THERE AND BACK AGAIN: FROM THE BORSUK-ULAM THEOREM TO QUANTUM SPACES

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Joint work with
Paul F. Baum, Ludwik Dąbrowski and Tomasz Maszczyk

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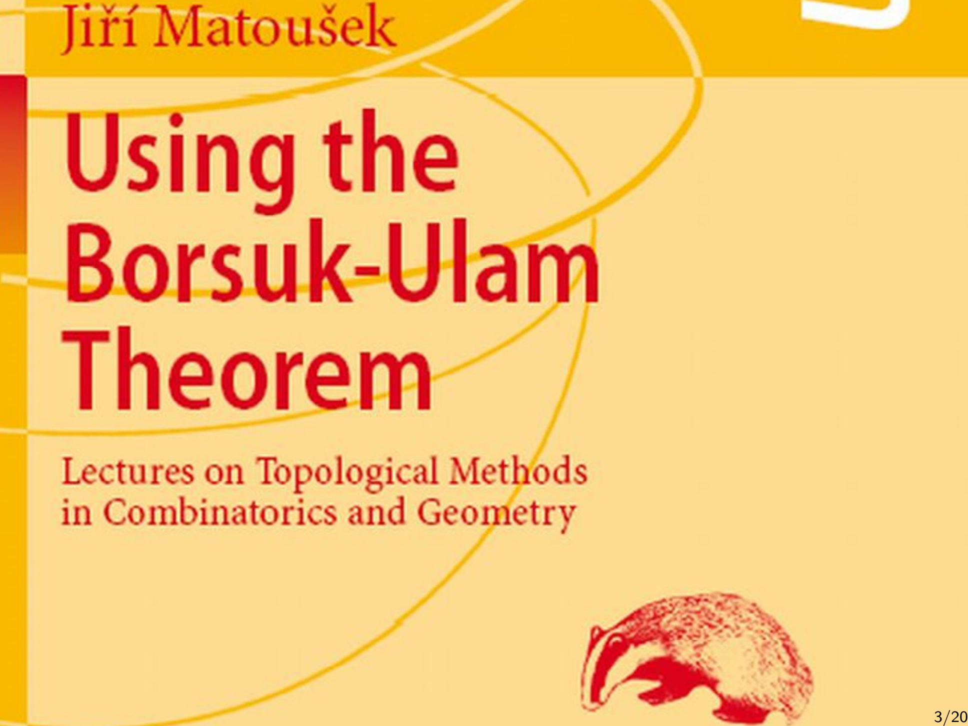
- Then, after riding swiftly through the Rohan of C*-algebras and Gelfand-Naimark Theorems and carefully avoiding the Mordor of incomprehensible technicalities, we shall arrive in the Gondor of compact quantum groups acting on unital C*-algebras.
- It is therein that the generalized Borsuk-Ulam-type statements dwell waiting to be proven or disproven.
- We end by paying tribute to the ancient quantum group $SU_q(2)$, and showing the non-trivializability of the $SU_q(2)$ compact quantum principal bundle $S_q^{4n+3} \to \mathbb{H}P_q^n$ defining noncommutative quaternionic projective spaces. This is the main result, which is a special case of the type II noncommutative Borsuk-Ulam conjecture.


Jiří Matoušek
Using the Borsuk-Ulam Theorem
Lectures on Topological Methods in Combinatorics and Geometry

The Borsuk-Ulam Theorem

Theorem (Borsuk-Ulam)

Let n be a positive natural number. If $f\colon S^n \to \mathbb{R}^n$ is continuous, then there exists a pair $(p, -p)$ of antipodal points on S^n such that $f(p) = f(-p)$.

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The logical negation of the theorem

There exists a continuous map $f\colon S^n \to \mathbb{R}^n$ such that for all pairs $(p, -p)$ of antipodal points on S^n we have $f(p) \neq f(-p)$.

The Borsuk-Ulam Theorem reformulated

For the antipodal action of $\mathbb{Z}/2\mathbb{Z}$ on S^n and $\mathbb{R}^n$, the latter statement is equivalent to:

Equivalent negation

There exists a $\mathbb{Z}/2\mathbb{Z}$-equivariant continuous map $\widetilde{f}\colon S^n \to S^{n-1}$.

