Advanced Course on Topological Quantum Field Theories

University of Almería (Spain), October 19th-23rd, 2009

Preface

This is the book of abstracts of the Advanced Course on Topological Quantum Field Theories held at the University of Almería, from October 19th to 23rd, 2009. This course was followed by the XVI Spanish Topology Meeting, from October 23rd to 24th, 2009.

The scientific program contained the following lecture series:

- *Frobenius algebras and 2D TQFTs*, by Joachim Kock (Universitat Autònoma de Barcelona).
- *TFT, RCFT and all that*, by Christoph Schweigert (Universität Hamburg).
- *TQFTs, operads and moduli spaces*, by Andrey Lazarev (University of Leicester).
- *TQFTs from the Kauffman bracket and Integral TQFTs*, by Gregor Masbaum (Institut de Mathématiques de Jussieu / Université Paris Diderot, Paris 7).
- *An introduction to Homotopy QFTs*, by Tim Porter (University of Wales, Bangor).

A poster session was also organized.

The course was organized by the University of Almería, under the sponsorship of the Spanish Topology Network (RET), the Ingenio Mathematica project (i-MATH), and the Spanish Ministry of Science and Innovation. It was offered as a complementary seminar in the Post-graduate Mathematics Programme of the Universities of Almería, Granada, Jaén, Málaga and Cádiz. Further collaboration was provided by the Faculty of Experimental Sciences, as well as the Department of Geometry, Topology and Organic Chemistry of our University. The social activities were partially financed by the Town Hall of Tabernas and the Tourism Department of the Town Hall of Almería.

Finally, we would like to express our gratitude to the scientific committee of the Spanish Topology Network, especially to its coordinator Carles Casacuberta, for their advice and support during the organization of this activity.

The organizing committee:

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Introduction to TQFTs

The study of Topological Quantum Field Theories (TQFTs) establishes new exciting relations between mathematics and physics connecting many of the most advanced ideas in topology, geometry and physics. On the one hand, the most sophisticated topological invariants of three and four-dimensional manifolds are encountered. On the other hand, the most recent achievements in Quantum Field Theory play a salient role especially in explicitly calculating these topological invariants. It is remarkable to observe that precisely these low dimensions in which Topology has shown to present important features are the dimensions where many interesting quantum field theories are renormalizable.

Though connections between Quantum Physics, Topology and Geometry can be traced back to the fifties, it is in the eighties when a new and unprecedented kind of relation between them took place. In 1982 E. Witten considered so-called supersymmetric sigma models in two dimensions and rewrote Morse theory in the language of Quantum Field Theory. Furthermore, he constructed out of those models a refined version of Morse theory nowadays known as Morse-Witten theory. Some years later A. Floer reformulated Morse-Witten theory providing a rigorous mathematical background.

This trend in which some mathematical structure is first constructed by Quantum Field Theory methods and then reformulated in a rigorous mathematical ground constitutes one of the tendencies in these new relations between Topology, Geometry and Physics. The influence of M. Atiyah on E. Witten in the fall of 1987 culminated with the construction by the latter of the first Topological Quantum Field Theory (TQFT) in January 1988. The Quantum Theory turned out to be a "twisted" version of supersymmetric Yang-Mills gauge theory. This theory, whose existence was conjectured by M. Atiyah, is related to Donaldson invariants for four-manifolds, and it is known nowadays as Donaldson-Witten theory.

In 1988 E. Witten formulated also two models which have been of fundamental importance in two and three dimensions: topological sigma models and Chern-Simons gauge theory. The first one can be understood as a twist of the supersymmetric sigma model considered by Witten in his work on Morse theory, and is related to Gromov invariants. The second one is not the result of a twist but a model whose action is the integral of the Chern-Simons form. In this case the corresponding topological invariants are knot and link invariants as the Jones polynomial and its generalizations. TQFTs provide a new point of view to study topological invariants of 3- and 4-dimensional manifolds.

Topological Quantum Field Theories are at the moment in the heart of fundamental research in mathematics being related to, among other things, knot theory and the theory of four-manifolds in Algebraic Topology, and to the theory of moduli spaces in Algebraic Geometry. Donaldson, Jones, Witten, and Kontsevich have all won Fields Medals for their work related to topological field theory and its relations to Topology and Geometry.

