

# Notes for Homological Mirror Symmetry

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## Contents

1	Introduction to homological mirror symmetry (2022-02-27 Su Weilin)	1
2	Derived category and triangulated category (2022-03-06 Zhang Nantao)	3
3	Derived functors and some examples of derived category of coherent sheaves (2022-03-13 Zhang Nantao)	9
4	Floer homology and Fukaya categories I (2022-03-27 Lan Zhuoming)	14
5	Floer homology and Fukaya categories II (2022-04-03 Lan Zhuoming)	16
6	Homological mirror symmetry for elliptic curves I (2022-04-10 Zhang Nantao)	18
7	Homological mirror symmetry for elliptic curves II (2022-04-17 Zhang Nantao)	21
8	Constructible sheaves and the Fukaya category (2022-04-24 Zhou Jiawei)	25

## 1 Introduction to homological mirror symmetry (2022-02-27 Su Weilin)

### 1.1 GW invariants

Let  $(M; \omega, J)$  be a symplectic manifold with symplectic form  $\omega$  and compatible almost complex structure  $J$ . Gromov-Witten invariants are roughly the number

$$\# \{ f: (u, v) \rightarrow M \mid f \text{ (pseudo-)holomorphic, } \omega\text{-constraints } g \}$$

These invariants are introduced by Gromov around 1985, who proves that the zero dimensional part of above moduli space is finite. In mirror symmetry, Gromov-Witten invariants belong to A-model.

#### Example 1.1.1

$$\# \{ \text{deg } 1 \text{ curves } u: \mathbb{CP}^1 \rightarrow \mathbb{CP}^n \text{ passing through } 2 \text{ generic points} \} = 1$$

However, in general the Gromov-Witten invariants are very difficult to compute because the moduli space of (pseudo-)holomorphic curves is far from smooth and intersections are not transversal. So people want to find some indirect ways to compute these invariants.

### 1.2 Mirror symmetry

Now consider  $(M; \bar{\partial})$  which is a complex manifold where  $\bar{\partial}$  is the complex structure. We can consider the sheaf cohomology and period integration of differential forms. Period integral belongs to B-models.

Suggested by physicists, there exists a diagram

$$\begin{array}{ccc} \text{GW invariants} & \longleftarrow & \text{symplectic manifold } M \\ \updownarrow & & \updownarrow \text{Mirror} \\ \text{period integral} & \longleftarrow & \text{complex manifold } M^- \end{array}$$

where  $M$  and  $M^-$  are called *mirror dual*. The problem of computing GW invariants can be transformed to the calculation of period integral. We now go to consider Kähler manifold  $(M; \omega, J)$ , where  $\omega$  is symplectic form

and  $\omega$  is complex structure where symplectic form and complex structure are compatible. Physically, above correspondence is from the duality of 2 dimensional supersymmetric field theory and is checked for quintic 3-fold. The question is why they coincide mathematically?

### 1.3 Homological mirror symmetry

The idea is to replace the space by some kind of categories. The correct “category” is the  $A_1$ -category, introduced by Stashef in 1963 to study group like topological spaces.

**Definition 1.3.1** An  $A_1$ -category is following collection of data.

1. A set of objects.
2. Morphisms between objects are  $\mathbb{Z}$ -graded linear space  $\text{hom}(X; Y)$ .
3.  $m_k$  the “composition” of morphisms

$$m_k : \text{hom}(X_0; X_1) \otimes \text{hom}(X_{k-1}; X_k) \rightarrow \text{hom}(X_0; X_k)$$

satisfying the  $A_1$ -relation

$$\sum_{i,j} (-1)^{j|x_i|+1} m_{k+1-j}(x_1; \dots; x_i; m_j(x_{i+1}; \dots; x_{i+j}); x_{i+j+1}; \dots; x_k) = 0$$

here  $|x_i|$  denote the grading of  $x_i$ .

for exmple, when  $k = 1$ , we have  $m_1(m_1(x)) = 0$  that is  $m_1^2 = 0$  is a differential. For  $k = 2$ , the  $A_1$ -relation gives Leibniz rule. It is more convenient to consider on homology level by differential  $m_1$ . That is  $\text{Hom}(X; Y) = H(\text{hom}(X; Y); m_1)$  and define the composition to be

$$\text{Hom}(X; Y) \otimes \text{Hom}(Y; Z) \rightarrow \text{Hom}(X; Z) \\ [x] \otimes [y] \mapsto [x] \otimes [y] := (-1)^{|x||y|} [m_2(x; y)]$$

In above notation, the  $k = 3$  relation gives associativity  $([x] \otimes [y]) \otimes [z] = [x] \otimes ([y] \otimes [z])$ .

Let  $(M; \omega)$  be a complex manifold, we can view it as an algebraic variety and consider the derived category of coherent sheaves of the variety which can be enhanced to be a dg-category. A rough definition of derived category is that the objects are bounded complexes of coherent sheaves and morphisms are  $\text{Ext}(E; F)$  and composition conditions. It is obtained from category of complexes by formally inverting the quasi-isomorphisms with some additional universal properties. This is the story on the complex side.

The story on the symplectic side is Fukaya category. The objects of Fukaya category is  $fL \subset M$   $j$   $L$  (compact) Lagrangian  $g$ . The morphism is generated by intersection points, that is

$$\text{hom}(L_1; L_2) = RhL_1 \otimes L_2^*$$

for transversal intersections. A Fukaya category is a  $A_1$ -category with coefficients of the composition map counting holomorphic discs satisfying some relations. Kontsevich suggest the two categories are related.

**Conjecture 1.3.2** [Homological Mirror Symmetry, [Kon95]] For any Calabi-Yau  $M$  there exists a mirror dual  $M^-$  such that

$$\text{Fuk}(M^-) = D^b(\text{Coh}M) \quad \text{Fuk}(M) = D^b(\text{Coh}M^-)$$

The above diagram is completed to be the following

$$\begin{array}{ccccc} \text{GW invariants} & \longleftarrow & \text{symplectic manifold } M & \longrightarrow & \text{Fuk}(M) \\ \updownarrow & & \updownarrow \text{Mirror} & & \updownarrow \text{HMS} \\ \text{period integral} & \longleftarrow & \text{complex manifold } M^- & \longrightarrow & D^b(\text{Coh}M^-) \end{array}$$

To go from period integral to Gromov-Witten invariants, we want to get some information of symplectic manifold  $M$  from its Fukaya category. We consider Hochschild cohomology. For associative algebras, we define

**Definition 1.3.3** We define **Hochschild complex**  $(HC; b)$  for a  $k$ -algebra to be

$$HC_p(A) = A^{\otimes (p+1)}$$

$$d_i : A^{\otimes p} \rightarrow A^{\otimes p} \quad a_p \mapsto a_0 \otimes \cdots \otimes a_i a_{i+1} \otimes \cdots \otimes a_p \quad (i = 0; \dots; p-1)$$

$$d_p : A^{\otimes p} \rightarrow A^{\otimes p} \quad a_p \mapsto \sum_{i=0}^p (-1)^i d_i$$

Then we define the homology of above complex to be **Hochschild homology** and cohomology of dual complex to be **Hochschild cohomology**, denoted by  $HH$  and  $HH^*$  respectively.

We can extend above definition to  $A_1$ -categories. Following conjecture relates Fukaya category to the geometry of original symplectic manifold.

**Conjecture 1.3.4** [Kontsevich?]

$$H^*(M) = HH^*(Fuk(M))$$

## 2 Derived category and triangulated category (2022-03-06 Zhang Nantao)

### 2.1 References

Chapter 1 of [KS94], Chapter 1 and 2 of [Huy06], Chapter 3 of [GM03].

### 2.2 Derived category

First, recall the complex of an abelian category  $A$  is of the form

$$A : \cdots \rightarrow A^{n-2} \xrightarrow{d^{n-2}} A^{n-1} \xrightarrow{d^{n-1}} A^n \rightarrow \cdots$$

satisfying  $d^i \circ d^{i-1} = 0$ . Morphism between the complex  $A$  and  $B$  are a series of morphisms  $f^i : A^i \rightarrow B^i$  making the following diagram commutes.

$$\begin{array}{ccccccc} \cdots & \rightarrow & A^{n-2} & \rightarrow & A^{n-1} & \rightarrow & A^n \rightarrow \cdots \\ & & \downarrow f^{n-2} & & \downarrow f^{n-1} & & \downarrow f^n \\ \cdots & \rightarrow & B^{n-2} & \rightarrow & B^{n-1} & \rightarrow & B^n \rightarrow \cdots \end{array}$$

where the differentials are omitted.

We then have a category of complex denoted by  $Kom(A)$  where objects are complexes of  $A$  and morphisms are given as above.

There exists a natural functor called **shift functor**,  $T : Kom(A) \rightarrow Kom(A)$ , such that

$$(T(A))^i := A^{i+1}$$

$$d_{T(A)} := d_A^{i+1}$$

For  $f : A \rightarrow B$ , we have

$$T(f) = f^{i+1}$$

Obviously,  $T$  is an equivalence of category. Usually, we denoted  $T(A)$  by  $A[1]$  and  $T(f)$  by  $f[1]$ , and we use  $A[n]$  and  $A[-1]$  in an obvious way.

**Definition 2.2.1** Recall, the  $i$ th **cohomology** of  $A$  denoted by  $H^i(A) := \frac{\ker(d^i)}{\text{im}(d^{i-1})} \subset A$ .

$A$  is called **acyclic** if  $H^i(A) = 0$  for all  $i \in \mathbb{Z}$ .

$f : A \rightarrow B$  induces morphisms  $H^i(f) : H^i(A) \rightarrow H^i(B)$  if all induced morphism are isomorphisms then we call  $f$  a **quasi-isomorphism** (qis for short).

**Remark 2.2.2** There exists complexes with same cohomology group but not quasi-isomorphic. For example

$$\begin{array}{ccc} C[x; y] & \xrightarrow{\sim} & C[x; y] \\ & \searrow & \downarrow \\ & & C[x; y] \end{array}$$

We first give a definition of derived category by universal properties.

**Definition 2.2.3** The **derived category** of  $A$  is a category  $D(A)$  with a functor  $Q: Kom(A) \rightarrow D(A)$ , such that

1. If  $A \xrightarrow{f} B$  qis in  $Kom(A)$  then  $Q(f)$  is an isomorphism in  $D(A)$ .
2. Any functor  $F: Kom(A) \rightarrow D$  satisfying condition (1) uniquely factor through  $Q$ . That is there exists unique  $G$  making the following diagram commutes

$$\begin{array}{ccc} Kom(A) & \xrightarrow{Q} & D(A) \\ & \searrow F & \swarrow \exists! G \\ & D & \end{array}$$

Before giving a construction of derived categories, we notice that the cohomology is well defined in derived category and  $A \rightarrow Kom(A) \rightarrow D(A)$  is a full subcategory.

**Definition 2.2.4** Given an abelian category  $A$ , we define **homotopy category**  $K(A)$  to be following data

$$Ob(K(A)) := Ob(Kom(A))$$

$$Hom_{K(A)}(A \rightarrow B) := Hom_{Kom(A)}(A \rightarrow B) =$$

where  $\sim$  denote the homotopy equivalence.

Recall two morphism of complexes  $f, g: A \rightarrow B$  are called **homotopy equivalent** if there exists a collection of homomorphisms  $h^i: A^i \rightarrow B^{i-1}$  such that  $f^i - g^i = h^{i+1} d_A^i + d_B^{i-1} h^i$ .

Notice that if  $f \sim g$  and  $g \sim f$ , then  $f$  and  $g$  are all quasi-isomorphisms.

Now we give another definition of derived category.

**Definition 2.2.5** A **derived category** is the following collection of data

$$\begin{array}{ccc} Ob(D(A)) := Ob(Kom(A)) & & \\ \cong & \swarrow C & \searrow \cong \\ Hom_{D(A)}(A \rightarrow B) = & \xrightarrow{qis} & B \end{array}$$

two morphisms are equivalent if there exists following commutative diagram in  $K(A)$ .

$$\begin{array}{ccccc} & & C & & \\ & \swarrow qis & & \searrow & \\ & C_1 & & C_2 & \\ \swarrow qis & & & & \searrow \\ A & & & & B \end{array}$$

The composition of morphisms are given by

$$\begin{array}{ccccc} & & C_0 & & \\ & \swarrow qis & & \searrow & \\ & C_1 & & C_2 & \\ \swarrow qis & & & \swarrow qis & \searrow \\ A & & B & & C \end{array}$$

The associativity of the composition is obvious. To check that  $D(A)$  is indeed a category, we only need to check that

1.  $C_0$  exists.
2. The composition is unique.