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Indeed, if $f\colon S^n \to \mathbb{R}^n$ is a continuous map with $f(p) \neq f(-p)$, then the formula

$$\widetilde{f}(p) := \frac{f(p) - f(-p)}{\|f(p) - f(-p)\|}$$

defines a continuous $\mathbb{Z}/2\mathbb{Z}$-equivariant map from S^n to S^{n-1}.

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defines a continuous $\mathbb{Z}/2\mathbb{Z}$-equivariant map from S^n to S^{n-1}. Also, composing any such a map with the inclusion map $S^{n-1} \subset \mathbb{R}^n$ yields a nowhere vanishing continuous map $f\colon S^n \to \mathbb{R}^n$ with $f(-p) = -f(p) \neq f(p)$.

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Theorem (equivariant formulation)

Let n be a positive natural number. There does not exist a $\mathbb{Z}/2\mathbb{Z}$-equivariant continuous map $\widetilde{f}\colon S^n \to S^{n-1}$.

Famous corollaries

Theorem (The Brouwer Fixed Point Theorem)

Let n be any positive integer, and B^n be a ball of dimension n. Then every continuous map $f : B^n \to B^n$ possesses a fixed point.

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Theorem (The sandwich theorem)

Let n be any positive integer. Given n measurable "objects" in the n-dimensional Euclidean space, it is possible to divide all of them in half (with respect to their measure, i.e. volume) with a single $(n-1)$-dimensional hyperplane.

What is a compact quantum space?

Definition (concrete)

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Every commutative unital C-algebra is naturally isomorphic to the algebra of all continuous complex-valued functions on a compact Hausdorff space.*

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Copernican-style revolution

Given a compact Hausdorff space of points, we can define the C*-algebra of functions on the space, but the central concept is that of a commutative C*-algebras, and points appear as characters (algebra homomorphisms into $\mathbb{C}$) rather than as primary objects. We think of noncommutative unital C*-algebras as algebras of functions on compact quantum spaces.

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18–22 July 2016, the Fields Institute

GEOMETRY, REPRESENTATION THEORY AND THE BAUM-CONNES CONJECTURE

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Sponsored by:

- The Fields Institute, University of Toronto, Canada
- National Science Foundation, USA
- The Pennsylvania State University, USA

FIELDS

What is a compact quantum group?

Definition (S. L. Woronowicz)

A compact quantum group is a unital C^*-algebra H with a given unital $*$-homorphism $\Delta\colon H \longrightarrow H \otimes_{\min} H$ such that the diagram

$$\begin{tikzcd}
H \arrow[r, "\Delta"] \arrow[d, "\Delta"] & H \underset{\min}{\otimes} H \arrow[d, "\Delta\otimes\mathrm{id}"] \\
H \underset{\min}{\otimes} H \arrow[r, "\mathrm{id}\otimes\Delta"'] & H \underset{\min}{\otimes} H \underset{\min}{\otimes} H
\end{tikzcd}$$

commutes and the two-sided cancellation property holds:

$$\{(a\otimes 1)\Delta(b) \mid a, b \in H\}^{\mathrm{cls}} = H \underset{\min}{\otimes} H = \{\Delta(a)(1\otimes b) \mid a, b \in H\}^{\mathrm{cls}}.$$

Here "cls" stands for "closed linear span".

Free actions of compact quantum groups

Let A be a unital C^*-algebra and $\delta : A \to A \otimes_{\min} H$ a unital $*$-homomorphism. We call δ a coaction of H on A (or an action of the compact quantum group (H, Δ) on A) iff

1. $(\delta \otimes \mathrm{id}) \circ \delta = (\mathrm{id} \otimes \Delta) \circ \delta$ (coassociativity),
2. $\{\delta(a)(1 \otimes h) \mid a \in A,\, h \in H\}^{\mathrm{cls}} = A \otimes_{\min} H$ (counitality)
3. $\ker \delta = 0$ (injectivity).

