigma^z$  acts on the  $\mathbb{C}^2$  at vertex  $i$ , and acts by the identity on the remaining factors, i.e. by  $\text{id} \otimes \text{id} \otimes \dots \otimes \sigma^z \otimes \dots \otimes \text{id}$ .  $\blacktriangleleft$

Given a quantum theory, the eigenvalues of the Hamiltonian  $\lambda_0 \leq \lambda_1 \leq \dots$  are called *energies* of the theory, and the nonzero eigenvectors of  $\lambda_0$  are called *ground states*. Nonzero eigenvectors for other eigenvalues are called *excited states*.

Here's the most important definition (albeit, again, not quite the real definition).

**Definition 12.6.** An  $n$ -dimensional Hamiltonian schema is (*sharply*) *gapped* if there is a constant  $c > 0$  such that for all  $n$ -manifolds and triangulations, in the quantum system assigned by the schema, the eigenvalues of the Hamiltonian satisfy  $\lambda_1 - \lambda_0 \geq c$ .

Crucially,  $c$  does not depend on the triangulation. Sharply gapped schemas are almost topological.

**Tentative definition 12.7.** An  $n$ -dimensional Hamiltonian schema is *topological* if it's gapped, and if there exists a unitary topological modular functor (i.e. a unitary TQFT-like object in dimension  $2 + 1$ , which is once-extended, but isn't necessary finite enough to assign partition functions to all 3-manifolds)  $Z$  such that for any closed 2-manifold  $\Sigma$ ,  $Z(\Sigma)$  is isomorphic to the space of ground states of the Hamiltonian schema on  $Y$  for any triangulation.

We expect that a topological Hamiltonian schema represents mathematically a topological phase of matter.

**Definition 12.8.** A *topological phase of matter* is a path component of the space of topologically ordered Hamiltonians.

Unfortunately, we're not yet sure what the space of topologically ordered Hamiltonians is, but we want to say that two Hamiltonians are equivalent if there's a path deforming one into the other, through topological Hamiltonian schema — in particular, the path cannot close the gap:  $c$  must always be greater than some  $\varepsilon > 0$ . Understanding this carefully in general would require opening the can of worms called renormalization.

The toric code is the model organism in topological phases. If you want to understand just about anything about topological phases of matter, you should probably begin by thinking about it for this example.

**Example 12.9** (Toric code). The toric code, first studied by Kitaev [Kit03], realizes the topological order given by untwisted  $\mathbb{Z}/2$ -Dijkgraaf-Witten theory, corresponding to the modular tensor category  $D(\mathbb{Z}/2)$ , with four simple objects  $\{1, e, m, \psi\}$  with  $e \otimes e = m \otimes m = \psi \otimes \psi = 1$  and  $e \otimes m = m \otimes e = \psi$  and twists  $\theta_1 = \theta_e = \theta_m = 1$  and  $\theta_\psi = -1$ .<sup>11</sup>

The toric code schema begins with a closed surface  $Y$  and a triangulation (or more generally, a cellulation), which is often just taken to be the torus with a cellulation given by a square tiling of the plane. The Hilbert space  $L$  is a tensor product of  $\mathbb{C}^2$  over all of the edges in the cellulation. Thus  $L$  is canonically identified with the group algebra for the group  $(\mathbb{Z}/2)^{|E|}$ , if  $E$  is the set of edges.

<sup>11</sup>So the anyon  $\psi$  is a fermion, but this is still a bosonic phase, because we started with bosonic spins, or mathematically, vector spaces and not super vector spaces.

The Hamiltonian is

$$(12.10) \quad H = - \sum_{\text{all vertices } v} A_v - \sum_{\text{all faces } P} B_P,$$

for some operators  $A_v$  and  $B_P$  we will define.<sup>12</sup>  $A_v$  is the tensor product of  $\sigma^z$  on all of the edges adjacent to  $v$ , and the identity on the remaining edges.  $B_P$  is the tensor product of  $\sigma^x$  on all edges in  $\partial P$ , and the identity on the remaining edges.

Here are three important properties of the toric code.

- (1) All  $A_v$  and  $B_P$  operators commute with each other. This is clear for  $A_v$  and  $A_{v'}$ , and for  $B_P$  and  $B_{P'}$ , since we just have a bunch of  $\sigma^z$  or  $\sigma^x$  operators, or for  $A_v$  and  $B_P$  when  $v \notin \overline{P}$ , but the interesting bit is when  $v$  and  $P$  are adjacent; then  $\sigma^x$  and  $\sigma^z$  don't commute, but they anticommute, and there is an even number of edges affected by both  $A_v$  and  $B_P$ , so two minuses make a plus and  $[A_v, B_P] = 0$ .
- (2) The space of ground states of this model on a closed surface  $\Sigma$  is canonically identified with the space of  $\mathbb{C}$ -valued functions on  $H_1(\Sigma; \mathbb{Z}/2)$ . This uses the fact that the Hamiltonian is *frustration-free*, which means that the ground states are precisely those stabilized by all  $A_v$  and  $B_P$  operators. Looking at  $B_P$  gives you cycles; then looking at  $A_v$  kills boundaries.
- (3) The elementary excitations for the toric code form the unitary modular tensor category  $D(\mathbb{Z}/2)$ .  $\blacktriangleleft$

**Exercise 12.11.** Modify the toric code to

$$(12.12) \quad H = \sum_v \varepsilon_1 A_v + \sum_P \varepsilon_2 B_P,$$

where  $\varepsilon_1, \varepsilon_2 \in \{\pm 1\}$ . Which of these phases are topologically ordered, and which aren't? If you understand that, you probably understand this lecture very well.

### 13. ANNA BELIAKOVA, QUANTUM INVARIANTS OF LINKS AND 3-MANIFOLDS, II

Recall that we're in the business of studying non-semisimple quantum invariants of knots and 3-manifolds. Last time, we discussed how surgery on a framed link can turn logarithmic framed link invariants into 3-manifold invariants, as studied by Hennings (1998), Beliakova-Blanchet-Geer [BBG18], and Costantino-Geer-Patureau-Mirand [CGPM14].

First, the algebraic data that we need. Let  $H$  be a finite-dimensional Hopf algebra, such as

$$(13.1) \quad u_\xi := u_q(\mathfrak{sl}_2) \otimes_{\mathcal{A}} \mathbb{C},$$

where  $\mathcal{A} := \mathbb{Z}[q^{\pm 1}]$ ,  $\xi$  is a  $p^{\text{th}}$  root of unity, and  $\mathcal{A}$  acts on  $u_q(\mathfrak{sl}_2)$  by  $q \mapsto \xi$ . We can also restrict to  $u^{\text{rest}} := u_\xi / \langle e^p, F^p, K^{2p} - 1 \rangle$ ; then  $K^p$  is central.

Radford showed that there exists a unique  $\mu^* \in H^\times$ , called the *integral*, such that

$$(13.2) \quad (\mu \otimes \text{id})\Delta(x) = \mu(x)\mathbf{1}$$

for all  $x \in H$ . For example, in  $u_\xi$ ,

$$(13.3) \quad \mu(E^m F^n K^\ell) = \delta_{m,p-1} \delta_{n,p-1} \delta_{\ell,p+1}.$$

**Theorem 13.4** (Hennings, Kauffman-Radford). *Let  $L$  be a framed link and  $M := S^3(L)$ . Let  $\sigma_+$ , resp.  $\sigma_-$ , be the number of positive, resp. negative eigenvalues of  $\ell k(L)$ . Then the Hennings invariant can be calculated as*

$$(13.5) \quad \text{Hen}(M) = \frac{\mu^{\otimes |L|}(J_L)}{\mu(J_{U_+})^{\sigma_+} \mu(J_{U_-})^{\sigma_-}}.$$

The proof is surprisingly simple.

*Proof.* Using the Kirby move K1, write  $L' = L \amalg u_+$ , where  $u_+$  indicates an unlinked unknot. Then

$$(13.6) \quad \text{Hen}(M) = \frac{\mu^{\otimes |L|}(J_L)\mu(J_{u_+})}{\mu(J_{u_+}^{\sigma_+ + 1})\mu(J_{u_-})^{\sigma_-}},$$

and we cancel out the factors of  $\mu(J_{u_+})$  in the numerator and denominator. Now, perform the Kirby move K2 and use (13.2) and we're done.  $\square$

<sup>12</sup>Why "P"? Because in the physics literature, faces are often referred to as *plaquettes*.

*Remark 13.7.* If  $H$  is semisimple,

$$(13.8) \quad \mu = \sum \text{qdim}(V_i) \text{tr}_q^{V_i},$$

where the sum is over the isomorphism classes of irreducible modules  $V_i$ , and the Hennings invariant for  $H$  and  $M$  and the Witten-Reshetikhin-Turaev invariant for  $H$  and  $M$  coincide.  $\blacktriangleleft$

Kuperberg [Kup91] constructed a related invariant using cointegrals in a Hopf algebra.

**Definition 13.9.** Let  $H$  be a Hopf algebra. A *left cointegral* is an element  $c \in H$  satisfying  $xc = \varepsilon(x)c$  for all  $x \in H$ ; a *right cointegral* satisfies  $cx = \varepsilon(x)c$  for all  $x \in H$ .

A Hopf algebra in which left and right cointegrals coincide is called *unimodular*.

Kuperberg's invariant is the simplest algebraic 3-manifold invariant one can define with Hopf algebras, and this lends it its usefulness — it will probably be one of the first things we fully categorify. For example, if we chose  $u_q(\mathfrak{sl}_2)$ , we'd need the data of the Borel part,  $\langle K, E \rangle$ . Chang-Cui [CC19] showed that the Kuperberg invariant for  $M$  and  $H$  coincides with the Hennings invariant for  $M$  and  $\mathcal{D}(H)$ , the double of  $H$ , analogous to the relationship between Reshetikhin-Turaev invariants for a modular tensor category and Turaev-Viro invariants for its Drinfeld double.

**Theorem 13.10** (Chen-Kuppum-Srinivasan [CKS09]). *If  $b_1(M) = 0$ , the Hennings invariant of  $M$  is  $|H_1(M)| \text{WRT}(M)$ ; otherwise, it vanishes.*

*Proof.* Our proof sketch follows Habiro-Lê. Note: I (the notetaker) didn't follow what was written on the board; sorry about that. I think what happened was: the Hennings invariant of  $M$  ends up being  $\sum_{i \in I} x_i \otimes y_i$ , where  $\{x_i\}$  and  $\{y_i\}$  are both bases of  $H$ . This induces a Hopf pairing, sometimes called the *quantum Killing form*, by declaring  $\langle x_i, y_j \rangle := \delta_{ij}$ . Hence if  $x = \sum a_i y_i$ ,  $\langle x, x_i \rangle = a_i$ .

