LQG as a TQFT with defects
New vacuum with a cosmological constant

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Based on work with B. Dittrich

Motivations

- ⋆ There are now different vacua (inequivalent quantum representations) for canonical LQG, spin foams, and group field theory (Ashtekar, Isham, Lewandowski; Koslowski, Sahlmann; Dittrich, MG)
- ⋆ How many vacua are there, how are they related, and what can they be used for?

Results

- ⋆ We extend the construction of the flat curvature BF vacuum to the case of $(2+1)$ Euclidean dimensions for $\Lambda > 0$ (in a sense the most peculiar case)
- ⋆ The conjectured underlying mathematical structure is that

$$\text{vacuum} \ + \ \text{excitations} \ = \ \text{TQFT} \ + \ \text{defects}$$

1. LQG as a TQFT with defects

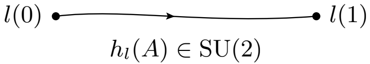
2. Contrasting the AL and BF representations

3. Constant curvature vacuum

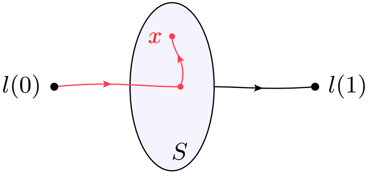
4. Conclusion and perspectives

Kinematical results

- ⋆ Boundary gravitational degrees of freedom: holonomies and fluxes encoding extrinsic and intrinsic spatial geometry



$$X^i_S(A,E) = \int_S h_{(0\to x)} E^i(x) h^{-1}_{(0\to x)}$$



- ⋆ Diffeomorphism-invariant Hilbert spaces supporting the holonomy-flux algebra
- ⋆ Derivation of quantum geometry (Ashtekar, Lewandowski; Rovelli, Smolin)
- ⋆ Vacuum tell us how to refine states and construct a kinematical continuum limit

Dynamical questions

- ⋆ How does a smooth diffeomorphism-invariant space-time emerge?
- ⋆ What is the phase diagram of our “discrete” gravity models?
- ⋆ What is a vacuum state?

Is LQG discrete or continuous?

- ⋆ Both, since we work on graphs or triangulations, but states live in $\mathcal{H}_\infty$
- ⋆ Field theory with arbitrary finite # of degrees of freedom = TQFT with defects

Classical kinematics as a TQFT with defects (Bianchi; Freidel, Ziprick, MG)

- ⋆ LQG phase space on a graph is $\mathcal{P}_\Gamma = \underset{\text{links}}{\times}\big(T^*\mathrm{SU}(2)\big)$
- ⋆ Same as that of gravity with almost-everywhere gauge-invariant flat connections

$$\mathcal{P}_\Gamma \simeq T^*\mathcal{A} /\!\!/ \big(\mathcal{F} \ltimes \mathcal{G}\big)_\Gamma$$

Which TQFT and which defects?

- ⋆ In the AL representation, $E=0$ and defects generate geometry
- ⋆ In the BF representation, $F(A)=0$ and defects generate curvature
- ⋆ Classically, these geometries are gauge choices in the reconstruction

$$\mathcal{P}_\Gamma \ni \big(h_l, X_S\big) \mapsto \big(A(x), E(x)\big) \in T^*\mathcal{A}$$

- ⋆ In the quantum theory, these vacua lead to inequivalent representations

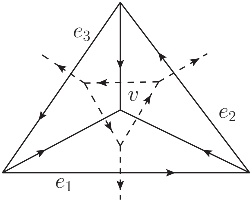
Contrasting the AL and BF representations

	AL	BF
background TQFT	$E = 0$	$F(A) = 0$
vacuum state	$\|\emptyset\rangle$ = nothing	$\|\emptyset\rangle = \prod_{\text{cycles}} \delta(g_c, \mathbb{1})$
excitations	holonomies $h_l \triangleright \|\emptyset\rangle = h_l$ dual graphs	exponentiated fluxes $R_i^h \triangleright \|\emptyset\rangle = \ldots \delta(g_i h, \mathbb{1}) \ldots$ $(d-1)$-simplices
defects	dual graphs	$(d-2)$-simplices
refinement	$j = 0$	flatness
measure	Haar	discrete
kin. C^∞ limit	✓	✓
generalization	background $E_\circ$	constant curvature $(\Lambda \neq 0)$

