Chapter 9

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1 | Background, Notation, Setup

Goals

- Construct Floer homology and prove the Arnold Conjecture

Theorem 1.1(*Symplectic Morse Inequalities*).

$$\# \{1\text{-Periodic trajectories of } X_H\} \geq \sum_{k \in \mathbb{Z}} HM_k(W; \mathbb{Z}/2\mathbb{Z}).$$

Here $HM_*(W)$ is the Morse homology.

Important Ideas for This Chapter:

- Using broken trajectories to compactify
- Gluing

Theorem 1.2(*Compactness*).
$\mathcal{L}(x, y)$ is compact, where the compactification is given by adding in

$$\partial \mathcal{L}(x, y) = \{\text{"Broken Trajectories"}\}$$

Theorem 1.3(*Yields a Chain Complex*).

$$\partial^2 = 0$$

Strategy:

1. Define the action functional $\mathcal{A}_H$

2. Construct the chain complex (graded vector space) CF_*.

3. Define X_H, which will be used to define ∂ later.

4. Count trajectories.

5. Show finite-energy trajectories connect critical points of $\mathcal{A}_H$.

6. Show compactness property for space of trajectories of finite energy.

7. Define ∂ (uses a compactness property in 9.1c)

8. Show space of trajectories is a manifold (plus genericity, "Smale property")

9. **Show that $\partial^2 = 0$.**

10. Show that HF_* doesn't depend on $\mathcal{A}_H$ or X_H

11. Show $HF_* \cong HM_*$, and compare dimensions of the vector spaces CM_* and CF_*.

Ingredients:

- (W, ω) with $\omega \in \Omega^2(W)$ is a symplectic manifold with an almost complex structure J.

- $H \in C^\infty(W; \mathbb{R})$ a Hamiltonian with X_H the corresponding symplectic gradient.

  - Defined by how it acts on tangent vectors in $T_x M$:

  $$\omega_x(\,\cdot\,, X_H(x)) = (dH)_x(\,\cdot\,).$$

  - Zeros of vector field X_H correspond to critical points of H:

  $$X_H(x) = 0 \iff (dH)_x = 0.$$

  - Take the associated flow $\psi^t : W \to W$, assumed 1-periodic so $\psi^1(x) = x$: critical points of H are periodic trajectories.

- $u \in C^\infty(\mathbb{R} \times S^1; W)$ is a solution to the Floer equation.

- The Floer equation and its linearization:

$$\mathcal{F}(u) = \frac{\partial u}{\partial s} + J\frac{\partial u}{\partial t} + \text{grad }_u(H) = 0$$
$$(d\mathcal{F})_u(Y) = \frac{\partial Y}{\partial s} + J_0\frac{\partial Y}{\partial t} + S \cdot Y$$

$$Y \in u^*TW, \ S \in C^\infty(\mathbb{R} \times S^1; \text{End}(\mathbb{R}^{2n})).$$

- $\mathcal{L}W$ is the *free loop space* on W, i.e. space of contractible loops on W, i.e. $C^\infty(S^1; W)$ with the C^∞ topology

  - Elements $x \in \mathcal{L}W$ can be viewed as maps $S^1 \to W$.
  - Can extend to maps from a closed disc, $u : \overline{\mathbb{D}}^2 \to M$.
  - Loops in $\mathcal{L}W$ can be viewed as maps $S^2 \to W$, since they're maps $I \times S^1 \to W$ with the boundaries pinched:

Figure 1: Loops in $\mathcal{L}W$

- The action functional is given by

$$\mathcal{A}_H : \mathcal{L}W \to \mathbb{R}$$

$$x \mapsto -\int_{\mathbb{D}} u^*\omega + \int_0^1 H_t(x(t)) \ dt$$

  - Example: $W = \mathbb{R}^{2n} \implies A_H(x) = \int_0^1 (H_t \ dt - p \ dq)$.
  - Correspondence between trajectories of the gradient of $\mathcal{A}_H$ and solutions to Floer equations.

- x, y periodic orbits of H (nondegenerate, contractible), equivalently critical points of $\mathcal{A}_H$.