Let  $M$  be an integral homology sphere, so we can realize  $M$  as surgery on a knot  $K$  framed with framing  $\pm 1$ . Then  $I_M = \langle r^{-1}, J_K \rangle$ , where  $r$  is a *ribbon element* in  $H$ . We claim that for all  $x \in H$ ,

$$(13.11) \quad \langle r^{-1}, x \rangle = \frac{\mu(x^r)}{\mu(r)},$$

and that  $\Delta(r) = (r \otimes r)M$ . This is because  $(\mu \otimes \text{id})\Delta(r) = \mu(r)\mathbf{1}$ , so

$$(13.12) \quad \sum_i \mu(rx_i)y_i = \mu(r)\mathbf{1},$$

and therefore

$$(13.13) \quad r^{-1} = \sum_i \frac{\mu(rx_i)}{\mu(r)} y_i$$

$$(13.14) \quad \langle r^{-1}, x_i \rangle = \frac{\mu(rx_i)}{\mu(r)}.$$

If  $b_1(M) > 0$ ,  $S^2 \times S^1 = S^3(U_0)$ , where  $U_0$  denotes an unknot, and  $J_{U_0} = \mathbf{1}$ , so the Hennings invariant is  $\mu(\mathbf{1}) = 0$ .  $\square$

This seems to spell doom for non-semisimple invariants, but not all of them are killed. This leads one to introduce *modified traces*, following Geer-Patureau (2008), functions  $t_P: \text{End } P \rightarrow k$ , where  $P$  is an  $H$ -module, such that  $t_P(fg) = t_P(gf)$  and  $t_P$  satisfies the *partial trace property* in Figure 7.

*Remark 13.15.* Now taking the invariant  $J_K$  as usual, this kind of invariant lands in

$$(13.16) \quad q\text{HH}_0(H) := H / \langle xy0S^2(y)x \mid x, y \in H \rangle. \quad \blacktriangleleft$$

**Theorem 13.17** (Beliakova-Blanchet-Gainutdinov [BBG17]). *Let  $H$  be a unimodular pivotal Hopf algebra. Then for  $f \in \text{End}_H(H)$ ,*

$$(13.18) \quad \text{tr}_H(f) = \mu_g(f(\mathbf{1})),$$

where  $g$  is the pivotal element:  $\mu_g(x) = \mu(gx)$ . In particular, the modified trace is uniquely determined.

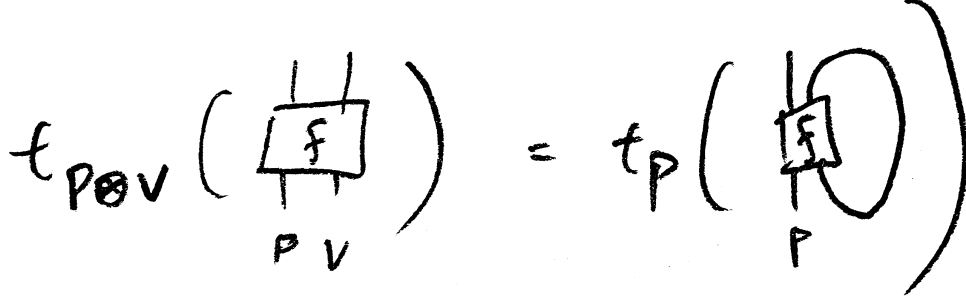


FIGURE 7. The partial trace property.

Then, Beliakova-Blanchet-Geer [BBG18] used this to define more invariants for a knot  $K_P$  in a 3-manifold  $M = S^3(L)$ : the invariant is  $(\mu^{\otimes |L|} \otimes t_P)J_{LUK_P}$ . These invariants were extended to a TQFT by De Renzi, Geer, and Patureau-Mirand [DRGPM18].

In the last few minutes, we'll discuss CGP invariants. Consider the Hopf algebra

$$(13.19) \quad u^{\text{unrolled}} := \langle K, E, F, H \rangle / \langle E^p, F^p \rangle.$$

Given  $\lambda \in \mathbb{C}$ , we have a  $p$ -dimensional irreducible  $u^{\text{unrolled}}$ -module  $V_\lambda$ , though thanks to some redundancy, really the classification is in  $\mathbb{C}/2\mathbb{Z}$ . This leads to an invariant of a manifold together with a cohomology class  $\lambda \in H^n(M; \mathbb{C}/2\mathbb{Z})$ , given by

$$(13.20) \quad \text{CGP}(M, \lambda) := \sum_{k=0}^{p-1} d^{\text{mod}}(V_{\lambda+2k}) J_K(V_{\lambda+2k})$$

This is a surprisingly simple description of this kind of invariant, which is nice. At  $p = 2$ , this specializes to the Alexander polynomial and Reidemeister torsion. Blanchet, Costantino, Geer, and Patureau-Mirand [BCGPM16] extended this invariant to a TQFT in which the order of the Dehn twist is trivial. The  $S$ - and  $T$ -matrices of this TQFT are related to work of Gukov and collaborators.

#### 14. COLLEEN DELANEY, MODULAR DATA AND BEYOND

This talk fits into the same line of ideas as Eric Rowell's, and to some extent also Anna Beliakova's, though here we work in the semisimple case, rather than the non-semisimple one. We always work over the ground field  $k = \mathbb{C}$ . We will discuss the modular data associated to a modular tensor category, how to think of them as quantum invariants, the role of the  $S$ - and  $T$ -matrices, and then invariants beyond modular data.

Let  $\mathcal{C}$  be a braided fusion category; thus we have data of  $\mathcal{C}$ , the monoidal tensor product  $\otimes$ , the unit  $\mathbf{1}$ , and the braiding  $c_{X,Y}: X \otimes Y \rightarrow Y \otimes X$ . We assume the braiding is *non-degenerate*, i.e. if  $c_{Y,X} \circ c_{X,Y} = \text{id}_{X \otimes Y}$  for all  $Y \in \mathcal{C}$ , then  $X \cong \mathbf{1}$ .

We can introduce more niceness into  $\mathcal{C}$ , in two ways.

- We can consider twists  $\theta \in \text{Aut}(\text{id}_{\mathcal{C}})$ , leading to the notion of a ribbon structure.
- We can consider a pivotal structure  $\phi_x: x \xrightarrow{\cong} x^{**}$ . This can satisfy a niceness condition called *sphericity*.

If we have both of these, and the nondegeneracy condition, we obtain a modular tensor category. Then the  $S$ -matrix is  $S_{a,b} = \text{tr}(c_{b,a} \circ c_{a,b})$ , as  $(a, b)$  ranges over all pairs of isomorphism classes of irreducible objects. The  $T$ -matrix is diagonal, with the diagonal entries the twists of the irreducible objects.

Modular tensor categories were first written down by Moore and Seiberg [MS89], who were investigating two-dimensional conformal field theory. To Moore and Seiberg, the  $S$ - and  $T$ -matrices were part of the data of a modular tensor category, though this is not the only approach. In particular, they extend to a representation of the entire modular group, which is the reason for their name. In this sense, modular tensor categories are a gift from quantum field theory.

Subsequently, people studied many aspects of modular tensor categories; in the 2000s there was strong focus on the invariants they define, and more recently, Bartlett, Douglas, Schommer-Pries, and Vicary [BDSPV15] showed that modular tensor categories are equivalent data to once-extended  $(2 + 1)$ -dimensional TQFTs.

There was a longstanding conjecture that the modular data is a complete invariant of the modular tensor category. This conjecture was disproven in 2017, and this and subsequent developments will be a significant part of this talk.

As a tool of convenience, we will work with *skeletal modular tensor categories*, in which there is a single object in each isomorphism class. Let  $\mathcal{L}$  denote the set of irreducible objects. This dehydrates modular tensor categories to equations: the structure coefficients  $N_{ab}^c$ , i.e. the number of copies of  $c$  inside  $a \otimes b$ , where  $a, b, c \in \mathcal{L}$ ; the *F-symbols*  $(F_a^{abc})_{ef}$  encoding the associator, and the *R-symbols*  $R_c^{ab}$  encoding the braiding. This loses some of the elegance and coherence, but can be useful for throwing mathematical or computer tools at the problem, and this has been a successful technique.

This leads to a graphical calculus for modular tensor calculus. We follow the conventions of Barkeshli-Bonderson-Cheng-Wang [BBCW19], which applies modular tensor categories to physics. Morphisms are represented by braided trivalent ribbon graphs.

The first Reidemeister move is not allowed in this calculus, but the second and third Reidemeister moves hold. Standard results in elementary knot theory implies this defines an invariant of framed links. Our pictures don't make the framing explicit, but we use the *blackboard framing*, which is the usual one you'd have if your links were mostly on the blackboard, with no surprising framing changes at crossings.

*Remark 14.1.* Since modular tensor categories also define anyon models, you can think of this graphical calculus as describing processes (such as particle creation or collision) in these physical systems. In this case the invariant we've just described calculates some sort of amplitudes.  $\blacktriangleleft$

Two basic elementary invariants of modular tensor categories are the rank and the *fusion ring* (i.e. the ring generated by the isomorphism classes of simple objects, with fusion as multiplication). These are "classical" (in the mathematical sense), in that the fusion ring is the decategorification of the modular tensor category, and these invariants don't see this categorical structure.

But we also have invariants that the fusion ring doesn't see, such as the *quantum dimension*  $d_a$  of an irreducible object  $a$ , namely  $\text{tr}(\text{id}_a)$ , and the *global dimension*  $D$ , the square root of the sum of the squares of the quantum dimensions of the irreducibles. We can also evaluate any link whose strands are colored by irreducible objects.

As a simple example, consider the figure-8 colored by an irreducible  $a$ , which the graphical calculus assigns an element of  $\text{End}_{\mathbb{C}}(\mathbf{1})$ , albeit maybe not a fast way to compute it:

$$(14.2) \quad \text{tr}(c_{a,a}) = \sum_c \frac{d_c}{d_a} R_c^{aa} = \theta_a = T_{aa}.$$

So this tells you the  $T$ -matrix. In a similar but more complicated way, the graphical calculus tells you that if you label the strands of the Hopf link with  $a$  and  $b$ ,

$$(14.3) \quad \frac{1}{D} \text{tr}(c_{b,a} \circ c_{a,b}) = \frac{1}{D} \sum_c N_c^{ab} \frac{\theta_c}{\theta_a \theta_b} d_c = S_{ab},$$

so you see the  $S$ -matrix.

