Proceedings of Symposia in
PURE MATHEMATICS

Volume 82

Low-dimensional and Symplectic Topology

Michael Usher
Editors

American Mathematical Society

http://dx.doi.org/10.1090/pspum/082

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Michael Usher
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American Mathematical Society
Providence, Rhode Island

2009 GEORGIA INTERNATIONAL TOPOLOGY CONFERENCE

with support from the National Science Foundation,
grant DMS-0852505

2010 *Mathematics Subject Classification.* Primary 57–06, 20F36, 53D12, 53D35, 55P48, 57M25, 57M27, 57R17, 57R91.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Library of Congress Cataloging-in-Publication Data

Georgia International Topology Conference (2009 : University of Georgia)
Low-dimensional and symplectic topology : Georgia International Topology Conference, May 18–29, 2009, University of Georgia, Athens, Georgia / Michael Usher, editor.
p. cm. — (Proceedings of symposia in pure mathematics ; v. 82)
Includes bibliographical references.
ISBN 978-0-8218-5235-4 (alk. paper)
1. Low-dimensional topology—Congresses. 2. Manifolds (Mathematics)—Congresses. 3. Simplexes (Mathematics)—Congresses. I. Usher, Michael, 1978– II. Title.

QA612.14.G46 2009
514′.22—dc23

2011025453

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10 9 8 7 6 5 4 3 2 1   16 15 14 13 12 11

To Clint McCrory
on the occasion of his retirement.

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Preface

The 2009 Georgia International Topology Conference was held at the University of Georgia in Athens, Georgia, from May 18-29, 2009. This event, attracting 222 participants from around the world, continued a longstanding tradition of major international topology conferences held in Athens every eight years since 1961.

The two main goals of the conference were to give wide exposure to new and important results, and to encourage interaction among graduate students and researchers in different stages of their careers. The conference featured 39 plenary talks aimed at a general audience of topologists by distinguished speakers from around the world, touching on breakthroughs in such topics as hyperbolic geometry, geometric group theory, symplectic and contact topology, Heegaard Floer theory, and knot theory, among others. There was also a session of informal presentations by graduate students during the weekend, as well as six evening introductory lectures by leading experts, aimed at graduate students, on a variety of topics in low-dimensional, contact, and symplectic topology. Slides for most of the talks remain available on the internet, at http://math.uga.edu/~topology/2009/schedule.htm.

A problem session was also held near the end of the conference, and a report on it is included in these proceedings. The other articles in the proceedings represent an array of survey and original research articles related to the topics discussed in the conference. I am grateful to both the authors of these articles and to the referees for the efforts that they have contributed toward the publication of the volume.

The conference was organized by Michael Ching, William Kazez, Gordana Matić, Clint McCrory and myself. The speakers were selected with the assistance of our Scientific Advisory Committee, consisting of Simon Donaldson, Yakov Eliashberg, David Gabai, Rob Kirby, Bruce Kleiner, Dusa McDuff, Dennis Sullivan, Cliff Taubes and Karen Vogtmann. The conference also benefited greatly from logistical support provided by Julie McEver, Connie Poore, Gail Suggs, Laura Ackerley, and Christy McDonald. Finally, the organizers are very grateful to the National Science Foundation (grant DMS-0852505) and to the University of Georgia for support which made the conference possible.

M.U.
June 2011

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Proceedings of Symposia in Pure Mathematics
Volume **82**, 2011

Open problems in geometric topology

Abstract. This is a report on the problem session that was held near the end of the conference on May 28, 2009, based on notes taken by Michael Usher and Dylan Thurston. The problem session was moderated by John Etnyre, Peter Kronheimer, Peter Ozsváth, and Saul Schleimer.

Contents

1. Knot theory
2. The mapping class group and other problems about groups in geometric topology
3. Three-manifolds
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5. Manifold topology in general dimensions
6. Symplectic topology
7. Contact topology
References

1. Knot theory

Problem 1.1 (K. Baker). *When do homotopic knots K_1 and K_2 in a given 3-manifold Y have identical-coefficient surgeries which are homeomorphic? When does it additionally hold that the dual knots K_1^* and K_2^* are homotopic?*

Problem 1.2 (K. Baker). *Given a rational number p/q, does there exist an infinite family $\{K_i\}_{i=1}^{\infty}$ with the property that the p/q-surgeries $S^3_{p/q}(Y_i)$ are mutually homeomorphic, independently of i?*

Osoinach [**Os**] produced examples with $p/q = 0/1$, and Teragaito [**Te**] modified Osoinach's construction to give examples with $p/q = 4/1$ and $S^3_4(K_i)$ a Seifert fibered space; however the problem for other coefficients remains open. [**Ki**, 3.6(D)] asks whether $S^3_{p/q}(K_i)$ can be arranged to be a homology sphere.

