The Jones representations of braid groups at $q = -1$ (Part II)

Winter Braids IV – Dijon

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December 4th, 2013

Notation

- Let $G = \mathrm{SU}(N)$, and let M be an (oriented connected framed) closed 3-manifold.
- Let $\mathcal{A} \cong \Omega^1(M, \mathfrak{g})$ be the space of connections in $G \times M \to M$, and let $\mathcal{G} \cong C^\infty(M, G)$ be the group of gauge transformations acting on $\mathcal{A}$.
- Define the Chern–Simons functional $\mathrm{CS} : \mathcal{A} \to \mathbb{R}$ by

$$\mathrm{CS}(A) = \frac{1}{8\pi^2} \int_M \mathrm{tr}(A \wedge dA + \frac{2}{3} A \wedge A \wedge A).$$

- For $g \in \mathcal{G}$, we have $\mathrm{CS}(g^* A) - \mathrm{CS}(A) \in \mathbb{Z}$, and we can consider

$$\mathrm{CS} : \mathcal{A}/\mathcal{G} \to \mathbb{R}/\mathbb{Z}$$

The Chern–Simons partition function

- Let $k \in \mathbb{N}$ (called the *level*) and define the *Chern–Simons partition function*

$$Z_k^{\mathrm{phys}}(M) = \int_{\mathcal{A}/\mathcal{G}} e^{2\pi i k\, \mathrm{CS}(A)} \mathcal{D}A \in \mathbb{C}.$$

- Assume that M contains a framed oriented link L, and choose for every component L_i of L a finite dimensional representation R_i of $G = \mathrm{SU}(N)$. Set

$$Z_k^{\mathrm{phys}}(M, L, R) = \int_{\mathcal{A}/\mathcal{G}} \prod_i \mathrm{tr}(R_i(\mathrm{hol}_A(L_i))) e^{2\pi i k\, \mathrm{CS}(A)} \mathcal{D}A.$$

Witten '89: This extends to a TQFT.

A possible construction

Theorem (Reshetikhin–Turaev, 1991)

One can construct a topological invariant Z_k of 3-manifolds, called the quantum invariant, which behaves under gluing (or surgery) the way Z_k^{phys} is supposed to do.

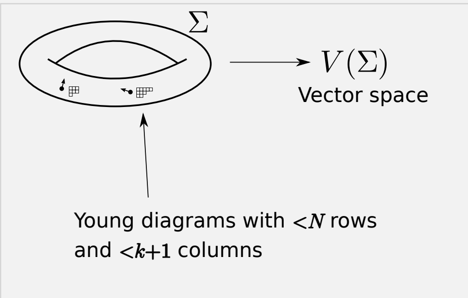
Source of inspiration

For a closed oriented 3-manifold M,

$$Z_k^{\mathrm{phys}}(M) = Z_k(M).$$

Topological quantum field theory

Reshetikhin and Turaev proved that the invariant Z_k is part of a $2+1$-dimensional topological quantum field theory (Z_k, V_k):



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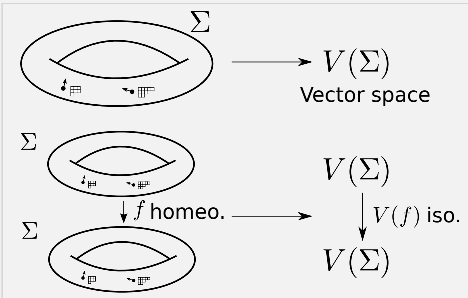

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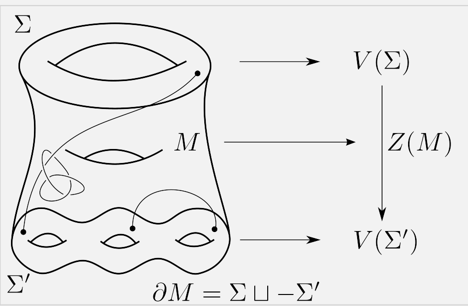


Quantum representations

The data (Z, V) satisfies a number of axioms.

Example

Let $\varphi : \Sigma \to \Sigma$ be a diffeomorphism and consider the *mapping cylinder*

$$C_\varphi = \Sigma \times [0, \tfrac{1}{2}] \cup_\varphi \Sigma \times [\tfrac{1}{2}, 1]$$

Then $Z(C_\varphi) : V(\Sigma) \to V(\Sigma)$ depends on φ only up to isotopy. Define the (projective) *quantum representations* $\rho : \mathrm{MCG}(\Sigma) \to \mathrm{PGL}(V(\Sigma))$ by $\rho([\varphi]) = Z(C_\varphi)$. Furthermore, $Z(C_\varphi) = V(\varphi)$.

