Invitation to the Arbeitsgemeinschaft at Oberwolfach:

Arnold Conjecture and Floer Homology

organized by Dietmar Salamon and Matthias Schwarz

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Symplectic Geometry has seen a rapid development since the 80's with the discovery of rigidity phenomena like the non-squeezing theorem based on Gromov's seminal theory of pseudo-holomorphic curves. A directly related development was Floer's method of using Morse theory in a new way, known as Floer homology, in order to solve the Arnold conjecture. In the 60's Arnold formulated his conjecture based on Poincaré's so-called "Last Geometric Theorem" proven by G. D. Birkhoff, about the existence of at least two fixed points of area preserving homeomorphisms of the annulus rotating the boundary circles in different directions. Arnold put his conjecture in the following terms, [A2]: *Any Hamiltonian diffeomorphism of a compact symplectic manifold has at least as many fixed points as a smooth function on this manifold has critical points.* Under the additional assumption that all fixed points are non-degenerate, a generic property, this conjecture was modified to

$$\#\,\mathrm{Fix}\,\phi \geqslant \sum_i \mathrm{rk}\,H_i(M)\,.$$

Moreover, there is a corresponding variant in terms of intersections of Lagrangian submanifolds giving a priori lower bounds on the minimal number of intersection points provided that one Lagrangian is a Hamiltonian deformation of the other and meets some additional conditions. This variant is a direct generalization of the version for symplectic fixed points when considering the graphs of the Hamiltonian diffeomorphism and of the identity in the symplectic manifold $(M \times M, \omega \oplus (-\omega))$. For the symplectic fixed points, one can relate the non-degenerate Arnold conjecture to the Lefschetz fixed point theorem in the same way as Morse theory with the Poincaré-Hopf theorem. The Arnold conjecture for non-degenerate symplectic fixed points has now been proved in full generality. It was first confirmed by Eliashberg [E] for Riemann surfaces and then by Conley and Zehnder [CZ1] for the $2n$-torus. In [G] Gromov proved the existence of at least one fixed point under the assumption $\pi_2(M) = 0$. The breakthrough came when Floer established the Arnold conjecture for Lagrangian intersections, and hence symplectic fixed points, again under the assumption $\pi_2(M) = 0$. In a series of papers [F1, F2, F3, F5] Floer combined the variational approach of

Conley and Zehnder with the elliptic techniques of Gromov and the Morse-Smale-Witten complex to develop his infinite dimensional approach to Morse theory which is now called Floer homology. This work culminated in the paper [F4], where Floer proved the non-degenerate Arnold conjecture for monotone symplectic manifolds. Floer's proof was extended by Hofer-Salamon [HS] and Ono [Ono] to the weakly monotone case, and recently by Fukaya-Ono [FO], Liu-Tian [LT] to the general case.

Originally, Floer devised his homology groups as obtained from a chain complex generated by the fixed points in question. This first step is to prove the chain complex property. This established, the second step is to understand the homology of this complex and to show that it is isomorphic to the (co-)homology of the closed symplectic manifold, thus providing *a posteriori* the conjectured existence result for the fixed points. Subsequently, Floer homology has been shown to carry a plentitude of additional structures. In [Sch2], a natural ring structure, the so-called pair-of-pants product, was established and shown to give a Frobenius structure together with a non-degenerate pairing. In [PSS], this Frobenius structure was shown to be isomorphic to the (small) quantum cohomology ring of the symplectic manifold.

Floer homology does not only apply to Hamiltonian diffeomorphisms, but to general symplectic diffeomorphisms ϕ as was observed by Floer and taken up later by Dostoglou-Salamon [DS2, DS1] in connection with the Atiyah-Floer conjecture [S3] and by Seidel in his thesis [Se2]. Donaldson observed that the pair-of-pants product extends to a natural product structure $\cup_F\colon HF(\phi) \otimes HF(\psi) \to HF(\phi \circ \psi)$ and in the Lagrangian case to a product $\cup_F\colon HF(L_0, L_1) \otimes HF(L_1, L_2) \to HF(L_0, L_2)$ defined in terms of holomorphic triangles. In his thesis Seidel discovered an exact sequence in Floer homology which can be interpreted as a symplectic version of Floer's original exact sequence for Instanton Floer homology. As a result he was able to compute Floer homology groups in certain cases and use them to distinguish symplectic isotopy classes of symplectomorphisms and Lagrangian submanifolds. His work includes other remarkable applications related to Kontsevich's homological mirror symmetry [K], referring to Fukaya's. A_∞-categories [FS].

