Homological Algebra

Labix

August 13, 2024

Abstract

Contents

1 Abelian Categories and its Properties

1.1 Category of Modules

Definition 1.1.1: Category of R-Modules

Define the category of R-modules to be ${}_R\text{Mod}$ where objects are exactly modules and morphisms are morphisms between modules. Define $\text{Hom}_R(A,B)$ to be the set of R-modules homomorphisms between R-modules A and B.

Proposition 1.1.2

For any R-modules A and B, $\text{Hom}_R(A,B)$ is an R-module.

Proof. Trivially $\text{Hom}_R(A,B)$ is an abelian group by defining

$$(f+g)(x)=f(x)+g(x)$$

for $f,g\in\text{Hom}_R(A,B)$. For $r\in R$, define

$$(rf)(x)=rf(x)$$

Then clearly $\text{Hom}_R(A,B)$ is an R-module. □

1.2 Additive Categories

Definition 1.2.1: Pre-Additive Categories

A category $\mathcal{C}$ is pre-additive if it is a category that satisfies the fact that each $\text{Hom}_\mathcal{C}(X,Y)$ is given the structure of an abelian group where

$$\text{Hom}_\mathcal{C}(X,Y)\times\text{Hom}_\mathcal{C}(Y,Z)\to\text{Hom}_\mathcal{C}(X,Z)$$

are bilinear. This means that if $f:X\to Y$ and $g,h:Y\to Z$, then $g+h=h+g:Y\to Z$ and $f\circ(g+h)=(f\circ g)+(f\circ h)$ and the same distributive property for the first element.

Definition 1.2.2: Additive Categories

A category $\mathcal{A}$ is additive if in addition to being pre-additive, it also satisfies the following:

- $\mathcal{A}$ has a zero object, denoted 0
- $\mathcal{A}$ has finite products

Lemma 1.2.3

Let $\mathcal{A}$ be an additive category. Then coproducts and products coincide, meaning that

$$X\times Y\cong X\sqcup Y$$

for any $X,Y\in Obj(\mathcal{A})$.

1.3 Abelian Categories

Definition 1.3.1: Abelian Categories

An additive category $\mathcal{A}$ is said to be abelian if it satisfies the following:

- Every morphism in $\mathcal{A}$ has a kernel and a cokernel
- Every monic morphism is the kernel of its cokernel
- Every epic morphism is the cokernel of its kernel

Proposition 1.3.2

The category of R-modules is an abelian category.

Theorem 1.3.3

Let $\mathcal{A}$ be an abelian category whose objects form a set. Then there exists a ring R and an exact functor $F : \mathcal{A} \to R -$ mod which is an embedding on objects and an isomorphism on Hom sets.

Definition 1.3.4: Injectivity and Surjectivity

Let $f : X \to Y$ be a morphism in an abelian category.

- We say that f is injective if $\ker(f) = 0$
- We say that f is surjective if coker$(f) = 0$

In particular, these notions coincide that of epics and monics in an abelian category.

Proposition 1.3.5

Let $f : X \to Y$ be a morphism in an abelian category. Then the following are true.

- f is injective if and only if f is a monomorphism
- f is surjective if and only if f is epimorphism

Theorem 1.3.6

The category R-mod of R-modules is an abelian category.

2 Chain Complexes in an Abelian Category

2.1 Chain Complexes

Definition 2.1.1: Chain Complex

Let $\mathcal{A}$ be an abelian category. A chain complex $(C_\bullet, \partial_\bullet)$ in $\mathcal{A}$ is a family of objects $C_n \in \mathcal{A}$ for $n \in \mathbb{Z}$ and morphisms $\partial_n : C_n \to C_{n-1}$ in $\mathcal{A}$ such that $\partial_n \circ \partial_{n+1} = 0$ for all n.

In other words, we have the diagram:

$$\cdots \longrightarrow C_{n+1} \xrightarrow{\partial_{n+1}} C_n \xrightarrow{\partial_n} C_{n-1} \longrightarrow \cdots$$

for which we require that

$$\operatorname{im}(\partial_{n+1}) \subseteq \ker(\partial_n)$$

for each n.

Definition 2.1.2: Homology Group

Let $(C_\bullet, \partial_\bullet)$ be a chain complex in an abelian category $\mathcal{A}$. Define $Z_n(C_\bullet) = \ker(\partial_n)$ and $B_n(C_\bullet) = \operatorname{im}(\partial_{n+1})$. Define the nth homology of $(C_\bullet, \partial_\bullet)$ to be

$$H_n(C_\bullet) = \frac{Z_n(C_\bullet)}{B_n(C_\bullet)} = \frac{\ker(\partial_n)}{\operatorname{im}(\partial_{n+1})}$$

Elements of $Z_n(C_\bullet) = \ker(\partial_n)$ are called n-cycles and elements of $B_n(C_\bullet) = \operatorname{im}(\partial_{n+1})$ are called n-boundaries.

Definition 2.1.3: Chain Map

Let $(C_\bullet, \partial_\bullet)$ and $(C'_\bullet, \partial'_\bullet)$ be two chain complexes in an abelian category $\mathcal{A}$. A chain map $f_\bullet : C_\bullet \to C'_\bullet$ is a family of maps

$$f_n : C_n \to C'_n$$

in $\mathcal{A}$ such that $\partial'_n \circ f_n = f_{n-1} \circ \partial_n$ for all n.

In other words, we have the following commutative diagram:

$$\begin{tikzcd}
\cdots \arrow[r] & C_{n+1} \arrow[r, "\partial_{n+1}"] \arrow[d, "f_{n+1}"] & C_n \arrow[r, "\partial_n"] \arrow[d, "f_n"] & C_{n-1} \arrow[r] \arrow[d, "f_{n-1}"] & \cdots \\
\cdots \arrow[r] & C'_{n+1} \arrow[r, "\partial'_{n+1}"] & C'_n \arrow[r, "\partial'_n"] & C'_{n-1} \arrow[r] & \cdots
\end{tikzcd}$$

Proposition 2.1.4

Let $f_\bullet : C_\bullet \to D_\bullet$ and $g_\bullet : D_\bullet \to E_\bullet$ be two chain maps. Then $g_\bullet \circ f_\bullet$ is also a chain map.

Definition 2.1.5: Category of Chain Complexes

Let $\mathcal{A}$ be an abelian category. Define $\text{Ch}(\mathcal{A})$ to be the category of chain complexes where

- The objects are chain complexes of objects in $\mathcal{A}$.
- The morphisms are chain maps.
- Composition is given by composition of functions.

Theorem 2.1.6

Let $\mathcal{A}$ be an abelian category. Then $\mathrm{Ch}(\mathcal{A})$ is also an abelian category.

2.2 Exact Sequences

Definition 2.2.1: Exact Sequence

A chain complex $(C_\bullet, \partial_\bullet)$ is said to be exact if $\mathrm{im}(\partial_{n+1}) = \ker(\partial_n)$ for all n.

Definition 2.2.2: Short Exact Sequence

Let $\mathcal{A}$ be an abelianc category. Let $A, B, C \in \mathcal{A}$. A short exact sequence is an exact sequence of the form

$$0 \longrightarrow A \xrightarrow{f} B \xrightarrow{g} C \longrightarrow 0$$

where $f : A \to B$ and $g : B \to C$ are morphisms in $\mathcal{A}$.