Why so much fuss about modular data? Because all of the invariants we've described so far are determined by modular data, as in the following examples.

- The rank is the dimension of the  $S$ - and  $T$ -matrix.
- The fusion rules can be recovered from the formula

$$(14.4) \quad N_c^{ab} = \frac{1}{D} \sum_e \frac{S_{ea} S_{eb} S_{ec}^*}{d_e}.$$

The mantra is "the  $S$ -matrix diagonalizes the fusion ring."

- The first column of the  $S$ -matrix is the quantum dimensions of the irreducibles, which also determine the global quantum dimension.
- The modular representation (which is a projective representation) is determined by  $S$  and  $T$ , viz. the generators  $s$  and  $t$  of  $\text{SL}_2(\mathbb{Z})$ .



- The *central charge*  $c$  satisfies

$$(14.5) \quad e^{2\pi ic/8} = \sum_{a \in \mathcal{L}} d_a^2 \theta_a.$$

Researchers in modular tensor categories also study higher Gauss sums, which are also determined by modular data.

- Frobenius-Schur indicators, one of the more subtle and bothersome aspects of modular tensor categories, in that they can get in the way of things you think are true but actually aren't. Anyways, they're all determined by modular data.

There are probably still yet other invariants we will apply to modular tensor categories, but which are determined by modular data.

Johnson-Freyd and Scheimbauer [JFS17] write down a 4-category of braided fusion categories. Not all of these are modular, but we can use modular data to understand this 4-category. Another thing we can do is enumerate the modular tensor categories of low rank; there are combinatorial constraints on modular data that shine a lot of light on the low-rank classification (and likewise for a related classification of “super modular tensor categories”).

There are various ways to build new modular tensor categories from preexisting ones, such as the Deligne tensor product. In a Deligne tensor product, the  $S$ - and  $T$ -matrices are tensor products, so the modular data is a strong sign that your category factors as a tensor product. In other settings, it's not as clear how the modular data transforms, but this is something people are working on, and in practice partial information plus the usual combinatorial constraints are often sufficient. Some of these operations include taking the Drinfeld center, and de-equivariantization of a  $G$ -action on a modular tensor category.<sup>13</sup> Similarly, there's also  $G$ -equivariantization, and combining these is called *gauging*; Cui-Galindo-Plavnik-Wang [CGPW16] showed this sends modular tensor categories to modular tensor categories.

So if you can find additional interesting operations, and understand how the modular data behaves under those operations, that would be excellent! This was how a newer operation called “zesting” was discovered, borne out of attempts to disambiguate modular tensor categories with similar-looking modular data.

People are also interested in studying “exotic modular tensor categories,” i.e. those not built out of group theory or Lie theory in the usual ways. For example, Grossman-Izumi [GI19] construct modular data from metric groups, and Bonderson-Rowell-Wang [BRW19] discuss realizations of exotic modular data.

So it's difficult to overstate how useful modular data is. But it's not a complete invariant, and this is a recent development! We'll finish by summarizing what we know now, and how life has changed in the aftermath.

**Theorem 14.6** (Mignard-Schauenberg [MS17]). *For  $G := \mathbb{Z}/q \rtimes \mathbb{Z}/p$ , where  $p$  and  $q$  are primes,  $p \mid q - 1$ , and  $p > 2$ , the modular categories  $\mathcal{Z}(\text{Vec}_G^\omega)$  are not always determined explicitly by their modular data; an explicit example is  $p = 5$  and  $q = 11$ .*

Lots of insight and brute force went into this discovery, but the five examples for  $p = 5$  and  $q = 11$  (since  $H^3(G; \mathbb{U}_1) \cong \mathbb{Z}/5$ ) are fairly explicit. These categories are rank 49, which is huge; it's open whether there are smaller examples.

One generalization of the  $S$ -matrix is the “punctured  $S$ -matrix,” corresponding to adding punctures to the torus. This determines the  $W$ -matrix, whose  $(a, b)$  entry is what the graphical calculus assigns to the *Whitehead link* colored by the two irreducible objects  $a$  and  $b$ .

**Theorem 14.7** (Bonderson-Delaney-Galindo-Rowell-Tran-Wang [BDG<sup>+</sup>18]). *The  $T$ - and  $W$ -matrices can distinguish the modular tensor categories from Theorem 14.6.*

## Part 5. Friday, January 31

### 15. CLAUDIA SCHEIMBAUER, TOPOLOGICAL FIELD THEORIES AND HIGHER CATEGORIES

We have spent plenty of time this week on objects closely related to topological field theories, including tensor categories and fusion categories. Today, we will begin with topological field theory and see among other things how tensor categories appear out of this formalism.

<sup>13</sup>This is not always a modular tensor category, but work of Nikshych shines light on when it is.

**Definition 15.1.** An  $n$ -dimensional *topological field theory* (TFT) is a symmetric monoidal functor  $Z: n\mathcal{Cob} \rightarrow \mathbf{Vect}$ .

Here  $\mathbf{Vect}$  is the symmetric monoidal category of vector spaces with tensor product.  $n\mathcal{Cob}$  is a symmetric monoidal category of bordisms:

- The objects of  $n\mathcal{Cob}$  are closed,  $(n - 1)$ -dimensional manifolds.<sup>14</sup>
- The morphisms are  $n$ -dimensional cobordisms.<sup>15</sup> That is, a morphism from  $M$  to  $N$  is a compact  $n$ -dimensional manifold  $X$  with boundary, together with a diffeomorphism  $\partial X \cong M \amalg N$ .
- Composition is gluing of cobordisms. Crucially, this must be associative on the nose, which means that we must identify cobordisms which are diffeomorphic rel boundary — so a morphism is in fact a diffeomorphism class of boundary.
- The symmetric monoidal structure is disjoint union of manifolds; the unit is the empty set, which is a compact  $(n - 1)$ -manifold.

If something you care about (e.g. some manifold invariant) is part of a TFT, that means that you can compute it by chopping a manifold into pieces as cobordisms, computing it on those pieces, and then putting them together, at least in principle. This is often a nice thing to have.

*Remark 15.2.* Why “topological?” Well, you can consider different kinds of *tangential structures* on the manifolds in  $n\mathcal{Cob}$ , including orientations, spin structures, or principal  $G$ -bundles with a flat connection. Most of what we do today will generalize to these settings.

But you can also consider other structures (arbitrary connections, Riemannian metrics, etc.), and studying these functorial field theories as in Definition 15.1 is much harder. ◀

One immediate consequence of the definition of a TFT is that if  $X$  is a closed  $n$ -dimensional manifold, it defines a cobordism  $\emptyset \rightarrow \emptyset$ , so if  $Z$  is a TFT,  $Z(M)$  is a map  $Z(\emptyset) \rightarrow Z(\emptyset)$ . Monoidality includes data of an isomorphism  $Z(\emptyset) \cong k$ , so  $Z(X)$  is a linear map  $k \rightarrow k$ , identified with a number. This number, called the *partition function* of  $X$ , is a diffeomorphism invariant.

Another lemma one can prove is that for any closed  $(n - 1)$ -manifold  $M$ ,  $Z(M)$  is a finite-dimensional vector space. This is reminiscent of the various finiteness conditions imposed on tensor categories this week, and this is not a coincidence.

**Example 15.3.** We’ve already seen a few examples of TFTs this week. In Belaikova’s talk, we discussed the Witten-Reshetikhin-Turaev invariants of 3-manifolds associated to a modular tensor category. If this is in addition a spherical fusion category, these specialize to Turaev-Viro invariants, which are computed by a *state-sum construction*: triangulate your manifold, then assign  $6j$ -symbols to the tetrahedra. ◀

The state-sum construction has an interesting consequence: we’ve chopped our axiom up not just into codimension-1 submanifolds, but also higher-codimension submanifolds: the edges and vertices. Can we capture this structure in a definition?

Unfortunately, symmetric monoidal categories aren’t enough to capture these ideas. One is led to “higher categories,” which more naturally incorporate lower-dimensional submanifolds into the cobordism category. We also saw in a previous talk the notion of a modular functor, which assigns invariants not just to 3-dimensional and 2-dimensional manifolds, but also to 1-dimensional manifolds. Here vector spaces are assigned to surfaces, and something new is assigned to 1-manifolds. We can hope this comes from some sort of extended TFT.

Another piece of motivation for extended TFT is: why fusion categories or modular tensor categories? We are led to them when formalizing Turaev-Viro or Witten-Reshetikhin-Turaev invariants, but are there others that we missed? If we understand conceptually why we get these TFTs, that will help us search for new TFTs in other dimensions. And why the specific adjectives that we put in front of fusion categories? Where do they come from?

To mathematically model these extended TFTs, we will add more layers of data. In a TFT as in Definition 15.1, we have a symmetric monoidal category, and we assign things to  $n$ - and  $(n - 1)$ -dimensional manifolds.

---

<sup>14</sup>There are many different variants, e.g. we could ask for manifolds and bordisms to be oriented, or framed, etc., but for now we just want smooth manifolds with no other data.

<sup>15</sup>Well, not quite — but we’ll get there in just a moment.

In an  $n$ -dimensional *once-extended TFT*, we replace symmetric monoidal categories with *symmetric monoidal bicategories*, and we can assign data to manifolds of dimension  $n$ ,  $n - 1$ , and  $n - 2$ . This has been studied by Schommer-Pries [SP09] and Morton [Mor06].

We can further extend to something called a *symmetric monoidal  $k$ -category*, which assigns data to manifolds of dimensions from  $n - k$  to  $n$ . Here we need  $k \leq n$ .

Another thing you can do is to consider moduli spaces of cobordisms: the idea is that nearby cobordisms should do similar things in a field theory. This leads one to a symmetric monoidal topological category of cobordisms, or alternatively a symmetric monoidal  $(\infty, 1)$ -category.<sup>16</sup> This assigns invariants to  $n$ - and  $(n - 1)$ -categories as usual, but we also have data in all dimensions higher than  $m$ , but because that data corresponds to paths or isotopy of paths in a moduli space, those morphisms are all invertible. These have been studied by Tillmann and Madsen, with key input from Galatius-Madsen-Tillmann-Weiss [GTMW09].

Finally, you can combine these into the notion of *fully extended TFT*, where you combine moduli spaces and extended TFT, in a symmetric monoidal  $(\infty, n)$ -category. We assign things in all dimensions, and above dimension  $n$  everything we define is invertible. There are different models of symmetric monoidal  $(\infty, n)$ -categories and the appropriate generalizations of  $n\mathcal{Cob}$ , due to work of Lurie [Lur09], Calaque-Scheimbauer [CS19], Verity, and Ayala-Francis-Rozenblyum.