Problem 1.3 (J. Bloom). *Does Khovanov homology detect Conway mutation* [**Con**] *of knots?*

2010 *Mathematics Subject Classification.* 57Mxx, 57Q45, 57R17, 20F65.

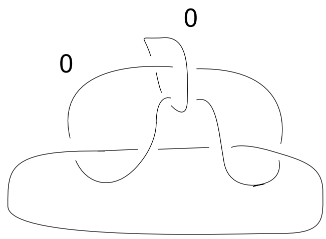

FIGURE 1. Does HFK detect this knot?

The Jones polynomial (of which Khovanov homology is a categorification) is invariant under mutation, as are the colored Jones and HOMFLYPT polynomials. Wehrli [**We1**] gave an example in which the Khovanov homology of a *link* changes under mutation. However, Bloom [**Bl**] has shown that, for knots, odd Khovanov homology is mutation-invariant, which in particular shows that (as was also proven by Wehrli [**We2**]) the Khovanov homology with $\mathbb{F}_2$-coefficients is unchanged under mutation.

PROBLEM 1.4 (D. Ruberman, following J. Cha). *Do there exist parts of classical knot theory which cannot be seen by Heegard Floer theory? Possible candidates include the Alexander* module *and higher-order signatures.*

Of course, the Alexander *polynomial* manifests itself as the graded Euler characteristic of HFK; the classical signature is closely related to the τ invariant [**OzSz1**].

PROBLEM 1.5 (P. Ozsváth). *It's known* [**OzSz3**] *that knot Floer homology detects the unknot. Does it also detect the knot in* $\#^{2n}S^1 \times S^2$ *given as the* n*-fold connect sum of the "Borromean" knot given by the surgery diagram in Figure 1? This knot is distinguished as the only fibered knot of genus* n *in any manifold with the fundamental group of* $\#^{2n}S^1 \times S^2$*, generalizing the unknot which corresponds to the case* $n = 0$.

1.1. Knot concordance.

PROBLEM 1.6 (C. Leidy–S. Harvey). *In the Cochran–Orr–Teichner filtration* [**COT**] *of the smooth knot concordance group, what is the structure of the groups* $\mathcal{F}_{n.5}/\mathcal{F}_{n+1}$ $(n \in \mathbb{N})$*?*

These groups have not yet even been shown to be nontrivial. By contrast, as was discussed in S. Harvey's talk at the conference, for each n the group $\mathcal{F}_n/\mathcal{F}_{n.5}$ has been shown to contain many different subgroups isomorphic to $\mathbb{Z}^\infty$ [**CHL1**] and to $\mathbb{Z}_2^\infty$ [**CHL2**]. One would also like to know the status of certain particular types of knots in the filtration; for instance:

PROBLEM 1.7 (C. Leidy–S. Harvey). *Can* 2*-torsion be found in the groups* $\mathcal{F}_n/\mathcal{F}_{n.5}$ *by infecting (see* [**CHL2**, Section 2]*) ribbon knots by negative amphichiral knots.*

All of the torsion that has so far been found in $\mathcal{F}_n/\mathcal{F}_{n.5}$ (for $n \geq 1$) is 2-torsion arising from constructions involving infection by negative amphichiral knots. In light of this, one might ask:

PROBLEM 1.8 (J. Cha). *Is it possible to detect the fact that a knot is "infected" by the fact that it represents* 2*-torsion in* $\mathcal{F}_n/\mathcal{F}_{n.5}$*?*

PROBLEM 1.9 (C. Leidy–S. Harvey). *Is there any two-torsion in $\mathcal{F}_n/\mathcal{F}_{n.5}$ that doesn't arise from infection by negative amphichiral knots?*

PROBLEM 1.10 (C. Leidy–S. Harvey). *For $n \geq 1$, is there any k-torsion in $\mathcal{F}_n/\mathcal{F}_{n.5}$ with $k \neq 2$? In particular, bearing in mind that a result of Levine* [**Le**] *implies that $\mathcal{F}_0/\mathcal{F}_{0.5} \cong \mathbb{Z}^\infty \oplus \mathbb{Z}_2^\infty \oplus \mathbb{Z}_4^\infty$, is there 4-torsion for $n \geq 1$?*

The *rational* knot concordance group is by definition that group generated by knots in rational homology spheres under the connect sum operation, with two such considered equivalent if they are related in the obvious way by a rational homology cobordism, see [**Cha**].