To address the above two questions, we introduce the notion of mapping cone.

**Definition 2.2.6** Let  $f : A \rightarrow B$  we define the **mapping cone**  $C(f)^i := A^{i+1} \rightarrow B^i$  and

$$d_{C(f)} := \begin{pmatrix} d_A^{i+1} & 0 \\ f^{i+1} & d_B^i \end{pmatrix}$$

Given a morphism  $f : A \rightarrow B$ , we have long exact sequence

$$\cdots \rightarrow H^i(A) \rightarrow H^i(B) \rightarrow H^i(C(f)) \rightarrow H^{i+1}(A) \rightarrow \cdots$$

**Proposition 2.2.7** Let  $f : A \rightarrow B$  a morphism,  $C(f)$  its mapping cone, and diagram of solid arrows

$$\begin{array}{ccccccc} B & \longrightarrow & C(f) & \longrightarrow & A[1] & \xrightarrow{f} & B[1] \\ \downarrow = & & \downarrow = & & \downarrow g & & \downarrow = \\ B & \longrightarrow & C(f) & \longrightarrow & C(\quad) & \xrightarrow{\quad} & B[1] \end{array}$$

Then there exists an isomorphism in  $K(A)$ ,  $g : A[1] \rightarrow C(\quad)$  making the diagram commutes in  $K(A)$ .

**Proof** Let  $g = (f^{i+1}; \text{id}; 0)$  and check the commutativity.

**Remark 2.2.8** The above isomorphism exists in  $K(A)$  but not in  $Kom(A)$  so we need to start from homotopy category instead of category of complexes.

**Proposition 2.2.9** Given a diagram

$$\begin{array}{ccc} & C & \\ & \downarrow g & \\ A & \xrightarrow{f} & B \end{array}$$

there exists  $C_0$  fill the following diagram

$$\begin{array}{ccc} C_0 & \xrightarrow{qis} & C \\ \downarrow & & \downarrow g \\ A & \xrightarrow{f} & B \end{array}$$

**Proof** We fill the diagram gradually, first we have

$$\begin{array}{ccccccc} & C & & & & & \\ & \downarrow g & & & & & \\ A & \xrightarrow{f} & B & \longrightarrow & C(f) & \longrightarrow & A[1] \end{array}$$

By Theorem 2.2.7, we can fill to the following diagram by isomorphism  $A[1] = C(\quad g)$ .

$$\begin{array}{ccccccc} & C & \xrightarrow{g} & C(f) & \longrightarrow & C(\quad g) & \\ & \downarrow g & & \downarrow & & \downarrow & \\ A & \xrightarrow{f} & B & \longrightarrow & C(f) & \longrightarrow & A[1] \end{array}$$

And finally,

$$\begin{array}{ccccccc} C(-g)[-1] & \longrightarrow & C & \xrightarrow{g} & C(f) & \longrightarrow & C(-g) \\ \downarrow & & \downarrow g & & \downarrow & & \downarrow \\ A & \xrightarrow{f} & B & \longrightarrow & C(f) & \longrightarrow & A[1] \end{array}$$

where  $C(-g)[-1]$  is the required  $C_0$  in the proposition. We only need to show that  $C(-g)[-1] \rightarrow C$  is a quasi-isomorphism, but it follows from long exact sequence and the five lemma.

We now solve the existence of the composition, but the uniqueness problem is still left.

**Definition 2.2.10** A class of morphism  $S \subset \text{Mor}(A)$  is said to be **localizing** if

1.  $S$  is closed under compositions and  $\text{id}_X \in S$  for every  $X \in \text{Ob}(A)$ .
2. Excision condition, that is for any  $f \in \text{Mor}(A)$  and  $s \in S$ , there exists  $g \in \text{Mor}(A)$  and  $t \in S$  such that

$$\begin{array}{ccc} C_0 & \xrightarrow{g} & C \\ \downarrow t & & \downarrow s \\ A & \xrightarrow{f} & B \end{array}$$

is commutative.

3. Let  $f, g \in \text{Hom}(X; Y)$ , the existence of  $s \in S$  such that  $sf = sg$  is equivalent to the existence of  $t \in S$  with  $ft = gt$ .

**Remark 2.2.11** Quasi-isomorphisms don't form a localizing class in  $\text{Kom}(A)$  but in  $K(A)$ .

Only condition 3 need to be checked for quasi-isomorphism class. Given  $f : A \rightarrow B$  in  $K(A)$  and a quasi-isomorphism  $s : B \rightarrow B$  with  $sf = 0$ , we want to show that there exists  $t : A \rightarrow A$  with  $ft = 0$ . To see that we only need to see the following diagram

$$\begin{array}{ccccc} C(s)[-1] & \xrightarrow{[-1]} & B & \xrightarrow{s} & B \\ \downarrow = & & \uparrow f & & \\ C(s)[-1] & \xleftarrow{g} & A & \xleftarrow{t} & C(g)[-1] \end{array}$$

where  $g^i : A \rightarrow B^i \rightarrow B^{i-1}$  is the map

$$g^i : (a^i) \mapsto (f^i(a^i); h^i(a^i))$$

where  $h^i : A^i \rightarrow B^{i-1}$  is the homotopy between  $sf$  and 0. Then  $ft = [-1]gt = 0$  and  $t$  is quasi-isomorphism by long exact sequence.

**Remark 2.2.12** The derived category is additive but not abelian, as it does not always have kernels and cokernels. But it is a triangulated category, which we will introduce later.

## 2.3 Triangulated category

**Definition 2.3.1** A **triangulated category** is an additive category  $D$  with an additive functor  $T : D \rightarrow D$  called the **shift functor** and a set of **distinguished triangles** satisfying 4 axioms. In convention, we use notation  $A[1] := T(A)$  and  $f[1] := T(f)$ .

1. (a) Any triangle of the form

$$A \xrightarrow{\text{id}} A \rightarrow 0 \rightarrow A[1]$$

is distinguished

- (b) Any triangle isomorphic to a distinguished triangle is distinguished

(c) Any morphism  $f : A \rightarrow B$  can be completed to a distinguished triangle

$$A \xrightarrow{f} B \rightarrow C \rightarrow A[1]$$

2

$$A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} A[1]$$

is a distinguished triangle if and only if

$$B \xrightarrow{g} C \xrightarrow{h} A[1] \xrightarrow{f[1]} B[1]$$

is.

3 If there exists a commutative diagram of solid arrows of the following diagram,

$$\begin{array}{ccccccc} A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ A^0 & \longrightarrow & B^0 & \longrightarrow & C^0 & \longrightarrow & A^0[1] \end{array}$$

then there exists a dashed arrow  $h : C \rightarrow C^0$  (not necessarily unique) to complete the diagram.

4. Suppose given distinguished triangles

$$X \xrightarrow{f} Y \rightarrow Z^0 \rightarrow X[1]$$

$$Y \xrightarrow{g} Z \rightarrow X^0 \rightarrow Y[1]$$

$$X \xrightarrow{g \circ f} Z \rightarrow Y^0 \rightarrow X[1]$$

then there exists a distinguished triangle

$$Z^0 \rightarrow Y^0 \rightarrow X^0 \rightarrow Z^0[1]$$

such that the following diagram is commutative

$$\begin{array}{ccccccc} X & \xrightarrow{f} & Y & \longrightarrow & Z^0 & \longrightarrow & X[1] \\ \downarrow \text{id}_X & & \downarrow g & & \downarrow & & \downarrow \text{id}_{X[1]} \\ X & \xrightarrow{g \circ f} & Z & \longrightarrow & Y^0 & \longrightarrow & X[1] \\ \downarrow f & & \downarrow \text{id}_Z & & \downarrow & & \downarrow f[1] \\ Y & \xrightarrow{g} & Z & \longrightarrow & X^0 & \longrightarrow & Y[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ Z^0 & \longrightarrow & Y^0 & \longrightarrow & X^0 & \longrightarrow & Z^0[1] \end{array}$$

**Remark 2.3.2** Basically, the 4th axiom means that  $(A=C)=(B=C) = A=B$  in abstract algebra. That axiom is sometimes called octahedral axiom because it can be arranged into an octahedron.

**Proposition 2.3.3** A derived category is a triangulated category where the distinguished triangles are those triangles isomorphic to

$$A \xrightarrow{f} B \rightarrow C(f) \rightarrow A[1]$$

**Remark 2.3.4** It may be interesting to know other examples of triangulated categories. One example is the derived category of  $A_1$ -category and another may be given by stable homotopy category. The basic idea is from the cofiber sequence in topology.

$$X \rightarrowtail Y \rightarrowtail C(f) \rightarrowtail X \rightarrowtail Y$$

and making  $T :=$  . However, is not invertible, so we have to do some additional work to make category of topological space a triangulated category.

**Lemma 2.3.5** For distinguished triangle

$$A \rightarrowtail B \rightarrowtail C \rightarrowtail A[1]$$

the composition  $A \rightarrowtail C = 0$ .

**Proof** Consider the following diagram

$$\begin{array}{ccccccc} A & \longrightarrow & A & \longrightarrow & 0 & \longrightarrow & A[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \end{array}$$

**Proposition 2.3.6** Let  $A \rightarrowtail B \rightarrowtail C \rightarrowtail A[1]$  be a distinguished triangle, and  $A_0 \in D$ , then

$$\text{Hom}(A_0; A) \rightarrowtail \text{Hom}(A_0; B) \rightarrowtail \text{Hom}(A_0; C)$$

$$\text{Hom}(C; A_0) \rightarrowtail \text{Hom}(B; A_0) \rightarrowtail \text{Hom}(A; A_0)$$

are exact.

**Proof** By Theorem 2.3.5, we have the composition of maps are equal to 0. To show that it is exact, we only need to consider the following diagram

$$\begin{array}{ccccccc} A_0 & \longrightarrow & A_0 & \longrightarrow & 0 & \longrightarrow & A_0[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \end{array}$$

**Definition 2.3.7** An additive functor  $F : D \rightarrowtail D^0$  between triangulated categories  $D$  and  $D^0$  is called **exact** if the following two conditions are satisfied:

1. There exists a functor isomorphism

$$F \circ T_D = T_{D^0} \circ F$$

2. Any distinguished triangle in  $D$  is mapped to distinguished triangle in  $D^0$ .

**Proposition 2.3.8** Let  $F : D \rightarrowtail D^0$  be an exact functor. If  $F \circ H$ , then  $H : D^0 \rightarrowtail D$  is exact. Similar result holds for  $G \circ F$ .

**Proof** We first check the commutativity with shift functor.

$$\begin{aligned} \text{Hom}(A; H(T^0(B))) &= \text{Hom}(F(A); T^0(B)) \\ &= \text{Hom}(T^{-1}(F(A)); B) \\ &= \text{Hom}(F(T^{-1}(A)); B) \\ &= \text{Hom}(T^{-1}(A); H(B)) \\ &= \text{Hom}(A; T(H(B))) \end{aligned}$$



Then we check that  $H$  maps distinguished triangles to distinguished triangles. Let  $A \rightarrow B \rightarrow C \rightarrow A[1]$  distinguished in  $D^0$ . We can completed to a distinguished triangle

$$H(A) \rightarrow H(B) \rightarrow C_0 \rightarrow H(A)[1]$$

in  $D$ . By applying  $F$ , and use adjoint property and exactness of  $F$ , we have

$$\begin{array}{ccccccc} F(H(A)) & \longrightarrow & F(H(B)) & \longrightarrow & F(C_0) & \longrightarrow & F(H(A)[1]) \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \end{array}$$

Applying  $H$ , combine two diagram and using adjointness  $h: \text{id} \rightarrow H \circ F$ , we have

$$\begin{array}{ccccccc} HA & \longrightarrow & HB & \longrightarrow & C_0 & \longrightarrow & HA[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ HFHA & \longrightarrow & HFHB & \longrightarrow & HFC_0 & \longrightarrow & HFHA[1] \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ HA & \longrightarrow & HB & \longrightarrow & HC & \longrightarrow & HA[1] \end{array}$$

The curved morphisms are isomorphism. And by exact sequence and five lemma, we have

$$\text{Hom}(A_0; C_0) = \text{Hom}(A_0; H(C))$$

for all  $A_0$  and hence

$$C_0 \cong H(C)$$

is an isomorphism. And therefore  $H(A) \rightarrow H(B) \rightarrow H(C) \rightarrow H(A)[1]$  is isomorphic to  $H(A) \rightarrow H(B) \rightarrow C_0 \rightarrow H(A)[1]$  and is therefore distinguished.