- Assumption of *symplectic asphericity*, i.e. the symplectic form is zero on spheres. Statement: for every $u \in C^\infty(S^2, W)$,

$$\int_{S^2} u^*\omega = 0 \quad \text{or equivalently} \quad \langle \omega, \ \pi_2 W \rangle = 0.$$

- Assumption of *symplectic trivialization*: for every $u \in C^\infty(S^2; M)$ there exists a symplectic trivialization of the fiber bundle u^*TM, equivalently

$$\langle c_1 TW, \ \pi_2 W \rangle = 0.$$

> Locally a product of base and fiber, transition functions are symplectomorphisms.

- Maslov index: used the fact that

  - Every path in $\gamma : I \to \mathrm{Sp}(2n, \mathbb{R})$ can be assigned an integer coming from a map $\tilde{\gamma} : I \to S^1$ and taking (approximately) its winding number.

- $\mathcal{M}(x, y)$, the moduli space of contractible finite-energy solutions to the Floer equation connecting x, y.

  - After perturbing H to get transversality, get a manifold of dimension $\mu(x) - \mu(y)$.

  - How we did it:

    * Describe as zeros of a section of a vector bundle over $\mathcal{P}^{1,p}(x, y)$

      (Banach manifold modeled on the Sobolev spaces $W^{1,p}$),

    * Apply Sard-Smale to show $\mathcal{M}(x, y)$ is the inverse image of a regular value of some map.

  - Needed tangent maps to be Fredholm operators, proved in Ch. 8 and used to show transversality.

    * Followed from showing $(d\mathcal{F})_u$ is a Fredholm operator of index $\mu(x) - \mu(y)$.

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2 | 9.1 and Review

- Defined moduli space of (parameterized) **solutions**:

  $\mathcal{M}(x, y) = \{\text{Contractible finite-energy solutions connecting } x, y\}$

  $\mathcal{M} = \{\text{All contractible finite-energy solutions to the Floer equation}\} = \bigcup_{x,y} \mathcal{M}(x, y).$

- Defined the moduli space of (unparameterized) **trajectories** connecting x to y:

  $$\mathcal{L}(x, y) := \mathcal{M}(x, y)/\mathbb{R}.$$

  - Use the quotient topology, define sequentially:

    $$\tilde{u}_n \overset{n \to \infty}{\longrightarrow} \tilde{u} \iff \exists \{s_n\} \subset \mathbb{R} \text{ such that } u_n(s_n + s, \cdot) \overset{n \to \infty}{\longrightarrow} u(s, \cdot).$$

  - When $|\mu(x) - \mu(y)| = 1$, get a compact 0-manifold, so the number of trajectories

    $$n(x, y) := \#\mathcal{L}(x, y)$$

    is well-defined.

- $C_k(H) := \mathbb{Z}/2\mathbb{Z}[S]$ where S is the set of periodic orbits of X_H of Maslov index k.

  - Finitely many since they are nondegeneracy implies they are isolated.

Remark 1.
Some notation:

$$\mathbb{R} \longrightarrow \mathcal{M}(x, z)$$
$$\downarrow \pi$$
$$\mathcal{L}(x, z)$$

Hats will generally denote maps induced on quotient.

- Defined a differential

$$\partial : C_k(H) \to C_{k-1}(H)$$
$$x \mapsto \sum_{\mu(y)=k-1} n(x,y)y$$

$$n(x,y) := \# \{\text{Trajectories of grad } \mathcal{A}_H \text{ connecting } x, y\} \mod 2$$
$$= \#\mathcal{L}(x,y) \mod 2.$$

