

# Notes on derived category

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ABSTRACT. In this note, we discuss basic theory of derived category following [Huy06]. After discussing some basic theories, we are interested to explore some of its applications in algebraic geometry.

## CONTENTS

0. Introduction	3
0.1. Motivation from modern physics	4
1. Some category theory	6
1.1. Abelian category	6
1.2. Triangulated category	10
1.3. Semi-orthogonal decomposition	13
1.4. $t$ -structure and heart	14
1.5. Tensor Triangulated Category	15
2. Derived category	16
2.1. Category of complexes	16
2.2. What is a derived category?	18
2.3. Derived categories: $D^-(\mathcal{A})$ , $D^+(\mathcal{A})$ , and $D^b(\mathcal{A})$	25
3. Derived functors	27
3.1. What is it?	27
4. Serre functor	35
4.1. Abstract Serre functor	35
4.2. Serre duality in $D^b(X)$	37

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5. Spectral sequence	38
5.1. What is it?	38
6. Derived functors in algebraic geometry	43
6.1. Cohomology	43
6.2. Derived direct image	44
6.3. Local $\mathcal{H}om^\bullet$ complex	45
6.4. Trace map	47
6.5. Derived dual	48
6.6. Derived tensor product	48
6.7. Derived pullback	50
6.8. Compatibilities	51
6.9. Grothendieck-Verdier duality	52
7. Examples of spectral sequence	52
8. Bondal–Orlov’s reconstruction theorem	53
8.1. What is it?	53
8.2. Equality of dimensions	54
8.3. Point like objects	55
8.4. Invertible objects	59
8.5. Spanning class of $D^b(X)$	64
8.6. Proof of the reconstruction theorem	64
8.7. Auto equivalence of derived category	71
9. Fourier-Mukai transforms	71
9.1. Integral functor	71
9.2. $K$ -theoretic integral transformation	81
9.3. Cohomological integral transformation	84
9.4. Derived Torelli theorem for complex elliptic curves	92
9.5. Canonical ring and Kodaira dimension	94
9.6. Derived Torelli theorem for K3 surface	98
9.7. Geometric aspects of kernels of Fourier-Mukai functors	105
9.8. Relative integral functor and base change formula	106
9.9. Proof of Orlov’s representability theorem	107

9.10. Bondal-Orlov's reconstruction theorem revisited	107
10. Grothendieck group	107
11. Bridgeland Stability	108
11.1. Stability condition in an abelian category	108
11.2. Stability conditions on $D^b(X)$	116
12. Birational Geometry	116
13. Mirror Symmetry	116
13.1. Fukaya category	116
Acknowledgments	116
References	116

**Caution!** I have started writing this note (around June 2020) for myself to learn basic theories of derived category, triangulated category, Bridgeland stability conditions, their connections with mathematical physics, and more importantly their applications in various areas of algebraic geometry. The present note is unorganized, incomplete, and may contains many inaccuracies to be fixed. I may post a polished version (as an expository note) in my home page after a year. Any suggestions to improve the exposition are welcome.

*Update (July 25, 2020): Since the present note become quite long, I have decided to keep its main focus on basic theories of derived category only. I am planning to write a separate note focusing on Bridgeland stability.*

Current version: <https://arjunpaul29.github.io/home/notes/derived.pdf>.

## 0. INTRODUCTION

One of my preliminary motivation to start this series of discussions is to understand *stability condition* in triangulated category as introduced by Tom Bridgeland in his celebrated 2007 paper published in the Annals of Mathematics [Bri07]. I also would like to learn some of its application in some other areas, like birational geometry, mirror symmetry etc.

Bridgeland's original motivation was to mathematically formulate the concept of  $\Pi$ -stability in theoretical physics as formulated by Douglas. In physics,  $\Pi$ -stability is something to relate a *super-symmetric non-linear sigma model* with a  $(2, 2)$  *Super Conformal Field Theory (SCFT)*. Let's have a quick tour into an interesting intersection of geometry and physics.

**0.1. Motivation from modern physics.** I am not an expert in mathematical physics, but am interested to understand its relation with mathematics, in particular with algebraic geometry. After exploring various available sources, what I initially found and become interested in, are summarized below.

Let us start with a tailor of a largely speculating theory, known as *mirror symmetry*. A *super-symmetric non-linear sigma model* consists of a complex Calabi-Yau variety  $X = (M, I)$  admitting a Ricci flat Kähler form  $\omega$  and a “ $B$ -field”. Let us explain the terminologies:

- $M$  is the underlined real manifold of  $X$  and  $I$  is a complex structure on it,
- the variety  $X$  is *Calabi-Yau* means that the canonical line bundle  $K_X$  is trivial,
- the Kähler form  $\omega$  is *Ricci flat* means that the curvature  $F_{\det(\nabla_\omega)} = 0$ , where  $\det(\nabla_\omega)$  is the connection on  $\det(TX)$  induced by the Chern connection  $\nabla_\omega$  on  $TX$  with respect to the Kähler form  $\omega$ , and
- that “ $B$ -field” is something mysterious.

In the context of SYZ mirror symmetry (an attempt to understand mathematically original version of mirror symmetry in physics), a  $B$ -field should be a class of a *unitary flat gerbe*, as suggested by Hitchin.

It is expected from physical ground that such a *super-symmetric non-linear sigma model* should give us a  $(2, 2)$  *Super Conformal Field Theory* (SCFT). However, we don’t know any precise mathematical formulation of  $(2, 2)$  SCFT, except for few cases! Roughly, a  $(2, 2)$  SCFT is some physical theory that depends on both complex and symplectic structures of varieties, and using *topological twists* one may separate its parts:

- *A-side*: depend only on symplectic structure, and
- *B-side*: depend only on complex structure.

In his famous ICM talk in 1994, Maxim Kontsevich proposed that the mathematical objects obtained from these topological twists should be in the derived category of coherent sheaves on the  $B$ -side (algebraic side), and in the derived Fukaya category of Lagrangian submanifolds on the  $A$ -side (symplectic side). Physically, objects of these categories are considered to be boundary conditions, known as *branes*. In this sense, Fukaya category is the category of  $A$ -branes and the derived category of coherent sheaves is the category of  $B$ -branes.

**Conjecture 0.1.1** (Kontsevich). *If two super-symmetric non-linear sigma models  $(X, \omega, B)$  and  $(X', \omega', B')$ , as described above, defines mirror symmetric SCFTs, then there are equivalences of categories:*

$$D^b(X) \simeq D^b(\text{Fukaya}(X', \omega')) \quad \text{and} \quad D^b(\text{Fukaya}(X, \omega)) \simeq D^b(X').$$

This is mathematically quite vague because we don't have precise mathematical formulation of SCFT!

From mathematical point of view, Kontsevich's Conjecture may be considered as a definition of *homological mirror symmetry*. Two super symmetric non-linear sigma models  $(X, \omega, B)$  and  $(X', \omega', B')$  are said to be *homological mirror partner* to each other if there are equivalences of such derived categories.

**Remark 0.1.2.** I think, finding explicit examples of such homological mirror symmetric pairs of super-symmetric non-linear sigma models would be very difficult problem. There is a notion of mirror symmetric varieties in SYZ sense, which identifies  $X$  and  $X'$  as dual to each other in an appropriate sense; see e.g., works of Hitchin, Hausel-Thaddeus, Donagi-Pantev etc. This notion is different from the notion of homological mirror symmetry.

We shall see from construction of  $D^b(X)$  that the derived category  $D^b(X)$  depends only on complex/algebraic structure of  $X$ , and so  $D^b(X)$  keeps only half information of the SCFT. Douglas argued that for any Ricci flat Kähler metric  $\omega$  on  $X$ , there is a subcategory of  $D^b(X)$ , whose objects are physical branes, and these subcategories changes as the Kähler class  $\omega$  moves in the stringy Kähler moduli.

To get an intuitive idea what this mathematically means, instead of looking at whole  $D^b(X)$ , consider the abelian category  $\mathcal{Coh}(X)$ . Then a choice of Kähler class (or polarization) singles out semistable and stable objects of  $\mathcal{Coh}(X)$ , and as we change the polarization, the collection of stable/semistable objects changes. Thus, there might be some way to encode more information of SCFT purely in terms of triangulated category  $D^b(X)$  together with some extra structure on it. In a series of papers, Bridgeland set out to put these ideas on a mathematical setting and introduced the notion of *stability conditions* on a triangulated category. He has shown that the space of such stability conditions forms an (infinite) dimensional manifold, and this can be thought of an approximation of the stringy Kähler moduli space.

Mathematically, interesting point is that this new theory associates to a very algebraic object, like a triangulated category, a moduli space with meaningful geometric structure.

Roughly, a *stability condition* on a triangulated category  $\mathcal{A}$  is given by a heart  $\mathcal{H}$  of a bounded  $t$ -structure on  $\mathcal{A}$  and an additive group homomorphism  $Z : K_0(\mathcal{H}) \rightarrow \mathbb{C}$ , called the “central charge”, satisfying Harder-Narasimhan property.

Well, enough introduction, and we shall see these in detail! Let's first set up some languages from category theory.

## 1. SOME CATEGORY THEORY

*Joke: Category theory is like Ramayana and Mahabharata — there are lots of arrows!*

— Nitin Nitsure

## 1.1. Abelian category.

**Definition 1.1.1.** A category  $\mathcal{A}$  consists of the following data:

- (i) a class of objects, denoted  $\text{Ob}(\mathcal{A})$ ,
- (ii) for  $X, Y \in \text{Ob}(\mathcal{A})$ , a class of morphisms from  $X$  into  $Y$ , denoted  $\text{Mor}_{\mathcal{A}}(X, Y)$ ,
- (iii) for each  $X, Y, Z \in \text{Ob}(\mathcal{A})$ , a composition map

$$\text{Mor}_{\mathcal{A}}(X, Y) \times \text{Mor}_{\mathcal{A}}(Y, Z) \rightarrow \text{Mor}_{\mathcal{A}}(X, Z), \quad (f, g) \mapsto g \circ f,$$

which satisfies associative property:  $h \circ (g \circ f) = (h \circ g) \circ f$ , for all  $f \in \text{Mor}_{\mathcal{A}}(X, Y)$ ,  $g \in \text{Mor}_{\mathcal{A}}(Y, Z)$  and  $h \in \text{Mor}_{\mathcal{A}}(Z, W)$ , for all  $X, Y, Z, W \in \text{Ob}(\mathcal{A})$ .

A category  $\mathcal{A}$  is said to be *locally small* if  $\text{Mor}_{\mathcal{A}}(X, Y)$  is a set, for all  $X, Y \in \text{Ob}(\mathcal{A})$ . A category  $\mathcal{A}$  is said to be *small* if it is locally small and the class of objects  $\text{Ob}(\mathcal{A})$  is a set.

**Example 1.1.2.** The category (Set), whose objects are sets and morphisms are given by set maps, is a locally small, but not small. However, the category (FinSet), whose objects are finite sets and morphisms are given by set maps, is a small category.

Two objects  $A_1, A_2 \in \mathcal{A}$  are said to be *isomorphic* if there are morphisms (arrows)  $f : A_1 \rightarrow A_2$  and  $g : A_2 \rightarrow A_1$  in  $\mathcal{A}$  such that  $g \circ f = \text{Id}_{A_1}$  and  $f \circ g = \text{Id}_{A_2}$ .

Let  $\mathcal{A}$  and  $\mathcal{B}$  be two categories. A functor  $\mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$  is given by the following data:

- (i) for each  $X \in \mathcal{A}$  there is an object  $\mathcal{F}(X) \in \mathcal{B}$ ,
- (ii) for  $X, Y \in \mathcal{A}$  and  $f \in \text{Hom}_{\mathcal{A}}(X, Y)$ , there is  $\mathcal{F}(f) \in \text{Mor}_{\mathcal{B}}(\mathcal{F}(X), \mathcal{F}(Y))$ , which are compatible with the composition maps.

A functor  $\mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$  is said to be *faithful* (resp., *full*) if for any two objects  $A_1, A_2 \in \mathcal{A}$ , the induced map

$$\mathcal{F} : \text{Mor}_{\mathcal{A}}(A_1, A_2) \longrightarrow \text{Mor}_{\mathcal{B}}(\mathcal{F}(A_1), \mathcal{F}(A_2))$$

is injective (resp., surjective). We say that  $\mathcal{F}$  is *fully faithful* if it is both full and faithful.

Let  $\mathcal{F}, \mathcal{G} : \mathcal{A} \rightarrow \mathcal{B}$  be two functors. A morphism of functors  $\varphi : \mathcal{F} \rightarrow \mathcal{G}$  is given by the following data: for each object  $A \in \mathcal{A}$ , a map  $\varphi_A : \mathcal{F}(A) \rightarrow \mathcal{G}(A)$  which

is *functorial*; that means, for any arrow  $f : A \rightarrow A'$  in  $\mathcal{A}$ , the following diagram commutes.

$$(1.1.3) \quad \begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(A') \\ \varphi_A \downarrow & & \downarrow \varphi_{A'} \\ \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(A') \end{array}$$

**Definition 1.1.4.** A morphism  $f \in \text{Mor}_{\mathcal{A}}(A, B)$  is said to be a *monomorphism* if for any object  $T \in \mathcal{A}$  and two morphisms  $g, h \in \text{Hom}_{\mathcal{A}}(T, A)$  with  $f \circ g = f \circ h$ , we have  $g = h$ .

A morphism  $f \in \text{Mor}_{\mathcal{A}}(A, B)$  is said to be a *epimorphism* if for any object  $T \in \mathcal{A}$  and two morphisms  $g, h \in \text{Mor}_{\mathcal{A}}(B, T)$  with  $g \circ f = h \circ f$ , we have  $g = h$ .

Given any two categories  $\mathcal{A}$  and  $\mathcal{B}$ , we can define a category  $\text{Fun}(\mathcal{A}, \mathcal{B})$ , whose objects are functors  $\mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$ , and for any two such objects  $\mathcal{F}, \mathcal{G} \in \text{Fun}(\mathcal{A}, \mathcal{B})$ , there is a morphism set  $\text{Mor}(\mathcal{F}, \mathcal{G})$  consisting of all morphisms of functors  $\varphi_A : \mathcal{F} \rightarrow \mathcal{G}$ , as defined above.

**Proposition 1.1.5.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be two small categories. Two objects  $\mathcal{F}, \mathcal{G} \in \text{Fun}(\mathcal{A}, \mathcal{B})$  are isomorphic if there exists a morphism of functors  $\varphi : \mathcal{F} \rightarrow \mathcal{G}$  such that for any object  $A \in \mathcal{A}$ , the induced morphism  $\varphi_A : \mathcal{F}(A) \rightarrow \mathcal{G}(A)$  is an isomorphism in  $\mathcal{B}$ .

**Definition 1.1.6.** A category  $\mathcal{A}$  is said to be *pre-additive* if for any two objects  $X, Y \in \mathcal{A}$ , the set  $\text{Mor}_{\mathcal{A}}(X, Y)$  has a structure of an abelian group such that the *composition map*

$$\text{Mor}_{\mathcal{A}}(X, Y) \times \text{Mor}_{\mathcal{A}}(Y, Z) \longrightarrow \text{Mor}_{\mathcal{A}}(X, Z),$$

written as  $(f, g) \mapsto g \circ f$ , is  $\mathbb{Z}$ -bilinear, for all  $X, Y, Z \in \mathcal{A}$ .

**Notation.** For any pre-additive category  $\mathcal{A}$ , we denote by  $\text{Hom}_{\mathcal{A}}(X, Y)$  the abelian group  $\text{Mor}_{\mathcal{A}}(X, Y)$ , for all  $X, Y \in \text{Ob}(\mathcal{A})$ .

Let  $\mathcal{A}$  and  $\mathcal{B}$  be pre-additive categories. A functor  $\mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$  is said to be *additive* if for all objects  $X, Y \in \mathcal{A}$ , the induced map

$$\mathcal{F}_{X,Y} : \text{Hom}_{\mathcal{A}}(X, Y) \longrightarrow \text{Hom}_{\mathcal{B}}(\mathcal{F}(X), \mathcal{F}(Y))$$

is a group homomorphism.

**Definition 1.1.7 (Additive category).** A category  $\mathcal{A}$  is said to be *additive* if for any two objects  $A, B \in \mathcal{A}$ , the set  $\text{Hom}_{\mathcal{A}}(A, B)$  has a structure of an abelian group such that the following conditions holds.

- (i) The composition map  $\text{Hom}_{\mathcal{A}}(A, B) \times \text{Hom}_{\mathcal{A}}(B, C) \longrightarrow \text{Hom}_{\mathcal{A}}(A, C)$ , written as  $(f, g) \mapsto g \circ f$ , is  $\mathbb{Z}$ -bilinear, for all  $A, B, C \in \mathcal{A}$ .



- (ii) There is a zero object  $0$  in  $\mathcal{A}$ , i.e.,  $\text{Hom}_{\mathcal{A}}(0, 0)$  is the trivial group with one element.
- (iii) For any two objects  $A_1, A_2 \in \mathcal{A}$ , there is an object  $B \in \mathcal{A}$  together with morphisms  $j_i : A_i \rightarrow B$  and  $p_i : B \rightarrow A_i$ , for  $i = 1, 2$ , which makes  $B$  the direct sum and the direct product of  $A_1$  and  $A_2$  in  $\mathcal{A}$ .

**Definition 1.1.8.** Let  $k$  be a field. A  $k$ -linear category is an additive category  $\mathcal{A}$  such that for any  $A, B \in \mathcal{A}$ , the abelian groups  $\text{Hom}_{\mathcal{A}}(A, B)$  are  $k$ -vector spaces such that the composition morphisms

$$\text{Hom}_{\mathcal{A}}(A, B) \times \text{Hom}_{\mathcal{A}}(B, C) \longrightarrow \text{Hom}_{\mathcal{A}}(A, C), \quad (f, g) \mapsto g \circ f$$

are  $k$ -bilinear, for all  $A, B, C \in \mathcal{A}$ .

**Remark 1.1.9.** Additive functors  $\mathcal{F} : \mathcal{A} \longrightarrow \mathcal{B}$  between two  $k$ -linear additive categories  $\mathcal{A}$  and  $\mathcal{B}$  over the same base field  $k$  are assumed to be  $k$ -linear, i.e., for any two objects  $A_1, A_2 \in \mathcal{A}$ , the map  $\mathcal{F}_{A_1, A_2} : \text{Hom}_{\mathcal{A}}(A_1, A_2) \longrightarrow \text{Hom}_{\mathcal{B}}(\mathcal{F}(A_1), \mathcal{F}(A_2))$  is  $k$ -linear.

Let  $\mathcal{A}$  be an additive category. Then there is a unique object  $0 \in \mathcal{A}$ , called the *zero object* such that for any object  $A \in \mathcal{A}$ , there are unique morphisms  $0 \rightarrow A$  and  $A \rightarrow 0$  in  $\mathcal{A}$ . For any two objects  $A, B \in \mathcal{A}$ , the *zero morphism*  $0 \in \text{Hom}_{\mathcal{A}}(A, B)$  is defined to be the composite morphism

$$A \longrightarrow 0 \longrightarrow B.$$

In particular, taking  $A = 0$ , we see that, the set  $\text{Hom}_{\mathcal{A}}(0, B)$  is the trivial group consisting of one element, which is, in fact, the zero morphism of  $0$  into  $B$  in  $\mathcal{A}$ .

**Definition 1.1.10.** Let  $f : A \rightarrow B$  be a morphism in  $\mathcal{A}$ . Then *kernel* of  $f$  is a pair  $(\iota, \text{Ker}(f))$ , where  $\text{Ker}(f) \in \mathcal{A}$  and  $\iota \in \text{Hom}_{\mathcal{A}}(\text{Ker}(f), A)$  such that

- (i)  $f \circ \iota = 0$  in  $\text{Hom}_{\mathcal{A}}(\text{Ker}(f), B)$ , and
- (ii) given any object  $C \in \mathcal{A}$  and a morphism  $g : C \rightarrow A$  with  $f \circ g = 0$ , there is a unique morphism  $\tilde{g} : C \rightarrow \text{Ker}(f)$  such that  $\iota \circ \tilde{g} = g$ .

$$\begin{array}{ccccc} & & C & & \\ & \swarrow \exists! \tilde{g} & \downarrow g & \searrow 0 & \\ \text{Ker}(f) & \xrightarrow{\iota} & A & \xrightarrow{f} & B \end{array}$$

The *cokernel* of  $f \in \text{Hom}_{\mathcal{A}}(A, B)$  is defined by reversing the arrows of the above diagram.

**Definition 1.1.11.** The *cokernel* of  $f : A \rightarrow B$  is a pair  $(\pi, \text{Coker}(f))$ , where  $\text{Coker}(f)$  is an object of  $\mathcal{A}$  together with a morphism  $\pi : B \rightarrow \text{Coker}(f)$  in  $\mathcal{A}$  such that



- (i)  $\pi \circ f = 0$  in  $\text{Hom}_{\mathcal{A}}(A, \text{Coker}(f))$ , and
- (ii) given any object  $C \in \mathcal{A}$  and a morphism  $g : B \rightarrow C$  with  $g \circ f = 0$  in  $\text{Hom}_{\mathcal{A}}(A, C)$ , there is a unique morphism  $\tilde{g} : \text{Coker}(f) \rightarrow C$  such that  $\tilde{g} \circ \pi = g$ .

$$\begin{array}{ccccc}
 A & \xrightarrow{f} & B & \xrightarrow{\pi} & \text{Coker}(f) \\
 & \searrow 0 & \downarrow g & \swarrow \exists! \tilde{g} & \\
 & & C & & 
 \end{array}$$

**Definition 1.1.12.** The *coimage* of  $f \in \text{Hom}_{\mathcal{A}}(A, B)$ , denoted by  $\text{Coim}(f)$ , is the cokernel of  $\iota : \text{Ker}(f) \rightarrow A$  of  $f$ , and the *image* of  $f$ , denoted  $\text{Im}(f)$ , is the kernel of the cokernel  $\pi : B \rightarrow \text{Coker}(f)$  of  $f$ .

**Lemma 1.1.13.** Let  $\mathcal{C}$  be a preadditive category, and  $f : X \rightarrow Y$  a morphism in  $\mathcal{C}$ .

- (i) If a kernel of  $f$  exists, then it is a monomorphism.
- (ii) If a cokernel of  $f$  exists, then it is an epimorphism.
- (iii) If a kernel and coimage of  $f$  exist, then the coimage is an epimorphism.
- (iv) If a cokernel and image of  $f$  exist, then the image is a monomorphism.

*Proof.* Assume that a kernel  $\iota : \text{Ker}(f) \rightarrow X$  of  $f$  exists. Let  $\alpha, \beta \in \text{Hom}_{\mathcal{C}}(Z, \text{Ker}(f))$  be such that  $\iota \circ \alpha = \iota \circ \beta$ . Since  $f \circ (\iota \circ \alpha) = f \circ (\iota \circ \beta) = 0$ , by definition of  $\text{Ker}(f) \xrightarrow{\iota} X$  there is a unique morphism  $g \in \text{Hom}(Z, \text{Ker}(f))$  such that  $\iota \circ \alpha = \iota \circ g = \iota \circ \beta$ . Therefore,  $\alpha = g = \beta$ .

The proof of (ii) is dual.

(iii) follows from (ii), since the coimage is a cokernel. Similarly, (iv) follows from (i).  $\square$

**Exercise 1.1.14.** Let  $\mathcal{A}$  be an additive category. Let  $f \in \text{Hom}_{\mathcal{A}}(X, Y)$  be such that  $\text{Ker}(f) \xrightarrow{\iota} X$  exists in  $\mathcal{A}$ . Then the kernel of  $\iota : \text{Ker}(f) \rightarrow X$  is the unique morphism  $0 \rightarrow \text{Ker}(f)$  in  $\mathcal{A}$ .

**Lemma 1.1.15.** Let  $f : X \rightarrow Y$  be a morphism in a preadditive category  $\mathcal{C}$  such that the kernel, cokernel, image and coimage all exist in  $\mathcal{C}$ . Then  $f$  uniquely factors as  $X \rightarrow \text{Coim}(f) \rightarrow \text{Im}(f) \rightarrow Y$  in  $\mathcal{C}$ .

*Proof.* Since  $\text{Ker}(f) \rightarrow X \rightarrow Y$  is zero, there is a canonical morphism  $\text{Coim}(f) \rightarrow Y$  such that the composite morphism  $X \rightarrow \text{Coim}(f) \rightarrow Y$  is  $f$ . The composition  $\text{Coim}(f) \rightarrow Y \rightarrow \text{Coker}(f)$  is zero, because it is the unique morphism which gives rise to the morphism  $X \rightarrow Y \rightarrow \text{Coker}(f)$ , which is zero. Hence  $\text{Coim}(f) \rightarrow Y$  factors uniquely through  $\text{Im}(f) = \text{Ker}(\pi_f)$  (see Lemma 1.1.13 (iii)). This completes

the proof.

$$(1.1.16) \quad \begin{array}{ccccccc} \text{Ker}(f) & \xrightarrow{\iota} & X & \xrightarrow{f} & Y & \xrightarrow{\pi_f} & \text{Coker}(f) \\ & & \searrow \pi_\iota & & \nearrow j & & \\ & & \text{Coim}(f) & \longrightarrow & \text{Im}(f) & & \end{array}$$

□

**Definition 1.1.17.** An *abelian category*  $\mathcal{A}$  is an additive category such that for any morphism  $f : A \rightarrow B$  in  $\mathcal{A}$ , its kernel  $\iota : \text{Ker}(f) \rightarrow A$  and cokernel  $p : B \rightarrow \text{Coker}(f)$  exists in  $\mathcal{A}$ , and the natural morphism  $\text{Coim}(f) \rightarrow \text{Im}(f)$  is an isomorphism in  $\mathcal{A}$  (c.f. Definition 1.1.12).

**Example 1.1.18.** (1) For any commutative ring  $A$  with identity, the category  $\text{Mod}_A$  of  $A$ -modules is an abelian category.

(2) Let  $X$  be a scheme. Let  $\mathfrak{Mod}(X)$  be the category of sheaves of  $\mathcal{O}_X$ -modules on  $X$ . Then  $\mathfrak{Mod}(X)$  is abelian. The full subcategory  $\mathfrak{Qcoh}(X)$  (reps.,  $\mathfrak{Coh}(X)$ ) of  $\mathfrak{Mod}(X)$  consisting of quasi-coherent (resp., coherent) sheaves of  $\mathcal{O}_X$ -modules on  $X$ , are also abelian. However, the full subcategory  $\mathcal{Vect}(X)$  of  $\mathfrak{Mod}(X)$  consisting of locally free coherent sheaves of  $\mathcal{O}_X$ -modules on  $X$ , is not abelian, because kernel of a morphism in  $\mathcal{Vect}(X)$  may not be in  $\mathcal{Vect}(X)$ .

**1.2. Triangulated category.** Let  $\mathcal{A}$  be an additive category. A *shift functor* is an additive functor

$$(1.2.1) \quad T : \mathcal{A} \longrightarrow \mathcal{A},$$

which is an equivalence of categories. A *triangle* in  $(\mathcal{A}, T)$  is given by a diagram

$$(1.2.2) \quad A \longrightarrow B \longrightarrow C \longrightarrow A[1] := T(A),$$

with objects and arrows in  $\mathcal{A}$ . A *morphism of triangles* in  $(\mathcal{A}, T)$  is given by a commutative diagram

$$(1.2.3) \quad \begin{array}{ccccccc} A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \\ \downarrow f & & \downarrow g & & \downarrow h & & \downarrow f[1] \\ A' & \longrightarrow & B' & \longrightarrow & C' & \longrightarrow & A'[1] \end{array}$$

where  $f[1] := T(f) \in \text{Hom}_{\mathcal{A}}(A[1], A'[1])$ . If, in addition,  $f, g, h$  are isomorphisms in  $\mathcal{A}$ , we say that (1.2.3) is an isomorphism of triangles. We denote by  $A[n]$  the object  $T^n(A) \in \mathcal{A}$ , and denote by  $f[n]$  the morphism  $T^n(f) \in \text{Hom}_{\mathcal{A}}(A[n], B[n])$ , for  $f \in \text{Hom}_{\mathcal{A}}(A, B)$ .

**Definition 1.2.4.** A *triangulated category* is an additive category  $\mathcal{A}$  together with an additive equivalence (*shift functor*)

$$(1.2.5) \quad T : \mathcal{A} \longrightarrow \mathcal{A} ,$$

and a set of *distinguished triangles*

$$(1.2.6) \quad A \longrightarrow B \longrightarrow C \longrightarrow A[1] := T(A) ,$$

satisfying the following axioms (TR1) – (TR4) below.

(TR1) (i) Any triangle of the form

$$A \xrightarrow{\text{Id}_A} A \longrightarrow 0 \longrightarrow A[1]$$

is a distinguished triangle.

(ii) Any triangle isomorphic to a distinguished triangle is distinguished.

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

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

(TR2) A triangle

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

is distinguished if and only if

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

is a distinguished triangle.

(TR3) Any commutative diagram of distinguished triangles with vertical arrows  $f$  and  $g$

$$(1.2.7) \quad \begin{array}{ccccccc} A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & A[1] \\ f \downarrow & & g \downarrow & & \exists h \downarrow & & f[1] \downarrow \\ A' & \longrightarrow & B' & \longrightarrow & C' & \longrightarrow & A'[1] \end{array}$$

can be completed to a commutative diagram (not necessarily in a unique way).

(TR4) (Octahedral axiom) Given any three distinguished triangles

$$A \xrightarrow{u} B \longrightarrow C' \longrightarrow A[1]$$

$$B \xrightarrow{v} C \longrightarrow A' \longrightarrow B[1]$$

$$A \xrightarrow{w} C \longrightarrow B' \longrightarrow A[1]$$

there is a distinguished triangle  $C' \longrightarrow B' \longrightarrow A' \longrightarrow C'[1]$  such that the following diagram is commutative.

$$\begin{array}{ccccccc}
 A & \xrightarrow{u} & B & \longrightarrow & C' & \longrightarrow & A[1] \\
 \downarrow \text{Id} & & \downarrow v & & \downarrow & & \downarrow \text{Id} \\
 A & \xrightarrow{w} & C & \longrightarrow & B' & \longrightarrow & A[1] \\
 \downarrow u & & \downarrow \text{Id} & & \downarrow & & \downarrow u[1] \\
 B & \xrightarrow{v} & C & \longrightarrow & A' & \longrightarrow & B[1] \\
 \downarrow & & \downarrow & & \downarrow \text{Id} & & \downarrow \\
 C' & \longrightarrow & B' & \longrightarrow & A' & \longrightarrow & C'[1]
 \end{array}$$

This axiom is called “*octahedron axiom*” because of its original formulation: given composable morphisms  $A \xrightarrow{u} B \xrightarrow{v} C$ , with  $w := v \circ u$ , we have the following octahedron diagram.



where any triangle of the form  $\begin{array}{ccc} & Z & \\ \swarrow & & \searrow \\ X & \longrightarrow & Y \end{array}$  are distinguished triangles, and the arrow  $Z \dashrightarrow X$  stands for  $Z \rightarrow X[1]$ .

**Remark 1.2.8.** A triangulated category need not be abelian, in general. In triangulated category, distinguished triangles play the roles of exact sequences in abelian categories. Examples of triangulated categories, we will be interested in, are derived categories of abelian categories.

**Definition 1.2.9.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be two triangulated categories. An *exact functor* of triangulated categories  $\mathcal{A}$  to  $\mathcal{B}$  is a functor  $F : \mathcal{A} \rightarrow \mathcal{B}$  such that for any distinguished triangle  $A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} A[1]$  in  $\mathcal{A}$ , there is an isomorphism  $F(A[1]) \xrightarrow{\phi} F(A)[1]$  such that

$$F(A) \xrightarrow{F(f)} F(B) \xrightarrow{F(g)} F(C) \xrightarrow{\phi \circ F(h)} F(A)[1]$$

is a distinguished triangle in  $\mathcal{B}$ . By a *morphism of triangulated categories*, we always mean an exact functor between them.

**Definition 1.2.10** (Adjoint functors). Let  $F : \mathcal{A} \longrightarrow \mathcal{B}$  be a functor between any two categories. A functor  $G : \mathcal{B} \longrightarrow \mathcal{A}$  is said to be *right adjoint to  $F$* , written as  $F \dashv G$ , if there is an isomorphism

$$(1.2.11) \quad \text{Hom}_{\mathcal{B}}(F(A), B) \cong \text{Hom}_{\mathcal{A}}(A, G(B)), \quad \forall A \in \mathcal{A}, B \in \mathcal{B},$$

which is functorial in both  $A$  and  $B$ .

Similarly, a functor  $H : \mathcal{B} \longrightarrow \mathcal{A}$  is said to be *left adjoint to  $F$* , written as  $H \dashv F$ , if there is an isomorphism

$$\text{Hom}_{\mathcal{B}}(B, F(A)) \cong \text{Hom}_{\mathcal{A}}(H(B), A), \quad \forall A \in \mathcal{A}, B \in \mathcal{B},$$

which is functorial in both  $A$  and  $B$ .

**Remark 1.2.12.** (1) Note that,  $G$  is right adjoint to  $F$  if and only if  $F$  is left adjoint to  $G$ .

(2) If  $F \dashv G$ , then  $\text{Id}_{F(A)} \in \text{Hom}_{\mathcal{B}}(F(A), F(A)) \cong \text{Hom}_{\mathcal{A}}(A, (G \circ F)(A))$  induces a morphism  $A \longrightarrow (G \circ F)(A)$ , for all  $A \in \mathcal{A}$ . The naturality of this morphism gives us a morphism of functors

$$\text{Id}_{\mathcal{A}} \longrightarrow G \circ F.$$

Similarly, taking  $A = G(B)$  in (1.2.11), we get a morphism of functors

$$F \circ G \longrightarrow \text{Id}_{\mathcal{B}}.$$

In particular, if  $F$  and  $G$  are quasi-inverse to each other (in case of equivalence of categories), then one is both left and right adjoint to the other one.

(3) Using Yoneda lemma, one can check that, left (resp., right) adjoint of a functor, if it exists, is unique up to isomorphisms.

**Proposition 1.2.13.** Let  $F : \mathcal{D} \longrightarrow \mathcal{D}'$  be an exact functor of triangulated categories. Let  $G : \mathcal{D}' \longrightarrow \mathcal{D}$  be a functor. If  $F \dashv G$ , or  $G \dashv F$ , then  $G$  is also exact.

**1.3. Semi-orthogonal decomposition.** Let  $\mathcal{D}$  be a  $k$ -linear triangulated category. An object  $E \in \mathcal{D}$  is said to be *exceptional* if

$$(1.3.1) \quad \text{Hom}_{\mathcal{D}}(E, E[\ell]) = \begin{cases} k & \text{if } \ell = 0, \\ 0 & \text{if } \ell \neq 0. \end{cases}$$

An *exceptional sequence* in  $\mathcal{D}$  is a sequence of exceptional objects  $E_1, E_2, \dots, E_n$  of  $\mathcal{D}$  such that  $\text{Hom}_{\mathcal{D}}(E_i, E_j[\ell]) = 0$ , for all  $i > j$  and all  $\ell$ . In other words, if

$$(1.3.2) \quad \text{Hom}_{\mathcal{D}}(E_i, E_j[\ell]) = \begin{cases} k & \text{if } i = j \text{ and } \ell = 0, \\ 0 & \text{if } i > j, \text{ or if } \ell \neq 0 \text{ and } i = j. \end{cases}$$

An exceptional sequence  $\{E_i\}_{i=1}^n$  is said to be *full* if, as a triangulated category,  $\mathcal{D}$  is generated by  $\{E_i\}_{i=1}^n$ ; i.e., if  $\mathcal{D}'$  is a triangulated full subcategory of  $\mathcal{D}$  containing  $E_i$ , for all  $i = 1, \dots, n$ , then the inclusion morphism  $\mathcal{D}' \hookrightarrow \mathcal{D}$  is an equivalence of categories.

**Lemma 1.3.3.** *Let  $\mathcal{D}$  be a  $k$ -linear triangulated category such that  $\bigoplus_i \text{Hom}(A, B[i])$  is a finite dimensional  $k$ -vector space, for all  $A, B \in \mathcal{D}$ . If  $E \in \mathcal{D}$  is exceptional, then the objects  $\bigoplus_i E[i]^{\oplus n_i}$  forms an admissible triangulated subcategories.*

**1.4.  $t$ -structure and heart.** Let  $(\mathcal{A}, T)$  be a triangulated category. Let  $\mathcal{B}$  be a subcategory of  $\mathcal{A}$ . For an integer  $n$ , we denote by  $\mathcal{B}[n]$  the full subcategory of  $\mathcal{A}$ , whose objects are of the form  $X[n]$ , with  $X \in \mathcal{B}$ . In other words,  $\mathcal{B}[n] = T^n(\mathcal{B}) \subset \mathcal{A}$ .

**Definition 1.4.1.** Let  $\mathcal{A}^{\leq 0}$  and  $\mathcal{A}^{\geq 0}$  be two full subcategories of  $\mathcal{A}$ . For an integer  $n$ , let  $\mathcal{A}^{\leq n} := \mathcal{A}^{\leq 0}[-n]$  and  $\mathcal{A}^{\geq n} := \mathcal{A}^{\geq 0}[-n]$ . A  $t$ -structure on  $\mathcal{A}$  is given by a pair  $(\mathcal{A}^{\leq 0}, \mathcal{A}^{\geq 0})$  of full subcategories of  $\mathcal{A}$  satisfying the following axioms.

- (t1)  $\mathcal{A}^{\leq -1} \subset \mathcal{A}^{\leq 0}$  and  $\mathcal{A}^{\geq 1} \subset \mathcal{A}^{\geq 0}$ .
- (t2) For any  $X \in \mathcal{A}^{\leq 0}$  and  $Y \in \mathcal{A}^{\geq 1}$ , we have  $\text{Hom}_{\mathcal{A}}(X, Y) = 0$ .
- (t3) For any  $X \in \mathcal{A}$ , there is a distinguished triangle

$$X_0 \longrightarrow X \longrightarrow X_1 \longrightarrow X_0[1],$$

with  $X_0 \in \mathcal{A}^{\leq 0}$  and  $X_1 \in \mathcal{A}^{\geq 1}$ .

In this case, the full subcategory  $\mathcal{A}^{\leq 0} \cap \mathcal{A}^{\geq 0}$  of  $\mathcal{A}$  is called the *heart* (or, *core*) of the  $t$ -structure  $(\mathcal{A}^{\leq 0}, \mathcal{A}^{\geq 0})$ .

**Example 1.4.2** (Standard  $t$ -structure on  $D^b(X)$ ). Consider the full subcategories

$$\begin{aligned} \mathcal{A}^{\leq 0} &:= \{E^\bullet \in D^b(X) : \mathcal{H}^i(E^\bullet) = 0, \forall i > 0\} \text{ and} \\ \mathcal{A}^{\geq 0} &:= \{E^\bullet \in D^b(X) : \mathcal{H}^i(E^\bullet) = 0, \forall i < 0\} \end{aligned}$$

of  $D^b(X)$ . The axiom (T1) is easy to see. To check axiom (T2), we need some notations. For an integer  $n \in \mathbb{Z}$ , let  $D^{\leq n}(X)$  (resp.,  $D^{\geq n}(X)$ ) be the full subcategory of  $D^b(X)$ , whose objects are  $E^\bullet \in D^b(X)$  satisfying  $E^i = 0$ , for all  $i \leq n$  (resp., for all  $i \geq n$ ). Consider the *truncation functors*

$$(1.4.3) \quad \tau^{\leq n} : D^b(X) \longrightarrow D^{\leq n}(X) \quad \text{and} \quad \tau^{\geq n} : D^b(X) \longrightarrow D^{\geq n}(X)$$

defined by

$$\begin{aligned} \tau^{\leq n}(E^\bullet) &:= (\cdots \rightarrow E^{n-2} \rightarrow E^{n-1} \rightarrow \text{Ker}(d_{E^\bullet}^n) \rightarrow 0 \rightarrow \cdots), \text{ and} \\ \tau^{\geq n}(E^\bullet) &:= (\cdots \rightarrow 0 \rightarrow \text{Ker}(d_{E^\bullet}^n) \rightarrow E^n \rightarrow E^{n+1} \rightarrow \cdots). \end{aligned}$$

where  $d_{E^\bullet}^n : E^n \rightarrow E^{n+1}$ , and  $E^\bullet \in D^b(X)$ . Now take  $E^\bullet \in \mathcal{A}^{\leq 0}$  and  $F^\bullet \in \mathcal{A}^{\geq 1}$ . If  $f \in \text{Hom}_{D^b(X)}(E^\bullet, F^\bullet)$ , then  $f$  factors as

$$\begin{array}{ccc} E^\bullet & \xrightarrow{\quad f \quad} & F^\bullet \\ \searrow \cong & & \nearrow \\ & \tau^{\leq 0}(E^\bullet) \xrightarrow{\tau^{\leq 0}(f)} \tau^{\leq 0}(F^\bullet) & \end{array} .$$

Since  $\tau^{\leq 0}(F^\bullet) = 0$  in  $D^b(X)$ , we conclude that  $f = 0$ . Axiom (T3) follows from the exact triangle

$$\tau^{\leq 0}(E^\bullet) \longrightarrow E^\bullet \longrightarrow \tau^{\geq 1}(E^\bullet) \longrightarrow \tau^{\leq 0}(E^\bullet)[1], \quad \forall E^\bullet \in D^b(X).$$

Thus  $(\mathcal{A}^{\leq 0}, \mathcal{A}^{\geq 0})$  is a  $t$ -structure on  $D^b(X)$ , and the associated heart  $\mathcal{A}^{\leq 0} \cap \mathcal{A}^{\geq 0}$  is isomorphic to  $\mathcal{Coh}(X)$ .

The above mentioned  $t$ -structure on  $D^b(X)$  is not interesting, and somehow useless. We shall be interested in some non-trivial  $t$ -structures on  $D^b(X)$  giving more interesting and useful hearts different from  $\mathcal{Coh}(X)$ .

The next proposition shows that, the truncation functors exists for general triangulated category admitting a  $t$ -structure.

**Proposition 1.4.4.** *Let  $\iota : \mathcal{A}^{\geq n} \rightarrow \mathcal{A}$  (resp.,  $\iota' : \mathcal{A}^{\geq n} \rightarrow \mathcal{A}$ ) be the inclusion functor. Then there is a functor  $\tau^{\geq n} : \mathcal{A} \rightarrow \mathcal{A}^{\geq n}$  (resp.,  $\tau^{\leq n} : \mathcal{A} \rightarrow \mathcal{A}^{\leq n}$ ) such that for any  $X \in \mathcal{A}$  and  $Y \in \mathcal{A}^{\leq n}$  (resp.,  $Y \in \mathcal{A}^{\geq n}$ ), we have an isomorphism*

$$(1.4.5) \quad \text{Hom}_{\mathcal{A}^{\leq n}}(Y, \tau^{\leq n}(X)) \xrightarrow{\cong} \text{Hom}_{\mathcal{A}}(X, \iota'(Y))$$

(resp.,

$$(1.4.6) \quad \text{Hom}_{\mathcal{A}^{\geq n}}(\tau^{\geq n}(X), Y) \xrightarrow{\cong} \text{Hom}_{\mathcal{A}}(X, \iota(Y)).$$

**Lemma 1.4.7.** *Let  $(\mathcal{A}^{\leq 0}, \mathcal{A}^{\geq 0})$  be a bounded  $t$ -structure on a triangulated category  $\mathcal{A}$ . Then  $\mathcal{H} := \mathcal{A}^{\leq 0} \cap \mathcal{A}^{\geq 0}$  is abelian.*

*Proof.* Let  $\mathcal{H} := \mathcal{A}^{\leq 0} \cap \mathcal{A}^{\geq 0}$  be the heart of a bounded  $t$ -structure  $(\mathcal{A}^{\leq 0}, \mathcal{A}^{\geq 0})$  on  $\mathcal{D}$ . □

**Remark 1.4.8.** If  $D^b(\mathcal{A}) \cong D^b(X)$  for some abelian subcategory  $\mathcal{A}$  of  $D^b(X)$ , then  $\mathcal{A}$  is a heart of a  $t$ -structure on  $D^b(X)$ . However, the converse is not true, in general.

## 1.5. Tensor Triangulated Category.



## 2. DERIVED CATEGORY

**2.1. Category of complexes.** Let  $\mathcal{A}$  be an abelian category. A *complex* in  $\mathcal{A}$  is given by

$$(2.1.1) \quad A^\bullet : \cdots \longrightarrow A^{i-1} \xrightarrow{d_A^{i-1}} A^i \xrightarrow{d_A^i} A^{i+1} \longrightarrow \cdots,$$

where  $A^i$  are objects of  $\mathcal{A}$  and  $d_A^i$  are morphisms in  $\mathcal{A}$  such that  $d_A^i \circ d_A^{i-1} = 0$ , for all  $i \in \mathbb{Z}$ . A complex  $A^\bullet$  in  $\mathcal{A}$  is said to be *bounded above* (resp., *bounded below*) if there is an integer  $i_0$  such that  $A^i = 0$ , for all  $i \geq i_0$  (resp., if there is an integer  $j_0$  such that  $A^j = 0$ , for all  $j \leq j_0$ ). If  $A^\bullet$  is both bounded above and bounded below, we say that  $A^\bullet$  is *bounded*.

A morphism  $f^\bullet : A^\bullet \rightarrow B^\bullet$  between two complexes  $A^\bullet$  and  $B^\bullet$  of objects and morphisms from  $\mathcal{A}$  is given by a collection of morphisms  $\{f^i : A^i \rightarrow B^i\}_{i \in \mathbb{Z}}$  in  $\mathcal{A}$  such that the following diagram commutes.

$$(2.1.2) \quad \begin{array}{ccccccc} \cdots & \longrightarrow & A^{i-1} & \xrightarrow{d_A^{i-1}} & A^i & \xrightarrow{d_A^i} & A^{i+1} \xrightarrow{d_A^{i+1}} \cdots \\ & & \downarrow f^{i-1} & & \downarrow f^i & & \downarrow f^{i+1} \\ \cdots & \longrightarrow & B^{i-1} & \xrightarrow{d_B^{i-1}} & B^i & \xrightarrow{d_B^i} & B^{i+1} \xrightarrow{d_B^{i+1}} \cdots \end{array}$$

Let  $Kom(\mathcal{A})$  be the category, whose objects are complexes of objects and morphisms from  $\mathcal{A}$ , and morphisms are given by morphism of complexes, as defined in (2.1.2). Denote by  $Kom^-(\mathcal{A})$ ,  $Kom^+(\mathcal{A})$  and  $Kom^b(\mathcal{A})$  the full subcategories of  $Kom(\mathcal{A})$ , whose objects are bounded above complexes, resp., bounded below complexes, resp., bounded complexes. Then we have the following.

**Proposition 2.1.3.** *For any abelian category  $\mathcal{A}$ , the categories  $Kom(\mathcal{A})$ ,  $Kom^-(\mathcal{A})$ ,  $Kom^+(\mathcal{A})$  and  $Kom^b(\mathcal{A})$  are abelian.*

**Definition 2.1.4.** For any complex  $A^\bullet \in Kom(\mathcal{A})$  and  $k \in \mathbb{Z}$ , we define its  $k^{\text{th}}$ -shift to be the complex  $A[k]^\bullet \in Kom(\mathcal{A})$  satisfying

- (i)  $A[k]^i := A^{k+i}$ , for all  $i \in \mathbb{Z}$ , and
- (ii)  $d_{A[k]}^i := (-1)^k d_A^{i+k} : A[k]^i \longrightarrow A[k]^{i+1}$ , for all  $i \in \mathbb{Z}$ .

**Proposition 2.1.5.** *For any integer  $k$ , the  $k^{\text{th}}$ -shift functor*

$$Kom(\mathcal{A}) \longrightarrow Kom(\mathcal{A}), \quad A^\bullet \longmapsto A[k]^\bullet$$

*is an equivalence of categories.*

*Proof.* Clearly, the  $(-k)^{\text{th}}$ -shift functor  $A^\bullet \longmapsto A[-k]^\bullet$  defines the inverse functor of the  $k^{\text{th}}$ -shift functor.  $\square$

**Remark 2.1.6.** We shall see later that the category  $Kom(\mathcal{A})$  together with the shift functor do not form a triangulated category, in general. However, we shall construct the derived category  $D^b(\mathcal{A})$  from  $Kom(\mathcal{A})$ , which will turn out to be a triangulated category.

Given a complex  $A^\bullet \in Kom(\mathcal{A})$ , we define its  $i^{\text{th}}$  cohomology sheaf

$$(2.1.7) \quad \mathcal{H}^i(A^\bullet) := \frac{\text{Ker}(d_{A^\bullet}^i)}{\text{Im}(d_{A^\bullet}^{i-1})} \in \mathcal{A}, \quad \forall i \in \mathbb{Z}.$$

A complex  $A^\bullet \in Kom(\mathcal{A})$  is said to be *acyclic* if  $\mathcal{H}^i(A^\bullet) = 0$ , for all  $i \in \mathbb{Z}$ . Any morphism  $f^\bullet : A^\bullet \rightarrow B^\bullet$  of complexes gives rise to natural homomorphisms

$$(2.1.8) \quad \mathcal{H}^i(f) : \mathcal{H}^i(A^\bullet) \rightarrow \mathcal{H}^i(B^\bullet), \quad \forall i \in \mathbb{Z}.$$

Let  $\mathcal{A}$  and  $\mathcal{B}$  be two abelian categories. Let

$$(2.1.9) \quad \mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$$

be an additive functor. Then  $\mathcal{F}$  induces a functor, also denoted by the same symbol,

$$(2.1.10) \quad \mathcal{F} : Kom(\mathcal{A}) \rightarrow Kom(\mathcal{B})$$

defined by sending  $A^\bullet \in Kom(\mathcal{A})$  to the complex  $\mathcal{F}(A^\bullet)$ , defined by

- (i)  $\mathcal{F}(A^\bullet)^i := \mathcal{F}(A^i)$ , for all  $i \in \mathbb{Z}$ , and
- (ii)  $d_{\mathcal{F}(A^\bullet)}^i : \mathcal{F}(A^i) \xrightarrow{\mathcal{F}(d_{A^\bullet}^i)} \mathcal{F}(A^{i+1})$ , for all  $i \in \mathbb{Z}$ ,

and for any morphism  $f^\bullet : A^\bullet \rightarrow B^\bullet$ , we have a natural morphism of complexes

$$\mathcal{F}(f^\bullet) : \mathcal{F}(A^\bullet) \rightarrow \mathcal{F}(B^\bullet)$$

defined by  $\mathcal{F}(f^\bullet)^i := \mathcal{F}(f^i) : \mathcal{F}(A^i) \rightarrow \mathcal{F}(B^i)$ , for all  $i \in \mathbb{Z}$ .

**Definition 2.1.11.** An additive functor  $\mathcal{F} : \mathcal{A} \rightarrow \mathcal{B}$  is said to be *exact* if it takes exact sequence to exact sequence.

**Remark 2.1.12.** Note that  $\mathcal{F}$  is exact if and only if for any acyclic complex  $A^\bullet \in Kom(\mathcal{A})$ , its image  $\mathcal{F}(A^\bullet) \in Kom(\mathcal{B})$  is acyclic.

Since  $Kom(\mathcal{A})$  is abelian for  $\mathcal{A}$  abelian, we can talk about short exact sequences in  $Kom(\mathcal{A})$ . Then by standard techniques from homological algebra, any short exact sequence

$$(2.1.13) \quad 0 \rightarrow A^\bullet \rightarrow B^\bullet \rightarrow C^\bullet \rightarrow 0$$

gives rise to a long exact sequence of cohomologies (which are objects of  $\mathcal{A}$ )

$$(2.1.14) \quad \cdots \rightarrow \mathcal{H}^i(A^\bullet) \rightarrow \mathcal{H}^i(B^\bullet) \rightarrow \mathcal{H}^i(C^\bullet) \rightarrow \mathcal{H}^{i+1}(A^\bullet) \rightarrow \cdots, \quad \forall i \in \mathbb{Z}.$$

**Definition 2.1.15.** A morphism of complexes  $f^\bullet : A^\bullet \rightarrow B^\bullet$  in  $\text{Kom}(\mathcal{A})$  is called *quasi-isomorphism* if the induced morphism

$$(2.1.16) \quad \mathcal{H}^i(f^\bullet) : \mathcal{H}^i(A^\bullet) \rightarrow \mathcal{H}^i(B^\bullet)$$

is an isomorphism, for all  $i \in \mathbb{Z}$ .

**Example 2.1.17.** Let  $X$  be a smooth projective  $k$ -variety and let  $E$  be a coherent sheaf on  $X$ . Then we can find a finite resolution

$$0 \rightarrow E^n \rightarrow E^{n-1} \rightarrow \cdots \rightarrow E^1 \rightarrow E^0 \rightarrow E \rightarrow 0.$$

of  $E$  with  $E^i$  projective (locally free)  $\mathcal{O}_X$ -modules. (We can use this to study many properties of  $E$  in terms of locally free coherent sheaves.) This gives rise to a morphism of complexes

$$f^\bullet : (0 \rightarrow E^n \rightarrow E^{n-1} \rightarrow \cdots \rightarrow E^1 \rightarrow E^0) \rightarrow (\cdots \rightarrow 0 \rightarrow E \rightarrow 0 \rightarrow \cdots),$$

which is a quasi-isomorphism.