PROBLEM 1.11 (J. Cha). *Understand in detail the map from the standard knot concordance group to the rational concordance group induced by inclusion.*

Not much is known about this, though [**Cha**, Theorem 1.4] finds infinite subgroups of both the kernel and the cokernel.

1.2. Higher-dimensional knot theory.

PROBLEM 1.12 (D. Ruberman). *Let $K \subset S^4$ be a 2-knot, and suppose that $\pi_1(S^4 \setminus K)$ has finitely generated commutator subgroup. Is K fibered? As a special case, if $\pi_1(S^4 \setminus K) \cong \mathbb{Z}$, is K the trivial 2-knot?*

A result of Stallings [**St**] shows that this holds for knots in S^3.

PROBLEM 1.13 (D. Ruberman). *Is every link in S^4 (or more generally in S^{2n}) slice?*

Equivalently (in light of results from [**Ke**] showing that every even-dimensional knot is slice), is the link concordant to a "boundary link" (one whose components each bound disjoint "Seifert surfaces")? In all odd dimensions, Cochran–Orr [**CoO**] (and, later and by a different method, Gilmer–Livingston [**GiL**]) found infinitely many concordance classes of links not containing any boundary links.

2. The mapping class group and other problems about groups in geometric topology

PROBLEM 2.1 (S. Schleimer). *Can Heegaard Floer homology be used to obtain information about the conjugacy problem in the mapping class group of a Riemann surface?*

Here "the conjugacy problem" refers to the problem of, given two elements in the group, determining if they are conjugate. Hemion [**He**] gave a combinatorial algorithm to solve the problem, though without any reasonable complexity bound. As discussed in her lecture at the conference, Hamenstadt [**Ham**] has shown that mapping class groups admit biautomatic structures, which implies an exponential bound on the length of a conjugating element. For pseudo-Anosov elements Masur-Minsky [**MaM2**] show that the problem can be solved in linear time.

PROBLEM 2.2 (S. Schleimer). *How much geometry does Heegaard Floer homology see? For instance, for a pseudo-Anosov mapping class ϕ, consider the mapping tori $M(\phi^n)$ of iterates of ϕ. Is there a relationship between the growth of $rk(\widehat{HF}(M(\phi^n)))$ and the growth of geometric quantities associated to $M(\phi^n)$? Geometrically, $M(\phi^n)$ converges as $n \to \infty$ to a doubly-degenerate manifold, but what happens to $HF^\bullet(M(\phi^n))$?*

PROBLEM 2.3 (T. Mrowka). *Where again $M(\phi)$ denotes the mapping torus of a mapping class ϕ, does $HF^{\bullet}(M(\phi))$ measure a geometric notion of the complexity of ϕ?*

PROBLEM 2.4 (T. Hall). *Prove or disprove the Andrews–Curtis conjecture* [**AnCu**]. *Could any new invariants help distinguish whether a given presentation yields the trivial group?*

This conjecture asserts that if $\langle x_1, \ldots, x_n | r_1, \ldots, r_n \rangle$ is a presentation of the trivial group, then this presentation can be reduced to the trivial presentation $\langle x_1, \ldots, x_n | x_1, \ldots, x_n \rangle$ by a sequence of the following four types of moves: inverting r_i; interchanging r_i with r_j; conjugating r_i by some word; and replacing r_i by $r_i r_j$. Of course, presentations correspond to 2-handlebodies, and the last move listed naturally corresponds to a handleslide. The consensus guess is that the conjecture is probably false. Certain proposed counterexamples would give interesting candidates for exotic S^4's [**GoS**, Remark 5.1.11].

3. Three-manifolds

PROBLEM 3.1 (P. Kronheimer). *Let Y be any closed 3-manifold which is not diffeomorphic to S^3. Does there always exist a nontrivial representation*

$$\rho\colon\ \pi_1(Y) \to SU(2)?$$

Note that Kronheimer-Mrowka's celebrated proof of Property P for knots [**KrM1**] rested on showing that the answer is affirmative when Y is obtained by $+1$-surgery on a knot other than the unknot (strictly speaking, that paper replaced $SU(2)$ by $SO(3)$), and indeed any Y obtained by Dehn surgery on a nontrivial knot with rational coefficient $r \in [-2, 2]$ has fundamental group admitting a representation to $SU(2)$ with non-cyclic image [**KrM2**].

