

## CHAPTER 5

# Homological Algebra

“For my own sake, I have made a systematic (as yet unfinished) review of my ideas of homological algebra. I find it very agreeable to stick all sorts of things, which are not much fun when taken individually, together under the heading of derived functors.”

- Alexander Grothendieck (in his letter to Serre)

5.1. Homological algebra was the most important development by Grothendieck, for example in his Tohoku paper. Our goal in this chapter is to discuss homological algebra in the context of EGA seminars. Of course, some of the material here might be very familiar to you. We will discuss the abstract idea behind chain complexes and them being valued in any category. We will introduce homotopy and chain maps in this chapter. Our focus will be to introduce the homotopy category of chain complexes and do some basic discussions about derived categories as well. Derived functors are discussed as well<sup>1</sup>.

### 1. Short Exact Sequences and Chain Complexes

5.2. Most of the focus on abelian categories are given because they admit short exact sequences

$$0 \xrightarrow{f_1} A \xrightarrow{f_2} B \xrightarrow{f_3} C \rightarrow 0 \tag{3}$$

such that at each point, it is ‘exact’ which means that  $\ker(f_{n+1}) = \operatorname{im}(f_n)$  and also notice that  $f_{n+1} \circ f_n = 0$ .

5.3. With the above definition, we have following examples

- (1) A sequence  $0 \rightarrow V \xrightarrow{f} W$  is exact if  $f$  is injective.
- (2) A sequence  $V \xrightarrow{f} W \rightarrow 0$  is exact if  $f$  is surjective.
- (3) A sequence  $0 \rightarrow V \xrightarrow{f} W \rightarrow 0$  is exact if  $f$  is an isomorphism.

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<sup>1</sup>A good part of these notes are taken from my written notes (and a poster) in a fall 2025 course in representation theory of quivers by Prof. Amit Kuber.

(4) A sequence  $0 \rightarrow V \xrightarrow{f} W \xrightarrow{g} U \rightarrow 0$  is exact if  $f$  is injective,  $g$  is surjective and  $\ker g = \text{im } f$ .

(5) Given  $V \xrightarrow{f} W$ , the following is always exact

$$0 \rightarrow \ker f \xrightarrow{i} V \xrightarrow{f} W \xrightarrow{q} \text{cok } f \rightarrow 0 \quad (4)$$

then  $\ker q = \text{im } f$  and  $\ker f = \text{im } i$ .

**DEFINITION 5.4.** A chain complex is defined as a sequence

$$\cdots \rightarrow C_{n+1} \xrightarrow{d_{n+1}} C_n \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \cdots \quad (5)$$

where the  $f_n \circ f_{n+1} = 0$ . The maps  $d_n$  are called differentials.

For example, for  $R - \text{Mod}$ , it is a family of  $R - \text{Mod}$ ,  $\{C_n\}_{n \in \mathbb{Z}}$  where  $C_n \in R - \text{Mod}$ .

5.5. We can define the kernel of  $d_n$  to be the module of n-cycles in  $R - \text{Mod}$ , denoted by  $Z_n(C_\bullet)$ . Again, we can define image of  $d_n$  to be the module of n-boundaries in  $R - \text{Mod}$ , denoted by  $B_n(C_\bullet)$ . It is clear to see that

$$0 \subseteq Z_n \subset B_n \subset C_n \quad (6)$$

Alternatively,  $\ker(f_{n+1}) \subseteq \text{img}(f_n)$ .

5.6. For a chain complex to be exact, we just mention that  $Z_n = B_n$  for some chain complex  $C_\bullet$ .

**DEFINITION 5.7.** When a chain complex fails to be exact, which means that  $Z_n/B_n$  is non-trivial quotient group. This quotient group is called ‘Homology’  $H_n(C_\bullet)$ .

This essentially measures by how much the chain complex fails to be ‘exact’ at  $n$ .

5.8. Similarly, one can define cochain complexes and cohomology groups for them. These are dual descriptions.

**EXAMPLE 5.9.** A very algebraically clean example of (co)-chain complex and (co)-homology in physics is electromagnetism.<sup>2</sup> We take a complex of differential forms  $\Omega^p$  on a manifold  $M$

$$0 \rightarrow \Omega^0(M) \xrightarrow{d} \Omega^1(M) \xrightarrow{d} \Omega^2(M) \xrightarrow{d} \Omega^3(M) \rightarrow \cdots \quad (7)$$

where  $\Omega^0(M)$  is space of functions on  $M$  and  $\Omega^1(M)$  is a space of 1-forms and so on. The map  $d : \Omega^p \rightarrow \Omega^{p+1}$  is an exterior derivative map with  $d^2 = 0$ . The failure of this sequence to be exact is measured by the de Rham co-homology. An excellent resource is [3].

