BIRS 09w5095: Interactions of Geometry and Topology in dimensions 3 and 4

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1 Introduction

This workshop focussed on interactions between symplectic geometry, gauge theory, contact topology, and applications to low-dimensional manifolds. While each of these areas has been very active for many years in an independent fashion, the theory of low-dimensional manifolds has greatly benefited from interactions with the other subjects represented at the event. Our workshop was a follow-up to the BIRS event *Interactions of geometry and topology in low dimensions* from March of 2007. Because the fields are progressing at a rapid pace, there were many new and interesting results presented at the workshop.

Participants were selected from among the world experts in these areas. Organizers made an effort to balance interest between the different research areas and to ensure that the most important current trends were well represented. There was a good mixture of well-established researchers (Fintushel, Gordon, Kirby, Kronheimer, Livingston) and younger talented mathematicians (Grigsby, Hedden, Jabuka, Lekili, Ng). This stimulated many lively discussions and enabled a rich exchange of ideas in all directions.

2 Overview of the Field

In recent years collaborations between contact and symplectic geometers, gauge theorists, and low-dimensional topologists have been highly fruitful, leading to solutions to long-standing conjectures in topology, illuminating the world of contact and symplectic manifolds, and providing new perspectives on fundamental questions in low-dimensional topology.

For some time, gauge theory has provided geometric topologists with powerful techniques yielding spectacular results on the classification problem for 4-dimensional manifolds, including the early 4-manifold invariants of Donaldson, the Seiberg-Witten invariants, and Ozsváth-Szabó invariants. In each case, when applied to 4-manifolds with boundary, the invariants take values in the Floer homology groups of the bounding 3-manifold. These Floer homology groups are important 3-manifold invariants in their own right and have been applied to a variety of problems, such as knot theory and the structure of the homology cobordism group in dimension three. Frequently, these invariants are easier to compute in the presence of extra structure. For example, all the above mentioned invariants are non-zero for symplectic 4-manifolds. These non-vanishing results are instrumental in the interactions between contact and symplectic geometry and low-dimensional topology.

In 2001 P. Ozsváth and Z. Szabó introduced the Heegaard Floer homology groups. Their theory was motivated by Seiberg-Witten theory, but is defined in a completely different way: it is a variant of lagrangian Floer homology that uses much of the 3-manifold topology in its definition (in particular a Heegaard decomposition). In many instances, this new theory has been able to reprove fundamental results obtained in gauge theory over the last few decades and has also provided many new applications. One of its advantages is that there are powerful exact sequences enabling one to obtain hard topological information. For example, it was shown by Y. Ni that it detects if a knot in S^3 fibres, see also [Ni07]. This theory is conjecturally equivalent to Seiberg-Witten Floer homology by an analogue of the Atiyah-Floer conjecture, and a very interesting research program of Yi Jen Lee proposes an approach for proving this conjecture. Heegaard Floer homology is also closely related to the contact homology groups introduced by Y. Eliashberg, H. Hofer . For example, recent work of Taubes gives a correspondence between the embedded contact homology of Hutchings and Seiberg-Witten Floer theory, and using this correspondence Taubes managed to give a proof of the 3-dimensional Weinstein conjecture.

Emmanuel Giroux revolutionized contact geometry by proving an equivalence between contact structures on 3-manifolds up to isotopy and open book decompositions up to stabilization. Open book decompositions are a classical topological concept and have been studied for some time. This result is analogous to Simon Donaldson's proof that symplectic 4-manifolds always admit Lefschetz pencils, and the analogy is strengthened by Bob Gompf's proof that all Lefschetz pencils admit symplectic structures. Both these correspondences relate geometric concepts to topological ones and have been the foundation for many of the applications of symplectic geometry to questions in low-dimensional topology. For example, this correspondence leads to two notable results, namely Giroux and Noah Goodman's positive resolution of Harer's conjecture that all fibered knots in S^3 are related by Hopf plumbings, and Ozsváth and Szabó's proof of Gordon's conjecture that the unknot is the only knot on which p surgery yields the lens space $-L(p,1)$. The correspondence also has implications in the other directions as well. It is the basis of the non-vanishing of the Ozsváth-Szabó invariant of symplectic 4-manifolds mentioned above. It is also the key tool in Eliashberg and John Etnyre's proof that any symplectic filling of a contact manifold can be embedded in a closed symplectic manifold. This result in turn is an integral part of Peter Kronheimer and Tom Mrowka's proof of the Property P conjecture that a nontrivial surgery on a nontrivial knot in S^3 has nontrivial fundamental group or that $\mathbb{R}\mathrm{P}^3$ cannot be obtained by Dehn surgery along a non-trivial knot in S^3.