**2.2. What is a derived category?** The main idea for definition of derived category is: *quasi-isomorphism of complexes should become isomorphism in the derived category*. Therefore, the derived category  $D(\mathcal{A})$  is the localization of  $\text{Kom}(\mathcal{A})$  by quasi-isomorphisms. This can be done by passing to the appropriate homotopy category.

**Theorem 2.2.1.** Let  $\mathcal{A}$  be an abelian category, and  $\text{Kom}(\mathcal{A})$  the category of complexes in  $\mathcal{A}$ . Then there is a category  $D(\mathcal{A})$ , known as the derived category of  $\mathcal{A}$ , together with a functor

$$(2.2.2) \quad Q : \text{Kom}(\mathcal{A}) \rightarrow D(\mathcal{A})$$

such that:

- (i) If  $f^\bullet : A^\bullet \rightarrow B^\bullet$  in  $\text{Kom}(\mathcal{A})$  is a quasi-isomorphism, then  $Q(f^\bullet)$  is an isomorphism in  $D(\mathcal{A})$ ,
- (ii) if a functor  $\mathcal{F} : \text{Kom}(\mathcal{A}) \rightarrow \mathcal{D}$  satisfies property (i), there is a unique functor  $\tilde{\mathcal{F}} : D(\mathcal{A}) \rightarrow \mathcal{D}$  such that  $\tilde{\mathcal{F}} \circ Q \cong \mathcal{F}$ .

$$(2.2.3) \quad \begin{array}{ccc} \text{Kom}(\mathcal{A}) & \xrightarrow{Q} & D(\mathcal{A}) \\ & \searrow \mathcal{F} & \swarrow \exists! \tilde{\mathcal{F}} \\ & \mathcal{D} & \end{array}$$

Now we go ahead for construction of the derived category  $D(\mathcal{A})$  of  $\mathcal{A}$ . Since we want any quasi-isomorphism  $C^\bullet \rightarrow A^\bullet$  of complexes in  $\text{Kom}(\mathcal{A})$  to become isomorphism in the derived category  $D(\mathcal{A})$ , any morphism of complexes  $C^\bullet \rightarrow B^\bullet$

in  $\text{Kom}(\mathcal{A})$  should give rise to a morphism  $A^\bullet \rightarrow B^\bullet$  in  $D^b(\mathcal{A})$ . This leads to the definition of morphisms in  $D^b(\mathcal{A})$  as diagrams of the form

$$\begin{array}{ccc} & C^\bullet & \\ \text{\textit{qis}} \swarrow & & \searrow \\ A^\bullet & & B^\bullet, \end{array}$$

where “*qis*” stands for “quasi-isomorphism” of complexes. To make this more precise, we need to define when two such roofs should be considered equal, and how to define their compositions. Then natural context for both problems is to consider the homotopy category  $K(\mathcal{A})$  of complexes in  $\text{Kom}(\mathcal{A})$ , which is an intermediate step for going from  $\text{Kom}(\mathcal{A})$  to  $\mathcal{D}(\mathcal{A})$ .

$$\begin{array}{ccc} \text{Kom}(\mathcal{A}) & \xrightarrow{Q} & D(\mathcal{A}) \\ & \searrow & \nearrow \\ & K(\mathcal{A}) & \end{array}$$

**Definition 2.2.4.** Two morphisms of complexes  $f^\bullet, g^\bullet : A^\bullet \rightarrow B^\bullet$  in  $\text{Kom}(\mathcal{A})$  are said to be *homotopically equivalent*, written as  $f^\bullet \sim g^\bullet$ , if there is a morphism of complexes  $h^\bullet : A^\bullet \rightarrow B^\bullet[-1]$  such that  $f^i - g^i = h^{i+1} \circ d_A^i + d_B^{i-1} \circ h^i$ .

$$\begin{array}{ccccccc} A^\bullet & \cdots & \longrightarrow & A^{i-1} & \xrightarrow{d_A^{i-1}} & A^i & \xrightarrow{d_A^i} & A^{i+1} & \xrightarrow{d_A^{i+1}} & \cdots \\ g^\bullet \downarrow & & & g^{i-1} \downarrow & & g^i \downarrow & & g^{i+1} \downarrow & & \\ B^\bullet & \cdots & \longrightarrow & B^{i-1} & \xrightarrow{d_B^{i-1}} & B^i & \xrightarrow{d_B^i} & B^{i+1} & \xrightarrow{d_B^{i+1}} & \cdots \end{array}$$

$\begin{array}{c} \xrightarrow{h^i} \\ \xleftarrow{h^{i+1}} \end{array}$

Let  $K(\mathcal{A})$  be the category, whose objects are the same as objects of  $\text{Kom}(\mathcal{A})$  and morphisms are given by  $\text{Hom}_{K(\mathcal{A})}(A^\bullet, B^\bullet) := \text{Hom}_{\text{Kom}(\mathcal{A})}(A^\bullet, B^\bullet) / \sim$ , for all  $A^\bullet, B^\bullet \in \text{Kom}(\mathcal{A})$ .

Following proposition is an easy consequence of the above definition.

- Proposition 2.2.5.** (i) Homotopy equivalence of morphisms  $A^\bullet \rightarrow B^\bullet$  of complexes is an equivalence relation.
- (ii) Homotopically trivial morphisms of complexes form an ‘ideal’ in the morphisms of  $\text{Kom}(\mathcal{A})$ .
- (iii) If  $f^\bullet$  and  $g^\bullet$  are two homotopically equivalent morphisms of complexes in  $\text{Kom}(\mathcal{A})$ , then the induced morphisms  $\mathcal{H}^i(f^\bullet)$  and  $\mathcal{H}^i(g^\bullet)$  from  $\mathcal{H}^i(A^\bullet)$  to  $\mathcal{H}^i(B^\bullet)$  coincide.
- (iv) Let  $f^\bullet : A^\bullet \rightarrow B^\bullet$  and  $g^\bullet : B^\bullet \rightarrow A^\bullet$  be two morphisms of complexes. If  $f^\bullet \circ g^\bullet \sim \text{Id}_{B^\bullet}$  and  $g^\bullet \circ f^\bullet \sim \text{Id}_{A^\bullet}$ , then  $f^\bullet$  and  $g^\bullet$  are quasi-isomorphisms, and  $\mathcal{H}^i(f^\bullet)^{-1} = \mathcal{H}^i(g^\bullet)$ , for all  $i \in \mathbb{Z}$ .

Now we complete the construction of derived category  $D(\mathcal{A})$ . Take  $\text{Ob}(D(\mathcal{A})) := \text{Ob}(\text{Kom}(\mathcal{A}))$ . As discussed before, a morphism  $f : A^\bullet \rightarrow B^\bullet$  in  $D(\mathcal{A})$  is given by equivalence class of roofs of the form

$$\begin{array}{ccc} & C^\bullet & \\ \swarrow \text{qis} & & \searrow \\ A^\bullet & & B^\bullet \end{array}$$

where  $C^\bullet \xrightarrow{\text{qis}} A^\bullet$  is a quasi-isomorphism of complexes in  $\text{Kom}(\mathcal{A})$ , and two such roofs

$$\begin{array}{ccc} & C_1^\bullet & \\ \swarrow \text{qis} & & \searrow \\ A^\bullet & & B^\bullet \end{array} \quad \begin{array}{ccc} & C_2^\bullet & \\ \swarrow \text{qis} & & \searrow \\ A^\bullet & & B^\bullet \end{array}$$

are considered to be equivalent if they are dominated by a third one of the same type

(2.2.6)

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

such that the above diagram commutes in the homotopy category  $K(\mathcal{A})$ . In particular, the compositions  $C_0^\bullet \rightarrow C_1^\bullet \rightarrow A^\bullet$  and  $C_0^\bullet \rightarrow C_2^\bullet \rightarrow A^\bullet$  are homotopically equivalent. To define composition of morphisms in  $D(\mathcal{A})$ , consider two roofs

$$\begin{array}{ccc} & C_1^\bullet & \\ \swarrow \text{qis} & & \searrow \\ A^\bullet & & B^\bullet \end{array} \quad \begin{array}{ccc} & C_2^\bullet & \\ \swarrow \text{qis} & & \searrow \\ B^\bullet & & C^\bullet \end{array}$$

representing two morphisms in  $D(\mathcal{A})$ . It is natural to guess that, one should be able to define their composition to be a morphism represented by 'the' following roof

(2.2.7)

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

which commutes in the homotopy category  $K(\mathcal{A})$ . Now we need to ensure that such a diagram exists uniquely, up to *equivalence of roofs* as defined in (2.2.6) (c.f., Proposition 2.2.12). For this, we need the concept of “mapping cone”.

**Definition 2.2.8.** The *mapping cone* of a morphism  $f^\bullet : A^\bullet \rightarrow B^\bullet$  in  $Kom(\mathcal{A})$  is a complex  $C(f^\bullet)$  defined as follow:

$$C(f^\bullet)^i = A^{i+1} \oplus B^i \quad \text{and} \quad d_{C(f^\bullet)}^i = \begin{pmatrix} -d_{A^\bullet}^{i+1} & 0 \\ f^{i+1} & d_{B^\bullet}^i \end{pmatrix}, \quad \forall i \in \mathbb{Z}.$$

Note that  $C(f^\bullet)$  is a complex. Moreover, there are natural morphisms of complexes

$$(2.2.9) \quad \tau : B^\bullet \rightarrow C(f^\bullet) \quad \text{and} \quad \pi : C(f^\bullet) \rightarrow A^\bullet[1]$$

given by natural injection  $B^i \rightarrow A^{i+1} \oplus B^i$  and the natural projection  $A^{i+1} \oplus B^i \rightarrow A^\bullet[1]^i = A^{i+1}$ , respectively, for all  $i$ . Then we have the following.

- (i) The composition  $B^\bullet \xrightarrow{\tau} C(f^\bullet) \xrightarrow{\pi} A^\bullet[1]$  is trivial. In fact,

$$0 \longrightarrow B^\bullet \xrightarrow{\tau} C(f^\bullet) \xrightarrow{\pi} A^\bullet[1] \longrightarrow 0$$

is a short exact sequence in  $Kom(\mathcal{A})$ , and gives us a long exact sequence of cohomologies

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

- (ii) The composition  $A^\bullet \xrightarrow{f^\bullet} B^\bullet \xrightarrow{\tau} C(f^\bullet)$  is homotopic to the trivial morphism. Indeed, take  $h^\bullet : A^\bullet \rightarrow C(f^\bullet)$  to be morphism of complexes defined by the natural injective morphism  $h^i : A^i \rightarrow C(f^\bullet)^{i-1} = A^i \oplus B^{i-1}$ , for all  $i$ . Then we have

$$h^{i+1} \circ d_{A^\bullet}^i + d_{C(f^\bullet)}^{i-1} \circ h^i = \tau^i \circ f^i, \quad \forall i \in \mathbb{Z}.$$

**Remark 2.2.10.** It follows from the above construction that any commutative diagram of complexes

$$\begin{array}{ccccccc} A_1^\bullet & \xrightarrow{f_1^\bullet} & B_1^\bullet & \xrightarrow{\tau_1} & C(f_1^\bullet) & \xrightarrow{\pi_1} & A_1^\bullet[1] \\ \downarrow \phi & & \downarrow \psi & & \downarrow \exists! \phi[1] \oplus \psi & & \downarrow \phi[1] \\ A_2^\bullet & \xrightarrow{f_2^\bullet} & B_2^\bullet & \xrightarrow{\tau_2} & C(f_2^\bullet) & \xrightarrow{\pi_2} & A_2^\bullet[1] \end{array}$$

can be completed by a **dashed arrow** as above (c.f., axiom (TR3) in Definition 1.2.4).

**Proposition 2.2.11.** Let  $f : A^\bullet \rightarrow B^\bullet$  be a morphism of complexes and let  $C(f)$  be its mapping cone. Let  $\tau : B^\bullet \rightarrow C(f)$  and  $\pi : C(f) \rightarrow A^\bullet[1]$  be the natural morphisms as in

(2.2.9). Then there is a morphism of complexes  $g : A^\bullet[1] \rightarrow C(\tau)$  which is an isomorphism in  $K(\mathcal{A})$  such that the following diagram commutes in the homotopy category  $K(\mathcal{A})$ .

$$\begin{array}{ccccc} B^\bullet & \xrightarrow{\tau} & C(f) & \xrightarrow{\pi} & A^\bullet[1] & \xrightarrow{-f} & B^\bullet[1] \\ & & \searrow \tau_\tau & & \downarrow g & & \nearrow \pi_\tau \\ & & & & C(\tau) & & \end{array}$$

*Proof.* Define  $g : A^\bullet[1] \rightarrow C(\tau)$  by setting

$$g^i : A^\bullet[1]^i = A^{i+1} \rightarrow C(\tau)^i = B^{i+1} \oplus A^{i+1} \oplus B^i$$

to be the morphism  $g^i = (-f^{i+1}, \text{Id}_{A^{i+1}}, 0)$ , for all  $i$ . Clearly,  $g$  is a morphism of complexes, and its inverse (in  $K(\mathcal{A})$ ) is given by the morphism of complexes  $g^{-1} : C(\tau) \rightarrow A^\bullet[1]$  defined by projection onto the middle factor. Clearly,  $\pi_\tau \circ g = -f$  in  $\text{Kom}(\mathcal{A})$ . However, the diagram

$$\begin{array}{ccc} C(f) & \xrightarrow{\pi} & A^\bullet[1] \\ & \searrow \tau_\tau & \downarrow g \\ & & C(\tau) \end{array}$$

does not commute in  $\text{Kom}(\mathcal{A})$ . We show that,  $\pi \circ g \sim \tau_\tau$ . For this, note that  $g^{-1} \circ \tau_\tau = \pi$  in  $\text{Kom}(\mathcal{A})$ . Since  $g \circ g^{-1} \sim \text{Id}_{C(\tau)}$ , we have  $\tau_\tau \sim g \circ \pi$ . This completes the proof.  $\square$

Now we use the above proposition to complete the proof of existence and uniqueness of composition of morphisms in  $D(\mathcal{A})$ .

**Proposition 2.2.12.** Let  $f : A^\bullet \rightarrow B^\bullet$  and  $g : C^\bullet \rightarrow B^\bullet$  be morphism of complexes with  $f$  a quasi-isomorphism. Then there is a complex  $C_0^\bullet$  together with a quasi-isomorphism  $C_0^\bullet \rightarrow C^\bullet$  and a morphism  $C_0^\bullet \rightarrow A^\bullet$  such that the following diagram commutes in the homotopy category  $K(\mathcal{A})$ .

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

*Proof.* Note that, there is a natural morphism of complexes  $\phi^i : C(\tau \circ g) \rightarrow A^\bullet[1]$  given by the natural projection

$$\phi^i : C(\tau \circ g)^i = C^{i+1} \oplus C(f)^i = C^{i+1} \oplus A^{i+1} \oplus B^i \xrightarrow{pr_2} A^{i+1} = A^\bullet[1]^i$$

onto the middle factor, for each  $i$ . By Proposition 2.2.11, there is morphism of complexes  $\psi : C(\tau) \xrightarrow{\sim} A^\bullet[1]$  which is an isomorphism in  $K(\mathcal{A})$ . Then the following



diagram is commutative in  $K(\mathcal{A})$ .

$$\begin{array}{ccccccc}
 C_0^\bullet := C(\tau \circ g)[-1] & \xrightarrow{\quad} & C^\bullet & \xrightarrow{\tau \circ g} & C(f) & \xrightarrow{\tau \circ g} & C(\tau \circ g) \\
 \downarrow \phi[-1] & & \downarrow g & & \parallel & & \downarrow \phi \\
 A^\bullet & \xrightarrow{f} & B^\bullet & \xrightarrow{\tau} & C(f) & \xrightarrow{\pi} & C(\tau) \xrightarrow{\sim} A^\bullet[1]
 \end{array}$$

Define  $C_0^\bullet := C(\tau \circ g)[-1]$ . Since  $f$  is a quasi-isomorphism, it follows from the commutativity of the above diagram that  $C_0^\bullet \rightarrow C^\bullet$  is a quasi-isomorphism.  $\square$

**Remark 2.2.13.** Existence and uniqueness of composition of morphisms in  $D(\mathcal{A})$  follows from the above Proposition 2.2.12 (c.f., diagram (2.2.7)). This completes the construction of the derived category  $D(\mathcal{A})$ .

**Proposition 2.2.14.** *The categories  $K(\mathcal{A})$  and  $D(\mathcal{A})$  are additive.*

*Proof.* Let  $A^\bullet, B^\bullet \in \text{Kom}(\mathcal{A})$ . Since  $\text{Kom}(\mathcal{A})$  is an abelian category, it follows from Proposition 2.2.5 that the quotient

$$\text{Hom}_{K(\mathcal{A})}(A^\bullet, B^\bullet) = \text{Hom}_{\text{Kom}(\mathcal{A})}(A^\bullet, B^\bullet) / \sim,$$

is an abelian group. Thus  $K(\mathcal{A})$  is an additive category.

To see  $D(\mathcal{A})$  is an additive category, let  $f_1, f_2 \in \text{Hom}_{D(\mathcal{A})}(A^\bullet, B^\bullet)$  be two morphisms in  $D(\mathcal{A})$  represented by following equivalence classes of roofs

$$\begin{array}{ccc}
 & C_1^\bullet & \\
 \phi_1 \swarrow & & \searrow \psi_1 \\
 A^\bullet & & B^\bullet
 \end{array}
 \quad \text{and} \quad
 \begin{array}{ccc}
 & C_2^\bullet & \\
 \phi_2 \swarrow & & \searrow \psi_2 \\
 A^\bullet & & B^\bullet
 \end{array},$$

respectively. It follows from Proposition 2.2.12 that there is an object  $C^\bullet \in D(\mathcal{A})$  and quasi-morphisms  $\delta_i : C^\bullet \rightarrow C_i^\bullet$ , for  $i = 1, 2$ , such that the following diagram commutes in the homotopy category.

$$(2.2.15) \quad
 \begin{array}{ccc}
 C^\bullet & \xrightarrow{\delta_2} & C_2^\bullet \\
 \text{qis} \downarrow \delta_1 & & \downarrow \phi_2 \\
 C_1^\bullet & \xrightarrow[\text{qis}]{\phi_1} & A^\bullet
 \end{array}$$

Note that, both  $\phi_1 \circ \delta_1$  and  $\phi_2 \circ \delta_2$ , are quasi-isomorphisms, and are equal in  $K(\mathcal{A})$ . Let  $\delta = \phi_1 \circ \delta_1 = \phi_2 \circ \delta_2$  in  $K(\mathcal{A})$ . Then in  $D(\mathcal{A})$ , we can write

$$f_1 + f_2 = \psi_1 \circ \phi_1^{-1} + \psi_2 \circ \phi_2^{-1} = (\psi_1 \circ \delta_1 + \psi_2 \circ \delta_2) \circ \delta^{-1}.$$

This defines  $f_1 + g_1$  in  $D(\mathcal{A})$ . One can check that,  $f + g$  as defined above, is well-defined in  $D(\mathcal{A})$ . Note that, the roof  $A^\bullet \xleftarrow[\text{qis}]{-\phi_1} C_1^\bullet \xrightarrow{\psi_1} B^\bullet$  is the additive inverse of  $f_1$  in  $D(\mathcal{A})$ . Now one can check that  $\text{Hom}_{D(\mathcal{A})}(A^\bullet, B^\bullet)$  is an abelian group.  $\square$

**Definition 2.2.16.** A triangle

$$A_1^\bullet \longrightarrow A_2^\bullet \longrightarrow A_3^\bullet \longrightarrow A_1^\bullet[1]$$

in  $K(\mathcal{A})$  (resp., in  $D(\mathcal{A})$ ) is said to be a *distinguished triangle* if it is isomorphic in  $K(\mathcal{A})$  (resp.,  $D(\mathcal{A})$ ) to a triangle of the form

$$A^\bullet \xrightarrow{f} B^\bullet \xrightarrow{\tau} C(f) \xrightarrow{\pi} A^\bullet[1],$$

where  $f$  is a morphism of complexes with mapping cone  $C(f)$ , and  $\tau$  and  $\pi$  are natural morphisms as defined in (2.2.9).

**Proposition 2.2.17.** *The categories  $D(\mathcal{A})$  and  $K(\mathcal{A})$  together with the shift functor are triangulated. Moreover, the natural functor  $Q : K(\mathcal{A}) \longrightarrow D(\mathcal{A})$  is an exact functor of triangulated categories.*

*Proof.* Triangulated structure on both  $K(\mathcal{A})$  and  $D(\mathcal{A})$  are given by shift functor  $A^\bullet \mapsto A^\bullet[1]$  together with the collection of ‘distinguished triangles’ as defined above. Verification of axioms (TR1) – (TR4) requires crucial use of mapping cone.  $\square$

**Example 2.2.18.** Let  $\mathcal{A} = \text{Vect}_{fd}(k)$  be the category, whose objects are finite dimensional  $k$ -vector spaces, and morphisms between objects are  $k$ -linear homomorphisms. Then  $D(\mathcal{A})$  is equivalent to the category  $\prod_{i \in \mathbb{Z}} \mathcal{A}$  of graded  $k$ -vector spaces. Note that, any complex of  $k$ -vector spaces  $A^\bullet \in D(\text{Vect}_{fd}(k))$  is isomorphic to its cohomology complex  $\bigoplus_{i \in \mathbb{Z}} H^i(A^\bullet)[-i]$  with trivial differentials. More generally, this holds for any *semisimple* abelian category  $\mathcal{A}$  (i.e., when  $\mathcal{A}$  is abelian and any short exact sequence in  $\mathcal{A}$  splits).

**Remark 2.2.19.** Contrary to the category  $\text{Kom}(\mathcal{A})$  of complexes in  $\mathcal{A}$ , the derived category  $D(\mathcal{A})$  is not abelian, in general. However,  $D(\mathcal{A})$  is always triangulated.  $D^b(\mathcal{A})$  is abelian if and only if  $\mathcal{A}$  is semisimple (see <https://math.stackexchange.com/questions/189769>).

**Corollary 2.2.20.** (a) *The functor  $Q : \text{Kom}(\mathcal{A}) \longrightarrow D(\mathcal{A})$  identifies set underlying set of objects of both categories (Apply property (ii) to the identity functor  $\text{Kom}(\mathcal{A}) \rightarrow \text{Kom}(\mathcal{A})$ ).*

(b) *For any complex  $A^\bullet \in D(\mathcal{A})$ , its cohomology objects  $\mathcal{H}^i(A^\bullet)$  are well-defined objects in  $\mathcal{A}$ . (This is because, quasi-isomorphisms of  $\text{Kom}(\mathcal{A})$  turns into isomorphisms in  $D(\mathcal{A})$ .)*

(c) *Considering  $A \in \mathcal{A}$  as a complex  $A^\bullet \in D(\mathcal{A})$  concentrated at degree zero only, gives an equivalence between  $\mathcal{A}$  and the full subcategory of objects of  $D(\mathcal{A})$  with  $\mathcal{H}^i(A^\bullet) = 0$  for  $i \neq 0$ .*

**Proposition 2.2.21.** *Let  $\mathcal{A}$  be an abelian category and  $K(\mathcal{A})$  its homotopy category. Let  $\mathcal{C}$  be any additive category.*

- (1) An additive functor  $F : K(\mathcal{A}) \rightarrow \mathcal{C}$  factors through an additive functor  $\tilde{F} : D(\mathcal{A}) \rightarrow \mathcal{C}$  if and only if  $F$  send quasi-isomorphisms to isomorphisms.
- (2) Let  $\mathcal{B}$  be an abelian category, and  $G : K(\mathcal{A}) \rightarrow K(\mathcal{B})$  an additive functor which maps quasi-isomorphism to quasi-isomorphism. Then  $G$  induces an additive functor  $\tilde{G} : D(\mathcal{A}) \rightarrow D(\mathcal{B})$  such that the following diagram commutes.

$$\begin{array}{ccc} K(\mathcal{A}) & \xrightarrow{G} & K(\mathcal{B}) \\ Q_{\mathcal{A}} \downarrow & & \downarrow Q_{\mathcal{B}} \\ D(\mathcal{A}) & \xrightarrow{\tilde{G}} & D(\mathcal{B}) \end{array}$$

*Proof.* If  $F : K(\mathcal{A}) \rightarrow \mathcal{C}$  sends quasi-isomorphisms to quasi-isomorphism, we define  $\tilde{F} : D(\mathcal{A}) \rightarrow \mathcal{C}$  by sending an object  $E^\bullet \in D(\mathcal{A})$  to  $F(E^\bullet) \in \mathcal{C}$ , and any morphism  $f/\phi : A^\bullet \xleftarrow[\sim]{\phi} C^\bullet \xrightarrow{f} B^\bullet$  in  $D(\mathcal{A})$  to the morphism

$$F(f) \circ F(\phi)^{-1} : F(A^\bullet) \xrightarrow[\simeq]{F(\phi)^{-1}} F(C^\bullet) \xrightarrow{F(f)} F(B^\bullet).$$

in  $\mathcal{C}$ . Converse follows from the construction of  $D(\mathcal{A})$  and Theorem 2.2.1.

The second assertion follows by applying the first one to the composition  $F : K(\mathcal{A}) \xrightarrow{G} K(\mathcal{B}) \xrightarrow{Q_{\mathcal{B}}} D(\mathcal{B})$ .  $\square$

### 2.3. Derived categories: $D^-(\mathcal{A})$ , $D^+(\mathcal{A})$ , and $D^b(\mathcal{A})$ .

**Definition 2.3.1.** Let  $Kom^*(\mathcal{A})$ , with  $*$  = +, −, or  $b$ , be the full subcategory of  $Kom(\mathcal{A})$ , whose objects are complexes  $A^\bullet \in Kom(\mathcal{A})$  with  $A^i = 0$  for all  $i \ll 0$ ,  $i \gg 0$ , or  $|i| \ll 0$ , respectively.

Note that,  $Kom^*(\mathcal{A})$  is again abelian, for  $*$   $\in$  {+, −,  $b$ }. So following similar construction (i.e., by dividing out first by homotopy equivalence, and then by localizing with respect to quasi-isomorphisms), we can construct a category, denoted by  $D^*(\mathcal{A})$ . There is a natural forgetful functor

$$\mathcal{F}^* : D^*(\mathcal{A}) \longrightarrow D(\mathcal{A}),$$

which just forgets boundedness condition.

**Proposition 2.3.2.** The natural forgetful functor  $\mathcal{F}^* : D^*(\mathcal{A}) \longrightarrow D(\mathcal{A})$ , where  $*$  = +, −, or  $b$ , gives an equivalence of  $D^*(\mathcal{A})$  with the full triangulated subcategories of all complexes  $A^\bullet \in D(\mathcal{A})$  with  $\mathcal{H}^i(A^\bullet) = 0$ , for  $i \ll 0$ , for  $i \gg 0$ , or for  $|i| \ll 0$ , respectively.

To give an idea how this works, let  $A^\bullet \in \text{Kom}(\mathcal{A})$  be such that  $\mathcal{H}^i(A^\bullet) = 0$ , for  $i > n$ . Then the commutative diagram

$$(2.3.3) \quad \begin{array}{ccccccc} B^\bullet : & \cdots & \longrightarrow & A^{n-2} & \longrightarrow & A^{n-1} & \longrightarrow \text{Ker}(d_A^n) \longrightarrow 0 \longrightarrow \cdots \\ & & & \parallel & & \parallel & \downarrow \text{hook} \\ A^\bullet : & \cdots & \longrightarrow & A^{n-2} & \longrightarrow & A^{n-1} & \longrightarrow A^n \longrightarrow A^{n+1} \longrightarrow \cdots \end{array}$$

defines a quasi-isomorphism between a complex  $B^\bullet \in \text{Kom}^-(\mathcal{A})$  and  $A^\bullet$ . Similarly, if  $\mathcal{H}^i(A^\bullet) = 0$  for  $i < m$ , then the commutative diagram

$$(2.3.4) \quad \begin{array}{ccccccc} A^\bullet : & \cdots & \longrightarrow & A^{m-1} & \longrightarrow & A^m & \longrightarrow A^{m+1} \longrightarrow \cdots \\ & & & \downarrow & & \downarrow & \parallel \\ C^\bullet : & \cdots & \longrightarrow & 0 & \longrightarrow & \text{Coker}(d_A^{m-1}) & \longrightarrow A^{m+1} \longrightarrow \cdots \end{array}$$

defines a quasi-isomorphism of a complex  $C^\bullet \in \text{Kom}^+(\mathcal{A})$  and  $A^\bullet$ . Similar idea works for  $\text{Kom}^b(\mathcal{A})$ . However, one need to pass from  $\text{Kom}^*(\mathcal{A})$  to the derived category  $D^*(\mathcal{A})$  by inverting quasi-isomorphisms. This needs some technical care.

Let  $\mathcal{A} \subset \mathcal{B}$  be full abelian subcategory of an abelian category  $\mathcal{B}$ . Then there is an obvious functor  $\iota : D(\mathcal{A}) \rightarrow D(\mathcal{B})$ . One might expect that this is an equivalence of  $D(\mathcal{A})$  with the full subcategory  $D_{\mathcal{A}}(\mathcal{B})$  of  $D(\mathcal{B})$  consisting of objects  $E^\bullet \in D(\mathcal{B})$  with  $\mathcal{H}^i(E^\bullet) \in \mathcal{A}$ , for all  $i \in \mathbb{Z}$ . However, this is not true, in general. There are several issues.

- $D_{\mathcal{A}}(\mathcal{B})$  need not be triangulated!
- The functor  $\iota$  is neither faithful nor full, in general.

However, the next proposition answers when the above expectation holds true. First, we need a definition.

**Definition 2.3.5.** Let  $\mathcal{A}$  be an abelian category. A *thick subcategory* of  $\mathcal{A}$  is a full abelian subcategory  $\mathcal{B} \subset \mathcal{A}$  of  $\mathcal{A}$  such that for any short exact sequence (in  $\mathcal{A}$ )

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

with  $A, C \in \mathcal{B}$ , we have  $B \in \mathcal{B}$ .

Let  $E, F \in \mathcal{A}$ . We say that  $F$  is *embedded* in  $E$  (or,  $F$  is a *subobject* of  $E$ ) if there is a monomorphism  $F \rightarrow E$  in  $\mathcal{A}$ . An object  $I \in \mathcal{A}$  is called *injective* if the functor

$$\text{Hom}_{\mathcal{A}}(-, I) : \mathcal{A} \rightarrow \text{Ab}$$

is exact.

**Proposition 2.3.6.** *Let  $\mathcal{A} \subset \mathcal{B}$  be a thick abelian subcategory of an abelian category  $\mathcal{B}$ . Assume that any object  $A \in \mathcal{A}$  is a subobject of an object  $I_A \in \mathcal{A}$ , which is *injective as an object of  $\mathcal{B}$* . Then the natural functor  $D(\mathcal{A}) \rightarrow D(\mathcal{B})$  induces an equivalence*

$$D^*(\mathcal{A}) \longrightarrow D^*_{\mathcal{A}}(\mathcal{B}), \quad \text{where } * = + \text{ or } b,$$

*of  $D^*(\mathcal{A})$  and the full triangulated subcategory  $D^*_{\mathcal{A}}(\mathcal{B}) \subset D^*(\mathcal{B})$  of complexes with cohomologies in  $\mathcal{A}$ .*

P.S.: I have not seen similar statement for  $* = \emptyset$  or  $-$ .

Next, we want to get a computable description of Hom's in the derived category. In the next section, using derived functor, we show that

$$\mathrm{Hom}_{D(\mathcal{A})}(A^\bullet, B^\bullet[i]) = \mathrm{Ext}^i(A^\bullet, B^\bullet), \quad \forall i.$$

### 3. DERIVED FUNCTORS

**3.1. What is it?** Let  $F : \mathcal{A} \rightarrow \mathcal{B}$  be an additive functor between abelian categories. We want to know when such a functor give rise to a natural functor between derived categories. Note that, if  $F$  is not exact, then image of an acyclic complex  $(\mathcal{H}^i(A^\bullet) = 0, \forall i)$  may not be acyclic. So to get a induced functor at the level of derived categories,  $F$  should be exact.

**Lemma 3.1.1.** *Let  $F : K^*(\mathcal{A}) \rightarrow K^*(\mathcal{B})$ , where  $* \in \{\emptyset, -, +, b\}$ , be an exact functor of triangulated categories. Then  $F$  induces a functor  $\tilde{F} : D^*(\mathcal{A}) \rightarrow D^*(\mathcal{B})$  making the following diagram commutative*

$$\begin{array}{ccc} K^*(\mathcal{A}) & \xrightarrow{F} & K^*(\mathcal{B}) \\ \downarrow & & \downarrow \\ D^*(\mathcal{A}) & \xrightarrow{\tilde{F}} & D^*(\mathcal{B}) \end{array}$$

*if and only if one of the following (equivalent) conditions holds:*

- (i)  *$F$  sends a quasi-isomorphism to a quasi-isomorphism.*
- (ii)  *$F$  sends any acyclic complex to an acyclic complex.*

However, if the functor  $F$  is not exact or  $F$  does not satisfies one of the equivalent conditions in (i) and (ii) above, still there is a bit complicated way to induce a natural functor between derived categories. This new functor is called the derived functor of  $F$ , but they will not produce a commutative diagram as in the above lemma. However, derived functor encodes more information about objects of the abelian categories.

To ensure existence of a derived functors, we need to assume some kind of exactness of  $F$ . If  $F$  is left exact (resp., right exact), we generally get a right derived functor (resp., left derived functor)

$$RF : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B}) \quad (\text{resp., } LF : D^-(\mathcal{A}) \longrightarrow D^-(\mathcal{B})).$$

Both constructions are similar, and we only discuss the case of left exact functor.

Let  $F : \mathcal{A} \rightarrow \mathcal{B}$  be a left exact functor of abelian categories. Assume that  $\mathcal{A}$  has enough injective (meaning that, for any  $A \in \mathcal{A}$ , there is an injective object  $I$  of  $\mathcal{A}$  together with a monomorphism  $\iota : A \hookrightarrow I$  in  $\mathcal{A}$ ). Let  $\mathcal{I}_{\mathcal{A}} \subset \mathcal{A}$  be the full subcategory of  $\mathcal{A}$  consisting of injective objects of  $\mathcal{A}$ . Note that,  $\mathcal{I}_{\mathcal{A}}$  is additive, but not necessarily abelian. However, the construction of homotopy category works for any additive category. Therefore,  $K^*(\mathcal{I}_{\mathcal{A}})$  is defined, and is a triangulated category. Now the inclusion functor  $\mathcal{I}_{\mathcal{A}} \hookrightarrow \mathcal{A}$  induces a natural exact functor  $K^*(\mathcal{I}_{\mathcal{A}}) \longrightarrow K^*(\mathcal{A})$ , and composing it with the exact functor  $Q_{\mathcal{A}} : K^+(\mathcal{A}) \rightarrow D^+(\mathcal{A})$ , we get a natural exact functor  $K^+(\mathcal{I}_{\mathcal{A}}) \longrightarrow D^+(\mathcal{A})$ .

**Proposition 3.1.2.** *The functor  $Q_{\mathcal{A}} : K^+(\mathcal{A}) \longrightarrow D^+(\mathcal{A})$  induces a natural equivalence of categories  $\iota : K^+(\mathcal{I}_{\mathcal{A}}) \longrightarrow D^+(\mathcal{A})$ .*

Then we have the following diagram

$$\begin{array}{ccccc} K^+(\mathcal{I}_{\mathcal{A}}) & \xhookrightarrow{\quad} & K^+(\mathcal{A}) & \xrightarrow{K(F)} & K^+(\mathcal{B}) \\ & \searrow \iota & \downarrow Q_{\mathcal{A}} & & \downarrow Q_{\mathcal{B}} \\ & & D^+(\mathcal{A}) & & D^+(\mathcal{B}) \end{array}$$

$\iota^{-1}$  (curved red arrow from  $D^+(\mathcal{A})$  to  $K^+(\mathcal{I}_{\mathcal{A}})$ )

where  $\iota^{-1}$  is the quasi-inverse functor. Such a quasi-isomorphism ( $\iota^{-1}$ ) is obtained by choosing a complex of injective objects quasi-isomorphic to a given bounded below complex in  $D^+(\mathcal{A})$ . Note that, the functor  $K(F)$  is well-defined at the level of homotopy category, because  $F$  is left exact and we are working with bounded below complexes.

**Definition 3.1.3.** The *right derived functor* of a left exact functor  $F : \mathcal{A} \rightarrow \mathcal{B}$  is the functor

$$RF := Q_{\mathcal{B}} \circ K(F) \circ \iota^{-1} : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B}).$$

**Proposition 3.1.4.** (i) *There is a natural morphism of functors*

$$Q_{\mathcal{B}} \circ K(F) \longrightarrow RF \circ Q_{\mathcal{A}}.$$

(ii) *The right derived functor  $RF : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B})$  is an exact functor of triangulated categories.*

(iii) Let  $G : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B})$  be an exact functor of triangulated categories. Then any morphism of functors

$$Q_{\mathcal{B}} \circ K(F) \longrightarrow G \circ Q_{\mathcal{A}},$$

factorize through a unique morphism of functors  $RF \longrightarrow G$ .

*Proof.* (i) Let  $A^\bullet \in K^+(\mathcal{A})$ . Note that,  $Q_{\mathcal{A}}(A^\bullet) = A^\bullet$ . Let  $I^\bullet := \iota^{-1}(A^\bullet) \in K^+(\mathcal{I}_{\mathcal{A}})$ . Then the natural isomorphism of functors  $\text{Id}_{D^+(\mathcal{A})} \xrightarrow{\cong} \iota \circ \iota^{-1}$  gives rise to a functorial isomorphism  $A^\bullet \xrightarrow{\cong} \iota(I^\bullet) \cong I^\bullet$ . Since  $I^\bullet$  is a complex of injective objects, the above isomorphism in  $D^+(\mathcal{A})$  gives rise to a unique morphism  $A^\bullet \longrightarrow I^\bullet$  in the homotopy category  $K(\mathcal{A})$  by Proposition 3.1.13 (see below). Therefore, we have a functorial morphism

$$K(F)(A^\bullet) \longrightarrow K(F)(I^\bullet) = RF(A^\bullet),$$

which gives the required morphism of functors.

(ii) Note that,  $K^+(\mathcal{I}_{\mathcal{A}})$  is a triangulated category and  $\iota : K^+(\mathcal{I}_{\mathcal{A}}) \longrightarrow D^+(\mathcal{A})$  is an exact equivalence of categories. Then  $\iota^{-1}$  being the adjoint of  $\iota$ , it is also exact (c.f. Proposition 1.2.13). Now  $RF := Q_{\mathcal{B}} \circ K(F) \circ \iota^{-1}$  being a composition of exact functors, is exact.

(iii) See [GM03, III.6.11].

□

One can rephrase the Proposition 3.1.4 as a universal property to define derived functor of a left exact functor as follow.

**Definition 3.1.5** (Universal property of derived functor). Let  $F : \mathcal{A} \longrightarrow \mathcal{B}$  be a left exact functor of abelian categories. Then the right derived functor of  $F$ , if it exists, is an exact functor  $RF : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B})$  of triangulated categories such that

- (i) there is a natural morphism of functors  $Q_{\mathcal{B}} \circ K(F) \longrightarrow RF \circ Q_{\mathcal{A}}$ , and
- (ii) for any exact functor  $G : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B})$ , there is a natural bijection

$$\text{Hom}(RF, G) \xrightarrow{\cong} \text{Hom}(Q_{\mathcal{B}} \circ F, G \circ Q_{\mathcal{A}}).$$

**Definition 3.1.6.** Let  $RF : D^+(\mathcal{A}) \longrightarrow D^+(\mathcal{B})$  be a right derived functor of a left exact functor  $F : \mathcal{A} \rightarrow \mathcal{B}$ . Then for any complex  $A^\bullet \in D^+(\mathcal{A})$ , we define

$$R^i F(A^\bullet) := \mathcal{H}^i(RF(A^\bullet)) \in \mathcal{B}, \quad \forall i \in \mathbb{Z}.$$

The induced functors  $R^i F : \mathcal{A} \longrightarrow \mathcal{B}$  given by composition

$$\mathcal{A} \hookrightarrow D^+(\mathcal{A}) \xrightarrow{R^i F} \mathcal{B}$$

are known as *higher derived functors* of  $F$ .



Given any  $A \in \mathcal{A}$ , choosing an injective resolution

$$A \longrightarrow I^0 \longrightarrow I^1 \longrightarrow \cdots$$

we see that,  $R^i F(A) = \mathcal{H}^i(\cdots \rightarrow F(I^0) \rightarrow F(I^1) \rightarrow \cdots)$ . In particular,

$$R^0 F(A) = \text{Ker}(F(I^0) \rightarrow F(I^1)) = F(A),$$

since  $F$  is left exact.

**Definition 3.1.7.** An object  $A \in \mathcal{A}$  is called *F-acyclic* if  $R^i F(A) \cong 0$ , for all  $i \neq 0$ .

**Corollary 3.1.8.** With the above assumptions, any short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

in  $\mathcal{A}$  give rise to a long exact sequence

$$0 \rightarrow F(A) \rightarrow F(B) \rightarrow F(C) \rightarrow R^1 F(A) \rightarrow R^1 F(B) \rightarrow R^1 F(C) \rightarrow R^2(A) \rightarrow \cdots .$$

To see how it works, note that any short exact sequence  $0 \rightarrow A \xrightarrow{f} B \rightarrow C \rightarrow 0$  in  $\mathcal{A}$  gives rise to a distinguished triangle  $A \rightarrow B \rightarrow C \rightarrow A[1]$  in  $D(\mathcal{A})$ . Again any distinguished triangle  $A^\bullet \rightarrow B^\bullet \rightarrow C^\bullet \rightarrow A^\bullet[1]$  in  $D(\mathcal{A})$  give rise to a long exact sequence of cohomologies

$$\cdots \rightarrow \mathcal{H}^{i-1}(C^\bullet) \rightarrow \mathcal{H}^i(A^\bullet) \rightarrow \mathcal{H}^i(B^\bullet) \rightarrow \mathcal{H}^i(C^\bullet) \rightarrow \mathcal{H}^{i+1}(A^\bullet) \rightarrow \cdots .$$

Now the above corollary follows by considering the distinguished triangle  $RF(A) \rightarrow RF(B) \rightarrow RF(C) \rightarrow RF(A)[1]$  in  $D(\mathcal{B})$ .

**Example 3.1.9.** Let  $\mathcal{A}$  be an abelian category, and let  $\text{Ab}$  be the category of abelian groups. Consider the covariant functor

$$\text{Hom}_{\mathcal{A}}(A, -) : \mathcal{A} \longrightarrow \text{Ab}.$$

Clearly,  $\text{Hom}(A, -)$  is left exact. If  $\mathcal{A}$  contains enough injectives (for example, if  $\mathcal{A}$  is  $\mathfrak{Mod}(\mathcal{O}_X)$  or  $\mathfrak{Qcoh}(X)$  for  $X$  a noetherian scheme; c.f., [Har77, Exercise III. 3.6]), then we define

$$(3.1.10) \quad \text{Ext}^i_{\mathcal{A}}(A, -) := H^i(R\text{Hom}_{\mathcal{A}}(A, -)).$$

**Proposition 3.1.11.** Let  $\mathcal{A}$  be an abelian category with enough injectives, and let  $A, B \in \mathcal{A}$ . Then there are natural isomorphisms

$$\text{Ext}^i_{\mathcal{A}}(A, B) \cong \text{Hom}_{D(\mathcal{A})}(A, B[i]), \quad \forall i,$$

where  $A$  and  $B$  are considered as complexes in  $D(\mathcal{A})$  concentrated at degree 0 place.

$$B \rightarrow I^0 \rightarrow I^1 \rightarrow \dots$$
$$\mathrm{Hom}(A, I^\bullet) : \mathrm{Hom}(A, I^0) \rightarrow \mathrm{Hom}(A, I^1) \rightarrow \mathrm{Hom}(A, I^2) \rightarrow \cdots$$

Note that, a morphism  $f \in \text{Hom}(A, I^i)$  is a *cycle* (i.e.,  $f \in \text{Ker}(\text{Hom}(A, I^i) \rightarrow \text{Hom}(A, I^{i+1}))$ ) if and only if  $f$  defines a morphism of complexes

$$f : A \longrightarrow I^\bullet[i].$$

$$\mathrm{Ext}^i(A, B) \cong H^i(\mathrm{Hom}(A, I^\bullet)) \cong \mathrm{Hom}_{K(\mathcal{A})}(A, I^\bullet[i]).$$
$$\mathrm{Hom}_{K(\mathcal{A})}(A, I^\bullet[i]) \cong \mathrm{Hom}_{D(\mathcal{A})}(A, I^\bullet[i]).$$
☐
$$\mathrm{Hom}_{K(\mathcal{A})}(A^\bullet, I^\bullet) = \mathrm{Hom}_{D(\mathcal{A})}(A^\bullet, I^\bullet).$$
$$\mathrm{Hom}_{K(\mathcal{A})}(A^\bullet, I^\bullet) \longrightarrow \mathrm{Hom}_{D(\mathcal{A})}(A^\bullet, I^\bullet).$$
$$\begin{array}{ccc}
 & C^\bullet & \\
 qis \swarrow & & \searrow \psi \\
 A^\bullet & \xrightarrow[\phi]{} & I^\bullet
 \end{array}$$
☐
$$\mathrm{Hom}_{K(\mathcal{A})}(A^\bullet, I^\bullet) \longrightarrow \mathrm{Hom}_{K(\mathcal{A})}(B^\bullet, I^\bullet),$$

obtained by precomposing with  $\phi$ , is bijective.

*Sketch of a proof.* Complete the morphism  $\phi : B^\bullet \rightarrow A^\bullet$  to a distinguished triangle in the triangulated category  $K^+(\mathcal{A})$ . Applying the functor  $\text{Hom}(-, I^\bullet)$  and then taking the associated long exact  $\text{Hom}(-, I^\bullet)$ -sequence, we see that it is enough to show that  $\text{Hom}_{K(\mathcal{A})}(E^\bullet, I^\bullet) = 0$ , for any **acyclic complex**  $E^\bullet$ .

Next, we take any morphism of complexes  $f : E^\bullet \rightarrow I^\bullet$ , and construct a homotopy between  $f$  and the zero morphism. This can be done by induction. Assume that  $h^i : E^i \rightarrow I^{i-1}$  is constructed by induction. If  $h^j$  is constructed for all  $j \leq i$ , then the morphism

$$f^i - d_{I^\bullet}^{i-1} \circ h^i : E^i \longrightarrow I^i$$

factors through  $E^i/E^{i-1} \longrightarrow I^i$ . Since  $I^i$  is injective, this lifts to a morphism  $h^{i+1} : E^{i+1} \longrightarrow I^i$  so that  $f^i - d_{I^\bullet}^{i-1} \circ h^i = h^{i+1} \circ d_{E^\bullet}^i$ . Thus the induction works!  $\square$

**Remark 3.1.14.** In practice, we need to deal with many important abelian categories without enough injective objects, or sometimes the functor  $F$  is defined at the level of homotopy categories only. However, one can still construct derived functors in that setup under certain assumption. Let us explain briefly.

Let  $\mathcal{A}$  and  $\mathcal{B}$  be abelian categories.

**Case I.**  $F$  is defined only at the level of homotopy category: let

$$(3.1.15) \quad F : K^+(\mathcal{A}) \longrightarrow K(\mathcal{B})$$

be an exact functor of triangulated categories. Then the right derived functor

$$(3.1.16) \quad RF : D^+(\mathcal{A}) \longrightarrow D(\mathcal{B})$$

of  $F$  satisfying the properties (i)–(iii) of Proposition 3.1.4 exists if there is a triangulated subcategory  $K_F \subset K^+(\mathcal{A})$  *adapted to  $F$* , meaning that  $K_F$  satisfies the following conditions:

- (i) if  $A^\bullet \in K_F$  is acyclic, then so is  $F(A^\bullet)$ , and
- (ii) any  $A^\bullet \in K^+(\mathcal{A})$  is quasi-isomorphic to a complex in  $K_F$ .

Roughly, with the above hypotheses (i)–(iii), we may localize the subcategory  $K^+(K_F)$  with respect to the quasi-isomorphisms of objects from  $K_F$  to produce an equivalence of categories  $K^+(K_F)_{qis} \xrightarrow{\cong} D^+(\mathcal{A})$ . Moreover, the functor  $K(F) : K^+(\mathcal{A}) \rightarrow K^+(\mathcal{B})$  give rise to a functor  $K^+(K_F)_{qis} \rightarrow K^+(\mathcal{B})$ . Then by choosing a quasi-inverse of the above equivalence, we get the required derived functor  $D^+(\mathcal{A}) \rightarrow D(\mathcal{B})$ .

**Case II.**  $F : \mathcal{A} \rightarrow \mathcal{B}$  a left exact functor, but  $\mathcal{A}$  has not enough injectives. In this situation, we may construct the right derived functor of  $F$  by looking at the  *$F$ -adapted class of objects*  $\mathcal{I}_F \subset \mathcal{A}$ , which is defined by the following properties.

- (a)  $\mathcal{I}_F$  is stable under finite sums,
- (b) if  $A^\bullet \in K^+(\mathcal{A})$  is acyclic with  $A^i \in \mathcal{I}_F$ , for all  $i$ , then  $F(A^\bullet)$  is acyclic, and
- (c) any object of  $\mathcal{A}$  can be embedded inside an object of  $\mathcal{I}_F$ .

Let  $K^+(\mathcal{I}_F)_{qis}$  be the localization of  $K^+(\mathcal{I}_F)$  by quasi-isomorphism of complexes with objects from  $\mathcal{I}_F$ . Then the above hypotheses (a)–(c) gives rise to an equivalence of categories

$$(3.1.17) \quad \iota_q : K^+(\mathcal{I}_F)_{qis} \xrightarrow{\sim} D^+(\mathcal{A}).$$

Then  $K(F) : K^+(\mathcal{A}) \rightarrow K^+(\mathcal{B})$  induces a functor  $K(F)_{qis} : K^+(\mathcal{I}_F)_{qis} \rightarrow K^+(\mathcal{B})$ . Now choosing a quasi-inverse  $\iota_q^{-1}$  of (3.1.17) and composing with  $Q_{\mathcal{B}} \circ K(F)_{qis}$ , we get the required right derived functor  $RF : D^+(\mathcal{A}) \rightarrow D(\mathcal{B})$  of  $F$  as discussed before.

The definition of Ext group as given in Example (3.1.9) can be generalized for complexes as follow. Given  $A^\bullet, B^\bullet \in Kom(\mathcal{A})$ , let  $\text{Hom}^\bullet(A^\bullet, B^\bullet)$  be the complex defined by

$$(3.1.18) \quad \text{Hom}^i(A^\bullet, B^\bullet) := \bigoplus_{j \in \mathbb{Z}} \text{Hom}(A^j, B^{i+j})$$

with the differential

$$d(f) := d_B \circ f - (-1)^i f \circ d_A, \quad \forall f \in \text{Hom}(A^*, B^{i+*}).$$

$$\begin{array}{ccc} A^j & \xrightarrow{f_i^j} & B^{i+j} \\ d_A^j \downarrow & & \downarrow d_B^{i+j} \\ A^{j+1} & \xrightarrow{f_i^{j+1}} & B^{i+j+1} \end{array}$$

The complex  $\text{Hom}^\bullet(A^\bullet, B^\bullet)$  is known as the *internal hom* of  $A^\bullet$  into  $B^\bullet$ .

Note that, any  $A^\bullet \in Kom(\mathcal{A})$  gives rise to an exact functor

$$(3.1.19) \quad \text{Hom}^\bullet(A^\bullet, -) : K^+(\mathcal{A}) \longrightarrow K(\mathbf{Ab}), \quad B^\bullet \longmapsto \text{Hom}^\bullet(A^\bullet, B^\bullet).$$

Let  $\mathcal{I} \subset K^+(\mathcal{A})$  be the full triangulated subcategory, whose objects are complexes  $I^\bullet$  with  $I^i$  injective object of  $\mathcal{A}$ , for all  $i$ . Then  $\mathcal{I}$  is  $F$ -adapted, where  $F = \text{Hom}^\bullet(A^\bullet, -)$ , as defined in Remark 3.1.14. Then the right derived functor

$$(3.1.20) \quad R\text{Hom}^\bullet(A^\bullet, -) : D^+(\mathcal{A}) \longrightarrow D(\mathbf{Ab}).$$

of  $\text{Hom}^\bullet(A^\bullet, -)$  exists. Then we define

$$(3.1.21) \quad \text{Ext}_{\mathcal{A}}^i(A^\bullet, B^\bullet) := H^i(R\text{Hom}^\bullet(A^\bullet, B^\bullet)), \quad \forall i.$$

Now the proof of Proposition 3.1.11 can be modified to prove the following.