Proposition 2.2.3

Let $\mathcal{A}$ be an abelianc category. Let $A, B, C \in \mathcal{A}$ and $f : A \to B$ and $g : B \to C$ be morphisms in $\mathcal{A}$. A chain complex

$$0 \longrightarrow A \xrightarrow{f} B \xrightarrow{g} C \longrightarrow 0$$

is short exact if and only if f is a monomorphism, g is epimorphism and $\ker(g) = \mathrm{im}(f)$.

Definition 2.2.4: Split Exact Sequence

Let $\mathcal{A}$ be an abelianc category. Let $A, B, C \in \mathcal{A}$ such that

$$0 \longrightarrow A \xrightarrow{f} B \xrightarrow{g} C \longrightarrow 0$$

is a short exact sequence. We say that it is split exact if $B \cong A \oplus C$.

The following is an important equivalent characterization of split exact sequence.

Theorem 2.2.5: The Splitting Lemma

Let $\mathcal{A}$ be an abelianc category. Let $A, B, C \in \mathcal{A}$. Then the following are equivalent for a short exact sequence

$$0 \longrightarrow A \xrightarrow{f} B \xrightarrow{g} C \longrightarrow 0$$

- The short exact sequence is split exact sequence
- There exists a morphism $p : B \to A$ such that $p \circ f = \mathrm{id}_A$
- There exists a morphism $s : C \to B$ such that $g \circ s = \mathrm{id}_C$

Lemma 2.2.6: Five Lemma

Consider the commutative diagram

$$\begin{tikzcd} A \arrow[r, "f"] \arrow[d, "l"] & B \arrow[r, "g"] \arrow[d, "m"] & C \arrow[r, "h"] \arrow[d, "n"] & D \arrow[r, "j"] \arrow[d, "p"] & E \arrow[d, "q"] \\ A' \arrow[r, "r"] & B' \arrow[r, "s"] & C' \arrow[r, "t"] & D' \arrow[r, "u"] & E' \end{tikzcd}$$

where all the objects lie in an abelian group $\mathcal{A}$. If the two rows are exact, $m : B \to B', p : D \to D'$ are isomorphisms, $l : A \to A'$ is an epimorphism and $q : E \to E'$ is an monomorphism, then n is an isomorphism.

Lemma 2.2.7: Snake Lemma

Consider the commutative diagram

$$\begin{tikzcd} & A \arrow[r, "f"] \arrow[d, "a"] & B \arrow[r, "g"] \arrow[d, "b"] & C \arrow[r] \arrow[d, "c"] & 0 \\ 0 \arrow[r] & A' \arrow[r, "f'"] & B' \arrow[r, "g'"] & C' & \end{tikzcd}$$

where all the objects lie in an abelian group $\mathcal{A}$. If the two rows are exact, then there is an exact sequence relating the kernels and cokernels of a, b, c

$$\ker(a) \longrightarrow \ker(b) \longrightarrow \ker(c) \xrightarrow{d} \operatorname{coker}(a) \longrightarrow \operatorname{coker}(b) \longrightarrow \operatorname{coker}(c)$$

where d is called the connecting homomorphism.

2.3 Chain Homotopy

Definition 2.3.1: Chain Homotopy

Let $\mathcal{A}$ be an abelian category. Let $a_\bullet, b_\bullet : C_\bullet \to C'_\bullet$ be two chain maps in $\text{Ch}(\mathcal{A})$. Then a chain homotopy from a to b is a collection of morphisms

$$\eta_n : C_n \to C'_{n+1}$$

in $\mathcal{A}$ such that

$$b_n - a_n = \partial'_{n+1}\eta_n + \eta_{n-1}\partial_n$$

for all $n \in \mathbb{Z}$. In this case, a and b are said to be chain homotopic.

In other words, we have the diagram:

$$\begin{tikzcd} \cdots \arrow[r] & C_{n+1} \arrow[r, "\partial_{n+1}"] \arrow[d, "b_{n+1}-a_{n+1}"] \arrow[dl, "\eta_{n+1}"'] & C_n \arrow[r, "\partial_n"] \arrow[d, "b_n-a_n"] \arrow[dl, "\eta_n"'] & C_{n-1} \arrow[r] \arrow[d, "b_{n-1}-a_{n-1}"] \arrow[dl, "\eta_{n-1}"'] & \cdots \\ \cdots \arrow[r] & C'_{n+1} \arrow[r, "\partial'_{n+1}"] & C'_n \arrow[r, "\partial'_n"] & C'_{n-1} \arrow[r] & \cdots \end{tikzcd}$$

In this case we write $f \simeq g$.

Lemma 2.3.2

Let a, b be chain homotopic. Then their induced maps in homology are equal. Meaning

$$a_n = b_n : H_n(X) \to H_n(Y)$$

Proof. Let $c \in \ker(\partial_n)$ be an n-cycle. Using the equation for chain homotopy, we have that

$$\begin{aligned} b(c) - a(c) &= \partial'_{n+1}(\eta_n(c)) + \eta_{n-1}(\partial(c)) \\ &= \partial'_{n+1}(\eta(c)) \end{aligned}$$

is a boundary in $\operatorname{im}(\partial'_{n+1}) \subseteq C'_n$. Thus $b_n(c)$ and $a_n(c)$ are of the same coset in $H_n(X)$. $\square$

Proposition 2.3.3

Let $\mathcal{A}$ be an abelian group. Let $f_1, g_1 : C_\bullet \to D_\bullet$ and $f_2, g_2 : D_\bullet \to E_\bullet$ be chain maps in $\text{Ch}(\mathcal{A})$. If f_1 and g_1 are chain homotopic and f_2 and g_2 are chain homotopic, then $f_2 \circ f_1$ is chain homotopic to $g_2 \circ g_1$.

Proof. The chain homotopies between f_1 and g_1 imposes the identity

$$\partial\eta + \eta\partial = g_1 - f_1$$

for $\eta : C_\bullet \to D_\bullet$ the given chain homotopy. Similarly, for $\nu : D_\bullet \to E_\bullet$ we have the identity

$$\partial\nu + \nu\partial = g_2 - f_2$$

Then we have that

$$\begin{aligned} g_2 \circ g_1 - f_2 \circ f - 1 &= g_2 \circ g_1 - g_2 \circ f_1 + g_2 \circ f_1 - f_2 \circ f_1 \\ &= g_2(g_1 - f_1) + (g_2 - f_2) \circ f_1 \\ &= g_2(\partial\eta + \eta\partial) + (\partial\nu + \nu\partial) \circ f_1 \\ &= \partial g_2\eta + g_2\eta\partial + \partial\nu f_1 + \nu f_1\partial \\ &= \partial(g_2\eta + \nu f_1) + (g_2\eta + \nu f_1)\partial \end{aligned}$$

Thus $g_2\eta + \nu f_1 : C_n \to E_{n+1}$ would be a valid chain homotopy from $g_2 \circ g_1$ to $f_2 \circ f_1$. $\square$

Lemma 2.3.4

Let $\mathcal{A}$ be an abelian category. Let $C_\bullet$ and $D_\bullet$ be two chain complexes in $\text{Ch}(\mathcal{A})$. Then the relation $\simeq$ on the chain maps from $C_\bullet$ to $D_\bullet$ is an equivalence relation.