3 Highlights from the Workshop

A variety of geometric approaches to low-dimensional topology were represented, and several high-profile recent results in the field were featured prominently in the workshop. Here are a few key recent developments that were presented at the workshop: new invariants of knots and 3-manifolds coming from gauge theoretic constructions of Floer homology, results on existence of closed Reeb orbits related to the Weinstein conjecture in dimension 3, connections between contact homology and symplectic field theory, and the relationship between Heegaard-Floer and Khovanov homologies.

The recent results of Kronheimer-Mrowka [KM08a, KM08b] and Wehrheim-Woodward [WW09a, WW09b, WW09c] have brought considerable new interest to instanton and Lagrangian Floer homologies. In Kronheimer's talk, he outlined a program to prove the non-vanishing of Donaldson invariants for symplectic 4-manifolds with $b^+(X) > 1$, which implies strong constraints on the fundamental group of a 3-manifold along which such a 4-manifold might split. He also explained how sutured Floer homology can be used to give a simplified proof of Property P for all knots. In Wehrheim's talk, she outlined a program of using Lagrangian correspondences and quilted Floer homology to construct new invariants, such as an $SU(n)$ Floer homology for 3-manifolds. Both of these talks generated much interest and the ensuing discussions at the workshop continued to shed new light on Floer-theoretic invariants of 3-manifolds.

In [Ta07], Taubes surprised the world by proving the 3-dimensional Weinstein conjecture, which states that for any compact oriented 3-manifold M and α a contact 1-form on M, the vector field that generates the kernel of the 2-form $d\alpha$ has at least one closed integral curve. What was most surprising was the strategy of the proof, which was inspired by a 3-dimensional analogue of his result $SW = Gr$. That result suggests a deep correspondence between Seiberg-Witten Floer theory and embedded contact homology that is explained in [Ta08]. One of the highlights of the conference was Hutchings talk which explained how to obtain

improvements to the statement of the Weinstein conjecture using this deep correspondence (see [HT09]).

There were a number of highlights from the workshop in contact homology and symplectic field theory: Lenny Ng outlined a program to give a string theoretic interpretation to knot contact homology [Ng08], Vincent Colin extended contact homology to the setting of sutured contact manifolds, Tobias Ekholm explained how to use Legendrian contact homology to obtain constraints on Lagrangian fillings of Legendrian knots [Ek09], and Frederic Bourgeiois applied ideas from contact homology to analyze the dynamics of the Reeb flow on the 3-sphere.

Given a knot, in [OS05] Ozsváth-Szabó established the existence of a spectral sequence with E_2 term given by Khovanov homology and which converges to the Heegaard-Floer homology of the double branched cover of the knot. This line of research offers the promise of allowing for geometric interpretations of the combinatorially defined Khovanov homology, and it was the basis of a number of interesting talks at the conference, including the ones given by Grigsby, Plamenevskaya, and Watson.

There was also quite a bit of interaction between the subjects represented at the workshop in other areas, such as exotic actions on 4-manifolds [FSS09], knot concordance problems, combinatorial approaches to computing Heegaard-Floer homology, and symplectic forms on 4-manifolds [KT09].