We will possibly de Rham (co)homology possibly later.

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<sup>2</sup>In electromagnetism, the 2-form  $F$  curvature solves  $dF = 0$ .

EXAMPLE 5.10. Now we will look at a very interesting example of **s.e.s.**. Given  $V, W$  in  $\text{Vect}_k$ , the sequence

$$0 \rightarrow V \xrightarrow{i_1} V \oplus W \xrightarrow{\pi_2} W \rightarrow 0 \quad (8)$$

where  $i_1 : V \rightarrow V \oplus W$  is an inclusion map and  $\pi_2 : V \oplus W \rightarrow W$  is a projection map, the above sequence (8) is an exact sequence since  $\ker(\pi_2) = \text{im}(i_1)$ . This sequence will serve as a canonical example of split sequences.

DEFINITION 5.11 (Split Sequence). A short exact sequence

$$0 \rightarrow V \xrightarrow{f} W \xrightarrow{g} U \rightarrow 0 \quad (9)$$

is said to be split if  $\exists g' : U \rightarrow W$  such that  $g \circ g' = 1_U$

$$0 \longrightarrow V \longrightarrow W \xrightleftharpoons[\substack{g \\ g'}]{\quad} U \longrightarrow 0$$

For example, the below sequence splits

$$0 \longrightarrow V \xrightarrow{i_1} V \oplus W \xrightleftharpoons[\substack{\pi_2 \\ i_2}]{\quad} W \longrightarrow 0$$

We have the following proposition.

5.12. A short exact sequence

$$0 \rightarrow V \xrightarrow{f} W \xrightarrow{g} U \rightarrow 0 \quad (10)$$

is said to be split if  $\exists f' : W \rightarrow V$  such that  $f' \circ f = 1_V$ .

So both are equal definitions which means that for our example, the existence of  $i_2$  implies the existence of  $\pi_1$ . These are statements of left split and right split in the Splitting Lemma. In general, the existence of  $g'$  will imply that  $f'$  exists. To see if this is true, we can look at the following diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & V & \xrightarrow{f} & W & \xrightarrow{g} & U \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \\ & & \left( \begin{matrix} f' \\ g \end{matrix} \right) & & & & \\ & & \downarrow & & \uparrow & & \\ 0 & \longrightarrow & V & \xrightarrow{i_1} & V \oplus U & \xrightarrow{\pi_2} & U \longrightarrow 0 \end{array}$$

where  $(f' g')$  is an isomorphism and the diagram must commute.

We suggest that the **s.e.s.**

$$0 \rightarrow V \xrightarrow{i_1} V \oplus W \xrightarrow{\pi_2} W \rightarrow 0 \quad (11)$$

is the canonical example of a split sequence. Any **s.e.s.** which is isomorphic to above sequence (11) is also a split sequence.

## 2. Chain Complexes and Chain Maps

**DEFINITION 5.13.** We define a category of chain complexes  $Ch(\mathcal{A})$  with objects as chain complexes, where the morphism are *chain complex maps*. Given two chain complexes  $C_\bullet, D_\bullet$ , we have a chain map  $u$

$$\begin{array}{ccccccc} \cdots & \longrightarrow & C_{n+1} & \longrightarrow & C_n & \longrightarrow & C_{n-1} \longrightarrow \cdots \\ & & \downarrow u_{n+1} & & \downarrow u_n & & \downarrow u_{n-1} \\ \cdots & \longrightarrow & D_{n+1} & \longrightarrow & D_n & \longrightarrow & D_{n-1} \longrightarrow \cdots \end{array}$$

where each square commutes. It is an important fact that a chain map  $u : C_\bullet \rightarrow D_\bullet$  induces a map  $H_n(C_\bullet) \rightarrow H_n(D_\bullet)$  since  $u$  sends boundaries  $B_n(C_\bullet)$  to boundaries  $B_n(D_\bullet)$  and cycles  $Z_n(C_\bullet)$  to cycles  $Z_n(D_\bullet)$ .