Floer homology is a currently rapidly developing area in symplectic geometry branching in different directions. We thus have been quite selective and decided to focus on the non-degenerate version of Arnold's conjecture, aiming more at the recent development of new structures and applications rather than covering the ultimately general proof of the non-degenerate Arnold conjecture. Moreover, this program will not touch the Instanton Floer homology in the gauge-theoretical setting. The interested participant will find a beautiful treatment of this in Donaldson's forthcoming book [D].

The Floer homology functor. One can think of Floer homology as a functor as follows. Consider the universal Novikov ring

$$\Lambda = \Big\{ \sum_{\alpha\in\mathbb{R}} \lambda_\alpha t^\alpha \,|\, \lambda_\alpha \in \mathbb{Q},\ \#\{\,\alpha \,|\, \lambda_\alpha \neq 0,\ \alpha < c\,\} < \infty\ \forall c \in \mathbb{R} \Big\}$$

with the obvious product structure. Consider a fixed, closed symplectic manifold and **Symp** to be the group of its symplectic diffeomorphisms and $\mathbf{Mod}_\Lambda$ the category of $\mathbb{Z}_2$-graded Λ-modules. We consider Floer homology as a map

$$HF\colon \mathbf{Symp} \to \mathbf{Mod}_\Lambda,\ \phi \mapsto HF(\phi),$$

satisfying the following properties:

1. *Naturality*: $HF(\psi^{-1}\phi\psi)$ and $HF(\phi)$ are canonically isomorphic.
2. *Isotopy*: Any Hamiltonian isotopy between ϕ_0 ϕ_1 induces an isomorphism $HF(\phi_0) \cong HF(\phi_1)$ (which may depend on the homotopy class).
3. *Identity*: $HF(\mathrm{id}) \cong H^*(M, \Lambda)$ as $\mathbb{Z}_2$-graded Λ-modules,
4. *Lefschetz property*: $\chi(HF(\phi)) = L(\phi)$, where χ is the Euler characteristic and $L(\phi)$ is the Lefschetz number,
5. *Dimension*: $\operatorname{graph}\phi \pitchfork \operatorname{graph}(\mathrm{id}) \Rightarrow \mathrm{rk}_\Lambda\, HF(\phi) \leqslant \#\operatorname{Fix}\phi$
6. *Duality*: $\exists$ non-degenerate pairing $\langle\cdot,\cdot\rangle\colon HF(\phi)\otimes HF(\phi^{-1}) \to \Lambda$
7. *Product*: $\exists \cup_F\colon HF(\phi)\otimes HF(\psi) \to HF(\phi\psi)$ satisfying:
   a) associativity,
   b) (skew)-commutativity,
   c) Frobenius condition: $\langle \phi \cup_F \psi, \chi\rangle = \langle \phi, \psi \cup_F \chi\rangle$,
   d) $\exists$ neutral element $e \in HF_{\mathsf{even}}(\mathrm{id})$

In view of these properties we can consider **Symp** as a category with symplectomorphisms ϕ as objects and $\mathrm{Mor}(\phi,\psi) = HF(\phi^{-1}\psi)$. Thus, HF becomes a functor with the composition from the product structure,

$$HF(\lambda) = \lambda \cup_F \cdot\colon HF(\phi) \to HF(\psi),\ \forall \lambda \in \mathrm{Mor}(\phi,\psi)\,.$$

Lecture 1. *Introduction: Arnold Conjecture, Symplectic Fixed Points and Lagrangian Intersections.*

- symplectic and Lagrangian (sub-)manifolds
- Darboux theorem, Weinstein's Lagrangian Neighbourhood Theorem.
- Hamiltonian Diffeomorphisms
- Formulation of the Arnold Conjecture:
  a) for general (degenerate) Hamiltonian diffeomorphisms ϕ on M
  $\# \operatorname{Fix} \phi \geqslant \inf\{ \# \operatorname{Crit} f \mid f \in C^\infty(M) \}$,
  b) for non-degenerate ϕ: $\# Fix \phi \geqslant \sum_i \operatorname{rk} H_i(M)$
- Proof for Hamiltonian diffeomorphisms C^1-close to the identity.
- Lagrangian intersection formulation
- variational framework: critical points of the action functional

References: [A2], [A1], [MS2] Chapter 11, [S2], [W2], [HZ] Chapter 6.