PROBLEM 3.2 (P. Ozsváth). *If Y is an integer homology 3-sphere and $\widehat{HF}(Y) = \mathbb{Z}$, must Y be a connected sum of Poincaré homology spheres?*

PROBLEM 3.3 (Y. Ni). *Can we use Heegaard Floer homology to study specific Heegaard splittings of a given 3-manifold? Or, more broadly, to obtain invariants of a closed surface in a 3- or 4-manifold?*

Analogously to a construction in Khovanov homology, one could probably obtain invariants of surfaces in $\mathbb{R}^4$; however, the relevant invariants in Khovanov homology have been shown to depend only on the genus of the surface [**Ca**].

PROBLEM 3.4 (S. Schleimer). *Given a hyperbolic 3-manifold, classify its Heegaard splittings.*

This appears to be a rather hard problem, as so far a classification exists only for the exteriors of two-bridge knots [**Ko**] (and hence also for their large surgeries in light of a result of [**MoR**]). Even estimating the Heegaard genera of hyperbolic manifolds tends to be somewhat difficult, but see the survey [**So**] for some results in this direction.

PROBLEM 3.5 (S. Schleimer). *How does the Heegaard genus of a manifold with torus boundary behave under Dehn filling?*

If the manifold is hyperbolic and the surgery coefficient is large then the Heegaard genus does not change [**MoR**]. Additional results for more general 3-manifolds appear in [**RiS1**],[**RiS2**].

PROBLEM 3.6 (S. Schleimer). *Give a practical method for computing the Hempel distance associated to a given Heegaard surface.*

If $Y = H_i \cup_\Sigma H_2$ is a Heegaard splitting, the Hempel distance $d(\Sigma)$ is the minimal distance in the curve complex from a compressing disk for Σ in H_1 to a compressing disc for Σ in H_2. One can obtain bounds on the Hempel distance based on the genera of certain other surfaces in Y (*e.g.*, [**Har**], [**ScT**]), but specific computations tend to be difficult.

PROBLEM 3.7 (S. Schleimer). *Consider the "sphere complex" $\mathbb{S}_n$, whose simplices given by disjoint systems of certain spheres in $\#n(S^1 \times S^2)$ (see* [**Hat**]*). Is $\mathbb{S}_n$ δ-hyperbolic?*

$\mathbb{S}_n$ is the splitting complex of the free group F_n, and has been useful in studying the automorphism group of F_n, see [**Hat**],[**HaV**]. Analogously, the curve complex (with simplices given by disjoint systems of curves in $\#n(S^1 \times S^1)$) is δ-hyperbolic by a famous result of Masur-Minsky [**MaM1**].

PROBLEM 3.8. *Is there a categorification of the Reshitikhin–Turaev invariants of* 3*-manifolds?*

Such a categorification could be viewed as a version of Khovanov homology [**Kh**] for 3-manifolds. Note that Cautis–Kamnitzer [**CaKa**] have categorified the Reshitikhin-Turaev tangle invariants associated to the standard representation of $\mathfrak{sl}(m)$.

PROBLEM 3.9 (P. Ozsváth–T. Mrowka). *Find a categorification for (any or all versions* [**Fl**],[**KMOS**, Theorem 2.4],[**OzSz2**, Theorem 1.7] *of) Floer's exact triangle, or prove that no such theory can exist.*

This appears challenging in part because the appropriate cobordism maps generally commute only up to homotopy.

PROBLEM 3.10 (P. Ozsváth). *Develop methods for computing various flavors of Floer homology.*

While the Sarkar–Wang algorithm [**SaW**] computes the version $\widehat{HF}$ of Heegaard Floer homology, other variants (including HF^+, which is needed in the construction of four–manifold invariants) did not admit known algorithmic descriptions at the time of the problem session. A few months later, the preprint [**MOT**] appeared, giving algorithms for the computation of the $\mathbb{Z}/2$-versions of all the Heegaard Floer groups and the four–manifold invariants; however these algorithms are still rather inefficient. Naturally, one would also like to have additional effective methods for computing monopole or instanton Floer homologies.