**DEFINITION 5.14.** We define *splitting maps*  $s_n$  for some chain complex  $C_n$  as  $s_n : C_n \rightarrow C_{n+1}$  such that it is called a split chain complex if  $d_n = d_{n+1} \circ s_n \circ d_n$ . If given two chain complexes  $C_n$  and  $D_n$  with a chain map  $u_n : C_n \rightarrow D_n$ , we choose maps  $s_n : C_n \rightarrow D_{n+1}$

$$\begin{array}{ccccccc} \cdots & \longrightarrow & C_{n+1} & \xrightarrow{d_{n+1}^C} & C_n & \xrightarrow{d_n^C} & C_{n-1} \xrightarrow{d_{n-1}^C} \cdots \\ & & \downarrow u_{n+1} & \nearrow s_n & \downarrow u_n & & \downarrow u_{n-1} \\ \cdots & \longrightarrow & D_{n+1} & \xrightarrow{d_{n+1}^D} & D_n & \xrightarrow{d_n^D} & D_{n-1} \xrightarrow{d_{n-1}^D} \cdots \end{array}$$

where the commutativity is given by  $d_{n+1}^D \circ u_{n+1} = u_n \circ d_{n+1}^C$  and the chain map  $u_n = d_{n+1} \circ s_n + s_{n-1} \circ d_n^C$ .

5.15. When there exist splitting maps  $s_n : C_n \rightarrow D_{n+1}$  and a chain map  $u_n : C_n \rightarrow D_n$  where  $u_n = d_{n+1} \circ s_n + s_{n-1} \circ d_n^C$ , then  $u$  is called a null homotopic chain map. When given two chain maps  $u_n, v_n : C_n \rightarrow D_n$ , we call them *null homotopic* if their difference is

$$u_n - v_n = d_{n+1} \circ s_n + s_{n-1} \circ d_n^C$$

(12)

and the maps  $\{s_n\}$  are called chain homotopy from  $u$  to  $v$ .

5.16. Furthermore, a chain map  $u_n : C_n \rightarrow D_n$  is a homotopy equivalence if there exists a map  $v_n : D_n \rightarrow C_n$  such that  $uv$  is chain homotopic to the identity on  $D$  and  $vu$  is chain homotopic to the identity on  $C$ .

### 3. Snake's Lemma

5.17. Snake's Lemma is a powerful tool to create six term exact sequences from two short exact sequences with a zero object. The proof of the lemma is usually a fun diagram chase. A succinct proof is also available in the beginning of the movie *It's my turn, 1980*. We will focus on the heuristics of the lemma.

5.18. Given two row short exact sequences in an abelian category  $\mathcal{A}$ , when we have a commutative diagram

$$\begin{array}{ccccccc} A & \xrightarrow{a} & B & \xrightarrow{b} & C & \longrightarrow & 0 \\ f \downarrow & & g \downarrow & & h \downarrow & & \\ 0 & \longrightarrow & A' & \xrightarrow{a'} & B' & \xrightarrow{b'} & C' \end{array}$$

it gives us a six-term exact sequence

$$\ker(f) \longrightarrow \ker(g) \longrightarrow \ker(h) \xrightarrow{\partial} \text{coker}(f) \longrightarrow \text{coker}(g) \longrightarrow \text{coker}(h)$$

where  $\partial : \ker(h) \rightarrow \text{coker}(f)$  is a connecting homomorphism. If the morphism  $a$  is a monomorphism, then  $\ker(f) \rightarrow \ker(g)$  is a monomorphism and if the morphism  $b'$  is an epimorphism, then so is  $\text{coker}(g) \rightarrow \text{coker}(h)$ .

We obtain the exact sequence by expanding the commutative diagram which gives us a sequence in shape of a ‘slithering snake’ [A visual diagram of the Snake!]

$$\begin{array}{ccccccccc} & & \ker(f) & \dashrightarrow & \ker(g) & \dashrightarrow & \ker(h) & \dashrightarrow & \bullet \\ & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \bullet & \leftarrow & A & \xrightarrow{a} & B & \xrightarrow{b} & C & \longrightarrow & 0 & \bullet \\ & & f \downarrow & & g \downarrow & & h \downarrow & & \\ & & 0 & \longrightarrow & A' & \xrightarrow{a'} & B' & \xrightarrow{b'} & C' \\ & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \bullet & \dashrightarrow & \text{coker}(f) & \dashrightarrow & \text{coker}(g) & \dashrightarrow & \text{coker}(h) & & \end{array}$$

The connecting homomorphisms  $\partial$  are important in constructing long exact sequences in homological algebra. The proof of the lemma is given by ‘diagram chasing’. The proof requires two step: 1) constructing the connecting homomorphism and 2) proving exactness at each point.