- Examined ∂^2:

$$\partial^2 : C_k(H) \to C_{k-2}(H)$$
$$x \mapsto \partial(\partial(x))$$
$$= \partial \left(\sum_{\mu(y)=\mu(x)-1} n(x,y)y \right)$$

$$= \sum_{\mu(y)=\mu(x)-1} n(x,y)\partial(y)$$

$$= \sum_{\mu(y)=\mu(x)-1} n(x,y) \left(\sum_{\mu(z)=\mu(y)-1} n(y,z)z \right)$$

$$= \sum_{\mu(y)=\mu(x)-1} \sum_{\mu(z)=\mu(y)-1} n(x,y)n(y,z)\, z$$

$$= \sum_{\mu(z)=\mu(y)-1} \left(\sum_{\mu(y)=\mu(x)-1} n(x,y)n(y,z) \right) z \qquad \text{(finite sums, swap order),}$$

so it suffices to show

$$\sum_{\mu(y)=\mu(x)-1} n(x,y)n(y,z) = 0 \quad \text{when} \quad \mu(z) = \mu(x) - 2.$$

Easier to examine parity, so we'll show it's zero mod 2.

- When $\mu(z) = \mu(x) - 2$, $\mathcal{L}(x, z)$ is a non-compact 1-manifold, so we compactify by adding in *broken trajectories* to get $\overline{\mathcal{L}}(x, y)$.

- We'll then have

$$\overline{\mathcal{L}}(x, z) = \mathcal{L}(x, z) \cup \partial\overline{\mathcal{L}}(x, z), \qquad \partial\overline{L}(x, z) = \bigcup_{\mu(y)=\mu(x)-1} \mathcal{L}(x, y) \times \mathcal{L}(y, z),$$

  which "space-ifies" the equation we want.

- We'll show $\partial\overline{\mathcal{L}}(x, z)$ is a 1-manifold, which must have an even number of points, and thus

$$\sum_{\mu(y)=\mu(x)-1} n(x, y)n(y, z) = \#\big(\partial\overline{\mathcal{L}}(x, z)\big) \equiv 0 \mod 2.$$

Image here of relations between spaces!

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3 | Three Important Theorems

3.1 First Theorem: Convergence to Broken Trajectories

- Recall: *broken trajectories* are unions of intermediate trajectories connecting intermediate critical points.

- Shown last time: a sequence of trajectories can converge to a broken trajectory, i.e. there are broken trajectories in the closure of $\mathcal{L}(x, z)$.

- This theorem describes their behavior:

> **Theorem 3.1** *(9.1.7: Convergence to Broken Trajectories).*
> Let $\{u_n\}$ be a sequence in $\mathcal{M}(x, z)$, then there exist
>
> - A subsequence $\{u_{n_j}\}$
>
> - Critical points $\{x_0, x_1, \cdots, x_{\ell+1}\}$ with $x_0 = x$ and $x_{\ell+1} = z$
>
> - Sequences $\{s_n^1\}, \{s_n^2\}, \cdots, \{s_n^\ell\}$.
>
> - Elements $u^k \in \mathcal{M}(x_k, x_{k+1})$ such that for every $0 \le k \le \ell$,
>
> $$u_{n_j} \cdot s_n^k \overset{n \to \infty}{\Longrightarrow} u^k.$$

- Upshots:
  - Every sequence upstairs has a subsequence which (after reparameterizing) converges
  - This descends to actual convergence after quotienting by $\mathbb{R}$?
  - Yields uniqueness of limits in $\mathcal{L}(x, z)$, thus a separated topology
  - Sequentially compact $\iff$ compact since $\mathcal{L}(x, z)$ is a metric space?

> **Corollary 3.2** *(Compactness).*
> $\overline{\mathcal{L}}(x, z)$ is compact.

3.2 Second Theorem: Compactness of $\overline{\mathcal{L}}(x,z)$

Definition 3.2.1 (Regular Pair)**.**
For an almost complex structure J and a Hamiltonian H, the pair (H, J) is **regular** if the Floer map $\mathcal{F}$ is transverse to the zero section in the following vector bundle:

$$E_u := \{\text{Vector fields tangent to } M \text{ along } u\} \longrightarrow C^\infty(\mathbb{R} \times S^1; TM)$$

$$\mathcal{F} \quad \Big\downarrow \quad \mathbf{0}$$

$$C^\infty(\mathbb{R} \times S^1; M)$$

Most of chapter 9 is spent proving this theorem:

Theorem 3.3*(9.2.1).*
Let (H, J) be a regular pair with H nondegenerate and x, z be two periodic trajectories of H such that

$$\mu(x) = \mu(z) + 2.$$

Then $\overline{\mathcal{L}}(x,z)$ is a compact 1-manifold with boundary with

$$\partial\overline{\mathcal{L}}(x,z) = \bigcup_{y \in \mathcal{I}(x,z)} \mathcal{L}(x,y) \times \mathcal{L}(y,z)$$

$$\text{where} \quad \mathcal{I}(x,z) = \Big\{ y \;\Big|\; \mu(x) < \mu(y) < \mu(z) \Big\}.$$

Note: possibly a typo in the book? Has x, y on the LHS.