In these various kinds of extended TFT, the cobordism category is some sort of symmetric monoidal higher category, and the target category, generalizing  $\mathcal{Vect}$ , must also be the same kind of symmetric monoidal higher category. Whatever we put there should allow us to recover the notion of an ordinary TFT from an extended one, in the same way that these cobordism higher categories should contain the data of  $n\mathcal{Cob}$ .

For example, let  $\mathcal{Bord}_{2,1,0}$  denote the symmetric monoidal bicategory of 0-manifolds, 1-manifolds (with boundary), and 2-manifolds (with corners). Consider the morphism category  $\mathcal{Bord}_{2,1,0}(\emptyset, \emptyset)$  — its objects are closed 1-manifolds, and its morphisms are (diffeomorphism classes of) compact bordisms between them — so this is just  $2\mathcal{Cob}$  again! So if  $\mathcal{C}$  is a suitable symmetric monoidal bicategory to use for extended TFT, then in any TFT  $Z: \mathcal{Bord}_{2,1,0} \rightarrow \mathcal{C}$ , we can restrict to  $\mathcal{Bord}_{2,1,0}(\emptyset, \emptyset)$ , i.e. the ordinary bordism category, and  $Z$  maps this to  $\Omega\mathcal{C} := \mathcal{C}(\mathbf{1}, \mathbf{1})$ . Thus we need  $\Omega\mathcal{C} \simeq \mathcal{Vect}$ .

**Example 15.4.** Here are two symmetric monoidal bicategories  $\mathcal{C}$  with  $\Omega\mathcal{C} \simeq \mathcal{Vect}$  as desired, and which are useful targets for once-extended TFT.

- The *Morita bicategory*  $\mathcal{Alg}_1(\mathcal{Vect})$  is the bicategory whose objects are algebras over  $k$ , whose 1-morphisms  $A \rightarrow B$  are  $(B, A)$ -bimodules, and whose 2-morphisms are bimodule homomorphisms.  $\Omega\mathcal{Alg}_1(\mathcal{Vect})$  is the symmetric monoidal category of  $(k, k)$ -bimodules, which is the same thing as vector spaces.
- The *bicategory of  $k$ -linear categories*  $\mathcal{LinCat}_k$  has for its objects the (finite, or finitely presented)  $k$ -linear categories, for 1-morphisms the  $k$ -linear functors, and for 2-morphisms the  $k$ -linear natural transformations. The unit is  $\mathcal{Vect}$ , and a  $k$ -linear functor  $\mathcal{Vect} \rightarrow \mathcal{Vect}$  determines and is determined by where it sends  $k$ , which can be an arbitrary vector space; hence  $\Omega\mathcal{LinCat}_k \simeq \mathcal{Vect}$ . ◀

**Example 15.5.** For another example,  $\mathcal{Alg}_1(\mathcal{LinCat}_k)$  is a symmetric monoidal  $(\infty, 3)$ -category, and is a natural target for three-dimensional TFT, and is useful for understanding Turaev-Viro theory. The objects are monoidal  $k$ -linear categories (which includes tensor categories); the 1-morphisms are  $k$ -linear bimodule categories; the 2-morphisms are  $k$ -linear bimodule functors; and the 3-morphisms are  $k$ -linear bimodule natural transformations. ◀

Ok, what about higher  $n$ ? In general, we can take some category  $\mathcal{Alg}_n(\mathcal{C})$  of higher algebras of some sort. Calaque-Scheimbauer [CS19] do this geometrically, and Haugseng [Hau17] does this with  $\infty$ -operads. This can be extended further in the spirit of Example 15.4, as done by Johnson-Freyd and Scheimbauer [JFS17].

**Definition 15.6.** A *fully extended TFT* is a symmetric monoidal functor  $Z: \mathcal{Bord}_{n,\dots,0} \rightarrow \mathcal{C}$ , where  $\mathcal{C}$  is some symmetric monoidal  $(\infty, n)$ -category.

**Theorem 15.7** (Cobordism hypothesis). *The map  $Z \mapsto Z(\text{pt})$  defines an equivalence from the symmetric monoidal  $(\infty, n)$ -category of fully extended TFTs valued in  $\mathcal{C}$  to the symmetric monoidal  $(\infty, n)$ -groupoid of units of  $n$ -dualizable objects in  $\mathcal{C}$ .*

<sup>16</sup>These are sometimes just called symmetric monoidal  $\infty$ -categories.

This theorem was conjectured by Baez-Dolan [BD95], and proven in dimension 2 by Schommer-Pries [SP09], Pstrągowski [Pst14], and Hopkins-Lurie. In general it's sketched by Lurie [Lur09] and Ayala-Francis [AF17], with closely related work by Harpaz and Schommer-Pries.

This leads to a strategy for finding fully extended TFTs: first, find an interesting symmetric monoidal  $(\infty, n)$ -category  $\mathcal{C}$ , e.g. via  $Alg_n(\mathcal{C})$  as above; then, find  $n$ -dualizable objects in  $\mathcal{C}$ .

**Example 15.8.** Douglas, Schommer-Pries, and Snyder [DSPS13] studied this for the 3-category of tensor categories inside  $Alg_1(\mathcal{L}inCat_k)$ , provided  $k$  is algebraically closed of characteristic zero. In particular, they showed that fusion categories are 3-dualizable, leading to fully extended 3d TFTs. (To get Turaev-Viro, you need to do something else to descend from framings to orientations.)<sup>17</sup> ◀

Here are some other related results.

- Brandenberg-Chirvasitu-Johnson-Freyd [BCJF15] show that  $\mathcal{L}inCat_k$ , having enough compact projectives implies 2-dualizability.
- Brochier-Jordan-Snyder [BJS18] showed that a fusion category in  $Alg_1(\mathcal{L}inCat)_k$  is 3-dualizable, and that a fusion-category in  $Alg_2(\mathcal{L}inCat)_k$  (the 4-category of braided  $k$ -linear categories) is 4-dualizable, so we get 4-dimensional framed TFTs.
- Gwilliam-Scheimbauer [GS18] showed that in  $Alg_n(\mathcal{C})$ , under mild assumptions on  $\mathcal{C}$ , all objects are dualizable.
- Douglas-Reutter [DR18] conjecture that fusion 2-categories are 4-dualizable in  $Alg_1(\mathcal{2}Cat_k)$ .

So we understand some things and are still learning others. Here are a few things we are still working on.

- Well, actually working with these TFTs, rather than knowing they're defined, is not necessarily made any easier by the cobordism hypothesis. Working with the TFTs that the work above has shown exists is still largely open.
- The target  $(\infty, n)$ -categories considered are not the only ones we might be interested in. What does the cobordism hypothesis say for other categories?
- Some field theories aren't fully extended, and we'd have to modify this framework. For example, relative field theories, related to boundary conditions, are studied by Stolz-Teichner and Freed-Teleman [FT14].
- If you're only  $k$ -dualizable for  $k < n$ , then you can build a "categorified TFT" which assigns invariants up to dimension  $k$ , but not farther. Less is known about these theories.
- What about other tangential structures? We know that in dimension 3, oriented theories are related to pivotal and spherical structures, by work of Douglas, Schommer-Pries, and Snyder [DSPS13]. But pretty much everything else here is open.

## 16. TERRY GANNON, CONFORMAL NETS II

Recall from last time we are interested in conformally invariant quantum field theory in one space and one time dimension, also known as 2d CFT. Our basic space is  $\mathbb{R}^{1,1}$ , which we compactify into  $S^1 \times S^1$ , leading to a splitting of the conformal group as  $\text{Diff}^+(S^1) \times \text{Diff}^+(S^1)$ . If we only impose half of this, asking for  $\text{Diff}^+(S^1)$ -covariance for a theory on  $S^1$ , we get what's called a *chiral* theory. This is sort of a cheat, and so we should expect/hope to recombine later. This is relatively well understood, at least for chiral theories that aren't too complicated, is well-understood, using modular categories. This is studied by Fuchs, Schweigert, and their collaborators. This trick works in certain simple settings (rational CFT), but otherwise is a bit too sneaky of a trick.

If you study VOAs or conformal nets, you must talk about their representations too — that's why they are. Recall that a conformal net is data of for each open interval  $I \subset S^1$ , a von Neumann algebra  $A(I)$  that's a subalgebra of the algebra of bounded operators on some Hilbert space. This is a type III<sub>1</sub> factor, which is the interesting kind — other kinds are less exciting.

Recall that a representation of this conformal net is data of maps  $\pi_I: A(I) \rightarrow B(K)$ , where  $K$  is some other Hilbert space (and  $B(K)$  denotes its algebra of bounded operators) which are compatible with the maps  $A(I_1) \rightarrow A(I_2)$  induced from an inclusion  $I_1 \subset I_2$ . Moreover, each  $\pi_I$  should be a continuous  $*$ -algebra homomorphism.

<sup>17</sup>And Reshetikhin-Turaev TFTs, which arise from modular tensor categories, aren't fully extended. There is work of Bartlett, Douglas, Schommer-Pries, and Vicary [BDSPV15] producing it in a similar vein.

Even if you don't care about physics, good physics leads to great mathematics, and so there's a very good chance that the mathematics of the future will be reminiscent of conformal nets and, more generally, the mathematical approach to CFT.

There is a rival mathematical formalism for CFTs called vertex operator algebras (VOAs). In this formalism, a quantum field is an operator-valued distribution on spacetime. Given an operator  $\varphi$  and a test function  $f(z)$  (a Laurent polynomial), the pairing  $\int \varphi(z)f(z) dz$ , which is to be interpreted formally, produces an operator. For  $f(z) = z^n$ , we obtain the operator  $\varphi_n \in \text{End}(V)$ , where  $V$  is the state space. This state space is graded by energy levels; the interesting cases are when each homogeneous component is finite-dimensional.

Often,  $\varphi$  is written in a Laurent-series-like manner, albeit in a formal sense:

$$(16.1) \quad \varphi = \sum_{n \in \mathbb{Z}} \varphi_n z^{-n-1},$$

and indeed everything in VOAs takes on a formal feel. As for conformal nets, there is a locality axiom: for all  $\varphi$  and  $\phi$ , and  $z$  and  $w$ , there is some  $N$  for which

$$(16.2) \quad (z - w)^N [\varphi(z), \phi(w)] = 0.$$

This means  $[\varphi(z), \phi(w)]$  is a finite linear combination of Dirac deltas and their derivatives at  $z$  and  $w$ . However, (16.2) is not how locality is usually stated in the VOA literature; usually, it's expressed in terms of operators  $Y(n, z) = \varphi(z)$ . In a VOA, these axioms automatically give you a representation of the Virasoro algebra, a central extension of the Lie algebra of vector fields on  $S^1$ , related to the  $\text{Diff}^+(S^1)$ -action arising in CFT.