**Theorem 3.1.22.** *Let  $\mathcal{A}$  be an abelian category with enough injectives, and let  $A^\bullet, B^\bullet \in \text{Kom}(\mathcal{A})$  be two bounded (or bounded below) complexes. Then there are natural isomorphisms of abelian groups*

$$\text{Ext}_{\mathcal{A}}^i(A^\bullet, B^\bullet) \cong \text{Hom}_{D(\mathcal{A})}(A^\bullet, B^\bullet[i]), \quad \forall i.$$

It follows from Theorem 3.1.22 that the abelian group  $\text{Ext}_{\mathcal{A}}^i(A^\bullet, B^\bullet)$  depends on the “isomorphism classes” of  $A^\bullet$  and  $B^\bullet$  in the derived category, not on the complexes. If  $A_1^\bullet \xrightarrow{\sim} A_2^\bullet$  is a quasi-isomorphism of complexes, then the induced morphism

$$R\text{Hom}^\bullet(A_1^\bullet, B^\bullet) \longrightarrow R\text{Hom}^\bullet(A_2^\bullet, B^\bullet)$$

is an isomorphism in  $D(\mathbf{Ab})$ , because their cohomologies are isomorphic. Therefore, the functor  $\text{Hom}^\bullet(-, B^\bullet)$  descends to the derived category to give a bifunctor

$$(3.1.23) \quad D(\mathcal{A})^{\text{op}} \times D^+(\mathcal{A}) \longrightarrow D(\mathbf{Ab}),$$

which is exact in each variable.

**Definition 3.1.24.** An abelian category  $\mathcal{A}$  is said to have *enough projectives* if for each object  $A \in \mathcal{A}$  there is a projective object  $P$  in  $\mathcal{A}$  together with an epimorphism  $A \rightarrow P$  in  $\mathcal{A}$ .

If the abelian category  $\mathcal{A}$  has enough projectives, then for any complex  $B^\bullet \in \text{Kom}(\mathcal{A})$ , the left exact functor

$$\text{Hom}^\bullet(-, B^\bullet) : K^-(\mathcal{A})^{\text{op}} \longrightarrow K(\mathbf{Ab})$$

admits a right derived functor

$$R\text{Hom}^\bullet(-, B^\bullet) : D^-(\mathcal{A})^{\text{op}} \longrightarrow D(\mathbf{Ab}).$$

One can check that, this depends only on  $B^\bullet$  as an object of derived category. Therefore, it defines a bifunctor

$$(3.1.25) \quad D^-(\mathcal{A})^{\text{op}} \times D(\mathcal{A}) \longrightarrow D(\mathbf{Ab}).$$

If  $\mathcal{A}$  has enough injectives and enough projectives, both bifunctors in (3.1.23) and (3.1.25) give rise to the same bifunctor

$$(3.1.26) \quad R\text{Hom}^\bullet(-, -) : D^-(\mathcal{A})^{\text{op}} \times D^+(\mathcal{A}) \longrightarrow D(\mathbf{Ab}).$$

**Remark 3.1.27.** If  $\mathcal{A}$  has enough injectives, but not necessarily have enough projectives, using (3.1.23) we can get the derived functor

$$(3.1.28) \quad R\text{Hom}^\bullet(-, B^\bullet) : D^-(\mathcal{A})^{\text{op}} \longrightarrow D(\mathbf{Ab}).$$

Note that, thanks to Theorem 3.1.22, composition of morphisms in the derived category can be used to define composition for Ext groups:

$$(3.1.29) \quad \text{Ext}_{\mathcal{A}}^i(A^\bullet, B^\bullet) \times \text{Ext}_{\mathcal{A}}^j(B^\bullet, C^\bullet) \longrightarrow \text{Ext}_{\mathcal{A}}^{i+j}(A^\bullet, C^\bullet),$$

for all  $A^\bullet, B^\bullet, C^\bullet \in D^+(\mathcal{A})$ . This follows because

$$\mathrm{Ext}_{\mathcal{A}}^j(B^\bullet, C^\bullet) \cong \mathrm{Hom}_{D(\mathcal{A})}(B^\bullet, C^\bullet[j]) \cong \mathrm{Hom}_{D(\mathcal{A})}(B^\bullet[i], C^\bullet[i+j]).$$

**Proposition 3.1.30** (Grothendieck's composite functor theorem). *Let  $F_1 : \mathcal{A} \rightarrow \mathcal{B}$  and  $F_2 : \mathcal{B} \rightarrow \mathcal{C}$  be left exact functors of abelian categories. Suppose that there are adapted classes  $\mathcal{I}_{F_1} \subset \mathcal{A}$  and  $\mathcal{I}_{F_2} \subset \mathcal{B}$  for  $F_1$  and  $F_2$ , respectively, such that  $F_1(\mathcal{I}_{F_1}) \subseteq \mathcal{I}_{F_2}$ . Then the derived functors  $RF_1 : D^+(\mathcal{A}) \rightarrow D^+(\mathcal{B})$ ,  $RF_2 : D^+(\mathcal{B}) \rightarrow D^+(\mathcal{C})$  and  $R(F_2 \circ F_1) : D^+(\mathcal{A}) \rightarrow D^+(\mathcal{C})$  exists, and there is a natural isomorphism of functors*

$$R(F_2 \circ F_1) \xrightarrow{\cong} RF_2 \circ RF_1.$$

*Proof.* Clearly  $RF_1$  and  $RF_2$  exists by given assumptions (c.f., Remark 3.1.14). Since  $F_1(\mathcal{I}_{F_1}) \subset \mathcal{I}_{F_2}$ , we see that  $\mathcal{I}_{F_1}$  is  $(F_2 \circ F_1)$ -adapted. Therefore,  $R(F_2 \circ F_1)$  exists. Then the natural morphism of functors

$$(3.1.31) \quad R(F_2 \circ F_1) \longrightarrow RF_2 \circ RF_1$$

follows from the universal property of derived functor  $R(F_2 \circ F_1)$  (c.f., Definition 3.1.5). To see (3.1.31) is an isomorphism, given any complex  $A^\bullet \in D^+(\mathcal{A})$  we choose a complex  $I^\bullet \in K^+(\mathcal{I}_{F_1})$  quasi-isomorphic to  $A^\bullet$ . Then we have

$$(3.1.32) \quad R(F_2 \circ F_1)(A^\bullet) \cong (K(F_2) \circ K(F_1))(I^\bullet)$$

and

$$(3.1.33) \quad RF_2(RF_1(A^\bullet)) \cong RF_2(K(F_1)(I^\bullet)) \cong K(F_2)(K(F_1)(I^\bullet)).$$

Now it follows from the natural isomorphism between (3.1.32) and (3.1.33) that the morphism of functor in (3.1.31) is an isomorphism.  $\square$

**Remark 3.1.34.** If both  $\mathcal{A}$  and  $\mathcal{B}$  have enough injectives, then the hypotheses of the above Proposition 3.1.30 are satisfied if  $F_1(\mathcal{I}_{\mathcal{A}}) \subset \mathcal{I}_{\mathcal{B}}$ .

#### 4. SERRE FUNCTOR

**4.1. Abstract Serre functor.** Let  $k$  be a field. Let  $\mathcal{A}$  be a  $k$ -linear additive category.

**Definition 4.1.1.** A *Serre functor* on  $\mathcal{A}$  is a  $k$ -linear equivalence of categories

$$S : \mathcal{A} \longrightarrow \mathcal{A}$$

such that for any two objects  $A, B \in \mathcal{A}$ , there is a natural  $k$ -linear isomorphism

$$\eta_{A,B} : \mathrm{Hom}(A, B) \longrightarrow \mathrm{Hom}(B, S(A))^*,$$

which is functorial in both  $A$  and  $B$ . We write the induced  $k$ -bilinear pairing as

$$\mathrm{Hom}(B, S(A)) \times \mathrm{Hom}(A, B) \longrightarrow k, \quad (f, g) \longmapsto \langle f|g \rangle.$$

**Proposition 4.1.2.** *Let  $\mathcal{A}$  be a  $k$ -linear additive category together with a Serre functor  $S : \mathcal{A} \rightarrow \mathcal{A}$ . Then for any  $A, B \in \mathcal{A}$ , the following diagram commutes.*

$$(4.1.3) \quad \begin{array}{ccc} \mathrm{Hom}(A, B) & \xrightarrow{\eta_{A,B}} & \mathrm{Hom}(B, S(A))^* \\ S_{A,B} \downarrow & \searrow \exists \eta_{B,S(A)}^* & \uparrow S_{B,S(A)}^* \\ \mathrm{Hom}(S(A), S(B)) & \xrightarrow{\eta_{S(A),S(B)}} & \mathrm{Hom}(S(B), S^2(A))^* \end{array}$$

*Proof.* By abuse of notation, we denote by  $\eta_{B,S(A)}^*$  the composite  $k$ -linear homomorphism

$$\eta_{B,S(A)}^* : \mathrm{Hom}(S(A), S(B)) \hookrightarrow \mathrm{Hom}(S(A), S(B))^{**} \xrightarrow{\eta_{B,S(A)}^*} \mathrm{Hom}(B, S(A))^*.$$

Therefore, it suffices to show that both upper and lower triangles in (4.1.3) commute. Note that, commutativity of upper triangle is equivalent to

$$\langle f|g \rangle = \langle S_{A,B}(g)|f \rangle, \quad \forall f \in \mathrm{Hom}(B, S(A)), g \in \mathrm{Hom}(A, B).$$

Applying functoriality of  $\eta$  in the second variable, we have the following commutative diagram.

$$(4.1.4) \quad \begin{array}{ccc} \mathrm{Hom}(A, B) & \xrightarrow{\eta_{A,B}} & \mathrm{Hom}(B, S(A))^* \\ - \circ g \uparrow & & \uparrow (S(g) \circ -)^* \\ \mathrm{Hom}(B, B) & \xrightarrow{\eta_{B,B}} & \mathrm{Hom}(B, S(B))^* \end{array}$$

Applying commutativity of (4.1.4) to  $\mathrm{Id}_B \in \mathrm{Hom}(B, B)$  we have  $\langle f|g \rangle = \langle S(g) \circ f | \mathrm{Id} \rangle$ . Applying functoriality of  $\eta$  in the first variable, we have the following commutative diagram

$$(4.1.5) \quad \begin{array}{ccc} \mathrm{Hom}(B, B) & \xrightarrow{\eta_{B,B}} & \mathrm{Hom}(B, S(B))^* \\ f \circ - \downarrow & & \downarrow (- \circ f)^* \\ \mathrm{Hom}(B, S(A)) & \xrightarrow{\eta_{B,S(A)}} & \mathrm{Hom}(S(A), S(B))^*, \end{array}$$

which gives  $\langle (S(g) \circ f) | \mathrm{Id}_B \rangle = \langle S(g) | f \rangle$ . This completes the proof.  $\square$

**Remark 4.1.6.** In order to avoid trouble with identifying  $\mathrm{Hom}(A, B)$  with its double dual  $\mathrm{Hom}(A, B)^{**}$ , we always assume that a  $k$ -linear additive category  $\mathcal{A}$  has finite dimensional Hom's (i.e.,  $\dim_k \mathrm{Hom}_{\mathcal{A}}(A, B) < \infty$ , for all  $A, B \in \mathrm{Ob}(\mathcal{A})$ ).

**Lemma 4.1.7.** *Let  $\mathcal{A}$  and  $\mathcal{B}$  be  $k$ -linear additive categories with finite dimensional Hom's. If  $\mathcal{A}$  and  $\mathcal{B}$  are endowed with Serre functors  $S_{\mathcal{A}}$  and  $S_{\mathcal{B}}$ , respectively, then any  $k$ -linear equivalence  $F : \mathcal{A} \rightarrow \mathcal{B}$  commutes with Serre functors (i.e., there is an isomorphism of functors  $F \circ S_{\mathcal{A}} \cong S_{\mathcal{B}} \circ F$ ).*



*Proof.* Since  $F$  is fully faithful, for any  $A, B \in \mathcal{A}$  we have a functorial isomorphism  $\mathrm{Hom}(A, S_{\mathcal{A}}(B)) \cong \mathrm{Hom}(F(A), F(S_{\mathcal{A}}(B)))$  and  $\mathrm{Hom}(B, A) \cong \mathrm{Hom}(F(B), F(A))$ . By definition of Serre functor, we have the following functorial (in both variables) isomorphisms

$$\mathrm{Hom}(A, S_{\mathcal{A}}(B)) \cong \mathrm{Hom}(B, A)^* \quad \text{and} \quad \mathrm{Hom}(F(B), F(A)) \cong \mathrm{Hom}(F(A), S_{\mathcal{B}}(F(B)))^*.$$

These gives a functorial isomorphism

$$\mathrm{Hom}(F(A), F(S_{\mathcal{A}}(B))) \xrightarrow{\cong} \mathrm{Hom}(F(A), S_{\mathcal{B}}(F(B))).$$

Since  $F$  is essentially surjective, any object in  $\mathcal{B}$  is isomorphic to an object of the form  $F(A)$ , for some  $A \in \mathcal{A}$ . Hence the result follows from the above functorial isomorphism.  $\square$

**Proposition 4.1.8.** *Let  $\mathcal{A}$  be a  $k$ -linear additive category. Then any two Serre functors on  $\mathcal{A}$  are isomorphic.*

*Proof.* This follows from the definition of Serre functor and Yoneda lemma.  $\square$

**4.2. Serre duality in  $D^b(X)$ .** Let  $X$  be a smooth projective  $k$ -variety of dimension  $n \geq 1$ . Note that, for any locally free coherent sheaf  $E$  on  $X$ , the functor

$$- \otimes E : \mathcal{Coh}(X) \longrightarrow \mathcal{Coh}(X), \quad F \longmapsto F \otimes E$$

is exact. Let  $\omega_X$  be the dualizing sheaf on  $X$ . Let  $D^*(X) = D^*(\mathcal{Coh}(X))$ , where  $*$   $\in \{\emptyset, b, -, +\}$ . Consider the composite functor

$$(4.2.1) \quad S_X : D^*(X) \xrightarrow{\omega_X \otimes -} D^*(X) \xrightarrow{[n]} D^*(X),$$

where  $[n] : D^*(X) \rightarrow D^*(X)$  is the  $n$ -th shift functor given by sending a complex  $E^\bullet$  to  $E^\bullet[n]$ . Since both the functors  $\omega_X \otimes -$  and  $[n]$  are exact, their composite functor  $S_X := \omega_X \otimes (-)[n]$  is exact.

**Theorem 4.2.2** (Grothendieck-Serre duality). *Let  $X$  be a smooth projective variety over a field  $k$ . Then the functor  $S_X : D^b(X) \longrightarrow D^b(X)$  as defined in (4.2.1) is a Serre functor in the sense of Definition 4.1.1.*

*Proof.* Given any two objects  $E^\bullet, F^\bullet \in D^b(X)$ , we need to give an isomorphism of  $k$ -vector spaces

$$(4.2.3) \quad \eta_{E^\bullet, F^\bullet} : \mathrm{Hom}_{D^b(X)}(E^\bullet, F^\bullet) \xrightarrow{\cong} \mathrm{Hom}_{D^b(X)}(F^\bullet, S_X(E^\bullet))^*$$

which is functorial in both  $E^\bullet$  and  $F^\bullet$ . Thanks to Theorem 3.1.22, we have

$$\mathrm{Hom}_{D^b(X)}(E^\bullet, F^\bullet[i]) = \mathrm{Ext}^i(E^\bullet, F^\bullet), \quad \forall i.$$

Since  $X$  is smooth and projective, choosing a resolution by complex of locally free sheaves on  $X$ , we may assume that  $E^i$  is locally free, for all  $i$ . Then we have functorial isomorphisms

$$\begin{aligned} \mathrm{Hom}^i(E^\bullet, F^\bullet) &= \bigoplus_{j \in \mathbb{Z}} \mathrm{Hom}(E^j, F^{i+j}) = \bigoplus_{j \in \mathbb{Z}} H^0(X, \mathcal{H}om(E^j, F^{i+j})) \\ &\cong \bigoplus_{j \in \mathbb{Z}} \mathrm{Ext}^n(F^{i+j}, E^j \otimes \omega_X)^*, \quad \text{by classical Serre duality theorem.} \\ &\cong \bigoplus_{j \in \mathbb{Z}} \mathrm{Hom}_{D^b(X)}(F^{i+j}, E^j \otimes \omega_X[n])^*, \quad \text{by Proposition 3.1.11.} \\ &\cong \mathrm{Hom}^{n-i}(F^\bullet, E^\bullet \otimes \omega_X)^*. \end{aligned}$$

Since for any two complexes  $A^\bullet, B^\bullet$ , we have

$$\mathrm{Ext}_{\mathcal{A}}^i(A^\bullet, B^\bullet) := H^i(R\mathrm{Hom}^\bullet(A^\bullet, B^\bullet)), \quad \forall i,$$

the theorem follows.  $\square$

**Remark 4.2.4.** Theorem 4.2.2 is a special case of Grothendieck-Verdier duality (c.f. Section §6.9). We shall see some interesting applications of the Serre functor  $\omega_X \otimes (-)[n]$  on  $D^b(X)$  in Section §8. For this, we need concept of local Hom complex, and spectral sequences to be explained in the next two sections.

## 5. SPECTRAL SEQUENCE

**5.1. What is it?** In this subsection, we explain how spectral sequence occur when we compose two derived functors. Let  $\mathcal{A}$  be an abelian category.

**Definition 5.1.1.** A spectral sequence in  $\mathcal{A}$  is given by a collection of objects

$$(E_r^{p,q}, E^n), \quad n, p, q, r \in \mathbb{Z}, \quad r \geq 1$$

and morphisms

$$d_r^{p,q} : E_r^{p,q} \longrightarrow E_r^{p+r, q-r+1}$$

satisfying that the following conditions.

- (i)  $d_r^{p+r, q-r+1} \circ d_r^{p,q} = 0$ , for all  $p, q, r$ . This yields a complex  $E_r^{p+\bullet, q-\bullet+r+\bullet}$ , for all  $r \geq 1$ .
- (ii) There are isomorphisms

$$E_{r+1}^{p,q} \cong H^0(E_r^{p+\bullet, q-\bullet+r+\bullet}),$$

which are part of the data.

- (iii) For any  $(p, q)$ , there is an  $r_0$  such that  $d_r^{p,q} = d_r^{p-r, q+r-1} = 0$ , for all  $r \geq r_0$ . In particular,  $E_r^{p,q} \cong E_{r_0}^{p,q}$ , for all  $r \geq r_0$ . This object is denoted by  $E_\infty^{p,q}$ .

(iv) There is a decreasing filtration

$$\dots \subset F^{p+1}E^n \subset F^pE^n \subset F^{p-1}E^n \subset \dots \subset F^0E^n := E^n$$

such that  $\bigcap_{p \in \mathbb{Z}} F^pE^n = 0$  and  $\bigcup_{p \in \mathbb{Z}} F^pE^n = E^n$ , and isomorphisms

$$E_\infty^{p,q} \cong F^pE^{p+q} / F^{p+1}E^{p+q}.$$

**Remark 5.1.2.** If  $E_\infty^{p,q} = 0$ , for all  $p, q$ , then  $E^{p+q} = 0$ . This follows from property (iv).

Let us try to visualize a spectral sequence. In page  $E_1$ , we have the following data.

$$\begin{array}{ccccccc} E_1^{p-2,q+1} & \longrightarrow & E_1^{p-1,q+1} & \longrightarrow & E_1^{p,q+1} & \longrightarrow & E_1^{p+1,q+1} & \dots \\ E_1^{p-2,q} & \longrightarrow & E_1^{p-1,q} & \longrightarrow & E_1^{p,q} & \longrightarrow & E_1^{p+1,q} & \dots \\ E_1^{p-2,q-1} & \longrightarrow & E_1^{p-1,q-1} & \longrightarrow & E_1^{p,q-1} & \longrightarrow & E_1^{p+1,q-1} & \dots \end{array}$$

In page  $E_2$ , we have the following data.

$$\begin{array}{ccccccc} E_2^{p-2,q+1} & & E_2^{p-1,q+1} & & E_2^{p,q+1} & & E_2^{p+1,q+1} & \dots \\ & \searrow & & \searrow & & \searrow & & \\ E_2^{p-2,q} & & E_2^{p-1,q} & & E_2^{p,q} & & E_2^{p+1,q} & \dots \\ & \searrow & & \searrow & & \searrow & & \\ E_2^{p-2,q-1} & & E_2^{p-1,q-1} & & E_2^{p,q-1} & & E_2^{p+1,q-1} & \dots \end{array}$$

In some sense, the condition (iv) says that the objects  $E_r^{p,q}$  converges towards a subquotient of certain filtration of  $E^n$ . Usually objects of one layer, say  $E_r^{p,q}$  with  $r$  fixed, are given, and objects of the next layer can be obtained using (ii). It is enough to give objects  $E_r^{p,q}$  with  $r \geq m$ , for some  $m$ ; the information is just the same. We express the spectral sequence by writing

$$E_r^{p,q} \implies E^{p+q}.$$

In most of the applications, only  $E_r^{p,q}$  are given for  $r \geq 2$ , and in most of the cases, we don't need to go beyond page  $E_2$  or  $E_3$ .

**Definition 5.1.3.** A *double complex*  $K^{\bullet,\bullet}$  is given by the following data: for each pair of integers  $(i, j)$ , an object  $K^{i,j} \in \mathcal{A}$  and morphisms

$$d_I^{i,j} : K^{i,j} \longrightarrow K^{i+1,j} \quad \text{and} \quad d_{II}^{i,j} : K^{i,j} \longrightarrow K^{i,j+1}$$

such that

$$d_I^2 = d_{II}^2 = d_I d_{II} + d_{II} d_I = 0.$$

$$\begin{array}{ccccccc}
& \vdots & & \vdots & & \vdots & \\
& \downarrow & & \downarrow & & \downarrow & \\
\cdots & \longrightarrow & K^{i-1,j-1} & \xrightarrow{d_I^{i-1,j-1}} & K^{i,j-1} & \xrightarrow{d_I^{i,j-1}} & K^{i+1,j-1} \longrightarrow \cdots \\
& & \downarrow d_{II}^{i-1,j-1} & & \downarrow d_{II}^{i,j-1} & & \downarrow d_{II}^{i+1,j-1} \\
\cdots & \longrightarrow & K^{i-1,j} & \xrightarrow{d_I^{i-1,j}} & K^{i,j} & \xrightarrow{d_I^{i,j}} & K^{i+1,j} \longrightarrow \cdots \\
& & \downarrow d_{II}^{i-1,j} & & \downarrow d_{II}^{i,j} & & \downarrow d_{II}^{i+1,j} \\
\cdots & \longrightarrow & K^{i-1,j+1} & \xrightarrow{d_I^{i-1,j+1}} & K^{i,j+1} & \xrightarrow{d_I^{i,j+1}} & K^{i+1,j+1} \longrightarrow \cdots \\
& & \downarrow d_{II}^{i-1,j+1} & & \downarrow d_{II}^{i,j+1} & & \downarrow d_{II}^{i+1,j+1} \\
& \vdots & & \vdots & & \vdots & 
\end{array}$$

The associated *total complex*  $K^\bullet := \text{tot}(K^{\bullet,\bullet})$  is defined by  $K^n := \bigoplus_{i+j=n} K^{i,j}$  with differentials  $d = d_I + d_{II}$ .

The total complex  $K^\bullet = \text{tot}(K^{\bullet,\bullet})$  admits a natural decreasing filtration  $\{F^\ell K^n\}_\ell$  given by

$$(5.1.4) \quad F^\ell K^n := \bigoplus_{j \geq \ell} K^{n-j,j},$$

which satisfies  $d_I(F^\ell K^n) \subset F^\ell K^{n+1}$ , for all  $n$ . Due to symmetry of the situation, there is another such natural filtration.

**Example 5.1.5.** The complex  $\text{Hom}^\bullet(A^\bullet, B^\bullet)$  is an example of a total complex of the double complex  $K^{i,j} := \text{Hom}(A^{-i}, B^j)$  together with the differentials  $d_I = (-1)^{j-i+1} d_A$  and  $d_{II} = d_B$  (there are different sign conventions in the literature; however one can choose one sign convention, and final conclusion would be the same).

**Definition 5.1.6.** A *filtered complex* is a complex  $K^\bullet$  together with a decreasing filtration

$$\cdots \subset F^\ell K^n \subset F^{\ell-1} K^n \subset \cdots \subset F^0 K^n := K^n, \quad \forall n,$$

such that  $d^n(F^\ell K^n) \subset F^\ell K^{n+1}$ , for all  $n$ .

$$\begin{array}{ccccccc}
\cdots & \longrightarrow & K^{n-1} & \longrightarrow & K^n & \longrightarrow & K^{n+1} \longrightarrow \cdots \\
& & \uparrow & & \uparrow & & \uparrow \\
\cdots & \longrightarrow & F^\ell(K^{n-1}) & \longrightarrow & F^\ell(K^n) & \longrightarrow & F^\ell(K^{n+1}) \longrightarrow \cdots \\
& & \uparrow & & \uparrow & & \uparrow \\
\cdots & \longrightarrow & F^{\ell+1}(K^{n-1}) & \longrightarrow & F^{\ell+1}(K^n) & \longrightarrow & F^{\ell+1}(K^{n+1}) \longrightarrow \cdots
\end{array}$$

Consider the filtrations  $\{F^\ell K^n\}_\ell$  of the total complex  $K^\bullet = \text{tot}(K^{\bullet,\bullet})$  in (5.1.4). The associated graded objects

$$\text{gr}^\ell(K^n) := F^\ell(K^n)/F^{\ell+1}(K^n) = K^{n-\ell,\ell}$$

forms a complex  $K^{\bullet,\ell}[-\ell]$  (up to a global sign  $(-1)^\ell$ ). Hence  $\mathcal{H}^k(\text{gr}^\ell(K^\bullet)) = \mathcal{H}^{k-\ell}(K^{\bullet,\ell})$ , for all  $\ell$ , and the cohomology of the complex  $\mathcal{H}_I^n(K^{\bullet,\bullet}) := (\mathcal{H}^n(K^{\bullet,j}))_{j \in \mathbb{Z}}$ , with respect to  $d_{II}$ , gives  $\mathcal{H}_{II}^\ell(\mathcal{H}_I^{k-\ell}(K^{\bullet,\bullet}))$ .

Assuming the following finiteness condition: for each  $n$ , there is  $\ell_+(n)$  and  $\ell_-(n)$  such that  $F^\ell K^n = 0$ , for all  $\ell \geq \ell_+(n)$  and  $F^\ell K^n = K^n$ , for all  $\ell \leq \ell_-(n)$ , one can show that any filtered complex gives rise to a spectral sequence. In case of double complex, we have the following.

**Proposition 5.1.7.** *Let  $K^{\bullet,\bullet}$  be a double complex such that for any  $n$ ,  $K^{n-\ell,\ell} = 0$ , for  $|\ell| \gg 0$ . Then there is a spectral sequence*

$$E_2^{p,q} := \mathcal{H}_{II}^p \mathcal{H}_I^q(K^{\bullet,\bullet}) \implies \mathcal{H}^{p+q}(K^\bullet).$$

**Definition 5.1.8.** Let  $A^\bullet \in K^+(\mathcal{A})$ . A Cartan-Eilenberg resolution of  $A^\bullet$  is a double complex  $C^{\bullet,\bullet}$  together with a morphism of complexes  $A^\bullet \rightarrow C^{\bullet,0}$  such that

- (i)  $C^{i,j} = 0$ , for  $j < 0$ ,
- (ii) the sequences  $A^n \rightarrow C^{n,0} \rightarrow C^{n,1} \rightarrow \cdots$  are injective resolutions of  $A^n$ , and the induced sequences

$$\begin{aligned}
\text{Ker}(d_A^n) &\rightarrow \text{Ker}(d_I^{n,0}) \rightarrow \text{Ker}(d_I^{n,1}) \rightarrow \cdots \\
\text{Im}(d_A^n) &\rightarrow \text{Im}(d_I^{n,0}) \rightarrow \text{Im}(d_I^{n,1}) \rightarrow \cdots \\
\mathcal{H}^n(A^\bullet) &\rightarrow \mathcal{H}_I^n(C^{\bullet,0}) \rightarrow \mathcal{H}_I^n(C^{\bullet,1}) \rightarrow \cdots
\end{aligned}$$

are injective resolutions of  $\text{Ker}(d_A^n)$ ,  $\text{Im}(d_A^n)$  and  $\mathcal{H}^n(A^\bullet)$ , respectively, and

- (iii) any short exact sequences of the form

$$0 \rightarrow \text{Ker}(d_I^{i,j}) \rightarrow C^{i,j} \rightarrow \text{Im}(d_I^{i,j}) \rightarrow 0$$

split.

**Proposition 5.1.9.** *If  $\mathcal{A}$  has enough injectives, then any  $A^\bullet \in K^+(\mathcal{A})$  admits a Cartan-Eilenberg resolution.*

**Theorem 5.1.10** (Grothendieck spectral sequence). *Let  $\mathcal{A}, \mathcal{B}$  and  $\mathcal{C}$  be abelian categories. Let  $F_1 : K^+(\mathcal{A}) \rightarrow K^+(\mathcal{B})$  and  $F_2 : K^+(\mathcal{B}) \rightarrow K(\mathcal{C})$  be exact functors. Suppose that  $\mathcal{A}$  and  $\mathcal{B}$  contains enough injectives, and for any complex  $I^\bullet \in K^+(\mathcal{A})$  of injective objects from  $\mathcal{A}$ , its image  $F_1(I^\bullet)$  is inside an  $F_2$ -adapted triangulated subcategory  $\mathcal{K}_{F_2}$ . Then for any complex  $A^\bullet \in D^+(\mathcal{A})$ , there is a spectral sequence*

$$(5.1.11) \quad E_2^{p,q} := R^p F_2(R^q F_1(A^\bullet)) \implies E^{p+q} := R^{p+q}(F_2 \circ F_1)(A^\bullet).$$

*Proof.* Note that, if  $F_1 = \text{Id}$ , then for a left exact functor  $F : K^+(\mathcal{A}) \rightarrow K^+(\mathcal{B})$ , the above spectral sequence reads

$$(5.1.12) \quad E_2^{p,q} := R^p F(\mathcal{H}^q(A^\bullet)) \implies E^{p+q} := R^{p+q} F(A^\bullet).$$

It follows from construction of derived functors that, given  $A^\bullet \in D^+(\mathcal{A})$  isomorphic to a complex  $I^\bullet \in K^+(\mathcal{I}_{F_1})$ , we have  $RF_1(A^\bullet) \cong F_1(I^\bullet)$  and

$$(5.1.13) \quad R^p F_2(R^q F_1(A^\bullet)) = R^p F_2(\mathcal{H}^q(F_1(I^\bullet))).$$

Since

$$(5.1.14) \quad \begin{aligned} R^n(F_2 \circ F_1)(A^\bullet) &= \mathcal{H}^n(R(F_2 \circ F_1)(I^\bullet)) \cong \mathcal{H}^n(RF_2(RF_1(A^\bullet))) \\ &\cong \mathcal{H}^n(RF_2(F_1(I^\bullet))) \cong R^n F_2(F_1(I^\bullet)), \end{aligned}$$

using (5.1.13), the general case (5.1.11) follows from the special case (5.1.12) above.

Therefore, it suffices to prove the result with  $F_1 = \text{Id}$  and  $F := F_2$ . For this we need an appropriate double complex, which is provided by a Cartan-Eilenberg resolution of  $A^\bullet$ . Let  $C^{\bullet,\bullet}$  be a Cartan-Eilenberg resolution of  $A^\bullet$ , and set  $K^{\bullet,\bullet} := F(C^{\bullet,\bullet})$ . Since  $F$  is additive, it preserve direct sums, and since  $C^{i,j} \cong \text{Ker}(d_I^{i,j}) \oplus \text{Im}(d_I^{i,j})$ , we have  $\mathcal{H}_I^q(K^{\bullet,p}) = F\mathcal{H}_I^q(C^{\bullet,p})$ . Fixing  $q$ , and allowing  $p$  to vary, we see that  $\mathcal{H}_I^q(C^{\bullet,p})$  defines an injective resolution of  $\mathcal{H}^q(K^{\bullet,p}) = \mathcal{H}^q(A^\bullet)$ . Then we have

$$\mathcal{H}_{II}^p \mathcal{H}_I^q(K^{\bullet,\bullet}) = R^p F(\mathcal{H}^q(A^\bullet)).$$

Now applying spectral sequence in Proposition 5.1.7 and using the fact that the natural morphism  $A^\bullet \rightarrow \text{tot}(C^{\bullet,\bullet})$  is a quasi-isomorphism, we see that

$$\begin{aligned} \mathcal{H}^{p+q}(\text{tot}(K^{\bullet,\bullet})) &= \mathcal{H}^{p+q}(F(\text{tot}(C^{\bullet,\bullet}))) \\ &= \mathcal{H}^{p+q}(RF(A^\bullet)) \\ &= R^{p+q} F(A^\bullet). \end{aligned}$$

This completes the proof. □

**Corollary 5.1.15.** *Let  $F : K^+(\mathcal{A}) \rightarrow K^+(\mathcal{B})$  be an exact functor admitting a right derived functor  $RF : D^+(\mathcal{A}) \rightarrow D^+(\mathcal{B})$ .*

- (i) If  $RF(A) \in D^b(\mathcal{B})$ , for all  $A \in \mathcal{A}$ , then  $RF(A^\bullet) \in D^b(\mathcal{B})$ , for all  $A^\bullet \in D^b(\mathcal{A})$ , and hence  $RF$  induces a functor

$$RF : D^b(\mathcal{A}) \longrightarrow D^b(\mathcal{B}).$$

- (ii) Suppose that  $\mathcal{A}$  has enough injectives. If  $\mathcal{C} \subset \mathcal{B}$  is a thick subcategory with  $R^i F(A) \in \mathcal{C}$ , for all  $A \in \mathcal{A}$ , and that there is an integer  $n$  such that  $R^i F(A) = 0$ , for all  $A \in \mathcal{A}$ . Then the image of  $RF$  lands inside  $D_{\mathcal{C}}^+(\mathcal{B})$ ; i.e.,

$$RF : D^+(\mathcal{A}) \longrightarrow D_{\mathcal{C}}^+(\mathcal{B}).$$

## 6. DERIVED FUNCTORS IN ALGEBRAIC GEOMETRY

**6.1. Cohomology.** Let  $X$  be a noetherian scheme defined over a field  $k$ . Then the global section functor

$$(6.1.1) \quad \Gamma : \mathfrak{Q}\mathfrak{Coh}(X) \longrightarrow \mathcal{V}ect(k), \quad E \mapsto \Gamma(X, E)$$

is left exact. Since  $\mathfrak{Q}\mathfrak{Coh}(X)$  has enough injectives, the right derived functor (exact)

$$(6.1.2) \quad R\Gamma : D^+(\mathfrak{Q}\mathfrak{Coh}(X)) \longrightarrow D^+(\mathcal{V}ect(k))$$

of  $\Gamma$  exists, and we define

$$(6.1.3) \quad H^i(X, E^\bullet) := R^i\Gamma(E^\bullet) := \mathcal{H}^i(R\Gamma(E^\bullet)), \quad \forall E^\bullet \in D^+(\mathfrak{Q}\mathfrak{Coh}(X)).$$

Classically, this is known as the *hypercohomology* of  $E^\bullet$ , and is denoted by  $\mathbb{H}^i(X, E^\bullet)$ . For  $E \in \mathfrak{Q}\mathfrak{Coh}(X)$ , the above definition (6.1.3) gives the usual  $i$ -th cohomology  $H^i(X, E)$  of  $E$ , for all  $i \geq 0$ . Since any complex of  $k$ -vector spaces splits, we have an isomorphism (in  $D^+(\mathcal{V}ect(k))$ )

$$(6.1.4) \quad R\Gamma(E^\bullet) \cong \bigoplus_i H^i(X, E^\bullet)[-i], \quad \forall E^\bullet \in D^+(\mathfrak{Q}\mathfrak{Coh}(X)).$$

Since for any  $E \in \mathfrak{Q}\mathfrak{Coh}(X)$ , by Grothendieck's theorem  $H^i(X, E) = 0$ , for all  $i > \dim(X)$  (see [Har77]), applying the Grothendieck spectral sequence

$$E_2^{p,q} := R^p\Gamma(\mathcal{H}^q(E^\bullet)) \implies R^{p+q}\Gamma(E^\bullet),$$

one can deduce that  $R\Gamma$  restrict to a functor

$$(6.1.5) \quad R\Gamma : D^b(\mathfrak{Q}\mathfrak{Coh}(X)) \longrightarrow D^b(\mathcal{V}ect(k))$$

(Hint: If  $E_\infty^{p,q} = 0$ , for all  $p, q$ , then it follows from property (iv) of the spectral sequence that  $E^{p+q} = 0$ ; c.f., Corollary 5.1.15). The above functor (6.1.5) is exact because  $R\Gamma$  in (6.1.2) is exact.

Next, we want to induce our derived functor  $R\Gamma$  at the level of  $D^b(X)$ . Let  $\mathcal{V}ect_{fd}(k)$  be the full subcategory of  $\mathcal{V}ect(k)$ , whose objects are finite dimensional  $k$ -vector spaces. If  $X$  is a proper  $k$ -scheme, by a theorem of Serre [Har77], for any  $E \in \mathfrak{Coh}(X)$

we have  $H^i(X, E) \in \mathcal{V}ect_{fd}(k)$ . Since the category  $\mathcal{C}oh(X)$  doesn't have enough injectives, we cannot directly get the right derived functor  $R\Gamma : D^b(X) \rightarrow D^b(\mathcal{V}ect_{fd}(k))$  of the left exact functor  $\Gamma : \mathcal{C}oh(X) \rightarrow \mathcal{V}ect_{fd}(k)$ . Nevertheless, we can construct the right derived functor, in this case, as the composition of the exact functors

$$(6.1.6) \quad D^b(X) \rightarrow D^b(\mathfrak{Q}\mathcal{C}oh(X)) \xrightarrow{R\Gamma} D^b(\mathcal{V}ect(k)).$$

Clearly, the image of the above composite functor lands inside  $D^b(\mathcal{V}ect_{fd}(k))$ .

**6.2. Derived direct image.** Let  $f : X \rightarrow Y$  be a morphism of noetherian schemes. Then the direct image functor

$$(6.2.1) \quad f_* : \mathfrak{Q}\mathcal{C}oh(X) \rightarrow \mathfrak{Q}\mathcal{C}oh(Y), \quad E \mapsto f_*E$$

is left exact. Since  $\mathfrak{Q}\mathcal{C}oh(X)$  has enough injectives, the right derived functor

$$(6.2.2) \quad Rf_* : D^+(\mathfrak{Q}\mathcal{C}oh(X)) \rightarrow D^+(\mathfrak{Q}\mathcal{C}oh(X))$$

of  $f_*$  exists. In particular,  $R^i f_*(E^\bullet) := \mathcal{H}^i(Rf_*(E^\bullet)) \in \mathfrak{Q}\mathcal{C}oh(X)$ , for all  $i$ . Thus,  $R^i f_* E \in \mathfrak{Q}\mathcal{C}oh(X)$ , for all  $E \in \mathfrak{Q}\mathcal{C}oh(X)$ . Since  $R^i f_*(E) = 0$  for all  $i > \dim(X)$  [Har77], by Corollary 5.1.15 (a) the functor  $Rf_*$  restricts to an exact functor

$$(6.2.3) \quad Rf_* : D^b(\mathfrak{Q}\mathcal{C}oh(X)) \rightarrow D^b(\mathfrak{Q}\mathcal{C}oh(Y)).$$

Next, we want to get our derived functor  $Rf_*$  at the level of  $D^b(X)$ . Recall that,  $\mathcal{C}oh(X)$  is a thick full subcategory of  $\mathfrak{Q}\mathcal{C}oh(X)$ , and the inclusion functor  $\mathcal{C}oh(X) \hookrightarrow \mathfrak{Q}\mathcal{C}oh(X)$  induces a natural fully faithful exact functor

$$(6.2.4) \quad D^b(X) \rightarrow D^b(\mathfrak{Q}\mathcal{C}oh(X)),$$

which gives an equivalence of categories

$$(6.2.5) \quad D^b(X) \xrightarrow{\cong} D_{\mathcal{C}oh(X)}^b(\mathfrak{Q}\mathcal{C}oh(X)),$$

where  $D_{\mathcal{C}oh(X)}^b(\mathfrak{Q}\mathcal{C}oh(X))$  is the triangulated full subcategory of  $D^b(\mathfrak{Q}\mathcal{C}oh(X))$ , whose objects are bounded complexes of quasi-coherent sheaves of  $\mathcal{O}_X$ -modules on  $X$  with coherent cohomology sheaves.

**Proposition 6.2.6.** *If  $f : X \rightarrow Y$  is a proper morphism of noetherian  $k$ -schemes, then the right derived functor  $Rf_* : D^b(\mathfrak{Q}\mathcal{C}oh(X)) \rightarrow D^b(\mathfrak{Q}\mathcal{C}oh(Y))$  restricts to give an exact functor*

$$(6.2.7) \quad Rf_* : D^b(X) \rightarrow D^b(Y).$$

*Proof.* Since  $f$  is proper, for any  $E \in \mathcal{C}oh(X)$ , we have  $R^i f_* E \in \mathcal{C}oh(Y)$ , for all  $i$ . Then by Corollary 5.1.15 (b), the image of the composite functor

$$(6.2.8) \quad D^b(X) \rightarrow D^b(\mathfrak{Q}\mathcal{C}oh(X)) \xrightarrow{Rf_*} D^b(\mathfrak{Q}\mathcal{C}oh(Y)).$$



lands inside  $D_{\mathfrak{Coh}(Y)}^b(\mathfrak{QCoh}(Y))$ . Then choosing a **quasi-inverse**

$$D_{\mathfrak{Coh}(Y)}^b(\mathfrak{QCoh}(Y)) \xrightarrow{\cong} D^b(Y)$$

of the **exact equivalence** in (6.2.5), which is **exact**, we get the desired functor (6.2.7). This completes the proof.  $\square$

**Proposition 6.2.9.** *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  be morphisms of noetherian  $k$ -schemes. The natural isomorphism of functors  $(g \circ f)_* \cong g_* \circ f_*$  give rise to a natural isomorphism of the corresponding derived functors*

$$(6.2.10) \quad R(g \circ f)_* \cong Rg_* \circ Rf_* : D^b(\mathfrak{QCoh}(X)) \rightarrow D^b(\mathfrak{QCoh}(Z)).$$

*Proof.* Recall that, an object  $E \in \mathfrak{QCoh}(X)$  is called *flabby* if the restriction morphism  $E(X) \rightarrow E(U)$  is surjective, for any open subset  $U$  of  $X$ . Note that, any injective  $\mathcal{O}_X$ -module is flabby. Moreover, if  $E \in \mathfrak{QCoh}(X)$  is flabby, then for any morphism of noetherian  $k$ -schemes  $f : X \rightarrow Y$ , we have  $R^i f_*(E) = 0$ , for all  $i > 0$ . Furthermore,  $f_*(E)$  is flabby whenever  $E$  is flabby.

Let  $\mathcal{I} \subset \mathfrak{QCoh}(X)$  be the full subcategory of injective  $\mathcal{O}_X$ -modules. Then  $\mathcal{I}$  is  $f_*$ -adapted (c.f., Remark 3.1.14) and  $f_*(\mathcal{I})$  is contained in the  $g_*$ -adapted full subcategory of all flabby  $\mathcal{O}_Y$ -modules. Hence the result follows.  $\square$

We can apply Grothendieck's spectral sequence to get what is known as *Leray spectral sequence*

$$(6.2.11) \quad E_2^{p,q} := R^p g_*(R^q f_*(E^\bullet)) \implies R^{p+q}(g \circ f)_*(E^\bullet).$$

Taking  $Y \rightarrow \text{Spec}(k)$  to be the structure morphism, we see that

$$(6.2.12) \quad R\Gamma(Y, -) \circ Rf_* \cong R\Gamma(X, -).$$

Then the above Leray spectral sequence gives its classical version

$$(6.2.13) \quad E_2^{p,q} := R^p g_* \mathcal{H}^q(E^\bullet) \implies R^{p+q} g_*(E^\bullet).$$

Even more specially, for  $f : X = Y \rightarrow \text{Spec}(k)$ , we get the following Leray spectral sequence

$$(6.2.14) \quad E_2^{p,q} := H^p(X, \mathcal{H}^q(E^\bullet)) \implies H^{p+q}(X, E^\bullet).$$

All of these are very useful computational tools in real life examples.

**6.3. Local  $\mathcal{H}om^\bullet$  complex.** Let  $X$  be a noetherian scheme. For  $E \in \mathfrak{QCoh}(X)$ , the functor

$$(6.3.1) \quad \mathcal{H}om(E, -) : \mathfrak{QCoh}(X) \rightarrow \mathfrak{QCoh}(X), \quad F \mapsto \mathcal{H}om(E, F),$$

is left exact. Moreover,  $\mathcal{H}om(E, F) \in \mathcal{Coh}(X)$  if both  $E, F$  are coherent. Since  $\mathcal{Q}\mathcal{Coh}(X)$  has enough injectives (c.f., [Har77, Chapter III, Exercise 3.6]), its right derived functor

$$(6.3.2) \quad R\mathcal{H}om(E, -) : D^+(\mathcal{Q}\mathcal{Coh}(X)) \longrightarrow D^+(\mathcal{Q}\mathcal{Coh}(X))$$

exists. Then for any  $E, F \in \mathcal{Q}\mathcal{Coh}(X)$  and any integer  $i$ , we define

$$(6.3.3) \quad \mathcal{E}xt^i(E, F) := R^i\mathcal{H}om(E, F) := \mathcal{H}^i(R\mathcal{H}om(E, F)) \in \mathcal{Q}\mathcal{Coh}(X).$$

If  $E \in \mathcal{Coh}(X)$ , the above definition is local in the sense that its stalk at  $x \in X$  can be computed as

$$(6.3.4) \quad \mathcal{E}xt^i(E, F)_x = \text{Ext}_{\mathcal{O}_{X,x}}^i(E_x, F_x),$$

which follows from commutativity of the following diagram.

$$(6.3.5) \quad \begin{array}{ccc} \mathcal{Q}\mathcal{Coh}(X) & \xrightarrow{\mathcal{H}om(E, -)} & \mathcal{Q}\mathcal{Coh}(X) \\ \downarrow & & \downarrow \\ \text{Mod}(\mathcal{O}_{X,x}) & \xrightarrow{\text{Hom}(E_x, -)} & \text{Mod}(\mathcal{O}_{X,x}). \end{array}$$

Note that,  $\mathcal{E}xt^i(E, F) \in \mathcal{Coh}(X)$  whenever both  $E, F \in \mathcal{Coh}(X)$ .

When  $E \in \mathcal{Coh}(X)$ , the functor (6.3.2) restricts to the bounded below derived category of coherent sheaves

$$(6.3.6) \quad R\mathcal{H}om(E, -) : D^+(X) \longrightarrow D^+(X).$$

Since for a non-regular local ring  $A$ , the groups  $\text{Ext}_A^i(M, -)$  can be non-trivial even for  $i \gg 0$ , only for non-singular schemes  $X$ , the above functor  $R\mathcal{H}om(E, -)$  restricts to  $D^b(X)$ , the bounded derived category of coherent sheaves on  $X$ .

As discussed before, the above construction easily generalizes for bounded above complexes of coherent sheaves  $E^\bullet \in D^-(X)$ . For this, we note that the following functor is exact.

$$\mathcal{H}om^\bullet(E^\bullet, -) : K^+(\mathcal{Q}\mathcal{Coh}(X)) \longrightarrow K^+(\mathcal{Q}\mathcal{Coh}(X))$$

given by sending a complex  $F^\bullet \in K^+(\mathcal{Q}\mathcal{Coh}(X))$  to the complex  $\mathcal{H}om^\bullet(E^\bullet, F^\bullet)$ , where

$$\mathcal{H}om^i(E^\bullet, F^\bullet) := \prod_{p \in \mathbb{Z}} \mathcal{H}om(E^p, F^{i+p})$$

and the differentials are given by  $d^i = d_{E^\bullet} - (-1)^i d_{F^\bullet}$ , for all  $i \in \mathbb{Z}$ . The following lemma follows from corresponding local statement for modules over a ring.

**Lemma 6.3.7.** *Let  $F^\bullet \in D^-(X)$  be a complex of injective sheaves. If  $F^\bullet$  or  $E^\bullet \in K^+(\mathcal{Q}\mathcal{Coh}(X))$  is acyclic, then  $\mathcal{H}om^\bullet(E^\bullet, F^\bullet)$  is acyclic.*

The above Lemma 6.3.7 applied to the class

$$\mathcal{I} := \{I^\bullet \in K^+(\mathfrak{Q}\mathfrak{Coh}(X)) : I^i \text{ is injective } \mathcal{O}_X\text{-module}\}$$

shows that  $\mathcal{I}$  is adapted to the functor  $\mathcal{H}om^\bullet(E^\bullet, -)$  (see Remark 3.1.14), and hence, the right derived functor

$$(6.3.8) \quad R\mathcal{H}om^\bullet(E^\bullet, -) : D^+(\mathfrak{Q}\mathfrak{Coh}(X)) \longrightarrow D^+(\mathfrak{Q}\mathfrak{Coh}(X))$$

exists. Note that, we are working with  $\mathfrak{Q}\mathfrak{Coh}(X)$ , because  $\mathfrak{Coh}(X)$  has not enough injectives. Similarly, to see that the functor

$$\mathcal{H}om^\bullet(-, F^\bullet) : D^-(\mathfrak{Q}\mathfrak{Coh}(X))^{\text{op}} \longrightarrow D^+(\mathfrak{Q}\mathfrak{Coh}(X))$$

descends to the derived category for any  $F^\bullet \in D^+(\mathfrak{Q}\mathfrak{Coh}(X))$ . Therefore, we get a bifunctor

$$(6.3.9) \quad R\mathcal{H}om^\bullet(-, -) : D^-(\mathfrak{Q}\mathfrak{Coh}(X))^{\text{op}} \times D^+(\mathfrak{Q}\mathfrak{Coh}(X)) \longrightarrow D^+(\mathfrak{Q}\mathfrak{Coh}(X)).$$

This enables us to define

$$(6.3.10) \quad \text{Ext}^i(E^\bullet, F^\bullet) := R^i\mathcal{H}om^\bullet(E^\bullet, F^\bullet) := \mathcal{H}^i(R\mathcal{H}om^\bullet(E^\bullet, F^\bullet)) \in \mathfrak{Q}\mathfrak{Coh}(X), \quad \forall i.$$

Assume that  $X$  is a regular noetherian  $k$ -scheme. Although the category  $\mathfrak{Coh}(X)$  has not enough injectives, for the purpose of computing local Ext's (i.e.,  $\text{Ext}$ ), locally free coherent sheaves are good enough. More precisely, if  $E^\bullet \in D^b(X)$  is a bounded complex of locally free coherent sheaves on  $X$ , then  $R\mathcal{H}om(E^\bullet, -)$  can be computed as  $\mathcal{H}om(E^\bullet, -)$ . This can be deduced from the corresponding local statement that, for any bounded complex  $M^\bullet$  of free modules over a local ring  $A$ ,  $R\mathcal{H}om(M^\bullet, -)$  can be computed as  $\mathcal{H}om(M^\bullet, -)$ , which follows because free  $A$ -modules are projective.

**Proposition 6.3.11.** *Let  $X$  be a non-singular noetherian  $k$ -scheme. Then any bounded complex  $E^\bullet \in D^b(X)$  is isomorphic to a bounded complex  $\mathcal{E}^\bullet \in D^b(X)$  of locally free coherent sheaves of  $\mathcal{O}_X$ -modules on  $X$ .*

*Proof.* Since  $X$  is a noetherian non-singular  $k$ -scheme,  $\mathfrak{Coh}(X)$  has enough projectives, meaning that any  $E \in \mathfrak{Coh}(X)$  admits a finite resolution

$$0 \rightarrow F_i^\ell \rightarrow F_i^{\ell-1} \rightarrow \cdots \rightarrow F_i^0 \rightarrow E \rightarrow 0,$$

with  $F_i^j$  a locally free coherent sheaves of  $\mathcal{O}_X$ -modules on  $X$ . Moreover, one can choose such a resolution of length  $\ell \leq \dim_k(X)$ . Hence the result follows.  $\square$

**6.4. Trace map.** Let  $X$  be a regular noetherian  $k$ -scheme. Since any  $E^\bullet \in D^b(X)$  is isomorphic to a bounded complex of locally free coherent sheaves of  $\mathcal{O}_X$ -modules  $\mathcal{E}^\bullet$  in  $D^b(X)$ , we may assume that each  $E^i$  is a locally free coherent sheaves of  $\mathcal{O}_X$ -modules. Then  $R\mathcal{H}om(E^\bullet, E^\bullet) = \mathcal{H}om^\bullet(E^\bullet, E^\bullet)$ . By definition,  $\mathcal{H}om^0(E^\bullet, E^\bullet) =$

$\bigoplus_i \mathcal{H}om(E^i, E^i)$ . Then the usual trace morphism  $\mathrm{tr}_{E^i} : \mathcal{H}om(E^i, E^i) \rightarrow \mathcal{O}_X$  for the locally free sheaves  $E^i$  give rise to the trace morphism

$$(6.4.1) \quad \mathrm{tr}_{E^\bullet} := \bigoplus_i (-1)^i \mathrm{tr}_{E^i} : R\mathcal{H}om(E^\bullet, E^\bullet) \rightarrow \mathcal{O}_X.$$

**6.5. Derived dual.** For  $E^\bullet \in D^-(\mathfrak{QCo}h(X))$ , we define its *dual* (or, more precisely, its *derived dual*) to be the object

$$(6.5.1) \quad E^{\bullet\vee} := R\mathcal{H}om(E^\bullet, \mathcal{O}_X) \in D^+(\mathfrak{QCo}h(X)).$$

If  $E^\bullet$  is a bounded above complex of locally free coherent sheaves on  $X$ , then we can compute its (derived) dual  $E^{\bullet\vee}$  as the bounded below complex

$$(6.5.2) \quad \cdots \rightarrow \mathcal{H}om(E^{i+1}, \mathcal{O}_X) \rightarrow \mathcal{H}om(E^i, \mathcal{O}_X) \rightarrow \mathcal{H}om(E^{i-1}, \mathcal{O}_X) \rightarrow \cdots.$$

If  $X$  is regular noetherian  $k$ -scheme, then for any  $E^\bullet \in D^b(X)$ , its (derived) dual  $E^{\bullet\vee} := R\mathcal{H}om(E^\bullet, \mathcal{O}_X) \in D^b(X)$ .