4 Featured Talks

What follows is a list of the the 23 one-hour talks featured at the workshop. The central themes were:

- **new gauge theoretic invariants of knots and 3-manifolds via Floer theory.** *(Talks 13, 23)*
- **symplectic field theory, contact homology, applications (esp. Weinstein conjecture) .** *(Talks 1, 2, 5, 11, 17)*
- **Heegaard-Floer and/or Khovanov homology.** *(Talks 4, 9, 10, 11, 15, 18, 19, 21, 22)*
- **4-dimensional manifolds and invariants.** *(Talks 6, 7, 13, 14, 20)*
- **Knots, invariants, concordance.** *(Talks 8, 10, 12, 13, 16, 20, 21)*

Below is a detailed list of speakers, titles, and brief descriptions of their talks.

1. **Frederic Bourgeois** (Bruxelles) *On the Reeb dynamics of the tight 3-sphere*
   The differential of linearized contact homology was shown to vanish if and only if the Reeb field has exactly 2 simple closed orbits. Connections with a quantitative version of the Weinstein conjecture were discussed.

2. **Vincent Colin** (Nantes) *Contact homologies for sutured manifolds*
   In this talk, contact homology for contact manifolds with sutured boundaries were defined and gluing theorems were established. Also discussed were new invariants of Legendrian submanifolds, a characterization of product sutured manifolds, and a possible ECH characterization of fibered knots and of 3-manifolds which fiber over S^1.

3. **Nathan Dunfield** (Illinois) *Increasing the number of fibered faces of arithmetic hyperbolic 3-manifolds*
   A specific closed hyperbolic 3-manifold which satisfies a very strong form of Thurston's Virtual Fibration Conjecture was presented. The manifold M is known to be arithmetic and admits finite covers which fiber over the circle in arbitrarily many different ways. The origin of the basic fibration of M over the circle is the modular elliptic curve $E = X_0(49)$, which admits multiplication by the ring of integers of $\mathbb{Q}[\sqrt{-7}]$.

4. **Eaman Eftekhary** (IPM, Tehran) *Floer homology and existence of incompressible tori in homology spheres*
   This talk demonstrated that a prime homology sphere with the same Floer homology as the standard 3-sphere cannot contain any incompressible tori. The main ingredient is a splicing formula for knot complements which is derived using combinatorial formulation of Heegaard Floer homology.

5. **Tobias Ekholm** (Uppsala) *Rational SFT, linearized Legendrian contact homology, and Lagrangian Floer cohomology*
   This talk showed that the rational SFT of a Lagrangian filling of a Legendrian submanifold equals the linearized contact homlogy of the Legendrian submanifold linearized with resect to the augmentaion induced by the filling. Combining this with a version of Lagrangian Floer cohomology leads to an exact sequence which in special cases, including Legendrian knots in the 3-sphere, implies that the linearized Legendrian contact cohomology is isomorphic to the singular homology of the filling.

6. **Ron Fintushel** (MSU) *Exotic Cyclic Group Actions on Smooth 4-Manifolds*
   This talk presented infinite families of exotic actions of cyclic groups on many simply connected smooth 4-manifolds with nontrivial Seiberg-Witten invariants. For example, we can exhibit infinite families of pairwise equivariantly homeomorphic but not equivariantly diffeomorphic actions of $\mathbb{Z}/2, \mathbb{Z}/3$, and $\mathbb{Z}/4$ on the K3-surface.

7. **David Gay** (Cape Town): *Uniqueness of broken Lefschetz fibrations*
   A broken Lefschetz fibration is a map $X \to S^2$ from a 4-manifold which is generic from the point of view of singularity theory and does not have any definite fold singularities. Perutz and Lekili have shown how broken Lefschetz fibrations can lead to computable 4-manifold invariants, but in order to show that they are really invariant you need a uniqueness result. This talk reported on a result proved by Gay and Kirby at the workshop, and the precise statement is that two broken fibrations which lie in a same homotopy class of maps are related by a certain set of moves which include the set of move described by Lekili and one extra move.

8. **Cameron Gordon** (Texas, Austin) *Unsolvable problems about higher-dimensional knot groups*
   Fundamental groups of complements of various kinds of codimension 2 embeddings were considered and it was shown that, in general, the problem of deciding whether or not a group in one class belongs to a smaller class is algorithmically unsolvable. The cases that are open involve questions about groups of 2-knots in S^4.