This advanced course emphasizes especially the interplay between Geometry, Topology and Physics and aims to engage PhD students and postdoctoral researchers in these new exciting developments together with international experts in the field.

Schedule

Monday 19

10:00 - 11:00	Reception, coffee
11:00 - 11:30	Opening ceremony
11:30 - 12:30	Joachim Kock
12:30 - 13:30	Joachim Kock
13:45 - 15:00	Lunch
15:30 - 16:30	Gregor Masbaum
16:30 - 17:00	Coffee break
17:00 - 18:00	Andrey Lazarev
21:00	Cocktail in Hotel Torreluz III

Tuesday 20

10:00 - 11:00	Joachim Kock
11:00 - 11:30	Coffee break
11:30 - 12:30	Joachim Kock
12:30 - 13:30	Christoph Schweigert
13:30 - 15:00	Lunch
15:30 - 16:30	Gregor Masbaum
16:30 - 17:00	Coffee break
17:00 - 18:00	Andrey Lazarev
18:15	Bus stop UAL: Conference bus to downtown
19:00	Guided visit to the Alcazaba. Meeting point “Puerta Purchena”

Wednesday 21

10:00 - 11:00	Gregor Masbaum
11:00 - 11:30	Coffee break
11:30 - 12:30	Christoph Schweigert
12:30 - 13:00	Christoph Schweigert
13:30 - 15:00	Lunch
15:30 - 16:30	Andrey Lazarev
16:30 - 17:30	Coffee break - Poster session (*)
17:30 - 18:30	Tim Porter

Thursday 22

09:00 - 10:00	Gregor Masbaum
10:00 - 11:00	Christoph Schweigert
11:00 - 11:30	Coffee break
11:30 - 12:30	Andrey Lazarev
12:30 - 13:30	Tim Porter
13:45 - 20:00	Visit to the western Fort Bravo / Plataforma Solar de Almería in Tabernas. Meeting point: Bus stop of the university

Friday 23 (additional information)

12:00 - 13:00	Public outreach talk by Jaume Aguadé (Universitat Autònoma de Barcelona): *Poincaré, Dalí, los 120 dodecaedros y la sonda espacial WMAP*

(*) POSTER SESSION:

Andrés Ángel: Cobordism of orbifolds

Boutheina Boutabia-Chéraitia: Scattering matrix in DKP theory: Barrier potential case

Krzysztof Kapulkin: Combinatorial approaches to the definition of opetope

Dorota Marciniak and Marcin Szamotulski: Total space of abelian gerbes

Luc Menichi: String topology of classifying spaces

Lectures series

Frobenius algebras and 2D TQFTs

Joachim Kock (Universitat Autònoma de Barcelona)

1. First two lectures: heuristics and formal definition of topological quantum field theory; the symmetric monoidal category nCob of cobordisms in dimension n; generators-and-relations presentation of 2Cob as a symmetric monoidal category.

2. Last two lectures: Introduction to Frobenius algebras, classical theory and graphical calculus; the 2D theorem characterising 2D TQFTs as commutative Frobenius algebras; some examples; some more categorical yoga, and the universal property of 2Cob.

TFT, RCFT and all that

Christoph Schweigert (Universität Hamburg)

1. In the first lecture, we reformulate the axioms of a two-dimensional topological field theory and present lattice topological field theories as examples.

2. In the second lecture, we review the compactified free boson as a motivating example for a two-dimensional rational conformal field theory.

3. In the last two lectures we formalize these lectures as a categorification of the structure of a lattice topological field theory.

TQFTs, Operads and Moduli Spaces

Andrey Lazarev (University of Leicester)

1. Formal structure of QFT and asymptotic expansion of finite-dimensional integrals.

   In this lecture we give an abstract formulation of a quantum field theory and consider its finite-dimensional model corresponding to the discrete spacetime. We show how the path integral formulation of QFT naturally leads to sums over Feynman diagrams.

2. Operads and topological conformal field theories.

   We describe how a string propagating in spacetime naturally leads one to consider Frobenius algebras; this is a simplest example of a topological conformal field theory. More sophisticated examples take into account the topology of the moduli spaces of Riemann surfaces. The underlying algebraic structure is that of an algebra over an operad and we discuss this notion in some detail.