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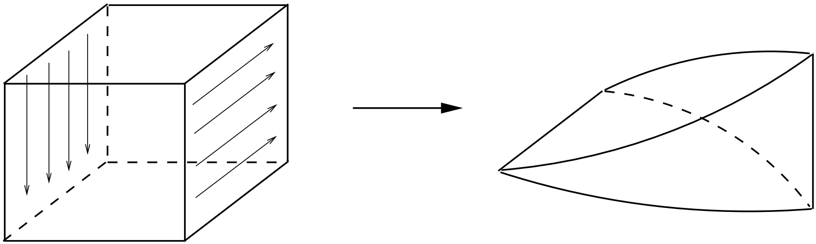
Definition (D. A. Ellwood)

A coaction δ is called free iff

$$\boxed{\{(x \otimes 1)\delta(y) \mid x, y \in A\}^{\mathrm{cls}} = A \underset{\min}{\otimes} H}\,.$$

Equivariant join construction

For any topological spaces X and Y, one defines the join space $X * Y$ as the quotient of $[0,1] \times X \times Y$ by a certain equivalence relation:



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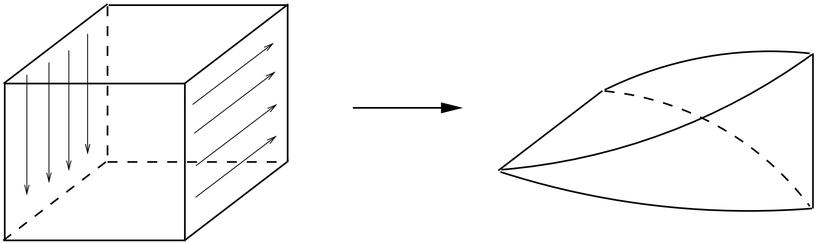

If X is a compact Hausdorff space with a continuous free action of a compact Hausdorff group G, then the diagonal action of G on the join $X * G$ is again continuous and free.

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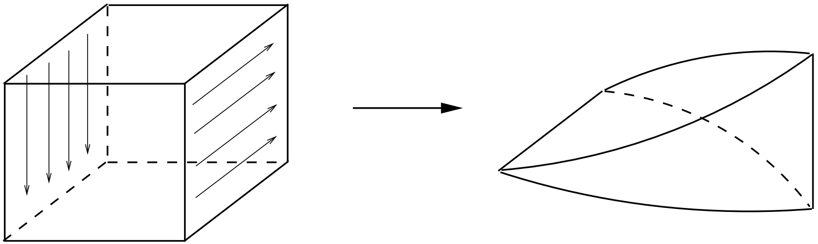

If X is a compact Hausdorff space with a continuous free action of a compact Hausdorff group G, then the diagonal action of G on the join $X * G$ is again continuous and free. In particular, for the antipodal action of $\mathbb{Z}/2\mathbb{Z}$ on S^{n-1}, we obtain a $\mathbb{Z}/2\mathbb{Z}$-equivariant identification $S^n \cong S^{n-1} * \mathbb{Z}/2\mathbb{Z}$ for the antipodal and diagonal actions respectively.

Gauged equivariant join construction

If $Y = G$, we can construct the join G-space $X * Y$ in a different manner: at 0 we collapse $X \times G$ to G as before, and at 1 we collapse $X \times G$ to $(X \times G)/R_D$ instead of X. Here R_D is the equivalence relation generated by

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More precisely, let R'_J be the equivalence relation on $I \times X \times G$ generated by

$$(0,x,h) \sim (0,x',h) \quad \text{and} \quad (1,x,h) \sim (1,x',h'),\ \text{where } xh = x'h'.$$

The formula $[(t,x,h)]k := [(t,x,hk)]$ defines a continuous right G-action on $(I \times X \times G)/R'_J$, and the formula

$$X * G \ni [(t,x,h)] \longmapsto [(t,xh^{-1},h)] \in (I \times X \times G)/R'_J$$

yields a G-equivariant homeomorphism.

Join formulation and classical generalization

Thus the Borsuk-Ulam Theorem is equivalent to:

Theorem (join formulation)

Let n be a positive natural number. There does not exist a $\mathbb{Z}/2\mathbb{Z}$-equivariant continuous map $\widetilde{f}\colon S^{n-1} * \mathbb{Z}/2\mathbb{Z} \to S^{n-1}$.