9. **Julia Grigsby** (Columbia) *Khovanov homology, Sutured Floer homology, and Naturality*
   An algebraic relationship between the Khovanov homology of certain tangles in product sutured manifolds and the Heegaard Floer homology of their sutured double-branched covers was presented. This relationship implies that Khovanov's categorification of the reduced n-colored Jones polynomial detects the unknot whenever $n > 1$. Furthermore, certain TQFT operations (e.g., cutting and stacking) on the tangles correspond naturally to geometric operations (e.g., a generalized Hopf plumbing) on the sutured double-branched covers, and the algebraic connection between Khovanov and Heegaard-Floer homology behaves naturally with respect to these operations.

10. **Matthew Hedden** (MSU) *Relative adjunction inequalities for knot Floer homology and applications*
    Numerical invariants of knots in three-manifolds Y were defined in terms of the knot Floer homology filtration. These invariants serve to bound the genera of properly embedded surfaces in smooth four-manifolds bounded by Y.It was shown how to use the invariants to give obstructions to the existence of a complex curve (resp. symplectic surface) bounded by a given knot in a complex surface (resp. symplectic four-manifold). In certain special cases, the invariants may also detect the existence of such a complex curve, generalizing a result proved by the speaker two years ago in Banff at the workshop BIRS 07w5033.

11. **Michael Hutchings** (UC Berkeley) *Using $ECH = SWF$ to improve on the Weinstein conjecture*
    The isomorphism between embedded contact homology and Seiberg-Witten Floer homology was sued to obtain some improvements on the Weinstein conjecture. Namely, let Y be a closed oriented three-manifold with a contact form such that all Reeb orbits are nondegenerate. If Y is not a lens space, then there must be at least three Reeb orbits, and at least one of which is a non-elliptic Reeb orbit. The Weinstein conjecture was extended from contact forms to stable Hamiltonian structures on three-manifolds that are not torus bundles over the circle.

12. **Slaven Jabuka** (U. Nevada Reno) *Rational Witt classes and unknotting numbers*
    This talk presented a novel use of Witt rings to give lower bounds of the unknotting number of a knot.

13. **Peter Kronheimer** (Harvard) *Floer's instanton homology for knots*
This talk described Floer's instanton homology of knots, which had been defined 20 years ago, and ways to extract extra structure much like that discovered in Heegaard Floer knot homology. This approach gives new proofs of several results, among them a non-vanishing theorem for the Donaldson invariants of symplectic 4-manifolds and Property P for knots.

14. **Cagatay Kutluhan** (Michigan) *Seiberg-Witten Floer homology and symplectic forms on $S^1 \times M^3$*
Let M be a closed, connected, orientable 3-manifold. This talk outlines a study of the Seiberg-Witten Floer homology of M under the condition that $S^1 \times M$ admits a symplectic form. In particular, it was proved that M fibers over the circle if it has first Betti number 1 and $S^1 \times M$ admits a symplectic form with non-torsion canonical class.

15. **Yanki Lekili** (MIT) *Heegaard Floer homology of broken fibrations over the circle*
A program for identifying Perutz's Lagrangian matching invariants and Ozsváth-Szabó's Heegaard Floer invariants of three and four manifolds was outlined. As applications, new calculations of Heegaard Floer homology of certain classes of 3-manifolds and a proof of Floer's excision theorem in the context of Heegaard Floer homology were given.

16. **Chuck Livingston** (Indiana) *Low crossing number knots: concordance and the 4-genus*
This talk discussed progress towards a general concordance classification of low crossing number knots.

17. **Lenny Ng** (Duke) *Knot contact homology and string topology*
This talk reviewed the current state of affairs regarding knot contact homology and explained an interpretation of knot contact homology in terms of string topology.

18. **Olga Plamenevskaya** (SUNY Stony Brook) *Khovanov homology, open books, and tight contact structures*
Khovanov homology may be used to prove tightness or non-fillability of certain contact structures. When (Y, ξ) is the branched double cover of a transverse link L, the Ozsváth-Szabó spectral sequence from Kh(L) to HF(-Y) and the correspondence between a transverse element in $Kh(L)$ and the contact invariant of ξ in $HF(-Y)$ can be used to obtain tight (but not Stein fillable) contact structures.