Corollary 3.4.

$$\partial^2 = 0.$$

3.3 Third Theorem: Gluing

Theorem 3.5 *(9.2.3: Gluing).*
Let x, y, z be three critical points of $\mathcal{A}_H$ with three consecutive indices

$$\mu(x) = \mu(y) + 1 = \mu(z) + 2.$$

and let

$$(u, v) \in \mathcal{M}(x, y) \times \mathcal{M}(y, z) \quad \rightsquigarrow \quad (\widehat{u}, \widehat{v}) \in \mathcal{L}(x, y) \times \mathcal{L}(y, z).$$

Then
1. There exists a $\rho_0 > 0$ and a differentiable map

$$\psi : [\rho_0, \infty) \to \mathcal{M}(x, z)$$

such that $\widehat{\psi}$, the induced map on the quotient

$$[\rho_0, \infty) \xrightarrow{\ \psi\ } \mathcal{M}(x, z)$$
$$\widehat{\psi} \searrow \qquad \downarrow \pi$$
$$\mathcal{L}(x, z)$$

   is an embedding that satisfies

$$\widehat{\psi}(\rho) \xrightarrow{\rho \to \infty} (\widehat{u}, \widehat{v}) \in \overline{\mathcal{L}}(x, z).$$

2. ("Uniqueness") For any sequence $\{\ell_n\} \subseteq \mathcal{L}(x, z)$,

$$\ell_n \xrightarrow{n \to \infty} (\widehat{u}, \widehat{v}) \quad \Longrightarrow \quad \ell_n \in \operatorname{im}(\widehat{\psi}) \text{ for } n \gg 0.$$

- We already know that $\overline{\mathcal{L}}(x, z)$ is compact and $\mathcal{L}(x, z)$ is a 1-manifold, so we look at neighborhoods of boundary points.

- Why unique: will show that the broken trajectory $(\widehat{u}, \widehat{v})$ is the endpoint of an embedded interval in $\overline{\mathcal{L}}(x, z)$.

    - Then show that any other sequence converging to $(\widehat{u}, \widehat{v})$ must approach via this interval, otherwise could have cuspidal points:
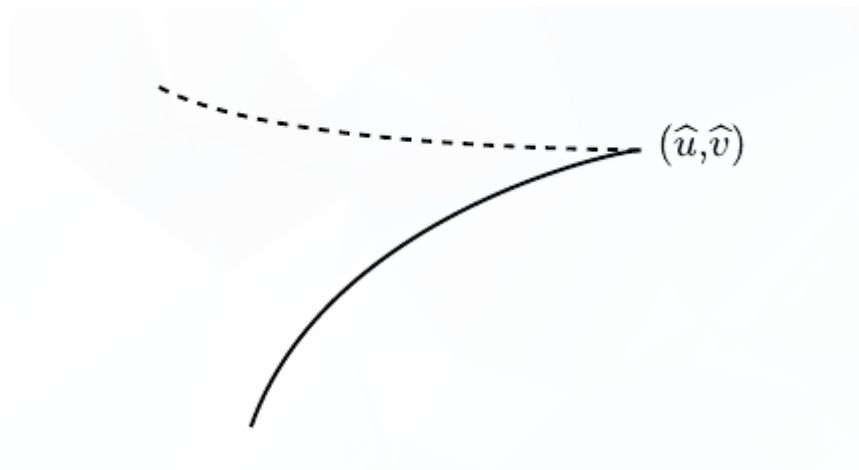
Figure 2: Cuspidal Point on Boundary

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4 | Gluing Theorem

Broken into three steps:

1. **Pre-gluing**:

- Get a function w_ρ which interpolates between u and v in the parameter ρ.