Definition 2.3.5: Chain Homotopy Equivalence

Let $\mathcal{A}$ be an abelian category. Let $C_\bullet$ and $D_\bullet$ be two chain complexes in $\text{Ch}(\mathcal{A})$. We say that they are chain homotopy equivalence if there exists chain maps $a_\bullet : C_\bullet \to D_\bullet$ and $b_\bullet : C_\bullet \to D_\bullet$ such that there are chain homotopies

$$b_\bullet \circ a_\bullet \simeq \text{id}_{C_\bullet} \quad \text{and} \quad a_\bullet \circ b_\bullet \simeq \text{id}_{D_\bullet}$$

Lemma 2.3.6

Let $\mathcal{A}$ be an abelian category. Let $C_\bullet$ and $D_\bullet$ be chain homotopy equivalent in $\text{Ch}(\mathcal{A})$. Then the chain maps induces an isomorphism

$$H_n(C_\bullet) \cong H_n(D_\bullet)$$

in all degrees $n \in \mathbb{N}$.

Proof. We know that $b_\bullet \circ a_\bullet \simeq \mathrm{id}_{C_\bullet}$ which means that they induce the same map:

$$b_* \circ a_* = \mathrm{id}_{H_n(C_\bullet)}$$

Similarly the chain homotopies $a_\bullet \circ b_\bullet \simeq \mathrm{id}_{D_\bullet}$ induce the same map

$$a_* \circ b_* : \mathrm{id}_{H_n(D_\bullet)}$$

as the identity. Then these two identities mean that a_* is both injective and surjective. $\square$

Proposition 2.3.7

Let $\mathcal{A}$ be an abelian category. Then chain homotopy equivalence defines an equivalence relation on all chain complexes in $\mathrm{Ch}(\mathcal{A})$.

Proof. Clearly any chain complex is chain homotopy equivalent to itself by the identity map. If $C_\bullet$ and $D_\bullet$ are chain homotopy equivalent by the chain maps $a_\bullet : C_\bullet \to D_\bullet$ and $b_\bullet : D_\bullet \to C_\bullet$, then we have the identities $b_\bullet \circ a_\bullet = \mathrm{id}_{C_\bullet}$ and $a_\bullet \circ b_\bullet = \mathrm{id}_{D_\bullet}$. We can then read them in reverse so that $D_\bullet$ and $C_\bullet$ are chain homotopy equivalence by the maps $b_\bullet$ and $a_\bullet$.

Suppose further that $D_\bullet$ and $E_\bullet$ are chain homotopy equivalent via the maps $u_\bullet : D_\bullet \to E_\bullet$ and $v_\bullet : E_\bullet \to D_\bullet$. Then the maps $u_\bullet \circ a_\bullet$ and $b_\bullet \circ v_\bullet$ give a chain homotopy equivalence between $C_\bullet$ and $E_\bullet$. Indeed, upon composition, we have that they are chain homtopic to the identity maps. $\square$

2.4 Sequences of Chain Complexes

One can even define short exact sequences of chain complexes themselves.

Definition 2.4.1: Short Exact Sequence of Chain Complexes

Let $A_\bullet, B_\bullet, C_\bullet$ be chain complexes in an abelian category $\mathcal{A}$. Let $i : A_\bullet \to B_\bullet$ and $j : B_\bullet \to C_\bullet$ be chain maps in $\mathrm{Ch}(\mathcal{A})$. A short exact sequence of chain complexes is a diagram of the form

$$\begin{tikzcd}
 & 0 \arrow[d] & 0 \arrow[d] & 0 \arrow[d] & \\
\cdots \arrow[r] & A_{n+1} \arrow[r, "d_A"] \arrow[d, "i"] & A_n \arrow[r, "d_A"] \arrow[d, "i"] & A_{n-1} \arrow[r] \arrow[d, "i"] & \cdots \\
\cdots \arrow[r] & B_{n+1} \arrow[r, "d_B"] \arrow[d, "j"] & B_n \arrow[r, "d_B"] \arrow[d, "j"] & B_{n-1} \arrow[r] \arrow[d, "j"] & \cdots \\
\cdots \arrow[r] & C_{n+1} \arrow[r, "d_C"] \arrow[d] & C_n \arrow[r, "d_C"] \arrow[d] & C_{n-1} \arrow[r] \arrow[d] & \cdots \\
 & 0 & 0 & 0 &
\end{tikzcd}$$

such that for each n (vertically in the diagram), the sequence

$$0 \longrightarrow A_n \xrightarrow{i} B_n \xrightarrow{j} C_n \longrightarrow 0$$

is a short exact sequence. We write this as

$$0 \longrightarrow A_\bullet \xrightarrow{i} B_\bullet \xrightarrow{j} C_\bullet \longrightarrow 0$$

Theorem 2.4.2

Let $\mathcal{A}$ be an abelian category. Let $A_\bullet, B_\bullet, C_\bullet$ be a chain complexes in $\text{Ch}(\mathcal{A})$ such that

$$0 \longrightarrow A_\bullet \xrightarrow{i} B_\bullet \xrightarrow{j} C_\bullet \longrightarrow 0$$

is a short exact sequence of chain complexes. Then there exists a connecting homomorphism $\partial : H_n(C_\bullet) \to H_{n-1}(A_\bullet)$ such that the following sequence of homology

$$\cdots \longrightarrow H_{n+1}(C_\bullet) \xrightarrow{\partial} H_n(A_\bullet) \xrightarrow{i_*} H_n(B_\bullet) \xrightarrow{j_*} H_n(C_\bullet) \xrightarrow{\partial} H_{n-1}(A_\bullet) \longrightarrow \cdots$$

is an exact sequence.

Theorem 2.4.3

Let $A_\bullet, B_\bullet, C_\bullet, A'_\bullet, B'_\bullet, C'_\bullet$ be six chain complexes in an abelian category $\mathcal{A}$ and let the following

$$0 \longrightarrow A_\bullet \xrightarrow{i} B_\bullet \xrightarrow{j} C_\bullet \longrightarrow 0$$

$$0 \longrightarrow A'_\bullet \xrightarrow[i']{} B'_\bullet \xrightarrow[j']{} C'_\bullet \longrightarrow 0$$

be two short exact sequence of chain complexes. Let the following diagram be a morphism of the two short exact sequence of chain complexes in $\text{Ch}(\mathcal{A})$.

$$\begin{tikzcd}
 & & & 0 \arrow[dd] & & 0 \arrow[dd] & & 0 \arrow[dd] & & \\
 & & 0 \arrow[dd] & & 0 \arrow[dd] & & 0 \arrow[dd] & & & \\
 & \cdots \arrow[rr] & & A'_{n+1} \arrow[rr, "\partial"] \arrow[dd, "i'"] & & A'_n \arrow[rr, "\partial"] \arrow[dd, "i'"] & & A'_{n-1} \arrow[rr] \arrow[dd, "i'"] & & \cdots \\
\cdots \arrow[rr] & & A_{n+1} \arrow[rr, "\partial"] \arrow[ur, "\alpha"] \arrow[dd, "i"] & & A_n \arrow[rr, "\partial"] \arrow[ur, "\alpha"] \arrow[dd, "i"] & & A_{n-1} \arrow[rr] \arrow[ur, "\alpha"] \arrow[dd, "i"] & & \cdots & \\
 & \cdots \arrow[rr] & & B'_{n+1} \arrow[rr, "\partial"] \arrow[dd, "j'"] & & B'_n \arrow[rr, "\partial"] \arrow[dd, "j'"] & & B'_{n-1} \arrow[rr] \arrow[dd, "j'"] & & \cdots \\
\cdots \arrow[rr] & & B_{n+1} \arrow[rr, "\partial"] \arrow[ur, "\beta"] \arrow[dd, "j"] & & B_n \arrow[rr, "\partial"] \arrow[ur, "\beta"] \arrow[dd, "j"] & & B_{n-1} \arrow[rr] \arrow[ur, "\beta"] \arrow[dd, "j"] & & \cdots & \\
 & \cdots \arrow[rr] & & C'_{n+1} \arrow[rr, "\partial"] \arrow[dd] & & C'_n \arrow[rr, "\partial"] \arrow[dd] & & C'_{n-1} \arrow[rr] \arrow[dd] & & \cdots \\
\cdots \arrow[rr] & & C_{n+1} \arrow[rr, "\partial"] \arrow[ur, "\gamma"] \arrow[dd] & & C_n \arrow[rr, "\partial"] \arrow[ur, "\gamma"] \arrow[dd] & & C_{n-1} \arrow[rr] \arrow[ur, "\gamma"] \arrow[dd] & & \cdots & \\
 & & & 0 & & 0 & & 0 & & \\
 & & 0 & & 0 & & 0 & & &
\end{tikzcd}$$