**Definition 2.3.9** Two triangulated categories  $D$  and  $D^0$  are **equivalent** if there exists an exact equivalence  $F: D \rightarrow D^0$ .

If  $D$  is a triangulated category the set  $\text{Aut}(D)$  of isomorphism classes of equivalence  $F: D \rightarrow D$  forms the **group of autoequivalence**.

A subcategory  $D^0 \subset D$  of a triangulated category is a **triangulated subcategory** if  $D^0$  admits the structure of triangulated category such that the inclusion  $D^0 \hookrightarrow D$  is exact.

We say a set of objects  $S$  **generates** triangulated category  $D$  if any triangulated subcategory of  $D$  contains  $S$  is  $D$  itself.

### 3 Derived functors and some examples of derived category of coherent sheaves (2022-03-13 Zhang Nantao)

#### 3.1 References

Chapter 1 of [KS94], Chapter 1 and 2 of [Huy06], Chapter 3 of [GM03].

#### 3.2 Derived functors

To define the derived functor, we first give a definition of boundedness.

**Definition 3.2.1** Let  $\text{Kom}(A)$  with  $\mathcal{A} = +; -$  or  $b$  be the category of complexes  $A$  with  $A^i = 0$  for  $i \rightarrow -\infty$ ,  $i \rightarrow +\infty$ ,  $j \rightarrow +\infty$ , and called **bounded from below**, **bounded from above** and **bounded**. We can define subcategory  $K^-(A)$  and  $D^-(A)$  similarly.

**Proposition 3.2.2** The natural functor  $D^-(A) \rightarrow D(A)$  defines equivalence of  $D^-(A)$  with the full triangulated subcategories of all complexes  $A \in D(A)$  with  $H^i(A) = 0$  for  $i \rightarrow -\infty$ ,  $i \rightarrow +\infty$ ,  $j \rightarrow +\infty$ .

**Remark 3.2.3** The above proposition is not true, if we replace  $D(A)$  by  $K(A)$ .

We now give a formal definition of derived functors.

**Lemma 3.2.4** Let  $F : K(A) \rightarrow K(B)$  be an exact functor of triangulated categories. Then  $F$  naturally induces a commutative diagram

$$\begin{array}{ccc} K^+(A) & \longrightarrow & K^+(B) \\ \downarrow & & \downarrow \\ D^+(A) & \longrightarrow & D^+(B) \end{array}$$

if one of the following two conditions holds (in fact two conditions are equivalent)

1.  $F$  maps quasi-isomorphism to quasi-isomorphism.
2.  $F$  maps acyclic complex to acyclic complex.

For  $F : A \rightarrow B$  left exact, we have  $F : K^+(A) \rightarrow K^+(B)$  satisfy above lemma and therefore induces a derived functor.

$$RF : D^+(A) \rightarrow D^+(B)$$

Dually, for right exact functor we have

$$LF : D^-(A) \rightarrow D^-(B)$$

The construction above is quite formal, we require some more explicit process for computation. Recall an abelian category contains enough injective if for any object  $A \in \mathcal{A}$  there exists an injective morphism  $A \rightarrow I$  with  $I \in \mathcal{A}$  injective.

**Proposition 3.2.5** Suppose  $\mathcal{A}$  is an abelian category with enough injectives. For any  $A \in K^+(A)$ , there exists a complex  $I \in K^+(A)$  with  $I^i \in \mathcal{A}$  injective objects and quasi-isomorphism  $A \rightarrow I$ .

**Proof** We construct the injective resolution directly. We may assume that first nonzero element in  $A$  is  $A^0$  or we shifted  $A$  to make it so. at position 0, we consider

$$\begin{array}{ccccc} 0 & \longrightarrow & A^0 & \xrightarrow{\quad} & A^1 \\ & & \downarrow & \nearrow & \downarrow \\ & & I^0 & \xrightarrow{\quad} & I^1 \end{array}$$

And if we already have  $I^i$ , we have step  $i+1$  by following construction.

$$\begin{array}{ccccc} \longrightarrow & A^i & \xrightarrow{\quad} & A^{i+1} \\ & \downarrow & \searrow & \downarrow \\ & I^i & \xrightarrow{\quad} & I^{i+1} \end{array}$$

$\text{coker } d_{I^i}^{i-1} \longrightarrow \text{coker } d_{I^{i+1}}^{i-1}$

Then you may check it is indeed a quasi-isomorphism. For details, you may consult [GM03].

**Lemma 3.2.6** Suppose  $A \rightarrow B$  quasi-isomorphism between two complexes in  $K^+(A)$  then for any complex  $I$  of injective objects  $I^i$  with  $I^i = 0$  for  $i < 0$  the induced map

$$\text{Hom}_{K(A)}(B, I) \rightarrow \text{Hom}_{K(A)}(A, I)$$

is bijective.

**Proof** By distinguished triangles and long exact sequence, we only need to prove that for acyclic  $C$ , we have  $\text{Hom}(C; I) = 0$ . Let  $g \in \text{Hom}(C; I)$ , we show that it is homotopic to 0 map. We argue by induction, first, for small enough  $i$ , we have  $C^i = I^i = 0$ , which may serve as the start of the induction. If we have  $h^j$  for  $j \leq i$ . Then we have  $g^i = d_I^{i-1} \circ h^i : C^i \rightarrow I^i$  factor through  $C^i = C^{i-1}$  by acyclic property of  $C^i$ . Then by injectivity of  $I^i$ , we may lift it to  $h^{i+1} : C^{i+1} \rightarrow I^i$  such that  $g^i = d_I^{i-1} \circ h^i = h^{i+1} \circ d_C^i$ .

**Lemma 3.2.7** Let  $A \in \text{Kom}^+(A)$  such that all  $I^i$  are injective. Then

$$\text{Hom}_{K(A)}(A; I) = \text{Hom}_{D(A)}(A; I)$$

**Proof**

$$\begin{array}{ccc} & B & \\ qis \swarrow & & \searrow \\ A & \dashrightarrow & I \end{array}$$

For any roof consisting of solid lines, it is equivalent to a dashed line representing a morphism in  $\text{Hom}(A; I)$ .

**Proposition 3.2.8** If  $A$  is an abelian category with enough injectives. Then the functor

$$: K^+(I) \rightarrow D^+(A)$$

is an equivalence.  $I$  is the full subcategory of all injectives of  $A$ .

Now we come back to derived functor. We have another definition for derived functor. Consider the diagram

$$\begin{array}{ccccc} K^+(I_A) & \hookrightarrow & K^+(A) & \xrightarrow{K(F)} & K^+(B) \\ & \swarrow 1 & \downarrow Q_A & & \downarrow Q_B \\ & & K^+(A) & \dashrightarrow & K^+(B) \end{array}$$

And we define  $RF := Q_B \circ K(F) \circ 1^{-1}$  is a well defined **derived functor**.

And we define

$$R^i F(A) := H^i(RF(A))$$

And object  $A \in A$  is called  **$F$ -acyclic** if  $R^i F(A) = 0$  for  $i \neq 0$ .

**Remark 3.2.9** We can develop the dual theory for left exact functor and  $D^-(A)$  with  $A$  having enough projectives. However, it is not so useful in algebraic geometry because category of coherent sheaves may not have enough projectives! [Har08, Chapter III]

By above remark, we will need a more general framework to do derived functors.

**Definition 3.2.10** Let  $F : A \rightarrow B$ . A class of objects  $I_F \subset A$  stable under finite sum is  **$F$ -adapted** if the following conditions hold:

1. If  $A \in K^+(A)$  acyclic with  $A \in I_F$  for all  $i$ , then  $F(A)$  is acyclic.
2. Any object in  $A$  can be embedded into an object of  $I_F$ .

Let  $F : K^+(A) \rightarrow K^+(B)$ . We define triangulated subcategory  $K_F \subset K^+(A)$   **$F$ -adapted** if it satisfying following conditions.

1. If  $A \in K_F$  is acyclic, then  $F(A)$  is.
2. Any  $A \in K^+(A)$  is quasi-isomorphic to a complex in  $K_F$ .

If  $I_F$  is  $F$ -adapted, then  $K^+(I_F)$  is  $F$ -adapted.

**Proposition 3.2.11** Suppose  $A \in B$  abelian category and  $F : K^+(A) \rightarrow K^+(B)$  exact functor, and there exists an  $F$ -adapted class  $K_F$ . Then there exists a right derived functor  $RF$  satisfying

1. The following diagram commutes.

$$\begin{array}{ccc} K^+(A) & \xrightarrow{K(F)} & K^+(B) \\ \downarrow Q_A & & \downarrow Q_B \\ K^+(A) & \xrightarrow{RF} & K^+(B) \end{array}$$

2. (Universal property) Suppose  $G : D^+(A) \rightarrow D^+(B)$  is exact. Then  $Q_B \circ K(F) \rightarrow G \circ Q_A$  factor through a unique morphism

$$RF \rightarrow G$$

Therefore, we can use flat resolution or other  $F$ -acyclic resolutions to do the computations. We can check that

$$\text{Ext}^i(A; \ ) := H^i(R\text{Hom}(A; \ ))$$

For  $A; B \in \mathcal{A}$  view as complex concentrated in degree 0.

Also, we have  $\text{Hom} : K^+(A)^{op} \rightarrow K^+(A) \rightarrow K(A)$  defined by

$$\text{Hom}^i(A; B) := \text{Hom}(A^k; A^{k+i})$$

$$d(f) := d_B \circ f - (-1)^i f \circ d_A$$

And

$$\text{Ext}^i(A; B) := H^i(R\text{Hom}(A; B))$$

By above definition, we have

$$\text{Ext}^i(A; B) = \text{Hom}_{D(A)}(A; B[i])$$

**Proposition 3.2.12** Let  $F_1 : A \rightarrow B$  and  $F_2 : B \rightarrow C$  left exact functor and adapted class  $I_{F_1} \subset A, I_{F_2} \subset B$  such that  $F_1(I_{F_1}) \subset I_{F_2}$ , then there is a natural transformation

$$R(F_2 \circ F_1) = RF_2 \circ RF_1$$

### 3.3 Some results about coherent sheaves

We have following comparison between complex algebraic geometry and complex analytic geometry.

Complex algebraic geometry	complex analytic geometry
scheme / variety	complex analytic space
affine scheme	$\text{aff}(z^i) = 0$
regular function	holomorphic function
morphism	holomorphic morphism
locally free sheaves	vector bundles
Zariski topology	analytic topology

We now introduce two famous result to communicate between complex algebraic geometry and complex analytic geometry.

**Theorem 3.3.1** [Serre's GAGA [Ser56]] Given algebraic variety  $X$ , we have

$$X \rightarrow X^{an}$$

making  $X$  an analytic space. Moreover the coherent sheaves on  $X$  maps to coherent sheaves on  $X$  bijectively.

**Theorem 3.3.2** [Chow's lemma [Cho49]] A compact analytic variety in  $\mathbb{P}^n$  is an algebraic variety.

So for projective variety, we can freely exchange the view of complex algebraic geometry and complex analytic geometry. By Jacobian criteria, the irreducible smooth projective complex algebraic variety is a complex manifold

By [Har08, Ex II.5.18, Ex III.6.8, 6.9], we have following result.

**Proposition 3.3.3** We have one to one correspondence between locally free sheaves of rank  $n$  on  $Y$  and isomorphism classes of vector bundles of rank  $n$  over  $Y$ .

**Proposition 3.3.4** If  $X$  is Noetherian (for example, projective or affine), integral, separated, locally factorial scheme, then every coherent sheaf on  $X$  is a quotient of locally free sheaf. Moreover, the locally free resolution is of finite length.

As regular schemes are locally factorial and regular is equivalent to smooth in characteristic 0. We can work in complex manifold with vector bundles if you wish to. Last, we rewrite Serre duality in the language of derived categories. We use  $D(X)$  to denote derived category of coherent sheaves on  $X$ .

**Theorem 3.3.5** [Serre duality] We define

$$S_X : D^b(X) \rightarrow D^b(X) \\ F \mapsto (!_X {}^L F)[n]$$

where  $!_X$  is the dualizing sheaf and  $n = \dim X$ . Then we have

$$\mathrm{Hom}(E, F) = \mathrm{Hom}(F, S_X(E))$$

**Remark 3.3.6** The category with a Serre functor equal to shifting is called a **Calabi-Yau category**. (For general definition of Serre functor, see [Huy06]) In [Kon95], Kontsevich make Calabi-Yau property as a sign for equivalence between derived category of coherent sheaves and derived category of Fukaya category.