19. **Andras Stipsicz** (Renyi Institute, Budapest) *Computation of Heegaard Floer homologies*
It was shown by using specific Heegaard diagrams that various versions of Heegaard Floer homology groups can be computed combinatorially, thus extending results of Sarkar and Wang.

20. **Saso Strle** (Ljubljana) *Surgeries on knots bounding definite manifolds*
An invariant of knots defined in terms of surgeries was presented along with computations for torus knots and applications.

21. **Dylan Thurston** (Columbia) *Bordered Heegaard-Floer homology*
This talk developed some of the algebra underlying the decomposition of planar grid diagrams and used it to give a useful model for an extension of Heegaard Floer homology to 3-manifolds with parametrized boundary called bordered Heegaard-Floer homology. This associates to every connected, parametrized surface a differential graded algebra, and to every 3-manifold with boundary a differential module over that algebra, well-defined up to quasi-isomorphism.

22. **Liam Watson** (UQAM) *Homological width and Dehn surgery*
The homological width in Khovanov homology was shown to provide obstructions to finding certain exceptional surgeries for strongly invertible knots.

23. **Katrin Wehrheim** (MIT) *SU(N) invariants for 3-manifolds via decomposition and Lagrangian correspondences*
A program for deriving invariants from Lagrangian correspondences via quilted Floer homology was described. For a 3-manifold Y, this gives an approach for defining the $SU(n)$ Floer homology groups of Y.

5 Scientific Progress Made

The workshop brought together leading experts from several different areas, and this sparked much scientific interaction. There were many very interesting talks proposed, and in making up the final schedule, the organizers tried to allow sufficient time for informal scientific discussions in order facilitate interactions between the subject areas. This was accomplished by scheduling enough break time throughout the talk timetable and some longer breaks during the day to encourage as much informal open-ended discussions as possible. The evenings provided collaborating teams of researchers time to meet and discuss their research projects.

There were a number of new results that were proved at the workshop or whose proof was stimulated by conversations held during the workshop. Some of these came out of long-term collaborative projects, others from newly formed collaborations, and some came from ideas stimulated by talks and other interactions at the workshop.

One exciting development was the proof worked out by David Gay and Rob Kirby in the days leading up to the workshop on uniqueness of broken Lefschetz fibrations. These are generic maps from a 4-manifold to S^2, and their result produces a sequence of moves that are sufficient to relate any two homotopic broken fibrations. David Gay and Rob Kirby both arrived in Banff a few days early and solved the problem shortly before presenting their result. On the last day of the workshop (actually on the shuttle ride to Calgary!), they figured out how to eliminate definite folds from the necessary moves, and this gives a considerable improvement. Their result is motivated by the work of Tim Perutz, and the potential application is to combine it with Tim Perutz's results to define and compute invariants of 4-manifolds from broken fibrations. The approach also dovetails naturally with the ideas of Katrin Wehrheim, and she is currently investigating the possibility of applying the technology of quilts and correspondences to better understand broken fibrations.

Frederic Bourgeois worked together with Tobias Ekholm on a joint project with Yasha Eliashberg, entitled "Legendrian surgery and linearized contact homology". Their discussions concentrated on the transversality issues (for moduli spaces of holomorphic curves) in this context, as well as in their consequences for the algebraic description of the theory. The goal was to establish invariance of linearized contact homology in the special situation of a contact manifold Y which is the convex end of a symplectic manifold X. An almost complex structure on X then determines an augmentation of the contact homology of Y, and their result is that the resulting linearized contact homology is invariant under deformations of X. This work in preparation.

Tobias Ekholm had fruitful discussions with Lenny Ng on the problem of correctly identifying parameters in two model spaces for conformal structures of the disk with boundary punctures and the computation of the "coherent orientation" sign of certain rigid holomorphic disks. These are important developments in the proof relating Lenny Ng's combinatorial knot contact homology to Legendrian contact homology and represent joint work with John Etnyre, Lenny Ng, and Michael Sullivan (in preparation).