*A detailed proof will be added in second draft of these notes (updated 05-Nov-25).*

#### 4. Abelian Categories and Homotopy Category of Complexes

**DEFINITION 5.19** (Pre-Additive Category). A category  $\mathcal{C}$  is pre-additive if each morphism set  $Mor_{\mathcal{C}}(a, b)$  has the structure of an abelian group such that the composition

$$Mor(a, b) \times Mor(b, c) \rightarrow Mor(a, c) \quad (13)$$

is bilinear.

**DEFINITION 5.20.** An object which is both a final object and an initial object in a pre-additive category  $\mathcal{C}$  is called a zero object and denoted by 0.

**DEFINITION 5.21** (Additive Category). We call a pre-additive category  $\mathcal{C}$  additive category if it admits finite bi-products<sup>3</sup>.

**DEFINITION 5.22** (Abelian Category). We call a category  $\mathcal{C}$  abelian if it satisfies the following properties

- (1) It is an additive category.
- (2) Kernels and their dual co-kernels exist.
- (3) Every injective morphism is a kernel of its own co-kernel.
- (4) Every surjective morphism is a co-kernel of its own kernel.

5.23. Essentially, an abelian category is an abstraction of the (basic) properties of category of abelian groups. It is believed to be introduced by Buchsbaum [4] in 1955 as exact categories and later standardized by Grothendieck in his Tohoku paper [5] using axiomatic approach. However, the term 'abelian category' was termed by Freyd [6].

**EXAMPLE 5.24.** A good example of abelian category is category of representation of a group  $Rep(G)$  or the module category of an artinian algebra  $\Lambda$  over field  $k$ .

5.25. The most interesting reason for studying abelian categories is that they admit short exact sequences that we have discussed above. In later parts of this project, we will be interested to read more than exact sequences like *triangles* in triangulated categories.

5.26. We will digress to recall what is a quasi-isomorphism. When we want to just know the homological information of the complexes and their equivalence.

**DEFINITION 5.27.** A chain map of complexes  $u : C_{\bullet} \rightarrow D_{\bullet}$  in abelian category  $\mathcal{A}$  is called a quasi-isomorphism if the induced homology morphism  $u_* = H^n(C_{\bullet}) \rightarrow H^n(D_{\bullet})$  is an isomorphism.

From homology point of view, two complexes  $C_{\bullet}$  and  $D_{\bullet}$  become distinguishable.

**EXAMPLE 5.28.** For example, there exists a quasi-isomorphism among any two projective resolutions (or injective resolutions) of same object.

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<sup>3</sup>The finite products and fintie co-products coincide here

**THEOREM 5.29.** If a map  $u : C_\bullet \rightarrow D_\bullet$  is a homotopy equivalence, then it is a quasi-isomorphism.

5.30. Note that a quasi-isomorphism is not always a homotopy equivalence.

**DEFINITION 5.31.** Let  $\mathcal{A}$  be an additive category, we define a homotopy category of chain complexes  $K(\mathcal{A})$  as follows

- Objects: The objects of  $K(\mathcal{A})$  are chain complexes.
- Morphisms: For any two chain complexes  $C_\bullet, D_\bullet \in \mathcal{A}$ , we define the set of morphisms as the set of homotopy classes of chain maps from  $C_\bullet$  to  $D_\bullet$ .

$$Hom_{K(\mathcal{A})}(C_\bullet, D_\bullet) = Hom_{Ch(\mathcal{A})}(C_\bullet, D_\bullet) / \sim \quad (14)$$

where any two chain maps  $u, v$  are chain homotopic, then  $u \sim v$ .

5.32. Essentially, we can define a functor  $Ch(\mathcal{A}) \rightarrow K(\mathcal{A})$  which is identity on the objects and quotient projection on the morphisms. Moreover,  $K(\mathcal{A})$  is an additive category as well as a *triangulated category*, however, it is not an abelian category in general.

5.33. The rescue needed to do homological algebras for  $K(\mathcal{A})$ , since it fails to be abelian category, is provided by triangulated structure on it which contain distinguished triangles from which we get a long exact sequence of homology groups. While  $K(\mathcal{A})$  is a 'nice' category to work with homotopical settings. It fails to identify the quasi-isomorphisms and that motivates the construction of derived categories.