### 3.4 Examples of derived category of coherent sheaves

We now consider two examples of schemes. First, we consider  $X = \mathbb{A}^1 = \mathrm{Spec} \mathbb{C}[x]$ . Two coherent sheaves  $\mathcal{O}_X$  trivial line bundle and skyscraper sheaf  $\mathcal{O}_a$ ;  $a \in \mathbb{A}^1$  generates the category  $\mathrm{Coh}(X)$  and therefore  $D^b(X)$ . We have  $\mathrm{Coh}(\mathrm{Spec} A) = A\text{-mod}$ . The morphism between generators are all easy to compute. For example, we compute  $R\mathrm{Hom}(\mathcal{O}_a, \mathcal{O}_b)$ , we need to take projective resolution for  $\mathcal{O}_a$ , that is

$$0 \rightarrow \mathbb{C}[x] \xrightarrow{(x-a)} \mathbb{C}[x] \rightarrow \mathbb{C}[x]/(x-a) \rightarrow 0$$

which is an example of locally free resolution. Then we have

$$R\mathrm{Hom}(\mathcal{O}_a, \mathcal{O}_b) = \begin{cases} 0 & \text{if } a \neq b \\ \mathbb{C} & \text{if } a = b \end{cases}$$

the second sequence started from index 0.

A similar result holds for cylinder  $S^1 = \mathbb{R}/\mathbb{Z} = \mathrm{Spec} \mathbb{C}[x; x^{-1}]$ .

Now we consider another example  $D^b(\mathbb{P}^1)$ .

**Proposition 3.4.1** Let  $M = \mathcal{O}(-1) \oplus \mathcal{O}(1)$ . Then graded algebra  $R\mathrm{Hom}(M; M)$  is concentrated in degree 0 and is the path algebra of Kronecker quiver  $\begin{matrix} & \xrightarrow{\quad} \\ & \xrightarrow{\quad} \end{matrix}$ .

**Proof** We have  $\mathrm{Ext}^i(\mathcal{O}(l), \mathcal{O}(k)) = H^i(X; \mathcal{O}(k-l))$ . For  $i > 0$ , this is nonzero unless  $i = 1$  and  $k-l = -2$  which is impossible. The equivalence between algebra is easy to see.

**Definition 3.4.2** A coherent sheaf  $T$  on  $X$  is called a **tilting sheaf** if

1.  $A := \mathrm{End}_{\mathcal{O}_X}(T)$  has finite global dimension.
2.  $\mathrm{Ext}_{\mathcal{O}_X}^i(T, T) = 0$  for  $i > 0$ .
3.  $T$  generates  $D^b(X)$ .

**Theorem 3.4.3** Let  $T$  be a tilting sheaf on a smooth projective scheme  $X$ , with tilting algebra  $A = \text{End}_{\mathcal{O}_X}(T)$ . Then the functors

$$F(-) := \text{Hom}_{\mathcal{O}_X}(T, -) \\ G(-) := {}_A T \otimes -$$

induces equivalence of triangulated categories

$$RF : D^b(X) \xrightarrow{\sim} D^b(A\text{-mod})^{op} \\ LG : D^b(A\text{-mod})^{op} \xrightarrow{\sim} D^b(X)$$

**Proof** First, by smoothness of  $X$ , coherent sheaves has finite length resolution and by property (1) Theorem 3.4.2  $A\text{-mod}^{op}$  has finite length resolution so we have  $RF, LG$  well defined as morphism between bounded categories.

By property (2) of Theorem 3.4.2, we have  $RF \circ LG(A) = RF(T) = A$ . Hence it is equivalence on finitely generated projective  $A$ -module and therefore on all  $A$ -modules. By property (3) of Theorem 3.4.2, we have the image of  $LG$ , the triangulated subcategory generated by  $T$ , is all of  $D^b(X)$ . So we for every  $F$ , we have  $F = LG(M)$  for some  $M$  and therefore have  $LG \circ RF(F) = LG \circ RF \circ LG(M) = LG(M) = F$ .

**Theorem 3.4.4**  $\mathcal{O}(-i) \otimes \mathcal{O}(i)$  is a tilting sheaf on  $X = \mathbb{P}^n$ .

## 4 Floer homology and Fukaya categories I (2022-03-27 Lan Zhuoming)

### 4.1 References

The main reference is [Aur13]. And for more details consult [Sei08].

### 4.2 Floer homology

Let  $(M; \omega)$  symplectic manifold of dimension  $2n$ . Let  $J$  be  $\omega$ -compatible almost complex structure. The set of  $\omega$ -compatible almost complex structures

$$J(M; \omega) = \{J \in \text{End}(TM) \mid J^2 = -1, g_J = \omega(\cdot, J\cdot) \text{ is a Riemannian metric}\}$$

is contractible.

**Example 4.2.1** The cotangent bundle  $T^*S$  is a symplectic manifold with symplectic form  $\omega = dr \wedge d\theta$  where  $\theta$  is the coordinate of circle and  $r$  is the coordinate of cotangent fiber.

Let  $L_0, L_1$  Lagrangian submanifold of dimension  $n$ . By definition of Lagrangian manifold,  $\omega|_{L_0} = 0, \omega|_{L_1} = 0$ . For simplicity, we first assume that  $L_0, L_1$  intersects transversally and  $L_0, L_1$  compact and  $[L_0] \in H_2(M; \mathbb{Z}) = 0$  and  $[L_1] \in H_2(M; \mathbb{Z}) = 0$ . Then for dimension reason  $(L_0, L_1) := L_0 \cap L_1 = \text{finite set}$ .

**Definition 4.2.2** Let  $k$  be a field. We define the **Novikov field** as follows:

$$\mathbb{X} = \left\{ \sum_{i \in \mathbb{Z}} a_i T^{-i} \mid a_i \in k; \lim_{i \rightarrow -\infty} a_i = 0 \right\}$$

The **Floer complex**  $CF(L_0, L_1) = \bigoplus_i \mathbb{X} \cdot \text{free module by } \text{fp}_i g$ . The differential of the complex  $\partial : CF(L_0, L_1) \rightarrow CF(L_0, L_1)$ .

$$\partial(p) = \sum_{q \in (L_0, L_1), \text{ind}([u])=1} (\#M(p, q; [u]; J)) T^{w([u])} q$$

where  $u \in \pi_2(M)$ . The definition  $\text{ind}([u])$  and  $M(p, q; [u]; J)$  will be discussed later.

If we want to count the points of moduli space  $M$  with sign, we need  $L_0; L_1$  to be oriented with spin structure and  $\text{char} k = 0$ . Then  $M(p; q; [u]; J)$  is orientable. If we count the points of moduli space  $M$  without sign, we require the base field  $\text{char} k = 0$ .

We count the number of  $u$  where

$$u : \mathbb{R} \setminus [0; 1] \rightarrow M^{2n}$$

satisfying following three conditions:

1. (Pseudo-holomorphic) Let  $(u; s) \in \mathbb{R} \setminus [0; 1]$ .

$$\frac{\partial u}{\partial s} + J \frac{\partial u}{\partial t} = 0$$

2. (Boundary condition)

$$u(s; 0) \in L_0$$

$$u(s; 1) \in L_1$$

$$\lim_{s \rightarrow -1} u(s; t) = p$$

$$\lim_{s \rightarrow 1} u(s; t) = q$$

3. (Finite energy condition)

$$E(u) = \int_{\mathbb{R} \setminus [0; 1]} |\frac{\partial u}{\partial s}|^2 ds dt < +\infty$$

$$M(p; q; [u]; J) = \{u \mid u \text{ satisfies (1)(2)(3) and } [u] = [u]_g\}$$

If  $u(s; t)$  satisfies (1)(2)(3), then  $u(s+a; t)$  satisfies (1)(2)(3). So we define

$$M(p; q; [u]; J) = M(p; q; [u]; J) = u(s+a; t) - u(s; t)$$

We now define **Maslov index**,  $\text{ind}([u])$ . Let  $\text{LGr}(n)$  be Lagrangian Grassmanian of  $\mathbb{R}^{2n} = \mathbb{C}^n$ . Then we have  $\pi_1(\text{LGr}(n)) = \mathbb{Z}$ . There is the map

$$\det^2 : \text{LGr}(n) \rightarrow S^1$$

which induces isomorphism on fundamental groups. To define Maslov index

$$u : TM \rightarrow \mathbb{R} \setminus [0; 1] \rightarrow \mathbb{R}^{2n}$$

$$u|_{T_p L_0} = \mathbb{R}^n; \quad u|_{T_p L_1} = i\mathbb{R}^n$$

$$u|_{T_q L_0} = \mathbb{R}^n; \quad u|_{T_q L_1} = i\mathbb{R}^n$$

Then  $u|_{T_p L_0} \rightarrow u|_{T_p L_1} \rightarrow u|_{T_q L_1} \rightarrow u|_{T_q L_0} \rightarrow u|_{T_p L_0}$  gives a loop in  $\text{LGr}(n)$ . The element of fundamental group isomorphic to  $\mathbb{Z}$  representing this loop is the Maslov index.

We now show that  $\partial_{J;u} = \frac{1}{2}(\frac{\partial}{\partial s} + J \frac{\partial}{\partial t})$ . The differential of  $\partial_{J;u}$ ,  $D_{\partial_{J;u}}$ , is a Fredholm operator (i.e. it has finite dimensional kernel and cokernel). We further require  $J$  to be regular, that is  $D_{\partial_{J;u}}$  is injective. By theory of analysis, we have

$$\dim M(p; q; [u]; J) = \text{Fredholm index} = \dim \text{coker } D_{\partial_{J;u}} = \text{ind}([u])$$

By above equation, for  $\text{ind}([u]) = 1$ , we have

$$\dim M(p; q; [u]; J) = \dim M(p; q; [u]; J) - 1 = 0$$

So counting the points of  $\dim M(p; q; [u]; J)$  is meaningful.

We now prove that  $\partial^2 = 0$  for Floer complex. By Gromov compactness theorem, the limiting behavior of  $M(p; q; [u]; J)$  will be broken strip or bubbling. By vanishing of second relative homotopy group the second case is impossible. So we have

$$\partial_{\text{ind}([u])=2} M(p; q; [u]; J) = \sum M(p; r; [u^0]; J) - M(r; q; [u^0]; J)$$

The right hand side is the  $q$  coefficient in  $\partial^2 p$ . And by differential geometry theory, the counting of points of boundary of 1-dimensional manifolds is 0. So we have  $\partial^2 = 0$ .

### 4.3 Grading of Floer homology

We wish to give a grading on Floer complex such that  $\text{ind}([u]) = \deg q - \deg p$ . To give a  $\mathbb{Z}$ -grading of elements, we require:

1.  $2c_1(TM) = 0$ .
2.  $\langle L, \text{pt} \rangle = 0 \cong H_1(L; \mathbb{Z})$ .

The condition  $2c_1(TM) = 0$  gives a fiberwise universal covering  $\mathbb{E}\text{Gr}(n) \rightarrow \text{LGr}(TM)$ . For a loop  $s : S^1 \rightarrow \text{LGr}(TM)$ , we can lift it to a loop  $\tilde{s} : S^1 \rightarrow \mathbb{E}\text{Gr}(n)$ , which may not be a loop, so give a element of fundamental group of  $\text{LGr}(n)$  isomorphic to  $\mathbb{Z}$ . So it defines an isomorphism  $\text{Hom}(\pi_1(S^1; \mathbb{Z}) = H_1(L; \mathbb{Z})$  called **Maslov class**  $\mu_L$ . If  $\mu_L = 0$ , then  $s$  can always be lifted to a loop.

Therefore, if two conditions are all satisfied, then given  $p, q$  two points, the difference of degree of  $p$  and  $q$  is given by lifting the section  $s_{L_1}$  linking  $p, q$  and counting. By above, lifting of  $s_{L_2}$  will give the same answer. So the difference of degrees are well defined.