3. Graph complexes.

   This lecture is devoted to graph complexes introduced by Kontsevich in the beginning of the 90's. These complexes are beautiful combinatorial structures; they are easy to define but very hard to compute with. We explain their relation to the homology of some infinite-dimensional Lie algebras and related geometric objects.

4. Modular operads.

   A modular operad is a notion introduced by Getzler and Kapranov some 10 years ago; it gives a proper homework encompassing graph complexes on the one hand and operads on the other. The most modular operads come from moduli spaces of various sort, hence the name. We consider examples and, if time permits, describe Feynman transforms of modular operads and algebras over them.

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TQFTs from the Kauffman bracket and Integral TQFTs

Gregor Masbaum (Institut de Math. de Jussieu / Univ. Paris Diderot, Paris 7)

According to Atiyah and Segal's axioms, a Topological Quantum Field Theory (TQFT) describes how to compute quantum invariants of 3-dimensional manifolds by cutting and pasting. This is the point of view we will take in this lecture series. In the first three lectures, I plan to explain the construction of TQFTs from the Kauffman bracket following [BHMV]. This is a very concrete approach to the Reshetikhin–Turaev $SU(2)$- and $SO(3)$-TQFTs which avoids quantum groups. (For the general story, see for example Turaev's book [Tu]. See also Witten [Wi] for the physicist's point of view.) In the last lecture, I will then focus on the $SO(3)$-TQFTs at odd primes which admit a natural integral structure [GM], meaning, for example, that we get representations of surface mapping class groups by matrices with integer coefficients. If time allows, I hope to discuss some applications of this as well.

Prerequisites for this lecture series: In the beginning, only elementary topology and algebra are needed. It will be helpful if students know a little bit of knot theory, such as how knot diagrams in the plane decribe knots in 3-space, and how to compute the linking number of two oriented knots in $\mathbb{R}^3$ (but we will review this at the beginning). Students who want to prepare more should study the construction of the Jones polynomial of knots from the Kauffman bracket. All of this can be found, for example, in [L] or [Ro]. In later lectures, some more topology will be needed, but I plan to explain it as we go along.

A rough plan of the lectures could be as follows.

1. Knots and knot diagrams. Kauffman bracket and Jones polynomial. Skein modules and Jones-Wenzl idempotents. Colored Jones polynomial. Extension to an invariant of colored trivalent graphs following [MV].

2. Kirby's theorem (how to describe 3-manifolds by knots and links.) Reshetikhin-Turaev invariant of closed 3-manifolds from the Kauffman bracket. Naïve definition of TQFT.

3. Brief discussion of signatures and Maslov indices. Extended cobordism category. Definition of the TQFT vector space $V_p(\Sigma)$ associated to a closed surface Σ and elementary TQFT-properties. Statement of main theorems: finite dimensionality, tensor product axiom [BHMV]. Some ideas of proofs.

4. Integral TQFT following [GM]: Some elementary number theory in the cyclotomic field $\mathbb{Q}(\zeta_p)$. Definition of the integral lattice $\mathcal{S}_p(\Sigma)$ inside $V_p(\Sigma)$. Main properties and some applications of Integral TQFT.

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An introduction to Homotopy QFTs

Tim Porter (University of Wales, Bangor)

1. Brief 'recall' of simplicial set theory (simplicial sets, simplicial groups, some examples from geometric topology, Moore complexes, homotopy groups etc., bundles and classifying spaces, $\overline{W}$, 'homotopy finite').

2. Crossed modules and crossed complexes; their relation with simplicial groups (2-types and generally n-types). Crossed modules and categorical groups (a special type of strict monoidal category). Nerves for crossed modules, etc. and their relationship with $\overline{W}$; Theorem of Bullejos and Cegarra.

3. Yetter's construction of TQFTs from a finite crossed module, extension to n-types (1997).

4. Relative theory (1998): $G \to H$ morphism of simplicial groups with sufficiently (homotopy) finite kernel, possibly interesting examples: essentially derived from $PL \to Top$, $O \to PL$, $Spin \to SO$ (other interesting cases???).

5. HQFT (Turaev 1998) then Rodrigues (2000), idea *an HQFT is a TQFT with 'background'*, Theorem of Rodrigues : HQFT based on d-dimensional manifolds with background B, depends only on the $(d+1)$-type of B :
Question: *take an algebraic model for an $(d+1)$-type, can we construct a HQFT with background its classifying space? And can we classify these HQFTs?*

6. Classification : Case 1 (Turaev) $B = K(\pi, 1)$, $d = 1$ solution crossed π-algebra.
   Case 2. (Brightwell-Turner, 2000) $B = K(A, 2)$, $d = 1$ solution Frobenius algebra with action of A.