5.34. The issue with  $K(\mathcal{A})$  being that it does not recognize homotopy equivalence which are not quasi-isomorphism requires an abstract settings of 'derived categories'. The goal is then to construct a category where all quasi-isomorphisms become isomorphisms.

5.35. We define derived category  $D(\mathcal{A})$  for an abelian category  $\mathcal{A}$  as the localization of the homotopy category  $K(\mathcal{A})$  with respect to the class of all quasi-isomorphisms. A morphism between complexes  $C_\bullet$  and  $D_\bullet$  is no more only class of chain maps. Instead using universality, we have following roof diagram

$$C_\bullet \xleftarrow{f} F_\bullet \xrightarrow{g} D_\bullet \quad (15)$$

where  $f$  is a quasi-isomorphism and  $g$  is a morphism in  $K(\mathcal{A})$ . In a sense, it is more natural way to construct homotopy categories.

Derived categories are natural playground for derived functors, higher algebra, representation theory, and mathematical physics.

## 5. Mapping Cones and Triangulated Category

Triangulated categories were introduced by Jean-Louis Verdier (Grothendieck) in 1963 [7].

**DEFINITION 5.36.** Let  $\mathcal{C}$  be an additive category, then define  $\Sigma$  to be automorphism of  $\mathcal{C}$ . The automorphism  $\Sigma : \mathcal{C} \rightarrow \mathcal{C}$  is called the translation functor of  $\mathcal{C}$ .

**5.37.** Define a sextuple  $(X, Y, Z, u, v, w)$  given by the objects  $(X, Y, Z) \in \mathcal{C}$  and morphisms  $u : X \rightarrow Y$ ,  $v : Y \rightarrow Z$  and  $w : Z \rightarrow \Sigma X$ . Basically, we can write the sextuple as

$$X \xrightarrow{u} Y \xrightarrow{v} Z \xrightarrow{w} Z \rightarrow \Sigma X \quad (16)$$

**5.38.** We can find the morphisms between two sextuples

$$\begin{array}{ccccccc} X & \xrightarrow{u} & Y & \xrightarrow{v} & Z & \xrightarrow{w} & \Sigma X \\ f \downarrow & & g \downarrow & & h \downarrow & & \downarrow \Sigma f \\ X' & \xrightarrow{u'} & Y' & \xrightarrow{v'} & Z' & \xrightarrow{w'} & \Sigma X' \end{array}$$

such that each square commutes.

Now, consider a set  $T$  of all sextuples in  $\mathcal{C}$ , then set  $T$  is a triangulation of  $\mathcal{C}$  if they satisfy Verdier's axioms. Any element of  $T$  is called a **triangle**.

**5.39.** These Verdier's axioms are as follows.

TR1 For every object  $X$ , the following is a distinguished triangle

$$X \rightarrow X \rightarrow 0 \rightarrow \Sigma X \quad (17)$$

(Also, consider any morphism  $u : X \rightarrow Y$ , we can get a triangle  $X \xrightarrow{u} Y \rightarrow \text{cone}(u) \rightarrow \Sigma X$ )

Any triangle isomorphic to a distinguished triangle is a distinguished triangle.p

TR2 The following is a distinguished triangle precisely

$$X \xrightarrow{u} Y \rightarrow Z \rightarrow \Sigma X \quad (18)$$

if

$$Y \xrightarrow{v} Z \xrightarrow{w} \Sigma X \xrightarrow{-\Sigma u} \Sigma Y \quad (19)$$

is a distinguished triangle.

TR3 The following diagram of morphism between two triangles commute

$$\begin{array}{ccccccc} X & \xrightarrow{u} & Y & \xrightarrow{v} & Z & \xrightarrow{w} & \Sigma X \\ f \downarrow & & g \downarrow & & h \downarrow & & \downarrow \Sigma f \\ X' & \xrightarrow{u'} & Y' & \xrightarrow{v'} & Z' & \xrightarrow{w'} & \Sigma X' \end{array}$$

TR4 Also called *octahedral axiom*. Consider three triangles and the axioms states that their mapping cones will form a distinguished triangle. [We can ignore this for this

talk but they are crucial in determining the non-functoriality of mapping cones<sup>4</sup> in triangulated categories.]