Then the induced diagram

$$\begin{tikzcd}
\cdots \arrow[r] & H_n(A) \arrow[r, "i_*"] \arrow[d, "\alpha_*"] & H_n(B) \arrow[r, "j_*"] \arrow[d, "\beta_*"] & H_n(C) \arrow[r, "\partial"] \arrow[d, "\gamma_*"] & H_{n-1}(A) \arrow[r] \arrow[d, "\alpha_*"] & \cdots \\
\cdots \arrow[r] & H_n(A') \arrow[r, "i'_*"'] & H_n(B') \arrow[r, "j'_*"'] & H_n(C') \arrow[r, "\partial"'] & H_{n-1}(A') \arrow[r] & \cdots
\end{tikzcd}$$

is a commutative diagram.

2.5 Cochain Complexes

2.6 Double Complexes

Definition 2.6.1: Double Complexes

Let $\mathcal{A}$ be an abelian category. A double complex $(C_{\bullet,\bullet}, d^h, d^v)$ in $\mathcal{A}$ is a sequence of objects $C_{p,q} \in \mathcal{A}$ that is bigraded $p, q \in \mathbb{Z}$, together with the horizontal differentials $d^h : C_{p,q} \to C_{p+1,q}$ and vertical differentials $d^v : C_{p,q} \to C_{p,q+1}$ such that the following diagram commutes:

$$\begin{tikzcd}
 & \vdots & \vdots & \vdots & \\
\cdots \arrow[r] & C_{p-1,q+1} \arrow[r, "d^h"] \arrow[u] & C_{p,q+1} \arrow[r, "d^h"] \arrow[u] & C_{p+1,q+1} \arrow[r] \arrow[u] & \cdots \\
\cdots \arrow[r] & C_{p-1,q} \arrow[r, "d^h"] \arrow[u, "d^v"] & C_{p,q} \arrow[r, "d^h"] \arrow[u, "d^v"] & C_{p+1,q} \arrow[r] \arrow[u, "d^v"] & \cdots \\
\cdots \arrow[r] & C_{p-1,q-1} \arrow[r, "d^h"] \arrow[u, "d^v"] & C_{p,q-1} \arrow[r, "d^h"] \arrow[u, "d^v"] & C_{p+1,q-1} \arrow[r] \arrow[u, "d^v"] & \cdots \\
 & \vdots \arrow[u] & \vdots \arrow[u] & \vdots \arrow[u] &
\end{tikzcd}$$

Definition 2.6.2: The Total Complex of a Double Complex

Let $\mathcal{A}$ be an abelian category where $\oplus$ denotes the product. Let $(C_{\bullet,\bullet}, d^h, d^v)$ be a double complex. Define the total complex $\text{Tot}^{\oplus}(C)_\bullet$ to be the chain complex in $\mathcal{A}$ constructed as follows.

- For each $n \in \mathbb{Z}$, define
$$\text{Tot}^{\oplus}(C)_n = \bigoplus_{p+q=n} C_{p,q}$$
- For each $n \in \mathbb{Z}$, define $d_n : \text{Tot}^{\oplus}(C)_n \to \text{Tot}^{\oplus}(C)_{n-1}$ by
$$d_n = d_n^v + (-1)^n d_n^h$$

In other words, the chain complex is of the form:

$$\cdots \longrightarrow \bigoplus_{p+q=n+1} C_{p,q} \xrightarrow{d_{n+1}^v + (-1)^{n+1} d_{n+1}^h} \bigoplus_{p+q=n} C_{p,q} \xrightarrow{d_n^v + (-1)^n d_n^h} \bigoplus_{p+q=n-1} C_{p,q} \longrightarrow \cdots$$

Definition 2.6.3: Total Homology of a Double Chain Complex

Let $\mathcal{A}$ be an abelian category. Let $(C_{\bullet,\bullet}, d^h, d^v)$ be a double complex in $\mathcal{A}$. Define the total homology of C to be the homology

$$H_\bullet^{\text{Tot}}(C_{\bullet,\bullet}, d^h, d^v) = H_\bullet(\text{Tot}^\oplus(C)_\bullet, d)$$

of the total complex $(\text{Tot}^\oplus(C)_\bullet, d)$

3 Derived Functors

3.1 Exact Functors

Definition 3.1.1: Additive Functors

Let $\mathcal{A},\mathcal{B}$ be abelian categories. We say that a functor $F:\mathcal{A}\to\mathcal{B}$ is additive if for every $X,Y\in\mathcal{A}$, the map
$$\text{Hom}_{\mathcal{A}}(X,Y)\to\text{Hom}_{\mathcal{B}}(F(X),F(Y))$$
is a homomorphism of abelian groups.

Definition 3.1.2: Exact Functors

Let $F:\mathcal{A}\to\mathcal{B}$ be an additive functor of abelian categories. Let $0\to A\to B\to C\to 0$ be an exact sequence in $\mathcal{A}$.

- We say that F is exact if the sequence
$$0\to F(A)\to F(B)\to F(C)\to 0$$
is exact.
- We say that F is right exact if the sequence
$$F(A)\to F(B)\to F(C)\to 0$$
is exact.
- We say that F is left exact if the sequence
$$0\to F(A)\to F(B)\to F(C)$$
is exact.

Proposition 3.1.3

Let $F:\mathcal{A}\to\mathcal{B}$ be an additive functor. Then F preserves split exact sequences.

Theorem 3.1.4: Freyd-Mitchell Embedding Theorem

Let $\mathcal{A}$ be a small abelian category. Then there exists a ring R and an exact, fully faithful functor $F:\mathcal{A}\to R-\text{mod}$.

This means that
$$\text{Hom}_{\mathcal{A}}(M,N)\cong\text{Hom}_R(F(M),F(N))$$

Lemma 3.1.5

The Freyd-Mitchell embedding preserves kernels and cokernels. Moreover, it maps the zero object to the zero object.

Theorem 3.1.6

Let $\mathcal{A}$ be an abelian category. Let $M\in\mathcal{A}$. Then the following are true.

- The covariant functor $\text{Hom}(M,-):\mathcal{A}\to\mathbf{Ab}$ is left exact.
- The contravariant functor $\text{Hom}(-,M):\mathcal{A}\to\mathbf{Ab}$ is right exact.

3.2 Injective and Projective Objects

Injectivity and Projectivity objects are created just for the sake of allowing the Hom functor to be exact. Therefore its definition is also direct.

Definition 3.2.1: Projective and Injective Objects

Let $\mathcal{A}$ be an abelian category.

- We say that an object Y of $\mathcal{A}$ is injective if the functor $\mathrm{Hom}(-, Y) : \mathcal{A} \to \mathbf{Ab}$ is exact.
- We say that an object Y of $\mathcal{A}$ is projective if the functor $\mathrm{Hom}(Y, -) : \mathcal{A} \to \mathbf{Ab}$ is exact.