### 4.4 Discussion of non-transversal case

If  $(L_0; L_1)$  don't intersect transversally and  $J$  is not regular, then we can always find time dependent almost complex structure  $J(t)$  and Hamiltonian  $H(t)$ . Let  $\frac{d}{dt} H$  is a Hamiltonian flow. And we define  $CF_0(L_0; L_1; J(t); H(t))$ , such that  $L_0; (\frac{d}{dt} H)^{-1} L_1$  intersects transversally and  $(\frac{d}{dt} H)^{-1} J(t)$  regular for  $t > 0$ . The pseudo-holomorphic conditions now comes

$$\begin{aligned} \frac{\partial u}{\partial s} + J(t) \frac{\partial u}{\partial t} &= 0 \\ J(t) &= (\frac{d}{dt} H)^{-1} J(t) \\ u(s; t) &= (\frac{d}{dt} H)^{-1} u(s; t) \end{aligned}$$

Different perturbations may not give same Floer complex, but these Floer complex will be homotopy invariant.

### 4.5 Fukaya categories

The objects of Fukaya category

$$\text{Ob}(F) = L$$

where  $\langle L, \text{pt} \rangle = 0$ , with spin structures and  $\langle L, \text{pt} \rangle = 0$ . And

$$\text{Hom}(L_i; L_j) = CF(L_i; L_j)$$

The Fukaya category does not have associativity but have  $A_\infty$ -relations.

## 5 Floer homology and Fukaya categories II (2022-04-03 Lan Zhuoming)

### 5.1 Fukaya categories

We now continue to discuss the Fukaya categories. We first define the product operation (composition) for homomorphisms. Let  $(M; \omega)$  be symplectic manifold, and  $(L_0; L_1; L_2)$  three Lagrangians which intersect transversally and  $[w] \in H_2(M; \mathbb{Z}) = 0$ ,  $\langle L_i, \text{pt} \rangle = 0$ . We also assume that  $2c_1(M) = 0$ . We try to define

$$\mu_2 : CF(L_1; L_2) \otimes CF(L_0; L_1) \rightarrow CF(L_0; L_2)$$

To avoid some subtle discussion, we assume that we are working over characteristic 2. To define the above morphism, we only need to define for generators. For  $p_2 \in L_1; L_2$  and  $p_1 \in L_0; L_1$ , then we define

$$p_2 \cdot p_1 = \sum_{q \in L_1; L_2; \text{ind}([u])=0} \# M(p_1; p_2; q; [u]; J) T^{w[u]} q$$

where  $M(p_1; p_2; q; [u]; J)$  is the moduli space of pseudo-holomorphic maps with boundary on  $L_0; L_1; L_2$  and boundary point  $p_1; p_2; q$  and homotopy class  $[u]$ .



**Remark 5.1.1** The dimension of moduli space  $\dim M(p_1; \dots; p_k; q; [u]; J) = k - 2 + \text{ind}([u])$ . That is because first every points gives a freedom of choice but biholomorphic map on disk makes the freedom minus 3 and  $\text{ind}([u])$  brings new freedom of choice. Therefore in above case the sum is over 0-dimensional manifold and is meaningful.

**Theorem 5.1.2**  $@(p_2, p_1) = @p_2, p_1 + p_2 @p_1$

**Proof** By Gromov compactness theorem, and vanishing of relative homotopy group, coefficient of  $q$  in  $@(p_2, p_1) + @p_2, p_1 + p_2 @p_1$  equals to  $\# \sum_{\text{ind}[u]=1} (@M(p_1; p_2; r; [u]; J))$  which equals 0.

We now define what is  $A_1$ -categories.

**Definition 5.1.3** An  $A_{\text{inf ty}}$ -category is following collection of data.

1.  $Ob(A)$  the object of  $A$ .
2. For every  $X_0, X_1 \in Ob(A)$ ,  $\text{hom}(X_0; X_1)$  graded vector space called morphisms between  $X_0; X_1$ .
3. A set of composition maps

$$*_k : \text{hom}(X_{k-1}; X_k) \otimes \text{hom}(X_0; X_1) \rightarrow \text{hom}(X_0; X_k)[2-k]$$

satisfying

$$\sum_{l=1}^y \sum_{j=0}^1 (-1)^{y-k+1-l} (p_k; \dots; p_{j+l-1}; (-1)^{p_{j+l}}; p_{j+1}; \dots; p_1) = 0 \quad (5.1)$$

where  $y = j + \deg(p_1) + \deg(p_j)$ .

**Definition 5.1.4** Let  $A; B$  two  $A_1$ -categories. An  $A_1$ -functor  $F : A \rightarrow B$  is the datum of

1. A map  $F : Ob(A) \rightarrow Ob(B)$ .
2. For all  $n \geq 1$  and all  $A_0, \dots, A_n \in A$  a graded map

$$F_n : \text{hom}(A_{n-1}; A_n) \otimes \text{hom}(A_0; A_1) \rightarrow \text{hom}_B(F A_0; F A_n)$$

of degree  $1 - n$  satisfying similar relations of equation 5.1.

An  $A_1$ -functor is called an  $A_1$ -equivalence if the underlying cohomological level functor is an equivalence.

**Remark 5.1.5** What we called equivalence are called quasi-equivalence in [Sei08].

For  $k = 1$ , it gives  $\sum_1^2 = 0$ . Therefore  $\sum_1$  is a differential. And for  $k = 2$ , we have  $\sum_1(-\sum_2(p_2; p_1)) - \sum_2(\sum_1(p_2); p_1) - \sum_2(p_2; \sum_1(p_1)) = 0$ . Here the plus-minus sign depends on the degree of  $p_1$ .  $k = 2$  gives Leibniz rule.

To show that Fukaya category is an  $A_{\text{inf ty}}$ -category, we have to define the higher composition maps. We define

$$*_k(p_k; \dots; p_1) = \sum_{q \in (L_0; L_k); \text{ind}([u])=2-k} \#M(p_1; p_2; \dots; p_k; q; [u]; J) T^{w([u])} q$$

Here we have  $M(p_1; \dots; p_k; q; [u]; J)$  denote the moduli space of pseudo-holomorphic maps with boundary on  $(L_0; \dots; L_k)$  and boundary points  $p_1; \dots; p_k; q$  within homotopy class  $[u]$ . The  $A_1$ -relation is deduced again from Gromov compactness theorem and no bubbling property.

Now we give the true definition of Fukaya categories.

**Definition 5.1.6** Let  $(M; \omega)$  be a symplectic manifold, with  $2c_1(TM) = 0$ . We define the **Fukaya category** associated to  $(M; \omega)$ , denoted by  $F(M; \omega)$  by

1.  $Ob(F)(M; \omega) = \text{compact closed Lagrangian manifolds with } \dim L = 0$
2.  $\text{hom}(L_1; L_2) = CF(L; L^0; J_{L; L^0}; H_{L; L^0})$  where  $H_{L; L^0}; J_{L; L^0}$  are Floer data to make Floer complexes well defined

3. The composition maps  $\circ_k$  are given as above, where  $(H; J)$  perturbation data is required to make the composition map well defined. In a neighborhood of  $(L_0; \dots; L_k)$ ,  $(H; J)$  and  $H_{L; L^0}; J_{L; L^0}$  can be chosen to coincide.

From definition, we can see that  $F(M; w)$  depends on some chosen data. But we can prove that

**Proposition 5.1.7** *A Fukaya category is well-defined up to  $A_1$ -equivalence.*

## 6 Homological mirror symmetry for elliptic curves I (2022-04-10 Zhang Nantao)

### 6.1 References

The main references are [Por15] and [PZ98].

### 6.2 Fukaya category of elliptic curves

We first state following facts.

1. In (complex) dimension 1 case, every closed 1-submanifold is Lagrangian.
2. The relative spin structure is a  $\mathbb{Z}_2$  choice and can be suppressed.
3. Each Hamiltonian isotopy class of closed Lagrangian submanifold has a unique special Lagrangian representative. In elliptic curve case, it is a line with rational slope when lifted to universal cover  $\mathbb{C}$ .

**Remark 6.2.1** *In general Calabi-Yau, uniqueness of special Lagrangian representative is true while the existence is unknown.*

Topologically, every elliptic curve is equivalent. The symplectic structure is determined by a real number. For mirror symmetry, we in fact need to determine a complex Kähler form  $w_{\mathbb{C}} = dx \wedge dy = (B + iA) dx \wedge dy$ , such that  $w = A dx \wedge dy$ . The elliptic curve with complex Kähler form  $dx \wedge dy$ . We always identify  $E$  with  $\mathbb{C}/\hbar\mathbb{1}; ii$ .

Our Fukaya category  $Fuk(E)$  will be a little different from previous talk, but follows [PZ98].

1. Object:  $Ob(Fuk(E))$  are graded, oriented, closed geodesics equipped with a flat complex vector bundle of monodromy with unit eigenvalue. That is a pair  $L = (L; \dots; M)$ , such that  $z(t) = z_0 + te^{-i}$ , orientation of  $L$  defined by  $\mathbb{Z}(\frac{1}{2}; \frac{1}{2}]$  and  $\mathbb{Z}\mathbb{Z}$ .

2. Morphism:

$$\text{Hom}(L; L^0) := \begin{cases} \bigoplus_{p \in L \setminus L^0} \text{Hom}(M_p; M_p^0) & \text{if } L \not\subset L^0 \\ \text{Hom}(M; M^0) & \text{if } L = L^0 \end{cases}$$

$\mathbb{Z}$  grading on morphism  $L \rightarrow L^0$  is given by Maslov index  $\mu(L; L^0) = d - \dim L^0$ .

We have a shifted functor  $(L; \dots; M)[1] = (L; \dots; M + 1)$ . Composition of morphisms are given by

$$m_k(u_1, \dots, u_k) = \sum_{p \in L_k \setminus L_0} C(u_1; \dots; u_k; p)p$$

where we assume that every  $u_i = \sum t_i p_i$ . And

$$C(u_1; \dots; u_k; p) = \sum_{\{j\}} e^{2\pi i \int w_{\mathbb{C}} h_{\otimes}(u_1, \dots, u_k)}$$

sum over  $\{j\}$  in

$$CM_{k+1}(X; L_0; \dots; L_k; p_0; \dots; p_k) := f(\dots; S_k = (0 = p_0 < p_1 < \dots < p_k < 2\pi))j$$

$$: D \rightarrow X \text{ is pseudo holomorphic}; (e^{it_j}) = p_j; (e^{it_j}) \in L_j \quad \forall t \in (\frac{j-1}{k}; \frac{j}{k})^{g=}$$

where  $(\cdot; S_{k+1}) = (\cdot; S_{k+1}^\theta)$  if there exists biholomorphic map  $f: D \rightarrow D$  such that  $f^\theta = f$  and  $f(e^{i\cdot}) = e^{i\cdot}$ . And

$$h_\theta(u_1, \dots, u_k) := P_{k-1} u_k - u_1 P_0$$

where  $P_j$  is parallel transport and  $t \in [j-1, j]$ . For simplicity, we may assume  $P = \exp(Ml)$  where  $M$  is monodromy and  $l$  normalized length. We now consider  $m_1: \text{Hom}(L_0; L_1) \rightarrow \text{Hom}(L_0; L_1)$  by some pictorial argument, we have  $CM_2 = 0$  and therefore  $m_1(u_1) = 0$  for every  $u_1$ . Therefore, by  $m_2(m_2(\cdot; \cdot); \cdot)$   $m_2(\cdot; m_2(\cdot; \cdot)) = m_1(m_3(\cdot; \cdot; \cdot)) = m_3(m_1(\cdot); \cdot) = m_3(\cdot; m_1(\cdot); \cdot) = m_3(\cdot; \cdot; m_1(\cdot)) = 0$ , we have  $m_2(\cdot; m_2(\cdot; \cdot)) = m_2(m_2(\cdot; \cdot); \cdot)$ ,  $m_2$  is associative. The simplest example, is  $\theta = iA$ , then  $L_d = (L_d; \cdot; M)$  where  $L_d$  had slope  $d$  passing through 0 and  $\mathbb{Z}(\frac{1}{2}; \frac{1}{2})$  and  $M$  trivial line bundle on  $L$ .