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This naturally leads to:

A classical Borsuk-Ulam-type conjecture

Let X be a compact Hausdorff space equipped with a continuous free action of a non-trivial compact Hausdorff group G. Then, for the diagonal action of G on $X * G$, there does not exist a G-equivariant continuous map $f : X * G \to X$.

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Corollary

Ageev's conjecture about the Menger compacta.

Equivariant noncommutative join construction

Definition (L. Dąbrowski, T. Hadfield, P. M. H.)

For any compact quantum group (H, Δ) acting freely on a unital C*-algebra A, we define its equivariant join with H to be the unital C*-algebra

$$A \overset{\delta}{\circledast} H := \left\{ f \in C([0,1], A) \underset{\min}{\otimes} H \;\middle|\; f(0) \in \mathbb{C} \otimes H,\ f(1) \in \delta(A) \right\}.$$

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Theorem (P. F. Baum, K. De Commer, P. M. H.)

*The *-homomorphism*

$$\mathrm{id} \otimes \Delta \colon\ C([0,1], A) \underset{\min}{\otimes} H \longrightarrow C([0,1], A) \underset{\min}{\otimes} H \underset{\min}{\otimes} H$$

defines a free action of the compact quantum group (H, Δ) on the equivariant join C-algebra $A \circledast^{\delta} H$.*

Noncommutative Borsuk-Ulam-type conjectures

Conjecture 1

Let A be a unital nuclear C*-algebra with a free action of a non-trivial compact quantum group (H, Δ). Then there does not exist an H-equivariant *-homomorphism $A \to A \circledast^{\delta} H$.

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The classical cases

If X is a compact Hausdorff principal G-bundle, $A = C(X)$ and $H = C(G)$, then Conjecture 2 states that the principal G-bundle $X * G$ is not trivializable unless G is trivial. This is clearly true because otherwise $G * G$ would be trivializable, which is tantamount to G being contractible, and the only contractible compact Hausdorff group is trivial.

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Iterated joins of the quantum $SU(2)$ group

Consider the defining fibration of the quaternionic projective space:

$$SU(2) * \cdots * SU(2) \cong S^{4n+3}, \quad S^{4n+3}/SU(2) = \mathbb{H}P^n.$$

To obtain a q-deformation of this fibration, we take $H = C(SU_q(2))$ and A equal to a finitely iterated equivariant join of H. The quantum principal $SU_q(2)$-bundle thus given is *not* trivializable:

Theorem (main)

*There does not exist a $C(SU_q(2))$-equivariant *-homomorphism $f\colon C(SU_q(2)) \to A \circledast^{\delta} C(SU_q(2))$.*

Iterated joins of the quantum $SU(2)$ group

Consider the defining fibration of the quaternionic projective space:

$$SU(2) * \cdots * SU(2) \cong S^{4n+3}, \quad S^{4n+3}/SU(2) = \mathbb{H}P^n.$$

To obtain a q-deformation of this fibration, we take $H = C(SU_q(2))$ and A equal to a finitely iterated equivariant join of H. The quantum principal $SU_q(2)$-bundle thus given is *not* trivializable:

Theorem (main)

*There does not exist a $C(SU_q(2))$-equivariant *-homomorphism $f\colon C(SU_q(2)) \to A \circledast^{\delta} C(SU_q(2))$.*

Proof outline: First, we prove that for any finite-dimensional representation V of a compact quantum group (H, Δ), the associated finitely-generated projective module $(H \circledast^{\Delta} H)\Box_H V$ is represented by a Milnor idempotent $p_{U^{-1}}$, where U is a matrix of the representation V. Then we choose V to be the fundamental representation of $SU_q(2)$, and infer from index paring considerations that $(H \circledast^{\Delta} H)\Box_H V$ is not stably free. Finally, by the Pulling Back Theorem, we conclude that $(A \circledast^{\delta} H)\Box_H V$ is *not* stably free, whence f does not exist . $\Box$

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