Definition 3.2.2: Enough Injectives and Enough Projectives

Let $\mathcal{A}$ be an abelian category. $\mathcal{A}$ is said to have enough injectives if every object is the subobject of an injective object. $\mathcal{A}$ is said to have enough projectives if every object is the quotient of an projective object.

There are however equivalent definitions from the categorical point of view.

3.3 Resolutions of Objects

There are in general, four types of resolutions. Namely injective resolutions, projective resolutions, free resolutions and acyclic resolutions. We will study all four of them and their relations in this section.

Definition 3.3.1: Injective Resolution

Let $\mathcal{A}$ be an abelian category. An injective resolution of an object $A \in \mathcal{A}$ is an exact sequence

$$0 \longrightarrow A \xrightarrow{\epsilon} I^0 \longrightarrow I^1 \longrightarrow I^2 \longrightarrow \cdots$$

where each I^k is injective.

Theorem 3.3.2

Let $\mathcal{A}$ be an abelian category. Then $\mathcal{A}$ has enough injectives if and only if every object of $\mathcal{A}$ has an injective resolution.

Proposition 3.3.3

Let $\phi : A \to A'$ be a morphism in an abelian category $\mathcal{A}$. Suppose that there are injective resolutions

$$\begin{tikzcd} 0 \arrow[r] & A \arrow[r] \arrow[d, "\phi"'] & I^0 \arrow[r] & I^1 \arrow[r] & \cdots \\ 0 \arrow[r] & A' \arrow[r] & J^0 \arrow[r] & J^1 \arrow[r] & \cdots \end{tikzcd}$$

for A and A' respectively. Then there exists a chain map extending ϕ such that the following diagram commutes:

$$\begin{tikzcd} 0 \arrow[r] & A \arrow[r] \arrow[d, "\phi"'] & I^0 \arrow[r] \arrow[d, "\phi^0"'] & I^1 \arrow[r] \arrow[d, "\phi^1"'] & \cdots \\ 0 \arrow[r] & A' \arrow[r] & J^0 \arrow[r] & J^1 \arrow[r] & \cdots \end{tikzcd}$$

Moreover, any two such chain maps are homotopic.

Lemma 3.3.4

Let $\mathcal{A}$ be an abelian category. Then any two injective resolutions of an object A are homotopically equivalent.

Definition 3.3.5: Projective Resolution

Let $\mathcal{A}$ be an abelian category. An projective resolution of an object A is an exact sequence

$$\cdots \longrightarrow P_2 \longrightarrow P_1 \longrightarrow P_0 \xrightarrow{d} A \longrightarrow 0$$

where each P_k is projective.

Theorem 3.3.6

Let $\mathcal{A}$ be an abelian category. Then $\mathcal{A}$ has enough projectives if and only if every object of $\mathcal{A}$ has a projective resolution.

Proposition 3.3.7

Let $\phi : A \to A'$ be a morphism in an abelian category $\mathcal{A}$. Suppose that there are projective resolutions

$$\begin{tikzcd} \cdots \arrow[r] & P_2 \arrow[r] & P_1 \arrow[r] & A \arrow[r] \arrow[d, "\phi"'] & 0 \\ \cdots \arrow[r] & Q_2 \arrow[r] & Q_1 \arrow[r] & A' \arrow[r] & 0 \end{tikzcd}$$

for A and A' respectively. Then there exists a chain map extending ϕ such that the following diagram commutes:

$$\begin{tikzcd} \cdots \arrow[r] & P_2 \arrow[r] \arrow[d, "\phi_2"'] & P_1 \arrow[r] \arrow[d, "\phi_1"'] & A \arrow[r] \arrow[d, "\phi"'] & 0 \\ \cdots \arrow[r] & Q_2 \arrow[r] & Q_1 \arrow[r] & A' \arrow[r] & 0 \end{tikzcd}$$

Moreover, any two such chain maps are homotopic.

Lemma 3.3.8

Let $\mathcal{A}$ be an abelian category. Then any two projective resolutions of an object A are homotopically equivalent.

3.4 Derived Functors

Definition 3.4.1: Right Derived Functors

Let $F : \mathcal{A} \to \mathcal{B}$ be a left exact functor. Suppose that $\mathcal{A}$ has enough injectives. Define the right derived functors $R^iF : \mathcal{A} \to \mathcal{B}$ for $i \geq 0$ as follows.

- On objects, $R^iF(A) = H^i(F(I^\bullet))$ where $d : A \to I^\bullet$ is an injective resolution of A
- On Morphisms, $R^iF(\phi : A \to B) = H^i(F(\phi^\bullet : I^\bullet \to (I')^\bullet))$ where $\phi^\bullet : I^\bullet \to (I')^\bullet$ is an extension of ϕ to resolutions.

Theorem 3.4.2

Let $F : \mathcal{A} \to \mathcal{B}$ be a left exact functor. The nth right derived functor $R^n F$ is an additive functor from $\mathcal{A}$ to $\mathcal{B}$.

Lemma 3.4.3

Let A be an injective object, then $R^n F(A) = 0$ for $n \neq 0$.

Corollary 3.4.4

If $F : \mathcal{A} \to \mathcal{B}$ is a left exact functor, then $R^0 F = F$.

Theorem 3.4.5

Let $\mathcal{A}, \mathcal{B}$ be abelian categories with enough injectives. Let $F : \mathcal{A} \to \mathcal{B}$ be a left exact functor. For any short exact sequence

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

there is a canonical long exact sequence

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow R^1(A) \longrightarrow R^1(B) \longrightarrow R^1(C) \longrightarrow R^2(A) \longrightarrow \cdots$$

Definition 3.4.6: Left Derived Functors

Let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. Suppose that $\mathcal{A}$ has enough projectives. Define the left derived functors $L_i F : \mathcal{A} \to \mathcal{B}$ for $i \geq 0$ as follows.

- On objects, $L_i F(A) = H_i(F(P^\bullet))$ where $d : P_\bullet \to A$ is an projective resolution of A
- On Morphisms, $L_i F(\phi : A \to B) = L_i(F(\phi_\bullet : P_\bullet \to (P')_\bullet))$ where $\phi_\bullet : P_\bullet \to (P')_\bullet$ is an extension of ϕ to resolutions.

Theorem 3.4.7

Let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. The nth left derived functor $L_n F$ is an additive functor from $\mathcal{A}$ to $\mathcal{B}$.

Lemma 3.4.8

Let A be a projective object, then $L_n F(A) = 0$ for $n \neq 0$.

Corollary 3.4.9

If $F : \mathcal{A} \to \mathcal{B}$ is a right exact functor, then $L_0 F = F$.

Theorem 3.4.10

Let $\mathcal{A}, \mathcal{B}$ be abelian categories with enough projectives. Let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. For any short exact sequence

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

there is a canonical long exact sequence

$$\cdots \longrightarrow L_2(C) \longrightarrow L_1(A) \longrightarrow L_1(B) \longrightarrow L_1(C) \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

3.5 δ-Functors

Definition 3.5.1: δ-Functors

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. A homological δ-functor is a collection $\{T_n : \mathcal{A} \to \mathcal{B} \mid n \in \mathbb{N}\}$ of additive functors such that for any short exact sequence

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

there are morphisms $\delta_n : T_n(C) \to T_n(A)$ for $n \in \mathbb{N}$ such that the following are true.