Constructing quantum representations

Several equivalent approaches to the construction of quantum representations exist:

- Categorical/combinatorial through modular functors: (V_k, ρ_k) obtained from representation theory of $U_q(\mathfrak{sl}_N)$, the skein theory of the Kauffman bracket/HOMFLYPT polynomial, ...
- Conformal field theory: the monodromy of the WZW connection in the sheaf of conformal blocks.
- Geometric quantization of moduli spaces: the monodromy of the Hitchin connection (no marked points).

The genus 0 case

- Let $\Sigma = \mathbb{C} \cup \{\infty\}$ be a genus zero surface with marked points $\{1, \dots, n, \infty\}$ labelled by Young diagrams $\{\square, \dots, \square, \lambda^\star\}$, where λ has at most 2 rows (1 if $N = 2$), and $\star$ denotes the dual diagram.
- Let $V_{N,k}^\lambda$ denote the vector space associated by any of the modular functors to Σ.
- The MCG of Σ naturally contains B_n. Let $\rho_{N,k}^\lambda : B_n \to \mathrm{GL}(V_{N,k}^\lambda)$ denote the restriction of the quantum representation to this B_n.

Theorem (Kanie)

For $k > n$, $\rho_{N,k}^\lambda$ is equivalent to the diagram representation $\eta_A^{n,d}$ from Jens Kristian's talk with $q = A^4 = \exp(2\pi i/(N + k))$, $d \leftrightarrow \lambda$.

Isotopy invariant dynamics

What dynamical information do mapping classes contain?

Theorem (Nielsen–Thurston)

A mapping class $\varphi \in \mathrm{MCG}(\Sigma)$ is either

- *finite order,*
- *infinite order but has a power preserving the homotopy class of an essential simple closed curve (φ is reducible), or*
- *pseudo-Anosov: there are transverse measured singular foliations $(\mathcal{F}^s, \mu^s)$, $(\mathcal{F}^u, \mu^u)$ of Σ, $\lambda > 1$ and a diffeo. f, $[f] = \varphi$, s.t.*

$$f(\mathcal{F}^s, \mu^s) = (\mathcal{F}^s, \lambda^{-1}\mu^s), \quad f(\mathcal{F}^u, \mu^u) = (\mathcal{F}^u, \lambda\mu^u).$$

Here, λ is called the stretch factor of φ.

Visualizing pseudo-Anosov braids

Figure: Source: Mark A. Stremler

- Left: Initial position.
- Center: Stirring by finite order braid.
- Right: Stirring by pseudo-Anosov braid.

The NT classification vs. quantum reps

Are the quantum reps ρ_k sensitive to the trichotomy?

Conjecture (Andersen–Masbaum–Ueno '06)

Let $2g + n > 2$, and let $\varphi \in \mathrm{MCG}(\Sigma)$ be a pseudo-Anosov. Then there exists k_0 s.t. $\rho_{N,k}(\varphi)$ has infinite order for $k > k_0$.

Question (Andersen–Masbaum–Ueno '06)

Do $\rho_{N,k}$ determine stretch factors of pseudo-Anosovs?

AMU: These are true for a sphere with four marked points.

Generalizing AMU

Theorem (Egsgaard, SFJ)

The AMU conjecture holds true for all $\rho_{N,k}^\lambda$ for homological pseudo-Anosovs $\varphi \in B_n$: those with only odd-pronged singularities in the marked points and even-pronged singularities in the other interior points. Furthermore, stretch factors may be determined as k-limits of eigenvalues of $\rho_{N,k}^\lambda$ for these pseudo-Anosovs.

Main steps in proof

- Recall that $\rho_{N,k}^\lambda \cong \eta_A^{n,d}$ for $A^4 = q = \exp(2\pi i/(k + N))$.
- The order of $\eta_A^{n,d}(\varphi)$ at a root of unity depends only on the order of the root.
- It suffices to show that the spectral radius of $\eta_A^\lambda(\varphi)$ is greater than 1 for an $A \in \mathrm{U}(1)$: Every $z \in \mathrm{U}(1)$ may be approximated by n'th roots of unity z_n (Iwaniec).

Generalizing AMU (continued)

Proof (continued).