**DEFINITION 5.40.** An additive category  $\mathcal{C}$  with translation functor  $\Sigma$  which admits triangulation is called a **triangulated** category  $(\mathcal{C}, \Sigma, T)$ .

5.41. Example of our interest: Derived category  $D(A)$  of an abelian category  $A$  is a triangulated category and so is  $D^b(A)$ .

We study triangulated categories because it generalizes short exact sequences to distinguished triangles

$$0 \rightarrow X \rightarrow Y \rightarrow Z \rightarrow 0 \quad (20)$$

in Abelian category  $A$  is generalized as a triangle in  $D^b(\text{mod-}A)$

$$X \rightarrow Y \rightarrow Z \rightarrow X[1] \quad (21)$$

## 6. Projective Resolutions and Dimension

5.42. In this section, we wish to discuss projective resolutions (and dually, injective resolutions) and various kinds of definitions of dimensions in homological algebra.

I believe the motivation is slightly to associate to every object (modules, representations and so on) a certain complex which helps us to get a larger picture about the category. This should become apparent in sometime.

**DEFINITION 5.43.** In an abelian category, an object  $P$  is called projective, if given any surjection  $f : A \rightarrow B$ , there exists a map  $g : P \rightarrow B$  such that one has a universal lifting property

$$\begin{array}{ccc} & P & \\ \exists h \swarrow & \downarrow g & \\ A & \xrightarrow{f} & B \end{array}$$

where  $g = fh$ .

5.44. We are mostly dealing with category of (right) modules over an algebra. And projective module is an important object for us. We also find that a projective  $P$  helps a sequence of  $\text{Hom}(P, -)$  to form a short exact sequence, in other words  $\text{Hom}(P, -)$  is an exact functor iff  $P$  is a projective.

**PROPOSITION 5.45.** A module in  $A - \text{mod}$   $P$  is projective if it is a direct summand of a free module.

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<sup>4</sup><https://aayushayh.blogspot.com/2025/09/the-quill-24-failure-of-functorial.html>

**PROOF.** A free module is a projective module. Let say  $F$  is a free module  $F \cong Q \oplus P$ . We have the following maps

$$i : P \rightarrow F \quad (22)$$

and if  $P$  is a projective, then by universal property

$$\pi : F \rightarrow P \quad (23)$$

which means  $\pi \circ i = id_P$  and

$$0 \rightarrow Q \rightarrow F \rightarrow P \rightarrow 0 \quad (24)$$

and hence  $P$  is a direct summand of free module  $F$ .

**PROPOSITION 5.46.** If  $P$  is a projective, then  $Ext^1(P, M) = 0$  for every  $A - mod$   $M$ .

**PROOF.** to be written

**REMARK 5.47.** Projective modules are closed under direct sums.

5.48. A chain complex with each object a projective is called a chain complex of projectives. Note that it does not have to be a projective object in the category of chain complexes.

5.49. We call an abelian category  $\mathcal{A}$  with enough projectives if for every object  $A$  in  $\mathcal{A}$ , there exists a surjective map  $P \rightarrow A$ . A dual definition exist for an abelian category with enough injectives.

5.50. As alluded earlier, for a projective  $P$  in  $\mathcal{A}$   $Hom(P, -)$  is an exact functor which means that for every s.e.s. in  $\mathcal{A}$

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0 \quad (25)$$

the functor  $Hom(P, -)$  gives a short exact sequence

$$0 \rightarrow Hom(P, A) \rightarrow Hom(P, B) \rightarrow Hom(P, C) \rightarrow 0 \quad (26)$$

and dually,  $Hom(-, I)$  is an exact functor for an injective object  $I$  in  $\mathcal{A}$ .

5.51. A object  $P$  is projective in **Ch** (category of chain complexes) if and only if it is a split exact complex. It is not hard to realize this proposition. Let us look at only if direction. Say,  $P_\bullet$  is a projective complex, then each  $P_n$  is a projective object.

To realize the split exactness of the complex, we say that a short exact sequence

$$0 \rightarrow P_\bullet \xrightarrow{i} Cone(id_{P_\bullet}) \xrightarrow{p} P_\bullet[-1] \rightarrow 0 \quad (27)$$

where  $Cone(id_{P_\bullet})$  is the mapping cone and since  $P_\bullet$  is a projective in **Ch**, every epimorphism  $p : Cone(id_{P_\bullet}) \rightarrow P_\bullet[-1]$  admits a lift of  $id_{P_\bullet}[-1]$  such that there is a chain map

$$q : P_\bullet[-1] \rightarrow Cone(id_{P_\bullet}) \quad (28)$$

and  $p \circ q = id_{P_\bullet}[-1]$ . One can also show split exactness as well. (incomplete, to be added in next update, see Exercise 2.2.1 in [8]).