   - Not exactly a solution itself, just an "approximation".

2. **Newton's Method**:

- Apply the Newton-Picard method to w_p to construct a true solution

$$\psi : [-\rho, \infty) \to \mathcal{M}(x, z)$$
$$\rho \mapsto \exp_{w_p}\left(\gamma(p)\right)$$

$$\text{for some } \gamma(p) \in W^{1,p}(w_p^* TW) = T_{w_p}\mathcal{P}(x, z)$$

- General idea: guess, intersect x-axis with tangent of graph, use that as a new guess and iterate.

- GIF of Newton's Method

3. **Project and Verify Properties**:

- Check that the projection $\widehat{\psi} = \pi \circ \psi$ satisfies the conditions from the theorem.

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5 | 9.3: Pre-gluing, Construction of w_ρ

- Choose (once and for all) a bump function β on $B_\varepsilon(0)^c \subset \mathbb{R} \to [0,1]$ which is 1 on $|x| \geq 1$ and 0 on $|x| < \varepsilon$
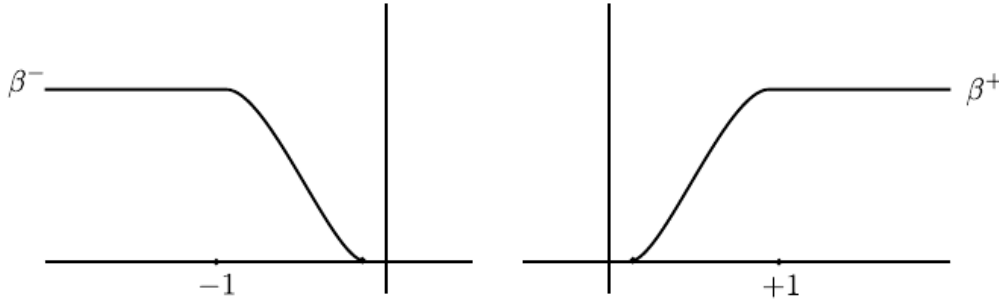- Split into positive and negative parts $\beta^\pm(s)$:

Figure 3: Bump away from zero

- Define an interpolation w_ρ from u to v in the following way: let
  - $\exp[\,\cdot\,] := \exp_{y(t)}(\,\cdot\,)$ and
  - $\ln(\,\cdot\,) := \exp_{y(t)}^{-1}(\,\cdot\,)$,

  then

  $$w_\rho : x \to z$$

  $$w_\rho(s,t) := \begin{cases} u(s+\rho,t) & s \in (-\infty, -1] \\[2mm] \exp\left[\beta^-(s)\ln(u(s+\rho,t)) + \beta^+(s)\ln(u(s-\rho,t))\right] & s \in [-1,1] \\[2mm] u(s-\rho,t) & s \in [1,\infty) \end{cases} \;.$$

- Why does this make sense?

  $$|s| \leq 1 \implies u(s\pm\rho,t) \in \left\{\exp_{y(t)} Y(t) \;\middle|\; \sup_{t\in S^1} \|Y(t)\| \leq r_0\right\} \subseteq \operatorname{im} \exp_{y(t)}(\,\cdot\,).,$$

  so we can apply $\exp_{y(t)}^{-1}(\,\cdot\,)$.

- Can make $|s| \leq 1$ for large ρ, since

$$u(s,t) \xrightarrow{s \to \infty} y(t)$$
$$v(s,t) \xrightarrow{s \to -\infty} y(t).$$

  – So pick a ρ_0 such that this holds for $\rho > \rho_0$.

  – Might have to increase ρ_0 later in the proof, so $\rho > \rho_0$ just means $\rho \gg 0$.