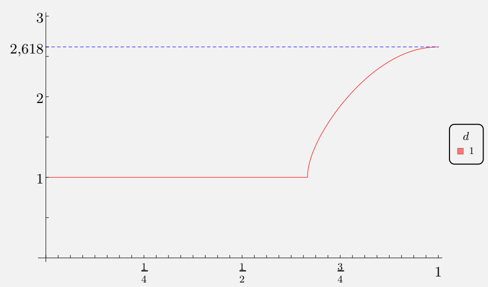
- Main result: $\eta_{\exp(\pi i/4)}^\lambda$ is essentially an exterior power of the lifted action on homology of the ramified double cover.
- The pseudo-Anosov φ lifts to a pseudo-Anosov $\tilde{\varphi}$ on the covering surface with the same stretch factor.
- The foliations of $\tilde{\varphi}$ have consistently orientable leaves. The stretch factor of such a pseudo-Anosov is the spectral radius of its action on homology.

□

Examples: Plots of spectral radii

For $\varphi \in B_n$, consider the functions $\mathrm{sr}_d(\varphi) : [0, 1] \to \mathbb{R}_+$

$$\mathrm{sr}_d(\varphi)(x) = \text{spectral radius of } \eta_A^{n,d}(\varphi) \text{ at } q = A^4 = \exp(\pi i x).$$



The pseudo-Anosov $\sigma_1\sigma_2^{-1} \in B_3$ (dashed line = stretch factor).

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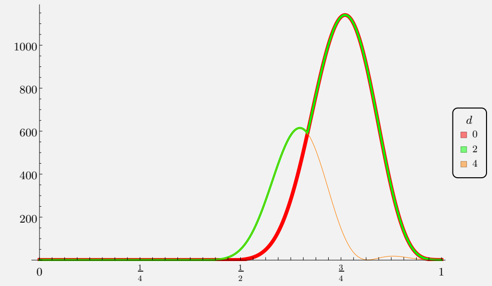

A pseudo-Anosov in B_6 acting trivially on homology (Brown).

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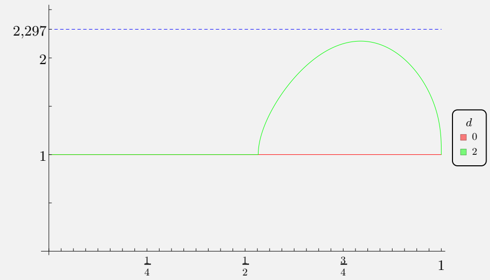

Small stretch factor, $\sigma_1\sigma_2\sigma_3^{-1} \in B_4$ (non-homological, Lanneau–Thiffeault).

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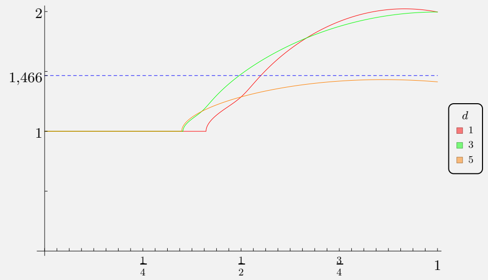
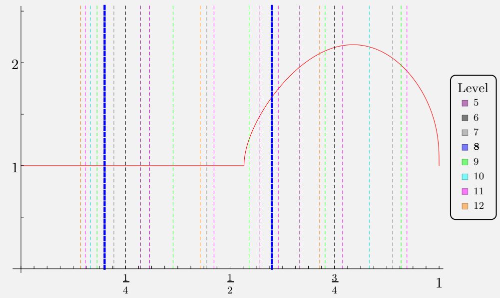


Small stretch factor, $\sigma_2^{-2}(\sigma_1 \cdots \sigma_6)^2 \in B_7$ (non-homological).

Concrete levels

We can read off at *which* levels, orders become infinite.



Plot for $d = 0$, $\sigma_1\sigma_2\sigma_3^{-1} \in B_6$; bold line is for SU(2) level $k = 8$.

Concrete levels

Theorem (Masbaum, '99)

Quantum representations have elements of infinite order for all levels k, except perhaps for $k = 1, 2, 4, 8$.

Proposition

Quantum representations have infinite order elements at level $k = 8$ as well.

A family of homological pseudo-Anosovs

Example (Penner)

- Assume n is even, and let $\sigma_1, \dots, \sigma_{n-1}$ be the standard generators of B_n.
- Take any word φ in the generators where the signs of powers correspond to the parity of the index.
- For example: $n = 6$, $\varphi = \sigma_1^2\sigma_2^{-4}\sigma_3^5\sigma_4^{-10}\sigma_5^{60}$.
- Suppose that each generator appears at least once in the word. Then φ is a homological pseudo-Anosov.