Note that, even for a coherent sheaf  $E$  on  $X$ , its derived dual

$$E^\vee := R\mathcal{H}om(E, \mathcal{O}_X) \in D^b(\mathfrak{QCo}h(X))$$

need not be a sheaf on  $X$ . For example, if  $E \in \mathfrak{Co}h(X)$  is a coherent sheaf on a smooth projective  $k$ -variety  $X$  with  $\mathrm{codim}_X(\mathrm{Supp}(E)) \geq d$ , then  $R\mathcal{H}om(E, \mathcal{O}_X)$  is a complex concentrated in degree  $\geq d$ . (Hint: Use Serre duality and [HL10, Proposition 1.1.6]).

We shall see later, using Grothendieck-Verdier duality (Theorem 6.9.1), that for any smooth closed  $k$ -subvariety  $\iota : Z \hookrightarrow X$  of codimension  $c$  in a smooth  $k$ -variety  $X$ , the derived dual of  $\iota_*\mathcal{O}_Z$  can be computed as

$$(6.5.3) \quad (\iota_*\mathcal{O}_Z)^\vee \cong (\iota_*\omega_Z \otimes_{\mathcal{O}_X} \mathcal{H}om(\omega_X, \mathcal{O}_X))[-c].$$

As an immediate consequence of this formula, we have the following. If  $D \xrightarrow{\iota} X$  is a divisor in  $X$ , then using the adjunction formula  $\omega_D \cong (\omega_X \otimes \mathcal{O}_X(D))|_D$  we have,  $(\iota_*\mathcal{O}_D)^\vee \cong \iota_*\mathcal{O}_D(D)[-1]$ .

**6.6. Derived tensor product.** Let  $X$  be a projective  $k$ -scheme. Then any coherent sheaf  $E \in \mathfrak{Co}h(X)$  admits a resolution (not necessarily finite) by locally free coherent sheaves of  $\mathcal{O}_X$ -modules

$$(6.6.1) \quad \mathcal{E}^\bullet \rightarrow E.$$

If  $X$  is smooth, we can choose  $\mathcal{E}^\bullet$  to be a bounded complex of length  $\leq \dim(X)$ . Note that, for any  $F \in \mathfrak{Co}h(X)$ , the tensor product functor  $F \otimes - : \mathfrak{Co}h(X) \rightarrow \mathfrak{Co}h(X)$  is right exact. If  $E^\bullet$  is a bounded above acyclic complex (i.e.,  $\mathcal{H}^i(E^\bullet) = 0$ , for all  $i$ ) of locally free coherent sheaves of  $\mathcal{O}_X$ -modules, then  $F \otimes E^\bullet$  is also acyclic. Therefore,

the full subcategory  $\mathcal{Vect}(X)$  of locally free coherent sheaves on  $X$  is adapted to the right exact functor  $F^\bullet \otimes -$ .

Consider a bounded above complex of coherent sheaves of  $\mathcal{O}_X$ -modules  $E^\bullet \in K^-(\mathfrak{Coh}(X))$ . Define a functor

$$(6.6.2) \quad E^\bullet \otimes - : K^-(\mathfrak{Coh}(X)) \longrightarrow K^-(\mathfrak{Coh}(X))$$

by sending  $F^\bullet \in K^-(\mathfrak{Coh}(X))$  to the complex  $E^\bullet \otimes F^\bullet$ :

$$(6.6.3) \quad (E^\bullet \otimes F^\bullet)^i := \bigoplus_{p+q=i} E^p \otimes F^q, \quad \text{with } d = d_E \otimes 1 + (-1)^i 1 \otimes d_F.$$

So by definition,  $E^\bullet \otimes F^\bullet$  is the total complex of the double complex  $K^{\bullet,\bullet}$  with  $K^{p,q} := E^p \otimes F^q$ , and the two differentials are  $d_I := d_E \otimes 1$  and  $d_{II} := (-1)^{p+q} 1 \otimes d_F$ . Therefore, to get the left derived functor of  $E^\bullet \otimes -$ , we need to check that the full subcategory  $\text{Kom}^-(\mathcal{Vect}(X))$  of bounded above complexes of locally free coherent sheaves of  $\mathcal{O}_X$ -modules is adopted to  $E^\bullet \otimes -$ . Since any coherent sheaf  $F \in \mathfrak{Coh}(X)$  admits a surjective morphism  $\mathcal{F} \rightarrow F$ , with  $\mathcal{F}$  locally free coherent sheaf of  $\mathcal{O}_X$ -modules, it remains to check that, for any acyclic complex  $F^\bullet \in K^-(\mathfrak{Coh}(X))$  with all  $F^i$  locally free,  $E^\bullet \otimes F^\bullet$  is acyclic. For this, we use the following spectral sequence

$$(6.6.4) \quad \mathbb{E}_2^{p,q} := \mathcal{H}_I^p \mathcal{H}_{II}^q(K^{\bullet,\bullet}) \implies \mathbb{E}^{p+q} := \mathcal{H}^{p+q}(E^\bullet \otimes F^\bullet).$$

Note that, for  $F^\bullet$  acyclic with all  $F^i$  locally free,  $E^p \otimes F^\bullet$  is acyclic, for all  $p$ . Therefore,  $\mathcal{H}_{II}(E^p \otimes F^\bullet) = 0$ , for all  $p$ , and hence,  $\mathbb{E}_2^{p,q} = 0$  for all  $p$  and  $q$ . Since  $\mathbb{E}_\infty^{p,q} \cong F^p \mathbb{E}^{p+q} / F^{p+1} \mathbb{E}^{p+q}$  and  $\bigcap_p F^p \mathbb{E}^{p+q} = 0$ , it follows that  $\mathbb{E}^{p+q} = 0$ . Hence  $E^\bullet \otimes F^\bullet$  is acyclic. Therefore, the left derived functor

$$(6.6.5) \quad E^\bullet \overset{L}{\otimes} - : D^-(X) \longrightarrow D^-(X)$$

exists. Similarly, one can show that for a complex of locally free sheaves  $F^\bullet$  and an acyclic complex  $E^\bullet$ , the tensor product complex  $E^\bullet \otimes F^\bullet$  is acyclic. In other words, the induced bifunctor

$$(6.6.6) \quad K^-(\mathfrak{Coh}(X)) \times D^-(X) \longrightarrow D^-(X)$$

need not be derived in the first factor, and descends to the bifunctor

$$(- \overset{L}{\otimes} -) : D^-(X) \times D^-(X) \longrightarrow D^-(X)$$

on the derived categories.

Suppose that  $X$  is a smooth projective  $k$ -scheme. Then any  $E^\bullet \in D^b(X)$  is isomorphic to a bounded complex of locally free coherent sheaves of  $\mathcal{O}_X$ -modules. Therefore, for  $E^\bullet, F^\bullet \in D^b(X)$ , replacing them with isomorphic bounded complexes of locally free coherent sheaves of  $\mathcal{O}_X$ -modules, we can compute their (derived) tensor

product  $E^\bullet \overset{L}{\otimes} F^\bullet$  as the ordinary tensor product  $E^\bullet \otimes F^\bullet$  of complexes. This gives us functorial isomorphisms

$$E^\bullet \overset{L}{\otimes} F^\bullet \cong F^\bullet \overset{L}{\otimes} E^\bullet \quad \text{and} \\ E^\bullet \overset{L}{\otimes} (F^\bullet \overset{L}{\otimes} G^\bullet) \cong (E^\bullet \overset{L}{\otimes} F^\bullet) \overset{L}{\otimes} G^\bullet.$$

For any  $E^\bullet, F^\bullet \in D^b(X)$ , we define

$$(6.6.7) \quad \text{Tor}_i(E^\bullet, F^\bullet) := \mathcal{H}^{-i}(E^\bullet \overset{L}{\otimes} F^\bullet);$$

which can be computed using the following spectral sequence.

**Proposition 6.6.8.** *There is a spectral sequence*

$$\mathbb{E}_2^{p,q} := \text{Tor}_{-p}(\mathcal{H}^q(E^\bullet), F^\bullet) \implies \mathbb{E}^{p,q} := \text{Tor}_{-(p+q)}(E^\bullet, F^\bullet).$$

**Remark 6.6.9.** For the sake of simplicity, we only have explained how to get the left derive functor of the tensor product functor in case  $X$  is a projective  $k$ -scheme. The general case is also similar, but require more technical cares to construct it.

**6.7. Defived pullback.** Recall that, for any morphism of locally ringed spaces

$$(6.7.1) \quad f : (X, \mathcal{O}_X) \longrightarrow (Y, \mathcal{O}_Y),$$

the pullback functor

$$(6.7.2) \quad f^* : \mathcal{M}\text{od}(\mathcal{O}_Y) \longrightarrow \mathcal{M}\text{od}(\mathcal{O}_X)$$

is defined to be the composition of the exact functor

$$(6.7.3) \quad f^{-1} : \mathcal{M}\text{od}(\mathcal{O}_Y) \longrightarrow \mathcal{M}\text{od}_X(f^{-1}(\mathcal{O}_Y))$$

with the right exact functor

$$(6.7.4) \quad \mathcal{O}_X \otimes_{f^{-1}\mathcal{O}_Y} (-) : \mathcal{M}\text{od}_X(f^{-1}\mathcal{O}_Y) \longrightarrow \mathcal{M}\text{od}(\mathcal{O}_X).$$

Thus,  $f^*$  is right exact. Let  $\mathcal{O}_X \overset{L}{\otimes}_{f^{-1}\mathcal{O}_Y} (-)$  be the left derived functor of  $\mathcal{O}_X \otimes_{f^{-1}\mathcal{O}_Y} (-)$ . Since  $f^{-1}$  is exact, we don't need to derive it. Then we can define the left derived functor of  $f^*$  to be the composite functor

$$(6.7.5) \quad Lf^* := (\mathcal{O}_X \overset{L}{\otimes}_{f^{-1}\mathcal{O}_Y} (-)) \circ f^{-1} : D^-(Y) \longrightarrow D^-(X).$$

Note that, we have discussed how to get the left derived functor  $\mathcal{O}_X \overset{L}{\otimes}_{f^{-1}\mathcal{O}_Y} (-)$  only for the case  $X$  is a projective  $k$ -scheme. However, general case being similar but little more technical in nature, we leave it to the reader to fill the gap. In most of the applications, we work with  $f$  a flat morphism, in which case, we don't need to derive  $f^*$  as it is already exact.

The following spectral sequence is useful to work with  $Lf^*$  in real life.

**Proposition 6.7.6.** *There is a spectral sequence*

$$\mathbb{E}_2^{p,q} := L^p f^*(\mathcal{H}^q(E^\bullet)) \implies \mathbb{E}^{p+q} := L^{p+q} f^*(E^\bullet),$$

where  $L^i f^*(E^\bullet) := \mathcal{H}^i(Lf^*(E^\bullet))$ , for all  $i \in \mathbb{Z}$ .

**6.8. Compatibilities.** In this subsection, we quickly go through compatibilities among various derived functors generalizing classical ones. We only sketch their proofs, leaving the details to the readers.

- (i) Let  $f : X \longrightarrow Y$  be a proper morphism of projective  $k$ -schemes. Then for any  $E^\bullet \in D^b(X)$  and  $F^\bullet \in D^b(Y)$ , we have a natural isomorphism (*projection formula*)

$$(6.8.1) \quad Rf_*(E^\bullet) \overset{L}{\otimes} F^\bullet \cong Rf_*(E^\bullet \overset{L}{\otimes} Lf^* F^\bullet).$$

This follows from the following classical projection formula [Har77]: for a coherent sheaf of  $\mathcal{O}_X$ -modules  $E$  on  $X$  and a locally free coherent sheaf of  $\mathcal{O}_Y$ -modules on  $Y$ , we have a natural isomorphism of  $\mathcal{O}_Y$ -modules

$$f_*(E \otimes_{\mathcal{O}_X} f^* F) \cong f_* E \otimes_{\mathcal{O}_Y} F.$$

- (ii) Let  $f : X \longrightarrow Y$  be a morphism of projective  $k$ -schemes. Then for any  $E^\bullet, F^\bullet \in D^b(Y)$ , there is a natural isomorphism

$$(6.8.2) \quad (Lf^* E^\bullet) \overset{L}{\otimes} (Lf^* F^\bullet) \xrightarrow{\sim} Lf^*(E^\bullet \overset{L}{\otimes} F^\bullet).$$

Since  $Y$  is projective  $k$ -scheme (smoothness is not required!), we can replace  $E^\bullet$  and  $F^\bullet$  by bounded above complexes of locally free coherent sheaves of  $\mathcal{O}_Y$ -modules on  $Y$ , and use them to compute their derived tensor product as the usual tensor product of complexes. The resulting complex of locally free coherent sheaves of  $\mathcal{O}_Y$ -modules is again bounded above, and so we can compute its derived pullback as the ordinary pullback of complex of locally free sheaves. Thus we obtain a bounded above complex of locally free coherent sheaves on  $X$ . Now the above formula (6.8.2) can be deduced by using the classical pullback formula  $f^* E \otimes f^* F \cong f^*(E \otimes F)$  for coherent sheaves.

- (iii) Let  $f : X \longrightarrow Y$  be a projective morphism of noetherian schemes. Then we have  $Lf^* \dashv Rf_*$ ; i.e., there is a functorial isomorphism

$$(6.8.3) \quad \mathrm{Hom}(Lf^* E^\bullet, F^\bullet) \xrightarrow{\sim} \mathrm{Hom}(E^\bullet, Rf_* F^\bullet),$$

for all  $E^\bullet \in D^-(\mathfrak{QCo}\mathfrak{h}(Y))$  and  $F^\bullet \in D^+(\mathfrak{QCo}\mathfrak{h}(X))$ . To see this, replacing  $E^\bullet$  with a bounded above complex of locally free sheave of  $\mathcal{O}_Y$ -modules quasi-isomorphic to  $E^\bullet$ , and  $F^\bullet$  with a bounded below complex of injective  $\mathcal{O}_X$ -modules quasi-isomorphic to  $F^\bullet$ , we can compute the corresponding derived functors as the usual pullback (resp., push-forward) of complexes along  $f$ . Then



the statement follows from the classical adjunction formula  $\mathrm{Hom}(f^*E, F) \cong \mathrm{Hom}(E, f_*F)$  for coherent sheaves.

- (iv) Assume that  $X$  is a smooth projective  $k$ -variety. Let  $E^\bullet, F^\bullet, G^\bullet \in D^b(X)$  be the bounded complexes of coherent sheaves on  $X$ . Then we have the following natural isomorphisms.

$$(6.8.4) \quad R\mathcal{H}om(E^\bullet, F^\bullet) \otimes^L G^\bullet \cong R\mathcal{H}om(E^\bullet, F^\bullet \otimes^L G^\bullet)$$

**6.9. Grothendieck-Verdier duality.** In this subsection, we state a deep duality theorem known as Grothendieck-Verdier duality, and show its applications. We refer the reader to [Con00] for its proof.

**Theorem 6.9.1** (Grothendieck-Verdier duality). *Let  $f : X \rightarrow Y$  be a morphism of smooth schemes over a field  $k$  of relative dimension  $\dim(f) := \dim(X) - \dim(Y)$ . Let*

$$(6.9.2) \quad \omega_f := \omega_X \otimes f^* \omega_Y^\vee$$

*be the relative dualizing sheaf of  $f$ . Then for any  $F^\bullet \in D^b(X)$  and  $E^\bullet \in D^b(Y)$ , there is a functorial isomorphism*

$$(6.9.3) \quad Rf_* R\mathcal{H}om(F^\bullet, Lf^*(E^\bullet) \otimes^L \omega_f[\dim(f)]) \xrightarrow{\cong} R\mathcal{H}om(Rf_* F^\bullet, E^\bullet).$$

## 7. EXAMPLES OF SPECTRAL SEQUENCE

Here we give some useful examples of Grothendieck spectral sequences, which will appear in next sections.

**Example 7.0.1.** Let  $\mathcal{A}$  be an abelian category with enough injectives. Let  $A^\bullet \in D(\mathcal{A})$  and  $B^\bullet \in D^+(\mathcal{A})$ . Take  $F_1 = \mathrm{Id}$  so that  $R^q F_1(B^\bullet) = \mathcal{H}^q(B^\bullet)$ , and take  $F_2 = \mathrm{Hom}^\bullet(A^\bullet, -)$ . Then we have,

$$R^p F_2(R^q F_1(B^\bullet)) = R^p \mathrm{Hom}^\bullet(A^\bullet, \mathcal{H}^q(B^\bullet)) = \mathrm{Ext}^p(A^\bullet, \mathcal{H}^q(B^\bullet)),$$

and

$$R^{p+q}(F_2 \circ F_1)(B^\bullet) = R^{p+q} \mathrm{Hom}^\bullet(A^\bullet, B^\bullet) = \mathrm{Ext}^{p+q}(A^\bullet, B^\bullet).$$

Since  $\mathrm{Ext}^{p+q}(A^\bullet, B^\bullet) = \mathrm{Hom}(A^\bullet, B^\bullet[p+q])$  and  $\mathrm{Ext}^p(A^\bullet, \mathcal{H}^q(B^\bullet)) \cong \mathrm{Hom}(A^\bullet, \mathcal{H}^q(B^\bullet)[p])$ , by Theorem 5.1.10, we have a spectral sequence

$$(7.0.2) \quad E_2^{p,q} := \mathrm{Hom}(A^\bullet, \mathcal{H}^q(B^\bullet)[p]) \implies \mathrm{Hom}(A^\bullet, B^\bullet[p+q]).$$

Similarly, if  $\mathcal{A}$  has enough projectives so that we can compute  $R^p \mathrm{Hom}^\bullet(A^\bullet, B^\bullet)$  for  $A^\bullet \in D^-(\mathcal{A})$  as the right derived functor of the contravariant functor  $\mathrm{Hom}^\bullet(-, B^\bullet) : K^-(\mathcal{A})^{\mathrm{op}} \rightarrow K(\mathbf{Ab})$ , we have the spectral sequence

$$(7.0.3) \quad E_2^{p,q} := \mathrm{Hom}(\mathcal{H}^{-q}(A^\bullet), B^\bullet[p]) \implies \mathrm{Hom}(A^\bullet, B^\bullet[p+q]).$$



If  $B^\bullet \in D^+(\mathcal{A})$  is bounded below, and  $\mathcal{A}$  has enough injectives, but may not have enough projectives, then also we have this spectral sequence.

**Remark 7.0.4.** It should be noted that, a spectral sequence  $E_2^{p,q} \Rightarrow E^{p+q}$  given at page  $E_2$  **does not imply** that the term  $E_\infty^{p,q}$  lies in page  $E_2$ .

**Example 7.0.5.** Let  $X$  be a noetherian scheme so that  $\mathcal{Q}\mathcal{C}\mathcal{O}\mathcal{h}(X)$  has enough injectives. Then for any  $E^\bullet, F^\bullet \in D^b(X)$ , we have the following spectral sequences

$$(7.0.6) \quad E_2^{p,q} := \text{Ext}^p(E^\bullet, \mathcal{H}^q(F^\bullet)) \Longrightarrow \text{Ext}^{p+q}(E^\bullet, F^\bullet),$$

and

$$(7.0.7) \quad E_2^{p,q} := \text{Ext}^p(\mathcal{H}^{-q}(E^\bullet), F^\bullet) \Longrightarrow \text{Ext}^{p+q}(E^\bullet, F^\bullet),$$

**Remark 7.0.8.** If  $X$  is a projective  $k$ -variety,  $\dim_k H^i(X, E) < \infty$  for any coherent sheaf  $E$  on  $X$ . Using this, one can deduce that  $\dim_k \text{Ext}^i(E, F) < \infty$ , for any  $E, F \in \mathcal{C}\mathcal{O}\mathcal{h}(X)$ . Then using the spectral sequences (7.0.6) and (7.0.7) one can show that  $\text{Ext}^i(E^\bullet, F^\bullet)$  has finite dimension, for all  $E^\bullet, F^\bullet \in D^b(X)$ .

**Example 7.0.9.** Let  $E^\bullet \in D^-(X)$ . Then by definition of local Hom complex, we have  $\Gamma \circ \mathcal{H}\text{om}^\bullet(E^\bullet, -) = \text{Hom}^\bullet(E^\bullet, -)$ . Since for a complex  $I^\bullet$  of injective sheaves of  $\mathcal{O}_X$ -modules, the complex  $\mathcal{H}\text{om}^\bullet(E^\bullet, I^\bullet)$  is  $\Gamma$ -acyclic (meaning that,  $\text{Ext}^i(E^\bullet, I^\bullet) = R^i\Gamma(\mathcal{H}\text{om}^\bullet(E^\bullet, I^\bullet)) = 0$  for all  $i \neq 0$ , which indeed holds), we have

$$R\Gamma \circ R\mathcal{H}\text{om}^\bullet(E^\bullet, -) = R\text{Hom}^\bullet(E^\bullet, -).$$

Therefore, applying Theorem 5.1.10 we have the following spectral sequence relating local and global Ext:

$$(7.0.10) \quad E_2^{p,q} := H^p(X, \mathcal{E}\text{xt}^q(E^\bullet, F^\bullet)) \Longrightarrow \text{Ext}^{p+q}(E^\bullet, F^\bullet).$$

## 8. BONDAL–ORLOV’S RECONSTRUCTION THEOREM

**8.1. What is it?** A famous theorem of Gabriel says that two  $k$ -varieties  $X$  and  $Y$  are isomorphic if and only if there is an equivalence of categories  $\mathcal{C}\mathcal{O}\mathcal{h}(X)$  with  $\mathcal{C}\mathcal{O}\mathcal{h}(Y)$ . In [Muk81], Mukai established an equivalence  $D^b(A) \simeq D^b(\check{A})$ , where  $A$  is an abelian variety and  $\check{A}$  its dual abelian variety. Therefore, equivalence between bounded derived category of coherent sheaves fails to ensure isomorphism of varieties, in general. In their famous paper [BO01], Bondal and Orlov shows how to reconstruct a smooth projective variety  $X$  from  $D^b(X)$  when  $\omega_X$  or its dual is ample (see Theorem 8.1.1). More precisely,

**Theorem 8.1.1** (Bondal–Orlov). *Let  $X$  be a smooth projective variety over  $k$  with canonical line bundle  $\omega_X$ . Assume that  $\omega_X$  (resp.,  $\omega_X^\vee$ ) is ample. Let  $Y$  be any smooth projective variety over  $k$ . If there is an exact equivalence  $F : D^b(X) \xrightarrow{\sim} D^b(Y)$ , then  $X \cong Y$  as  $k$ -varieties. In particular,  $\omega_Y$  (resp.,  $\omega_Y^\vee$ ) is ample.*

The main idea behind the proof is to “cohomologically” characterize closed points, invertible sheaves and Zariski topology of a smooth projective  $k$ -variety. For this we need “Serre functor” as defined in Definition 4.1.1. Note that, both  $D^b(X)$  and  $D^b(Y)$  admits Serre functors  $S_X := (\omega_X \otimes -)[\dim_k(X)]$  and  $S_Y := (\omega_Y \otimes -)[\dim(Y)]$ , respectively. As a first step towards this theorem, we now establish equality of dimensions of  $X$  and  $Y$ .

**8.2. Equality of dimensions.** Let  $k$  be a field. A  $k$ -variety is an integral separated finite type  $k$ -scheme. For any smooth projective  $k$ -variety  $X$ , we define  $D^b(X) := D^b(\mathcal{Coh}(X))$ . A rank one invertible sheaf  $L$  on  $X$  is said to have *finite order* if  $L^r \cong \mathcal{O}_X$  for some integer  $r > 0$ . The smallest positive integer  $r$  such that  $L^r \cong \mathcal{O}_X$  is called the *order* of  $L$ . If  $L^r \not\cong \mathcal{O}_X$ ,  $\forall r > 0$ , we say that  $L$  has *infinite order*. For any  $x \in X$ , let  $k(x) := \mathcal{O}_{X,x}/\mathfrak{m}_x$  be the residue field at  $x$ . For any closed point  $x \in X$ , we can consider  $k(x)$  as a coherent sheaf on  $X$  supported at  $x$  by taking its push-forward along the closed embedding  $\iota_x : \text{Spec}(k(x)) \hookrightarrow X$ . This is the skyscraper sheaf supported at  $x$  given by

$$k(x)(U) = \begin{cases} k(x), & \text{if } x \in U, \text{ and} \\ 0, & \text{otherwise.} \end{cases}$$

**Proposition 8.2.1.** *Let  $X$  and  $Y$  be smooth projective varieties over  $k$ . If there is an exact equivalence  $D^b(X) \xrightarrow{\sim} D^b(Y)$  of bounded derived categories, then  $\dim_k(X) = \dim_k(Y)$ . In this case, both  $\omega_X$  and  $\omega_Y$  have the same order (can be infinity too).*

*Proof.* Since both  $X$  and  $Y$  are smooth projective  $k$ -varieties, by Theorem 4.2.2, they admit natural Serre functors  $S_X := (\omega_X \otimes -)[\dim_k(X)]$  and  $S_Y := (\omega_Y \otimes -)[\dim_k(Y)]$ , respectively. By Lemma 4.1.7, any  $k$ -linear equivalence  $F : D^b(X) \rightarrow D^b(Y)$  commutes with Serre functors  $S_X$  and  $S_Y$  (i.e., there is a natural isomorphism of functors  $F \circ S_X \cong S_Y \circ F$ ).

For a closed point  $x \in X$ , we have  $k(x) \cong k(x) \otimes \omega_X \cong S_X(k(x))[-\dim_k(X)]$ . So,

$$\begin{aligned} (8.2.2) \quad F(k(x)) &\cong F(k(x) \otimes \omega_X) = F(S_X(k(x))[-\dim_k(X)]) \\ &\cong F(S_X(k(x)))[- \dim_k(X)], \quad \text{since } F \text{ is exact.} \\ &\cong S_Y(F(k(x)))[- \dim_k(X)], \quad \text{since } F \circ S_X \cong S_Y \circ F. \\ &\cong F(k(x)) \otimes \omega_Y[\dim_k(Y) - \dim_k(X)]. \end{aligned}$$

Since  $F$  is an equivalence of categories,  $F(k(x))$  is a non-trivial bounded complex. Let  $i$  be the maximal (resp., minimal) integer such that  $\mathcal{H}^i(F(k(x))) \neq 0$ . Now from

(8.2.2) we have

$$\begin{aligned}
 0 \neq \mathcal{H}^i(F(k(x))) &\cong \mathcal{H}^i(F(k(x)) \otimes \omega_Y[\dim_k(Y) - \dim_k(X)]) \\
 &\cong \mathcal{H}^{i+\dim_k(Y)-\dim_k(X)}(F(k(x)) \otimes \omega_Y) \\
 (8.2.3) \quad &\cong \mathcal{H}^{i+\dim_k(Y)-\dim_k(X)}(F(k(x))) \otimes \omega_Y.
 \end{aligned}$$

Since  $\omega_Y$  is a line bundle, (8.2.3) contradicts maximality (resp., minimality) of  $i$  whenever  $\dim_k(X) < \dim_k(Y)$  (resp.,  $\dim_k(X) > \dim_k(Y)$ ). Therefore,  $\dim_k(X) = \dim_k(Y)$ .

To see that both  $\omega_X$  and  $\omega_Y$  have the same order, assume that  $\omega_X^k \cong \mathcal{O}_X$ . Let  $n = \dim_k(X) = \dim_k(Y)$ . Note that,  $S_X^k[-kn] \cong \text{Id}_{D^b(X)}$ . Since  $F \circ S_X \cong S_Y \circ F$ , choosing a quasi-inverse of the equivalence  $F$ , we have

$$\begin{aligned}
 F^{-1} \circ S_Y^k[-kn] \circ F &\cong S_X^k[-kn] \cong \text{Id}_{D^b(X)} \\
 \Rightarrow S_Y^k[-kn] &\cong \text{Id}_{D^b(Y)}.
 \end{aligned}$$

Applying  $\mathcal{O}_Y$  to the above isomorphism of functors, we get  $\omega_Y^k \cong \mathcal{O}_Y$ .  $\square$

**Remark 8.2.4.** In the proof of above Proposition, to show both  $\omega_X$  and  $\omega_Y$  have the same order, under the assumption that  $\dim(X) = \dim(Y)$ , we don't need  $F$  to be exact.

### 8.3. Point like objects.

**Definition 8.3.1.** A *graded category* is a pair  $(\mathcal{D}, T_{\mathcal{D}})$  consisting of a category  $\mathcal{D}$  and an equivalence functor  $T_{\mathcal{D}} : \mathcal{D} \rightarrow \mathcal{D}$ , known as *shift functor*. A functor  $F : \mathcal{D} \rightarrow \mathcal{D}'$  between graded categories is called *graded* if there is an isomorphism of functors  $F \circ T_{\mathcal{D}} \xrightarrow{\cong} T_{\mathcal{D}'} \circ F$ .

**Example 8.3.2.** Any triangulated category is a graded category, and any morphism between two triangulated categories is a graded morphism.

**Definition 8.3.3.** Let  $\mathcal{D}$  be a  $k$ -linear triangulated category with Serre functor  $S$ . An object  $P \in \mathcal{D}$  is said to be *point like* of codimension  $s$  if

- (i)  $S(P) \cong P[s]$ ,
- (ii)  $\text{Hom}(P, P[i]) = 0$ , for  $i < 0$ , and
- (iii)  $k(P) := \text{Hom}(P, P)$  is a field.

An object  $E$  of an additive category is called *simple* if  $\text{Hom}(E, E)$  is a field.

**Example 8.3.4.** Let  $X$  be a smooth projective  $k$ -variety of dimension  $n$ .

- (i) For any closed point  $x \in X$ , we have  $S_X(k(x)) = (k(x) \otimes \omega_X)[n] \cong k(x)[n]$ . Therefore,  $k(x) \in D^b(X)$  is a point like object of codimension  $d$ .

- (ii) Let  $\omega_X \cong \mathcal{O}_X$  (for example when  $X$  is an abelian variety or a K3 surface). Then any simple object  $E \in \mathfrak{Coh}(X)$  defines a point like object of codimension  $n$  in  $D^b(X)$ .

**Proposition 8.3.5.** *Let  $\mathcal{A}$  be an abelian category, and  $A^\bullet \in D^b(\mathcal{A})$ . Let*

$$i^+ := \max\{i : \mathcal{H}^i(A^\bullet) \neq 0\} \quad \text{and} \quad i^- := \min\{i : \mathcal{H}^i(A^\bullet) \neq 0\}.$$

*Then in  $D^b(\mathcal{A})$ , there are morphisms  $\phi : A^\bullet \rightarrow \mathcal{H}^{i^+}(A^\bullet)[-i^+]$  and  $\psi : \mathcal{H}^{i^-}(A^\bullet)[-i^-] \rightarrow A^\bullet$  such that  $\mathcal{H}^{i^+}(\phi) = \text{Id}_{\mathcal{H}^{i^+}(A^\bullet)}$  and  $\mathcal{H}^{i^-}(\psi) = \text{Id}_{\mathcal{H}^{i^-}(A^\bullet)}$ .*

*Proof.* There is a natural quasi-isomorphism of complexes

$$\begin{array}{ccccccc} A_-^\bullet : & \cdots & \longrightarrow & A^{i^+-1} & \longrightarrow & \text{Ker}(d^{i^+}) & \longrightarrow \cdots \\ & & & \parallel & & \downarrow & \\ & & & A^{i^+-1} & \longrightarrow & A^{i^+} & \xrightarrow{d^{i^+}} A^{i^++1} \longrightarrow \cdots \end{array}$$

Since the natural morphism of complexes  $A_-^\bullet \rightarrow \mathcal{H}^{i^+}(A^\bullet)[-i^+]$  induces identity morphism at  $i^+$ -th cohomology, the first part follows. The second part is similar.  $\square$

**Corollary 8.3.6.** *With the above notations, for any  $B \in \mathcal{A}$ , we have the following natural isomorphisms*

- (i)  $\text{Hom}_{D^b(\mathcal{A})}(\mathcal{H}^{i^+}(A^\bullet), B) \cong \text{Hom}_{D^b(\mathcal{A})}(A^\bullet, B[-i^+]),$  and
- (ii)  $\text{Hom}_{D^b(\mathcal{A})}(B, \mathcal{H}^{i^-}(A^\bullet)) \cong \text{Hom}_{D^b(\mathcal{A})}(B[-i^-], A^\bullet).$

*Proof.* Send  $f \in \text{Hom}_{D^b(\mathcal{A})}(\mathcal{H}^{i^+}(A^\bullet), B)$  to  $f[-i^+]$  and use above Proposition 8.3.5. To get the inverse map, send any  $\phi \in \text{Hom}_{D^b(\mathcal{A})}(A^\bullet, B[i^+])$  to  $\mathcal{H}^{i^+}(\phi)[-i^+]$ . The second part is similar.  $\square$

**Exercise 8.3.7.** Let  $A^\bullet \in D(\mathcal{A})$  with  $\mathcal{H}^i(A^\bullet) = 0$ , for all  $i < m$ . Then there is a distinguished triangle

$$\mathcal{H}^m(A^\bullet)[-m] \longrightarrow A^\bullet \xrightarrow{\varphi} B^\bullet \longrightarrow \mathcal{H}^m(A^\bullet)[1-m]$$

in the derived category  $D(\mathcal{A})$  such that

$$\mathcal{H}^i(B^\bullet) \cong \begin{cases} \mathcal{H}^i(A^\bullet) & \text{if } i \leq m, \text{ and} \\ 0, & \text{if } i > m. \end{cases}$$

**Remark 8.3.8.** Let  $X$  be a smooth projective  $k$ -variety of dimension  $d$ . Then any point like object  $P \in D^b(X)$  has codimension  $d$ . This follows from assumption (i) in the Definition 8.3.3, because looking at minimal  $i$  with non-zero cohomologies, the isomorphism  $P \otimes \omega_X[d] \cong P[s]$  implies

$$(8.3.9) \quad \mathcal{H}^i(P) \otimes \omega_X[d] \cong \mathcal{H}^i(P)[s].$$

This forces  $d = s$ .

**Lemma 8.3.10.** *Let  $M$  be a finitely generated non-zero module over a noetherian ring  $A$ . Then there is a finite chain of  $A$ -submodules*

$$0 = M_0 \subsetneq M_1 \subsetneq \cdots \subsetneq M_n = M$$

*such that  $M_i/M_{i-1} \cong A/\mathfrak{p}_i$  (as  $A$ -modules), for some  $\mathfrak{p}_i \in \text{Supp}(M)$ .*

*Proof.* Denote by  $\text{Ass}(M)$  the set of all associated primes of  $M$ . Recall that,  $\text{Ass}(M) \subseteq \text{Supp}(M)$  for any finitely generated  $A$ -module  $M$ . Since  $M \neq 0$ , we can choose a  $\mathfrak{p}_1 \in \text{Ass}(M)$  to get an  $A$ -submodule

$$M_1 := \text{image}(A/\mathfrak{p}_1 \hookrightarrow M) \subset M.$$

If  $M_1 \neq M$ , we do the same for  $M/M_1$  to choose a  $\mathfrak{p}_2 \in \text{Ass}(M/M_1)$  and apply the same to obtain a sequence  $M_1 \subsetneq M_2 \subseteq M$  with  $M_2/M_1 \cong A/\mathfrak{p}_2$ . Since  $(M/M_1)_{\mathfrak{p}_2} \neq 0$ , we see that  $\mathfrak{p}_2 \in \text{Supp}(M)$ . Since  $M$  is finitely generated, the result follows by induction.  $\square$

**Corollary 8.3.11.** *With the above notation, if  $\text{Supp}(M) = \{\mathfrak{m}\}$ , for some maximal ideal  $\mathfrak{m}$  of  $A$ , there is a surjective (resp., injective)  $A$ -module homomorphism  $M \twoheadrightarrow A/\mathfrak{m}$  (resp.,  $A/\mathfrak{m} \hookrightarrow M$ ).*

*Proof.* Since  $\text{Ass}(M) = \{\mathfrak{m}\}$ , the result follows from the above Lemma 8.3.10.  $\square$

**Definition 8.3.12.** Support of a complex  $E^\bullet \in D^b(X)$  is the union of the supports of its cohomologies. In other words,  $\text{Supp}(E^\bullet)$  is the closed subset of  $X$  defined by

$$\text{Supp}(E^\bullet) := \bigcup_{i \in \mathbb{Z}} \text{Supp}(\mathcal{H}^i(E^\bullet)).$$

**Lemma 8.3.13.** *Let  $E^\bullet \in D^b(X)$  with  $\text{Supp}(E^\bullet) = Z_1 \cup Z_2$ , for some disjoint closed subsets  $Z_1$  and  $Z_2$  in  $X$ . Then  $E^\bullet \cong E_1^\bullet \oplus E_2^\bullet$ , for some non-zero objects  $E_j^\bullet \in D^b(X)$  with  $\text{Supp}(E_j^\bullet) \subseteq Z_j$ , for all  $j = 1, 2$ .*

*Proof.* This is clear for any  $E \in \mathcal{Coh}(X)$ , and hence the result follows for  $E^\bullet \cong E[n] \in D^b(X)$ , for  $E \in \mathcal{Coh}(X)$  and  $n \in \mathbb{Z}$ . Let

$$i_{E^\bullet}^+ := \max\{i \in \mathbb{Z} : \mathcal{H}^i(E^\bullet) \neq 0\} \quad \text{and} \quad i_{E^\bullet}^- := \min\{i \in \mathbb{Z} : \mathcal{H}^i(E^\bullet) \neq 0\};$$

and we drop the subscript  $E^\bullet$  when there is no confusion likely to arise. The *length* of an object  $E^\bullet \in D^b(X)$  is the difference  $i^+ - i^-$ . For general case, we use induction on the length of a complex.

Let  $E^\bullet \in D^b(X)$  be a complex of length at least 2. Let  $m = i_{E^\bullet}^-$ , and write  $\mathcal{H} := \mathcal{H}^m(E^\bullet)$ . The sheaf  $\mathcal{H}$  can be decomposed as  $\mathcal{H} \cong \mathcal{H}_1 \oplus \mathcal{H}_2$ , with  $\text{Supp}(\mathcal{H}_j) \subset Z_j$ , for

$j = 1, 2$ . By Proposition 8.3.5, we have a natural morphism  $\mathcal{H}[-m] \xrightarrow{\varphi} E^\bullet$  inducing identity morphism on the  $m$ -th cohomology; complete it to a distinguished triangle

$$\mathcal{H}[-m] \xrightarrow{\varphi} E^\bullet \longrightarrow F^\bullet := C(\varphi) \longrightarrow \mathcal{H}[1-m].$$

Then from long exact sequence of cohomologies we have

$$\mathcal{H}^i(F^\bullet) = \begin{cases} \mathcal{H}^i(E^\bullet), & \text{if } i > m, \text{ and} \\ 0, & \text{if } i \leq m; \end{cases}$$

(c.f. Exercise 8.3.7). Since the length of  $F^\bullet$  is less than the length of  $E^\bullet$ , induction hypothesis applied to  $F^\bullet$  gives a decomposition  $F^\bullet \cong F_1^\bullet \oplus F_2^\bullet$  with  $\text{Supp}(\mathcal{H}^i(F_j^\bullet)) \subset Z_j$ , for all  $j = 1, 2$ , and  $i \in \mathbb{Z}$ . Since  $\mathcal{H}^{-q}(F_1^\bullet)$  and  $\mathcal{H}_2$  are coherent sheaves of  $\mathcal{O}_X$ -modules with disjoint supports, we have

$$\text{Hom}_{D^b(X)}(\mathcal{H}^{-q}(F_1^\bullet), \mathcal{H}_2[p]) = \text{Ext}^p(\mathcal{H}^{-q}(F_1^\bullet), \mathcal{H}_2) = 0, \quad \forall p \in \mathbb{Z},$$

which can be verified locally. Then  $\text{Hom}(F_1^\bullet, \mathcal{H}_2[1-m]) = 0$  follows from the spectral sequence

$$E_2^{p,q} := \text{Hom}(\mathcal{H}^{-q}(F_1^\bullet), \mathcal{H}_2[p]) \implies E^{p+q} := \text{Hom}(F_1^\bullet, \mathcal{H}_2[p+q]);$$

c.f., Example 7.0.1. Similarly, we have  $\text{Hom}(F_2^\bullet, \mathcal{H}_1[1-m]) = 0$ . Choose a complex  $E_j^\bullet$  to complete a distinguished triangle

$$E_j^\bullet \longrightarrow F_j^\bullet \longrightarrow \mathcal{H}_j[1-m] \longrightarrow E_j^\bullet[1], \quad \forall j = 1, 2,$$

we have a decomposition  $E^\bullet \cong E_1^\bullet \oplus E_2^\bullet$ . Since  $\text{Supp}(F_j^\bullet) \subset Z_j$ , it follows that  $\text{Supp}(E_j^\bullet) \subset Z_j$ , for all  $j = 1, 2$ .  $\square$

**Lemma 8.3.14.** *Let  $E^\bullet$  be a simple object in  $D^b(X)$  with zero dimensional support. If  $\text{Hom}(E^\bullet, E^\bullet[i]) = 0$  for all  $i < 0$ , then  $E^\bullet \cong k(x)[m]$  for some closed point  $x \in X$  and integer  $m$ .*

*Proof.* Since  $E^\bullet$  is supported in dimension zero,  $\text{Supp}(E)$  is a finite subset of closed points in  $X$ . If  $\text{Supp}(E)$  is not a singleton set, then it has disjoint components. Then in  $D^b(X)$ , we have an isomorphism  $E^\bullet \cong E_1^\bullet \oplus E_2^\bullet$ , with  $E_j^\bullet \neq 0$ ,  $\forall j = 1, 2$ , which contradicts simplicity of  $E^\bullet$ . Therefore,  $\text{Supp}(E^\bullet)$  is a closed point, say  $x \in X$ . Let  $i^+ := \max\{i : \mathcal{H}^i(E^\bullet) \neq 0\}$  and  $i^- := \min\{j : \mathcal{H}^j(E^\bullet) \neq 0\}$ . Since both  $\mathcal{H}^{i^+}(E^\bullet)$  and  $\mathcal{H}^{i^-}(E^\bullet)$  have support  $\{x\}$ , they are given by finite modules over the noetherian local ring  $\mathcal{O}_{X,x}$  supported at  $\mathfrak{m}_x$ . Then applying Corollary 8.3.11, we get a non-trivial  $\mathcal{O}_{X,x}$ -module homomorphism  $\phi : \mathcal{H}^{i^+}(E^\bullet) \longrightarrow \mathcal{H}^{i^-}(E^\bullet)$  given by the composition

$$\mathcal{H}^{i^+}(E^\bullet) \twoheadrightarrow k(x) := \mathcal{O}_{X,x}/\mathfrak{m}_x \hookrightarrow \mathcal{H}^{i^-}(E^\bullet).$$

Now it follows from Proposition 8.3.5 that the following composite morphism is non-trivial.

$$E^\bullet[i^+] \longrightarrow \mathcal{H}^{i^+}(E^\bullet) \xrightarrow{\phi} \mathcal{H}^{i^-}(E^\bullet) \longrightarrow E^\bullet[i^-].$$

Since  $\text{Hom}(E^\bullet, E^\bullet[i]) = 0$  for all  $i < 0$ , we must have  $i^- - i^+ \geq 0$ . Hence,  $i^- = i^+ =: m$  (say). Therefore,  $E^\bullet \cong E[m]$ , for some  $E \in \mathfrak{Coh}(X)$  with  $\text{Supp}(E) = \{x\}$ . Since  $\text{Hom}(E[m], E[m]) \cong \text{Hom}(E, E)$ , so  $E$  is simple. Then the natural surjective homomorphism  $E \rightarrow k(x)$  must be isomorphism. Therefore,  $E^\bullet \cong k(x)[m]$ .  $\square$

**Proposition 8.3.15** (Bondal–Orlov). *Let  $X$  be a smooth projective  $k$ -variety with  $\omega_X$  or  $\omega_X^\vee$  ample. Then any point like object in  $D^b(X)$  is isomorphic to an object of the form  $k(x)[m]$ , for some closed point  $x \in X$  and some integer  $m$ .*

**Remark 8.3.16.** Above result fails if neither  $\omega_X$  nor  $\omega_X^\vee$  is ample; c.f. Example 8.3.4.

*Proof.* Note that  $X$  is projective because there is an ample line bundle on  $X$ . Clearly for any closed point  $x \in X$  and any integer  $m$ , the shifted skyscraper sheaf  $k(x)[m] \in D^b(X)$  is a point like object of codimension  $d = \dim(X)$  (c.f., Example 8.3.4).

To see the converse, let  $P \in D^b(X)$  be a point like object of codimension  $n$ . It follows from  $P \otimes \omega_X[d] \cong P[n]$  that  $n = d$  (c.f., Remark 8.3.8). Then we have,

$$(8.3.17) \quad \mathcal{H}^i(P) \otimes \omega_X \cong \mathcal{H}^i(P), \quad \forall i \in \mathbb{Z}.$$

Suppose that  $\omega_X$  is ample. Let

$$m \mapsto P_E(m) := \chi(E \otimes \omega_X^m)$$

be the Hilbert polynomial of  $E \in \mathfrak{Coh}(X)$ . Since  $\deg(P_E(m)) = \dim(\text{Supp}(E))$ , taking tensor product with  $\omega_X$  makes difference only if  $\dim(\text{Supp}(E)) > 0$ . Therefore, from (8.3.17) we conclude that  $\mathcal{H}^i(P)$  is supported in dimension zero. Since  $P$  is simple, the result follows from Lemma 8.3.14. The same argument applies for  $\omega_X^\vee$  ample.  $\square$

**8.4. Invertible objects.** Now we realize line bundles on  $X$  as objects of  $D^b(X)$ .

**Definition 8.4.1.** Let  $\mathcal{D}$  be a triangulated category together with a Serre functor  $T_{\mathcal{D}} : \mathcal{D} \rightarrow \mathcal{D}$ . An object  $L \in \mathcal{D}$  is said to be *invertible* if for each point like object  $P \in \mathcal{D}$ , there is an integer  $n_P$  (which also depends on  $L$ ) such that

$$\text{Hom}_{\mathcal{D}}(L, P[i]) = \begin{cases} k(P), & \text{if } i = n_P, \text{ and} \\ 0, & \text{otherwise.} \end{cases}$$

Next, we characterize invertible objects in  $D^b(X)$ . For this, we need the following well-known result from commutative algebra.

**Lemma 8.4.2.** *Let  $M$  be a finitely generated module over a noetherian local ring  $(A, \mathfrak{m})$ . If  $\text{Ext}^1(M, A/\mathfrak{m}) = 0$ , then  $M$  is free.*

*Proof.* Let  $k = A/\mathfrak{m}$ . Then any  $k$ -basis of  $M/\mathfrak{m}M$  lifts to a minimal set of generators for the  $A$ -module  $M$  by Nakayama lemma. Thus we get a short exact sequence of



$A$ -modules

$$0 \longrightarrow N \xrightarrow{\iota} A^n \xrightarrow{\phi} M \longrightarrow 0.$$

Note that,  $N = \text{Ker}(\phi)$  is finitely generated, and  $\iota$  induces a trivial homomorphism  $\tilde{\iota}: N/\mathfrak{m}N \longrightarrow k^n$ . Since  $\text{Ext}^1(M, k) = 0$ , the induced homomorphism

$$\text{Hom}(A^n, k) \longrightarrow \text{Hom}(N, k)$$

is surjective. Since  $\text{Hom}_A(A^n, k) \cong \text{Hom}_k(k^n, k)$  and  $\text{Hom}_A(N, k) \cong \text{Hom}_k(N/\mathfrak{m}N, k)$ , the homomorphism  $\text{Hom}_k(k^n, k) \longrightarrow \text{Hom}_k(N/\mathfrak{m}N, k)$  induced by  $\tilde{\iota}$  is surjective. Since  $\tilde{\iota} = 0$ , this forces  $N/\mathfrak{m}N = 0$ . Then  $N = 0$  by Nakayama lemma, and hence  $M$  is a free  $A$ -module.  $\square$

**Proposition 8.4.3** (Bondal–Orlov). *Let  $X$  be a smooth projective  $k$ -variety. Any invertible object in  $D^b(X)$  is of the form  $L[m]$ , for some line bundle  $L$  on  $X$  and some integer  $m$ . Conversely, if any point like object of  $D^b(X)$  is of the form  $k(x)[\ell]$ , for some closed point  $x \in X$  and some integer  $\ell$ , then for any line bundle  $L$  on  $X$  and any integer  $m$ ,  $L[m] \in D^b(X)$  is invertible.*

**Remark 8.4.4.** Note that, by Proposition 8.3.15 the condition in the converse part of the above Proposition is satisfied when  $\omega_X$  or  $\omega_X^\vee$  is ample.

*Proof of Proposition 8.4.3. Step 1.* Let  $E^\bullet \in D^b(X)$  be an invertible object. Let  $m = \max\{i \in \mathbb{Z} : \mathcal{H}^i(E^\bullet) \neq 0\}$ . Then by Proposition 8.3.5, there is a morphism

$$E^\bullet \longrightarrow \mathcal{H}^m(E^\bullet)[-m]$$

in  $D^b(X)$  inducing identity morphism at  $m$ -th cohomology  $\mathcal{H}^m(E^\bullet)$ . This gives

$$(8.4.5) \quad \text{Hom}(\mathcal{H}^m(E^\bullet), k(x_0)) = \text{Hom}_{D^b(X)}(E^\bullet, k(x_0)[-m]),$$

(c.f., Corollary 8.3.6). Fix a closed point  $x_0 \in \text{Supp}(\mathcal{H}^m(E^\bullet))$ . Then by Lemma 8.3.10, there is an associated prime ideal  $\mathfrak{p} \subseteq \mathfrak{m}_{x_0}$  and a surjective homomorphism  $\mathcal{H}^m(E^\bullet) \twoheadrightarrow \mathcal{O}_{X, x_0}/\mathfrak{p}$ , which gives a surjective homomorphism  $\mathcal{H}^m(E^\bullet) \twoheadrightarrow k(x_0)$ . Therefore, by (8.4.5), we have

$$0 \neq \text{Hom}_{D^b(X)}(\mathcal{H}^m(E^\bullet), k(x_0)) = \text{Hom}_{D^b(X)}(E^\bullet, k(x_0)[-m]).$$

This forces  $n_{k(x_0)} = -m$  (c.f., Definition 8.4.1).