- Some properties:

  – $w_\rho \in C^\infty(x,z)$ and is differentiable in ρ.
  – $s \in [-\varepsilon, \varepsilon] \implies w_\rho(s,t) = y(t)$.

$$w_\rho(s - \rho, t) \xrightarrow{\rho \to \infty} u(s,t) \quad \text{in} \quad C^\infty_{\text{loc}}$$

$$w_\rho(s,t) \xrightarrow{\rho \to \infty} y(t) \quad \text{in} \quad C^\infty_{\text{loc}}.$$

- Now carry out the linearized version on tangent vectors

  – Let $Y \in T_u \mathcal{P}(x,y)$
  – Let $Z \in T_v \mathcal{P}(x,y)$
  – Replace w_ρ with the interpolation

$$Y \#_\rho Z \in T_{w_\rho} \mathcal{P}(x,y) = W^{1,p}(w_\rho^* TW).$$

  defined by

$$(Y \#_\rho Z)(s,t) = \begin{cases} Y(s+\rho, t) & s \in (-\infty, -1] \\ \exp_T \left[\beta^-(s) \ln_T(Y(s+\rho, t)) + \beta^+(s) \ln_T(Z(s-\rho, t)) \right] & s \in [-1, 1] \\ Z(s-\rho, t) & s \in [1, \infty) \end{cases},$$

  where the subscript T indicates taking tangents of the exponential maps at appropriate points.

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6 | 9.4: Construction of ψ.

6.1 Summary

- $\mathcal{F}_\rho$ will be $F \circ \exp w_\rho$ expanded in the bases Z_i coming from a trivialization of TW.

- $L_\rho = (d\mathcal{F}_\rho)_0$ will be the linearization of the Floer operator at zero.

- Newton-Picard method, general idea:

  - Allows finding zeros of f given an approximate zero x_0, using the extra information of the 1st derivative f'.

  - Original method and variant: find the limit of a sequence

  $$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}, \qquad x_{n+1} = x_n - \frac{f(x_n)}{f'(x_0)}.$$

  - Second variant more useful: only need to know the derivative at one point.
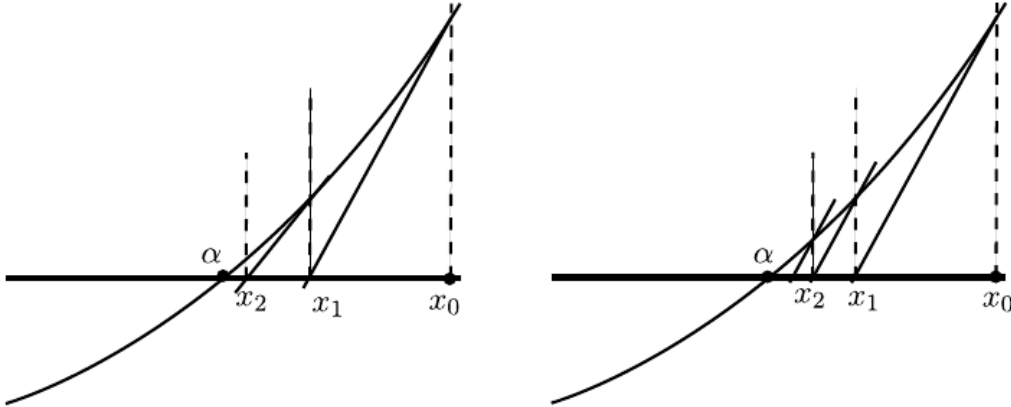

Fig. 9.6

Figure 4: Newton Method Variants

- Adapting Newton-Picard to operators:

  - $\dfrac{1}{f'(x_0)}$ will correspond to L_ρ^{-1}, but it won't be invertible on entire space.

  - Decompose

  $$T_{w_\rho}\mathcal{P}(x,z) = W^{1,p}(w_\rho^* TW) = W^{1,p}(\mathbb{R} \times S^1; \mathbb{R}^{2n}) = \ker(L_\rho) \oplus W_\rho^{\perp},$$

  where L_ρ will have a right inverse on $W_\rho^{\perp} \subseteq T_{w_\rho}\mathcal{P}(x,z)$.