**DEFINITION 5.52** (Projective Resolution). For every object<sup>5</sup>  $M$  in  $\mathcal{A}$ , we write a projective resolution as an exact sequence

$$\cdots \rightarrow P_2 \rightarrow P_1 \rightarrow P_0 \xrightarrow{\epsilon} M \rightarrow 0 \quad (29)$$

where  $\epsilon : P_0 \rightarrow M$  is augmentation map. One can think of it as a surjective cover of  $M$  which is an epimorphism. Alternatively, we can think of a chain complex  $P_\bullet$  which is concentrated in nonnegative degree such that  $P_i = 0$  for  $i < 0$  along with an augmentation map  $\epsilon : P_0 \rightarrow M$  such that (29) is exact.

**DEFINITION 5.53.** We have delayed the definition of an injective object but we rely on the dualness of projective-injective to mention every definition. One defines an injective object  $I$  in  $\mathcal{A}$  as following. Given an injection  $f : A \rightarrow B$ , there exist a map  $\alpha : A \rightarrow I$  such that following commutes

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ g \downarrow & \swarrow \exists h & \\ I & & \end{array}$$

5.54. As mentioned in 5.50,  $\text{Hom}(P, -)$  is an exact functor. Dually,  $\text{Hom}(-, I)$  is an exact functor for the short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0 \quad (30)$$

where  $\text{Hom}(-, I)$  is a contravariant functor.

5.55. We will find projective resolutions introduced above in 5.52 very important at many places. Similarly, we can define an injective resolution as

$$M \rightarrow I_0 \rightarrow I_1 \rightarrow I_2 \rightarrow \cdots \quad (31)$$

where  $I_i$  are injectives.

It is also interesting to see that  $P_\bullet \rightarrow M$  and  $M \rightarrow I_\bullet$  are chain map and cochain map respectively and describe the same complex when  $M$  is concentrated in degree 0.

## 7. Derived Functors

5.56. Given a short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0 \quad (32)$$

and a  $\text{Hom}(-, X)$  functor, which is a contravariant functor (a functor for which domain is objects in  $\mathcal{C}^{op}$ ) and is a left-exact functor

$$0 \rightarrow \text{Hom}(C, X) \rightarrow \text{Hom}(B, X) \rightarrow \text{Hom}(A, X) \quad (33)$$

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<sup>5</sup>Technically, one would need a category with enough projectives and fortunately, an abelian category admits enough projectives which means that there is a projective cover for each object in the category.

but we can not guarantee the last zero unless  $X$  is injective. Conversely, the same argument applies for  $\text{Hom}(X, -)$  which is a right exact functor and becomes exact if and only if  $X$  is projective.

5.57. Before we discuss finding a long exact sequence for any short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0 \quad (34)$$

for any functor  $F : \mathcal{A} \rightarrow \mathcal{B}$ , we should briefly allude to our discussion on Snake's lemma before here. Snake's lemma is a way to get a long exact sequence from short exact sequence. One should emphasize on the connecting morphisms  $\delta$ .

EXAMPLE 5.58. Let us take an example of sheaves

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0 \quad (35)$$

and the long exact sequences of sheaf (co)homology on a topological space  $X$  is given by

$$\cdots \rightarrow H^n(X, \mathcal{F}) \rightarrow H^n(X, \mathcal{G}) \rightarrow H^n(X, \mathcal{H}) \rightarrow H^{n+1}(X, \mathcal{G}) \rightarrow \cdots \quad (36)$$

A good example in physics would be consider a short exact sequence of sheaves

$$0 \rightarrow \mathbb{Z} \rightarrow C^\infty(R) \rightarrow C^\infty(U(1)) \rightarrow 0 \quad (37)$$

and since we have  $H^n(X, C^\infty(R)) = 0$  for  $n > 0$ , we have the isomorphism

$$H^1(X, C^\infty(U(1))) \cong H^2(X, \mathbb{Z}) \quad (38)$$

and

$$H^2(X, C^\infty(U(1))) \cong H^3(X, \mathbb{Z}) \quad (39)$$

write physics relevance

## 8. More on Derived Categories