Then  $L_0 \setminus L_1 = f e_1 g$ ,  $L_1 \setminus L_2 = f e_1 g$  and  $L_0 \setminus L_2 = f e_1; \cdot; e_2 g$ . We have  $m_2(e_1; e_1) = C(e_1; e_1; e_1) e_1 + C(e_1; e_1; e_2) e_2$ , where

$$C(e_1; e_1; e_1) = \sum_{n \in \mathbb{Z}} e^{-2\pi n^2}$$

$$C(e_1; e_1; e_2) = \sum_{n \in \mathbb{Z}} e^{-2\pi A(n + \frac{1}{2})^2}$$

### 6.3 Derived category of coherent sheaves for elliptic curves

Now we define  $E = \mathbb{C}/\hbar\mathbb{Z}$ , or  $E_q = \mathbb{C}/\mathbb{Z}$  with  $\mathbb{Z}$  action generated by  $z \mapsto qz$ ,  $q = e^{2\pi i}$ . To understand the derived category of coherent sheaves on  $E_q$ , we first study the line bundles on  $E_q$ . By covering  $\mathbb{C} \rightarrow E_q$  every line bundle on  $E_q$  lifts to a line bundle on  $\mathbb{C}$ . But topologically every complex line bundle on  $\mathbb{C}$  is trivial. So any holomorphic function  $\phi: \mathbb{C} \rightarrow \mathbb{C}$  give rise to a line bundle

$$L(q)(\cdot) := \mathbb{C} \times_{\mathbb{C}=\langle u;v \rangle} (uq; (u)v)$$

Later I fixed  $q$  and omit it in subscript. All line bundles on  $E_q$  can be described in this way, and  $L(\cdot) = L(\cdot)^\theta$  if and only if there exists some holomorphic  $B: \mathbb{C} \rightarrow GL(\mathbb{C})$  such that  $\theta(u) = B(qu)(u)B^{-1}(u)$ . We have that

$$L(\cdot_1) \otimes L(\cdot_2) = L(\cdot_1 + \cdot_2)$$

By directly check the transition function.

Let  $\text{Pic}^d(C)$  denote the space of degree  $d$  line bundles on a curve  $C$  of genus  $g$ . Let  $L_d \in \text{Pic}^d(C)$ , we have isomorphism

$$J(C) := \text{Pic}^0(C) \times \text{Pic}^d(C)$$

$$L \mapsto L \otimes_{\mathcal{O}_C} L_d$$

By Abel-Jacobi theorem, Jacobian variety of  $C$  is isomorphic to a complex torus of dimension  $g$ . In elliptic curve case,  $J(E) = E$ . Also, give  $x \in E$ , we have  $L_x$  is degree 1 line bundle on  $C$ . By above notation, we fix an degree 1 line bundle  $L$ . Then every degree  $n$  line bundle is determined by  $(t_x L) \otimes L^{n-1}$  where  $t_x$  is the automorphism of  $E_{\text{tau}}$  given by translation. If  $L = L(y)$ , we have  $t_x L = L(x+y)$ .

We define  $L := L(\cdot_0)$  where  $\theta_0(u) = q^{-1/2} u^{-1}$ . Later we will show that  $L$  has a holomorphic section with a simple zero. So  $L$  has degree 1. Given two holomorphic line bundles  $L_1 = (t_x L) \otimes L^{n-1}$  and  $L_2 = (t_y L) \otimes L^{m-1}$ . We need to determine homomorphism between them.

$$\text{Hom}(L_1; L_2) = H^0(L_1 \otimes L_2) = H^0((t_x L \otimes t_y L) \otimes L^{m-n})$$

By using  $t_0^k = e^{-2\pi i k} t_0^k$ . We have

$$L^\theta = L(t_{x_0}^{-1} \otimes t_{y_0}^{m-n}) = t(L^k)$$

for  $k = m - n$  and  $\theta := \frac{y}{x}$  and where last equality holds for  $k \neq 0$ . For  $k < 0$ , we have  $H^0(L^\theta) = 0$ , and for  $k = 0$ , we have  $H^0(L^\theta) = 0$  if  $x \neq y$  and  $k$  if  $x = y$ .

We now determine  $H^0(L^\theta)$ . This is done by theory of  $\theta$ -functions to solve these questions. Consider the classical Jacobi **theta function**,  $\theta: \mathbb{C} \rightarrow \mathbb{C}$  given by

$$(z) := \sum_{m \in \mathbb{Z}} e^{-\pi(m^2 + 2mz)} = \sum_{m \in \mathbb{Z}} q^{\frac{1}{2}m^2} u^m$$

where  $q = e^{2\pi i}$ ,  $u = e^{2\pi iz}$ . Since  $\text{Re}(z) > 0$ , the summation converges.

**Proposition 6.3.1** 1.  $\theta(z+1) = \theta(z)$

$$2 \quad \theta\left(\frac{z}{2}\right) = \theta(z)$$

$$3 \quad \theta(z + \frac{1}{2}) = e^{-2\pi i \lfloor z \rfloor + 2\pi i z} \theta(z) = q^{-1/2} u^{-1} q(u)$$

$$4 \quad \theta\left(\frac{z}{2} - z\right) = e^{2\pi i z} \theta\left(\frac{z}{2} + z\right)$$

$$5 \quad \theta(x) = 0 \text{ if and only if } z = \frac{1}{2} + \frac{z}{2} + (k + l), \quad k, l \in \mathbb{Z} \text{ and these zeros are simple.}$$

Recall  $\theta_0 = q^{-1/2} u^{-1}$ , so  $\theta(z)$  gives a global section of  $L$ .

**Proof** 1,2,3,4 are easy from definition. Also,

$$\left(\frac{1}{2} + \frac{z}{2}\right) = \sum_{m \in \mathbb{Z}} (-1)^m e^{i(m^2 + m)} = 0$$

To show it is a simple pole, we consider the integral of  $\theta =$  around the fundamental parallelogram using property 1 and 2. Such that

$$\frac{1}{2} \oint_{\text{parallelogram}} \frac{d}{dz} (\log f) dz = 1$$

Let  $\theta^{(x)}$  denote the  $\theta$  function with zero at  $x$ , i.e.,

$$\theta^{(x)}(z) := \theta\left(z - \frac{1}{2} - \frac{z}{2} - x\right)$$

**Theorem 6.3.2** A function  $R: E \rightarrow \mathbb{C}$  is meromorphic if and only if it can be written in the form

$$R(z) = \frac{\prod_{i=1}^d \theta^{(x_i)}(z)}{\prod_{i=1}^d \theta^{(y_i)}(z)}$$

For  $f x_i g; f y_i g$  finite set of  $d > 0$  such that  $\sum x_i = \sum y_i \in \mathbb{Z}$ .

Now, we go to compute  $H^0(L^{-\theta})$ . We have following generalization of theta functions.

$$[a; z_0](z) = \sum_{m \in \mathbb{Z}} e^{i(m+a)^2 + 2(m+a)(z+z_0)}$$

**Proposition 6.3.3** 1.  $[a+b; 0](z) = e^{i[a^2 + 2az]} [b; z](z+a)$

2. Let  $a, b \in \mathbb{Q}$ ,  $n_1, n_2 \in \mathbb{Z}_{>0}$ ,  $k = n_1 + n_2$  and  $c_j = j n_1 + a + b$ . Then

$$[a; n; 0](n_1; z_1) [b; n_2; 0](n_2; z_2) = \sum_{j \in \mathbb{Z}, k \in \mathbb{Z}} \left[\frac{c_j}{k}; 0\right](k; z_1 + z_2) \left[\frac{n_2 c_j}{n_1 n_2 k}; 0\right](n_1 n_2 k; n_2 z_1 - n_1 z_2)$$

By setting  $n_1 = n_2 = 1$ ,  $a = b = 0$ ,  $z = z_1 = z_2 = x$ , we have

$$\theta(z) \theta(z+x) = \theta\left(\frac{z}{2}\right) \theta\left(\frac{2z+x}{2}\right) = \left[\frac{1}{2}; 0\right](2; x) \left[\frac{1}{2}; 0\right](2r; 2z+x)$$

For  $k = m - n > 0$  and  $x := \frac{y-x}{k}$  we have

$$\text{Hom}(L_1; L_2) = H^0(L^{-\theta}) = \text{span}_{\mathbb{C}} \{ [j=k; k](k; kz) g_{j \in \mathbb{Z}, k \in \mathbb{Z}} \}$$

To see this, we only need to consider  $H^0(L^{-\theta})$ , and we notice the dimension of  $H^0(L^{-\theta})$ , are equal to  $\deg(L^{-\theta})$  by Riemann-Roch theorem. And theta functions are linear independent.

## 6.4 First example of HMS

We assume  $\omega = iA$  and consider  $L_0 = \mathcal{O}$ ,  $L_1 = L$  and  $L_2 = L^2$  in  $D^b(E)$  which are mapped by mirror functor to  $L_0; L_1; L_2$  discussed before. We have  $\text{Hom}(L_0; L_1) = \text{Hom}(L_1; L_2) = \text{span}\{g\}$ . And

$$\text{Hom}(L_0; L_2) = \text{span}\{[0;0](2r;2z); [1=2;0](2z;2z)g\}$$

We map  $e_1 \in \text{Hom}(L_0; L_1) \xrightarrow{g} (z) \in \text{Hom}(L_0; L_1)$ ,  $e_1 \in \text{Hom}(L_1; L_2) \xrightarrow{g} (z) \in \text{Hom}(L_0; L_1)$ . Also,  $\text{Hom}(L_0; L_2) \xrightarrow{g} \text{Hom}(L_0; L_2)$  mapping  $e_1 \mapsto [0;0](2r;2z)$ ,  $e_2 \mapsto [1=2;0](2r;2z)$ . Recall,  $m_2(e_1; e_1) = C(e_1; e_1; e_1)e_1 + C(e_1; e_1; e_2)e_2$  where

$$C(e_1; e_1; e_1) = \frac{1}{2} (0)$$

$$C(e_1; e_1; e_2) = [1=2;0](2z;0)$$

But we have

$$(g(z))^2 = \frac{1}{2} (0) \frac{1}{2} (2z) + [1=2;0](2z;0) [1=2;0](2r;2z)$$

Therefore the composition law holds for the mirror functor.

## 7 Homological mirror symmetry for elliptic curves II (2022-04-17 Zhang Nantao)

### 7.1 Derived category of coherent sheaves (continued)

We first introduce following theorems.

**Theorem 7.1.1** *All indecomposable coherent sheaves over a Riemann surface are either an indecomposable vector bundle or a torsion sheaf supported at one point.*

**Theorem 7.1.2** *Let  $C$  be a compact Riemann surface, finite direct sums of objects  $F[n]$ , where  $F$  is an indecomposable coherent sheaf on  $C$ , form a full subcategory of  $D^b(C)$  which is equivalent to  $D^b(C)$ .*

The above theorem is proved using following lemma.

**Lemma 7.1.3** *If  $A$  is an abelian category of homological dimension  $\leq 1$ , then we have*

$$A = \bigoplus_k H^k(A)[k]$$

in  $D^b(A)$ .

By Serre duality, we have

$$\text{Hom}(F; G) = \text{Ext}^1(G; F)$$

for coherent sheaves  $F; G$ .

We first consider vector bundles on  $E$ . First, we have holomorphic vector bundles on  $E$  given by  $F_q(V; A) = \mathbb{C} \oplus V = (u; v) \mapsto (uq; Av)$  for  $A \in GL(V)$ . It is unique up to  $B : \mathbb{C} \rightarrow GL(V)$ ,  $A(u) = B(qu)A^0(u)B(u)^{-1}$ .

If  $A = \exp(N)$ , with  $N$  nilpotent with one dimensional kernel, then  $F_q(V; \exp(N))$  is indecomposable. Let  $\pi : E_{q^r} \rightarrow E_q$   $r$ -fold covering. We have following theorem from Atiyah.

**Theorem 7.1.4** *Every indecomposable holomorphic vector bundle on  $E$  is of the form*

$$\pi^*(L_{q^r} \otimes F_{q^r}(V; \exp(N)))$$

for some  $r, N$  and  $r$ .

Let us ignore  $\pi$  first and consider  $L(\cdot) = F(V; \exp(N))$ .