**Step 2.** *We show that,  $\text{Ext}^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0$ .*

Since  $n_{k(x_0)} = -m$ , it follows from the definition of invertible object  $E^\bullet \in D^b(X)$  that

$$(8.4.6) \quad \text{Hom}(E^\bullet, k(x_0)[1 - m]) = \text{Hom}(E^\bullet, k(x_0)[1 + n_{k(x_0)}]) = 0.$$



Consider the spectral sequence (see Example 7.0.5)

$$(8.4.7) \quad E_2^{p,q} := \text{Hom}(\mathcal{H}^{-q}(E^\bullet), k(x_0)[p]) = \text{Ext}^p(\mathcal{H}^{-q}(E^\bullet), k(x_0)) \\ \implies E^{p+q} := \text{Hom}(E^\bullet, k(x_0)[p+q]).$$

Since  $\mathcal{H}^{m+1}(E^\bullet) = 0$ , we have

$$(8.4.8) \quad E_2^{3,-m-1} = \text{Hom}(\mathcal{H}^{m+1}(E^\bullet), k(x_0)[3]) = 0.$$

Also

$$(8.4.9) \quad E_2^{-1,-m+1} = \text{Hom}(\mathcal{H}^{m-1}(E^\bullet), k(x_0)[-1]) = \text{Ext}^{-1}(\mathcal{H}^{m-1}(E^\bullet), k(x_0)) = 0.$$

Now using (8.4.8) and (8.4.9), and taking  $H^0$  of the complex

$$\cdots \longrightarrow 0 = E_2^{-1,-m+1} \xrightarrow{d} E_2^{1,-m} \xrightarrow{d} E_2^{3,-m-1} = 0 \longrightarrow \cdots,$$

we see that  $E_3^{1,-m} = E_2^{1,-m}$ ; similarly,  $E_r^{1,-m} = E_2^{1,-m}$ , for all  $r \geq 2$ . The following picture of page  $E_2$  could be useful to understand the situation.

$$\begin{array}{ccccccc} & & E_2^{0,-m+1} & E_2^{1,-m+1} & E_2^{2,-m+1} & E_2^{3,-m+1} & \\ & \searrow & & & & & \\ 0 & & & & & & \\ & & E_2^{0,-m} & E_2^{1,-m} & E_2^{2,-m} & E_2^{3,-m} & \\ & \searrow & & & & & \\ 0 & & 0 & 0 & 0 & 0 & \end{array}$$

This shows that,

$$(8.4.10) \quad E_2^{1,-m} = E_\infty^{1,-m}.$$

Since  $E_\infty^{1,-m}$  is isomorphic to a subquotient of

$$(8.4.11) \quad E^{1-m} = \text{Hom}(E^\bullet, k(x_0)[1-m]) = 0$$

(see, (8.4.6) and (8.4.7)), using (8.4.10) we conclude that  $E_2^{1,-m} = 0$ . Therefore,

$$(8.4.12) \quad \text{Ext}^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0, \quad \forall x_0 \in \text{Supp}(\mathcal{H}^m(E^\bullet)).$$

**Step 3.** *We show that  $\mathcal{H}^m(E^\bullet)$  is a locally free  $\mathcal{O}_X$ -module.*

For this, we consider the *local-to-global* spectral sequence (see Example 7.0.9)

$$(8.4.13) \quad E_2^{p,q} := H^p(X, \mathcal{E}xt^q(\mathcal{H}^m(E^\bullet), k(x_0))) \implies \text{Ext}^{p+q}(\mathcal{H}^m(E^\bullet), k(x_0)),$$

which allow us to pass from the global vanishing  $\text{Ext}^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0$  to the local one  $\mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0$ .

Since  $\mathcal{E}xt^0(\mathcal{H}^m(E^\bullet), k(x_0))$  is a skyscraper sheaf supported at  $x_0$ , it is flasque, and hence is  $\Gamma$ -acyclic. Then from (8.4.13), we have

$$(8.4.14) \quad E_2^{2,0} = H^2(X, \mathcal{E}xt^0(\mathcal{H}^m(E^\bullet), k(x_0))) = 0.$$

Again,

$$(8.4.15) \quad E_2^{-2,2} = H^{-2}(X, \mathcal{E}xt^2(\mathcal{H}^m(E^\bullet), k(x_0))) = 0.$$

Since at page  $E_2$ , we have morphisms

$$0 = E_2^{-2,2} \xrightarrow{d} E_2^{0,1} \xrightarrow{d} E_2^{2,0} = 0,$$

we have  $E_3^{0,1} = \mathcal{H}^0(\cdots \rightarrow 0 \rightarrow E_2^{0,1} \rightarrow 0 \rightarrow \cdots) = E_2^{0,1}$ . Similar computations shows that  $E_r^{0,1} = E_2^{0,1}$ , for all  $r \geq 2$ . Hence we conclude that,

$$(8.4.16) \quad E_2^{0,1} = H^0(X, \mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0))) = E_\infty^{0,1}.$$

Since  $E^1 = \mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0$  by Step 2, we have  $E_2^{0,1} = E_\infty^{0,1} = 0$ . Since  $k(x_0)$  is a skyscraper sheaf supported at  $x_0$ , we see that  $\mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0))$  is supported over  $\{x_0\}$ , and hence is globally generated. Since

$$H^0(X, \mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0))) = E_2^{0,1} = 0,$$

we have  $\mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0)) = 0$ . Since  $\mathcal{H}^m(E^\bullet) \in \mathfrak{Coh}(X)$ , we have

$$(8.4.17) \quad \mathcal{E}xt_{\mathcal{O}_{X,x_0}}^1(\mathcal{H}^m(E^\bullet), k(x_0)) = \mathcal{E}xt^1(\mathcal{H}^m(E^\bullet), k(x_0))_{x_0} = 0.$$

The by Lemma 8.4.2,  $\mathcal{H}^m(E^\bullet)_{x_0}$  is free  $\mathcal{O}_{X,x_0}$ -module. Since freeness is an open property, there is a non-empty open (dense) subset  $U$  of  $X$  containing  $x_0$  such that  $U \subseteq \text{Supp}(\mathcal{H}^m(E^\bullet))$  and  $\mathcal{H}^m(E^\bullet)|_U$  is a free  $\mathcal{O}_U$ -module. Since  $X$  is irreducible,  $\mathcal{H}^m(E^\bullet)$  is locally free on  $X$ .

**Step 4.** *We show that,  $\mathcal{H}^m(E^\bullet)$  is a line bundle on  $X$ .*

Since  $\text{Supp}(\mathcal{H}^m(E^\bullet)) = X$ , there is a surjective homomorphism  $\mathcal{H}^m(E^\bullet) \twoheadrightarrow k(x)$ , for each  $x \in X$ . Then following argument of Step 1, we have

$$(8.4.18) \quad \text{Hom}(E^\bullet, k(x)[-m]) = \text{Hom}(\mathcal{H}^m(E^\bullet), k(x)) \neq 0, \quad \forall x \in X.$$

Now it follows from Definition 8.4.1 of invertible objects that

$$(8.4.19) \quad n_{k(x)} = -m, \quad \forall x \in X.$$

If  $r$  is the rank of  $\mathcal{H}^m(E^\bullet)$ , we have

$$(8.4.20) \quad \begin{aligned} k(x) &= \text{Hom}(E^\bullet, k(x)[-m]) = \text{Hom}(\mathcal{H}^m(E^\bullet), k(x)) \\ &= \text{Hom}(\mathcal{O}_{X,x}^{\oplus r}, k(x)) \cong k(x)^{\oplus r}. \end{aligned}$$

Therefore,  $r = 1$ , and hence  $\mathcal{H}^m(E^\bullet)$  is a line bundle on  $X$ .

**Step 5.** *We show that,  $\mathcal{H}^i(E^\bullet) = 0$ , for all  $i < m$ .*

From the spectral sequence in (8.4.7), we have

$$(8.4.21) \quad \begin{aligned} E_2^{q,-m} &= \text{Hom}(\mathcal{H}^m(E^\bullet), k(x)[q]) \\ &= \text{Ext}^q(\mathcal{H}^m(E^\bullet), k(x)) \\ &\cong H^q(X, \mathcal{H}om(\mathcal{H}^m(E^\bullet), k(x))) = 0, \quad \forall q > 0, \end{aligned}$$

because  $\mathcal{H}om(\mathcal{H}^m(E^\bullet), k(x))$  is a skyscraper sheaf supported on  $\{x\}$ , and hence is  $\Gamma$ -acyclic.

Suppose that  $i < m$ . Then it follows from Definition 8.4.1 and (8.4.19) that

$$(8.4.22) \quad E^{-i} = \text{Hom}(E^\bullet, k(x)[-i]) = 0, \quad \forall x \in X.$$

Now to show  $\mathcal{H}^i(E^\bullet) = 0$ , it is enough to show that

$$(8.4.23) \quad E_2^{0,-i} = \text{Hom}(\mathcal{H}^i(E^\bullet), k(x)) = 0, \quad \forall x \in X.$$

Since  $E^{-i} = 0$ , if we can show that

$$(8.4.24) \quad E_2^{0,-i} = E_\infty^{0,-i},$$

then from the spectral sequence (8.4.7) we would get  $E_2^{0,-i} = 0$ . We prove this by induction on  $i$ .

If  $i = m - 1$ , then  $E_2^{2,-i-1} = E_2^{2,-m} = 0$  by (8.4.21). Since negative indexed Ext groups between two coherent sheaves are zero, we have  $E_2^{-2,-(m-2)} = 0$ . Then (8.4.24), for the case  $i = m - 1$ , follows from the complex

$$\cdots \rightarrow 0 = E_2^{-2,-(m-2)} \xrightarrow{d} E_2^{0,1-m} \xrightarrow{d} E_2^{2,-m} = 0 \rightarrow \cdots.$$

Therefore,  $\mathcal{H}^{m-1}(E^\bullet) = 0$ . Assume inductively that  $\mathcal{H}^i(E^\bullet) = 0$ , for all  $i \in \mathbb{Z}$ , with  $i_0 < i \leq m - 1$ . Then putting  $m = i_0 + 1$  in (8.4.21) and using  $\mathcal{H}^{i_0+1}(E^\bullet) = 0$ , we have  $E_2^{2,-i_0-1} = 0$ . Then (8.4.24) follows from the complex

$$\cdots \rightarrow 0 = E_2^{-2,1-i_0} \xrightarrow{d} E_2^{0,-i_0} \xrightarrow{d} E_2^{2,-i_0-1} = 0 \rightarrow \cdots.$$

This completes induction. Therefore,  $\mathcal{H}^i(E^\bullet) = 0$ ,  $\forall i < m$ , and hence for all  $i \neq m$ .

**Step 6.** Now we prove converse part of the Proposition 8.4.3. Suppose that any point like object  $P \in D^b(X)$  is of the form  $k(x)[\ell]$ , for some closed point  $x \in X$  and  $\ell \in \mathbb{Z}$ . Let  $L$  be a line bundle on  $X$ , and  $m \in \mathbb{Z}$ . Then from Definition 8.4.1 we get

$$(8.4.25) \quad \begin{aligned} \text{Hom}(L[m], P[i]) &\cong \text{Hom}(L, k(x)[\ell + i - m]) \\ &= \text{Ext}^{\ell+i-m}(\mathcal{O}_X, L^\vee \otimes k(x)) \\ &\cong H^{\ell+i-m}(X, L^\vee \otimes k(x)), \end{aligned}$$

which vanishes except for  $i = m - \ell$ . Then we set  $n_P := m - \ell$ . This completes the proof.  $\square$

**Remark 8.4.26.** Let  $\mathcal{D}$  be a (tensor) triangulated category admitting a Serre functor  $S$ . If we naively define *Picard group* of  $\mathcal{D}$  to be the set  $\text{Pic}(\mathcal{D})$  of all invertible objects in  $\mathcal{D}$ , then for a smooth projective  $k$ -variety  $X$  with  $\omega_X$  or  $\omega_X^\vee$  ample, we have  $\text{Pic}(D^b(X)) = \text{Pic}(X) \times \mathbb{Z}$ .

### 8.5. Spanning class of $D^b(X)$ .

**Definition 8.5.1.** A collection  $\Omega$  of objects in a triangulated category  $\mathcal{D}$  is called a *spanning class of  $\mathcal{D}$*  (or *spans  $\mathcal{D}$* ) if for all  $B \in \mathcal{D}$  the following conditions hold.

- (i) If  $\text{Hom}(A, B[i]) = 0$ ,  $\forall A \in \Omega$  and all  $i \in \mathbb{Z}$ , then  $B \cong 0$ .
- (ii) If  $\text{Hom}(B[i], A) = 0$ ,  $\forall A \in \Omega$  and all  $i \in \mathbb{Z}$ , then  $B \cong 0$ .

**Remark 8.5.2.** If a triangulated category  $\mathcal{D}$  admits a Serre functor, then the conditions (i) and (ii) in the above Definition 8.5.1 are equivalent.

**Proposition 8.5.3.** *Let  $X$  be a smooth projective  $k$ -variety. Then the objects of the form  $k(x)$ , with  $x \in X$  a closed point, spans  $D^b(X)$ .*

*Proof.* It is enough to show that, for any non-zero object  $E^\bullet \in D^b(X)$  there exists closed points  $x_1, x_2 \in X$  and integers  $i_1, i_2$  such that

$$\text{Hom}(E^\bullet, k(x_1)[i_1]) \neq 0 \quad \text{and} \quad \text{Hom}(k(x_2), E^\bullet[i_2]) \neq 0.$$

Since  $\text{Hom}(k(x_2), E^\bullet[i_2]) \cong \text{Hom}(E^\bullet, k(x_2)[\dim(X) - i_2])^*$  by Serre duality, it is enough to show that  $\text{Hom}(E^\bullet, k(x_1)[i_1]) \neq 0$ , for some closed point  $x \in X$  and some  $i \in \mathbb{Z}$ . Let  $m := \max\{i \in \mathbb{Z} : \mathcal{H}^i(E^\bullet) \neq 0\}$ . Then  $\text{Hom}(E^\bullet, k(x)[-m]) = \text{Hom}(\mathcal{H}^m(E^\bullet), k(x))$  by Corollary 8.3.6. Now choosing a closed point  $x$  in the support of  $\mathcal{H}^m(E^\bullet)$ , we see that  $\text{Hom}(E^\bullet, k(x)[-m]) \neq 0$ . This completes the proof.  $\square$

**Remark 8.5.4.** Spanning class in  $D^b(X)$  is not unique. For a smooth projective  $k$ -variety  $X$ , for a choice of an ample line bundle  $L$  on  $X$ , we shall see later that,  $\{L^{\otimes i} : i \in \mathbb{Z}\}$  forms a spanning class in  $D^b(X)$ .

**8.6. Proof of the reconstruction theorem.** Now we are in a position to prove the reconstruction theorem of Bondal and Orlov in the light of the following well-known results.

**Proposition 8.6.1.** [Sta20, Tag01PR] *Let  $X$  be a quasi-compact scheme. Let  $L$  be an invertible sheaf of  $\mathcal{O}_X$ -modules on  $X$ . Consider the graded algebra  $S := \bigoplus_{i \geq 0} H^0(X, L^i)$ , and its ideal  $S_+ = \bigoplus_{i > 0} H^0(X, L^i)$ . For each homogeneous element  $s \in H^0(X, L^i)$ , for  $i > 0$ , let  $X_s := \{x \in X : s_x \notin \mathfrak{m}_x L_x^i\}$ . Then the following are equivalent.*

- (i)  $L$  is ample.
- (ii) The collection of open sets  $X_s$ , with  $s \in S_+$  homogeneous, covers  $X$ , and the natural morphism  $X \rightarrow \mathbf{Proj}(S)$  is an open immersion.
- (iii) The collection of open sets  $X_s$ , with  $s \in S_+$  homogeneous, forms a basis for the Zariski topology on  $X$ .

**Proposition 8.6.2.** *Let  $X$  be a smooth projective  $k$ -variety. Let  $L$  be a line bundle on  $X$ . If  $L$  or  $L^\vee$  is ample, then the natural morphism of  $k$ -schemes*

$$X \longrightarrow \mathbf{Proj} \left( \bigoplus_n H^0(X, L^n) \right)$$

*is an isomorphism.*

**Theorem 8.1.1** (Bondal–Orlov). *Let  $X$  be a smooth projective variety over  $k$  with canonical line bundle  $\omega_X$ . Assume that  $\omega_X$  (resp.,  $\omega_X^\vee$ ) is ample. Let  $Y$  be any smooth projective variety over  $k$ . If there is an exact equivalence  $F : D^b(X) \xrightarrow{\sim} D^b(Y)$ , then  $X \cong Y$  as  $k$ -varieties. In particular,  $\omega_Y$  (resp.,  $\omega_Y^\vee$ ) is ample.*

*Proof. Step 1. If  $F(\mathcal{O}_X) = \mathcal{O}_Y$ , and  $\omega_Y$  or  $\omega_Y^\vee$  is ample, the theorem follows.*

Indeed, assume that  $F(\mathcal{O}_X) = \mathcal{O}_Y$ . Since  $F$  is an exact equivalence of categories,  $F \circ S_X \cong S_Y \circ F$  and  $\dim(X) = \dim(Y) = n$  (say), (see Proposition 8.2.1). Then we have

$$(8.6.3) \quad F(\omega_X^k) = F(S_X^k(\mathcal{O}_X))[-kn] = S_Y^k(\mathcal{O}_Y)[-kn] = \omega_Y^k, \quad \forall k.$$

Since  $F$  is fully faithful, we have

$$(8.6.4) \quad H^0(X, \omega_X^k) = \mathrm{Hom}(\mathcal{O}_X, \omega_X^k) = \mathrm{Hom}(\mathcal{O}_Y, \omega_Y^k) = H^0(Y, \omega_Y^k), \quad \forall k.$$

The product structure on the graded  $k$ -algebra  $\bigoplus_k H^0(X, \omega_X^k)$  can be expressed in terms of following composition: for  $s_i \in H^0(X, \omega_X^{k_i})$ ,  $i = 1, 2$ , we have

$$s_1 \cdot s_2 = S_X^{k_1}(s_2)[-k_1n] \circ s_1.$$

Note that,  $s_1 \cdot s_2 = s_2 \cdot s_1$  follows from the commutativity of the following diagram.

$$(8.6.5) \quad \begin{array}{ccc} \mathcal{O}_X & \xrightarrow{s_1} & \omega_X^{k_1} \\ s_2 \downarrow & & \downarrow S_X^{k_1}(s_2)[-k_1n] \\ \omega_X^{k_2} & \xrightarrow{S_X^{k_2}(s_1)[-k_2n]} & \omega_X^{k_1+k_2} \end{array}$$

Similarly, we have product structure on  $\bigoplus_k H^0(Y, \omega_Y^k)$ . Therefore,  $F$  naturally induces an isomorphism of graded  $k$ -algebras

$$(8.6.6) \quad \tilde{F} : \bigoplus_k H^0(X, \omega_X^k) \longrightarrow \bigoplus_k H^0(Y, \omega_Y^k),$$

which induces isomorphism of  $k$ -schemes

$$(8.6.7) \quad X \xrightarrow{\cong} \mathbf{Proj} \left( \bigoplus_k H^0(X, \omega_X^k) \right) \xrightarrow{\cong} \mathbf{Proj} \left( \bigoplus_k H^0(Y, \omega_Y^k) \right) \xrightarrow{\cong} Y,$$

whenever  $\omega_Y$  or its dual  $\omega_Y^\vee$  is ample (c.f., Proposition 8.6.2). Therefore, it is enough to show that  $F(\mathcal{O}_X) = \mathcal{O}_Y$ , and  $\omega_Y$  or  $\omega_Y^\vee$  is ample whenever  $\omega_X$  or  $\omega_X^\vee$  is ample.

**Step 2.** We can assume that  $F(\mathcal{O}_X) = \mathcal{O}_Y$ .

Indeed, it follows from Definition 8.3.3 and Definition 8.4.1 that an exact equivalence  $F : D^b(X) \rightarrow D^b(Y)$  induce bijections

$$(8.6.8) \quad \begin{array}{ccc} \{\text{point like objects of } D^b(X)\} & \xrightarrow[\simeq]{F} & \{\text{point like objects of } D^b(Y)\} \\ \parallel & & \uparrow (*) \\ \{k(x)[m] : x \in X_{\text{closed}} \text{ and } m \in \mathbb{Z}\} & & \{k(y)[m] : y \in Y_{\text{closed}} \text{ and } m \in \mathbb{Z}\} \end{array}$$

and

$$(8.6.9) \quad \begin{array}{ccc} \{\text{invertible objects of } D^b(X)\} & \xrightarrow[\simeq]{F} & \{\text{invertible objects of } D^b(Y)\} \\ \parallel & & \downarrow (**) \\ \{L[m] : L \in \text{Pic}(X) \text{ and } m \in \mathbb{Z}\} & & \{M[m] : M \in \text{Pic}(Y) \text{ and } m \in \mathbb{Z}\}, \end{array}$$

where  $X_{\text{closed}}$  (resp.,  $Y_{\text{closed}}$ ) is the set of all closed points of  $X$  (resp.,  $Y$ ), and the vertical inclusions and equalities are given by Proposition 8.3.15 and Proposition 8.4.3. Therefore,  $F(\mathcal{O}_X) = M[m]$ , for some  $M \in \text{Pic}(Y)$  and some  $m \in \mathbb{Z}$ .

If  $F(\mathcal{O}_X) \neq \mathcal{O}_Y$ , replacing  $F$  with the following composite functor

$$(8.6.10) \quad D^b(X) \xrightarrow{F} D^b(Y) \xrightarrow{(M^\vee \otimes -)[-m]} D^b(Y),$$

which is an exact equivalence sending  $\mathcal{O}_X$  to  $\mathcal{O}_Y$ , we may assume that  $F(\mathcal{O}_X) = \mathcal{O}_Y$ . Therefore, it remains to show is that  $\omega_Y$  or its dual is ample.

**Step 3.** We establish bijections  $X_{\text{closed}} \xleftarrow{F} Y_{\text{closed}}$  and  $\text{Pic}(X) \xleftarrow{F} \text{Pic}(Y)$ .

Using the equivalence  $F$ , we first show that the vertical inclusion  $(*)$  in the diagram (8.6.8) is a bijection. This immediately imply that the vertical inclusion  $(**)$  in the diagram (8.6.9) is bijective by Proposition 8.4.3. Then Step 3 will follow.

By horizontal bijection in the diagram (8.6.8), for any closed point  $y \in Y$  there is a closed point  $x_y \in X$  and  $m_y \in \mathbb{Z}$  such that  $F(k(x_y)[m_y]) \cong k(y)$ . Suppose on the contrary that there is a point like object  $P \in D^b(Y)$ , which is not of the form  $k(y)[m]$ , for any closed point  $y \in Y$  and integer  $m$ . Because of bijection in (8.6.8), there is a unique closed point  $x_P \in X$  and integer  $m_P$  such that  $F(k(x_P)[m_P]) \cong P$ . Then  $x_P \neq x_y$ , for all closed point  $y \in Y$ . Hence, for any closed point  $y \in Y$  and any integer  $m$ , we have

$$(8.6.11) \quad \begin{aligned} \text{Hom}(P, k(y)[m]) &= \text{Hom}(F(k(x_P)[m_P]), k(y)[m]) \\ &= \text{Hom}(k(x_P)[m_P], k(x_y)[m_y + m]) \\ &= \text{Hom}(k(x_P), k(x_y)[m_y + m - m_P]) = 0, \end{aligned}$$

because  $k(x_P)$  and  $k(x_y)$  being skyscraper sheaves supported at different points,  $\text{Ext}^i(k(x_P), k(x_y)) = 0$ , for all  $i$ . Since the objects  $k(y)$ , with  $y \in Y$  a closed point, form a spanning class of  $D^b(X)$  (c.f. Definition 8.5.1),  $P \cong 0$  by Proposition 8.5.3, which contradicts our assumption that  $P$  is a point like object in  $D^b(Y)$ . Therefore, point like objects of  $D^b(Y)$  are exactly of the form  $k(y)[m]$ , for  $y \in Y$  a closed point and  $m \in \mathbb{Z}$ .

Note that, for any closed point  $x \in X$ , there is a closed point  $y_x \in Y$  such that  $F(k(x)) \cong k(y_x)[m_x]$ , for some  $m_x \in \mathbb{Z}$ . Since  $F$  is fully faithful and  $F(\mathcal{O}_X) = \mathcal{O}_Y$ , we have  $\text{Hom}(\mathcal{O}_X, k(x)) = \text{Hom}(\mathcal{O}_Y, k(y_x)[m_x]) = \text{Ext}^{m_x}(\mathcal{O}_Y, k(y_x)) \neq 0$ . This forces  $m_x = 0$ , and hence  $F(k(x)) \cong k(y_x)$  (no shift!). This immediately imply that, for any  $L \in \text{Pic}(X)$ ,  $F(L) \cong M$ , for some  $M \in \text{Pic}(Y)$ . Indeed, from bijections in the diagram (8.6.9), we find unique  $M \in \text{Pic}(Y)$  and  $m_L \in \mathbb{Z}$  such that  $F(L) \cong M[m_L]$ . Take closed points  $x \in X$  and  $y_x \in Y$  such that  $F(k(x)) \cong k(y_x)$ . Then

$$\begin{aligned} \text{Ext}^{-m_L}(M, k(y_x)) &= \text{Hom}(M, k(y_x)[-m_L]) = \text{Hom}(M[m_L], k(y_x)) \\ &= \text{Hom}(F(L), F(k(x))) = \text{Hom}(L, k(x)) \neq 0. \end{aligned}$$

This forces  $m_L = 0$ .

#### Step 4. Recovering Zariski topology from derived category to conclude ampleness.

Let  $Z$  be a quasi-compact  $k$ -scheme. Denote by  $Z_0$  the subset of all closed points of  $Z$ . Take line bundles  $L_1$  and  $L_2$  on  $Z$ , and take  $\alpha \in \text{Hom}(L_1, L_2) = H^0(X, L_1^\vee \otimes L_2)$ . For each closed point  $z \in Z$ , let

$$(8.6.12) \quad \alpha_z^* : \text{Hom}(L_2, k(z)) \longrightarrow \text{Hom}(L_1, k(z))$$

be the homomorphism induced by  $\alpha$ . Then  $U_\alpha := \{z \in Z : \alpha_z^* \neq 0\}$  is a Zariski open subset of  $Z$ , and hence  $U_\alpha \cap Z$  is open in  $Z_0$ .

Fix a line bundle  $L_0 \in \text{Pic}(X)$ . Then it follows from Proposition 8.6.1 that the collection of all such  $U_\alpha$ , where  $\alpha \in H^0(X, L_0^n)$  and  $n \in \mathbb{Z}$ , forms a basis for the Zariski topology on  $Z$  if and only if either  $L_0$  or  $L_0^\vee$  is ample.

By Step 3, the exact equivalence  $F : D^b(X) \longrightarrow D^b(Y)$  sends closed points of  $X$  to closed points of  $Y$  bijectively, and sends line bundles on  $X$  to line bundles on  $Y$  bijectively. In particular,  $F(\omega_X^i) \cong \omega_Y^i$ , for all  $i \in \mathbb{Z}$ . Then the natural isomorphisms  $H^0(X, \omega_X^i) \cong H^0(Y, \omega_Y^i)$ ,  $\forall i \in \mathbb{Z}$ , give rise to a bijection between the collection of open subsets

$$\begin{aligned} \mathcal{B}_X &:= \{U_\alpha : \alpha \in H^0(X, \omega_X^i) \text{ and } i > 0 \text{ (resp., } i < 0)\}, \text{ and} \\ \mathcal{B}_Y &:= \{V_\alpha : \alpha \in H^0(Y, \omega_Y^i) \text{ and } i > 0 \text{ (resp., } i < 0)\}. \end{aligned}$$

Since  $\omega_X$  (resp.,  $\omega_X^\vee$ ) is ample,  $\mathcal{B}_X$  is a basis for the Zariski topology on  $X$ , and hence  $\mathcal{B}_{X_0} := \{U_\alpha \cap X_0 : \alpha \in H^0(X, \omega_X^i) \text{ and } i > 0 \text{ (resp., } i < 0)\}$  is a basis for the Zariski



topology on  $X_0$ . Therefore,  $\mathcal{B}_{Y_0} := \{V_\alpha \cap Y_0 : \alpha \in H^0(Y, \omega_Y^i) \text{ and } i > 0 \text{ (resp., } i < 0)\}$  is a basis for the Zariski topology on  $Y_0$ , and hence  $\mathcal{B}_Y$  is a basis for the Zariski topology on  $Y$  (see Lemma 8.6.13 below). Therefore,  $\omega_Y$  (resp.,  $\omega_Y^\vee$ ) is ample. This completes the proof.  $\square$

I thank Arideep Saha for useful discussion leading to the following Lemma.

**Lemma 8.6.13.** *Let  $X$  be a scheme locally of finite type over  $\text{Spec}(\mathbb{k})$ , where  $\mathbb{k}$  is a field or  $\mathbb{Z}$ . Let  $X_0$  be a subset of  $X$  containing all closed points of  $X$ . Let  $\mathcal{B}_X := \{U_\alpha : \alpha \in \Lambda\}$  be a collection of open subsets of  $X$  such that  $\mathcal{B}_{X_0} := \{U_\alpha \cap X_0 : \alpha \in \Lambda\}$  is a basis for the subspace Zariski topology on  $X_0$ . Then  $\mathcal{B}$  is a basis for the Zariski topology on  $X$ .*

*Proof. Step 1.* First we show that, *if an open set  $U \subset X$  contains a closed point  $x_0$ , then for any point  $x \in X$  which contains  $x_0$  in its closure (i.e.,  $x_0 \in \overline{\{x\}}$ ), we have  $x \in U$ .* Since  $\mathcal{B}_{X_0}$  is a basis, there is  $\alpha \in \Lambda$  such that  $x_0 \in U_\alpha \cap X_0 \subseteq U \cap X_0$ . If  $x \notin U_\alpha$ , then  $x$  belongs to the closed set  $X \setminus U_\alpha$ , and hence  $\overline{\{x\}} \subseteq X \setminus U_\alpha$ , which contradicts the assumption that  $x_0 \in \overline{\{x\}}$ . Therefore,  $x \in U_\alpha$ . Since closure of any point in  $X$  contains a closed point, it follows that  $\mathcal{B}_X$  is an open cover for  $X$ .

It remains to show that for  $x \in U_\alpha \cap U_\beta$ , there is  $\gamma \in \Lambda$  such that  $x \in U_\gamma \subseteq U_\alpha \cap U_\beta$ .

**Step 2.** Assume that, *for any open subset  $U$  of  $X$  with  $x \in U$ , there is a closed point  $x_0 \in \overline{\{x\}} \cap U$ .* For then, taking  $U = U_\alpha \cap U_\beta$ , we can find a  $\gamma \in \Lambda$  such that

$$x_0 \in U_\gamma \cap X_0 \subseteq U_\alpha \cap U_\beta \cap X_0.$$

Then we will have  $U_\gamma \subseteq U_\alpha \cap U_\beta$ . Indeed, for each  $z \in U_\gamma$ , by *above assumption* there is a closed point  $z_0 \in \overline{\{z\}} \cap U_\alpha \cap U_\beta$ . Then by **Step 1**, we have  $z \in U_\alpha \cap U_\beta$ .

**Step 3.** We now prove the *assumption* of Step 2. Since the statement is local, we may assume that  $X = \text{Spec}(A)$ , for some finitely generated  $\mathbb{k}$ -algebra  $A$ . For each  $f \in A$ , let  $D_f := \{\mathfrak{q} \in \text{Spec}(A) : f \notin \mathfrak{q}\}$ . Since  $\{D_f : f \in A\}$  forms a basis for the Zariski topology on  $\text{Spec}(A)$ , any point  $\mathfrak{p} \in \text{Spec}(A)$  is contained in  $D_f$ , for some  $f \in A \setminus \{0\}$ . We claim that, there is a closed point (maximal ideal)  $\mathfrak{m} \in D_f$  with  $\mathfrak{p} \subset \mathfrak{m}$ . If not, then all closed points (maximal ideal)  $\mathfrak{m} \in \text{Max}(A/\mathfrak{p}) \subset \text{Spec}(A/\mathfrak{p})$  lies outside  $D_f$ . Since  $A/\mathfrak{p}$  is a finitely generated  $\mathbb{k}$ -algebra, we have

$$\text{Jac}(A/\mathfrak{p}) = \bigcap_{\mathfrak{m} \in \text{Max}(A/\mathfrak{p})} \mathfrak{m} = \bigcap_{\mathfrak{q} \in \text{Spec}(A/\mathfrak{p})} \mathfrak{q} = \text{Nil}(A/\mathfrak{p}),$$

which is zero because  $A/\mathfrak{p}$  is an integral domain. This contradicts the fact that  $f \neq 0$  in  $A/\mathfrak{p}$ . This completes the proof.  $\square$

Although we don't need full strength of the following Lemma 8.6.14 here, let me mention it here since it can be useful in may purpose. I thank Saurav Bhaumik for explaining it to me.



**Lemma 8.6.14.** *Any polarized reduced projective scheme locally of finite type over a field can be reconstructed from its set of closed points.*

*Proof.* Let  $X$  be a reduced projective  $k$ -scheme, which is locally of finite type over  $\text{Spec}(k)$ . If  $\mathcal{I}_X \subset \mathcal{O}_{\mathbb{P}_k^n}$  is the ideal sheaf of a closed embedding  $\iota : X \hookrightarrow \mathbb{P}_k^n$ , for some integer  $n \geq 1$ , then  $X \cong \text{Proj}(S/I)$ , where  $I := \bigoplus_{i \geq 0} H^0(\mathbb{P}_k^n, \mathcal{I}_X(i))$  is the homogeneous ideal of the graded  $k$ -algebra  $S := k[x_0, \dots, x_n]$ . Therefore, it suffices to show that,  $I$  coincides with the ideal of homogeneous polynomials in  $S$  vanishing at each closed point of  $X$ . It follows from the exact sequence

$$0 \longrightarrow H^0(\mathbb{P}_k^n, \mathcal{I}_X(i)) \longrightarrow H^0(\mathbb{P}_k^n, \mathcal{O}_X(i)) \longrightarrow H^0(X, \mathcal{O}_X(i))$$

that  $H^0(\mathbb{P}_k^n, \mathcal{I}_X(i))$  can be identified with the set of all homogeneous polynomials of degree  $i$  in  $S$  that vanishes at each point of  $X$ . Therefore, it suffices to show that, if  $X$  is a finite type reduced  $k$ -subscheme of a  $k$ -scheme  $\tilde{X}$ , a section  $s \in H^0(\tilde{X}, L)$  of a line bundle  $L$  on  $\tilde{X}$  vanishes at every closed points of  $X$  if and only if  $s|_X = 0$ . This can be checked locally. Take an affine open subset  $U = \text{Spec}(A)$  of  $X$  such that  $L|_U$  is trivial. Then  $s|_U$  is given by an element  $f \in A$ . Since  $s$  vanishes at every closed points of  $X$ ,  $f \in \text{Jac}(A)$ . Since  $X$  is locally of finite type over  $\text{Spec}(k)$ ,  $\text{Jac}(A) = \text{Nil}(A)$ , which is zero because  $X$  is reduced. Therefore,  $f = 0$ , and hence  $s|_X = 0$ . Hence the result follows.  $\square$

**Remark 8.6.15.** There is a more geometric proof of ampleness of  $\omega_Y$  or its dual in Theorem 8.1.1 when  $k$  is algebraically closed. The idea is to use the fact that line bundle is very ample if and only if it separates points and tangent vectors.

*Alternative proof of ampleness of  $\omega_Y$  or its dual, for  $k = \bar{k}$ .* In this subsection, we assume that  $k$  is algebraically closed. Let  $X$  be a projective  $k$ -scheme.

**Definition 8.6.16.** An invertible sheaf of  $\mathcal{O}_X$ -modules  $L$  on  $X$  is said to be *very ample* if there is a closed embedding  $\iota : X \hookrightarrow \mathbb{P}_k^n$ , for some  $n \geq 1$ , such that  $L \cong \iota^*(\mathcal{O}_{\mathbb{P}_k^n}(1))$ .

It should be noted that, an invertible sheaf  $L$  on  $X$  is ample if and only if  $L^m$  is very ample, for some integer  $m \gg 0$ ; [Har77].

**Definition 8.6.17.** Let  $L$  be an invertible sheaf of  $\mathcal{O}_X$ -modules on  $X$ . We say that,

- (i)  $L$  *separates points* if for any two closed points  $p, q \in X$ , there is a section  $s \in H^0(X, L)$  such that  $s_p \in \mathfrak{m}_p L_p$  and  $s_q \notin \mathfrak{m}_q L_q$ .
- (ii)  $L$  *separates tangent vectors* if for any closed point  $p \in X$  and any tangent vector  $v \in T_p X = (\mathfrak{m}_p / \mathfrak{m}_p^2)^*$ , there is a non-zero section  $s \in H^0(X, L)$  such that  $s_p \in \mathfrak{m}_p L_p$  and  $v \notin T_p V$ , where  $V$  is the divisor of zero locus of  $s$ .

Note that, an invertible sheaf  $L$  on  $X$  separate tangent vectors if and only if for each closed point  $x \in X$ , the set  $\{s \in H^0(X, L) : s_x \in \mathfrak{m}_x L_x\}$  spans the  $k$ -vector space  $L_x \otimes (\mathfrak{m}_x / \mathfrak{m}_x^2)$ .

**Theorem 8.6.18.** [Har77, Proposition II.7.3] *Let  $X$  be a projective  $k$ -scheme. An invertible sheaf of  $\mathcal{O}_X$ -modules on  $X$  is very ample if and only if it separate points and tangent vectors.*

Continuing with above notations, it follows from the Definition 8.6.17 that  $L \in \text{Pic}(X)$  separates points if and only if for any two closed points  $x_1, x_2 \in X$  with  $x_1 \neq x_2$ , the restriction homomorphism (to the fibers)

$$(8.6.19) \quad r_{x_1, x_2} : L \longrightarrow (L \otimes k(x_1)) \oplus (L \otimes k(x_2)) \cong k(x_1) \oplus k(x_2)$$

induces a surjective homomorphism

$$(8.6.20) \quad H^0(r_{x_1, x_2}) : H^0(X, L) \longrightarrow H^0(X, k(x_1) \oplus k(x_2)).$$

Let  $Y$  be a smooth projective  $k$ -variety, and  $F : D^b(X) \longrightarrow D^b(Y)$  be an exact equivalence of  $k$ -linear graded categories. Then we have the following commutative diagram

$$(8.6.21) \quad \begin{array}{ccc} H^0(X, \omega_X^i) & \xrightarrow{H^0(r_{x_1, x_2})} & H^0(X, k(x_1) \oplus k(x_2)) \\ F \downarrow \cong & & \cong \downarrow F \\ H^0(Y, \omega_Y^i) & \xrightarrow{H^0(r_{y_1, y_2})} & H^0(Y, k(y_1) \oplus k(y_2)) \end{array}$$

where  $y_j \in Y$  is the closed point such that  $F(k(x_j)) = k(y_j)$ , for all  $j = 1, 2$ . Therefore,  $\omega_X^i$  separates points if and only if  $\omega_Y^i$  separates points.

To see  $\omega_Y^i$  separates tangent vectors if and only if  $\omega_X^i$  do the same, first we need the following observation.

**Lemma 8.6.22.** *Let  $X$  be a scheme over any field  $k$ . To give a point  $x \in X$  with residue field  $k(x) = k$  and a tangent vector  $v \in T_x X = (\mathfrak{m}_x / \mathfrak{m}_x^2)^*$  is equivalent to give a subscheme  $Z_x \subset X$ , supported at  $x$ , of length 2 (i.e.,  $\dim_k H^0(Z_x, \mathcal{O}_{Z_x}) = 2$ ).*

Let  $Z_y \subset Y$  be a subscheme of length 2 supported at a closed point  $y \in Y$ . Then we have an exact sequence

$$(8.6.23) \quad 0 \longrightarrow k(y) \longrightarrow \mathcal{O}_{Z_y} \longrightarrow k(y) \longrightarrow 0.$$

Therefore,  $Z_y$  is given by a non-trivial extension class

$$(8.6.24) \quad \Phi_{Z_y} \in \text{Ext}^1(k(y), k(y)).$$

Since  $F$  is fully faithful,  $\Phi_{Z_y} \in \text{Ext}^1(k(y), k(y))$  corresponds to a non-trivial extension class

$$(8.6.25) \quad F(\Phi_{Z_y}) \in \text{Ext}^1(k(x_y), k(x_y)),$$

where  $x_y \in X$  is the closed point satisfying  $F(k(x_y)) = k(y)$ . Then  $F(\Phi_{Z_y})$  defines a subscheme  $Z_x \subset X$  of length 2 supported at  $x \in X$ . Therefore,  $F(\mathcal{O}_{Z_x}) = \mathcal{O}_{Z_y}$ . Moreover,  $F$  gives an isomorphism

$$F : \operatorname{Hom}(\omega_X^i, \mathcal{O}_{Z_x}) \xrightarrow{\simeq} \operatorname{Hom}(\omega_Y^i, \mathcal{O}_{Z_y}).$$

It follows from the Lemma 8.6.22 that a line bundle  $L$  on  $X$  separate tangent vectors if and only if the homomorphism (induced by the restriction morphism)

$$(8.6.26) \quad H^0(X, L) \longrightarrow H^0(X, \mathcal{O}_{Z_x})$$

is surjective. Now it follows from the commutative diagram

$$(8.6.27) \quad \begin{array}{ccc} H^0(X, \omega_X^i) & \longrightarrow & H^0(X, \mathcal{O}_{Z_x}) \\ F \downarrow \simeq & & \simeq \downarrow F \\ H^0(Y, \omega_Y^i) & \longrightarrow & H^0(Y, \mathcal{O}_{Z_y}) \end{array}$$

that  $\omega_X^i$  separate tangent vectors if and only if  $\omega_Y^i$  separate tangent vectors. Hence,  $\omega_X$  (resp.,  $\omega_X^\vee$ ) is ample if and only if  $\omega_Y^i$  (resp.,  $\omega_Y^\vee$ ) is ample.

## 8.7. Auto equivalence of derived category.

### 9. FOURIER-MUKAI TRANSFORMS

**9.1. Integral functor.** Let  $X$  and  $Y$  be smooth projective schemes defined over a field  $k$ . Consider the two projections

$$(9.1.1) \quad p_X : X \times Y \longrightarrow X \quad \text{and} \quad p_Y : X \times Y \longrightarrow Y.$$

**Definition 9.1.2.** An *integral functor* with kernel  $P \in D^b(X \times Y)$  is a functor

$$(9.1.3) \quad \Phi_P^{X \rightarrow Y} : D^b(X) \longrightarrow D^b(Y)$$

defined by

$$\Phi_P^{X \rightarrow Y}(E) := p_{Y*}(p_X^*E \otimes P), \quad \forall E \in D^b(X);$$

where  $p_{Y*}$ ,  $p_X^*$  and  $\otimes$  are derived functors.

When there is no confusion regarding the direction of the functor likely to arise, we just drop the superscript  $X \rightarrow Y$  from  $\Phi_P^{X \rightarrow Y}$ , and simply denote it by  $\Phi_P$ . An integral functor  $\Phi_P$ , which is an equivalence of categories, is called a *Fourier-Mukai functor* with kernel  $P$ . We say that  $X$  and  $Y$  are *Fourier-Mukai partner* if there is a Fourier-Mukai transform  $\Phi_P : D^b(X) \rightarrow D^b(Y)$ .

**Remark 9.1.4.** Since the derived functors  $p_X^*$ ,  $p_{Y*}$  and  $\otimes$  are exact,  $\Phi_P$  is exact.

**Example 9.1.5** (Examples of integral functors). Let  $X$  be a proper  $k$ -scheme.

- (i) The identity functor  $\text{Id} : D^b(X) \rightarrow D^b(X)$  is naturally isomorphic to the Fourier-Mukai transform with kernel  $\mathcal{O}_{\Delta_X}$ , where  $\Delta_X \subset X \times X$  is the diagonal.

Let  $p_i : X \times X \rightarrow X$  be the projection onto the  $i$ -th factor, for  $i = 1, 2$ . Let  $\iota : X \xrightarrow{\sim} \Delta \subset X \times X$  be the embedding of the diagonal into  $X \times X$ . Let  $\mathcal{O}_\Delta$  be the structure sheaf of the diagonal  $\Delta$ . Then for any  $E^\bullet \in D^b(X)$ , we have

$$\begin{aligned} \Phi_{\mathcal{O}_\Delta}(E^\bullet) &= p_{1*}(p_2^*E^\bullet \otimes \mathcal{O}_\Delta) = p_{1*}(p_2^*E^\bullet \otimes \iota_*\mathcal{O}_X) \\ &\cong p_{1*}(\iota_*(\iota^*(p_2^*E^\bullet) \otimes \mathcal{O}_X)), \quad \text{by projection formula;} \\ &\cong (p_1 \circ \iota)_*(p_2 \circ \iota)^*(E^\bullet) \cong E^\bullet, \quad \text{since } p_1 \circ \iota = \text{Id}_X = p_2 \circ \iota. \end{aligned}$$

- (ii) (Pullback and direct image functors) Let  $f : X \rightarrow Y$  be a morphism of smooth projective  $k$ -schemes. Then  $Rf_* : D^b(X) \rightarrow D^b(Y)$  is isomorphic to the integral functor  $\Phi_{\mathcal{O}_{\Gamma_f}}^{X \rightarrow Y}$ , where  $\Gamma_f \subset X \times Y$  is the graph of  $f$ . Indeed, take any  $E^\bullet \in D^b(X) := D^b(\mathcal{Coh}(X))$ . Then

$$\Phi_{\mathcal{O}_{\Gamma_f}}^{X \rightarrow Y}(E^\bullet) = Rp_{2*}((Rp_1^*E^\bullet) \otimes^L \mathcal{O}_{\Gamma_f}) \cong Rf_*E^\bullet.$$

On the other hand, taking integral functor on the reverse direction with the same kernel gives a natural isomorphism of functors  $\Phi_{\mathcal{O}_{\Gamma_f}}^{Y \rightarrow X} \cong Lf^*$ .

- (iii) The cohomology functor  $H^*(X, -) : D^b(X) \rightarrow D^b(\mathcal{Vect}(k))$  is isomorphic to the integral functor  $\Phi_{\mathcal{O}_{\Gamma_f}}^{X \rightarrow \text{Spec}(k)}$ , where  $\Gamma_f \subset X \times \text{Spec}(k)$  is the graph of the structure morphism  $f : X \rightarrow \text{Spec}(k)$  of  $X$ .
- (iv) Let  $\mathcal{L}$  be an invertible sheaf on a proper  $k$ -scheme  $X$ . Let  $\iota : X \xrightarrow{\sim} \Delta_X \subset X \times X$  be the diagonal immersion. Then the integral functor  $\Phi_{\iota_*\mathcal{L}}$  is isomorphic to the functor  $\mathcal{L} \otimes^L -$ . Indeed, for any  $E^\bullet \in D^b(X)$  we have

$$\Phi_{\iota_*\mathcal{L}}(E^\bullet) = p_{2*}((p_1^*E^\bullet) \otimes \iota_*(\mathcal{L})) \cong E^\bullet \otimes^L \mathcal{L}.$$

- (v) The shift functor  $T : D^b(X) \rightarrow D^b(X)$  given by  $T(E^\bullet) = E^\bullet[1]$ , for all  $E^\bullet \in D^b(X)$ , is isomorphic to the integral functor  $\Phi_{\mathcal{O}_{\Delta}[1]}$ .
- (vi) Let  $X$  be a smooth projective  $k$ -variety of dimension  $n$ . Recall that the Serre functor  $S_X : D^b(X) \rightarrow D^b(X)$  is defined by  $E^\bullet \mapsto (E^\bullet \otimes \omega_X)[n]$ . Since the integral functor  $\Phi_{\iota_*\omega_X^i}$  is isomorphic to  $S_X^i[-ni]$  for all  $i \in \mathbb{Z}$ , as a corollary to Proposition 9.1.21 below, we conclude that  $S_X$  is an integral functor with kernel  $(\iota_*\omega_X) * (\mathcal{O}_\Delta[n])$ .
- (vii) (Kodaira-Spencer morphism) Let  $X$  and  $T$  be smooth projective  $k$ -varieties. Let  $\mathcal{P}$  be a coherent sheaf on  $X \times T$  flat over  $T$ , and consider the integral functor  $\Phi_{\mathcal{P}}^{T \rightarrow X} : D^b(T) \rightarrow D^b(X)$  with kernel  $\mathcal{P}$ . Fix a  $k$ -rational point  $t \in T$  (i.e., a

closed point  $t \in T$  with  $k(t) \cong k$ , we have

$$\Phi_{\mathcal{P}}^{T \rightarrow X}(k(t)) = R p_{X*}((L p_T^* k(t)) \otimes^L \mathcal{P}) \cong \mathcal{P}_t,$$

where  $\mathcal{P}_t := \mathcal{P}|_{X \times \{t\}}$  considered as a coherent sheaf on  $X$ .

Note that, a tangent vector  $v \in T_t T$  at  $t$  is uniquely defined by a subscheme  $Z_v \subset T$  of length 2 (i.e.,  $\dim_k H^0(Z_v, \mathcal{O}_{Z_v}) = 2$ ) concentrated at  $t$ . Then we have a short exact sequence

$$(9.1.6) \quad 0 \longrightarrow k(t) \longrightarrow \mathcal{O}_{Z_v} \longrightarrow k(t) \longrightarrow 0.$$

Pulling back this exact sequence by  $p_T$  and tensoring with  $\mathcal{P}$  (note that,  $\mathcal{P}$  is flat over  $T$  by assumption), we get a short exact sequence

$$(9.1.7) \quad 0 \longrightarrow \mathcal{P}_t \longrightarrow \mathcal{P}|_{X \times Z_v} \longrightarrow \mathcal{P}_t \longrightarrow 0.$$

Considering this as a sequence on  $X$ , we get an extension class in  $\text{Ext}_X^1(\mathcal{P}_t, \mathcal{P}_t)$ .

Now one can check that, this gives a  $k$ -linear map

$$(9.1.8) \quad \text{KS}_t : T_t T \longrightarrow \text{Ext}_X^1(\mathcal{P}_t, \mathcal{P}_t),$$

known as the *Kodaira-Spencer map*. It follows from the above construction that the following diagram is commutative.

$$(9.1.9) \quad \begin{array}{ccc} T_t T = \text{Ext}_T^1(k(t), k(t)) & \xrightarrow{\text{KS}_t} & \text{Ext}_X^1(\mathcal{P}_t, \mathcal{P}_t) \\ \simeq \downarrow & & \downarrow \simeq \\ \text{Hom}_{D^b(T)}(k(t), k(t)[1]) & \xrightarrow{\Phi_{\mathcal{P}}^{X \rightarrow T}} & \text{Hom}_{D^b(X)}(\mathcal{P}_t, \mathcal{P}_t[1]) \end{array}$$

In other words, the Kodaira-Spencer morphism  $\text{KS}_t$  is compatible with the integral functor  $\Phi_{\mathcal{P}}^{T \rightarrow X}$ .

**Remark 9.1.10.** Note that, an integral functor need not be compatible with Serre functors (c.f., Section §4). For example, let  $X$  be a smooth projective  $k$ -scheme of dimension  $n \geq 1$ . Let  $f : X \longrightarrow \text{Spec}(k)$  be the structure morphism. Then the right derived functor  $Rf_* : D^b(X) \longrightarrow D^b(\text{Vect}(k))$  sends a coherent sheaf  $E$  on  $X$  to the graded  $k$ -vector space  $H^*(X, E) := \bigoplus_{i \geq 0} H^i(X, E)$ . Note that  $S_{\text{Spec}(k)}(H^0(X, E)) = H^0(X, E)$ , for all  $i \geq 0$ . Again  $R^0 f_*(S_X(E)) \cong \text{Ext}^0(\mathcal{O}_X, S_X(E)) = \text{Ext}^0(\mathcal{O}_X, E \otimes \omega_X[n]) \cong \text{Ext}^n(\mathcal{O}_X, E \otimes \omega_X) \cong H^n(X, E \otimes \omega_X)$ . Since  $H^n(X, E \otimes \omega_X) \not\cong H^0(X, E)$ , in general, we conclude that  $Rf_* \circ S_X \not\cong S_{\text{Spec}(k)} \circ Rf_*$ .

We are interested to know when an integral functor  $\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  is a Fourier-Mukai transform (i.e., an equivalence of categories). For  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  to be an equivalence of categories, it must admit both left adjoint and right adjoint. As a first step towards this, we show that an integral functor  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  always admit both left

adjoint and right adjoint, which are again integral functors, and their kernels can be explicitly described.

Let  $X$  and  $Y$  be smooth projective  $k$ -schemes, and  $p_X$  and  $p_Y$  denote the projection morphisms from  $X \times Y$  onto  $X$  and  $Y$ , respectively.

**Definition 9.1.11.** For any object  $\mathcal{P} \in D^b(X \times Y)$ , we define

$$\mathcal{P}_L := \mathcal{P}^\vee \otimes p_Y^* \omega_Y[\dim Y], \quad \text{and} \quad \mathcal{P}_R := \mathcal{P}^\vee \otimes p_X^* \omega_X[\dim X].$$

Note that, both  $\mathcal{P}_L$  and  $\mathcal{P}_R$  are objects of  $D^b(X \times Y)$ .