  - Find that $x_0 = 0$ is "approximately" a solution and run Newton-Picard in $W_\rho^{\perp}$

  - Where does $W_\rho^{\perp}$ come from? Essentially the kernel of some linear functional given by an integral:

  $$W_\rho^{\perp} := \left\{ Y \in W^{1,p} \; \middle| \; \int_{\mathbb{R} \times S^1} \langle Y, \; \cdots \rangle \, ds \, dt = 0, \;\; \text{plus conditions} \right\}.$$

- Will obtain for every $\rho \geq \rho_0$ an element $\gamma(\rho) \in W_\rho^{\perp}$ with

  $$\mathcal{F}_\rho(\gamma(\rho)) = 0.$$

  - Where does γ come from? Intersection-theoretic interpretation on page 320:

$$\left(\exp_{w_\rho}\right)^{-1}\mathcal{M}(x,z)\cap W_\rho^\perp \subseteq T_{w_\rho}\mathcal{P}(x,z) \qquad\qquad \rightsquigarrow \gamma$$

$$\mathcal{M}(x,z)\cap\left\{\exp_{w_\rho} W_\rho^\perp \;\middle|\; \rho\geq\rho_0\right\}\subseteq\mathcal{P}(x,z) \qquad\qquad \rightsquigarrow \psi(\rho),$$

which we get by exponentiating.

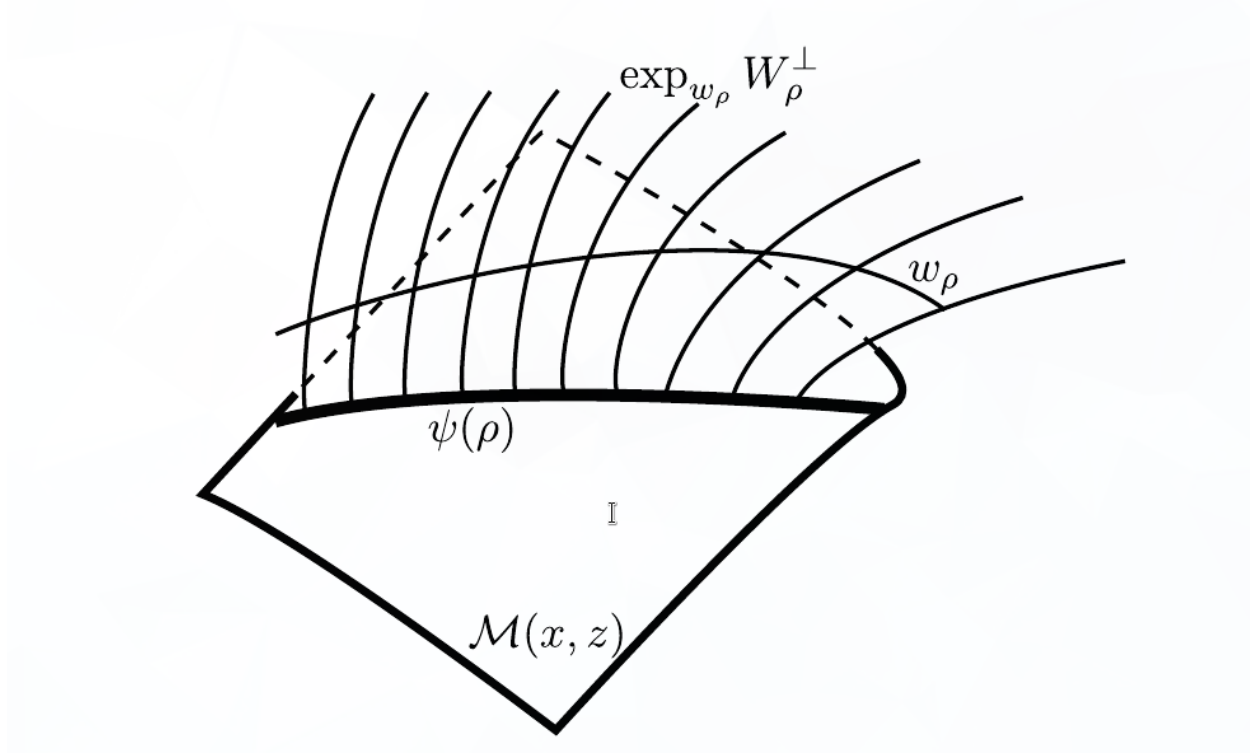- This gives a codimension 1 subspace in $\mathcal{M}(x,z)$, which we take to be $\psi(\rho)$:

Figure 5: Intersection interpretation

Schematic picture here for $\gamma, \psi(\rho)$.