Conformal nets are more like Lie groups, and VOAs like Lie algebras — certainly, conformal nets involve some analysis, and VOAs are more algebraic. Conformal nets are forced to be unitary, and VOAs do not; one can also study them over characteristic  $p$ . And VOAs are friendlier in general.

Non-unitary or non-semisimple VOAs/CFTs are a new and interesting world, with rich examples, such as the triplet model, or symplectic fermions; even though we don't have many examples, we expect almost every CFT to be non-logarithmic. There is no analogue of this in conformal nets.

In a VOA, we have a lot of extra structure: a doubly infinite tower of mapping class group representations. This encodes the relationships to moonshine phenomena and more, and this is a vital component of the theory. This is much harder to see using conformal nets.

Associated to a nice VOA and its associated modular tensor category  $\mathcal{C}$  there are characters

$$(16.3) \quad \chi_M(\tau) = \sum_{n=0}^{\infty} \dim M_n q^n,$$

and if you write  $q = e^{2\pi i \tau}$ , then these are modular functions.

**Conjecture 16.4** (Atkin-Swinnerton-Dyer [ASD71]). Given a modular function  $f(\tau)$  for  $\Gamma \subset \text{SL}_2(\mathbb{Z})$ , if  $f(\tau) = \sum q^n a_n$  and  $a_n \in \mathbb{Z}$ , then  $\Gamma$  contains some  $\Gamma(N)$ .

This conjecture is from the 1970s, and is still open, but the evidence has been leaning in favor of its truth. It suggests that there isn't much of a difference between modular tensor categories and conformal nets or VOAs.

We have relatively good control over the tensor products of conformal nets, which has something to do with the fact that the representation theory of type III<sub>1</sub> factors is nearly trivial — all left modules are isomorphic. The theory of bimodules is more interesting: the classification of  $(M, M)$ -bimodules, where  $M$  is a type III<sub>1</sub> factor, is equivalent to the classification of  $*$ -endomorphisms of  $M$  up to conjugation by unitary operators. The tensor product of bimodules passes to composition of morphisms, which is nice — but direct sum is trickier to translate.

One can try to see explicitly what happens in the finite-dimensional case, with matrices, but it turns out the answer is specific to the infinite-dimensional case. If  $\lambda, \mu: M \rightrightarrows M$ , then  $(\lambda \oplus \mu)(x) = P\lambda(x)P^* + Q\mu(x)Q^*$ , where  $P$  and  $Q$  are ways to split  $M$  into two copies:  $P^*P = Q^*Q = I$ , and  $P^*Q = 0$ .

You can use these to build exotic fusion categories with good control on their modular data: the magic trick is to realize simple objects in your fusion category as endomorphisms of an algebra, which makes tensor product easy and direct sum hard. And because tensor product comes from composition, this category is automatically strict, which is a nice but generally more artificial condition. This leads to many interesting exotic fusion categories, and it really seems like almost all fusion categories and modular tensor categories

are exotic, even though currently we know of very few exotic examples. Maybe this is an unusual view from within the field.

Likewise, the representations of a conformal net can be realized as endomorphisms of said conformal net. This is a useful tool for getting a handle on braidings, etc., within the representation category. If  $\pi$  is a representation of the conformal net  $A$  and  $\lambda^\pi$  is the corresponding endomorphism  $A(I) \rightarrow A(I)$  for each interval  $I \subset S^1$ , then composition passes to tensor product, but you can also see the braiding. This is just as in any quantum field theory, though in higher dimensions this braiding is symmetric.

The dimension of a representation is  $d_\pi := \sqrt{[A(I) : \lambda_I^\pi(A(I))]} \in [1, \infty]$ . From this data, one can get a subfactor:  $A(I) \subset A(I')$ , where  $I'$  is the interior of  $S^1 \setminus I$ . This is unfortunately a boring subfactor, in that  $A(I) = A(I')$ , so we instead need to choose two points inside  $I'$ , and divides the circle into four intervals,  $I_1, I_2, I_3$ , and  $I_4$ , which we assume are in cyclic order around the circle. Then we have a subfactor

$$(16.5) \quad (A(I_1) \cup A(I_3)) \subset (A(I_3) \cup A(I_4)).$$

This is used in one of the most important definitions in the area.

**Definition 16.6.** A *rational conformal net* is one in which the index of the subfactor (16.5) is finite.

Rational conformal nets should model rational CFTs. In this case, the sum of the squares of the (Frobenius-Perron) dimensions of the *superselection sectors* (i.e. the models) is finite. Crucially, this means all of the representations are finite, and in fact the category of representations of a rational conformal net is a modular tensor category!

There is also a definition of rationality for VOAs, and the category of modules for a rational VOA is a modular tensor category, but this is harder to work with.

One useful thing you can do with a rational conformal net with a group action (e.g. the one associated to the  $E_8$  lattice, with an involution) is *gauging* or the *orbifold construction*. It is a theorem that the result is always rational, but this is still a conjecture in the world of VOAs. In the  $E_8$  example, the result of gauging, depending on the involution, can be the  $D_8$  theory, whose modular tensor category is the Drinfeld double of  $\mathbb{Z}/2$ ; or we can get  $A_1 \oplus E_7$ , whose modular tensor category is  $D^\omega(\mathbb{Z}/2)$ , the twisted Drinfeld double.

This tells us that what's actually acting is a finite group and a 3-cocycle, i.e. what's really acting on the conformal net is a fusion category! This suggests that exotic fusion categories should lead to exotic orbifolds and CFTs. There is related work by Marcel Bischoff.

Just as finite groups are finite collections of objects that act, these are the quantum analogue: finite collections of things that act, albeit in this more modern manner.

## 17. ZHENGHAN WANG, TOPOLOGICAL ORDERS II

There's no single comprehensive reference for this talk, but [RW18, §4] is a good approximation.

Recall that a *topological order* is a catch-all higher-category of all universal properties of a topological phase of matter. For example, in dimension  $2 + 1$ , we have unitary modular tensor categories (though there's no proof that all topological phases in this dimension are given by modular tensor categories, nor should we necessarily expect that it's true). A *topological phase of matter* is a path-connected component of a space of topologically ordered Hamiltonians — though making this into a mathematically rigorous definition is a significant open problem.

**Example 17.1** (1d Ising chain). Consider a triangulation of a circle with  $N$  vertices, which we identify with  $1, \dots, N$  in cyclic order. The Hilbert space  $L_N$  is a tensor product of a  $\mathbb{C}^2$  for each vertex, and the Hamiltonian is

$$(17.2) \quad H_N := - \sum_{i=1}^N \underbrace{\sigma_i^z \sigma_{i+1}^z}_{h_i},$$

where  $i + 1$  is interpreted mod  $N$ . One can check that  $[h_i, h_j] = 0$ , and each  $h_i$  is a projector, simplifying analysis of the Hamiltonian. The ground state degeneracy (i.e. the dimension of the space of ground states) is 2; if  $\{|0\rangle, |1\rangle\}$  is a basis for  $\mathbb{C}^2$ , a basis for the ground state is

$$(17.3) \quad \{|0\rangle \otimes \dots \otimes |0\rangle, |1\rangle \otimes \dots \otimes |1\rangle\}.$$

If you think of this as a spin model, so  $|0\rangle$  is a  $\uparrow$  spin and  $|1\rangle$  is a  $\downarrow$  spin, this is saying that the Hamiltonian enforces that neighboring spins are synchronized. ◀

Physicists worked out that there is no bosonic topological order in  $(1+1)d$ , at least without additional symmetries. So why isn't the Ising model topological? The issue is that the analysis above is not stable under small perturbations of the Hamiltonian: the multiple eigenvalues that produced the ground state degeneracy split into distinct, different eigenvalues.<sup>18</sup> In TFT land, you have all these interesting Frobenius algebras, but they are unstable, just as the Ising model.

So let's turn to the toric code, which is actually a topological phase. Recall the Hamiltonian from last time:  $H = -\sum_v A_v - \sum_P B_P$ . This is a frustration-free Hamiltonian, in that  $|\psi\rangle$  is a ground state iff it's fixed by all  $A_v$  and  $B_P$  operators, which is a local condition. Relatedly, the Hamiltonian is a sum of commuting projections.

The key insight is that if  $A_v|\psi\rangle = |\psi\rangle$ , then  $\psi$ , which is a function from the edges to  $\{0,1\}$ , must have an even number of 1s on the edges adjacent to the vertex  $v$ . This implies that  $S := \psi^{-1}(1)$  is a sum of cycles. Now,  $B_P|\psi\rangle$  switches the 0s and 1s on  $\partial P$ , which is the same thing as adding the boundary  $\partial P$ . Every boundary is a sum of such cycles, so what we recover is the set of functions on  $H_1(M; \mathbb{Z}/2)$ . Something a little weird happened here, because homology is a subquotient, and the space of ground states is a subspace, but it's OK. For example, on a torus, the ground state degeneracy is 4. There's an argument to be made as to why this is nontrivial, unlike the Ising model.

We can now upgrade the definition of a topological order to a better one, which might be quite close to whatever we eventually discover is the right definition.

**Definition 17.4.** An  $n$ -dimensional Hamiltonian schema is *topological* if it's gapped; its ground states form an error-correcting code; its ground states are locally indistinguishable; and the ground state degeneracy does not depend on the cellulation once the manifold is fixed.

This is due to Bravyi-Hastings-Michalakis [BHM10]. The idea of an error-correcting code is the source of the name "code" in toric code; this isn't really related to programming. In a quantum error-correcting code, one has a large finite-dimensional Hilbert space of *physical qubits*, and a subspace which contains the information we'd like to protect against errors. This is sort of analogous to the Gauss-Bonnet theorem: the Euler characteristic of a surface does not change, even as you adjust the curvature. The subspace  $V$  behaves like a one-dimensional subspace, even if it isn't: when you project back down after a measurement, either you get the projection you started with, or you get zero! The toric code is an error-correcting code.

Local indistinguishability is a little tricky to write down carefully; it's expressed in terms of density matrices.