**Proposition 9.1.12.** *There is a natural isomorphism of functors*

$$\Phi_{\mathcal{P}_R}^{Y \rightarrow X} \cong S_X \circ \Phi_{\mathcal{P}_L} \circ S_Y^{-1}.$$

*Proof.* It suffices to show that there are natural isomorphism of functors

$$(9.1.13) \quad \Phi_{\mathcal{P}_L}^{Y \rightarrow X} \cong \Phi_{\mathcal{P}^\vee}^{Y \rightarrow X} \circ S_Y \quad \text{and} \quad \Phi_{\mathcal{P}_R}^{Y \rightarrow X}(E^\bullet) \cong S_X \circ \Phi_{\mathcal{P}^\vee}^{Y \rightarrow X}.$$

For any  $E^\bullet \in D^b(Y)$ , we have

$$\begin{aligned} \Phi_{\mathcal{P}_L}^{Y \rightarrow X}(E^\bullet) &= Rp_{X*}((Lp_Y^* E^\bullet) \overset{L}{\otimes} \mathcal{P}_L) \\ &\cong Rp_{X*}((Lp_Y^* E^\bullet) \overset{L}{\otimes} (\mathcal{P}^\vee \otimes p_Y^* \omega_Y[\dim Y])) \\ &\cong Rp_{X*}((Lp_Y^* E^\bullet) \overset{L}{\otimes} (p_Y^* \omega_Y[\dim Y]) \overset{L}{\otimes} \mathcal{P}^\vee) \\ &\cong Rp_{X*}(Lp_Y^*(E^\bullet \overset{L}{\otimes} \omega_Y[\dim Y]) \overset{L}{\otimes} \mathcal{P}^\vee) \\ &\cong Rp_{X*}(Lp_Y^*(S_Y(E^\bullet)) \overset{L}{\otimes} \mathcal{P}^\vee) = (\Phi_{\mathcal{P}^\vee}^{Y \rightarrow X} \circ S_Y)(E^\bullet) \end{aligned}$$

Similarly, we have

$$\begin{aligned} \Phi_{\mathcal{P}_R}^{Y \rightarrow X}(E^\bullet) &= Rp_{X*}((Lp_Y^* E^\bullet) \overset{L}{\otimes} (\mathcal{P}^\vee \otimes p_X^* \omega_X[\dim X])) \\ &\cong Rp_{X*}((Lp_Y^* E^\bullet) \overset{L}{\otimes} \mathcal{P}^\vee) \overset{L}{\otimes} \omega_X[\dim X], \quad \text{by projection formula.} \\ &= \Phi_{\mathcal{P}^\vee}(E^\bullet) \overset{L}{\otimes} \omega_X[\dim X] \\ &= (S_X \circ \Phi_{\mathcal{P}^\vee}^{Y \rightarrow X})(E^\bullet). \end{aligned}$$

Hence the result follow.  $\square$

**Theorem 9.1.14** (Grothendieck-Verdier duality). *Let  $f : X \rightarrow Y$  be a morphism of smooth schemes over a field  $k$  of relative dimension  $\dim(f) := \dim(X) - \dim(Y)$ . Let*

$$(9.1.15) \quad \omega_f := \omega_X \otimes f^* \omega_Y^\vee$$

*be the relative dualizing sheaf of  $f$ . Then for any  $F^\bullet \in D^b(X)$  and  $E^\bullet \in D^b(Y)$ , there is a functorial isomorphism*

$$(9.1.16) \quad Rf_* R\mathcal{H}om(F^\bullet, Lf^*(E^\bullet) \overset{L}{\otimes} \omega_f[\dim(f)]) \xrightarrow{\cong} R\mathcal{H}om(Rf_* F^\bullet, E^\bullet).$$

**Proposition 9.1.17 (Mukai).** *Let  $X$  and  $Y$  be smooth projective  $k$ -schemes. Let  $F = \Phi_{\mathcal{P}} : D^b(X) \rightarrow D^b(Y)$  be an integral functor with kernel  $\mathcal{P} \in D^b(X \times Y)$ . Then  $\Phi_{\mathcal{P}_L}$  (resp.,  $\Phi_{\mathcal{P}_R}$ ) is the left adjoint (resp., right adjoint) of  $F$ .*

*Proof.* This is an application of Grothendieck-Verdier duality (Theorem 6.9.1), projection formula and compatibilities among derived functors. The relative dualizing sheaf for the projection morphism  $p_X : X \times Y \rightarrow X$  is

$$\omega_{p_X} := \omega_{X \times Y} \otimes p_X^* \omega_X^\vee \cong p_Y^* \omega_Y \otimes p_X^* \omega_X \otimes p_X^* \omega_X^\vee \cong p_Y^* \omega_Y,$$

and the relative dimension of  $p_X$  is  $\dim(p_X) := \dim(X \times Y) - \dim(X) = \dim(Y)$ . For any  $E^\bullet \in D^b(Y)$  and  $F^\bullet \in D^b(X)$ , we have

$$\begin{aligned} \mathrm{Hom}_{D^b(X)}(\Phi_{\mathcal{P}_L}^{Y \rightarrow X}(E^\bullet), F^\bullet) &= \mathrm{Hom}_{D^b(X)}(Rp_{X*}(Lp_Y^* E^\bullet \otimes^L \mathcal{P}_L), F^\bullet) \\ &\cong \mathrm{Hom}_{D^b(X \times Y)}(Lp_Y^* E^\bullet \otimes^L \mathcal{P}_L, p_X^* F^\bullet \otimes^L \omega_{p_X}[\dim(p_X)]), \text{ by Theorem 6.9.1.} \\ &\cong \mathrm{Hom}_{D^b(X \times Y)}(Lp_Y^* E^\bullet \otimes^L \mathcal{P}_L, p_X^* F^\bullet \otimes^L p_Y^* \omega_Y[\dim(Y)]) \\ &\cong \mathrm{Hom}_{D^b(X \times Y)}(\mathcal{P}^\vee \otimes^L p_Y^* \omega_Y[\dim(Y)] \otimes^L p_Y^* E^\bullet, Lp_X^* F^\bullet \otimes^L p_Y^* \omega_Y[\dim(Y)]) \\ &\cong \mathrm{Hom}_{D^b(X \times Y)}(\mathcal{P}^\vee \otimes^L p_Y^* E^\bullet, p_X^* F^\bullet) \\ &\cong \mathrm{Hom}_{D^b(X \times Y)}(p_Y^* E^\bullet, \mathcal{P} \otimes^L p_X^* F^\bullet) \\ &\cong \mathrm{Hom}_{D^b(Y)}(E^\bullet, Rp_{Y*}(\mathcal{P} \otimes^L p_X^* F^\bullet)) \\ &= \mathrm{Hom}_{D^b(Y)}(E^\bullet, \Phi_{\mathcal{P}}^{X \rightarrow Y}(F^\bullet)). \end{aligned}$$

Therefore,  $\Phi_{\mathcal{P}_L}^{Y \rightarrow X}$  is the left adjoint of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$ . To show  $\Phi_{\mathcal{P}_R}^{Y \rightarrow X}$  is the right adjoint of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$ , one can again do similar calculations as above, or alternatively use Proposition 9.1.12 and Lemma 9.1.18 (below) to complete the proof.  $\square$

**Lemma 9.1.18.** *Let  $\mathcal{A}$  and  $\mathcal{B}$  be two  $k$ -linear categories with finite dimensional Homs. Assume that  $\mathcal{A}$  and  $\mathcal{B}$  admits Serre functors  $S_{\mathcal{A}}$  and  $S_{\mathcal{B}}$ , respectively. Let  $F : \mathcal{A} \rightarrow \mathcal{B}$  and  $G : \mathcal{B} \rightarrow \mathcal{A}$  be  $k$ -linear functors. If  $G$  is the left adjoint of  $F$ , then  $S_{\mathcal{A}} \circ G \circ S_{\mathcal{B}}^{-1}$  is the right adjoint of  $F$ .*

*Proof.* For  $A \in \mathcal{A}$  and  $B \in \mathcal{B}$  we have the following sequence of natural isomorphisms

$$\begin{aligned} \mathrm{Hom}(A, (S_{\mathcal{A}} \circ G \circ S_{\mathcal{B}}^{-1})(B)) &\cong \mathrm{Hom}((G \circ S_{\mathcal{B}}^{-1})(B), A)^* \\ &\cong \mathrm{Hom}(S_{\mathcal{B}}^{-1}(B), F(A)) \\ &\cong \mathrm{Hom}(F(A), S_{\mathcal{B}}(S_{\mathcal{B}}^{-1}(B))) \\ &\cong \mathrm{Hom}(F(A), B). \end{aligned}$$

Hence the result follow.  $\square$

An important property of integral functors is that composition of two integral functors is again integral, and its kernel is given by *convolution product*, which we explain below. Let  $X, Y$  and  $Z$  be proper  $k$ -schemes. Consider the diagram

$$(9.1.19) \quad \begin{array}{ccccc} & & X \times Y \times Z & & \\ & \swarrow p_{XY} & \downarrow p_{XZ} & \searrow p_{YZ} & \\ X \times Y & & X \times Z & & Y \times Z, \end{array}$$

where  $p_{XY}, p_{YZ}$  and  $p_{XZ}$  are projection morphisms. For  $P \in D^-(X \times Y)$  and  $Q \in D^-(Y \times Z)$ , we define their *convolution product* to be the object

$$(9.1.20) \quad Q * P := p_{XZ*}((p_{XY}^* P) \otimes (p_{YZ}^* Q)) \in D^-(X \times Z).$$

Clearly,  $Q * P$  is naturally isomorphic to  $P * Q$ . Proof of the following result is an easy consequence of projection formula.

**Proposition 9.1.21 (Mukai).** *For any  $\mathcal{P} \in D^-(X \times Y)$  and  $\mathcal{Q} \in D^-(Y \times Z)$ , there is a natural isomorphism of functors*

$$\Phi_{\mathcal{Q}}^{Y \rightarrow Z} \circ \Phi_{\mathcal{P}}^{X \rightarrow Y} \cong \Phi_{\mathcal{Q} * \mathcal{P}}^{X \rightarrow Z}.$$

*Proof.* Proof is very simple, but what makes it difficult is to work with 11 projection morphisms. The following commutative diagram could be useful to keep track of the morphisms.

$$\begin{array}{ccccc} & & p_{XY}^* \mathcal{P} \otimes p_{YZ}^* \mathcal{Q} & & \\ & \swarrow p_X & \downarrow p_{XZ} & \searrow p_Z & \\ & X \times Y & X \times Y \times Z & Y \times Z & \\ & \swarrow q & \downarrow p_{XZ} & \searrow u & \\ X & & X \times Z & & Z \\ & \swarrow p & \downarrow p_{XZ} & \searrow t & \\ & Y & X \times Z & Y & \\ & \swarrow s & \downarrow p_{XZ} & \searrow r & \\ & X & \mathcal{R} & Z & \end{array}$$



Let  $\mathcal{R} := \mathcal{Q} * \mathcal{P} = p_{XZ*}(p_{XY}^* \mathcal{P} \otimes p_{YZ}^* \mathcal{Q}) \in D^b(X \times Z)$  be the convolution product of  $\mathcal{P}$  and  $\mathcal{Q}$ . Then for any  $E^\bullet \in D^-(X)$ , we have

$$\begin{aligned}
 \Phi_{\mathcal{R}}^{X \rightarrow Z}(E^\bullet) &= r_*(Ls^* E^\bullet \otimes \mathcal{R}) \\
 &= r_*(s^* E^\bullet \otimes p_{XZ*}(p_{XY}^* \mathcal{P} \otimes p_{YZ}^* \mathcal{Q})) \\
 &\cong r_*(p_{XZ*}(p_X^* E^\bullet \otimes p_{XY}^* \mathcal{P} \otimes p_{YZ}^* \mathcal{Q})), \text{ by projection formula.} \\
 &\cong p_{Z*}(p_{XY}^*(q^* E^\bullet \otimes \mathcal{P}) \otimes p_{YZ}^* \mathcal{Q}), \text{ since } r \circ p_{XZ} = p_Z. \\
 &\cong t_{*p_{YZ*}}(p_{XY}^*(q^* E^\bullet \otimes \mathcal{P}) \otimes p_{YZ}^* \mathcal{Q}), \text{ since } t \circ p_{YZ} = p_Z. \\
 &\cong t_*(p_{YZ*} p_{XY}^*(q^* E^\bullet \otimes \mathcal{P}) \otimes \mathcal{Q}), \text{ by projection formula.} \\
 &\cong t_*(u^* p_*(q^* E^\bullet \otimes \mathcal{P}) \otimes \mathcal{Q}), \text{ by flat base change } p_{YZ*} \circ p_{XY}^* = u^* \circ p_*. \\
 &= t_*(u^* \Phi_{\mathcal{P}}^{X \rightarrow Y}(E^\bullet) \otimes \mathcal{Q}) = (\Phi_{\mathcal{Q}}^{Y \rightarrow Z} \circ \Phi_{\mathcal{P}}^{X \rightarrow Y})(E^\bullet)
 \end{aligned}$$

This completes the proof.  $\square$

**Remark 9.1.22.** If the composite functor  $\Phi_{\mathcal{Q}}^{Y \rightarrow Z} \circ \Phi_{\mathcal{P}}^{X \rightarrow Y}$  is not an equivalence of categories, then the kernel  $\mathcal{R} := \mathcal{P} * \mathcal{Q}$  is not necessarily unique. However this choice of  $\mathcal{R}$  is a natural one in the sense that it is compatible with taking left adjoint and right adjoint. More precisely, we have natural isomorphism of functors

$$(9.1.23) \quad \Phi_{\mathcal{R}_L} \cong p_{XZ*}(p_{XY}^* \mathcal{P}_L \otimes p_{YZ}^* \mathcal{Q}_L) \quad \text{and} \quad \Phi_{\mathcal{R}_R} \cong p_{XZ*}(p_{XY}^* \mathcal{P}_R \otimes p_{YZ}^* \mathcal{Q}_R).$$

This can easily be checked using Grothendieck-Verdier duality as in Proposition 9.1.17.

**Remark 9.1.24.** Let  $\mathcal{P}, \mathcal{Q} \in D^b(X \times Y)$ . Then any morphism  $\varphi \in \text{Hom}_{D^b(X \times Y)}(\mathcal{P}, \mathcal{Q})$  induces a morphism of the associated integral functors:  $\Phi_\varphi : \Phi_{\mathcal{P}} \rightarrow \Phi_{\mathcal{Q}}$ . One might wonder if this induced morphism  $\Phi_\varphi$  is non-trivial if  $\varphi$  is non-trivial. In general, the answer is no! For example, let  $C$  be an elliptic curve over a field  $k$ , and denote by  $\Delta$  the image of the diagonal embedding  $C \hookrightarrow C \times C$ . Consider  $\mathcal{O}_\Delta$  as an object of  $D^b(C \times C)$ . Using Serre duality on the product  $C \times C$ , one can conclude that  $\dim_k \text{Ext}^2(\mathcal{O}_\Delta, \mathcal{O}_\Delta) = 1$ . So there is a non-trivial morphism

$$(9.1.25) \quad f : \mathcal{O}_\Delta \rightarrow \mathcal{O}_\Delta[2]$$

in  $D^b(C \times C)$ . This morphism  $f$  induce a morphism of associated integral functors

$$(9.1.26) \quad \Phi_f : \Phi_{\mathcal{O}_\Delta} \rightarrow \Phi_{\mathcal{O}_\Delta[2]}.$$

Note that,  $\Phi_{\mathcal{O}_\Delta} \cong \text{Id}_{D^b(C)}$ , and  $\Phi_{\mathcal{O}_\Delta[2]}$  is isomorphic to the 2-shift functor  $E^\bullet \mapsto E^\bullet[2]$ . However,  $\Phi_f = 0$ . To see this, note that  $C$  being one dimensional,  $\text{Ext}^2(E, E) = 0$  for any coherent sheaf  $E$  on  $C$ . So the induced morphism  $\Phi_f(E) : \Phi_{\mathcal{O}_\Delta}(E) \rightarrow \Phi_{\mathcal{O}_\Delta[2]}(E)$  is trivial. Since any object of  $D^b(C)$  is isomorphic to a finite direct sum of shifted coherent sheaves on  $C$ , we conclude that  $\Phi_f(E^\bullet) : E^\bullet \rightarrow E^\bullet[2]$  is zero, for any  $E^\bullet \in D^b(C)$ .

The following useful results are easy to verify.

**Proposition 9.1.27.** *Let  $X, Y$  and  $Z$  be smooth projective  $k$ -schemes. Let  $\mathcal{P} \in D^b(X \times Y)$ .*

- (i) *For any morphism  $f : Y \rightarrow Z$  of  $k$ -schemes, we have an isomorphism of functors*  

$$Rf_* \circ \Phi_{\mathcal{P}}^{X \rightarrow Y} \cong \Phi_{(\text{Id}_X \times f)_* \mathcal{P}}^{X \rightarrow Z}.$$
- (ii) *For any morphism  $f' : Z \rightarrow Y$  of  $k$ -schemes, we have an isomorphism of functors*  

$$Lf^* \circ \Phi_{\mathcal{P}}^{X \rightarrow Y} \cong \Phi_{(\text{Id}_X \times f')^* \mathcal{P}}^{X \rightarrow Z}.$$
- (iii) *For any morphism  $g : Z \rightarrow X$  of  $k$ -schemes, we have an isomorphism of functors*  

$$\Phi_{\mathcal{P}}^{X \rightarrow Y} \circ Rg_* \cong \Phi_{(g \times \text{Id}_Y)^* \mathcal{P}}^{Z \rightarrow Y}.$$
- (iv) *For any morphism  $g' : X \rightarrow Z$  of  $k$ -schemes, we have an isomorphism of functors*  

$$\Phi_{\mathcal{P}}^{X \rightarrow Y} \circ Lg^* \cong \Phi_{(g' \times \text{Id}_Y)^* \mathcal{P}}^{Z \rightarrow Y}.$$

It is natural to ask which functors are isomorphic to an integral functor? The answer is given by the celebrated representability theorem due to Orlov [Orl03]. Orlov's representability theorem says that, *if  $X$  and  $Y$  are smooth projective varieties defined over a field  $k$ , then any exact fully faithful functor  $F : D^b(X) \rightarrow D^b(Y)$  admitting both left and right adjoints is isomorphic to an integral functor  $\Phi_{P_F}^{X \rightarrow Y}$ , where  $P_F \in D^b(X \times Y)$  is unique up to isomorphism.*

In their celebrated paper [BvdB03], Bondal and Van den Bergh proved a deep result which ensures that any exact functor  $F : D^b(X) \rightarrow D^b(Y)$  admits a right adjoint. Since both  $D^b(X)$  and  $D^b(Y)$  admit Serre functors, it follows from Lemma 9.1.18 that  $F$  admits a left adjoint too. Therefore, the assumption of existence of both left and right adjoints of  $F$  is redundant, and we get the following stronger version of Orlov's representability theorem (whose proof will be given later).

**Theorem 9.1.28.** *Let  $X$  and  $Y$  be two smooth projective  $k$ -varieties. Let*

$$F : D^b(X) \rightarrow D^b(Y)$$

*be an exact fully faithful functor (resp., exact equivalence of categories). Then there is an object  $P_F \in D^b(X \times Y)$ , unique up to isomorphism, such that  $F$  is isomorphic to the integral functor  $\Phi_{P_F}^{X \rightarrow Y}$  with kernel  $P_F$ .*

As an immediate corollary to this, we get the following.

**Corollary 9.1.29.** *Let  $X$  and  $Y$  be smooth projective  $k$ -varieties with an exact equivalence of derived categories  $F : D^b(X) \rightarrow D^b(Y)$ . Then  $\dim_k(X) = \dim_k(Y)$ .*

*Proof.* By Orlov's representability theorem, there is an object  $\mathcal{P} \in D^b(X \times Y)$ , unique up to isomorphism, such that  $F \cong \Phi_{\mathcal{P}}$ . By Proposition 9.1.17, due to Mukai,  $F$  admits both left adjoint and right adjoint, which are also Fourier-Mukai transformations

with kernels

$$(9.1.30) \quad \mathcal{P}_L := \mathcal{P}^\vee \otimes_{p_Y^* \omega_Y}^L [\dim Y] \quad \text{and} \quad \mathcal{P}_R := \mathcal{P}^\vee \otimes_{p_X^* \omega_X}^L [\dim X],$$

respectively. Since  $F$  is an equivalence of categories,  $\Phi_{\mathcal{P}_L}^{Y \rightarrow X} \cong \Phi_{\mathcal{P}_R}^{Y \rightarrow X}$ . Since quasi-inverse of  $F$  is also an exact equivalence from  $D^b(Y)$  to  $D^b(X)$ , using uniqueness (up to isomorphism) of kernel of a Fourier-Mukai transformation (c.f., Theorem 9.1.28), we conclude that  $\mathcal{P}_L \cong \mathcal{P}_R$  in  $D^b(X \times Y)$ . Therefore,

$$(9.1.31) \quad \mathcal{P}^\vee \cong \mathcal{P}^\vee \otimes^L (p_X^* \omega_X \otimes^L p_Y^* \omega_Y^\vee [\dim X - \dim Y]).$$

From this, it follows that  $\dim X = \dim Y$ . □

Let  $X$  and  $Y$  be smooth projective  $k$ -varieties. We show that if an exact equivalence  $F : D^b(X) \rightarrow D^b(Y)$  sends skyscraper sheaves  $k(x)$  to skyscraper sheaves  $k(y_x)$ , where  $x \in X$  and  $y_x \in Y$  are closed points, then there is an isomorphism of  $k$ -schemes  $f : X \rightarrow Y$  sending  $x$  to  $y_x$ , and that  $F$  is isomorphic to  $(- \otimes L) \circ f_*$ , for some  $L \in \text{Pic}(Y)$ . In particular,  $F$  is a Fourier-Mukai transform. First, we need the following.

**Lemma 9.1.32.** *Let  $\phi : X \rightarrow S$  be a morphism of  $k$ -schemes. For a closed point  $s \in S$ , we denote by  $\iota_s : X_s \hookrightarrow X$  the closed embedding of the scheme theoretic fiber  $X_s := X \times_S \text{Spec}(k(s))$  over  $s$  into  $X$ . Let  $\mathcal{P} \in D^b(X)$  be such that for each closed point  $s \in S$ , the derived pullback  $L\iota_s^* \mathcal{P} \in D^b(X_s)$  is a complex concentrated at degree 0. Then  $\mathcal{P}$  is isomorphic to a coherent sheaf on  $X$  flat over  $S$ .*

*Proof.* Let

$$m := \max\{i \in \mathbb{Z} : \mathcal{H}^i(\mathcal{P}) \neq 0\}.$$

First, we show that  $m = 0$ . Then we show that

$$\mathcal{H}^{-1}(L\iota_s^* \mathcal{H}^0(\mathcal{P})) = 0, \quad \forall s \in S,$$

which implies  $\text{Tor}_1(\mathcal{H}^0(\mathcal{P}), k(s)) = 0$ , for all  $s \in S$ , and hence  $\mathcal{H}^0(\mathcal{P})$  is flat over  $S$ . Finally to complete the proof, we show that  $\mathcal{H}^q(\mathcal{P}) = 0$ , for all  $q < 0$ .

Let  $s \in S$  be a closed point. Consider the spectral sequence

$$(9.1.33) \quad E_2^{p,q} := \mathcal{H}^p(L\iota_s^*(\mathcal{H}^q(\mathcal{P}))) \implies E^{p+q} := \mathcal{H}^{p+q}(L\iota_s^*(\mathcal{P})), \quad \forall \mathcal{P} \in D^b(X).$$

Then there is a closed point  $s \in S$  such that

$$E_2^{0,m} = \mathcal{H}^0(L\iota_s^*(\mathcal{H}^m(\mathcal{P}))) \neq 0;$$

note that, this is just the ordinary pullback of  $\mathcal{H}^m(\mathcal{P}) \in \mathfrak{Coh}(X)$  over  $X_s$ .

$$\begin{array}{ccccccccc}
 E_2^{-2,m+1} = 0 & E_2^{-1,m+1} = 0 & E_2^{0,m+1} = 0 & E_2^{1,m+1} = 0 & E_2^{2,m+1} & & & & \\
 & \searrow & \searrow & \searrow & \searrow & & & & \\
 E_2^{-2,m} & E_2^{-1,m} & E_2^{0,m} & E_2^{1,m} = 0 & E_2^{2,m} & & & & \\
 & \searrow & \searrow & \searrow & \searrow & & & & \\
 E_2^{-2,m-1} & E_2^{-1,m-1} & E_2^{0,m-1} & E_2^{1,m-1} = 0 & E_2^{2,m-1} = 0 & & & & 
 \end{array}$$

Since, by assumption,  $E^m = \mathcal{H}^m(L\iota_s^*(\mathcal{P})) = 0$  except possibly for  $m = 0$ , we conclude that  $m = 0$ . Similarly, since  $\mathcal{H}^{-1}(L\iota_s^*\mathcal{P}) = 0$  by assumption, we have  $E_2^{-1,0} = \mathcal{H}^{-1}(L\iota_s^*\mathcal{H}^0(\mathcal{P})) = 0$ , for all  $s \in S$ . Then  $\text{Tor}_1(\mathcal{H}^0(\mathcal{P}), k(s)) = 0$ , for all closed points  $s \in S$ , and hence  $\mathcal{H}^0(\mathcal{P})$  is flat over  $S$ . Now  $\mathcal{H}^0(\mathcal{P})$  being flat over  $S$ , its higher derived pullbacks  $E_2^{-p,0} = \mathcal{H}^{-p}(L\iota_s^*\mathcal{H}^0(\mathcal{P})) = \text{Tor}_p(\mathcal{H}^0(\mathcal{P}), k(s))$  are trivial for  $p > 0$ .

Now it remains to show that  $\mathcal{H}^q(\mathcal{P}) = 0$ , for all  $q < 0$ . If not, then let  $n$  be the largest integer such that  $n < 0$  and  $\mathcal{H}^n(\mathcal{P}) \neq 0$ . Choose a closed point  $s \in S$  such that  $X_s \cap \text{Supp}(\mathcal{H}^n(\mathcal{P})) \neq \emptyset$ . Since  $E_2^{-p,q} = \mathcal{H}^{-p}(L\iota_s^*\mathcal{H}^q(\mathcal{P})) = 0$ , for all  $p < 0$  and  $q > m = 0$ , it follows that  $E_\infty^{0,n} = E_2^{0,n} = \mathcal{H}^0(L\iota_s^*\mathcal{H}^n(\mathcal{P})) \neq \emptyset$ . This is a contradiction because  $E^n = \mathcal{H}^n(L\iota_s^*\mathcal{P}) = 0$ , since  $n < 0$ . This completes the proof.  $\square$

**Proposition 9.1.34.** *Let  $k$  be an algebraically closed field. Let  $X$  and  $Y$  be smooth projective  $k$ -varieties with an exact equivalence  $F : D^b(X) \rightarrow D^b(Y)$ . Suppose that for each closed point  $x \in X$  there is a (unique) closed point  $y_x \in Y$  such that  $F(k(x)) \cong k(y_x)$ . Then  $f$  gives rise to an isomorphism of  $k$ -schemes, also denoted by  $f : X \rightarrow Y$ , such that  $F \cong (L \otimes -) \circ f_*$ , for some  $L \in \text{Pic}(Y)$ .*

*Proof.* We only sketch a proof leaving the details to the readers. By Orlov's representability theorem 9.1.28, there is an object  $\mathcal{P} \in D^b(X \times Y)$ , unique up to isomorphism, such that  $F \cong \Phi_{\mathcal{P}}^{X \rightarrow Y}$ . By assumption,

$$(9.1.35) \quad k(y_x) \cong F(k(x)) \cong \Phi_{\mathcal{P}}^{X \rightarrow Y}(k(x)) = p_{Y*}(\mathcal{P} \otimes_{p_X^*}^L k(x)) \cong \mathcal{P}|_{\{x\} \times Y}.$$

Then by above Lemma 9.1.32, we may assume that  $\mathcal{P}$  is a coherent sheaf on  $X \times Y$  flat over  $X$ . Then choosing local sections of  $\mathcal{P}$ , using (9.1.35) we find a morphism of  $k$ -schemes  $f : X \rightarrow Y$  such that  $f(x) = y_x$ , for all closed points  $x \in X$ .

Since  $\{k(x) \in D^b(X) : x \text{ is a closed point of } X\}$  spans  $D^b(X)$ , the exact equivalence  $F : D^b(X) \rightarrow D^b(Y)$  ensures that the objects  $F(k(x)) \cong k(f(x))$  spans  $D^b(Y)$ . Therefore, for a closed point  $y \in Y$ , there is a closed point  $x_y \in X$  such that

$$\text{Hom}_{D^b(Y)}(F(k(x_y)), k(y)[m_y]) \neq 0,$$

for some integer  $m_y$ . This implies,  $k(y)$  is of the form  $k(f(x))$  in  $D^b(Y)$ . Therefore,  $f$  is surjective over the set of closed points. Similarly, one can show that  $f$  is injective at the level of closed points. Since the set of all closed points is dense in a finite type  $k$ -scheme,  $f$  is birational. Then one can use Zariski's main theorem and Stein factorization to deduce that  $f$  is an isomorphism of  $k$ -schemes in characteristic 0. In positive characteristic, one need to use exact quasi-inverse  $F^{-1} : D^b(Y) \rightarrow D^b(X)$  of  $F$  to produce a morphism of  $k$ -schemes  $g : Y \rightarrow X$ , which gives the inverse of  $f$  in the category of  $k$ -schemes.

Eventually,  $\mathcal{P}$  considered as a sheaf on its support, which is the graph of  $f$  in  $X \times Y$ , is a sheaf of constant fiber dimension 1, and hence is a line bundle. Since the projection  $p_Y$  induces an isomorphism  $\text{Supp}(\mathcal{P}) \xrightarrow{\sim} Y$ , we can consider  $\mathcal{P}$  as a line bundle over  $Y$ . Then the result follows.  $\square$

**Corollary 9.1.36** (Gabriel). *Let  $X$  and  $Y$  be smooth projective  $k$ -varieties. If there is an exact equivalence of abelian categories  $F : \mathcal{Coh}(X) \rightarrow \mathcal{Coh}(Y)$ , then  $X$  is isomorphic to  $Y$ .*

*Proof.* Clearly  $F$  give rise to an exact equivalence of derived categories  $\tilde{F} : D^b(X) \rightarrow D^b(Y)$ . Then by Orlov's theorem 9.1.28, there is an object  $\mathcal{P} \in D^b(X \times Y)$ , unique up to isomorphism, such that  $\tilde{F} \cong \Phi_{\mathcal{P}}$ . An object  $E \in \mathcal{Coh}(X)$  is called *indecomposable* if any non-trivial epimorphism  $E \twoheadrightarrow E''$  in  $\mathcal{Coh}(X)$  is an isomorphism. One can check that,  $E \in \mathcal{Coh}(X)$  is indecomposable if and only if  $E \cong k(x)$ , for some closed point  $x \in X$ . Since an exact equivalence  $F : \mathcal{Coh}(X) \rightarrow \mathcal{Coh}(Y)$  sends indecomposable object to indecomposable object, for each closed point  $x \in X$ , we find a closed point  $f(x) \in Y$  with  $\Phi_{\mathcal{P}}(k(x)) \cong k(f(x))$ . Then by above Proposition,  $f$  give rise to a morphism of  $k$ -schemes  $f : X \rightarrow Y$  such that  $\Phi_{\mathcal{P}} \cong (L \otimes -) \circ f_*$ , for some  $L \in \text{Pic}(Y)$ .  $\square$

## 9.2. $K$ -theoretic integral transformation.

**Definition 9.2.1.** Let  $\mathcal{A}$  be an abelian category. Let  $\mathbf{F}(\mathcal{A})$  be the free abelian group generated by the set of all isomorphism classes of objects of  $\mathcal{A}$ . Let  $\mathbf{N}(\mathcal{A})$  be the normal subgroup of  $\mathbf{F}(\mathcal{A})$  generated by the elements  $[E'] - [E] + [E''] \in \mathbf{F}(\mathcal{A})$ , where  $0 \rightarrow E' \rightarrow E \rightarrow E'' \rightarrow 0$  is an exact sequence in  $\mathcal{A}$ . Then the *Grothendieck group* of  $\mathcal{A}$  is defined to be the quotient group

$$K_0(\mathcal{A}) := \mathbf{F}(\mathcal{A}) / \mathbf{N}(\mathcal{A}).$$

**Remark 9.2.2.** The above definition of Grothendieck group perfectly make sense for exact categories.

Let  $X$  be a smooth projective  $k$ -variety. Let  $\mathcal{Vect}(X)$  be the full subcategory of  $\mathcal{Coh}(X)$ , whose objects are locally free coherent sheaves on  $X$ . The category  $\mathcal{Vect}(X)$  is exact, but not abelian.

**Lemma 9.2.3.** *There is a natural isomorphism  $K_0(\mathcal{V}ect(X)) \cong K_0(\mathfrak{Coh}(X))$ .*

*Proof.* The homomorphism  $\iota_* : K_0(\mathcal{V}ect(X)) \rightarrow K_0(\mathfrak{Coh}(X))$  induced by the fully faithful (inclusion) functor  $\iota : \mathcal{V}ect(X) \hookrightarrow \mathfrak{Coh}(X)$  is injective. Since  $X$  is a smooth projective algebraic  $k$ -variety, any  $E \in \mathfrak{Coh}(X)$  admits a finite resolution

$$0 \rightarrow E_n \rightarrow E_{n-1} \rightarrow \cdots \rightarrow E_1 \rightarrow E_0 \rightarrow E \rightarrow 0,$$

with  $E_i \in \mathcal{V}ect(X)$ , for all  $i$ . The map given by sending  $[E] \in K_0(\mathfrak{Coh}(X))$  to  $\sum_{i=0}^n (-1)^i [E_i] \in K_0(\mathcal{V}ect(X))$  is independent of choice of the resolution of  $E$ , and is a group homomorphism. This gives the inverse of  $\iota_*$ .  $\square$

Define  $K_0(X) := K_0(\mathfrak{Coh}(X))$ . For  $E^\bullet \in D^b(X)$ , we associate an element

$$(9.2.4) \quad [E^\bullet] := \sum_j (-1)^j [E^j] \in K_0(X).$$

Since any object of  $\mathfrak{Coh}(X)$  admits a finite resolution by locally free coherent sheaves on  $X$ , any element of  $K_0(X)$  can be written as a finite  $\mathbb{Z}$ -linear combination  $\sum_i \alpha_i [E_i]$ , with  $E_i$  locally free coherent sheaves on  $X$ . One can use this to define a ring structure on  $K_0(X)$  by setting

$$(9.2.5) \quad [E] \cdot [F] := [E \otimes F], \quad \forall E, F \in \mathfrak{Coh}(X),$$

and then extending this operation  $\mathbb{Z}$ -linearly over  $K_0(X)$ . Define a map

$$(9.2.6) \quad D^b(X) \longrightarrow K_0(X)$$

by sending  $E^\bullet \in D^b(X)$  to  $[E^\bullet] := \sum_j (-1)^j [E^j] \in K_0(X)$ . One can check that,

$$(9.2.7) \quad [E^\bullet] = \sum_j (-1)^j [\mathcal{H}^j(E^\bullet)]$$

in  $K_0(X)$ , and hence  $[E^\bullet] = [F^\bullet]$  in  $K_0(X)$  whenever  $E^\bullet \cong F^\bullet$  in  $D^b(X)$ . Note that,

$$[E^\bullet[i]] = \sum_j (-1)^j [E^{i+j}] = (-1)^i [E^\bullet] \quad \text{and} \quad [E^\bullet \oplus F^\bullet] = [E^\bullet] + [F^\bullet].$$

Since  $X$  is a smooth projective  $k$ -variety, derived tensor product of two complexes in  $D^b(X)$  can be computed as a ordinary tensor product of bounded complexes of locally free coherent sheaves on  $X$  isomorphic to them,  $[E^\bullet \overset{L}{\otimes} F^\bullet] = [E^\bullet] \cdot [F^\bullet]$  in  $K_0(X)$ . Therefore, the map  $D^b(X) \rightarrow K_0(X)$  given by  $E^\bullet \mapsto [E^\bullet]$  is compatible with the natural additive and multiplicative structures on both sides.

**Lemma 9.2.8.** *Let  $f : X \rightarrow Y$  be a morphism of smooth projective  $k$ -varieties. Then  $f$  induces a homomorphism of their Grothendieck groups  $f^* : K_0(Y) \rightarrow K_0(X)$ .*

*Proof.* Let  $E \in \mathfrak{Coh}(Y)$ . Then  $\tilde{f}(E) := \sum_{i \geq 0} (-1)^i [L^i f^* E]$  is an element of the free abelian group generated by the isomorphism classes of objects from  $\mathfrak{Coh}(X)$ . Since any exact sequence

$$0 \rightarrow E' \rightarrow E \rightarrow E'' \rightarrow 0$$

in  $\mathfrak{Coh}(Y)$  induces a (bounded) long exact sequence of  $\mathcal{O}_X$ -modules

$$\cdots \rightarrow L^{i+1} f^* E'' \rightarrow L^i f^* E' \rightarrow L^i f^* E \rightarrow L^i f^* E'' \rightarrow L^{i-1} f^* E' \rightarrow \cdots,$$

we see that  $\tilde{f}(E) = \tilde{f}(E') + \tilde{f}(E'')$  in  $K_0(X)$ . Thus  $\tilde{f}$  induces a well-defined group homomorphism  $f^* : K_0(Y) \rightarrow K_0(X)$ .  $\square$

**Lemma 9.2.9.** *Let  $f : X \rightarrow Y$  be a proper morphism of projective  $k$ -schemes. Then  $f$  induces a homomorphism of Grothendieck groups  $f_! : K_0(X) \rightarrow K_0(Y)$ .*

*Proof.* Since  $f$  is proper,  $R^i f_*(E) \in \mathfrak{Coh}(Y)$ , for all  $E \in \mathfrak{Coh}(X)$ . Then following the proof of the above Lemma 9.2.8, we see that  $[E] \mapsto \sum_{i \geq 0} (-1)^i [R^i f_*(E)]$  gives the required group homomorphism.  $\square$

**Remark 9.2.10.** Both  $f^* : K_0(Y) \rightarrow K_0(X)$  and  $f_! : K_0(X) \rightarrow K_0(Y)$  are compatible with derived pullback and derived direct image functors in the sense that the following diagrams are commutative.

$$(9.2.11) \quad \begin{array}{ccc} D^b(Y) & \xrightarrow{Lf^*} & D^b(X) \\ \downarrow [\ ] & & \downarrow [\ ] \\ K_0(Y) & \xrightarrow{f^*} & K_0(X) \end{array} \quad \begin{array}{ccc} D^b(X) & \xrightarrow{Rf_*} & D^b(Y) \\ \downarrow [\ ] & & \downarrow [\ ] \\ K_0(X) & \xrightarrow{f_!} & K_0(Y) \end{array}$$

Commutativity of the square on the left hand side is easy to check. To see the commutativity of the square on the right hand side, we need to show that  $[Rf_* E^\bullet] = \sum_j (-1)^j [R^j f_* E^\bullet]$  is equal to

$$f_![E^\bullet] = \sum_j (-1)^j f_![\mathcal{H}^j(E^\bullet)] = \sum_j (-1)^j \sum_i (-1)^i [R^i f_* \mathcal{H}^j(E^\bullet)],$$

which can be checked by using the Leray spectral sequence

$$(9.2.12) \quad E_2^{p,q} := R^p f_* \mathcal{H}^q(E^\bullet) \implies E^{p+q} := R^{p+q} f_*(E^\bullet).$$

**Definition 9.2.13.** We define the  $K$ -theoretic integral transform

$$\Phi_\xi^{K_0, X \rightarrow Y} : K_0(X) \longrightarrow K_0(Y)$$

with kernel  $\xi \in K_0(X \times Y)$  by sending  $\alpha \in K_0(X)$  to  $\Phi_\xi^{K_0, X \rightarrow Y}(\alpha) := p_{Y!}(\xi \otimes p_X^* \alpha)$ .



It follows from the above compatibility relations in (9.2.11) that the integral transform is compatible with the corresponding  $K$ -theoretic integral transform in the sense that the following diagram commutes.

$$(9.2.14) \quad \begin{array}{ccc} D^b(X) & \xrightarrow{\Phi_{\mathcal{P}}^{X \rightarrow Y}} & D^b(Y) \\ \downarrow [\ ] & & \downarrow [\ ] \\ K_0(X) & \xrightarrow{\Phi_{[\mathcal{P}]}^{K_0, X \rightarrow Y}} & K_0(Y) \end{array}$$

**Remark 9.2.15.** The above compatibility between  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  and  $\Phi_{[\mathcal{P}]}^{K_0, X \rightarrow Y}$  can also be seen from the following more general fact: any exact functor  $F : D^b(X) \rightarrow D^b(Y)$  induces a group homomorphism  $F^{K_0} : K_0(X) \rightarrow K_0(Y)$  such that  $F^{K_0}([E^\bullet]) = [F(E^\bullet)]$ , for all  $E^\bullet \in D^b(X)$ . In other words, the above diagram commutes.

**Proposition 9.2.16.** *Let  $\mathcal{P} \in D^b(X \times Y)$ . If the integral functor  $\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  is an equivalence of categories, then the induced  $K$ -theoretic integral transform  $\Phi_{[\mathcal{P}]}^{K, X \rightarrow Y} : K_0(X) \rightarrow K_0(Y)$  is an isomorphism of abelian groups.*

*Proof.* Note that, for  $Y = X$  and  $\mathcal{P} = \mathcal{O}_{\Delta_X}$ , the induced  $K$ -theoretic integral transform

$$\Phi_{\mathcal{O}_{\Delta_X}}^{K, X \rightarrow X} : K_0(X) \rightarrow K_0(X)$$

is just the identity map  $K_0(X)$ . Since  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  is an equivalence of categories, its left adjoint and right adjoint functors are isomorphic, and they are quasi-inverse to  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$ . Note that, the left adjoint and right adjoint of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  are again Fourier-Mukai functors whose kernels are explicitly given by Proposition 9.1.17. Since the composite Fourier-Mukai functor  $\Phi_{\mathcal{P}_R}^{Y \rightarrow X} \circ \Phi_{\mathcal{P}}^{X \rightarrow Y} \cong \Phi_{\mathcal{O}_{\Delta_X}}$  (resp.,  $\Phi_{\mathcal{P}}^{X \rightarrow Y} \circ \Phi_{\mathcal{P}_R}^{Y \rightarrow X} \cong \Phi_{\mathcal{O}_{\Delta_Y}}$ ) is isomorphic to the identity functor on  $D^b(X)$  (resp.,  $D^b(Y)$ ), we have  $\Phi_{[\mathcal{P}]}^{K, X \rightarrow Y} \circ \Phi_{[\mathcal{P}_R]}^{K, Y \rightarrow X} \in \text{Aut}(K_0(Y))$  and  $\Phi_{[\mathcal{P}_R]}^{K, Y \rightarrow X} \circ \Phi_{[\mathcal{P}]}^{K, X \rightarrow Y} \in \text{Aut}(K_0(X))$ . Hence  $\Phi_{[\mathcal{P}]}^{K, X \rightarrow Y}$  is an isomorphism.  $\square$

**Remark 9.2.17.** For  $X$  and  $Y$  smooth projective  $k$ -varieties, following the similar procedure, one can also define integral transformation at the level of Chow groups  $\Phi_Z^{\text{Chow}, X \rightarrow Y} : \text{CH}^*(X) \rightarrow \text{CH}^*(Y)$  with kernel  $Z \in \text{CH}^*(X \times Y)$ . However, since Chow group and  $K_0$ -group coincides after tensoring with  $\mathbb{Q}$ , we don't gain much.

**9.3. Cohomological integral transformation.** Let  $X$  be a smooth projective variety over  $\mathbb{C}$ . We denote by  $H^*(X, \mathbb{Q})$  the cohomology of the constant sheaf  $\mathbb{Q}$  over the underlying complex manifold of  $X$ . Note that,  $H^*(X, \mathbb{Q})$  has a natural ring structure. Moreover, any continuous map of compact connected complex manifolds  $f : X \rightarrow Y$  induces a ring homomorphism

$$(9.3.1) \quad f^* : H^*(Y, \mathbb{Q}) \rightarrow H^*(X, \mathbb{Q}).$$



Let  $n = \dim(X)$  and  $m = \dim(Y)$ . Then by Poincaré duality

$$H^i(X, \mathbb{Q}) \cong H^{2n-i}(X, \mathbb{Q})^* \quad \text{and} \quad H^i(Y, \mathbb{Q}) \cong H^{2m-i}(Y, \mathbb{Q})^*$$

to define

$$(9.3.2) \quad f_* : H^*(X, \mathbb{Q}) \longrightarrow H^{*+2m-2n}(Y, \mathbb{Q})$$

as the dual of  $f_*$  in (9.3.1). Then we have the following projection formula:

$$(9.3.3) \quad f_*(f^*(\alpha) \cdot \beta) = \alpha \cdot f_*(\beta).$$

**Definition 9.3.4.** Let  $X$  and  $Y$  be smooth projective varieties over  $\mathbb{C}$ . Denote by  $p_X$  and  $p_Y$  the projection morphisms from  $X \times Y$  onto  $X$  and  $Y$ , respectively. Given a cohomology class  $\alpha \in H^*(X \times Y, \mathbb{Q})$ , we define the *cohomological integral transform*

$$\Phi_\alpha^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \longrightarrow H^*(Y, \mathbb{Q})$$

by  $\Phi_\alpha^{H, X \rightarrow Y}(\beta) := p_{Y*}(\alpha \cdot p_X^* \beta)$ , for all  $\beta \in H^*(X, \mathbb{Q})$ . Note that,  $\Phi_\alpha^{H, X \rightarrow Y}$  is  $\mathbb{Q}$ -linear.

Now one can use the *Chern character map*

$$(9.3.5) \quad \text{ch} : K_0(X) \longrightarrow H^*(X, \mathbb{Q})$$

to pass from Grothendieck's  $K_0$ -group to cohomology. Unfortunately, the Chern character map (9.3.5) does not commute with integral transforms at the level of  $K_0$ -group and cohomology (i.e., the following diagram is not commutative), in general.

$$\begin{array}{ccc} K_0(X) & \xrightarrow{\Phi_\alpha^{K_0, X \rightarrow Y}} & K_0(Y) \\ \text{ch} \downarrow & & \downarrow \text{ch} \\ H^*(X, \mathbb{Q}) & \xrightarrow{\Phi_{\text{ch}(\alpha)}^{H, X \rightarrow Y}} & H^*(Y, \mathbb{Q}) \end{array}$$

To remedy the situation, we need to consider the Todd class. By definition, Todd class is multiplicative, i.e.,

$$(9.3.6) \quad \text{td}(E_1 \oplus E_2) = \text{td}(E_1) \cdot \text{td}(E_2), \quad \forall E_1, E_2 \in \mathcal{V}ect(X),$$

and for a line bundle  $L$  on  $X$ , we have

$$(9.3.7) \quad \text{td}(L) := \frac{c_1(L)}{1 - \exp(-c_1(L))}.$$

For  $X$  a smooth variety over  $\mathbb{C}$ , we denote  $\text{td}(X) := \text{td}(TX)$ . The key ingredient for the compatibility relation is the Grothendieck-Riemann-Roch formula.

**Theorem 9.3.8** (Grothendieck-Riemann-Roch). *Let  $f : X \longrightarrow Y$  be a projective morphism of smooth projective  $k$ -varieties. Then for any  $\alpha \in K_0(X)$ , we have*

$$\text{ch}(f_!(\alpha)) \cdot \text{td}(Y) = f_*(\text{ch}(\alpha) \cdot \text{td}(X)).$$

Taking  $f : X \rightarrow \text{Spec}(k)$ , the structure morphism of  $X$ , we get the following.

**Corollary 9.3.9** (Hirzebruch-Riemann-Roch formula). *For any  $\alpha \in K_0(X)$ , we have*

$$\chi(\alpha) = \int_X \text{ch}(\alpha) \cdot \text{td}(X).$$

**Remark 9.3.10.** We define  $\chi(E^\bullet) := \sum_i (-1)^i \chi(E^i)$ , for all  $E^\bullet \in D^b(X)$ . By definition of the map  $[\ ] : D^b(X) \rightarrow K_0(X)$  we have  $[E^\bullet[j]] = \sum_i (-1)^i [E^{i+j}] = (-1)^j [E^\bullet]$  (see (9.2.4)). Since the Chern character map

$$\text{ch} : K_0(X) \rightarrow H^*(X, \mathbb{Q})$$

is additive, we have  $\text{ch}(E^\bullet) := \sum_i (-1)^i \text{ch}([E^i])$ . As a result, for any  $E^\bullet \in D^b(X)$ , from Corollary 9.3.9 we have

$$\chi(E^\bullet) = \sum_j (-1)^j \chi(E^j) = \sum_j (-1)^j \int_X \text{ch}([E^j]) \cdot \text{td}(X) = \int_X \text{ch}([E^\bullet]) \cdot \text{td}(X).$$

**Definition 9.3.11** (Mukai vector). *Mukai vector* of a class  $\alpha \in K_0(X)$  (resp., an object  $E^\bullet \in D^b(X)$ ) is defined to be the cohomology class

$$(9.3.12) \quad v(\alpha) := \text{ch}(\alpha) \cdot \sqrt{\text{td}(X)} \quad \left( \text{resp., } v(E^\bullet) := v([E^\bullet]) = \text{ch}([E^\bullet]) \cdot \sqrt{\text{td}(X)} \right).$$

Here  $\sqrt{\text{td}(X)}$  is the cohomology class whose square is  $\text{td}(X)$ , and its existence can be shown by explicit computation with the formal (but finite) power series calculation. It follows from the above definition that the *Mukai vector map*

$$(9.3.13) \quad v : K_0(X) \longrightarrow H^*(X, \mathbb{Q})$$

is additive.

**Corollary 9.3.14.** *Let  $X$  and  $Y$  be smooth projective  $\mathbb{C}$ -varieties, and let  $\alpha \in K_0(X \times Y)$ . Then for any  $\beta \in K_0(X)$ , we have*

$$(9.3.15) \quad \Phi_{v(\alpha)}^{H, X \rightarrow Y} \left( \text{ch}(\beta) \cdot \sqrt{\text{td}(X)} \right) = \text{ch} \left( \Phi_\alpha^{K, X \rightarrow Y}(\beta) \right) \cdot \sqrt{\text{td}(Y)}.$$

*In other words, the following diagram is commutative.*

$$(9.3.16) \quad \begin{array}{ccc} K_0(X) & \xrightarrow{\Phi_\alpha^{K, X \rightarrow Y}} & K_0(Y) \\ v \downarrow & & \downarrow v \\ H^*(X, \mathbb{Q}) & \xrightarrow{\Phi_{v(\alpha)}^{H, X \rightarrow Y}} & H^*(Y, \mathbb{Q}). \end{array}$$

*Proof.* It suffices to show that the following diagram is commutative.

$$\begin{array}{ccccccc}
 K_0(X) & \xrightarrow{p_X^*} & K_0(X \times Y) & \xrightarrow{\cdot \alpha} & K_0(X \times Y) & \xrightarrow{p_{Y!}} & K_0(Y) \\
 \downarrow v & & \downarrow v(-) \cdot (\sqrt{\text{td}(Y)})^{-1} & & \downarrow v(-) \cdot \sqrt{\text{td}(X)} & & \downarrow v \\
 H^*(X, \mathbb{Q}) & \xrightarrow{p_X^*} & H^*(X \times Y) & \xrightarrow{\cdot v(\alpha)} & H^*(X \times Y) & \xrightarrow{p_{Y*}} & H^*(Y, \mathbb{Q}).
 \end{array}$$

Commutativity of the first two squares follows from projection formula and the commutativity of the last square follows from Grothendieck-Riemann-Roch formula.  $\square$

**Remark 9.3.17.** In general, cohomological integral transform **neither preserve grading nor the multiplicative structure** of  $H^*(-, \mathbb{Q})$ , even for the Mukai vector  $\alpha = v(\beta)$ . However, it indeed preserve parity. More precisely, let  $\mathcal{P} \in D^b(X \times Y)$ , and consider the associated integral functor

$$\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \longrightarrow D^b(Y).$$

Denote by

$$(9.3.18) \quad \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \rightarrow H^*(Y, \mathbb{Q}), \quad \beta \longmapsto p_{Y*}(v(\mathcal{P}) \cdot p_X^* \beta)$$

the cohomological integral transform with the Kernel  $v(\mathcal{P}) = \text{ch}([\mathcal{P}]) \cdot \sqrt{\text{td}(X \times Y)} \in H^*(X \times Y, \mathbb{Q})$ . Since the characteristic classes  $\text{ch}$  and  $\text{td}$  takes values in even pieces of  $H^*(-, \mathbb{Q})$ , it follows that

$$\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(H^{\text{even}}(X, \mathbb{Q})) \subset H^{\text{even}}(Y, \mathbb{Q}) \quad \text{and} \quad \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(H^{\text{odd}}(X, \mathbb{Q})) \subset H^{\text{odd}}(Y, \mathbb{Q}).$$

Actually the singular cohomology theory  $H^*(X, \mathbb{Q})$  is not the right target for the Mukai vector to consider. A. Căldăraru argued that it is the Hochschild cohomology theory one need to consider for studying the map  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}$  to get the graded and multiplicative structure of the corresponding source and target of  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}$  be preserved. We shall discuss it later.

**Remark 9.3.19.** In general, given an exact equivalence of categories  $F : D^b(X) \longrightarrow D^b(Y)$ , we don't know how to associate a cohomological integral transform  $\tilde{F} : H^*(X, \mathbb{Q}) \longrightarrow H^*(Y, \mathbb{Q})$  with  $F$  without using the existence of kernel  $\mathcal{P}$  of  $F$  (coming from the Orlov's representability theorem 9.1.28).

**Proposition 9.3.20.** Let  $\Phi_{\mathcal{P}} : D^b(X) \rightarrow D^b(Y)$  and  $\Phi_{\mathcal{Q}} : D^b(Y) \rightarrow D^b(Z)$  be two integral functors with kernels  $\mathcal{P} \in D^b(X \times Y)$  and  $\mathcal{Q} \in D^b(Y \times Z)$ , respectively. Let  $\Phi_{\mathcal{R}} : D^b(X) \rightarrow D^b(Z)$  be their composite integral functor with  $\mathcal{R} = \mathcal{Q} * \mathcal{P} \in D^b(X \times Z)$ . Then the induced cohomological integral transforms  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}$ ,  $\Phi_{v(\mathcal{Q})}^{H, Y \rightarrow Z}$  and  $\Phi_{v(\mathcal{R})}^{H, X \rightarrow Z}$  satisfies  $\Phi_{v(\mathcal{Q})}^{H, Y \rightarrow Z} \circ \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} = \Phi_{v(\mathcal{R})}^{H, X \rightarrow Z}$ .