PROBLEM 3.11 (R. Lipshitz). *To what extent are Floer-theoretic invariants continuous with respect to appropriate notions of convergence of spaces (* e.g.*, Gromov–Hausdorff limits of hyperbolic* 3*-manifolds, larger-and-larger-coefficient surgeries on a given knot in a* 3*-manifold, higher-and-higher order cabling...)?*

4. Four-manifolds

PROBLEM 4.1 (P. Kronheimer). *In the Barlow surface, can the Poincaré dual of the canonical class be represented by a smoothly embedded, genus two surface? More generally, in any of the other symplectic* 4*-manifolds that have been constructed more recently which are homeomorphic but not diffeomorphic to* $\mathbb{C}P^2 \# k\overline{\mathbb{C}P^2}$ *(*e.g.*,* [**AkPa**],[**PPS**]*), is the Poincaré dual of the canonical class represented by a smoothly embedded surface of genus* $10 - k$*?*

For instance, a connected symplectic representative of the Poincaré dual of the canonical class would necessarily have the desired genus. Taubes' $SW = Gr$ equivalence [**Ta1**] provides a smoothly embedded (though not always connected) symplectic representative of the Poincaré dual of the canonical class of a symplectic four-manifold with $b^+ > 1$; however the manifolds in question have $b^+ = 1$ so the story is more complicated for them. For those small exotic manifolds which admit a complex structure (such as the Barlow surface and that in [**PPS**]), the fact that $b^+ = 1$ implies that one has $p_g = 0$, so there is no holomorphic representative of the Poincaré dual of the canonical class. Meanwhile, [**LL**, Corollary 2] shows that these manifolds admit symplectic representatives of *twice* the Poincaré dual of the canonical class in all cases.

PROBLEM 4.2 (P. Kronheimer). *Let* X *be, say, the* $K3$ *surface, and let* X' *be some fake (homotopy equivalent but not diffeomorphic) copy of* X*, with* $\phi\colon X \to X'$ *a homotopy equivalence. Compare* $Diff_0(X)$ *to* $Diff_0(X')$*.*

For instance, in the diagram

$$\begin{array}{ccc} Diff_0(X) & & \\ & \searrow & \\ & & Map(X,X), \\ & \nearrow_{\phi^*} & \\ Diff_0(X') & & \end{array}$$

do $Diff_0(X)$ and $Diff_0(X')$ have the same image on π_n for all n?

In a somewhat different vein, the behavior of finite subgroups of the diffeomorphism group of a homotopy $K3$ surface is quite sensitive to the smooth structure [**ChKw**].

PROBLEM 4.3 (J. Etnyre). *Given a smooth* 4*-manifold* X *and a class* $A \in H_2(X;\mathbb{Z})$*, let* $g(A, X)$ *denote the minimal genus of any smoothly embedded surface representing* A*. Under what circumstances can one find a smooth manifold* X' *homeomorphic to* X *and with* $g(A, X') < g(A, X)$*? In particular, can this ever be done with* X *equal to the* $K3$ *surface?*

Using the adjunction inequality (see, *e.g.*, [**GoS**, Theorem 2.4.8]) and standard surgery operations, it's not difficult to find examples where an exotic $K3$ surface has *larger* minimal genus function than does the $K3$ surface, but the adjunction inequality suggests that it would be difficult to decrease the minimal genus function without some new tools.

PROBLEM 4.4 (T. Mrowka). *Let X_K denote the result of knot surgery* [**FiS2**] *on the $K3$ surface using a knot K which has Alexander polynomial $\Delta_K = 1$. Is the minimal genus function $g(\cdot, X_K)$ the same as that for the $K3$ surface?*

The assumption that $\Delta_K = 1$ ensures that the Seiberg–Witten invariant of X_K is the same as that of the $K3$ surface, so the adjunction inequality cannot shed any light on this question. Relatedly, consider:

PROBLEM 4.5 (D. Auckly). *Suppose that X and X' are homeomorphic and that the minimal genus functions $g(\cdot, X)$ and $g(\cdot, X')$ coincide. Are X and X' diffeomorphic?*

PROBLEM 4.6 (D. Auckly). *Does there exist an exotic smooth structure on the 4-torus T^4?*

Part of what causes this to be a challenging problem given current techniques is that many of the surgery operations that are often used to produce exotic 4-manifolds (*e.g.*, [**FiS2**]) would, when applied to T^4, result in a change in the fundamental group. Note that for all $n \geq 5$ exotic T^n's do exist ([**HsS**],[**HsW**],[**Wa**]).