Anyways, once we have a topological order, at least in dimension  $2+1$ , we can try to extract a modular tensor category. We will focus on the ground states and also the first and second excited states, given by the eigenspaces of the first two eigenvalues above the ground state energy. These correspond to excitations that cannot be factored into pieces, and which are called *elementary excitations* — though this is not a completely mathematical term.

Let's try this for the toric code. We have two conservation laws:  $\prod_v A_v = \text{id}$  and  $\prod_P B_P = \text{id}$ . This means you can't just break invariance under a single operator; you have to do two, in order to cancel signs out. So, for example, you could ask for a state  $|\psi\rangle$  such that  $A_v|\psi\rangle = \pm|\psi\rangle$ , where the sign is  $+$  except at exactly two vertices  $v_1$  and  $v_2$ . This is an elementary excitation with energy 2 above the ground state.

These elementary excitations are anyons: they behave like particles, in that you can move them around. The toric code corresponds to the modular tensor category  $D(\mathbb{Z}/2)$ , with simple objects  $\{1, e, m, \psi\}$  and  $e \otimes m = m \otimes e = \psi$ ; the above excitation corresponds to producing two  $e$  particles located at  $v_1$  and  $v_2$ . Similarly, there is a minimal excitation that creates two  $m$  particles, specified by asking for  $B_P|\psi\rangle = \pm|\psi\rangle$  where the sign is  $+$  except at exactly two plaquettes.

And now something weird happens.  $e$  and  $m$  are bosons, but if you braid them around each other, which corresponds to applying a sequence of operators winding their positions around each other, the ground state wavefunction is multiplied by  $-1$ , which is strange for two bosons. This sounds physical, but can be translated into a precise mathematical statement leading you to a modular tensor category; the beginnings of this story date back to Kitaev's original paper on the toric code [Kit03].

---

<sup>18</sup>One of the eigenvalues is  $-N$ . If you want energy to be positive, this is a bit perplexing, but energy is really an  $\mathbb{R}$ -torsor, and you can shift up by adding some multiple of the identity to the Hamiltonian, relabeling the same ground states with different energy values, so long as the energy is bounded below.

The toric code has been well-studied, but the proof that the topological order, in the sense of Definition 17.4, for the toric code is  $\mathbb{Z}/2$ -Dijkgraaf-Witten theory was done only recently, in [CDH<sup>+</sup>19]. There are a few other correspondences that are open problems with a similar flavor.

- More generally, the low-energy TQFT of the Levi-Wen model should be the Turaev-Viro TQFT.
- The low-energy TQFT of the Walker-Wang model (which is in dimension  $3 + 1$ ) should be the Crane-Yetter TQFT.
- The low-energy TQFT of the Williamson-Wang model should be the TQFT constructed by Cui from the same data.

These should all be true, though.

Another difficult problem is that of Haldane’s *hardcore boson Hamiltonian* on the honeycomb lattice: this is not a commuting projector Hamiltonian, which should have the topological order of  $\mathfrak{su}(2)_1$  (i.e. quantum  $\mathfrak{su}_2$  at level 1). Computers can work with it and provide evidence, but nobody knows how to analytically solve it and prove that. Similarly, a model called the  $J_1 - J_2$  *anti-ferromagnetic Heisenberg model* at  $J_1 = J_2 = 1$  on the kagome lattice should have the same topological order as the toric code. Again, this is borne out by numerical simulations, but no proof is known. This is particularly interesting because there is an actual material called Herbertsmithite which can be coaxed into this topological order, so it would be good to better understand it.

These days, researchers are moving beyond anyons and anyon models in a few ways, such as studying symmetry defects, gapped boundaries,  $(2 + 1)$ -dimensional black holes, and fractons. *Fracton order* should have a definition similar to Definition 17.4, but the condition that the ground state degeneracy is independent of the cellulation is thrown out, replaced by the condition that it’s unbounded!

**Example 17.5** (Haah code [Haa11]). The Haah code is a  $(3 + 1)$ -dimensional example of fracton order, discovered by a computer search by Jeongwaan Haah. (Again, this hasn’t been mathematically shown yet, but is certainly true.) There is a cubic lattice (say, on  $T^3$ ), with a  $\mathbb{C}^2 \otimes \mathbb{C}^2$  on each vertex. The Hamiltonian is a sum over the cubes, with operators associated to each edge of the cube.

This is an error-correcting code, and its ground state degeneracy depends on the lattice and is unbounded. It’s very unclear what the continuum limit is, but if one runs renormalization group flow on this model, the degrees of freedom increase. This implies that the continuum limit cannot be a Lorentz-invariant quantum field theory; whatever it is will be interesting to discover.

Suppose the lattice on the torus has length  $L$  in all three directions. In this case the ground state degeneracy of the Haah code is  $O(e^{\beta L})$  for some  $\beta > 0$ . What other possible growth rates are possible in fracton phases? It would be particularly interesting to find a smaller, but still unbounded, growth rate.

Another interesting question is: this only works on cubic lattices. Are there fracton phases which can be defined on more general lattices, akin to topological orders? (For example, the toric code works on any cellulation.) ◀

## 18. JAMES TENER, SEGAL CFTs

This will be a relatively introductory talk on the mathematics of CFTs, beginning with the definitions for functorial CFT, then passing to vertex operator algebras, chiral theories, and, near the end, the relationship to conformal nets. We will focus on two-dimensional CFTs.

We would like to model 2d CFTs as symmetric monoidal functors from a bordism category to some category of vector spaces. The objects of the bordism category should be compact, smooth 1-manifolds, and the morphisms (appropriate isomorphism classes of) oriented compact surfaces with a conformal structure, i.e. an equivalence class of metrics under conformal transformations. In dimension 2, this is made simpler by the fact that on closed surfaces, a conformal structure is equivalent to a complex structure. The target category will be something like topological vector spaces, maybe Hilbert spaces, maybe Fréchet spaces. The axioms for this were written down by Segal [Seg88].

However, this isn’t exactly what we’ll talk about in this talk. These are “full CFTs,” but we’ll focus on “chiral CFTs,” as in Terry Gannon’s talk. Confusingly, researchers on both full and chiral CFTs both just call their subjects CFTs.

Anyways, in a full CFT, let  $\Sigma$  be a pair of pants with a specified conformal structure; if  $V := V(S^1)$  denotes the topological vector space assigned to a circle, this assigns a map  $V \otimes V \rightarrow V$ . We take as an



ansatz from physics that  $V$  splits as

$$(18.1) \quad V = \bigoplus_{\lambda \in \Lambda} V_\lambda \otimes \tilde{V}_\lambda,$$

where the  $V_\lambda$  pieces are the *chiral pieces* of  $V$ , and  $\tilde{V}_\lambda$  are the *anti-chiral pieces*.

But really, we should expect a family of vector spaces associated to a circle, and many different maps between them, since we have many different conformal structures. Segal axiomatizes this as a *weak CFT*. You can reshape this data into a category of vector spaces and maps between them, and this is the genesis of the idea that you can extract a modular tensor category from a CFT; we will zoom in on the tensor unit of that tensor category, obtaining a simpler structure called a vertex operator algebra.

The definition of a vertex operator algebra (VOA) is not very enlightening, so instead we'll discuss the meaning of the axioms, which should make it easier to parse and digest the definition on Wikipedia. The point of a VOA is to axiomatize a chiral CFT in the *vacuum sector* (i.e. corresponding to the tensor unit), and restricted to conformal surfaces of genus zero. We'll give a geometrically-motivated definition of a VOA.

**Definition 18.2.** A *vertex operator algebra* (VOA) is data of a topological vector space  $V$  and data of, for all genus-zero  $n$ -punctured Riemann surfaces with parameterized boundary  $\Sigma$ , a map

$$(18.3) \quad Z_\Sigma: V^{\otimes(n-1)} \longrightarrow V,$$

satisfying some axioms, notably that gluing of Riemann surfaces is sent to composition of the  $Z_\Sigma$  maps. We also ask that this multiplication depends holomorphically on  $\Sigma$ : any such Riemann surface is biholomorphic to a subset of  $\mathbb{C}$ , so you can imagine taking a family given by translating by  $w$  for  $w \in \mathbb{C}$ ; then we ask that the multiplication map is a holomorphic function in  $w$ .

Unlike what you might be used to in TFT, the maps for diffeomorphic but not isomorphic surfaces are not equivalent! In fact, if you had topological invariance rather than holomorphic invariance, this notion of a VOA rapidly collapses to that of a commutative algebra — so you can think of VOAs as things like commutative algebras, but complexified: we have a complex parameter space of multiplications, which vary holomorphically.

*Remark 18.4.* You can describe these as holomorphic algebras for a certain operad, though that's a nontrivial theorem. ◀

If you want to understand the Wikipedia definition of a VOA, work with the two-holed annulus, and expand formally around the puncture. This gives you functions  $Y(s^{L_0-}, w)r^{L_0-}$ , which satisfy some axioms, and these are what appear in the dictionary definition of a VOA.

**Example 18.5** (WZW model). Pick a simple complex finite-dimensional Lie algebra  $\mathfrak{g}$  and a positive integer  $k$  called the *level*. The level defines a certain infinite-dimensional representation  $V$  of the *loop algebra*  $L\mathfrak{g} := C^\infty(S^1, \mathfrak{g})$ , called the *vacuum representation* of level  $k$ . ◀

Given  $\Sigma$ , a pair of pants with a conformal structure, we want to define a map  $Z_\Sigma: V \otimes V \rightarrow V$  such that for all  $f \in \mathcal{O}_{\text{hol}}(\Sigma; \mathfrak{g})$ ,

$$(18.6) \quad f|_{\partial_{\text{out}}\Sigma} \cdot Z_\Sigma(v_1 \otimes v_2) = Z_\Sigma(f|_{\partial_{\text{in}}\Sigma} \cdot v_1 \otimes v_2) + Z_\Sigma(v_1 \otimes f|_{\partial_{\text{out}}\Sigma} \cdot v_2).$$

Equation (18.6) is called the *Segal commutation relations*. We will eventually be able to do this up to a complex scalar; that problem is resolved using central charge.

To obtain the maps satisfying the Segal commutation relations, we will use a trick called *holomorphic induction*. The idea is that “ $Z_\Sigma$  satisfies the Segal relations” makes sense, and we can try to do something universal. So we can ask for a pair of  $u \in V$  and  $Z_\Sigma$  such that all other such pairs satisfying the Segal condition factor through  $(u, \Sigma)$ . A chiral CFT is essentially a formalization of what axioms these are supposed to satisfy — “supposed to” because there's an issue with the fact that we'd like the representation to have positive energy again, but this is not actually known to be true.