*Proof.* Similar to proof of Proposition 9.1.21.  $\square$

**Remark 9.3.21.** The analogous statement for  $K$ -theoretic integral transforms follows from Proposition 9.1.21 and the fact that the map  $D^b(X) \rightarrow K_0(X)$ , given by  $E^\bullet \mapsto [E^\bullet] := \sum_j (-1)^j [E^j]$ , is surjective. However, the map  $K_0(X) \rightarrow H^*(X, \mathbb{Q})$  is not surjective, in general. In fact, the image of the Mukai vector map  $v : K_0(X) \rightarrow H^*(X, \mathbb{Q})$  could be very small. Nevertheless, surprisingly we have the following.

**Proposition 9.3.22.** *If  $\mathcal{P} \in D^b(X \times Y)$  defines an equivalence of categories*

$$\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y),$$

*then the induced cohomological integral transform*

$$(9.3.23) \quad \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \rightarrow H^*(Y, \mathbb{Q})$$

*is an isomorphism of  $\mathbb{Q}$ -vector spaces.*

*Proof.* Since  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  is an exact equivalence, we have

$$\Phi_{\mathcal{P}_R}^{Y \rightarrow X} \circ \Phi_{\mathcal{P}}^{X \rightarrow Y} \cong \text{Id}_{D^b(X)} \cong \Phi_{\mathcal{O}_{\Delta_X}}^{X \rightarrow X} \quad \text{and} \quad \Phi_{\mathcal{P}}^{X \rightarrow Y} \circ \Phi_{\mathcal{P}_R}^{Y \rightarrow X} \cong \text{Id}_{D^b(Y)} \cong \Phi_{\mathcal{O}_{\Delta_Y}}^{Y \rightarrow Y}.$$

Then by above Proposition 9.3.20, we have

$$\begin{aligned} \Phi_{v(\mathcal{P}_R)}^{H, Y \rightarrow X} \circ \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} &= \Phi_{v(\mathcal{O}_{\Delta_X})}^{H, X \rightarrow X}, \quad \text{and} \\ \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} \circ \Phi_{v(\mathcal{P}_R)}^{H, Y \rightarrow X} &= \Phi_{v(\mathcal{O}_{\Delta_Y})}^{H, Y \rightarrow Y}. \end{aligned}$$

Therefore, it is enough to show that  $\Phi_{v(\mathcal{O}_{\Delta_X})}^{H, X \rightarrow X} = \text{Id}_{H^*(X, \mathbb{Q})}$  for any smooth projective  $\mathbb{C}$ -variety  $X$ . For this, using Grothendieck-Riemann-Roch theorem 9.3.8 for the diagonal embedding  $\iota : X \xrightarrow{\cong} \Delta_X \hookrightarrow X \times X$  and  $[\mathcal{O}_X] \in K_0(X)$ , we have

$$(9.3.24) \quad \text{ch}(\mathcal{O}_{\Delta_X}) \cdot \text{td}(X \times X) = \iota_* (\text{ch}(\mathcal{O}_X) \cdot \text{td}(X)) = \iota_* \text{td}(X).$$

Since  $\iota^* \sqrt{\text{td}(X \times X)} = \text{td}(X)$ , dividing both sides of (9.3.24) by  $\sqrt{\text{td}(X \times X)}$ , we have

$$(9.3.25) \quad v(\mathcal{O}_{\Delta_X}) = \text{ch}(\mathcal{O}_{\Delta_X}) \cdot \sqrt{\text{td}(X \times X)} = \iota_*(1).$$

Therefore, for any  $\beta \in H^*(X, \mathbb{Q})$ , we have

$$\begin{aligned} \Phi_{v(\mathcal{O}_{\Delta_X})}^{H, X \rightarrow X}(\beta) &= p_{2*}(v(\mathcal{O}_{\Delta_X}) \cdot p_1^*(\beta)) \\ &= p_{2*}(\iota_*(1) \cdot p_1^*(\beta)) \\ &= p_{2*}(\iota_*(1 \cdot \iota^* p_1^*(\beta))) = \beta. \end{aligned}$$

This completes the proof. □

We shall show that the above  $\mathbb{Q}$ -linear isomorphism  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}$  in (9.3.23) is, in fact, an isometry with respect to a natural quadratic form on  $H^*(-, \mathbb{Q})$ , known as the

*Mukai pairing:*

$$(9.3.26) \quad \langle v, v' \rangle_X := \int_X \exp \left( \frac{1}{2} c_1(X) \right) \cdot (v^\vee \cdot v'),$$

where for  $v = \sum_j v_j \in \bigoplus_j H^j(X, \mathbb{C})$  we define its dual  $v^\vee := \sum_j (\sqrt{-1})^j v_j \in \bigoplus_j H^j(X, \mathbb{C})$ , and  $c_1(X) := c_1(TX)$ . More precisely, we shall show that

$$(9.3.27) \quad \langle \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha), \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\beta) \rangle_Y = \langle \alpha, \beta \rangle_X, \quad \forall \alpha, \beta \in H^*(X, \mathbb{Q}).$$

**Definition 9.3.28.** For  $E^\bullet, F^\bullet \in D^b(X)$ , we define

$$\chi(E^\bullet, F^\bullet) := \sum_j (-1)^j \dim_k \operatorname{Ext}^j(E^\bullet, F^\bullet).$$

Let  $\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  be an equivalence of categories. Then the naturally induced isomorphism of  $k$ -vector spaces

$$(9.3.29) \quad \operatorname{Ext}_X^i(E^\bullet, F^\bullet) \cong \operatorname{Ext}_Y^i(\Phi_{\mathcal{P}}^{X \rightarrow Y}(E^\bullet), \Phi_{\mathcal{P}}^{X \rightarrow Y}(F^\bullet))$$

gives

$$(9.3.30) \quad \chi(E^\bullet, F^\bullet) = \chi(\Phi_{\mathcal{P}}^{X \rightarrow Y}(E^\bullet), \Phi_{\mathcal{P}}^{X \rightarrow Y}(F^\bullet)).$$

We shall see that both sides of (9.3.30) can be interpreted as natural bilinear pairing of Mukai vectors in  $H^*(-, \mathbb{Q})$ , known as the Mukai pairing.

Since  $X$  is a smooth projective  $k$ -variety, replacing  $E^\bullet$  and  $F^\bullet$  with bounded complexes of locally free coherent sheaves of  $\mathcal{O}_X$ -modules isomorphic to them in  $D^b(X)$ , one can show that

$$(9.3.31) \quad \chi(E^\bullet, F^\bullet) = \chi(X, (E^\bullet)^\vee \otimes F^\bullet).$$

Then by Hirzebruch-Riemann-Roch formula, we have

$$(9.3.32) \quad \begin{aligned} \chi(E^\bullet, F^\bullet) &= \chi(X, (E^\bullet)^\vee \otimes F^\bullet) = \int_X \operatorname{ch}(E^{\bullet\vee}) \cdot \operatorname{ch}(F^\bullet) \cdot \operatorname{td}(X) \\ &= \int_X (\operatorname{ch}(E^{\bullet\vee}) \cdot \sqrt{\operatorname{td}(X)}) \cdot (\operatorname{ch}(F^\bullet) \cdot \sqrt{\operatorname{td}(X)}) \\ &= \int_X v(E^{\bullet\vee}) \cdot v(F^\bullet). \end{aligned}$$

Now we need to determine  $v(E^{\bullet\vee})$  in terms of  $v(E^\bullet)$ . For this, we need the following notion of dual vector.

**Definition 9.3.33.** For  $\alpha = \sum_i \alpha_i \in \bigoplus_i H^{2i}(X, \mathbb{Q})$ , we define its *dual* vector

$$\alpha^\vee := \sum_i (-1)^i \alpha_i \in \bigoplus_i H^{2i}(X, \mathbb{Q}).$$

Clearly, for any  $\alpha = \sum_i \alpha_i, \beta = \sum_i \beta_i \in \bigoplus_i H^{2i}(X, \mathbb{Q})$ , we have

$$(9.3.34) \quad \begin{aligned} (\alpha + \beta)^\vee &= \alpha^\vee + \beta^\vee, \quad \text{and} \\ \alpha^\vee \cdot \beta^\vee &= \sum_i \sum_j (-1)^{i+j} \alpha_i \cdot \beta_j = (\alpha \cdot \beta)^\vee. \end{aligned}$$

**Lemma 9.3.35.** *With the above notations, we have*

$$v(E^{\bullet\vee}) = \text{ch}(E^{\bullet\vee}) \cdot \sqrt{\text{td}(X)} = v(E^\bullet)^\vee \cdot \exp\left(\frac{1}{2}c_1(X)\right),$$

where  $c_1(X) := c_1(TX)$ .

*Proof.* Recall that, for any locally free coherent sheaf of  $\mathcal{O}_X$ -modules  $E$  on  $X$ , we have  $c_i(E^\vee) = (-1)^i c_i(E)$  and  $\text{ch}_i(E^\vee) = (-1)^i \text{ch}_i(E)$ , for all  $i \geq 0$ . Therefore, we have

$$\begin{aligned} \text{ch}(E^\bullet)^\vee &= \left( \sum_i (-1)^i \text{ch}(E^i) \right)^\vee = \left( \sum_{j \geq 0} \left( \sum_i (-1)^i \text{ch}_j(E^i) \right) \right)^\vee \\ &= \sum_{j \geq 0} (-1)^j \left( \sum_i (-1)^i \text{ch}_j(E^i) \right) \\ &= \sum_i (-1)^i \sum_{j \geq 0} (-1)^j \text{ch}_j(E^i) \\ &= \sum_i (-1)^i \sum_{j \geq 0} \text{ch}_j((E^i)^\vee) = \text{ch}(E^{\bullet\vee}). \end{aligned}$$

Then we have,

$$\begin{aligned} v(E^\bullet)^\vee &= (\text{ch}(E^\bullet) \cdot \sqrt{\text{td}(X)})^\vee = \text{ch}(E^\bullet)^\vee \cdot \sqrt{\text{td}(X)}^\vee \\ \Rightarrow v(E^\bullet)^\vee \frac{\sqrt{\text{td}(X)}}{\sqrt{\text{td}(X)}^\vee} &= \text{ch}(E^{\bullet\vee}) \sqrt{\text{td}(X)} = v(E^{\bullet\vee}). \end{aligned}$$

Therefore, it suffices to show that  $\sqrt{\text{td}(X)} = \sqrt{\text{td}(X)}^\vee \cdot \exp(c_1(X)/2)$  or, equivalently,  $\text{td}(X) = \text{td}(X)^\vee \cdot \exp(c_1(X))$ . Since Todd class is multiplicative, using splitting principal, we can write it as  $\text{td}(X) = \prod_i \frac{\gamma_i}{1 - \exp(-\gamma_i)}$ . Using multiplicative property of dual as in (9.3.34), we have  $\text{td}(X)^\vee = \prod_i \frac{(-\gamma_i)}{1 - \exp(\gamma_i)}$ . Then using additivity of  $c_1$  we have,

$$\frac{\text{td}(X)}{\text{td}(X)^\vee} = \prod_i \frac{\gamma_i}{1 - \exp(-\gamma_i)} \prod_j \frac{1 - \exp(\gamma_j)}{-\gamma_j} = \prod_i \exp(\gamma_i) = \exp(c_1(TX)).$$

Hence the lemma follows.  $\square$

With the above observations in mind, it is natural to extend the Definition 9.3.33 to the following.

**Definition 9.3.36.** For  $\alpha = \sum_j \alpha_j \in \bigoplus_j H^j(X, \mathbb{C})$ , we define its dual

$$\alpha^\vee := \sum_j (\sqrt{-1})^j \alpha_j \in \bigoplus_j H^j(X, \mathbb{C}).$$

Clearly, the above definition of dual vector is compatible with Definition 9.3.33.

**Definition 9.3.37.** The *Mukai pairing* on  $H^*(X, \mathbb{C})$  is a quadratic form defined by

$$(9.3.38) \quad \langle \alpha, \beta \rangle_X := \int_X \exp\left(\frac{1}{2}c_1(X)\right) \cdot (\alpha^\vee \cdot \beta).$$

Here  $(\alpha^\vee \cdot \beta)$  is the intersection product. Now it follows from (9.3.32) and Lemma 9.3.35 that

$$(9.3.39) \quad \begin{aligned} \chi(E^\bullet, F^\bullet) &= \int_X v(E^{\bullet\vee}) \cdot v(F^\bullet) \\ &= \int_X v(E^\bullet)^\vee \cdot \exp\left(\frac{1}{2}c_1(X)\right) \cdot v(F^\bullet) = \langle v(E^\bullet), v(F^\bullet) \rangle. \end{aligned}$$

Note that, the Mukai pairing is non-degenerate  $\mathbb{C}$ -bilinear pairing on  $H^*(X, \mathbb{C})$ .

**Remark 9.3.40.** (i) It is clear from the above Definition 9.3.37 that if  $c_1(X) = 0$ , then  $\langle \cdot, \cdot \rangle_X$  is symmetric if  $\dim(X)$  is even, and alternating if  $\dim(X)$  is odd.  
(ii) If  $p_Y : X \times Y \rightarrow Y$  is the projection morphism, then for any  $\alpha \in H^*(X \times Y, \mathbb{C})$  we have,

$$(p_{Y*}(\alpha))^\vee = (-1)^{\dim(X)} p_{Y*}(\alpha^\vee).$$

**Proposition 9.3.41** (Andrei Căldăraru). *Let  $\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  be an equivalence of categories. Then the induced cohomological Fourier-Mukai transform*

$$\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \longrightarrow H^*(X, \mathbb{Q})$$

*is isometric with respect to the Mukai pairing; i.e., for all  $\alpha, \beta \in H^*(X, \mathbb{Q})$ , we have*

$$\langle \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha), \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\beta) \rangle_Y = \langle \alpha, \beta \rangle_X.$$

*Proof.* Since  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  is an exact equivalence of categories,  $\dim(X) = \dim(Y) = n$ , say. Since  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}$  is a  $\mathbb{Q}$ -linear isomorphism (see Proposition 9.3.22), it is enough to show that,

$$(9.3.42) \quad \langle \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha), \beta \rangle_Y = \langle \alpha, (\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y})^{-1}(\beta) \rangle_X,$$

for all  $\alpha \in H^*(X, \mathbb{Q})$  and  $\beta \in H^*(Y, \mathbb{Q})$ . Since  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  is an equivalence of categories, by Proposition 9.1.17  $\Phi_{\mathcal{P}_L}^{X \rightarrow Y}$  is a quasi-inverse of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$ , where  $\mathcal{P}_L = \mathcal{P}^\vee \otimes p_Y^*(\omega_Y)[n]$

and  $n = \dim(X) = \dim(Y)$ . Then by Proposition 9.3.20,  $(\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y})^{-1} = \Phi_{v(\mathcal{P}_L)}^{H, X \rightarrow Y}$ . Note that,

$$\begin{aligned} v(\mathcal{P}_L) &= v(\mathcal{P}^\vee \otimes p_Y^* \omega_Y[n]) = (-1)^n v(\mathcal{P}^\vee) \cdot \text{ch}(p_Y^* \omega_Y) \\ (9.3.43) \quad &= (-1)^n v(\mathcal{P}^\vee) \cdot p_Y^* \exp(-c_1(Y)). \end{aligned}$$

Now using multiplicative property of dual vectors (see (9.3.34)), Remark 9.3.40 (ii), Lemma 9.3.35 and equation (9.3.43), we have

$$\begin{aligned} &\langle \Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha), \beta \rangle_Y \\ &= \int_Y \exp(c_1(Y)/2) \cdot (p_{Y*}(v(\mathcal{P}) \cdot p_X^* \alpha))^\vee \cdot \beta \\ &= (-1)^n \int_Y \exp(c_1(Y)/2) \cdot p_{Y*} \left( (v(\mathcal{P}) \cdot p_X^* \alpha)^\vee \right) \cdot \beta \\ &= (-1)^n \int_{X \times Y} p_Y^*(\exp(c_1(Y)/2)) \cdot v(\mathcal{P})^\vee \cdot (p_X^* \alpha)^\vee p_Y^* \beta \\ &= (-1)^n \int_{X \times Y} p_Y^*(\exp(c_1(Y)/2)) \cdot v(\mathcal{P}^\vee) \cdot \exp(-c_1(X \times Y)/2) \cdot (p_X^* \alpha)^\vee p_Y^* \beta \\ &= \int_{X \times Y} p_X^* \exp(c_1(X)/2) \cdot p_X^* \alpha^\vee \cdot v(\mathcal{P}_L) \cdot p_Y^* \beta \\ &= \int_X \exp(c_1(X)/2) \cdot \alpha^\vee p_{X*}(v(\mathcal{P}_L) \cdot p_Y^* \beta) \\ &= \langle \alpha, \Phi_{v(\mathcal{P}_L)}^{H, Y \rightarrow X}(\beta) \rangle_X \end{aligned}$$

This completes the proof.  $\square$

**9.4. Derived Torelli theorem for complex elliptic curves.** Let  $C$  be a complex elliptic curve. We would like to know if we can reconstruct  $C$  from its bounded derived category  $D^b(C)$ . Since the canonical line bundle  $\omega_C$  is trivial, Bondal-Orlov's reconstruction theorem 8.1.1 does not apply here. However, by analyzing Hodge structure under cohomological Fourier-Mukai transforms, we can recover  $C$  from  $D^b(C)$  as follow.

Let  $X$  be a connected smooth projective variety over  $\mathbb{C}$ . By Hodge theory, for each  $i = 0, 1, \dots, 2 \dim_{\mathbb{C}}(X)$ , we have a direct sum decomposition

$$(9.4.1) \quad H^i(X, \mathbb{C}) = H^i(X, \mathbb{Q}) \otimes \mathbb{C} = \bigoplus_{p+q=i} H^{p,q}(X),$$

with  $\overline{H^{p,q}(X)} = H^{q,p}(X)$ . Moreover,  $H^{p,q}(X) \cong H^q(X, \Omega_X^p)$ . Since the Chern classes, and hence all characteristic classes, are algebraic (i.e., of the type  $(p, p)$ ), the Mukai



vector map factors through the algebraic part of the cohomology

$$(9.4.2) \quad v(-) := \text{ch}(-) \cdot \sqrt{\text{td}(X)} : K_0(X) \longrightarrow \bigoplus_p H^{p,p}(X) \cap H^{2p}(X, \mathbb{Q}).$$

Then we have the following.

**Proposition 9.4.3.** *Let  $X$  and  $Y$  be connected smooth complex projective varieties. Let  $\mathcal{P} \in D^b(X \times Y)$ . If  $\Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  is an equivalence of categories, then the induced cohomological Fourier-Mukai transform  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \rightarrow H^*(Y, \mathbb{Q})$  gives isomorphisms*

$$(9.4.4) \quad \bigoplus_{p-q=i} H^{p,q}(X) \xrightarrow{\sim} \bigoplus_{p-q=i} H^{p,q}(Y), \quad \forall i = 0, \pm 1, \dots, \pm \dim_{\mathbb{C}}(X).$$

*Proof.* Since  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  is an equivalence of categories, the induced  $\mathbb{Q}$ -linear homomorphism  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \rightarrow H^*(Y, \mathbb{Q})$  of rational cohomologies is an isomorphism by Proposition 9.3.22. Therefore, it is enough to show that its  $\mathbb{C}$ -linear extension (obtained by applying  $(-) \otimes_{\mathbb{Q}} \mathbb{C}$ )

$$\widetilde{\Phi}_{v(\mathcal{P})}^{H, X \rightarrow Y} : H^*(X, \mathbb{C}) \longrightarrow H^*(Y, \mathbb{C})$$

satisfies

$$\widetilde{\Phi}_{v(\mathcal{P})}^{H, X \rightarrow Y}(H^{p,q}(X)) \subseteq \bigoplus_{r-s=p-q} H^{r,s}(Y).$$

For this, let

$$(9.4.5) \quad \sum \alpha^{p',q'} \boxtimes \beta^{r,s},$$

with  $\alpha^{p',q'} \in H^{p',q'}(X)$  and  $\beta^{r,s} \in H^{r,s}(Y)$ , be the Künneth decomposition of  $v(\mathcal{P}) = \text{ch}(\mathcal{P}) \cdot \sqrt{\text{td}(X \times Y)}$ . Since the cohomology class  $v(\mathcal{P})$  is algebraic (i.e., of type  $(t, t)$ ), only terms with  $p' + r = q' + s$  contributes in (9.4.5).

Let  $\alpha \in H^{p,q}(X)$  be such that  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha) = p_{Y*}(v(\mathcal{P}) \cdot p_X^* \alpha) \in H^{r,s}(Y)$ . We need to show that  $(r, s)$  satisfies  $r - s = p - q$ . Note that, by above assumption, only terms in (9.4.5) with

$$(p, q) + (p', q') = (\dim(X), \dim(X))$$

contribute to  $\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha)$ . Hence  $p - q = q' - p' = r - s$ . In fact, we have

$$\Phi_{v(\mathcal{P})}^{H, X \rightarrow Y}(\alpha) = \sum \left( \int_X \alpha \wedge \alpha^{p',q'} \right) \beta^{r,s} \in \bigoplus_{r-s=p-q} H^{r,s}(Y).$$

This completes the proof.  $\square$

**Theorem 9.4.6.** *Let  $C$  be an elliptic curve over  $\mathbb{C}$ , and let  $C'$  be any connected smooth projective variety over  $\mathbb{C}$ . If there is an exact equivalence of categories  $F : D^b(C) \rightarrow D^b(C')$ , then  $C \cong C'$  as complex varieties.*

*Proof.* Since  $F$  is an exact equivalence, we have  $\dim(C') = \dim(C) = 1$ . Denote by  $g(C')$  the genus of the curve  $C'$ . If  $g(C') \neq 1$ , then  $\omega_{C'}$  is either ample or anti-ample, and hence  $C \cong C'$  by Bondal-Orlov's reconstruction theorem 8.1.1, which is not possible since  $C$  is an elliptic curve. Therefore,  $g(C') = 1$ , i.e.,  $C'$  is an elliptic curve.

Now by Orlov's representability theorem 9.1.28, there is an object  $\mathcal{P} \in D^b(C \times C')$ , unique up to isomorphism, such that  $F \cong \Phi_{\mathcal{P}}^{C \rightarrow C'}$ . Since  $v(\mathcal{P}) = \text{ch}(\mathcal{P}) \cdot \sqrt{\text{td}(C \times C')}$  is algebraic (i.e., of type  $(t, t)$ ), the induced cohomological Fourier-Mukai transform

$$(9.4.7) \quad \Phi_{v(\mathcal{P})}^{H, C \rightarrow C'} : H^*(C, \mathbb{Q}) \longrightarrow H^*(C', \mathbb{Q})$$

is a  $\mathbb{Q}$ -linear isomorphism satisfying

$$(9.4.8) \quad \begin{aligned} &\Phi_{v(\mathcal{P})}^{H, C \rightarrow C'}(H^1(C, \mathbb{Q})) = H^1(C', \mathbb{Q}), \text{ and} \\ &\Phi_{v(\mathcal{P})}^{H, C \rightarrow C'}(H^0(C, \mathbb{Q}) \oplus H^2(C, \mathbb{Q})) = H^0(C', \mathbb{Q}) \oplus H^2(C', \mathbb{Q}). \end{aligned}$$

Recall that, the weight 1 Hodge structure determines the elliptic curve completely. More precisely, we have  $C \cong H^{1,0}(C)^*/H_1(C, \mathbb{Z}) \cong H^{0,1}(C)/H^1(C, \mathbb{Z})$ .

Therefore, it suffices to show that the induced cohomological Fourier-Mukai transform in (9.4.7) descends to

$$(9.4.9) \quad \Phi_{v(\mathcal{P})}^{H, C \rightarrow C'} : H^*(C, \mathbb{Z}) \longrightarrow H^*(C', \mathbb{Z}).$$

Since  $C$  and  $C'$  are elliptic curves over  $\mathbb{C}$ , we have  $\text{td}(C \times C') = 1$  and  $\text{ch}(\mathcal{P}) = r + c_1(\mathcal{P}) + \frac{1}{2}(c_1^2(\mathcal{P}) - 2c_2(\mathcal{P}))$ . Note that, the degree 4 term  $\frac{1}{2}(c_1^2(\mathcal{P}) - 2c_2(\mathcal{P}))$  could a priori be non-integral. However, this term does not contribute to  $H^1(C, \mathbb{Q}) \rightarrow H^1(C', \mathbb{Q})$ . Hence the result follows.  $\square$

**Remark 9.4.10.** It turns out that,  $\text{ch}_2(\mathcal{P}) = \frac{1}{2}(c_1^2(\mathcal{P}) - 2c_2(\mathcal{P}))$  is also integral.

**9.5. Canonical ring and Kodaira dimension.** In this subsection, we briefly recall the notions of canonical ring and Kodaira dimension of a smooth projective  $k$ -variety, and use Fourier-Mukai functor to show derived equivalence implies isomorphism of canonical rings, and hence equality of Kodaira dimensions.

**Definition 9.5.1.** Let  $X$  be a smooth projective  $k$ -variety and  $L$  a line bundle on  $X$ . The *Kodaira dimension* of  $L$  on  $(X)$  is the integer  $\text{kod}(X, L) := m$  such that the function

$$(9.5.2) \quad \mathbb{Z} \rightarrow \mathbb{Z}, \quad \ell \mapsto h^0(L^\ell) := \dim_k H^0(X, L^\ell)$$

grows like a polynomial of degree  $m$ , for  $\ell \gg 0$ . If  $h^0(L^\ell) = 0$ , for all  $\ell > 0$ , we define  $\text{kod}(X, L) = -\infty$ . The integer  $\text{kod}(X) := \text{kod}(X, \omega_X)$  is called the *Kodaira dimension* of  $X$ .

For a line bundle  $L$  on  $X$ , the linear system  $|L|$  defines a rational morphism  $\varphi_L : X \dashrightarrow \mathbb{P}_k^{h^0(L)-1}$ . The associated graded  $k$ -algebra  $R(X, L) := \bigoplus_{i \geq 0} H^0(X, L^i)$  is called

the canonical ring of  $L$ . If  $\mathrm{kod}(X, L) \geq 0$ , it turns out that

$$\begin{aligned}\mathrm{kod}(X, L) &= \max\{\dim(\mathrm{Im}(\varphi_{L^i})) : i \geq 0\} \\ &= \mathrm{trdeg}_k Q(R(X, L)) - 1,\end{aligned}$$

where  $Q(R(X, L))$  is the field of fractions of  $R(X, L)$ . Moreover, we have  $\mathrm{kod}(X, L) \leq \mathrm{kod}(X)$ , for all  $L \in \mathrm{Pic}(X)$ . It is a well-known fact that Kodaira dimension is birational invariant, i.e., if  $X$  and  $Y$  are two birational smooth projective  $k$ -varieties, then  $\mathrm{kod}(X) = \mathrm{kod}(Y)$ .

For a smooth projective  $k$ -variety  $X$ , we define  $R(X) := R(X, \omega_X) = \bigoplus_{i \geq 0} H^0(X, \omega_X^i)$ .

**Proposition 9.5.3 (Orlov).** *Let  $X$  and  $Y$  be smooth projective  $k$ -varieties. If there is an exact equivalence  $F : D^b(X) \rightarrow D^b(Y)$ , then  $R(X) \cong R(Y)$  as graded  $k$ -algebras. In particular,  $\mathrm{kod}(X) = \mathrm{kod}(Y)$ .*

**Remark 9.5.4.** Since we are not assuming  $\omega_X$  is ample or anti-ample, we cannot conclude if  $\mathcal{O}_X$  is an invertible object in  $D^b(X)$ . Therefore, one cannot apply the arguments given in Step 1 and 2 of the proof of Bondal-Orlov's reconstruction Theorem 8.1.1 to obtain the above result! Here we need Orlov's representability theorem and Fourier-Mukai functors to prove this result.

To prove Proposition 9.5.3, we need the following result, which is easy to check.

**Proposition 9.5.5.** *Let  $X_1, X_2, Y_1$  and  $Y_2$  be smooth projective  $k$ -schemes. For each  $i = 1, 2$ , consider the objects  $\mathcal{P}_i \in D^b(X_i \times Y_i)$ , and denote by  $\mathcal{P}_1 \boxtimes \mathcal{P}_2 \in D^b((X_1 \times Y_1) \times (X_2 \times Y_2))$  their external derived tensor product.*

(i) *Consider the induced integral functors  $\Phi_{\mathcal{P}_i} : D^b(X_i) \rightarrow D^b(Y_i)$ , for  $i = 1, 2$ , and  $\Phi_{\mathcal{P}_1 \boxtimes \mathcal{P}_2} : D^b(X_1 \times X_2) \rightarrow D^b(Y_1 \times Y_2)$ . Then there is an isomorphism*

$$(9.5.6) \quad \Phi_{\mathcal{P}_1 \boxtimes \mathcal{P}_2}(E_1^\bullet \boxtimes E_2^\bullet) \cong \Phi_{\mathcal{P}_1}(E_1^\bullet) \boxtimes \Phi_{\mathcal{P}_2}(E_2^\bullet),$$

*which is functorial in  $E_i^\bullet \in D^b(X_i)$ , for all  $i = 1, 2$ .*

(ii) *If  $\Phi_{\mathcal{P}_i} : D^b(X_i) \rightarrow D^b(Y_i)$  is an equivalence of categories, for  $i = 1, 2$ , then*

$$\Phi_{\mathcal{P}_1 \boxtimes \mathcal{P}_2} : D^b(X_1 \times X_2) \rightarrow D^b(Y_1 \times Y_2)$$

*is also an equivalence of categories.*

(iii) *For  $\mathcal{R} \in D^b(X_1 \times X_2)$ , let  $\mathcal{S} = \Phi_{\mathcal{P}_1 \boxtimes \mathcal{P}_2}(\mathcal{R}) \in D^b(Y_1 \times Y_2)$ . Then the following diagram commutes.*

$$(9.5.7) \quad \begin{array}{ccc} D^b(X_1) & \xleftarrow{\Phi_{\mathcal{P}_1}^{Y_1 \rightarrow X_1}} & D^b(Y_1) \\ \Phi_{\mathcal{R}} \downarrow & & \downarrow \Phi_{\mathcal{S}} \\ D^b(X_2) & \xrightarrow{\Phi_{\mathcal{P}_2}} & D^b(Y_2) \end{array}$$

(It should be noted that,  $\mathcal{P}_1$  is used in the above diagram to define integral functor in the opposite direction).

We use the above Proposition with  $X_1 = X_2 = X$ ,  $Y_1 = Y_2 = Y$ ,  $\mathcal{P}_1 = \mathcal{P}$  and  $\mathcal{P}_2 = \mathcal{Q}$  in the proof of Proposition 9.5.3 below.

*Proof of Proposition 9.5.3.* By Orlov's representability theorem 9.1.28, there is an object  $\mathcal{P} \in D^b(X \times Y)$ , unique up to isomorphism, such that  $F \cong \Phi_{\mathcal{P}}^{X \rightarrow Y}$ . In particular, the left adjoint and the right adjoint functors of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$ ,

$$(9.5.8) \quad \Phi_{\mathcal{P}_L}^{Y \rightarrow X} : D^b(Y) \rightarrow D^b(X) \quad \text{and} \quad \Phi_{\mathcal{P}_R}^{Y \rightarrow X} : D^b(Y) \rightarrow D^b(X),$$

respectively, are isomorphic, and hence by uniqueness (up to isomorphism) of kernel in Orlov's representability theorem 9.1.28, we have

$$(9.5.9) \quad \mathcal{P}^\vee \otimes p_Y^* \omega_Y[n] =: \mathcal{P}_L \cong \mathcal{P}_R := \mathcal{P}^\vee \otimes p_X^* \omega_X[n],$$

where  $n = \dim(X) = \dim(Y)$  (c.f., Proposition 8.2.1).

Now we show that, the functor (note the change of direction from (9.5.8))

$$(9.5.10) \quad \Phi_{\mathcal{P}_R}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$$

is also an equivalence. Since the composite functor

$$(9.5.11) \quad D^b(X) \xrightarrow{\Phi_{\mathcal{P}}} D^b(Y) \xrightarrow{\Phi_{\mathcal{P}_R}} D^b(X)$$

is isomorphic to the identity functor on  $D^b(X)$ , again by uniqueness (up to isomorphism) of kernel, we have  $\mathcal{P} * \mathcal{P}_R := p_{13*}(p_{12}^* \mathcal{P} \otimes p_{23}^* \mathcal{P}_R) \cong \mathcal{O}_{\Delta_X}$ .

$$\begin{array}{ccccc}
 & & Y \times X & & \\
 & \swarrow \simeq & & \nwarrow p_{23} & \\
 X \times Y & \xleftarrow{p_{12}} & X \times Y \times X & \xleftarrow{\tau_{13}} & X \times Y \times X \\
 & \swarrow p_{23} & \downarrow p_{32} & \searrow p_{13} & \searrow p_{13} \\
 Y \times X & \xrightarrow{\sigma_{12}} & X \times Y & & X \times X \xleftarrow{\tau_{12}} X \times X \\
 & \simeq & & & \simeq
 \end{array}$$

Applying the automorphism  $\tau_{12} : X \times X \rightarrow X \times X$ , which interchanges two factors, we have

$$\begin{aligned}
 \mathcal{O}_{\Delta_X} &\cong \tau_{12}^* \mathcal{O}_{\Delta_X} \cong \tau_{12}^* p_{13*}(p_{12}^* \mathcal{P} \otimes p_{23}^* \mathcal{P}_R) \\
 &\cong p_{13*} \tau_{13}^* (p_{12}^* \mathcal{P} \otimes p_{23}^* \mathcal{P}_R) \\
 &\cong p_{13*} (p_{32}^* \mathcal{P} \otimes p_{21}^* \mathcal{P}_R) \\
 &\cong p_{13*} (p_{12}^* \mathcal{P}_R \otimes p_{23}^* \mathcal{P}).
 \end{aligned}$$

Therefore, the composite functor

$$(9.5.13) \quad D^b(X) \xrightarrow{\Phi_{\mathcal{P}_R}^{X \rightarrow Y}} D^b(Y) \xrightarrow{\Phi_{\mathcal{P}}^{Y \rightarrow X}} D^b(X)$$

is also isomorphic to the identity functor on  $D^b(X)$ . Since  $\Phi_{\mathcal{P}}^{Y \rightarrow X}$  is adjoint to  $\Phi_{\mathcal{P}_R}^{X \rightarrow Y}$ , we conclude that  $\Phi_{\mathcal{P}_R}^{X \rightarrow Y}$  is fully faithful.

Now interchanging the role of  $\mathcal{P}$  and  $\mathcal{Q} := \mathcal{P}_R \cong \mathcal{P}_L$ , and using the fact that  $\Phi_{\mathcal{Q}}^{Y \rightarrow X}$  is the quasi-inverse of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  and hence  $\Phi_{\mathcal{Q}}^{Y \rightarrow X}$  is fully faithful, the same argument shows that the composite functor

$$(9.5.14) \quad D^b(Y) \xrightarrow{\Phi_{\mathcal{P}}} D^b(X) \xrightarrow{\Phi_{\mathcal{Q}}} D^b(Y)$$

is also isomorphic to the identity functor on  $D^b(Y)$ . Therefore,  $\Phi_{\mathcal{Q}}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  is also an equivalence of categories.

By Proposition 9.5.5 the external derived tensor product  $\mathcal{Q} \boxtimes \mathcal{P} \in D^b((Y \times X) \times (X \times Y)) \cong D^b((X \times X) \times (Y \times Y))$  defines a Fourier-Mukai equivalence functor  $\Phi_{\mathcal{Q} \boxtimes \mathcal{P}} : D^b(X \times X) \rightarrow D^b(Y \times Y)$ , and if we define

$$(9.5.15) \quad \mathcal{S} := \Phi_{\mathcal{Q} \boxtimes \mathcal{P}}(\iota_* \omega_X^i) \in D^b(Y \times Y),$$

where  $\iota : X \hookrightarrow \Delta_X \subset X \times X$  is the diagonal embedding, then  $\Phi_{\mathcal{S}} : D^b(Y) \rightarrow D^b(Y)$  is an equivalence of categories, which can be computed as the composite functor

$$(9.5.16) \quad D^b(Y) \xrightarrow{\Phi_{\mathcal{Q}}} D^b(X) \xrightarrow{\Phi_{\iota_* \omega_X^i}} D^b(X) \xrightarrow{\Phi_{\mathcal{P}}} D^b(Y).$$

Since  $\Phi_{\iota_* \omega_X^i}^{X \rightarrow X} \cong S_X^i[-in]$ , where  $S_X$  is the Serre functor on  $X$  and  $n = \dim_k(X)$ , and since any equivalence of derived categories  $D^b(X) \rightarrow D^b(Y)$  commutes with Serre functors  $S_X$  and  $S_Y$ , we conclude that

$$(9.5.17) \quad \begin{aligned} \Phi_{\mathcal{S}} &\cong \Phi_{\mathcal{P}} \circ S_X^i[-in] \circ \Phi_{\mathcal{Q}} \\ &\cong \Phi_{\mathcal{P}} \circ \Phi_{\mathcal{Q}} \circ S_Y^i[-in] \\ &\cong S_Y^i[-in] \cong \Phi_{j_* \omega_Y^i}^{Y \rightarrow Y}, \end{aligned}$$

where  $j : Y \hookrightarrow \Delta_Y \subset Y \times Y$  is the diagonal embedding of  $Y$ . Then by uniqueness (up to isomorphism) of kernel in Orlov's representability theorem (Theorem 9.1.28), we conclude that  $\mathcal{S} \cong j_* \omega_Y^i$ . Then from (9.5.15) we have

$$(9.5.18) \quad \Phi_{\mathcal{Q} \boxtimes \mathcal{P}}(\iota_* \omega_X^i) = j_* \omega_Y^i, \quad \forall i \in \mathbb{Z}.$$

Since  $\Phi_{\mathcal{Q} \boxtimes \mathcal{P}}$  is an exact equivalence of categories, we have

$$(9.5.19) \quad \mathrm{Hom}_{D^b(X \times X)}(\iota_* \omega_X^p, \iota_* \omega_X^q) \cong \mathrm{Hom}_{D^b(Y \times Y)}(j_* \omega_Y^p, j_* \omega_Y^q), \quad \forall p, q \in \mathbb{Z}.$$

Putting  $p = 0$  and  $q$  arbitrary, the above isomorphism gives a  $k$ -linear isomorphism

$$(9.5.20) \quad \begin{aligned} H^0(X, \omega_X^q) &\cong \mathrm{Hom}_{D^b(X \times X)}(\iota_* \mathcal{O}_X, \iota_* \omega_X^q) \\ &\cong \mathrm{Hom}_{D^b(Y \times Y)}(j_* \mathcal{O}_Y, j_* \omega_Y^q) \\ &\cong H^0(Y, \omega_Y^q). \end{aligned}$$

As we have already seen in the Step 1 of the proof of the Theorem 8.1.1, the multiplicative structure of the canonical graded ring  $R(X) := \bigoplus_{i \geq 0} H^0(X, \omega_X^i)$  can be given by compositions, and hence is compatible with any exact functor. Therefore, the  $k$ -linear isomorphisms in (9.5.20) gives an isomorphism of graded  $k$ -algebras

$$(9.5.21) \quad R(X) := \bigoplus_{i \geq 0} H^0(X, \omega_X^i) \xrightarrow{\cong} R(Y) := \bigoplus_{i \geq 0} H^0(Y, \omega_Y^i).$$

This completes the proof.  $\square$

**Remark 9.5.22.** An immediate consequence of the above Proposition 9.5.3 is that  $\text{kod}(X) = \text{kod}(Y)$ . It is clear from the above proof that  $F$  gives rise to an isomorphism of graded anti-canonical  $k$ -algebras  $R(X, \omega_X^\vee) \cong R(Y, \omega_Y^\vee)$ , and hence  $\text{kod}(X, \omega_X^\vee) = \text{kod}(Y, \omega_Y^\vee)$ . The above Proposition 9.5.3 also provides an alternative proof of Bondal-Orlov's reconstruction theorem (Theorem 8.1.1) when both  $\omega_X$  and  $\omega_Y$  are ample or anti-ample.

**9.6. Derived Torelli theorem for K3 surface.** Let  $k$  be a field. A  $k$ -variety is a separated geometrically integral finite type  $k$ -scheme.

**Definition 9.6.1.** An algebraic K3 surface over  $k$  is a proper smooth  $k$ -variety  $X$  of dimension 2 such that  $\omega_X \cong \mathcal{O}_X$  and  $H^1(X, \mathcal{O}_X) = 0$ .

It is a well-known fact that, any smooth proper algebraic surface over an algebraically closed field is projective. Therefore, an algebraic K3 surface defined over an algebraically closed field is always projective.

In complex geometry, a K3 surface is a compact complex manifold  $X$  of dimension 2 with trivial canonical bundle and  $H^1(X, \mathcal{O}_X) = 0$ . This definition includes non-projective K3 surfaces. However, it turns out that any complex K3 surface is Kähler (not easy to see).

The complex analytic manifold  $X_{\text{an}}$  associated to a complex algebraic K3 surface  $X$  is again a K3 surface over  $\mathbb{C}$ . Moreover, the natural functor sending  $X$  to  $X_{\text{an}}$  (by Serre's GAGA principal) gives a full embedding of the category of complex algebraic K3 surfaces into the category of complex K3 surfaces.

**Proposition 9.6.2.** Let  $X$  be an algebraic K3 surface over  $\mathbb{C}$ . Let  $Y$  be a smooth projective variety over  $\mathbb{C}$ . If there is an exact equivalence of categories  $F : D^b(X) \rightarrow D^b(Y)$ , then  $Y$  is an algebraic K3 surface.

*Proof.* Hodge theory for a smooth complex projective surface  $S$  gives a direct sum decomposition (for each  $i \geq 0$ ),  $H^i(S, \mathbb{C}) = \bigoplus_{p+q=i} H^{p,q}(S)$ , with

$$(9.6.3) \quad \overline{H^{p,q}(S)} \cong H^{q,p}(S) \quad \text{and} \quad H^{p,q}(S) \cong H^q(S, \Omega_X^p),$$

for all  $p, q \geq 0$ . Since  $F$  is an exact equivalence of categories,  $Y$  is a surface with  $\omega_Y \cong \mathcal{O}_Y$  by Proposition 8.2.1. Since  $\Omega_S^2 \cong \mathcal{O}_S$ , for  $S \in \{X, Y\}$ , using (9.6.3), we have

$$(9.6.4) \quad h^{1,2}(X) = h^{2,1}(X) = h^{0,1}(X) \quad \text{and} \quad h^{1,2}(Y) = h^{2,1}(Y) = h^{0,1}(Y).$$

By Orlov's representability theorem 9.1.28, there is an object  $\mathcal{P} \in D^b(X \times Y)$ , unique up to isomorphism, such that  $F \cong \Phi_{\mathcal{P}}^{X \rightarrow Y}$ . For  $i = -1$ , the functor  $F \cong \Phi_{\mathcal{P}}^{X \rightarrow Y}$  induces an isomorphism

$$(9.6.5) \quad H^{0,1}(X) \oplus H^{1,2}(X) \xrightarrow{\cong} H^{0,1}(Y) \oplus H^{1,2}(Y),$$

(see Proposition 9.4.3). Since  $X$  is a K3 surface, using (9.6.5) and (9.6.4) we have

$$\begin{aligned} h^1(Y, \mathcal{O}_Y) &= h^{0,1}(Y) = \frac{1}{2}(h^{0,1}(Y) + h^{1,2}(Y)) \\ &= \frac{1}{2}(h^{0,1}(X) + h^{1,2}(X)) = h^{0,1}(X) = h^1(X, \mathcal{O}_X) = 0. \end{aligned}$$

Hence the result follows.  $\square$

Let  $X$  be a smooth projective surface over  $\mathbb{C}$ . Let  $E$  be a locally free coherent sheaf of  $\mathcal{O}_X$ -modules on  $X$ . Then by Hirzebruch-Riemann-Roch formula (Corollary 9.3.9), we have

$$(9.6.6) \quad \begin{aligned} \chi(E) &= \int_X \text{ch}(E) \cdot \text{td}(X) \\ &= \frac{1}{12}(c_1^2(X) + c_2(X)) + \frac{1}{2}c_1(E)c_1(X) + \frac{1}{2}(c_1^2(E) - 2c_2(E)). \end{aligned}$$

Putting  $E = \mathcal{O}_X$  in (9.6.6) we get Max Noether's formula (c.f., [Har77, p. 433])

$$(9.6.7) \quad \chi(\mathcal{O}_X) = \frac{1}{12}(c_1^2(X) + c_2(X)).$$

Now assume that  $X$  is an algebraic K3 surface over  $\mathbb{C}$ . Then  $h^0(X, \mathcal{O}_X) = 1$  and  $h^1(X, \mathcal{O}_X) = 0$ . Therefore, by Serre duality,  $h^2(X, \mathcal{O}_X) = h^0(X, \Omega_X^2) = 0$ , and hence  $\chi(X, \mathcal{O}_X) = 2$ . Since  $\omega_X$  is trivial,  $c_1(X) = 0$ . Therefore, interpreting  $c_2(X)$  as the *topological Euler number*  $e(X) := \sum_{i \geq 0} (-1)^i b_i(X)$ , we have  $e(X) = 24$ . Since  $H^{0,1}(X) \cong H^1(X, \mathcal{O}_X)$ , Hodge decomposition  $H^1(X, \mathbb{C}) = H^{1,0}(X) \oplus H^{0,1}(X)$  gives  $b_1(X) = 0$ , and hence by Poincaré duality,  $b_3(X) = 0$ . Then we have

$$(9.6.8) \quad b_0(X) = b_4(X) = 1, \quad b_1(X) = b_3(X) = 0, \quad \text{and} \quad b_2(X) = 22.$$



Moreover, the Hodge diamond for a K3 surface looks like

$$\begin{array}{ccccccc}
 & & h^{2,2} & & & & 1 \\
 & & & & & & \\
 & h^{2,1} & & h^{1,2} & & 0 & 0 \\
 h^{2,0} & & h^{1,1} & & h^{0,2} & 1 & 20 & 1 \\
 & h^{1,0} & & h^{0,1} & & 0 & 0 & \\
 & & h^{0,0} & & & & 1
 \end{array}$$

If  $L \in \text{Pic}(X)$ , then for  $\alpha = c_1(L) \in H^2(X, \mathbb{Z})$ , it follows from Hirzebruch-Riemann-Roch formula (9.6.6) that the self intersection number of  $\alpha$  is even:

$$(9.6.9) \quad \alpha^2 = 2\chi(L) - 4 \in 2\mathbb{Z}.$$

**Remark 9.6.10.** More generally, for compact Kähler manifold with  $c_1(X) = 0$ , one can show that the self intersection pairing

$$(9.6.11) \quad (\cdot, \cdot) : H^2(X, \mathbb{Z}) \times H^2(X, \mathbb{Z}) \longrightarrow \mathbb{Z}$$

is even (i.e.,  $\alpha^2 := (\alpha, \alpha) \in 2\mathbb{Z}$ , for all  $\alpha \in H^2(X, \mathbb{Z})$ ). From topological point of view, the evenness of the intersection pairing also follows from the vanishing of second Stiefel-Whitney class.

Since for any smooth compact complex surface  $X$ , the the Hodge-Frölicher spectral sequence

$$(9.6.12) \quad H^q(X, \Omega_X^p) \implies H^{p+q}(X, \mathbb{C})$$

degenerates at page  $E_1$ , we have an isomorphism of complex vector spaces

$$(9.6.13) \quad H^1(X, \mathbb{C}) \cong H^1(X, \mathcal{O}_X) \oplus H^0(X, \Omega_X^1).$$

The (exponential) short exact sequence of sheaves of abelian groups

$$(9.6.14) \quad 0 \longrightarrow \mathbb{Z} \longrightarrow \mathcal{O}_X \xrightarrow{\exp} \mathcal{O}_X^\times \longrightarrow 0$$

gives a long exact sequence of cohomologies

$$(9.6.15) \quad 0 \longrightarrow H^1(X, \mathbb{Z}) \longrightarrow H^1(X, \mathcal{O}_X) \longrightarrow H^1(X, \mathcal{O}_X^\times) \xrightarrow{c_1} H^2(X, \mathbb{Z})$$

$$(9.6.16) \quad \longrightarrow H^2(X, \mathcal{O}_X) \longrightarrow H^2(X, \mathcal{O}_X^\times) \longrightarrow H^3(X, \mathbb{Z}) \longrightarrow 0,$$

which, for  $X$  a K3 surface, gives  $H^1(X, \mathbb{Z}) = 0$  since  $H^1(X, \mathcal{O}_X) = 0$ . Therefore,  $H^1(X, \mathbb{C}) = 0$ , and we get  $H^0(X, \Omega_X^1) = 0$  for free! In other words, a complex K3 surface has no non-zero global vector fields. Since  $H^1(X, \mathbb{Z}) = 0$ , by Poincaré duality  $H^3(X, \mathbb{Z}) = 0$  up to torsion. Also  $H^0(X, \mathbb{Z}) \cong H^4(X, \mathbb{Z}) \cong \mathbb{Z}$ .

**Remark 9.6.17.** It is a non-trivial fact that any K3 surface is simply connected, and hence  $H^2(X, \mathbb{Z})$  is torsion free.



The most interesting structure on cohomology of a K3 surface  $X$  is its weight 2 Hodge structure

$$(9.6.18) \quad H^2(X, \mathbb{C}) = H^{2,0}(X) \oplus H^{1,1}(X) \oplus H^{0,2}(X).$$

Since  $H^{2,0}(X) \cong H^0(X, \Omega_X^2) = H^0(X, \mathcal{O}_X) = \mathbb{C}$ , we have  $h^{0,2}(X) = h^{2,0} = 1$ . Since  $H^1(X, \mathcal{O}_X) = 0$ , the first Chern class map

$$(9.6.19) \quad c_1 : \text{Pic}(X) \longrightarrow H^{1,1}(X) \cap H^2(X, \mathbb{Z})$$

is injective. Since  $b_2(X) = 22$ , this gives an upper bound for the Picard number  $\rho(X)$  of  $X$  (i.e., the rank of  $\text{Pic}(X)$ ):

$$(9.6.20) \quad \rho(X) := \text{rk}(\text{Pic}(X)) \leq 20.$$

**Remark 9.6.21.** Since the Hodge decomposition is orthogonal with respect to the intersection pairing, it is completely determined by the complex line  $H^{2,0}(X) \subset H^2(X, \mathbb{C})$ .

**Definition 9.6.22.** A *Hodge isometry* between two complex K3 surfaces  $X$  and  $Y$  is a group isomorphism

$$\varphi : H^2(X, \mathbb{Z}) \longrightarrow H^2(Y, \mathbb{Z})$$

such that

- (i) (intersection product is preserved):  $(\varphi(\alpha), \varphi(\beta)) = (\alpha, \beta)$ ,  $\forall \alpha, \beta \in H^2(X, \mathbb{Z})$ , and
- (ii)  $\varphi(H^{2,0}(X)) \subseteq H^{2,0}(Y)$ .

One of the most important theorem for a K3 surface is the global Torelli theorem.

**Theorem 9.6.23** (Global Torelli). *Let  $X$  and  $Y$  be two complex K3 surfaces. Then  $X$  and  $Y$  are isomorphic as complex varieties if and only if there is a Hodge isometry*

$$\varphi : H^2(X, \mathbb{Z}) \longrightarrow H^2(Y, \mathbb{Z}).$$

*Moreover, if  $\varphi$  maps at least one Kähler class of  $X$  to a Kähler class of  $Y$ , then there is a unique isomorphism  $f : X \xrightarrow{\simeq} Y$  such that  $f_* = \varphi$ .*

A natural question to ask at this point is if there is a cohomological criterion to decide equivalence of bounded derived categories of K3 surfaces? This is given by derived Torelli theorem for K3 surface. For this, we need some preliminary results.

Recall that, for  $E^\bullet \in D^b(X)$ , its Mukai vector

$$(9.6.24) \quad v(E^\bullet) := \text{ch}(E^\bullet) \cdot \sqrt{\text{td}(X)}$$

is algebraic, and hence lies in  $\widetilde{H}^{1,1}(X) \subset \widetilde{H}(X, \mathbb{Z})$ . Since  $c_1(X) = 0$  for  $X$  a K3 surface, we have  $\text{td}(X) = 1 + \frac{1}{2}c_1(X) + \frac{1}{12}(c_1^2(X) + c_2(X)) = c_2(X)/12 = \chi(X, \mathcal{O}_X) = 2$  (see Max

Noether's formula (9.6.7)). Therefore,  $\mathrm{td}(X) = (1, 0, 2)$  and hence  $\sqrt{\mathrm{td}(X)} = (1, 0, 1)$ . If we write  $v(E^\bullet) = (v_0(E^\bullet), v_1(E^\bullet), v_2(E^\bullet)) \in H^*(X, \mathbb{Z})$ , then we have

$$(9.6.25) \quad (v_0(E^\bullet), v_1(E^\bullet), v_2(E^\bullet)) = (\mathrm{rk}(E^\bullet), c_1(E^\bullet), \mathrm{rk}(E^\bullet) + \frac{1}{2}c_1^2(E^\bullet) - c_2(E^\bullet)).$$

Since the intersection pairing on  $H^2(X, \mathbb{Z})$  is even, the Mukai vector  $v(E^\bullet)$  is an integral cohomology class.