- There is a long exact sequence

$$\cdots \longrightarrow T_{n+1}(C) \xrightarrow{\delta_{n+1}} T_n(A) \longrightarrow T_n(B) \longrightarrow T_n(C) \xrightarrow{\delta_n} T_{n-1}(A) \longrightarrow \cdots$$

- If there is a morphism of short exact sequences

$$\begin{tikzcd} 0 \arrow[r] & A \arrow[r] \arrow[d] & B \arrow[r] \arrow[d] & C \arrow[r] \arrow[d] & 0 \\ 0 \arrow[r] & A' \arrow[r] & B' \arrow[r] & C' \arrow[r] & 0 \end{tikzcd}$$

  the following diagram commutes:

$$\begin{tikzcd} T_n(C) \arrow[r, "\delta_n"] \arrow[d] & T_{n-1}(A) \arrow[d] \\ T_n(C') \arrow[r, "\delta'_n"] & T_{n-1}(A') \end{tikzcd}$$

4 A Second Course on Modules

4.1 Projective and Injective Modules

Definition 4.1.1: Projective Modules

An R-module M is said to be projective if for every surjective homomorphism $f : N \twoheadrightarrow M$ and every module homomorphism $g : P \to M$, there exists a module homomorphism $h : P \to N$ such that $f \circ h = g$. In other words, the following diagram commutes:

$$\begin{tikzcd} & N \arrow[d, two heads, "f"] \\ P \arrow[ur, dashed, "\exists h"] \arrow[r, "g"'] & M \end{tikzcd}$$

Lemma 4.1.2

Every free module is projective.

Proof. Let R be a ring and let F be a free R-module. Suppose that F has basis B. Let M, N be R-modules. Suppose that $f : N \to M$ is surjective and there exists an R-module homomorphism $g : R^n \to M$. Since f is surjective, for each $b \in B$, we can choose a pre-image for $g(b)$ in N for all $b \in B$. Call it n_b. Now define $h : F \to N$ by $b \mapsto n_b$ and then extend it R-linearly. Now if $\sum_{b\in B} k_b b \in F$, we have that

$$\begin{aligned} (f \circ h)\left(\sum_{b\in B} k_b b\right) &= f\left(\sum_{b\in B} k_b h(b)\right) \\ &= f\left(\sum_{b\in B} k_b n_b\right) & &= f\left(\sum_{b\in B} k_b n_b\right) = \sum_{b\in B} k_b f(n_b) \\ &= \sum_{b\in B} k_b g(b) \\ &= g\left(\sum_{b\in B} k_b b\right) \end{aligned}$$

so that $f \circ h = g$. Thus F is projective. □

Theorem 4.1.3

Let P be an R-module. Then the following are equivalent.

- P is projective
- For every short exact sequence $0 \to A \xrightarrow{f} B \xrightarrow{g} C \to 0$ we have that

$$0 \to \text{Hom}(P, A) \xrightarrow{f} \text{Hom}(P, B) \xrightarrow{g} \text{Hom}(P, C) \to 0$$

  is exact.
- $P \oplus Q$ is a free R-module for some R-module Q.

Proof.

- $(3) \implies (1)$: Suppose that there exists a module Q such that $P \oplus Q$ is free. Let $f : N \to M$ be a surjective R-module homomorphism and let $g : P \to M$ be an R-module homomorphism.

$\square$

Proposition 4.1.4

A direct sum $\oplus_{i\in I} P_i$ is projective if and only if each P_i is.

Proposition 4.1.5

Let P be a module. Then P is projective if and only if every exact sequence of the following form splits:

$$0 \longrightarrow A \longrightarrow B \longrightarrow P \longrightarrow 0$$

Definition 4.1.6: Injective Modules

An R-module M is said to be projective if for every injective homomorphism $f : N \rightarrowtail M$ and every module homomorphism $g : N \to I$, there exists a module homomorphism $h : M \to I$ such that $f \circ h = g$. In other words, the following diagram commutes:

$$\begin{tikzcd}
N \arrow[d, tail, "f"'] \arrow[dr, "g"] & \\
M \arrow[r, dashed, "\exists h"'] & I
\end{tikzcd}$$

Theorem 4.1.7

An R-module I is injective if and only if for every short exact sequence $0 \to A \xrightarrow{f} B \xrightarrow{g} C \to 0$ we have that

$$0 \to \text{Hom}(A, I) \xrightarrow{f} \text{Hom}(B, I) \xrightarrow{g} \text{Hom}(C, I) \to 0$$

is exact.

Proposition 4.1.8

Let E be a module. Then E is injective if and only if every exact sequence of the following form splits:

$$0 \longrightarrow E \longrightarrow B \longrightarrow C \longrightarrow 0$$

4.2 Flat Modules

Definition 4.2.1: Flat Modules

Let R be a ring. An R-module M is said to be flat if for every injective linear map $\phi : K \to L$ of R-modules, the map

$$\phi \otimes \text{id}_M : K \otimes_R M \to L \otimes_R M$$

is also injective.

Theorem 4.2.2

Let R be a ring and M an R-module. Let $0 \to K \to L \to J \to 0$ be an exact sequence, then the sequence

$$K \otimes_R M \to L \otimes_R M \to J \otimes_R M \to 0$$

is also exact.

Theorem 4.2.3

Let R be a ring and M an R-module. Then M is a flat module if and only if for every short exact sequence $0 \to K \to L \to J \to 0$, the sequence

$$0 \to K \otimes_R M \to L \otimes_R M \to J \otimes_R M \to 0$$

is also exact.

Theorem 4.2.4

Let R be a ring. Then the following are true.

- Product: If A and B are flat over R then $A \otimes_R B$ is flat over R
- Base Change: Let S be an R-algebra ($R \to S$ a ring hom). Then $M \otimes_R S$ is flat over S for any flat R-module M
- Transitivity: Let S be an R-algebra such that S is flat over R. If C is flat over S then C is flat over R.

We have the following inclusion of modules

$$\text{Free Modules} \subset \text{Projective Modules} \subset \text{Flat Modules} \subset \text{Torsion Free Modules}$$

4.3 Extensions and Torsions

Definition 4.3.1: Extensions

Let R be a ring. Let M, N be R-modules. An extension of M by N is a short exact sequence

$$0 \longrightarrow N \longrightarrow E \longrightarrow M \longrightarrow 0$$

of R-modules.

Definition 4.3.2: Equivalent Extensions

Let R be a ring. Let M, N be R-modules. We say that two extensions

$$0 \longrightarrow N \longrightarrow E \longrightarrow M \longrightarrow 0$$

$$0 \longrightarrow N \longrightarrow F \longrightarrow M \longrightarrow 0$$

are equivalent if there exists an R-module homomorphism $\phi : E \to F$ such that the following diagram commutes:

$$\begin{tikzcd}
0 \arrow[r] & N \arrow[r] \arrow[d, "\mathrm{id}_N"] & E \arrow[r] \arrow[d, "\phi"] & M \arrow[r] \arrow[d, "\mathrm{id}_M"] & 0 \\
0 \arrow[r] & N \arrow[r] & F \arrow[r] & M \arrow[r] & 0
\end{tikzcd}$$

Proposition 4.3.3

Let R be a ring. Let M, N be R-modules. Suppose that the following two extensions are equivalent:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & N & \longrightarrow & E & \longrightarrow & M & \longrightarrow & 0 \\ & & \big\downarrow{\scriptstyle \mathrm{id}_N} & & \big\downarrow{\scriptstyle \phi} & & \big\downarrow{\scriptstyle \mathrm{id}_M} & & \\ 0 & \longrightarrow & N & \longrightarrow & F & \longrightarrow & M & \longrightarrow & 0 \end{array}$$

Then ϕ is an isomorphism. Moreover, equivalent extensions is an equivalence relation.