7. $1 + 1$-dim FHQFT (so again $d = 1$) (Porter-Turaev, 2003-2005) Crossed $\mathcal{C}$-algebras.

8. Links with relative TQFT situations?

9. HQFTs classify what?

Plan: sections 1-4 in first session, the remainder in the second.

Poster session

Cobordism of Orbifolds

Andrés Ángel (Hausdorff Center for Mathematics, Bonn)

Abstract: Orbifolds are useful generalizations of manifolds that appear naturally in the study of moduli spaces. For example, Gromov-Witten invariants are suitable defined characteristic numbers of a moduli space of pseudo-holomorphic maps.

These characteristic numbers are invariant under cobordism and therefore is natural to try to understand the cobordism groups of orbifolds.

By resolving the singularities of an orbifold, we obtain decompositions of cobordism groups of orbifolds in terms of usual bordism theory, these decompositions involve information around the singularities and provide a way to define new invariants for orbifolds.

These cobordism groups are the coefficients of a new generalized homology theory on spaces, orbi-bordism.

Scattering matrix in DKP theory: Barrier potential case

Boutheina Boutabia-Chéraitia (University Badji Mokhtar-Annaba)

Abstract: We consider the interaction of the DKP (Duffin-Kemmer-Pétiau) particles (of spin 0 and 1) with a barrier potential. The problem is reduced to the FV (Feshbach-Villars) form indicating that there is a symmetry charge in the formailsm. We give the wave functions in both cases of spin 1 and spin 0. The coefficients of reflection and transmission are given and are identical. In this work we define a pseudo unitarity for the scattering matrix S, and we construct it. In case of the scalar particle, S becomes of dimension 4×4 identically to the case of FV.

Combinatorial approaches to the definition of opetope

Krzysztof Kapulkin (University of Warsaw)

Abstract: Opetopes are a natural class of algebraically or combinatorially defined shapes appearing in higher dimensional categories. They were first introduced by John Baez and James Dolan in [BD], but since then many authors have given alternative definitions (eg. [HMP], [L]). I would like to present these definitions, with special emphasis on the combinatorial approaches.

In particular I would like to survey [KJBM], [P], and [Z]. Some comparisons between those have been made — I will sketch some of the proofs. The last part is partially joint work in progress with Joachim Kock (Universitat Autònoma de Barcelona).

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Total space of abelian gerbes

Dorota Marciniak & Marcin Szamotulski
(Polish Academy of Sciences)

Abstract: *Abelian gerbes* as shown by R.Picken in '*TQFT and Gerbes*' naturally arise as *Topological Quantum Field Theories.* We want to present a generalization of the construction of a principal G-bundle from a one Čech cocycle to the case of higher abelian gerbes. We will prove that the sheaf of local sections of the associated bundle to a higher abelian gerbe is isomorphic to the sheaf of sections of the gerbe itself. Our main result states that equivalence classes of higher abelian gerbes are in bijection with isomorphism classes of the corresponding bundles. We also present topological characterization of these bundles. In the last section, we show that the usual notion of Ehresmann connection leads to the gerbe connection for higher $\mathbb{C}^*$-gerbes.

String topology of classifying spaces

Luc Menichi (University of Angers)

Abstract: Let G be a finite group or a compact connected Lie group and let BG be its classifying space. Let $\mathcal{L}BG := map(S^1, BG)$ be the free loop space of BG i.e. the space of continuous maps from the circle S^1 to BG. The purpose of this paper is to study the singular homology $H_*(\mathcal{L}BG)$ of this loop space. We prove that when taken with coefficients in a field the homology of $\mathcal{L}BG$ is a homological conformal field theory. As a byproduct of our main theorem, we get a Batalin-Vilkovisky algebra structure on the cohomology $H^*(\mathcal{L}BG)$. We also prove an algebraic version of this result by showing that the Hochschild cohomology $HH^*(S_*(G), S_*(G))$ of the singular chains of G is a Batalin-Vilkovisky algebra. This is a joint work with David Chataur.

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