Lecture 2. *Morse Homology*
Present Morse homology based on the Morse-Smale-Witten complex as finite-dimensional model for Floer homology

- chain complex generated by critical points
- boundary operator from counting connecting trajectories of relative index 1
- continuation method for obtaining isomorphisms between Morse homologies associated to different Morse functions and Riemannian metrics

References: [Sch1], [S1]

Lecture 3. *Introduction to the concept of Floer homology, Overview*
Present the program of analysis required to obtain well-defined Floer homology groups

- axiomatic description as functor associating modules to symplectic diffeomorphisms
- action functional on free loop space (real valued, $\omega_{|\pi_2} = 0$)
- unregularized L^2-gradient flow trajectories
- Fredholm theory
- Tranversality
- Compactness
- Continuation to small autonomous Hamiltonian

References: [Sch3],[S2],[HZ] Section 6.5

Lecture 4. *Floer's connecting orbits*
Discuss spaces of connecting trajectories, in particular compactness based on elliptic regularity, consider simpler case of $\omega_{|\pi_2} = 0$

- space of bounded energy trajectories

$$\mathcal{M} = \{\, u\colon \mathbb{R} \times S^1 \to M,\ u_2 + J(u_t - X_H) = 0,\ \iint |u_s|^2 ds dt < \infty\}$$

  stratified into spaces of connecting trajectories
- exponential decay for connecting trajectories
- elliptic regularity
- non-bubbling-off analysis
- compactness in C^∞_{loc} for $\omega_{|\pi_2} = 0$
- convergence in C^∞_{loc} and convergence of the energy implies uniform exponential decay and convergence in $W^{1,p}(\mathbb{R} \times S^1)$.

References: [HZ] Section 6.4, in partic. Theorem 8, [Sch2],[RS3], [S2],[HZ]

Lecture 5. *Floer homology for symplectic fixed pts I: Fredholm theory*

- Fredholm theory for linearized flow equation
- Fredholm index = spectral flow = relative Conley-Zehnder index
- carry out L^2-theory, mention L^p-theory

References: [SZ2], [Sch2], [S2],[RS2],[RS1]

Lecture 6. *Floer homology for symplectic fixed pts. II: Moduli Spaces and Transversality*

- moduli spaces as zero sets of a nonlinear Fredholm map
- implicit function theorem approach
- parametrized Sard-Smale method
- problem of multipy covered curves, dealt with by using almost complex structure explicitly S^1-dependent

References: [FHS],[SZ2],[Sch2],[Sch3]

Lecture 7. *Floer homology for symplectic fixed pts. III: Gluing Theorem*

- linear gluing theorem for Fredholm operators
- nonlinear gluing result for connecting trajectories, including local surjectivity of the gluing map (cf. Prop. 3.1.3 in [Sch3])
- proof of chain complex property: $\partial \circ \partial = 0$

References: [Sch3],[SZ2], [FH] Sect. 3, [Sch2], [S2]

Lecture 8. *Floer homology for symplectic fixed pts. IV: Floer homology for symplectic diffeomorphisms*

- finish compactness proof for case of monotone symplectic manifolds
- apply continuation to prove independence of choice of H and J
- formulation of Floer homology associated to symplectic diffeomorphism, $HF(\phi)$
- Gromov's graph trick to deal with the Hamiltonian term of the nonlinear Cauchy-Riemann operator, Seidel's method of sections in symplectic fibrations

References: [HZ] Proof of Lemma 6.4.6, [SZ2], [Sch2], [S2], [Se2],[Se3],[DS1]

Lecture 9. *Proof for semi-positive case, Novikov rings*

- Novikov ring for $\omega_{|\pi_2}$
- proof of Arnold conjecture for semi-positive case by Hofer & Salamon

References: [HS],[Po]

Lecture 10. *Ring Structures I: Pair-of-Pants product*

- pair-of-pants product, unit element, Frobenius structure
- compatibility with composition of symplectic diffeomorphisms
- product property (7) of the functor HF

References: [Sch2],[Sch5] Section 4,[Se3], [Se2],[S3]

Lecture 11. *Ring Strucutres II: Quantum Cohomology*
Consider the so-called small quantum cohomology ring as a deformation of the cup-product by the interaction with holomorphic spheres. This ring carries a Frobenius structure. Floer homology associated to a Hamiltonian diffeomorphism with the pair-of-pants ring structure is ring isomorphic to the small quantum cohomology ring.