Definition 4.3.4: Split Extensions

Let R be a ring. Let M, N be R-modules. We say that an extension splits if it is equivalent to the following extension

$$0 \longrightarrow N \longrightarrow N \oplus M \longrightarrow M \longrightarrow 0$$

of R-modules. The above extension is called a trivial extension.

Theorem 4.3.5

Let R be a ring. Let M, N be R-modules. There is a bijection

$$\frac{\{\text{Extensions of } M \text{ by } N\}}{\cong} \quad \overset{1:1}{\longleftrightarrow} \quad \mathrm{Ext}^1_R(M, N)$$

where $\cong$ means equivalence of extensions. Moreover, the trivial extension corresponds to the zero element of $\mathrm{Ext}^1_R(M, N)$.

4.4 Derived Functors in the Category of R-Modules

Definition 4.4.1: The Ext Functor

Denote ${}_R\mathbf{Mod}$ the category of R-modules. Let A be an R-module. Define the right derived functor of the functor $\mathrm{Hom}(A, -) : {}_R\mathbf{Mod} \to \mathbf{Ab}$ to be

$$\mathrm{Ext}^i_R(A, -) : {}_R\mathbf{Mod} \to \mathbf{Ab}$$

Explicitly, for

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

an injective resolution, form the cochain complex

$$0 \to \mathrm{Hom}_R(A, I^0) \to \mathrm{Hom}_R(A, I^1) \to \cdots$$

and define Ext to be the cohomology group

$$\mathrm{Ext}^i_R(A, B) = \frac{\ker(\mathrm{Hom}_R(A, I^i) \to \mathrm{Hom}_R(A, I^{i+1}))}{\mathrm{im}(\mathrm{Hom}_R(A, I^{i-1}) \to \mathrm{Hom}_R(A, I^i))}$$

Theorem 4.4.2

Let A, B be R-modules. Then the following are true regarding the Ext group.

- $\mathrm{Ext}^0_R(A, B) \cong \mathrm{Hom}_R(A, B)$
- $\mathrm{Ext}^i_R(A, B) = 0$ for all $i > 0$ if A is projective or B is injective

- $\text{Ext}^i_R(A,B)=0$ for all $i\geq 2$ if A,B are $\mathbb{Z}$-modules.

Definition 4.4.3: The Tor Functor

Denote ${}_R\mathbf{Mod}$ the category of R-modules. Let B be an R-module. Define the right derived functor of the functor $-\otimes_R B:{}_R\mathbf{Mod}\to{}_R\mathbf{Mod}$ to be

$$\text{Tor}_i^R(-,B):{}_R\mathbf{Mod}\to\mathbf{Ab}$$

Explicitly, for

$$\cdots\to P_1\to P_0\to B\to 0$$

an injective resolution, form the chain complex

$$\cdots\to P_1\otimes_R B\to P_0\otimes_R B\to 0$$

and define Tor to be the homology group

$$\text{Tor}_i^R(A,B)=\frac{\ker(P_i\otimes_R B\to P_{i-1}\otimes_R B)}{\text{im}(P_{i+1}\otimes_R B\to P_i\otimes_R B)}$$

5 Spectral Sequences

5.1 General Spectral Sequences

Definition 5.1.1: Homological Spectral Sequences

Let $\mathcal{A}$ be an abelian category. A homological spectral sequence consists of the following data.

- A collection of objects $E^r_{\bullet,\bullet} = \{E^r_{p,q} \in \mathcal{A} \mid p,q \in \mathbb{Z}\}$ called pages for each $r \in \mathbb{N}$. So that there is a sequence
$$E^1_{\bullet,\bullet}, E^2_{\bullet,\bullet}, E^3_{\bullet,\bullet}, \dots$$
of family of objects
- A degree (p,q) map
$$d^r_{p,q} : E^r_{p,q} \to E^r_{p-r,q+r-1}$$
for each $p,q \in \mathbb{Z}$ and $r \in \mathbb{N}$ such that $d^r \circ d^r = 0$
- Isomorphisms of the form $E^{r+1}_{\bullet,\bullet} = H_\bullet(E^r_{\bullet,\bullet}, d^r)$. This means that
$$E^{r+1}_{p,q} = \frac{\ker(d^r : E^r_{p,q} \to E^r_{p-r,q+r-1})}{\operatorname{im}(d^r : E^r_{p+r,q-r+1} \to E^r_{p,q})}$$

We say that the total degree of $E^r_{p,q}$ is $n = p + q$.

Definition 5.1.2: Cohomological Spectral Sequences

Let $\mathcal{A}$ be an abelian category. A cohomological spectral sequence consists of the following data.

- A collection of objects $E_r^{\bullet,\bullet} = \{E_r^{p,q} \in \mathcal{A} \mid p,q \in \mathbb{Z}\}$ called pages for each $r \in \mathbb{N}$. So that there is a sequence
$$E_1^{\bullet,\bullet}, E_2^{\bullet,\bullet}, E_3^{\bullet,\bullet}, \dots$$
of family of objects
- A degree (p,q) map
$$d_r^{p,q} : E_r^{p,q} \to E_r^{p-r,q+r-1}$$
for each $p,q \in \mathbb{Z}$ and $r \in \mathbb{N}$ such that $d_r \circ d_r = 0$
- Isomorphisms of the form $E_{r+1}^{\bullet,\bullet} = H^\bullet(E_r^{\bullet,\bullet}, d_r)$. This means that
$$E_{r+1}^{p,q} = \frac{\ker(d_r : E_r^{p,q} \to E_r^{p-r,q+r-1})}{\operatorname{im}(d_r : E_r^{p+r,q-r+1} \to E_r^{p,q})}$$

Notice that cohomological spectral sequences are really the same thing as homological spectral sequences, just reindex the objects by $E_r^{p,q} = E^r_{-p,-q}$.

Definition 5.1.3: Bounded Spectral Sequences

Let $(E^r_{\bullet,\bullet}, d^r)$ be a homological spectral sequence. We say that it is bounded if for each $n \in \mathbb{N}$, there are only finitely many non-zero terms of total degree n in $E^r_{\bullet,\bullet}$ for each $r \in \mathbb{N}$.

We say that it is bounded below if there exists $s_n \in \mathbb{Z}$ for each $n \in \mathbb{N}$ such that terms $E^r_{\bullet,\bullet}$ of total degree n are 0 for all $p < s$.

Lemma 5.1.4

Let $(E^r_{\bullet,\bullet}, d^r)$ be a bounded homological spectral sequence. Then for each $(p,q) \in \mathbb{Z}^2$, there exists $r_0 \in \mathbb{N}$ such that $E^{r+1}_{p,q} \cong E^r_{p,q}$ for all $r \geq r_0$.