Anyways, this leads one to the definition (or a sketch of the definition) of a Segal CFT.

- We want for all  $C^\infty$  closed 1-manifolds  $S$ , a category  $\mathcal{C}(S)$  equipped with a functor  $\mathcal{C}(S) \rightarrow \mathcal{T}opVect$  (or maybe Fréchet or Hilbert spaces), and
- for all compact Riemann surface bordisms  $\Sigma$ , a functor  $F_\Sigma: \mathcal{C}(S_{\text{in}}) \rightarrow \mathcal{C}(S_{\text{out}})$ , and a map  $Z_\Sigma: V_\lambda \rightarrow V_{F_\Sigma(\lambda)}$ .

This is the first thing you'd write down if you wanted a generalization of topological field theory but for more than one vector space. But we need another axiom to control how this behaves in families of  $\Sigma$ ; one way to guarantee this is via a third axiom,

- for every annulus  $A$  with parameterized boundary, an isomorphism  $T_A F_A \cong \text{id}$ , with a positive-energy condition.

The first two axioms stitch together into a functor from a bordism category not to  $\mathcal{Vect}$ , but to a category of *concrete categories*, i.e. equipped with a functor to  $\mathcal{TopVect}$ .<sup>19</sup> This is called a *weak CFT*.

This structure induces a VOA on the vector space assigned to the disc. So this is quite a bit of structure, and would also encode a great deal of the associated representation theory coming from a given CFT. Thus these are quite difficult to construct.

In the last part of this lecture, we will make contact with the idea of conformal nets, a different approach to conformal field theory. We will try to go from a VOA (as defined geometrically above) to a conformal net. This forces us to restrict to unitary CFTs, so Hilbert spaces, rather than just topological vector spaces. To do this, we will need to pass through a conjecture on when we can pass from pairs of pants to all Riemann surfaces. Take an  $(n + 1)$ -punctured genus 0 Riemann surface and identify some subset of the incoming boundary with some subset of the outgoing boundary; call such a space an *extended  $n$ -to-1 Riemann surface*.

**Conjecture 18.7.** Reasonable VOAs take values on extended  $n$ -to-1 Riemann surfaces, i.e. given only the data we had before, there is a canonical way to assign invariants to these spaces.

This is a step in the direction towards extended CFT (in the higher-categorical sense). You should think of the extension as unique because nonsingular surfaces are dense in the space of extended surfaces. This is sort of an analysis question, asking whether a limit exists. Recent work of the speaker attempts to use this and then build conformal nets.

**Theorem 18.8** (Tener [Ten19]). *For all WZW models, this produces conformal nets.*

Work continues on the general setting, and on related questions.

## REFERENCES

- [AF17] David Ayala and John Francis. The cobordism hypothesis. 2017. <https://arxiv.org/abs/1705.02240>. 36
- [AH99] M. Asaeda and U. Haagerup. Exotic subfactors of finite depth with Jones indices  $(5 + \sqrt{13})/2$  and  $(5 + \sqrt{17})/2$ . *Comm. Math. Phys.*, 202(1):1–63, 1999. <https://arxiv.org/abs/math/9803044>. 26
- [ASD71] A. O. L. Atkin and H. P. F. Swinnerton-Dyer. Modular forms on noncongruence subgroups. In *Combinatorics (Proc. Sympos. Pure Math., Vol. XIX, Univ. California, Los Angeles, Calif., 1968)*, pages 1–25, 1971. 37
- [AY09] Marta Asaeda and Seidai Yasuda. On Haagerup's list of potential principal graphs of subfactors. *Comm. Math. Phys.*, 286(3):1141–1157, 2009. <https://arxiv.org/abs/0711.4144>. 26
- [BBCW19] Maissam Barkeshli, Parsa Bonderson, Meng Cheng, and Zhenghan Wang. Symmetry fractionalization, defects, and gauging of topological phases. *Phys. Rev. B*, 100:115147, Sep 2019. <https://arxiv.org/abs/1410.4540>. 32
- [BBG17] Anna Beliakova, Christian Blanchet, and Azat M. Gainutdinov. Modified trace is a symmetrised integral. 2017. <https://arxiv.org/abs/1801.00321>. 30
- [BBG18] Anna Beliakova, Christian Blanchet, and Nathan Geer. Logarithmic Hennings invariants for restricted quantum  $\mathfrak{sl}(2)$ . *Algebr. Geom. Topol.*, 18(7):4329–4358, 2018. <https://arxiv.org/abs/1705.03083>. 29, 31
- [BBL11] Anna Beliakova, Irmgard Bühler, and Thang Lê. A unified quantum  $\text{SO}(3)$  invariant for rational homology 3-spheres. *Invent. Math.*, 185(1):121–174, 2011. <https://arxiv.org/abs/0801.3893>. 17
- [BCGPM16] Christian Blanchet, Francesco Costantino, Nathan Geer, and Bertrand Patureau-Mirand. Non semi-simple TQFTs from unrolled quantum  $\mathfrak{sl}(2)$ . In *Proceedings of the Gökova Geometry-Topology Conference 2015*, pages 218–231. Gökova Geometry/Topology Conference (GGT), Gökova, 2016. <https://arxiv.org/abs/1605.07941>. 31
- [BCJF15] Martin Brandenburg, Alexandru Chirvasitu, and Theo Johnson-Freyd. Reflexivity and dualizability in categorified linear algebra. *Theory Appl. Categ.*, 30:Paper No. 23, 808–835, 2015. <https://arxiv.org/abs/1409.5934>. 36
- [BCL14] Anna Beliakova, Qi Chen, and Thang T. Q. Lê. On the integrality of the Witten-Reshetikhin-Turaev 3-manifold invariants. *Quantum Topol.*, 5(1):99–141, 2014. <https://arxiv.org/abs/1010.4750>. 16
- [BD95] John C. Baez and James Dolan. Higher-dimensional algebra and topological quantum field theory. *J. Math. Phys.*, 36(11):6073–6105, 1995. <https://arxiv.org/abs/q-alg/9503002>. 36
- [BD96] Anna Beliakova and Bergfinnur Durhuus. On the relation between two quantum group invariants of 3-cobordisms. *J. Geom. Phys.*, 20(4):305–317, 1996. <https://arxiv.org/abs/q-alg/9502010>. 16
- [BDG<sup>+</sup>18] Parsa Bonderson, Colleen Delaney, César Galindo, Eric C. Rowell, Alan Tran, and Zhenghan Wang. On invariants of modular categories beyond modular data. 2018. <https://arxiv.org/abs/1805.05736>. 33

<sup>19</sup>There's a slight category number mismatch here, which we're not going to worry about right now.

- [BDSPV15] Bruce Bartlett, Christopher L. Douglas, Christopher J. Schommer-Pries, and Jamie Vicary. Modular categories as representations of the 3-dimensional bordism 2-category. 2015. <https://arxiv.org/abs/1509.06811>. 32, 36
- [BHM10] Sergey Bravyi, Matthew B. Hastings, and Spyridon Michalakis. Topological quantum order: Stability under local perturbations. *Journal of Mathematical Physics*, 51(9):093512, 2010. <https://arxiv.org/abs/1001.0344>. 39
- [Bis98] Dietmar Bisch. Principal graphs of subfactors with small Jones index. *Math. Ann.*, 311(2):223–231, 1998. 26
- [BJS18] Adrien Brochier, David Jordan, and Noah Snyder. On dualizability of braided tensor categories. 2018. <https://arxiv.org/abs/1804.07538>. 36
- [BK01] Bojko Bakalov and Alexander Kirillov, Jr. *Lectures on tensor categories and modular functors*, volume 21 of *University Lecture Series*. American Mathematical Society, Providence, RI, 2001. 4
- [BMPS12] Stephen Bigelow, Scott Morrison, Emily Peters, and Noah Snyder. Constructing the extended Haagerup planar algebra. *Acta Math.*, 209(1):29–82, 2012. <https://arxiv.org/abs/0909.4099>. 26
- [BNRW16] Paul Bruillard, Siu-Hung Ng, Eric C. Rowell, and Zhenghan Wang. Rank-finiteness for modular categories. *J. Amer. Math. Soc.*, 29(3):857–881, 2016. <https://arxiv.org/abs/1310.7050>. 14
- [BPW19] Petter Andreas Bergh, Julia Yael Plavnik, and Sarah Witherspoon. Support varieties for finite tensor categories: Complexity, realization, and connectedness. 2019. <https://arxiv.org/abs/1905.07031>. 21
- [BRW19] Parsa Bonderson, Eric C. Rowell, and Zhenghan Wang. On realizing modular data. 2019. <https://arxiv.org/abs/1910.07061>. 33
- [CC19] Liang Chang and Shawn X. Cui. On two invariants of three manifolds from Hopf algebras. *Adv. Math.*, 351:621–652, 2019. <https://arxiv.org/abs/1710.09524>. 30
- [CDH<sup>+</sup>19] Shawn X. Cui, Dawei Ding, Xizhi Han, Geoffrey Penington, Daniel Ranard, Brandon C. Rayhaun, and Zhou Shangnan. Kitaev’s quantum double model as an error correcting code. 2019. <https://arxiv.org/abs/1908.02829>. 40
- [CGPM14] Francesco Costantino, Nathan Geer, and Bertrand Patureau-Mirand. Quantum invariants of 3-manifolds via link surgery presentations and non-semi-simple categories. *J. Topol.*, 7(4):1005–1053, 2014. <https://arxiv.org/abs/1202.3553>. 29
- [CGPW16] Shawn X. Cui, César Galindo, Julia Yael Plavnik, and Zhenghan Wang. On gauging symmetry of modular categories. *Comm. Math. Phys.*, 348(3):1043–1064, 2016. <https://arxiv.org/abs/1510.03475>. 33
- [CKLW18] Sebastiano Carpi, Yasuyuki Kawahigashi, Roberto Longo, and Mihály Weiner. From vertex operator algebras to conformal nets and back. *Mem. Amer. Math. Soc.*, 254(1213):vi+85, 2018. <https://arxiv.org/abs/1503.01260>. 19
- [CKS09] Qi Chen, Srikanth Kuppum, and Parthasarathy Srinivasan. On the relation between the WRT invariant and the Hennings invariant. *Math. Proc. Cambridge Philos. Soc.*, 146(1):151–163, 2009. <https://arxiv.org/abs/0709.2318>. 30
- [CS19] Damien Calaque and Claudia Scheimbauer. A note on the  $(\infty, n)$ -category of cobordisms. *Algebr. Geom. Topol.*, 19(2):533–655, 2019. <https://arxiv.org/abs/1509.08906>. 35
- [Del02] P. Deligne. Catégories tensorielles. volume 2, pages 227–248. 2002. Dedicated to Yuri I. Manin on the occasion of his 65th birthday. 8
- [DGNO10] Vladimir Drinfeld, Shlomo Gelaki, Dmitri Nikshych, and Victor Ostrik. On braided fusion categories. I. *Selecta Math. (N.S.)*, 16(1):1–119, 2010. <https://arxiv.org/abs/0906.0620>. 23
- [DR18] Christopher L. Douglas and David J. Reutter. Fusion 2-categories and a state-sum invariant for 4-manifolds. 2018. <https://arxiv.org/abs/1812.11933>. 36
- [DRGPM18] Marco De Renzi, Nathan Geer, and Bertrand Patureau-Mirand. Renormalized Hennings invariants and 2+1-TQFTs. *Comm. Math. Phys.*, 362(3):855–907, 2018. 31
- [DSPS13] Christopher L. Douglas, Christopher Schommer-Pries, and Noah Snyder. Dualizable tensor categories. 2013. <https://arxiv.org/abs/1312.7188>. 36
- [EG14] David E. Evans and Terry Gannon. Near-group fusion categories and their doubles. *Adv. Math.*, 255:586–640, 2014. <https://arxiv.org/abs/1208.1500>. 12
- [EGNO15] Pavel Etingof, Shlomo Gelaki, Dmitri Nikshych, and Victor Ostrik. *Tensor categories*, volume 205 of *Mathematical Surveys and Monographs*. American Mathematical Society, Providence, RI, 2015. 4, 13
- [ENO05] Pavel Etingof, Dmitri Nikshych, and Viktor Ostrik. On fusion categories. *Ann. of Math. (2)*, 162(2):581–642, 2005. <https://arxiv.org/abs/math/0203060>. 11
- [ERW08] Pavel Etingof, Eric Rowell, and Sarah Witherspoon. Braid group representations from twisted quantum doubles of finite groups. *Pacific J. Math.*, 234(1):33–41, 2008. <https://arxiv.org/abs/math/0703274>. 14
- [FL18] Ilaria Flandoli and Simon Lentner. Logarithmic conformal field theories of type  $B_n$ ,  $\ell = 4$  and symplectic fermions. *J. Math. Phys.*, 59(7):071701, 35, 2018. <https://arxiv.org/abs/1706.07994>. 23
- [FP86] Eric M. Friedlander and Brian J. Parshall. Support varieties for restricted Lie algebras. *Invent. Math.*, 86(3):553–562, 1986. 21
- [FP87] Eric M. Friedlander and Brian J. Parshall. Geometry of  $p$ -unipotent Lie algebras. *J. Algebra*, 109(1):25–45, 1987. 21
- [FS97] Eric M. Friedlander and Andrei Suslin. Cohomology of finite group schemes over a field. *Invent. Math.*, 127(2):209–270, 1997. 21
- [FT14] Daniel S. Freed and Constantin Teleman. Relative quantum field theory. *Comm. Math. Phys.*, 326(2):459–476, 2014. <https://arxiv.org/abs/1212.1692>. 36
- [GI19] Pinhas Grossman and Masaki Izumi. Infinite families of potential modular data related to quadratic categories. 2019. <https://arxiv.org/abs/1906.07397>. 33