PROBLEM 4.7 (P. Kronheimer). *Given a natural number $p \geq 2$, let B_p denote the rational ball arising in Fintushel-Stern's rational blowdown construction* [**FiS1**]. *For which p does B_p embed into the quintic surface?*

PROBLEM 4.8 (J. Etnyre, following R. Fintushel-R. Stern). *If X_1 and X_2 are two homeomorphic smooth closed four-manifolds, can one be obtained from the other by a sequence of surgeries on nullhomologous tori?*

For instance, the knot surgery operation [**FiS2**] can be described as a sequence of such surgeries. Also, for every $2 \leq k \leq 8$ an there is an infinite collection of exotic $\mathbb{C}P^2 \# k\overline{\mathbb{C}P^2}$'s that can be obtained by surgery on a single nullhomologous torus in a certain homotopy $\mathbb{C}P^2 \# k\overline{\mathbb{C}P^2}$ (for $5 \leq k \leq 8$ this was shown in [**FiS3**], and a few months after the conference a different construction for $2 \leq k \leq 7$ was presented in [**FiS4**]).

PROBLEM 4.9 (J. Etnyre). *Suppose that X_1 and X_2 are a pair of homeomorphic smooth four-manifolds which are related by a sequence of surgeries on nullhomologous tori. Since X_1 and X_2 are homeomorphic, there is a (by definition contractible)* Akbulut cork *$W \subset X_1$ and an involution $\Phi\colon \partial W \to \partial W$ so that $X_2 = (X_1 \setminus W) \cup_\Phi W$* [**Mat**],[**CHMS**]. *Is it possible to explicitly identify W?*

5. Manifold topology in general dimensions

PROBLEM 5.1 (M. Hogancamp, following M. Hill). *Give an explicit construction of a 62-manifold with Kervaire invariant one. Then generalize this to construct a 126-manifold with Kervaire invariant one.*

An old result of Browder [**Br**] showed that the Kervaire invariant vanishes for all manifolds of dimension not of the form $2^k - 2$. There are explicit examples of Kervaire-invariant-one manifolds in dimensions 2, 6, 14, and 30 [**Jo**], while in dimension 62 the behavior of the Adams spectral sequence implies [**BJM**] that a Kervaire-invariant-one manifold must exist, but no such manifold has yet been constructed. As M. Hill discussed in his talk at the conference, recent landmark work of Hill–Hopkins–Ravenel [**HHR**] proves that the Kervaire invariant vanishes in all dimensions larger than 126, leaving 126 as the only dimension for which the problem is unresolved. Hill suggests that the constructions would likely be related to the Lie groups E_7 and E_8.

PROBLEM 5.2 (Y. Rudyak). *Let $f\colon M^n \to N^n$ be a degree-one map from one closed oriented manifold to another. Must it hold that*

$$cd(\pi_1(M)) \geq cd(\pi_1(N))?$$

Here cd denotes cohomological dimension. In the case where $cd(\pi_1(M)) = 1$ (which is to say that $\pi_1(M)$ is free) the answer is affirmative by Theorem 5.2 of [**DrRu**].

PROBLEM 5.3 (Y. Rudyak). *For a closed manifold M let $crit(M)$ denote the minimal number of critical points of a smooth function on M, and let $cat(M)$ denote the Lusternik-Schnirelmann category of M. If $crit(M) \geq crit(N)$, does it follow that $cat(M) \geq cat(N)$?*

By definition, $cat(M)$ is one less than the minimal possible size of a cover of M by contractible open subsets. Note that $crit(M) \geq cat(M) + 1$; however there are many examples where the inequality is strict.

6. Symplectic topology

PROBLEM 6.1 (Y. Rudyak). *What groups arise as the fundamental groups of closed symplectically aspherical manifolds? In particular, does there exist a group Γ with the property that, for every $n \in \mathbb{Z}_{>0}$, there is a closed symplectically aspherical manifold M^{2n} of dimension $2n$ with $\pi_1(M^{2n}) = \Gamma$?*

Recall that a symplectic manifold (M, ω) is called symplectically aspherical provided that, for every $A \in \pi_2(M)$, one has $\int_A \omega = 0$ (some conventions additionally require that $\langle c_1(TM), A\rangle = 0$ for all $A \in \pi_2(M)$).

In particular if M is closed, it can't be simply connected, since if it were the Hurewicz theorem would force ω to be exact and then Stokes' theorem would prevent ω from being nondegenerate. By passing to covers, one sees additionally that $\pi_1(M)$ cannot be finite. A variety of results and examples relating to the problem can be found in [**IKRT**] and [**KRT**]. Among finitely generated abelian groups G, [**KRT**, Theorem 1.2] shows that G is the fundamental group of a symplectically aspherical manifold iff $G = \mathbb{Z}^2$ or $rk(G) \geq 4$.