Other advantages of the BF representation

- ⋆ Deals for the first time successfully with the gauge-covariant fluxes $X(A,E)$
- ⋆ Diffeomorphisms as vertex displacement (in $2+1$)
- ⋆ Coarse-graining of the fluxes
- ⋆ Encode the interplay between curvature and torsion excitations

$$X_{e_3 \circ e_2 \circ e_1} \neq 0 \quad \text{if} \quad g_v \neq \mathbb{1}$$



Relation with point particles and quantum double structure

- ⋆ Exponentiated fluxes and gauge transformations respectively generate curvature and torsion excitations
- ⋆ In $(2+1)$ gravity coupled to point particles, curvature and torsion are related to mass and spin, and these label unitary irreps of the Drinfeld double DSU(2)

Constant curvature vacuum

Setup

- ⋆ $(2+1)$ spacetime dimensions with $\Lambda \neq 0$
- ⋆ It is known that quantum groups emerge in the quantum theory

What we will not (but could/should) do

- ⋆ Dynamical emergence: take flat SU(2) BF vacuum and solve $F[A] = \pm\Lambda(e \wedge e)$
- ⋆ Kinematical emergence: construct BF vacuum with non-commutative holonomies $h\big(A \pm \sqrt{\Lambda}e\big)$ (Noui, Perez, Pranzetti)

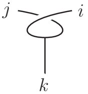
Strategy and goal

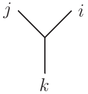
- ⋆ Assume quantum group structure from the onset
- ⋆ For Euclidean $\Lambda < 0$, we could construct a vacuum based on the deformed phase space $\mathrm{SL}(2,\mathbb{C}) \xrightarrow{\Lambda \to 0} \mathrm{ISU}(2)$ (Bonzom, Dupuis, Girelli, Livine)
- ⋆ For Euclidean $\Lambda > 0$, the quantum group is $\mathcal{U}_q\big(\mathfrak{su}(2)\big)$ at root of unity, the TQFT is known (Turaev, Viro), but there is no group picture!
- ⋆ We will show that the Turaev–Viro TQFT with defects is like a BF_Λ vacuum with excitations

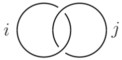
What we need to construct

1) A way of writing down and manipulating states (since there is no group picture)
2) A Hilbert space which contains flat states (vacuum) and excited states
3) A creation/excitation operator

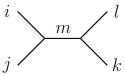
1) Writing and manipulating states: graphical calculus

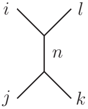
- ⋆ $\mathcal{U}_q\big(\mathfrak{su}(2)\big)$ at root of unity is a modular braided fusion category $\mathcal{C}$
  - Category: irreps given by spins $j \in \{0, 1/2, \dots, \mathrm{k}/2\}$, with $\mathrm{k} = \big(G_{\mathrm{N}}\hbar\sqrt{\Lambda}\big)^{-1}$
  - Fusion: there are fusion coefficients such that $i \otimes j = \bigoplus_k N_{ij}^k k$
  - Braided: there is an R-matrix such that 

$= R_k^{ij}$ 

  - Modular: $\det(S) \neq 0$ with $S_{ij} = \dfrac{1}{\mathcal{D}}$ 

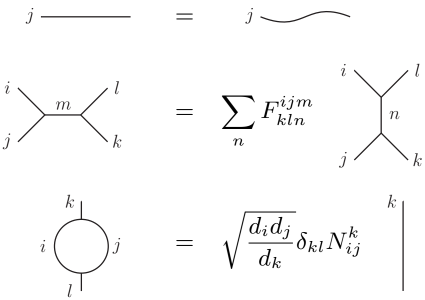
and $\mathcal{D}^2 = \sum_j d_j^2$
- ⋆ Dynamics (topological invariance) encoded in $\{6j\}_q$ symbol