**Lemma 7.1.5** *Let  $\pi = (t_x \ 0) \begin{pmatrix} n & 1 \\ 0 & 0 \end{pmatrix}$  for some  $n > 0$ . Then for any nilpotent  $N \in \text{End}(V)$  there is a canonical isomorphism*

$$\pi^* : H^0(L(\cdot)) \rightarrow V \oplus H^0(L(\cdot) \otimes F(V; \exp(N)))$$

$$f \mapsto v \oplus \exp(DN=n)f$$

where  $D = u \frac{d}{du}$ .

$$\exp(DN=n)f(qu)v = \sum_{k=0}^N \frac{1}{k!n^k} D^k(f) N^k v = \exp(N) \left( \exp \frac{DN}{n} f \right) v$$
$$\text{Hom}(V_1; V_2) = H^0(L(\begin{smallmatrix} & 1 \\ 1 & \end{smallmatrix})) \quad F(V_1 \oplus V_2; \exp(\begin{smallmatrix} N_1 & 0 \\ 0 & N_2 \end{smallmatrix})) = H^0(L(\begin{smallmatrix} & 1 \\ 1 & \end{smallmatrix})) \quad \text{Hom}(V_1; V_2)$$
$$Ob(Fuk^0) = Ob(Fuk(E))$$
$$\mathrm{Hom}_{Fuk^0}(L; L^\theta) = \begin{cases} 0 & \text{if } \theta \in \mathcal{B}[0; 1) \\ \mathrm{Hom}(M_p; M_p^\theta) & \text{if } \theta \in \mathcal{Z}[0; 1) \end{cases}$$
$$\mathrm{Hom}_{Fuko}(L; L^{\theta}) = \begin{cases} \geq 0 & \text{if } \theta \notin 0; 1 \\ H^0(L; \mathrm{Hom}(M; M^{\theta})) & \text{if } \theta = \\ H^1(L; \mathrm{Hom}(M; M^{\theta})) & \text{if } \theta = +1 \end{cases}$$
$$\mathrm{Hom}(L_1; L_2[1]) = \mathrm{Hom}(L_2; L_1)$$
$$O(n!) = O(n!)$$

22

given by

$$p_r(L; \cdot; M) \cong (p_r(L); \cdot^0; p_r^* M)$$

with  $\cdot; \cdot^0$  both contained in  $[k - \frac{1}{2}, k + \frac{1}{2})$  for some  $k$ .  $p_r^* M$  has monodromy

$$(v_1; \cdot; v_d) \cong (v_2; \cdot; v_d; M v_1)$$

$$\begin{array}{ccc} \mathrm{Hom}(L; L^\theta) & \xrightarrow{=} & \bigoplus_{x \in L \setminus L^\theta} \mathrm{Hom}(M_x; M_x^\theta) \\ \downarrow p_r & & \downarrow \\ \mathrm{Hom}(p_r^* L; p_r^* L^\theta) & \xrightarrow{=} & Z \end{array}$$

And  $Z := \bigoplus_{x \in p_r(L) \setminus p_r(L^\theta)} \mathrm{Hom}(\bigoplus_{\mathbf{x} \in p_r(j_L)^{-1}(x)} M_{\mathbf{x}}; \bigoplus_{\mathbf{x} \in p_r(j_L^\theta)^{-1}(x)} M_{\mathbf{x}}^\theta)$ .

Also, we have pullback,  $p_r: FK(E^r) \rightarrow FK(E)$  given by

$$p_r(L; \cdot; M) = \bigoplus_{k=1}^N (L^{(k)}; \cdot^0; (p_r^{(k)})^* M)$$

where  $p_r^{(k)} := p_r j_{L^{(k)}}$  and  $(p_r^{(k)})^* M$  is the local system pullback.

**Proposition 7.3.3** Let  $p = t_{n=m}^\theta p_r$  for  $n=m \in \mathbb{Q}$  and  $t^\theta(x; y) := (x \cdot; y)$  then

$$\mathrm{Hom}(p^* L; L^\theta) = \mathrm{Hom}(L; p^* L^\theta)$$

and

$$\mathrm{Hom}(p^* L; L^\theta) = \mathrm{Hom}(L; p^* L^\theta)$$

the same is true for derived category of coherent sheaves when  $\cdot = t_{n=m}^\theta \cdot_r$ .

That is if we establish the mirror functor  $\cdot: D^b(E) \rightarrow FK(E)$  on  $L(\cdot) \rightarrow F(V; \exp(N))$ , we can extend to all indecomposable vector bundles by assigning

$$(\cdot_r A) := p_r^*(\cdot(A))$$

And we also need to define

$$\mathrm{Hom}(\cdot_{r_1} E_1; \cdot_{r_2} E_2) \cong \mathrm{Hom}(p_{r_1}^*(E_1); p_{r_2}^*(E_2))$$

To do this, we consider the fiber product  $E_{r_1} \times_E E_{r_2}$  disjoint union of elliptic curves  $E_r \rightarrow \mathbb{Z}_d$ , where  $d = \gcd(r_1; r_2)$  and  $r = \mathrm{lcm}(r_1; r_2)$ . Let  $\sim_{r_1; v}: E_r \rightarrow \mathrm{fvg} \rightarrow E_{r_1}$  and  $\tilde{p}_{r_1; v}: E_r \rightarrow \mathrm{fvg} \rightarrow E_{r_1}$ . Then we have  $\tilde{p}_{r_2} \circ \tilde{p}_{r_1} = p_{r_1} \circ p_{r_2}$ . Then we define

$$\begin{array}{ccc} \mathrm{Hom}(\cdot_{r_1} E_1; \cdot_{r_2} E_2) & \xrightarrow{=} & \bigoplus_{v=1}^d \mathrm{Hom}(\sim_{r_1; v} E_1; \sim_{r_2; v} E_2) \\ \downarrow & & \downarrow \\ \mathrm{Hom}(\cdot_{r_1} E_1; \cdot_{r_2} E_2) & \xrightarrow{=} & \bigoplus_{v=1}^d \mathrm{Hom}(\sim_{r_1; v} E_1; \sim_{r_2; v} E_2) \\ \downarrow & & \downarrow \\ \mathrm{Hom}(p_{r_1}^*(E_1); p_{r_2}^*(E_2)) & \xrightarrow{=} & \bigoplus_{v=1}^d \mathrm{Hom}(\tilde{p}_{r_1; v}^* E_1; \tilde{p}_{r_2; v}^* E_2) \end{array}$$

By Serre duality on both side, the splitting of complex and Grothendieck vanishing, we only need to consider the the morphisms in  $\mathrm{Coh}(E) \rightarrow D^b(E)$ .

Second, we need to construct the morphism for  $F(V; \exp(N))$  and  $S = S(a \cdot b; V; N)$ . For  $A = L(\cdot) \rightarrow F(V; \exp(N))$ ,  $\cdot = (t_{a+b}^\theta) \cdot_0^{n-1}$ , then  $\cdot(A) = (L; \cdot; M)$  where

- $L$  is the submanifold of  $E$  with lift parametrized by  $t \mapsto (a + t; (n-1)a + nt)$ .
- $\cdot$  is the unique  $\cdot$  such that  $\cdot_1 = 2 < \cdot < \cdot_1 = 2$ .
- $M = e^{-2 \cdot ib} \exp(N)$ .

For indecomposable torsion sheaf  $S = S(a, b; V; N)$ , we then  $r(S) = (L; \frac{1}{2}; e^{-2ib} \exp(N))$  with  $L$  vertical with  $x$ -interception  $a$ . Now we consider the functor between morphisms. If  $A_i = L(t_i) \otimes F(V_i; \exp(N_i))$ ,  $x_i = a_i = n_i$ , we define

$$r : \text{Hom}(A_1; A_2) \rightarrow \text{Hom}_{FK(E)}(r(A_1); r(A_2))$$

Let  $r = t_{21} + 21 f_k^{(n_2 - n_1)}$  for  $21 := \frac{n_2 x_2 - n_1 x_1}{n_2 - n_1}$  and  $21 := \frac{2 - 1}{n_2 - n_1}$ ,  $f_k^{(n_2 - n_1)}(z) := [\frac{k}{n_2 - n_1}; 0]((n_2 - n_1); (n_2 - n_1)z)$ . Then

$$(r(f)) = e^{i \frac{2}{21}(n_1 - n_2)} \exp(21(N_2 - N_1 - 2i(n_2 - n_1)21)) f e_k$$

where

$$e_k = (\frac{n_1 x_1 - n_2 x_2 + k}{n_1 - n_2}; \frac{n_1}{n_1 - n_2} [n_2(x_1 - x_2) + k])$$

for  $k \in \mathbb{Z} = (n_1 - n_2)\mathbb{Z}$ . If  $n_2 = n_1$  then the morphism space is zero unless  $2 = 1$  and we have the map between morphism identity map.

For  $S = S(a, b; V^0; N^0)$ , then  $\text{Hom}(S; A) = 0$  and  $\text{Hom}(r(S); r(A)) = 0$  for  $A = L(t_a + \frac{n}{0} 1) \otimes F(V; \exp(N))$  then  $\text{Hom}(A; S) = \text{Hom}(V; V^0)$ . The Lagrangian intersects at 1 point and therefore we have

$$r : V^0 \rightarrow V \rightarrow V^0 \rightarrow V$$

$$r = e^{-i(na^2 - 2a) + 2i(a + b - nab)} \exp[(na - 1)V - N^0 + N - 1V^0]$$

For  $S_i = S(a_i, b_i; V_i; N_i)$ , since they supported at a point, we only need to consider the case  $a_1 + b_1 = a_2 + b_2$ , then

$$\text{Hom}(S_1; S_2) = f f \in \mathbb{Z} \text{Hom}(V_1; V_2) \text{ if } N_1 = N_2 \text{ if } f g = \text{Hom}(r(S_1); r(S_2))$$

By above construction, we explicitly describe the functor  $r$  for indecomposable object in  $\text{Coh}(E)$ .

Finally, we need to check the composition law holds, which we omitted.

## 7.4 Derived category of $A_1$ categories

Now we discussion more on Fukaya categories. We want to construct a triangulated category from this  $A_1$ -category. First, we construct the additive enhancement of  $A_1$ -category  $A$ ,  $\tilde{A}$ .

$$\text{Ob}(\tilde{A}) = fX = \sum_{i \in I} V^i \otimes X^i g$$

where  $V^i$  is graded vector space and  $I$  totally orderd. Morphisms are given by

$$\text{hom}_{\tilde{A}}(\sum_{i \in I_0} V_0^i \otimes X_0^i; \sum_{i \in I_1} V_1^j \otimes X_1^j) = \sum_{i, j} \text{hom}(V_0^i; V_1^j) \otimes \text{hom}_A(X_0^i; X_1^j)$$

and compositions are given by shifting compositions in  $A$ .

Second, we consider the  $twA$  as closure under extensions.

$$\text{Ob}(twA) = fX; \sum_{X \in \mathcal{G}}$$

where  $\sum_{X \in \mathcal{G}} \text{hom}_{\tilde{A}}^1(X; X)$ , and  $\sum_{X \in \mathcal{G}} = (i, j)$  a matrix for  $i, j \in \mathbb{Z} \text{hom}_{\tilde{A}}^1(V^i \otimes X^i; V^j \otimes X^j)$ . We require  $i, j = 0$  for all  $i > j$ , and

$$\sum_{t=1}^{\infty} r_A(\sum_{X \in \mathcal{G}}; \sum_{X \in \mathcal{G}}) = 0$$

since  $\sum$  is strictly upper triangle, the sum is finite. The morphisms are given by

$$\text{hom}((X; \sum); (X^0; \sum)) = \text{hom}_{\tilde{A}}(X; X^0)$$

The composition is given by

$$\sum_{i_1, \dots, i_d} d_{twA}(a_d; \dots; a_1) = \sum_{A} d_A^{d+i_0+1} + i_d(\sum_{X_d} a_d; \dots; \sum_{X_{d-1}} a_{d-1}; \dots; \sum_{X_1} a_1; \dots; \sum_{X_0} a_0)$$

there are  $i_d$  times  $\sum_{X_d}$ .



The purpose of above enhancement is to make direct sum and shift  $(S(-) = (-) \otimes k[1])$  possible. Further, we have mapping cone for  $c \in \text{hom}_{\text{tw}A}(Y_0; Y_1)$

$$C = SY_0 \rightarrow Y; \quad c = \begin{pmatrix} S(Y_0) & 0 \\ S(c) & Y_1 \end{pmatrix}$$

such that  $D(A) = H^0(\text{tw}A)$  is an triangulated category, called **derived category** of  $A$ .

Furthermore, we want the category to be **split closed**, that is for  $p \in \text{Hom}_A(Y; Y)$ ,  $p^2 = p$  idempotent, then  $Y = Z \oplus Z^\perp$  respect to  $p$ . As derived category of coherent sheaves is split closed, we have to take the **split closure** of  $H^0(\text{tw}A)$  by formally adding all splittings to get

$$D^{\text{sc}}(A) = PH^0(\text{tw}A)$$

called **split closed derived category**.  $P$  is the **Karoubi completion**. For  $A$  category, we have  $Ob(PA) = (Y; p)$ , where  $p$  is idempotent morphism.  $\text{Hom}_{PA}((Y_0; p_0); (Y_1; p_1)) = p_1 \text{Hom}(Y_0; Y_1) p_0$ .