Vincent Colin, Paolo Ghiggini, Ko Honda, and Michael Hutchings worked collaboratively at the workshop and made progress on their project to define sutured versions of contact homology and embedded contact homology at the workshop. At Banff they discussed the new invariants it should give for Legendrian knots and ways to prove that the invariant of the sutured manifold should be the "Hat version" of the contact homology of the corresponding closed manifold in the special case when the contact 3-manifold is bounded by a sphere and the suture on the sphere is connected. They have nearly completed writing the first of two papers and are just starting to write the second.

Another area of progress was stimulated by Dylan Thurston's talk on bordered Heegaard-Floer homology. His ideas led Denis Auroux to propose an alternative description of Lipshitz-Ozsváth-Thurston's construction [LOT08] in terms of Fukaya categories of symmetric products of open Riemann surfaces. This led to Denis Auroux to conceive of his project "Lefschetz fibrations on symmetric products and the algebra $\mathcal{A}(F)$," which represents work in progress. Building on the work of Denis Auroux described above, Robert Lipshitz, Peter Ozsvath and Dylan Thurston simplified their proof of a "Hom-pairing" theorem in bordered Floer homology. This gives a way of constructing the Heegaard Floer homology invariant for a closed 3-manifold from the invariant for two pieces, without involving much homological algebra. This will appear in their forthcoming paper [LOT09].

Matt Hedden and Yi Ni began a new collaborative project on manifolds with small Heegaard-Floer ranks. They proved a number of interesting results in their recent joint paper, which is posted on the ArXiv [HN09]. Also, Eamon Eftekhary discussed some aspects of his research project on Heegaard Floer homology of Seifert

fibered 3-manifolds with Yi Ni, and these results will appear in [Ef09].

Yanki Lekili used the ideas he learned from Peter Kronheimer's talk to derive an application of his earlier results toward proving the equivalence of sutured Floer homology constructions of Juhasz's and Kronheimer-Mrowka's. He worked this out during the conference and posted an update to his paper on the arXiv to include this new application.

Chuck Livingston and Swatee Naik worked together on problems related to the new perspective on the four-ball genus of a knot presented in Chuck Livingston's talk. An array of algebraic and analytic tools (some of which were described and elucidated in other talks at the workshop) apply in one direction and geometric constructions squeeze the problem from a different one. During the workshop, Chuck Livingston and Swatee Naik discovered new geometric results and this program of research is still under investigation.

Saso Strle realized based on conversations with other participants that the concordance invariant he presented in his talk might actually be subadditive. This would make it comparable to other concordance invariants, both classical (e.g. signature) and modern (e.g. tau invariant of Ozsváth-Szábo). In Banff he was able to verify subadditivity for the integral version of the invariant and is currently working (with Brendan Owens) on the corresponding result for the rational version.

During the workshop Steven Boyer and Cameron Gordon discussed and made good progress on their project on exceptional Dehn filling, and their results are the subject of forthcoming joint work with Xingru Zhang [BGZ09a, BGZ09b]. The goal is to analyze the situation where a hyperbolic 3-manifold has two Dehn fillings, one of which is a Seifert fiber space and the other is toroidal. In particular, one aim is to show that, apart from some explicit and well-known examples, the distance between the two fillings is at most 5. Steve Boyer and Cameron Gordon will soon be returning to Banff to work on this project for the BIRS Research in Teams: *Exceptional Dehn filling* (Oct 25 – Nov 1, 2009).

Eli Grigsby began a colloboration with Liam Watson at the workshop on the Berge conjecture, which specifies those knots in S^3 which admit Lens space surgeries. This project is currently under investigation. The article [Wa09] by Liam Watson can be said to have its origins at the Banff workshop, in the sense that it is based on the ideas presented in his talk and the finished article represents ideas he gleaned from the discussions it generated.

We conclude with a short bibliography that provide some recent articles relevant to the talks at the workshop. It is hoped that consulting these articles and the papers they refer to will enable one to gain a broad perspective on the various areas represented at the event.

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