$= \sum_n F_{kln}^{ijm}$


2) Ribbon graph Hilbert space

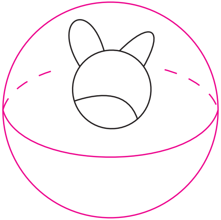
- ⋆ Consider a p-punctured $2d$ manifold Σ_p
- ⋆ A puncture is obtained by removing a disc and placing a marked point on $\partial\Sigma$
- ⋆ Allow for graphs in Σ_p to have one link ending at each puncture ●
- ⋆ Define $\mathcal{H}_p$ as the span of such graphs modulo the local equivalence relations



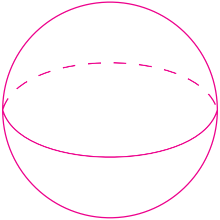
Constant curvature vacuum

Examples

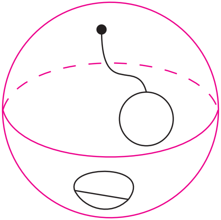
- 2-sphere with 0 punctures: $\dim \mathcal{H}_0 = 1$



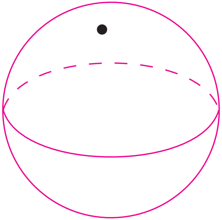
$=$ (some number) $\times$



- 2-sphere with 1 puncture: $\dim \mathcal{H}_1 = 1$

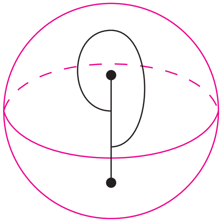


$=$ (some number) $\times$

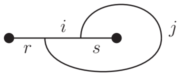


Examples

- ⋆ 2-sphere with 2 punctures ≃ topologically a cylinder
- ⋆ Non-trivial states corresponding to allowed spin labelings of

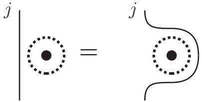


- ⋆ Introduce $\mathcal{Q}$ basis given by

$\mathcal{Q}^{ij}_{rs} =$ 

- ⋆ $\dim \mathcal{H}_2 = \sum_{ijrs} N^r_{ij} N^s_{ij}$ depends on the level k
- ⋆ Punctures can carry curvature (non-contractible cycles) and torsion (open links)
- ⋆ Graphs can be seen as dual to degenerate triangulations
- ⋆ Basis found for arbitrary topology and p with pants and tree decomposition

Vacuum state

- The vacuum is selected by two projections imposing (Levin, Wen)
  - Gauge-invariance: $B_v \triangleright \text{vertex}(i,j,k) = N_{ij}^{k}\ \text{vertex}(i,j,k)$
  - Flatness: $B_p \triangleright \bullet = \dfrac{1}{\mathcal{D}} \sum_j d_j \odot^{j} :=$ 
- These dotted (vacuum) lines have the property that 

  i.e. make the punctures invisible, i.e. remove the curvature that they carry
- In the SU(2) case, B_p becomes $\sum_j d_j \chi_j(g) = \delta(g)$
- If Γ is dual to a triangulation, one gets the Turaev–Viro invariant (Kirillov Jr.)

$$\langle \Gamma | \prod_{\text{faces}} B_p | \Gamma \rangle = \text{TV}\big(\Sigma \times [0,1]\big)$$

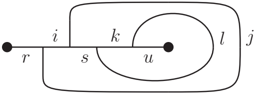
- The embedding map adds a puncture with no curvature, i.e. 