- [GK93] Victor Ginzburg and Shrawan Kumar. Cohomology of quantum groups at roots of unity. *Duke Math. J.*, 69(1):179–198, 1993. 21
- [GN19] Jason Green and Dmitri Nikshych. On the braid group representations coming from weakly group-theoretical fusion categories. 2019. <https://arxiv.org/abs/1911.02633>. 14
- [GS18] Owen Gwilliam and Claudia Scheimbauer. Duals and adjoints in higher Morita categories. 2018. <https://arxiv.org/abs/1804.10924>. 36
- [GTMW09] Søren Galatius, Ulrike Tillmann, Ib Madsen, and Michael Weiss. The homotopy type of the cobordism category. *Acta Math.*, 202(2):195–239, 2009. <https://arxiv.org/abs/math/0605249>. 35
- [Haa11] Jeongwan Haah. Local stabilizer codes in three dimensions without string logical operators. *Phys. Rev. A*, 83:042330, Apr 2011. <https://arxiv.org/abs/1101.1962>. 40
- [Hab08] Kazuo Habiro. A unified Witten-Reshetikhin-Turaev invariant for integral homology spheres. *Invent. Math.*, 171(1):1–81, 2008. <https://arxiv.org/abs/math/0605314>. 16, 17
- [Hau17] Rune Haugseng. The higher Morita category of  $\mathbb{E}_n$ -algebras. *Geom. Topol.*, 21(3):1631–1730, 2017. <https://arxiv.org/abs/1412.8459>. 35
- [HL16] Kazuo Habiro and Thang T. Q. Lê. Unified quantum invariants for integral homology spheres associated with simple Lie algebras. *Geom. Topol.*, 20(5):2687–2835, 2016. <https://arxiv.org/abs/1503.03549>. 17
- [HLZ11] Yi-Zhi Huang, James Lepowsky, and Lin Zhang. Logarithmic tensor category theory, VIII: Braided tensor category structure on categories of generalized modules for a conformal vertex algebra. 2011. <https://arxiv.org/abs/1110.1931>. 23
- [IT19] Masaki Izumi and Henry Tucker. Algebraic realization of noncommutative near-group fusion categories. 2019. <https://arxiv.org/abs/1908.01655>. 12
- [JFS17] Theo Johnson-Freyd and Claudia Scheimbauer. (Op)lax natural transformations, twisted quantum field theories, and “even higher” Morita categories. *Adv. Math.*, 307:147–223, 2017. <https://arxiv.org/abs/1502.06526>. 33, 35
- [Jon83] V. F. R. Jones. Index for subfactors. *Invent. Math.*, 72(1):1–25, 1983. 25
- [Jon99] Vaughan F. R. Jones. Planar algebras, I. 1999. <https://arxiv.org/abs/math/9909027>. 8
- [Kau00] Horst G. Kausch. Symplectic fermions. *Nuclear Physics B*, 583(3):513 – 541, 2000. <https://arxiv.org/abs/hep-th/0003029>. 23
- [Kit03] A.Yu. Kitaev. Fault-tolerant quantum computation by anyons. *Annals of Physics*, 303(1):2 – 30, 2003. <https://arxiv.org/abs/quant-ph/9707021>. 28, 39
- [Kup91] Greg Kuperberg. Involutory Hopf algebras and 3-manifold invariants. *Internat. J. Math.*, 2(1):41–66, 1991. <https://arxiv.org/abs/math/9201301>. 30
- [KW93] David Kazhdan and Hans Wenzl. Reconstructing monoidal categories. In *I. M. Gelfand Seminar*, volume 16 of *Adv. Soviet Math.*, pages 111–136. Amer. Math. Soc., Providence, RI, 1993. 14
- [Lur09] Jacob Lurie. On the classification of topological field theories. *Current Developments in Mathematics*, 2008:129–280, 2009. <https://arxiv.org/abs/0905.0465>. 35, 36
- [Mor06] Jeffrey C. Morton. Double bicategories and double cospans. 2006. <https://arxiv.org/abs/math/0611930>. 35
- [MPSW10] M. Mastnak, J. Pevtsova, P. Schauenburg, and S. Witherspoon. Cohomology of finite-dimensional pointed Hopf algebras. *Proc. Lond. Math. Soc. (3)*, 100(2):377–404, 2010. <https://arxiv.org/abs/0902.0801>. 21
- [MS89] Gregory Moore and Nathan Seiberg. Classical and quantum conformal field theory. *Communications in Mathematical Physics*, 123(2):177–254, Jun 1989. 31
- [MS17] Michaël Mignard and Peter Schauenburg. Modular categories are not determined by their modular data. 2017. <https://arxiv.org/abs/1708.02796>. 33
- [Neg18] Cris Negron. Twists of quantum Borel algebras. *J. Algebra*, 514:113–144, 2018. <https://arxiv.org/abs/1707.07802>. 22
- [Nik19] Dmitri Nikshych. Classifying braidings on fusion categories. In *Tensor categories and Hopf algebras*, volume 728 of *Contemp. Math.*, pages 155–167. Amer. Math. Soc., Providence, RI, 2019. <https://arxiv.org/abs/1801.06125>. 14
- [NP18] Cris Negron and Julia Yael Plavnik. Cohomology of finite tensor categories: duality and Drinfeld centers. 2018. <https://arxiv.org/abs/1807.08854>. 21
- [NS10] Siu-Hung Ng and Peter Schauenburg. Congruence subgroups and generalized Frobenius-Schur indicators. *Comm. Math. Phys.*, 300(1):1–46, 2010. <https://arxiv.org/abs/0806.2493>. 13
- [NW14] Van C. Nguyen and Sarah Witherspoon. Finite generation of the cohomology of some skew group algebras. *Algebra Number Theory*, 8(7):1647–1657, 2014. <https://arxiv.org/abs/1310.0724>. 21
- [NWW17] Van C. Nguyen, Xingting Wang, and Sarah Witherspoon. Finite generation of some cohomology rings via twisted tensor product and Anick resolutions. 2017. <https://arxiv.org/abs/1710.07141>. 21
- [NWW19] Van C. Nguyen, Xingting Wang, and Sarah Witherspoon. New approaches to finite generation of cohomology rings. 2019. <https://arxiv.org/abs/1911.04552>. 21
- [Pst14] Piotr Pstrągowski. On dualizable objects in monoidal bicategories, framed surfaces and the cobordism hypothesis. 2014. <https://arxiv.org/abs/1411.6691>. 36
- [RW18] Eric C. Rowell and Zhenghan Wang. Mathematics of topological quantum computing. *Bull. Amer. Math. Soc. (N.S.)*, 55(2):183–238, 2018. <https://arxiv.org/abs/1705.06206>. 26, 38
- [Seg88] G. B. Segal. *The Definition of Conformal Field Theory*, pages 165–171. Springer Netherlands, Dordrecht, 1988. 40
- [SP09] Christopher John Schommer-Pries. *The classification of two-dimensional extended topological field theories*. PhD thesis, University of California, Berkeley, 2009. <https://arxiv.org/abs/1112.1000>. 35, 36
- [Ten19] James E. Tener. Fusion and positivity in chiral conformal field theory. 2019. <https://arxiv.org/abs/1910.08257>. 42