PROBLEM 6.2 (P. Kronheimer). *Does every simply-connected, non-spin symplectic 4-manifold contain a Lagrangian $\mathbb{R}P^2$?*

Of course, the fact that the normal bundle of a Lagrangian submanifold is isomorphic to its tangent bundle shows that a Lagrangian $\mathbb{R}P^2$ necessarily has $\mathbb{Z}_2$-intersection number 1, and in particular $\mathbb{R}P^2$ cannot arise as a Lagrangian submanifold of $\mathbb{R}^4$, or of any simply-connected spin manifold.

PROBLEM 6.3 (K. Wehrheim, following L. Polterovich). *Let T denote the following monotone Lagrangian torus, considered as a submanifold of $S^2 \times S^2 \subset \mathbb{R}^3 \times \mathbb{R}^3$:*

$$T = \{(\vec{v}, \vec{w}) \in S^2 \times S^2 | \vec{v} \cdot \vec{w} = -1/2,\ v_3 + w_3 = 0\}.$$

*Is T displaceable (*i.e.*, is there a Hamiltonian diffeomorphism $\phi\colon S^2 \times S^2 \to S^2 \times S^2$ such that $\phi(T) \cap T = \varnothing$)?*

In the months following the conference, this question was answered **negatively** by Fukaya, Oh, Ohta, and Ono [**FOOO**, Remark 3.1]. Note that, where Δ is the diagonal, $S^2 \times S^2 \setminus \Delta$ can be identified with T^*S^2, and under this identification T corresponds to a Lagrangian submanifold of T^*S^2 which had earlier been shown [**AlFr**] to nondisplaceable. Recent work of Chekanov and Schlenk [**CheS**] constructs nondisplaceable Lagrangian "twist tori" in $(S^2)^n$, and in the case that $n = 2$ it seems likely that T is equivalent to such a twist torus, which would give another proof of its nondisplaceability. Yet another proof of the nondisplaceability of T is outlined in the recent preprint [**ElP**].

PROBLEM 6.4 (K. Wehrheim, following L. Polterovich). *Moving up a dimension from the previous question, is the monotone Lagrangian submanifold*

$$L = \{(\vec{u}, \vec{v}, \vec{w}) \in S^2 \times S^2 \times S^2 | \vec{u} + \vec{v} + \vec{w} = 0, \vec{u} \cdot \vec{v} = \vec{v} \cdot \vec{w} = -1/2\}$$

displaceable in $S^2 \times S^2 \times S^2$.

In light of recent developments, note that if L is equivalent to a twist torus [**CheS**], then it would be nondisplaceable.

PROBLEM 6.5 (K. Wehrheim). *(When) can Lagrangian submanifolds in symplectic quotients be lifted? In other words, given a Hamiltonian action of a Lie group G on a symplectic manifold (M, ω) with moment map $\mu\colon M \to \mathfrak{g}^*$, and given a Lagrangian submanifold ℓ of the symplectic reduction $\mu^{-1}(0)/G$, is there a Lagrangian submanifold $L \subset M$ which meets $\mu^{-1}(0)$ transversely and so that projection $\mu^{-1}(0) \to \mu^{-1}(0)/G$ restricts as a diffeomorphism $L \cap \mu^{-1}(0) \to \ell$? If ℓ is monotone, can L also be taken to be monotone?*

There are simple examples where the answer is no; for instance the reduction of the standard rotation action of S^1 on S^2 is a point, and setting ℓ equal to this point we note that no Lagrangian $L \subset S^2$ meets the equator $\mu^{-1}(0)$ transversely in just one point. For the standard S^1 action on $\mathbb{C}P^2$ (with quotient $\mathbb{C}P^1$) one has $\mu^{-1}(0) = S^3$ with projection given by the Hopf map, and the answer is again no. However, it's conceivable that the construction could work for the action of S^1 on a blowup of $\mathbb{C}P^2$.

More broadly, one would like to have a better general understanding of Lagrangian submanifolds of symplectic manifolds with Hamiltonian group actions.

7. Contact topology

PROBLEM 7.1 (J. Etnyre). *Given a Legendrian knot K in a tight contact* 3-*manifold Y, is the contact manifold resulting from Legendrian surgery on K necessarily tight?*

If Y is allowed to have boundary, a tight contact structure on the genus-four handlebody shows that the answer is no [**Ho**, Theorem 4.1]. However, the closed case remains unresolved. Note that a number of important contact topological properties of closed 3-manifolds are preserved by Legendrian surgery, such as weak [**EtH2**], strong [**Wei**], and Stein [**El2**] fillability, and nonvanishing of the Ozsváth-Szabó contact invariant [**LS1**].