Constant curvature vacuum

The tube algebra

- ⋆ States $\mathcal{Q}$ on the cylinder (2-punctured 2-sphere) can be thought of as operators
- ⋆ Stacking two cylinders (matching the marked points) gives back a cylinder, and in terms of $\mathcal{Q}$'s this multiplication defines the tube algebra (Ocneanu; Müger)

$$\mathcal{Q}^{ij}_{rs}\mathcal{Q}^{kl}_{su} =$$



$$= \cdots = \sum_{mn} \alpha\big(F(\text{spins})\big)\,\mathcal{Q}^{mn}_{ru}$$

- ⋆ The $\mathcal{Q}$ states therefore define both a vector space and an algebra
- ⋆ The quasi-particle excitations we are looking for are representations of (or modules over) this algebra (Lan, Wen)
- ⋆ More precisely, we look for states ξ with a stability property $\mathcal{Q} \triangleright \xi = \xi$

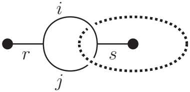
Remark: back to the group picture

- ⋆ Consider the idempotent (or projector) fluxes X_h such that $X_h X_{h'} = \delta_{hh'} X_h$
- ⋆ Gauge transformations act on the fluxes by conjugation, so $gX_h = X_{ghg^{-1}}g$
- ⋆ Then the algebra satisfies the multiplication rule of the Drinfeld double

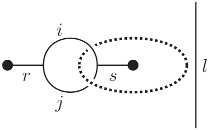
$$X_h g X_{h'} g' = \delta_{h,ghg^{-1}} X_h g g'$$

Quantum double

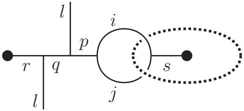
- ⋆ Irreducible representations of the tube algebra (or the category of modules) form a quantum double category $\mathcal{Z}(\mathcal{C})$, and because here $\mathcal{C}$ is modular, $\mathcal{Z}(\mathcal{C}) = \mathcal{C} \otimes \mathcal{C}^*$

- ⋆ Basis states $\mathcal{O}^{ij}_{rs} =$ 

satisfy the projection condition $\mathcal{O}\mathcal{O} \propto \mathcal{O}$, are orthonormal (König, Kuperberg, Reichardt), and are stable in the sense that



$$= \sum_{pq} \Omega^{ij}_{rp,ql}$$



- ⋆ The objects

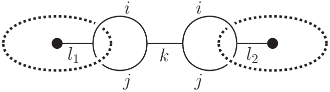
$$\Omega^{ij}_{rp,ql} = \sum_{mn} \sqrt{\frac{d_m d_n}{d_r d_l^2}} R^{il}_m R^{lj}_n F^{nmr}_{ijl} F^{qlp}_{ijm} F^{rlq}_{jmn}$$

are called half-braiding tensors and label elements of the quantum double $\mathcal{Z}(\mathcal{C})$

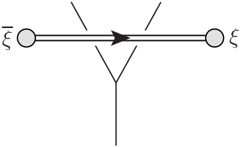
3) Excitations

- The excitation operators are given by the following oriented ribbons

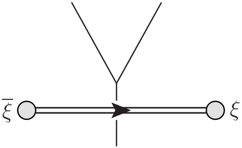
$$:= \frac{1}{\mathcal{D}^2}\sum_k \sqrt{\frac{d_k}{d_i d_j}}$$



- By definition, the half-braiding tensors have to satisfy so-called naturality conditions $\leftrightarrow$ fixed point conditions for the $\mathcal{Q}$ algebra $\leftrightarrow$ sliding property



$$=$$



- E.g., acting on the cylinder vacuum state  gives a basis state $\mathcal{O}^{ij}_{l_1 l_2}$
- Open/closed ribbon operators correspond respectively to fluxes/holonomies
- Automatically describes the Turaev–Viro model coupled to point particles

New framework and results

- New physical BF vacuum for SU(2) in $d = 2, 3$ spatial dimensions
- Full continuum Hilbert space supporting curvature excitations
- Allows for geometrical coarse graining of the fluxes
- New take on the dynamics and extraction of physics
- Same structures found in wider class of TQFTs with defects (allows $\Lambda \neq 0$)
- Establishes link with other areas (condensed matter, extended TQFTs)
- Right mathematical framework to describe fixed points of coarse-graining flow

Generalizations and applications

- Other quantum groups, signature, and signs of Λ
- Extension to $(3 + 1)$
- Dynamics of the defects (ILQGS by Wolfgang Wieland on April 5^{th})
- Non-commutative flux representation
- Non-compact gauge groups
- Cosmology
- Black holes