**Lemma 9.6.26 (Mukai).** *Let  $X$  and  $Y$  be two complex K3 surfaces. Then for any  $E^\bullet \in D^b(X \times Y)$ , its Mukai vector  $v(E^\bullet)$  is an integral cohomology class (i.e.,  $v(E^\bullet) \in H^*(X \times Y, \mathbb{Z})$ ).*

*Proof.* Recall that,  $v(E^\bullet) := \mathrm{ch}(E^\bullet) \cdot \sqrt{\mathrm{td}(X \times Y)}$ . If we write  $\sqrt{\mathrm{td}(X)} = (r, c, s) \in H^*(X, \mathbb{Q})$ , then  $\mathrm{td}(X) = (r^2, 2rc, 2rs)$ . Since  $c_1(X) = 0$  and  $c_2(X) = 24$ , for  $X$  a K3 surface, we have  $\mathrm{td}(X) = 1 + \frac{1}{2}c_1(X) + \frac{1}{12}(c_1^2(X) + c_2(X)) = (1, 0, 2)$ . Then  $\sqrt{\mathrm{td}(X)} = (r, c, s) = (1, 0, 1)$ , and we can compute  $\sqrt{\mathrm{td}(X \times Y)}$  as

$$(9.6.27) \quad \sqrt{\mathrm{td}(X \times Y)} = \pi_X^* \sqrt{\mathrm{td}(X)} \cdot \pi_Y^* \sqrt{\mathrm{td}(Y)} = \pi_X^*(1, 0, 1) \cdot \pi_Y^*(1, 0, 1),$$

where  $\pi_X : X \times Y \rightarrow X$  and  $\pi_Y : X \times Y \rightarrow Y$  are projection morphisms. Therefore, it is enough to show that  $\mathrm{ch}(E^\bullet) \in H^*(X \times Y, \mathbb{Z})$ , for all  $E^\bullet \in D^b(X \times Y)$ . Note that,

$$(9.6.28) \quad \mathrm{ch}(E^\bullet) = (\mathrm{rk}(E^\bullet), c_1(E^\bullet), \frac{1}{2}(c_1^2(E^\bullet) - 2c_2(E^\bullet)), \mathrm{ch}_3(E^\bullet), \mathrm{ch}_4(E^\bullet)),$$

where  $\mathrm{rk}(E^\bullet)$  and  $c_1(E^\bullet)$  are certainly integral classes. The Künneth formula gives

$$H^2(X \times Y, \mathbb{Z}) \cong \bigoplus_{p+q=2} H^p(X, \mathbb{Z}) \otimes H^q(Y, \mathbb{Z}) \cong H^2(X, \mathbb{Z}) \oplus H^2(Y, \mathbb{Z}),$$

since  $H^0(-, \mathbb{Z}) \cong \mathbb{Z}$  and  $H^1(-, \mathbb{Z}) = 0$  for complex K3 surfaces. Therefore,  $c_1(E^\bullet) \in H^2(X \times Y, \mathbb{Z})$  can be written as

$$c_1(E^\bullet) = \pi_X^* \alpha \oplus \pi_Y^* \beta,$$

for some  $\alpha \in H^2(X, \mathbb{Z})$  and  $\beta \in H^2(Y, \mathbb{Z})$ . Then

$$c_1^2(E^\bullet) = \pi_X^* \alpha^2 + 2\pi_X^* \alpha \cdot \pi_Y^* \beta + \pi_Y^* \beta^2,$$

which is even because the self intersection product on  $H^2(-, \mathbb{Z})$  is even for K3 surfaces. Therefore,  $\mathrm{ch}_1(E^\bullet) = \frac{1}{2}(c_1^2(E^\bullet) - 2c_2(E^\bullet))$  is integral.

Now it remains to show that  $\mathrm{ch}_3(E^\bullet)$  and  $\mathrm{ch}_4(E^\bullet)$  are integral. Since Todd class is multiplicative, using Grothendieck-Riemann-Roch theorem (Theorem 9.3.8) for the projection map  $\pi_Y : X \times Y \rightarrow Y$ , we have

$$(9.6.29) \quad \mathrm{ch}(\pi_{Y*} E^\bullet) = \pi_{Y*} (\mathrm{ch}(E^\bullet) \cdot \pi_X^* \mathrm{td}(X)).$$

Note that the self intersection pairing on  $H^2(-, \mathbb{Z})$  being even for K3 surfaces,

$$(9.6.30) \quad \mathrm{ch}(-) = \mathrm{rk}(-) + c_1(-) + \frac{1}{2}(c_1^2(-) + 2c_2(-))$$

is integral. Consider the Künneth decomposition

$$(9.6.31) \quad \sum_{i=0}^4 \text{ch}_i(E^\bullet) = \text{ch}(E^\bullet) = \sum_{p,q \leq 4} \gamma_p^q,$$

where  $\gamma_p^q := \pi_X^* \alpha_p \otimes \pi_Y^* \beta_q$  with  $\alpha_p \in H^p(X, \mathbb{Q})$  and  $\beta_q \in H^q(Y, \mathbb{Q})$ , for all  $p, q \in \{0, 1, 2, 3, 4\}$ . We have seen in the above computation that  $\gamma_p^q$  is integral for  $p + q \leq 4$ . Since  $\text{td}(X) = (1, 0, 2)$ , from (9.6.29) we have  $c_1(\pi_{Y!}(E^\bullet)) = \int_X \gamma_4^2 + 2\gamma_0^2$ , which implies that  $\gamma_4^2$  is integral. Similarly using Grothendieck-Riemann-Roch theorem for the projection morphism  $\pi_X : X \times Y \rightarrow X$ , interchanging the roles of  $X$  and  $Y$ , we see that  $\gamma_2^4$  is integral. Since  $\gamma_2^4$  and  $\gamma_4^2$  are the only terms contributing in  $\text{ch}_3(E^\bullet)$ , we conclude that  $\text{ch}_3(E^\bullet)$  is integral. Similarly, from  $\text{ch}_2(\pi_{Y!}(E^\bullet)) = \int_X \gamma_4^4 + 2\gamma_0^4$ , using integrality of second Chern character (c.f. (9.6.30)), we conclude that  $\gamma_4^4$  is integral, and hence  $\text{ch}_4(E^\bullet)$  is integral. This completes the proof.  $\square$

Let  $X$  be a K3 surface over  $\mathbb{C}$ . Since  $c_1(X) = 0$ , for any  $\alpha = (\alpha_0, \alpha_1, \alpha_2), \beta = (\beta_0, \beta_1, \beta_2) \in H^*(X, \mathbb{Z}) = H^0(X, \mathbb{Z}) \oplus H^2(X, \mathbb{Z}) \oplus H^4(X, \mathbb{Z})$ , the Mukai pairing on  $X$  is given by

$$(9.6.32) \quad \langle \alpha, \beta \rangle_X = \int_X \exp\left(\frac{1}{2}c_1(X)\right)(\alpha^\vee \cdot \beta) = \alpha_0 \cdot \beta_2 + \alpha_2 \cdot \beta_0 - \alpha_1 \cdot \beta_1,$$

(c.f. Definition 9.3.37).

**Remark 9.6.33.** It should be noted that, classically Mukai pairing on  $X$  is defined by

$$(9.6.34) \quad \langle (\alpha_0, \alpha_1, \alpha_2), (\beta_0, \beta_1, \beta_2) \rangle_X = \alpha_1 \cdot \beta_1 - \alpha_0 \cdot \beta_2 - \alpha_2 \cdot \beta_0,$$

which differs from the above definition (9.6.32) by a minus sign.

Mukai introduced a weight 2 Hodge structure on  $H^*(X, \mathbb{Z})$  by declaring  $H^0(X, \mathbb{C}) \oplus H^4(X, \mathbb{C})$  to be of type  $(1, 1)$  and by keeping the standard Hodge structure on  $H^2(X, \mathbb{C})$ . More precisely,

$$(9.6.35) \quad \begin{aligned} \tilde{H}^{1,1}(X) &= H^0(X, \mathbb{C}) \oplus H^4(X, \mathbb{C}) \oplus H^{1,1}(X), \\ \tilde{H}^{2,0}(X) &= H^{2,0}(X) \quad \text{and} \quad \tilde{H}^{0,2}(X) = H^{0,2}(X). \end{aligned}$$

We denote by  $\tilde{H}(X, \mathbb{Z})$  to mean  $H^*(X, \mathbb{Z})$  together with the Mukai pairing and this weight 2 Hodge structure.

**Definition 9.6.36.** Let  $X$  and  $Y$  be K3 surfaces over  $\mathbb{C}$ . With the above weight 2 Hodge structure structure on  $\tilde{H}(-, \mathbb{Z})$ , a *Hodge isometry* of two K3 surfaces  $X$  and  $Y$  is a group isomorphism

$$\varphi : \tilde{H}(X, \mathbb{Z}) \longrightarrow \tilde{H}(Y, \mathbb{Z})$$

such that

- (i) (Mukai pairing is preserved):  $\langle \varphi(\alpha), \varphi(\beta) \rangle_X = \langle \alpha, \beta \rangle_X$ ,  $\forall \alpha, \beta \in H^2(X, \mathbb{Z})$ , and
- (ii)  $\varphi(H^{2,0}(X)) \subseteq H^{2,0}(Y)$ .

**Corollary 9.6.37** (Mukai). [Muk87] *Let  $X$  be a complex K3 surface and  $Y$  is a smooth complex projective variety. Let  $E^\bullet \in D^b(X \times Y)$ . If  $\Phi_{E^\bullet}^{X \rightarrow Y} : D^b(X) \rightarrow D^b(Y)$  is an equivalence of categories, then the induced cohomological Fourier-Mukai transform  $\Phi_{v(E^\bullet)}^{H, X \rightarrow Y}$  defines a Hodge isometry (in the sense of Definition 9.6.36)*

$$\Phi_{v(E^\bullet)}^{H, X \rightarrow Y} : \tilde{H}(X, \mathbb{Z}) \xrightarrow{\sim} \tilde{H}(Y, \mathbb{Z}).$$

*Proof.* By Proposition 9.6.2,  $Y$  is also a K3 surface over  $\mathbb{C}$ . Recall that the Fourier-Mukai functor  $\Phi_{E^\bullet}^{X \rightarrow Y}$  induces a cohomological Fourier-Mukai transform

$$\Phi_{v(E^\bullet)}^{H, X \rightarrow Y} : H^*(X, \mathbb{Q}) \xrightarrow{\sim} H^*(Y, \mathbb{Q}), \quad \alpha \mapsto \pi_{Y!}(v(E^\bullet) \cdot \pi_X^* \alpha),$$

which is an isometry with respect to the Mukai pairing (see Proposition 9.3.41). Now by Lemma 9.6.26, we have  $\Phi_{v(E^\bullet)}^{H, X \rightarrow Y}(\alpha) \in H^*(Y, \mathbb{Z})$ , for all  $\alpha \in H^*(X, \mathbb{Z})$ . Since the quasi-inverse of  $\Phi_{E^\bullet}^{X \rightarrow Y}$  is also a Fourier-Mukai functor  $\Phi_{E_L^\bullet}^{Y \rightarrow X}$ , applying the above argument to the corresponding induced cohomological Fourier-Mukai transform  $\Phi_{v(E_L^\bullet)}^{H, Y \rightarrow X}$ , we can conclude that the induced map

$$(9.6.38) \quad \Phi_{v(E^\bullet)}^{H, X \rightarrow Y} : H^*(X, \mathbb{Z}) \longrightarrow H^*(Y, \mathbb{Z})$$

is an isomorphism, which is also an isometry with respect to the Mukai pairing. Therefore, to conclude that  $\Phi_{v(E^\bullet)}^{H, X \rightarrow Y}$  in (9.6.38) is a Hodge isometry, it is enough to show that its  $\mathbb{C}$ -linear extension sends  $H^{2,0}(X)$  to  $H^{2,0}(Y)$ , which follows from Proposition 9.4.3. This completes the proof.  $\square$

**Theorem 9.6.39** (Derived Torelli theorem for K3 surfaces). *Let  $X$  and  $Y$  be two K3 surfaces over  $\mathbb{C}$ . Then there is an exact equivalence of derived categories  $D^b(X) \rightarrow D^b(Y)$  if and only if there is a Hodge isometry  $\tilde{H}(X, \mathbb{Z}) \xrightarrow{\sim} \tilde{H}(Y, \mathbb{Z})$ .*

Since any exact equivalence  $D^b(X) \rightarrow D^b(Y)$  is isomorphic to a Fourier-Mukai functor by Orlov's representability theorem (Theorem 9.1.28), thanks to the above Corollary 9.6.37 of Mukai, it remains to show that existence of a Hodge isometry  $\tilde{H}(X, \mathbb{Z}) \xrightarrow{\sim} \tilde{H}(Y, \mathbb{Z})$  implies an exact equivalence of derived categories  $D^b(X) \xrightarrow{\sim} D^b(Y)$ . This part, due to Orlov [Orl97], is quite involved. It requires some theories from moduli space of semistable bundles on K3 surfaces, and some technical tools on integral functors. **We shall come back here to complete the proof after discussing required technologies.**

**Remark 9.6.40.** In general, the cohomological Fourier-Mukai transform  $\Phi_{v(E^\bullet)}^{H, X \rightarrow Y}$  need not preserve cohomological degree. In fact, it need not give a Hodge isometry  $H^2(X, \mathbb{Z}) \xrightarrow{\sim} H^2(Y, \mathbb{Z})$  in the sense of Definition 9.6.22; for otherwise by Global

Torelli theorem (Theorem 9.6.23) it would give an isomorphism of  $X$  with  $Y$ , which is not true in general.

In fact, for each K3 surface  $X$  there are only finitely many non-isomorphic K3 surfaces  $Y$  with exact equivalence  $D^b(X) \xrightarrow{\simeq} D^b(Y)$ . More surprisingly, for each positive integer  $n > 1$ , there is a K3 surface  $X$  with at least  $n$  non-isomorphic Fourier-Mukai partner  $Y$  (proof of this result, due to Oguiso [Ogu02], depends on a result on “almost primes” from analytic number theory).

**9.7. Geometric aspects of kernels of Fourier-Mukai functors.** In this subsection, we discuss a series of technical but useful results that shed light on the geometry of the support of the kernel of an integral functor

$$(9.7.1) \quad \Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \longrightarrow D^b(Y).$$

When  $\mathcal{P}$  is a locally free coherent sheaf on  $X \times Y$  (e.g., when  $\mathcal{P}$  is the Poincaré sheaf on the product of abelian variety and its dual), noting interesting can be said about the geometry of its support  $\text{Supp}(\mathcal{P})$ , which is just  $X \times Y$ . However, when the kernel  $\mathcal{P}$  is supported on a smaller subvariety of  $X \times Y$  (e.g., a graph of a morphism or a correspondence), then it encodes interesting geometric relation between  $X$  and  $Y$ . This usually happens when the canonical bundles of the variety has some kind of positivity property.

Let  $X$  be smooth projective  $k$ -variety. Recall that the support of an object  $E^\bullet \in D^b(X)$ , which we denote and define by

$$(9.7.2) \quad \text{Supp}(E^\bullet) := \bigcup_i \text{Supp}(\mathcal{H}^i(E^\bullet)),$$

is a closed subset of  $X$  with possibly many irreducible components. Note that, for any line bundle  $L$  on  $X$ , we have  $\text{Supp}(E^\bullet \otimes L) = \text{Supp}(E^\bullet)$ .

**Lemma 9.7.3.** *For any  $E^\bullet \in D^b(X)$ , we have  $\text{Supp}(E^\bullet) = \text{Supp}(E^{\bullet\vee})$ .*

*Proof.* Consider the spectral sequence

$$(9.7.4) \quad E_2^{p,q} := \text{Ext}^p(\mathcal{H}^{-q}(E^\bullet), \mathcal{O}_X) \implies E^{p+q} := \text{Ext}^{p+q}(E^\bullet, \mathcal{O}_X) \cong \mathcal{H}^{p+q}(E^{\bullet\vee}).$$

It follows from the above spectral sequence that  $\text{Supp}(E^{\bullet\vee}) \subseteq \text{Supp}(E^\bullet)$ . Since  $E^{\bullet\vee\vee} \cong E^\bullet$ , we get the reverse inclusion, which completes the proof.  $\square$

Let  $X$  and  $Y$  be smooth projective  $k$ -varieties, and  $\mathcal{P} \in D^b(X \times Y)$ . Let

$$(9.7.5) \quad \Phi_{\mathcal{P}}^{X \rightarrow Y} : D^b(X) \longrightarrow D^b(Y)$$

be an integral functor with kernel  $\mathcal{P}$ . Recall that the left and the right adjoint of  $\Phi_{\mathcal{P}}^{X \rightarrow Y}$  are integral functors with kernels  $\mathcal{P}_L := \mathcal{P}^\vee \otimes p_Y^* \omega_Y[\dim(Y)]$  and  $\mathcal{P}_R := \mathcal{P}^\vee \otimes$

$p_X^* \omega_X[\dim(X)]$ , respectively. Then from the above Lemma 9.7.3 we have,

$$(9.7.6) \quad \text{Supp}(\mathcal{P}) = \text{Supp}(\mathcal{P}^\vee) = \text{Supp}(\mathcal{P}_L) = \text{Supp}(\mathcal{P}_R).$$

When  $\Phi_{\mathcal{P}}$  is fully faithful, by uniqueness of kernel (up to isomorphism) ensured by Orlov's representability theorem (Theorem 9.1.28) we have

$$(9.7.7) \quad \mathcal{P} \otimes p_X^* \omega_X[\dim(X)] = \mathcal{P} \otimes p_Y^* \omega_Y[\dim(Y)].$$

Moreover, when  $\dim(X) = \dim(Y)$  (e.g., if  $\Phi_{\mathcal{P}}$  is an equivalence of categories), we can further deduce that

$$(9.7.8) \quad \mathcal{H}^i(\mathcal{P}) \otimes p_X^* \omega_X \cong \mathcal{H}^i(\mathcal{P}) \otimes p_Y^* \omega_Y, \quad \forall i \in \mathbb{Z}.$$

**Lemma 9.7.9.** *With the above notations, the natural projection*

$$(9.7.10) \quad \text{Supp}(\mathcal{P}) \longrightarrow X$$

*is surjective.*

*Proof.* □

**9.8. Relative integral functor and base change formula.** Let  $S$  be a proper  $k$ -scheme, to be used as a parameter scheme. For any  $k$ -scheme  $Z$ , define  $Z_S := Z \times S$ . Let  $X$  and  $Y$  be smooth projective  $k$ -schemes, and consider the projection morphisms

$$\pi_{12} : (X \times Y)_S := X \times Y \times S \longrightarrow X \times Y$$

$$\pi_{13} : (X \times Y)_S := X \times Y \times S \longrightarrow X_S := X \times S$$

$$\pi_{23} : (X \times Y)_S := X \times Y \times S \longrightarrow Y_S := Y \times S.$$

For  $\mathcal{P} \in D^b(X \times Y)$ , let  $\mathcal{P}_S := L\pi_{12}^* \mathcal{P} \in D^b((X \times Y)_S)$ . Define a *relative integral functor*

$$(9.8.1) \quad \Phi_{\mathcal{P}_S}^{X_S \rightarrow Y_S} : D^b(X_S) \longrightarrow D^b(Y_S)$$

by sending  $E^\bullet \in D^b(X_S)$  to

$$(9.8.2) \quad \Phi_{\mathcal{P}_S}^{X_S \rightarrow Y_S}(E^\bullet) := R\pi_{23*}(\iota_* \mathcal{P}_S \otimes^L L\pi_{13}^* E^\bullet) \in D^b(Y_S),$$

where  $\iota : X_S \times_S Y_S \hookrightarrow X_S \times Y_S$ .

**Proposition 9.8.3.** *Let  $f : T \longrightarrow S$  be a morphism of proper  $k$ -schemes. For any  $k$ -scheme  $Z$ , we denote by  $f_Z$  the induced morphism  $f_Z : Z_T \longrightarrow Z_S$ . Let  $X, Y$  be smooth projective  $k$ -schemes. Denote by  $\pi_{ij}^{XY?}$  the projection morphism from  $X \times Y \times ?$  onto the  $(i, j)$ -th factor, where  $? \in \{S, T\}$ . For  $\mathcal{P} \in D^b(X \times Y)$ , let  $\mathcal{P}_? := (\pi_{12}^{XY?})^* \mathcal{P}$ , where  $? \in \{S, T\}$ . Then there is a functorial isomorphism of functors*

$$(9.8.4) \quad Lf_Y^* \circ \Phi_{\mathcal{P}_S}^{X_S \rightarrow Y_S} \cong \Phi_{\mathcal{P}_T}^{X_T \rightarrow Y_T} \circ Lf_X^*.$$

*Proof.* For any  $E^\bullet \in D^b(X_S)$ , we have

$$\begin{aligned}
 Lf_Y^* \circ \Phi_{\mathcal{P}_S}^{X_S \rightarrow Y_S}(E^\bullet) &\cong Lf_Y^*(R(\pi_{23}^{XYS})_*(\mathcal{P}_T \otimes^L (\pi_{13}^{XYS})^* E^\bullet)) \\
 &\cong R(\pi_{23}^{XYT})_*(Lf_{X \times Y}^*((\pi_{13}^{XYS})^* E^\bullet \otimes^L \mathcal{P}_S)), \text{ by base change.} \\
 &\cong R(\pi_{13}^{XYT})_*((Lf_X^* E^\bullet) \otimes^L \mathcal{P}_T) \\
 &= (\Phi_{\mathcal{P}_T}^{X_T \rightarrow Y_T} \circ Lf_X^*)(E^\bullet).
 \end{aligned}$$

This completes the proof.  $\square$

The following proposition can be considered as the first step towards recovering the kernel of an integral transform, uniquely up to isomorphism.

**Proposition 9.8.5.** *Let  $X$  and  $Y$  be smooth projective  $k$ -schemes. Denote by  $\pi_{ij}$  the projection morphism from  $X \times X \times Y$  onto the  $(i, j)$ -th factor. Let  $\mathcal{P} \in D^b(X \times Y)$ , and  $\mathcal{P}_X := \pi_{23}^* \mathcal{P} \in D^b(X \times X \times Y)$ . Then*

$$\mathcal{P} \cong \Phi_{\mathcal{P}_X}^{X \times X \rightarrow X \times Y}(\mathcal{O}_\Delta),$$

where  $\Delta \subset X \times X$  is the image of the diagonal embedding  $X \rightarrow X \times X$ .

*Proof.* Let  $\delta : X \hookrightarrow X \times X$  be the diagonal embedding and  $\delta_Y : X \times Y \xrightarrow{\delta \times \text{Id}_Y} X \times X \times Y$  the induced embedding. Note that,  $\mathcal{O}_\Delta \cong \delta_* \mathcal{O}_X$ . Let  $\pi_X : X \times Y \rightarrow X$  be the projection morphism. Then we have

$$\begin{aligned}
 \Phi_{\mathcal{P}_X}^{X \times X \rightarrow X \times Y}(\mathcal{O}_\Delta) &= R\pi_{23*}(\mathcal{P}_X \otimes^L \pi_{12}^*(\delta_* \mathcal{O}_X)) \\
 &\cong R\pi_{23*}(\pi_{23}^* \mathcal{P} \otimes^L \delta_{Y*} \pi_X^* \mathcal{O}_X) \\
 &\cong R\pi_{23*}(\delta_{Y*} \delta_Y^* \pi_{23}^* \mathcal{P}) \\
 &\cong R\pi_{23*}(\delta_{Y*} \mathcal{P}) \cong \mathcal{P}.
 \end{aligned}$$

$\square$

## 9.9. Proof of Orlov's representability theorem.

## 9.10. Bondal-Orlov's reconstruction theorem revisited.

## 10. GROTHENDIECK GROUP

**Definition 10.0.1.** Let  $\mathcal{A}$  be a small abelian category. The *Grothendieck group* of  $\mathcal{A}$ , denoted by  $K_0(\mathcal{A})$ , is the quotient of the free abelian group generated by the set of all isomorphism classes of objects of  $\mathcal{A}$  by its normal subgroup generated by all elements  $[B] - [A] - [C]$ , where  $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$  is an exact sequence in  $\mathcal{A}$ .



Let  $\mathcal{A}$  be an abelian category. For an object  $A \in \mathcal{A}$ , we denote by  $A^\bullet \in \text{Kom}(\mathcal{A})$  the complex defined by

$$A^i = \begin{cases} A, & \text{if } i = 0, \\ 0, & \text{if } i \neq 0. \end{cases}$$

We also denote by  $A^\bullet \in D^b(\mathcal{A})$ , the object in  $D^b(\mathcal{A})$  represented by the complex  $A^\bullet$ .

**Definition 10.0.2.** Let  $\mathcal{T}$  be a small triangulated category. For example,  $\mathcal{T}$  can be the bounded derived category  $D^b(\mathcal{A})$  of a small abelian category  $\mathcal{A}$ . Let  $F(\mathcal{T})$  be the free abelian group generated by the set of all objects of  $\mathcal{T}$ . Let  $\mathcal{R}(\mathcal{T})$  be the normal subgroup of  $F(\mathcal{T})$  generated by the elements  $[A] + [C] - [B] \in F(\mathcal{A})$ , whenever there is a distinguished triangle

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

in  $\mathcal{T}$ . The quotient abelian group

$$(10.0.3) \quad K_0(\mathcal{T}) := F(\mathcal{T})/\mathcal{R}(\mathcal{T})$$

is called the *Grothendieck group* of  $\mathcal{T}$ .

**Remark 10.0.4.** It follows from the axiom (TR3) in Definition 1.2.4 that  $A[1] = 0$  in  $K_0(\mathcal{T})$ .

The following proposition establishes relation between  $K_0(\mathcal{A})$  and  $K_0(D^b(\mathcal{A}))$ .

**Proposition 10.0.5.** Let  $\mathcal{A}$  be a small abelian category, and let  $D^b(\mathcal{A})$  be the bounded derived category of  $\mathcal{A}$ . Then the natural functor  $\iota : \mathcal{A} \longrightarrow D^b(\mathcal{A})$  defined by sending an object  $A \in \mathcal{A}$  to  $A^\bullet \in D^b(\mathcal{A})$  induces an isomorphism of their Grothendieck groups  $K_0(\mathcal{A}) \xrightarrow{\cong} K_0(D^b(\mathcal{A}))$ .

## 11. BRIDGELAND STABILITY

The definition of stability condition generalized in different ways from curve to higher dimensional varieties. We follow [MS17, BBHR09, Huy06].

**11.1. Stability condition in an abelian category.** Let  $\mathcal{A}$  be an abelian category.

**Definition 11.1.1.** A *subobject* of an object  $E \in \mathcal{A}$  is a monomorphism  $\iota : F \hookrightarrow E$ .

Let  $\iota_1 : F_1 \hookrightarrow E$  and  $\iota_2 : F_2 \hookrightarrow E$  be two subobjects of  $E \in \mathcal{A}$ . Since direct sum of two objects in  $\mathcal{A}$  is both product and coproduct in  $\mathcal{A}$ , by the universal property of coproduct there is a unique morphism  $\varphi : F_1 \oplus F_2 \rightarrow E$  such that the following diagram commutes.

$$\begin{array}{ccccc} & & E & & \\ & \nearrow \iota_1 & \uparrow \varphi & \nwarrow \iota_2 & \\ F_1 & \longrightarrow & F_1 \oplus F_2 & \longleftarrow & F_2 \end{array}$$



Since the image of  $\varphi : F_1 \oplus F_2 \rightarrow E$  is the kernel of the cokernel  $E \rightarrow \text{Coker}(\varphi)$ ,  $\text{im}(\varphi) \hookrightarrow E$  is a monomorphism, and hence is a *subobject* of  $E$ , denoted by  $F_1 + F_2$ . We denote by  $F_1 \cap F_2$  the kernel of the epimorphism  $F_1 \oplus F_2 \rightarrow \text{im}(\varphi)$  in  $\mathcal{A}$ . Thus, we have an exact sequence

$$(11.1.2) \quad 0 \longrightarrow F_1 \cap F_2 \longrightarrow F_1 \oplus F_2 \longrightarrow F_1 + F_2 \longrightarrow 0.$$

Note that,  $F_1 \cap F_2$  is the kernel of both composite morphisms

$$(11.1.3) \quad F_1 \xrightarrow{\iota_1} E \longrightarrow \text{Coker}(\iota_2) \quad \text{and} \quad F_2 \xrightarrow{\iota_2} E \longrightarrow \text{Coker}(\iota_1).$$

Therefore,  $F_1 \cap F_2$  is a subobject of both  $F_1$  and  $F_2$ , and hence of  $E$ . Note that, for any two morphisms  $f_i : A_i \rightarrow B$ ,  $i = 1, 2$ , their fiber product  $A_1 \times_{f_1, B, f_2} A_2$  exists in  $\mathcal{A}$ , and can be described as  $\text{Ker}((f_1, -f_2) : A_1 \oplus A_2 \rightarrow B)$ . In particular, the *preimage* (fiber product) of a subobject  $C \subset B$  along a morphism  $f : A \rightarrow B$  exists uniquely as a subobject of  $A$ .

**Remark 11.1.4.** Note that, “being a subobject” is a transitive relation on  $\text{Ob}(\mathcal{C})$ . (This may fail to hold if we consider equivalence class of monomorphisms instead of just monomorphism).

Let  $\mathcal{A}$  be an abelian category. Denote by  $K_0(\mathcal{A})$  the Grothendieck group of  $\mathcal{A}$  (c.f., Definition 10.0.1). For any complex number  $z$ , we denote by  $\text{Im}(z)$  (resp.,  $\text{Re}(z)$ ) the *imaginary part* (resp., the *real part*) of  $z$ .

**Definition 11.1.5.** A *stability function* on  $\mathcal{A}$  is an additive group homomorphism

$$Z : K_0(\mathcal{A}) \longrightarrow \mathbb{C}$$

such that for any non-zero object  $A \in \mathcal{A}$ , we have  $\text{Im}(Z(A)) \geq 0$ , and if  $\text{Im}(Z(A)) = 0$ , then  $\text{Re}(Z(A)) < 0$ .

Note that, “ $\text{Im}(Z(A)) \geq 0, \forall A \in \mathcal{A}$ ” **does not imply** that “ $\text{Im}(Z(B)) \geq 0, \forall B \in K_0(\mathcal{A})$ ”.

Given a stability function  $Z : K_0(\mathcal{A}) \rightarrow \mathbb{C}$ , we may think of

$$\deg_Z(A) := -\text{Re}(Z(A)) \quad \text{and} \quad \text{rk}_Z(A) := \text{Im}(Z(A))$$

to be the *degree* and the *rank* of  $A$  with respect to the stability function  $Z$ , respectively. We may define the *slope* of  $A \in \mathcal{A} \setminus \{0\}$  with respect to  $Z$  by

$$(11.1.6) \quad \mu_Z(A) := \begin{cases} \frac{\deg_Z(A)}{\text{rk}_Z(A)}, & \text{if } \text{rk}_Z(A) \neq 0, \text{ and} \\ +\infty, & \text{otherwise.} \end{cases}$$

**Example 11.1.7.** Let  $X$  be a smooth projective curve defined over an algebraically closed field  $k$ . Let  $\mathcal{Coh}(X)$  be the category of coherent sheaves of  $\mathcal{O}_X$ -modules on  $X$ .

Let  $Z : K_0(\mathfrak{Coh}(X)) \longrightarrow \mathbb{C}$  be the additive group homomorphism defined by sending a non-zero object  $E \in \mathfrak{Coh}(X)$  to

$$Z(E) := -\deg(E) + \sqrt{-1} \cdot \mathrm{rk}(E) \in \mathbb{C}.$$

Clearly,  $Z$  is a stability function on  $\mathfrak{Coh}(X)$ . Note that,  $\mu_Z(E)$  coincides with the usual slope  $\mu(E) := \deg(E)/\mathrm{rk}(E)$  of  $E$ , and hence in this case,  $Z$ -(semi)stability coincides with the usual slope (semi)stability of coherent sheaves on  $X$ .

Let  $X$  be a smooth projective variety of dimension  $n \geq 2$  defined over an algebraically closed field  $k$ . Fix an ample class  $\omega \in \mathrm{Amp}(X) \subseteq N^1(X) := \mathrm{NS}(X) \otimes_{\mathbb{Z}} \mathbb{R}$ , and a divisor class  $B \in N^1(X)$ .

**Definition 11.1.8** (K. Matsuki, R. Wentworth). The  *$B$ -twisted Chern character* of  $E \in \mathfrak{Coh}(X)$  is defined by

$$\mathrm{ch}^B(E) := \mathrm{ch}(E) \cdot e^{-B} = \sum_{i \geq 0} \mathrm{ch}_i(E) \cdot \sum_{j \geq 0} \frac{(-1)^j}{j!} B^j.$$

Thus, for  $i \geq 0$ , the  *$B$ -twisted  $i$ -th Chern character of  $E$* , denoted  $\mathrm{ch}_i^B(E)$ , are given by

$$\begin{aligned} \mathrm{ch}_0^B(E) &= \mathrm{ch}_0(E) = \mathrm{rk}(E), \\ \mathrm{ch}_1^B(E) &= \mathrm{ch}_1(E) - \mathrm{ch}_0(E) \cdot B, \\ \mathrm{ch}_2^B(E) &= \mathrm{ch}_2(E) - \mathrm{ch}_1(E) \cdot B + \frac{1}{2} \mathrm{rk}(E) \cdot B^2, \end{aligned}$$

and so on. Note that, taking  $B = 0$ , we get back the usual Chern characters.

Define an additive group homomorphism

$$Z_{\omega,B} : K_0(\mathfrak{Coh}(X)) \longrightarrow \mathbb{C}$$

by sending a non-zero object  $E$  of  $\mathfrak{Coh}(X)$  to the complex number

$$(11.1.9) \quad Z_{\omega,B}(E) := -\omega^{n-1} \cdot \mathrm{ch}_1^B(E) + \sqrt{-1} \cdot \omega^n \cdot \mathrm{ch}_0^B(E).$$

If  $T$  is a *torsion* coherent sheaf on  $X$  supported in dimension  $\leq n-2$ , then  $\mathrm{rk}(T) = 0$ , and the line bundle  $\det(E)$  admits a nowhere vanishing global section (c.f., [Kob87, Proposition 5.6.14]). Then  $\det(T) \cong \mathcal{O}_X$ , and hence  $\mathrm{ch}_1(T) = 0$ . Therefore,  $Z_{\omega,B}(T) = 0$ . This shows that,  $Z_{\omega,B}$  is *not a stability function*.

**Remark 11.1.10.** Let  $\mathfrak{Coh}_{\leq n-2}(X)$  be the full subcategory of coherent sheaves on  $X$  whose supports have dimension  $\leq n-2$ , and let  $\mathcal{A}$  be the localized category

$$\mathfrak{Coh}_{n,n-2}(X) = \mathfrak{Coh}(X) / \mathfrak{Coh}_{\leq n-2}(X).$$

Then the function

$$Z_{\omega,B} : K_0(\mathcal{A}) \longrightarrow \mathbb{C}$$

as defined in (11.1.9) above, is a stability function.

**Definition 11.1.11.** A *stability condition* is a pair  $(\mathcal{A}, Z)$ , where  $\mathcal{A}$  is an abelian category and  $Z : K_0(\mathcal{A}) \rightarrow \mathbb{C}$  is a stability function such that for any non-zero object  $E$  of  $\mathcal{A}$ , there is a filtration of  $E$  by its subobjects

$$(11.1.12) \quad 0 = E_0 \subsetneq E_1 \subsetneq \cdots \subsetneq E_\ell = E,$$

such that all  $E_i/E_{i-1}$  are  $Z$ -semistable, and their  $Z$ -slopes satisfies

$$\mu_Z(E_1) > \mu_Z(E_2/E_1) > \cdots > \mu_Z(E_\ell/E_{\ell-1}).$$

Such a filtration (11.1.12) is known as *Harder-Narasimhan filtration* of  $E$ .

**Proposition 11.1.13.** Let  $\mathcal{A}$  be an abelian category. Given a stability function  $Z : K_0(\mathcal{A}) \rightarrow \mathbb{C}$ , Harder-Narasimhan filtration of an object  $E \in \mathcal{A}$ , if it exists, is unique up to isomorphism in  $\mathcal{A}$ .

Existence of Harder-Narasimhan filtration requires some additional assumption on the category  $\mathcal{A}$  and the stability function  $Z$ . For this we need some definitions.

**Definition 11.1.14.** An additive category  $\mathcal{A}$  is said to be *noetherian* if for any object  $E \in \mathcal{A}$ , and any ascending chain of subobjects

$$E_0 \subseteq E_1 \subseteq E_2 \subseteq \cdots \subseteq E,$$

of  $E$ , there is an integer  $i_0 \geq 0$  such that  $E_i = E_{i+1}$ , for all  $i \geq i_0$ .

**Lemma 11.1.15.** Let  $\mathcal{A}$  be a noetherian abelian category. Let  $Z : K_0(\mathcal{A}) \rightarrow \mathbb{C}$  be a stability function. If the image of the imaginary part of  $Z$ ,

$$\text{Im}(Z) : K_0(\mathcal{A}) \rightarrow \mathbb{R},$$

is discrete in  $\mathbb{R}$ , then for any object  $E \in \mathcal{A}$ , there is a number  $D_E \in \mathbb{R}$  such that for any subobject  $F$  of  $E$  in  $\mathcal{A}$ , we have  $D(F) \leq D_E$ .

*Proof.* Since the image of  $R$  is discrete in  $\mathbb{R}$ , we can do induction on  $R(E)$ . Our induction hypothesis would be the following: *if  $E' \in \mathcal{A}$  with  $R(E') < R(E)$ , then there is  $D_{E'} \in \mathbb{R}$  such that for any subobject  $F' \subset E'$  we have  $D(F') \leq D_{E'}$ .*

If  $R(E) = 0$ , then  $D(E) > 0$ . Then for any subobject  $F \subset E$ , from the exact sequence  $0 \rightarrow F \rightarrow E \rightarrow E/F \rightarrow 0$ , we have  $R(E) = R(F) + R(E/F)$  and  $D(E) = D(F) + D(E/F)$  (since both  $D := -\text{Re } Z$  and  $R := \text{Im } Z$  are homomorphisms of additive groups). Since  $Z$  is a stability function, we have  $R(F), R(E/F) \geq 0$ . Then  $R(F) = 0$ , and hence  $D(F) > 0$ . Thus,  $0 < D(F) \leq D(E)$ ; note that,  $D(E/F) \geq 0$ , and the inequality is strict if  $E/F \neq 0$ .

Assume that  $R(E) > 0$ . Suppose on the contrary that there is an infinite sequence of subobjects  $\{F_n\}_{n \in \mathbb{N}}$  such that

$$(11.1.16) \quad \lim_{n \rightarrow \infty} D(F_n) = +\infty.$$

If for some  $n \in \mathbb{N}$ ,  $R(F_n) = R(E)$ , then  $R(E/F_n) = 0$  implies  $D(E/F_n) \geq 0$ , and so  $D(F_n) \leq D(E)$ . Therefore, we may assume that

$$(11.1.17) \quad R(F_n) < R(E), \quad \forall n \in \mathbb{N}.$$

Note that, (by induction) it suffices to construct *an increasing sequence of positive integers  $\{n_k\}_{k \in \mathbb{N}}$  such that*

$$(11.1.18) \quad D\left(\sum_{i=1}^k F_{n_i}\right) \geq k \quad \text{and} \quad R\left(\sum_{i=1}^k F_{n_i}\right) < R(E).$$

Because then,  $\{\sum_{i=1}^k F_{n_i}\}_{k \in \mathbb{N}}$  would form an increasing sequence of proper subobjects of  $E$ , contradicting the fact that  $\mathcal{A}$  is noetherian.

By our assumption (11.1.16), there is  $n_1 \in \mathbb{N}$  such that  $D(F_{n_1}) \geq 1$ . Suppose that we have constructed  $n_1, \dots, n_{k-1}$ . Then we have an exact sequence

$$(11.1.19) \quad 0 \longrightarrow F_n \cap \sum_{i=1}^{k-1} F_{n_i} \longrightarrow F_n \oplus \sum_{i=1}^{k-1} F_{n_i} \longrightarrow F_n + \sum_{i=1}^{k-1} F_{n_i} \longrightarrow 0,$$

where the sum and intersection are taken inside of  $E$  in  $\mathcal{A}$  (see (11.1.2)). This gives

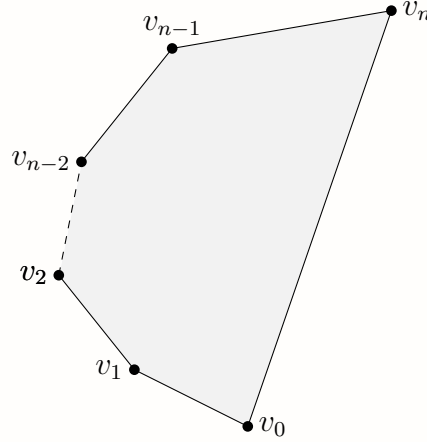
$$(11.1.20) \quad D(F_n + \sum_{i=1}^{k-1} F_{n_i}) = D(F_n) + D(\sum_{i=1}^{k-1} F_{n_i}) - D(F_n \cap \sum_{i=1}^{k-1} F_{n_i}).$$

Since  $R(\sum_{i=1}^{k-1} F_{n_i}) < R(E)$  by induction hypothesis (11.1.18) and  $F_n \cap \sum_{i=1}^{k-1} F_{n_i}$  is a subobject of  $\sum_{i=1}^{k-1} F_{n_i}$ , by **induction hypothesis**  $D(F_n \cap \sum_{i=1}^{k-1} F_{n_i}) \leq D_0$ , for some  $D_0 \in \mathbb{R}$ , which depends only on  $\sum_{i=1}^{k-1} F_{n_i}$ . Then from (11.1.20) and (11.1.18), we have

$$(11.1.21) \quad D(F_n + \sum_{i=1}^{k-1} F_{n_i}) \geq D(F_n) + (k-1) - D_0.$$

Taking limit as  $n \rightarrow +\infty$  in (11.1.21) and using (11.1.16), we have

$$(11.1.22) \quad \lim_{n \rightarrow +\infty} D(F_n + \sum_{i=1}^{k-1} F_{n_i}) = +\infty.$$

FIGURE 1. The polygon  $\mathcal{P}(E)$ 

As before, it follows from the exact sequence

$$0 \longrightarrow F_n + \sum_{i=1}^{k-1} F_{n_i} \longrightarrow E \longrightarrow E / (F_n + \sum_{i=1}^{k-1} F_{n_i}) \longrightarrow 0$$

that, if  $R(F_n + \sum_{i=1}^{k-1} F_{n_i}) = R(E)$  then  $D(F_n + \sum_{i=1}^{k-1} F_{n_i}) \leq D(E)$ . Therefore, in view of the limit in (11.1.22), we must have

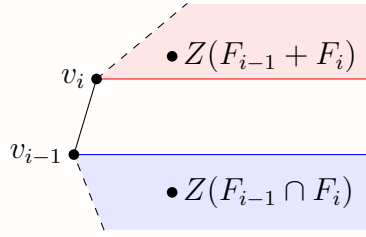
$$(11.1.23) \quad R(F_n + \sum_{i=1}^{k-1} F_{n_i}) < R(E), \quad \forall n \gg 0.$$

Therefore, we can choose  $n_k$  to be some integer  $n > n_{k-1}$  for which (11.1.23) holds, as claimed in (11.1.18). This completes the proof.  $\square$

**Theorem 11.1.24.** *Let  $\mathcal{A}$  be a noetherian abelian category. Let  $Z : K_0(\mathcal{A}) \rightarrow \mathbb{C}$  be a stability function. Assume that  $R := \text{Im}(Z) : K_0(\mathcal{A}) \rightarrow \mathbb{R}$  has discrete image in  $\mathbb{R}$ . Then any non-zero object  $E \in \mathcal{A}$  admits a unique Harder-Narasimhan filtration.*

*Proof.* Since we have nothing to prove in case  $E$  is  $Z$ -semistable, we assume that  $E$  is not  $Z$ -semistable. Suppose that the image of  $D := -\text{Re}(Z)$  is discrete in  $\mathbb{R}$  (and hence the image of  $Z$  is discrete in  $\mathbb{C}$ ). Let  $\mathcal{H}(E)$  be the convex hull in  $\mathbb{C}$  of the (discrete) subset  $\{Z(F) \in \mathbb{C} : F \text{ is a subobject of } E\}$ . Then by Lemma 11.1.15,  $\mathcal{H}(E)$  is bounded from the left side in  $\mathbb{C}$ . Let  $\mathcal{H}_\ell$  be the half plane to the left of the straight line passing through  $Z(E)$  and 0 in  $\mathbb{C}$ . Since the image of  $Z$  is discrete,  $\mathcal{P}(E) := \mathcal{H}_\ell \cap \mathcal{H}(E)$  is a convex polygon in  $\mathbb{C}$ . Let  $v_0 = 0, v_1, \dots, v_{n-1}, v_n := Z(E)$  be the extremal vertices of  $\mathcal{P}(E)$  in the ascending order of their imaginary parts. For each  $i \in \{1, \dots, n-1\}$ , choose a subobject  $F_i \subset E$  with  $Z(F_i) = v_i$ . We claim that,

- (i)  $F_{i-1} \subset F_i$ , for all  $i = 1, \dots, n$ , with  $F_0 := 0$  and  $F_n := E$ ,

FIGURE 2. Locations of  $Z(F_{i-1} \cap F_i)$  and  $Z(F_{i-1} + F_i)$ 

- (ii)  $Q_i := F_i/F_{i-1}$  is  $Z$ -semistable, for all  $i = 1, \dots, n$ , and
- (iii)  $\mu_Z(Q_1) > \dots > \mu_Z(Q_{n-1})$ .

Since  $F_{i-1} \cap F_i$  and  $F_{i-1} + F_i$  are subobjects of  $E$ , we have

$$(11.1.25) \quad Z(F_{i-1} \cap F_i), Z(F_{i-1} + F_i) \in \mathcal{H}(E).$$

Moreover, we have

$$(11.1.26) \quad R(F_{i-1} \cap F_i) \leq R(F_{i-1}) < R(F_i) \leq R(F_{i-1} + F_i).$$

Therefore,  $Z(F_{i-1} \cap F_i) \in \mathcal{P}(E)$  lies on or below the line  $\text{Im}(z) = \text{Im}(v_{i-1})$ , and  $Z(F_{i-1} + F_i) \in \mathcal{P}(E)$  lies on or above the line  $\text{Im}(z) = \text{Im}(v_i)$ ; see Figure 2. From the exact sequence  $0 \rightarrow F_{i-1} \cap F_i \rightarrow F_{i-1} \oplus F_i \rightarrow F_{i-1} + F_i \rightarrow 0$ , we have

$$(11.1.27) \quad Z(F_{i-1} \cap F_i) + Z(F_{i-1} + F_i) = v_{i-1} + v_i;$$

which gives

$$(11.1.28) \quad Z(F_{i-1} + F_i) - Z(F_{i-1} \cap F_i) = (v_{i-1} - Z(F_{i-1} \cap F_i)) + (v_i - Z(F_{i-1} \cap F_i)).$$

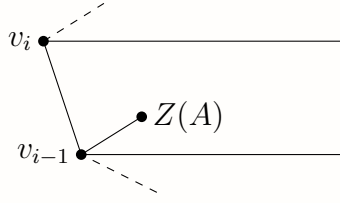
Comparing the real parts, in view of the Figure 2, we conclude that

$$(11.1.29) \quad Z(F_{i-1} \cap F_i) = v_{i-1} \quad \text{and} \quad Z(F_{i-1} + F_i) = v_i.$$

Therefore,  $Z(F_{i-1}/(F_{i-1} \cap F_i)) = 0$ . Since  $Z$  is a stability function,  $F_{i-1}/(F_{i-1} \cap F_i) = 0$ , and hence  $F_{i-1} \cap F_i = F_{i-1}$ . This proves our claim (i).

Note that, the  $Z$ -slope  $\mu_Z(F_i/F_{i-1})$  is given by the slope of the line segment joining  $v_{i-1}$  to  $v_i$ . Hence the convexity of the polygon  $\mathcal{P}(E)$  proves claim (iii); see Figure 1. Let  $\bar{A}$  be a non-zero subobject of  $Q_i := F_i/F_{i-1}$ . Let  $A \subset F_i$  be the preimage of  $\bar{A}$  in  $F_i$  along the epimorphism  $F_i \rightarrow F_i/F_{i-1}$ . Then  $Z(A) \in \mathcal{H}(E)$  and  $R(F_{i-1}) \leq R(A) \leq R(F_i)$ , since  $F_{i-1}$  is a subobject of  $A$ . Then  $Z(A) - Z(F_{i-1}) = Z(A) - v_{i-1}$  has smaller or equal slope than that of  $Z(F_i) - Z(F_{i-1}) = v_i - v_{i-1}$ . In other words,  $\mu_Z(\bar{A}) \leq \mu_Z(Q_i)$ , which proves claim (ii); c.f. Figure 3.

It remains to prove the theorem without assuming that the image of  $D := -\text{Re}(Z)$  is discrete in  $\mathbb{R}$ . Since the image of  $Z$  need not be discrete in  $\mathbb{C}$  anymore, we cannot directly conclude if the extremal vertices of  $\mathcal{P}(E)$  are of the form  $Z(F_i)$ , for some

FIGURE 3. Slope of subobjects of  $F_i/F_{i-1}$ 

subobject  $F_i$  of  $E$ . Suppose on the contrary that, there is an integer  $i \in \{1, \dots, n-1\}$  for which there is no subobject  $F_i \subset E$  with  $Z(F_i) = v_i$ . By definition of  $\mathcal{P}(E)$ , there is a sequence of subobjects  $\{F_j\}_{j \in \mathbb{N}}$  of  $E$  such that  $\lim_{j \rightarrow +\infty} Z(F_j) = v_i$ . Since the image of  $R := \text{Im}(Z)$  is discrete in  $\mathbb{R}$ , there is an integer  $n_0(i) \geq 1$  such that  $\text{Im}(Z(F_j)) = \text{Im}(v_i)$ , for all  $j \geq n_0(i)$ . Therefore, we can find a subsequence  $\{F_{n_k}\}_{k \in \mathbb{N}}$  such that

$$(11.1.30) \quad R(v_i) = R(F_{n_k}) \quad \text{and} \quad D(v_i) - D(F_{n_k}) < \frac{1}{k}, \quad \forall k \in \mathbb{N}.$$

Therefore, we may assume that all terms in the sequence  $\{F_{n_k}\}_{k \in \mathbb{N}}$  are distinct. From the exact sequence

$$(11.1.31) \quad 0 \longrightarrow F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j} \longrightarrow F_{n_k} \oplus \sum_{j=1}^{k-1} F_{n_j} \longrightarrow \sum_{j=1}^k F_{n_j} \longrightarrow 0$$

we have

$$(11.1.32) \quad D\left(\sum_{j=1}^k F_{n_k}\right) - D\left(\sum_{j=1}^{k-1} F_{n_k}\right) = D(F_{n_k}) - D\left(F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}\right) = D(F_{n_k}/F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j})$$

and

$$(11.1.33) \quad R\left(\sum_{j=1}^k F_{n_k}\right) - R\left(\sum_{j=1}^{k-1} F_{n_k}\right) = R(F_{n_k}) - R\left(F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}\right) = R(F_{n_k}/F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}).$$

Since  $F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}$  is a subobject of  $F_{n_k}$ , and  $Z$  is a stability condition,

$$(11.1.34) \quad R(F_{n_k}) - R\left(F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}\right) \geq 0,$$

and if equality holds in (11.1.34) then  $D(F_{n_k}) - D(F_{n_k} \cap \sum_{j=1}^{k-1} F_{n_j}) > 0$ . Since  $\sum_{j=1}^{k-1} F_{n_j}$  is a subobject of  $\sum_{j=1}^k F_{n_j}$ , now it follows from (11.1.32) and (11.1.33) that  $\{\sum_{j=1}^k F_{n_j}\}_{k \in \mathbb{N}}$  is a strictly increasing sequence of subobjects of  $E$ , which contradicts our assumption that  $\mathcal{A}$  is noetherian. This completes the proof.  $\square$

**11.2. Stability conditions on  $D^b(X)$ .** Let  $k$  be a field. Let  $X$  be a connected smooth projective  $k$ -variety. For any two objects  $E^\bullet, F^\bullet \in D^b(X)$ , we define

$$\chi(E^\bullet, F^\bullet) := \sum_i (-1)^i \dim_k \operatorname{Ext}^i(E^\bullet, F^\bullet).$$

Let

$$(11.2.1) \quad K_0(X)^\perp := \{\alpha \in K_0(X) : \chi(\alpha, \beta) = 0, \forall \beta \in K_0(X)\}.$$

**Definition 11.2.2.** Let

## 12. BIRATIONAL GEOMETRY

## 13. MIRROR SYMMETRY

### 13.1. Fukaya category.

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