- small quantum cohomology ring
- ring isomorphism

References: [MS1],[Sch4],[PSS],[Se3]

Lecture 12. *Lagrangian Intersections I*

- formulate Floer homology for Lagrangian Intersections, consider only monotone case
- new phenomenon of bubbling-off of holom. disks

References: [F1],[F2],[O1],[O2],[O3],[O7]

Lecture 13. *Lagrangian Intersections II: Oh's spectral sequence and applications*

Describe Oh's spectral sequence from [O4] and present the following results:

1. Let $L \subset \mathbb{C}P^n$ be a Lagrangian submanifold such that $H_1(L;\mathbb{Z})$ is 2-torsion. Then $H^*(L;\mathbb{Z}_2) \cong H^*(\mathbb{R}P^n;\mathbb{Z}_2)$ (as vector spaces over $\mathbb{Z}_2$),
$H^1(L;\mathbb{Z}_2) \cup H^{\mathsf{even}}(L;\mathbb{Z}_2) = H^{\mathsf{odd}}(L;\mathbb{Z}_2)$ and $H^{\mathsf{even}}(L;\mathbb{Z}_2)$ is generated by the pullback of the generator $h \in H^2(\mathbb{C}P^n;\mathbb{Z}_2)$. Moreover, if n is even, then the isomorphism $H^*(L;\mathbb{Z}_2) \cong H^*(\mathbb{R}P^n;\mathbb{Z}_2)$ is a ring homomorphism.
2. If $L \subset \mathbb{C}P^n \times \mathbb{C}P^n$ is a Lagrangian submanifold such that $H_1(L;\mathbb{Z}) = 0$, then $H^*(L;\mathbb{Z}_2) \cong H^*(\mathbb{C}P^n;\mathbb{Z}_2)$ (as rings). Moreover, $H^*(L;\mathbb{Z}_2)$ is generated by the pullback of the generator of H^2 in either factor in $\mathbb{C}P^n \times \mathbb{C}P^n$.
3. If $L \subset \mathbb{C}P^n \times \mathbb{T}^{2m}$ is a Lagrangian sphere then m is congruent to $n+1$ modulo $2n+2$. (There's an example in the case $m = n+1$.)

The proof of one of these results should be explained in detail. They're all based on Lagrangian Floer homology and Oh's spectral sequence.
References: [O4], [B]

Lecture 14. *Generalized Dehn Twists*

1. Define a generalized Dehn twist as a symplectomorphism of T^*S^n.
2. Show that, if $n = 2$, then $\tau \circ \tau$ is smoothly isotopic to the identity (among all diffeomorphisms with compact support).
3. Show how the generalized Dehn twist arises as the monodromy of the singular fibration $(z_0, \dots, z_n) \mapsto \sum_j z_j^2$ from $\mathbb{C}^{n+1}$ to $\mathbb{C}$.
4. If $\Lambda \subset M$ is a Lagrangian sphere consider the generalized Dehn twist $\tau_\Lambda : M \to M$ (obtained by embedding a neighbourhood of the cotangent bundle of Λ into M). Show that M is the generic fibre of a singular fibration $E \to D$ (the disk in $\mathbb{C}$) with an isolated Morse singularity in the fibre over zero as in 3).
5. If $E \to D$ is a singular fibration with an isolated Morse singularity as in 3), show that the generic fibre contains a Lagrangian sphere.

References: [Se2],[Se4],[Se5],[Se6]

Lecture 15. *Seidel's exact sequence*

- Explain Seidel's exact sequence in symplectic Floer homology.

- Prove the following theorem: Let X be a simply connected symplectic 4-manifold with $b_2 \geqslant 3$ and $\Lambda \subset X$ be a Lagrangian sphere which represents a nontrivial homology class in $H_2(X;\mathbb{Z}_2)$. Let $\tau : X \to X$ be the generalized Dehn twist about Λ. Then $\tau \circ \tau$ is not symplectically isotopic to the identity.

References: [Se2],[Se10]

Lecture 16. *Graded Lagrangian submanifolds*

- Explain the notion of graded Lagrangian submanifolds.
- notion of symplectically knotted Lagrangian spheres
- existence result for infinitely many symplectically knotted Lagrangian spheres based on graded Lagr. submfds., Section 5 in [Se6], Theorems 5.10 and 5.11.

References: [Se5], [Se6]

The scope of Lectures 13-16 is set in a somewhat ambitious way. The respective speaker is encouraged to restrict the focus on a suitable subset of the suggested material if that appears appropriate.

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Availability of referenced material:

[Se3, Se4, Se5, Se6, Se7, Se8, Se9, Se10] are available from the ArXiv.

[DS1, DS2, FHS, HS, RS1, RS2, RS3, S2, S3] are available from the web page `http://www.math.ethz.ch/ salamon/publications.html`

PS-file of [Sch2] available on demand

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