- Apply the implicit function theorem to show differentiability of γ in ρ.

- Use a trivialization Z_i^ρ of TW to get a vector field along w_ρ (also called $\gamma(\rho)$)

    - This is exactly an element of $T_{w_\rho}\mathcal{P}(x,z)$

- Exponentiate to get an element of $\mathcal{M}(x,z)$:

$$\psi(\rho) := \exp_{w_\rho}(\gamma(\rho)).$$

- Project onto $\mathcal{L}(x,z)$ to get $\widehat{\psi}$.

- Prove $\widehat{\psi}$ is a proper injective immersion and thus an embedding.

- Show that the broken trajectory $(\widehat{u}, \widehat{v})$ is the endpoint of an embedded interval in $\overline{\mathcal{L}}(x,z)$.

    - Then show that any other sequence converging to $(\widehat{u}, \widehat{v})$ must approach via this interval, otherwise could have cuspidal points:
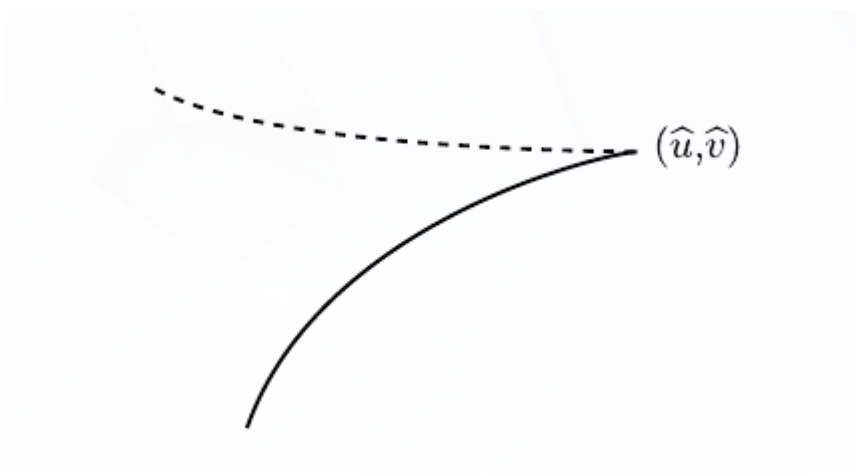

Figure 6: Cuspidal Point on Boundary

Probably not worth going farther than this!

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6.2 Details

- Have constructed $w_\rho \in C^\infty_\searrow(x, z)$ for every $\rho \geq \rho_0$, since there is exponential decay.

- Yields $\psi_\rho \in \mathcal{M}(x, z)$ a true solution (to be defined).

- Need to check that $\mathcal{F}(\psi_\rho) = 0$ where

$$\mathcal{F} = \frac{\partial}{\partial s} + J \frac{\partial}{\partial t} + \text{grad } Hx$$

  in the weak sense.

- ψ_ρ already continuous, and by elliptic regularity, makes it a strong solution.

- Defining $\mathcal{F}_\rho$.

$$W^{1,p}\left(\mathbf{R} \times S^1; \mathbf{R}^{2n}\right) \xrightarrow{\mathcal{F}_\rho} L^p\left(\mathbf{R} \times S^1; \mathbf{R}^{2n}\right)$$
$$(y_1, \ldots, y_{2n}) \longmapsto \left[\left(\frac{\partial}{\partial s} + J \frac{\partial}{\partial t} + \text{grad } H_t\right)\left(\exp_{w_\rho} \sum y_i Z_i^\rho\right)\right]_{Z_i}$$

where $\mathcal{F}_\rho := \mathcal{F} \circ \exp_{w_\rho}$ written in the bases Z_i. sd

- Linearize $\mathcal{F}_\rho$.