PROBLEM 7.2 (J. Etnyre). *If L_1 and L_2 are two Legendrian knots in S^3 which are* not *Legendrian isotopic, can the respective Legendrian surgeries on them be contactomorphic?*

For any n, there is a tight contact manifold (M_n, ξ_n) containing distinct Legendrian knots $L_1, \ldots, L_n$ so that Legendrian surgery on the L_i produce the same contact manifold [**Et**, Corollary 2], but as yet there are no examples with $M_n = S^3$.

Problem 7.3 (J. Etnyre). *Which closed 3-manifolds admit tight contact structures? In particular, do all hyperbolic 3-manifolds admit tight contact structures?*

Etnyre-Honda [**EtH1**] showed some years ago that the Poincaré homology sphere Σ admits no tight contact structures compatible with its nonstandard orientation (and hence that the connect sum $\Sigma \# \overline{\Sigma}$ admits no tight contact structures at all). More recently Lisca-Stipsicz [**LS2**] determined precisely which Seifert fibered spaces admit tight contact structures. In the class of hyperbolic manifolds, not much is known beyond some isolated examples (for instance the Weeks manifold admits a tight contact structure).

Problem 7.4 (J. Etnyre). *Which odd-dimensional manifolds admit contact strucutures?*

The fact that every 3-manifold admits a contact structure goes back to Martinet [**Mar**]. In higher dimensions, at least if the contact structure is to be cooriented, there is a topological obstruction arising from the fact that, if the manifold has dimension $2n+1$, the structure group needs to reduce to $U(n)$ (such a reduction is called an *almost contact structure*). In dimensions 5 and 7, this translates to the requirement that the second Stiefel-Whitney class should admit an integral lift. Geiges (see [**Ge**, Chapter 8]) has shown that any almost contact structure on an oriented simply connected 5-manifold arises from a contact structure, thus reducing the existence question on simply-connected 5-manifolds to characteristic classes. For more results in dimension 5 and 7 see [**GeTh**],[**GeSt**]. In dimensions above 7 very little is known; the existence of a contact structure on T^{2n+1} for every n was only established in 2002 [**Bo1**].

Problem 7.5 (J. Etnyre). *Understand the space of contact structures on a given manifold.*

Eliashberg [**El3**, Theorem 2.4.2] showed that the space of tight contact structures on S^3 which are fixed at a given point is contractible. On the other hand, Geiges-Gonzalo [**GeGo**] found, for each member of the standard sequence ξ_n of tight contact structures on T^3, an element of infinite order in the fundamental group of the space of contact structures based at ξ_n. Infinite subgroups of some other homotopy groups of spaces of contact structures were subsequently found by Bourgeois [**Bo2**]. Ding-Geiges [**DiGe**] have recently shown that the fundamental group of the space of contact structures on $S^1 \times S^2$ (based at the standard tight one) is $\mathbb{Z}$.

With respect to overtwisted contact structures, Eliashberg [**El1**] showed that, given an overtwisted disk Δ in a contact 3-manifold (M, ξ), the space of overtwisted contact structures on M coinciding with ξ near Δ is homotopy equivalent to the space of 2-plane fields coinciding with ξ near Δ. Thus, up to homotopy, understanding the space of overtwisted contact structures on a given manifold is essentially a classical (albeit nontrivial) matter.

Problem 7.6 (L. Ng). *Formulate "embedded sutured contact homology" for Legendrian knots.*

Recall here that the complement of a Legendrian knot has a standard description as a sutured manifold, and so has an associated sutured (Heegaard) Floer homology which is isomorphic to its knot Floer homology [**Ju**]. Meanwhile, embedded contact homology has recently been proven to be isomorphic to monopole Floer homology [**Ta2**]. Thus the putative embedded sutured contact homology should be isomorphic to knot Floer homology (or at any rate the monopole version thereof [**KrM3**]) and may lead to some interesting links between the contact homology world and the Heegaard Floer world.

Legendrian knots do have a Legendrian contact homology [**Che**] constructed in the spirit of symplectic field theory; however, this invariant vanishes for stabilized Legendrian knots, in contrast to the Legendrian knot invariants constructed from Heegaard Floer theory as in [**OzSzT**].

Since the conference, a version of sutured embedded contact homology has been defined [**CGHH**], though certain foundational questions, such as independence of the choice of auxiliary data, remain unresolved.

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