In [Sei15; She15], they prove there exists an equivalence of triangulated categories

$$D^{\text{sc}}(\text{Fuk}(M^n)) \cong D^b \text{Coh}(N_{\text{nov}}^n)$$

where  $\gamma \in \mathbb{C} \setminus \mathbb{R}$ ,  $|\gamma| = 1$ , and  $\gamma$  is an automorphism of  $\mathbb{C} \setminus \mathbb{R}$ , such that  $\gamma(r) = \bar{r} \gamma(r)$ . And  $\gamma^2$  is a lifting of  $\gamma$  to Novikov field.

$$= \sum_{j=0}^{\infty} c_j r^j; \quad j \in \mathbb{R}; \quad \lim_{j \rightarrow +\infty} j = +\infty$$

$M^n \subset \mathbb{C}P^{n-1}$  is  $(n-2)$ -dimensional Calabi-Yau hypersurface. And  $N_{\text{nov}}^n = f_{W_{\text{nov}}} = 0$  where  $W_{\text{nov}} = u_1 \dots u_n + r \sum_{j=1}^n u_j^n \in [u_1; \dots; u_n]$ , with  $\gamma := (Z_n)^n = (1; \dots; 1)$  acting on  $P^n$  by multiplication by root of unity. And  $\gamma = \ker(\gamma - 1)$  acts on  $N_{\text{nov}}^n$ . Then we define

$$N_{\text{nov}}^n := N_{\text{nov}}^n / \gamma$$

is the stacky root. So we have  $D^b \text{Coh}(N_{\text{nov}}^n) = D^b(\text{Coh}(\gamma(N_{\text{nov}}^n)))$ .

**Remark 7.4.1** It can be made an (quasi)equivalence of  $A_1$ -categories by choosing dg enhancement of right hand side and making split closure of  $\text{twFuk}(M^n)$  on the right hand side.

**Remark 7.4.2** The equivalence is only proved for one side, that A-side of  $M^n$  is equivalent to B-side of  $N_{\text{nov}}^n$ . Homological mirror symmetry also conjectures the dual part that is the B-side of  $M^n$  is equivalent to the A-side of  $N_{\text{nov}}^n$ , which is proved for qurtic surface in [SS21] but not for higher dimensional case.

## 8 Constructible sheaves and the Fukaya category (2022-04-24 Zhou Jiawei)

### 8.1 References

We discuss paper [NZ09].

### 8.2 Constructible sheaves

We always assume that  $X$  is a real analytic manifold. The main theorem is that

**Theorem 8.2.1**  $D_c(X) = D(\text{Sh}(X)) \cong D^b \text{Fuk}(T^*X)$  where  $\text{Sh}(X)$  is the category of constructible sheaves.

**Definition 8.2.2** A sheaf  $F$  is called **constructible** if there exists a Whitney stratification  $X = \bigcup X_i$  such that  $F|_{X_i}$  is a local system (and finitely generated).

We consider the dg category  $\text{Sh}_{\text{naive}}(X)$  where the objects are complex of sheaves with bounded constructible cohomology. And morphisms are internal hom between complexes. Let  $N \subset \text{Sh}$  subcategory of acyclic objects. And we define  $\text{Sh}(X)$  as the dg quotient  $\text{Sh}_{\text{naive}}(X)/N$ . The proof of the main theorem consists of three part, equivalence of  $D(\text{Sh}(X))$  and  $D(\text{Open}(X))$ , equivalence of  $\text{Open}(X)$  and  $\text{Mor}(X)$  and equivalence of  $\text{Mor}(X)$  and  $\text{Fuk}(T^*X)$ .

### 8.3 Category $Open(X)$

We first define  $Open(X)$ . The objects are pairs  $U = (U; m)$ , where  $U \subset X$  is open and  $m : X \rightarrow \mathbb{R}^0$  is the defining function for  $X \setminus U$ , i.e.  $m(x) = 0$  if and only if  $x \in X \setminus U$ . The morphisms between pairs  $U_0; U_1$  are relative de Rham complex  $\text{hom}_{Open(X)}(U_0; U_1) = (U_0 \setminus U_1; @U_0 \setminus U_1; d)$ . We consider the morphism  $p : Open(X) \rightarrow Sh(X)$ ,  $(U; m) \mapsto i^! C_U$ , where  $C_U$  is the locally constant sheaf of complex value on  $U$  and  $i : U \hookrightarrow X$  the inclusion.

**Proposition 8.3.1**  $D(Open(X)) = D(Sh(X))$ .

Firstly, we have the following lemma.

**Lemma 8.3.2**  $\text{hom}_{Sh(X)}(i_0^! C_{U_0}; i_1^! C_{U_1}) \xrightarrow{qis} (U_0 \setminus U_1; @U_0 \setminus U_1; d)$ .

Assuming the above lemma, the result follows from the following proposition.

**Proposition 8.3.3** Any objects of  $Sh(X)$  is isomorphic to an object obtained by shifting of  $i^! C_U$ ,  $U$  open and  $i : U \hookrightarrow X$  inclusion, by iteratively forming cones.

**Proof** We have  $Z \subset X$ ,  $i : U \hookrightarrow Z$  open and  $j : Y = Z \setminus U \hookrightarrow Z$  closed. For all  $F$  sheaf on  $Z$ , there exists a distinguished triangle

$$j_* j^! F \rightarrow F \rightarrow i_* i^! F$$

Using above fact, we first claim that any object in  $Sh(X)$  is isomorphic to an object shifting by standard object by iteratively forming cones. The standard objects are those of the form  $i^! L_Y$ , where  $L_Y$  is a local system on  $Y \subset X$  and  $i : Y \hookrightarrow X$ . Let  $S$  strata with respect to which  $F$  is constructible. We define  $S_k = \{f\text{strata of dimension } k\}$ , and  $S_{<k} = \{f\text{strata of dimension } < k\}$ . We denote  $i_k : S_k \hookrightarrow X$  and  $j_k : S_{<k} \hookrightarrow X$  suppose  $\dim X = n$ , then we have distinguished triangle

$$j_{<n} j_{<n}^! F \rightarrow F \rightarrow i_k i_k^! F$$

The last term is standard. Let's denote the first term by  $F_n$ . Then we have

$$j_{<n-1} j_{<n-1}^! F_n \rightarrow F_n \rightarrow i_{n-1} i_{n-1}^! F_n$$

By induction we prove our claim.

It remains to show when  $T$  is a stratification and  $T$  strata, then  $i^! C_T$  can be obtained by  $i^! C_U$  for  $U$  open. To prove this, we define  $Star(T) = \{f\text{strata whose closure containing } Tg \text{ which is open}\}$ . And we denote  $Star^0(T) = Star(T) \setminus T$  which is also open.  $s : Star(T) \hookrightarrow X$  and  $s^0 : Star^0(T) \hookrightarrow X$ ,  $j : T \hookrightarrow X$ , then we have distinguished triangle

$$j_* j^! C_{Star(T)} \rightarrow s_* C_{Star(T)} \rightarrow s_* C_{Star^0(T)}$$

But we have  $j^! C_{Star(T)}$  is isomorphic to some shift of  $C_T$ , and thus finish our proof.

### 8.4 Category $Mor(X)$

We now define the category  $Mor(X)$  whose objects are the same as  $Open(X)$  and the morphisms are generated by

$$CfCrit(X_{m_0=0} \setminus X_{m_1>1}; f_1 \rightarrow_0 f_0)g$$

where  $f_i = \log m_i : U_i \rightarrow \mathbb{R}$  and  $1; 0; 0$  is to guarantee finding a metric  $g$  such that  $(f_1 \rightarrow_0 f_0; g)$  is direct pair on  $X_{m_0=0; m_1=1}$ . We call  $(f_1 \rightarrow_0 f_0; g)$  a **direct pair** if  $r(f_1 \rightarrow_0 f_0)$  is inward pointing along  $X_{m_1=1}$  and outward pointing along  $X_{m_0=0}$ .

To define the  $A_1$  structure on  $Mor(X)$ , we need to introduce **based metric ribbon tree**,  $(T; i; v_0; \cdot)$ , where  $T$  finite tree with  $d+1$  vertices, with no vertices has exact 2 edges,  $i : T \rightarrow D \subset \mathbb{R}^2$  where  $D$  is the closed disk and vertices are mapped to  $@D$  and edges are mapped to  $D \setminus v_0$  is a chosen end vertex and  $\cdot : f\text{internaledge} \rightarrow \mathbb{R}^+$ . Orientation of edges are given by the minimal path point to root vertex. Label the  $d+1$  components in  $D \setminus T$  with number  $\in \mathbb{Z} \setminus \{d+1\}\mathbb{Z}$  counterclockwisely. Starting from 0, the left part of the edge terminate at  $v_0$ .

Suppose  $i \in \mathbb{Z} \setminus \{d+1\}\mathbb{Z}$ ,  $U_i \subset X$  open, and  $f_i : U_i \rightarrow \mathbb{R}$  extended to a neighborhood of  $U_i$  and critical point of  $f_{i+1} - f_i$  is nondegenerate, and lies in  $U_i \setminus U_{i+1}$ , such that  $g$  is a metric and  $(f_{i+1} - f_i; g)$  is a direct pair. If such  $g$  exists, call  $f(U_i; f_i)g$  **transverse collection**. A pair  $(T; i; v_0; \cdot)$  is a **gradient tree** where  $\cdot : T \rightarrow X$  is continuous such that

1. For all vertex  $v \in T$ , and  $e$  external edge containing  $v$ , we have

$$(v) \in \text{Crit}(U_{r(e)} \setminus U_{l(e)}; f_{r(e)} - f_{l(e)})$$

where  $l(e)$  and  $r(e)$  are left and right side of the edge  $e$ .

2. Identifying internal edge  $e = [0; (e)]$ , we have

$$j_e = r(f_{l(e)} - f_{r(e)})$$

3. Identifying external edge  $e = (-1; 0]$ ,

$$j_e = r(f_{r(e)} - f_{l(e)})$$

Now fix  $x_i \in \text{Crit}(U_i \setminus U_j; f_{i+1} - f_i)$ , we have the moduli space of gradient trees

$$M(T; f_0; \dots; f_d; x_0; \dots; x_d)$$

where the vertices of  $T$  are mapped to  $x_i$ . We now define the  $A_1$  structure on  $\text{Mor}(X)$  by

$$1(x_0) = \sum_{T \ni x_1} \sum_{x_1} \deg M(T; f_0; f_1; x_0; x_1) x_1$$

where first summation over  $T$  with  $1 + 1$  vertices. If the dimension  $M$  is nonzero, the degree is 0. For higher composition,

$$d(x_0; \dots; x_{d-1}) = \sum_{T \ni x_d} \sum_{x_d} \deg M(T; f_0; \dots; f_{d-1}; f_d; x_0; \dots; x_d) x_d$$

**Proposition 8.4.1** *We have quasi-equivalence between  $A_1$  categories  $\text{Open}(X) \rightarrow \text{Mor}(X)$ .*

To show that  $\text{Open}(X)$  is quasi-equivalent to  $\text{Mor}(X)$ , we have to use idea of Kontsevich-Soibelman by constructing map  $i : \text{Open}(X) \rightarrow \text{Mor}(X)$ ,  $j : \text{Mor}(X) \rightarrow \text{Open}(X)$ ,  $h : \text{Mor}(X) \rightarrow \text{Mor}(X)$  such that  $i = \text{id}_{\text{Open}(X)}$  and  $i = dh + hd$ . In grading 0 term, it is basically the isomorphism between de Rham cohomology and Morse cohomology. The details are omitted here.

Finally, we have following proposition.

**Proposition 8.4.2** *We have quasi-equivalence between  $A_1$  categories  $\text{Mor}(X) \rightarrow \text{Fuk}(T \times X)$ .*

The morphism is given by mapping  $(U_i; m_i)$  to perturbation of  $L_{U_i; f_i} := (\text{zero section of } T^*X)j_{U_i} + \alpha_i j_{U_i}$ . The proof goes by comparing the moduli space.

All together, we have

$$D(\text{Sh}(X)) \rightarrow D(\text{Open}(X)) \rightarrow D(\text{Mor}(X)) \rightarrow D\text{Fuk}(T \times X)$$

the equivalence and gives our main theorem.

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