Definition 5.1.5: Stable Values

Let $(E^r_{\bullet,\bullet}, d^r)$ be a bounded homological spectral sequence. Let $(p,q) \in \mathbb{Z}^2$ and $r_0 \in \mathbb{N}$ such that $E^{r+1}_{p,q} = E^r_{p,q}$ for all $r \geq r_0$. Define the stable values of the sequence to be

$$E^\infty_{p,q} = E^{r_0}_{p,q}$$

5.2 The Spectral Sequence of Exact Couples

Definition 5.2.1: Exact Couple

An exact couple consists of bigraded abelian groups $E_{\bullet,\bullet}$ and $A_{\bullet,\bullet}$ and maps $i : A_{\bullet,\bullet} \to A_{\bullet,\bullet}$ of degree (a,a'), $j : A_{\bullet,\bullet} \to E_{\bullet,\bullet}$ of degree (b,b') and $k : E_{\bullet,\bullet} \to A_{\bullet,\bullet}$ of degree (c,c') such that the triangle

$$\begin{tikzcd} A_{\bullet,\bullet} \arrow[rr, "i"] & & A_{\bullet,\bullet} \arrow[dl, "j"] \\ & E_{\bullet,\bullet} \arrow[ul, "k"] & \end{tikzcd}$$

is exact at each vertex ($\text{im}(i) = \ker(j)$ and so on). We write the exact couple as (A, E, i, j, k).

Notice that this actually just the data of a long exact sequence. If we look at what happens nearby $E_{p,q}$, we see that we can expand out the triangle ad infinum:

$$\cdots \longrightarrow A_{p-a,q-a'} \longrightarrow E_{p,q} \longrightarrow A_{p+a,q+a'} \longrightarrow A_{p+a+b,q+a'+b'} \longrightarrow \cdots$$

Definition 5.2.2: Derived Couple

Suppose that there is an exact couple of the form

$$\begin{tikzcd} A_{\bullet,\bullet} \arrow[rr, "i"] & & A_{\bullet,\bullet} \arrow[dl, "j"] \\ & E_{\bullet,\bullet} \arrow[ul, "k"] & \end{tikzcd}$$

for some gradation of i, j, k. Define the derived couple with the following data. Write $d = j \circ k$.

- For each $p, q \in \mathbb{Z}$, define
$$E'_{p,q} = \frac{\ker(d : E_{p,q} \to E_{p+c+b,q+c'+b'})}{\text{im}(d : E_{p-c-b,q-c'-b'} \to E_{p,q})}$$
so that $E'_{\bullet,\bullet}$ is bigraded.
- For each $p, q \in \mathbb{Z}$, define
$$A'_{p,q} = \text{im}(i : A_{p,q} \to A_{p+a,q+a'})$$
so that $A'_{\bullet,\bullet}$ is bigraded.
- For each $p, q \in \mathbb{Z}$, define
$$i' : A'_{p,q} \subseteq A_{p+a,q+a'} \to A'_{p+a,q+a} \subseteq A_{p+2a,q+2a'}$$

by $i' = i|_{A'_{p,q}}$. We simplify and write it as $i' : A'_{\bullet,\bullet} \to A'_{\bullet,\bullet}$

- For each $p, q \in \mathbb{Z}$, define
$$j' : A'_{p-b,q-b'} \to E'_{p,q}$$
as follows. For all $i(t) \in A'_{p-b,q-b'}$ where $t \in A_{p-b,q-b'}$, $j'(i(t)) = [j(t)] \in E'_{p,q}$. We simplify and write it as $j' : A'_{\bullet,\bullet} \to E'_{\bullet,\bullet}$

- For each $p, q \in \mathbb{Z}$, define
$$k' : E'_{p,q} \to A'_{p+c,q+c'}$$
as follows. For all $[e] \in E'_{p,q}$, $k'([e]) = k(e)$. We simplify and write it as $k' : E'_{\bullet,\bullet} \to A'_{\bullet,\bullet}$

We write the derived couple as $(A^1, E^1, i^1, j^1, k^1)$

Theorem 5.2.3

The derived couple of any exact couple is also an exact couple with the same grading of maps.

Theorem 5.2.4

Let (A, E, i, j, k) be an exact couple. Then $E, E^1, E^2, \dots$ together with maps $d^r = j^r \circ k^r$ for $r \in \mathbb{N}$ defines a homological spectral sequence.

5.3 The Spectral Sequence of Filtrations

Definition 5.3.1: Filtered Chain Complexes

Let $\mathcal{A}$ be an abelian category. Let $C \in \text{Ch}(\mathcal{A})$ be a chain complex. A filtered chain complex is a sequence of subchain complexes of C with inclusions
$$\cdots \subseteq F_pC \subseteq F_{p+1}C \subseteq \cdots$$
such that the boundary map $d : C_n \to C_{n-1}$ of C has the property that
$$d(F_pC_n) \subseteq F_pC_{n-1}$$

Definition 5.3.2: Exhaustive Filtered Chain Complexes

Let $\mathcal{A}$ be an abelian category. Let $C \in \text{Ch}(\mathcal{A})$ be a chain complex. A filtered chain complex F_pC is said to be exhaustive if $\bigcup_{p\in\mathbb{Z}} F_pC = C$.

Definition 5.3.3: Spectral Sequence Arising from Filtered Chain Complexes

Let $\mathcal{A}$ be an abelian category. Let $(C_\bullet, d_\bullet) \in \text{Ch}(\mathcal{A})$ be a chain complex. Let F_pC be a filtered chain complex that is exhaustive. Define the following objects and subobjects in $\mathcal{A}$.

- Define an object $E^0_{p,q} = \frac{F_pC_{p+q}}{F_{p-1}C_{p+q}}$ and a chain complex $E^0_p = \frac{F_pC}{F_{p-1}C}$.
- For each $p, r \in \mathbb{N}$, define
$$A^r_p = \{c \in F_pC \mid d(c) \in F_{p-r}C\}$$
called approximately cycles
- Write $\eta_p : F_pC \to \frac{F_pC}{F_{p-1}C} = E^0_p$ for the sujection, which is a chain map.
- For each $p, r \in \mathbb{N}$, define
$$Z^r_p = \eta_p(A^r_p) \subseteq E^0_p$$

- For each $p,r\in\mathbb{N}$, define
$$B_{p-r}^{r+1}=\eta_{p-r}(d(A_p^r))\subseteq E_{p-r}^0$$
- For each $p\in\mathbb{N}$, define
$$Z_p^\infty=\bigcap_{r=1}^\infty Z_p^r \quad\text{and}\quad B_p^\infty=\bigcup_{r=1}^\infty B_p^r$$

Evidently, there is a tower of subobjects of E_p^0 given by
$$0=B_p^0\subseteq B_p^1\subseteq\cdots B_p^\infty\subseteq Z_p^\infty\subseteq\cdots Z_p^1\subseteq Z_p^0=E_p^0$$
Thus we finally define
$$E_p^r=\frac{Z_p^r}{B_p^r}\quad\text{for all } r\in R\quad\text{and}\quad E_p^\infty=\frac{Z_p^\infty}{B_p^\infty}$$
together with $d:E_p^r\to E_{p-r}^r$ to be the differential induced by the differential of C.

Lemma 5.3.4

Let $\mathcal{A}$ be an abelian category. Let $(C_\bullet,d_\bullet)\in\text{Ch}(\mathcal{A})$ be a chain complex. Let F_pC be a filtered chain complex that is exhaustive. Then the following are true.

- For any $p,r\in\mathbb{N}$, $A_p^r+F_{p-1}C=A_{p-1}^{r-1}$
- For any $p,r\in\mathbb{N}$, $Z_p^r\cong A_p^r/A_{p-1}^{r-1}$
- For any $p,r\in\mathbb{N}$, there are isomorphisms
$$E_p^r=\frac{Z_p^r}{B_p^r}\cong\frac{A_p^r+F_{p-1}C}{d(A_{p+r-1}^{r-1})+F_{p-1}C}\cong\frac{A_p^r}{d(A_{p+r-1}^{r-1})+A_{p-1}^{r-1}}$$

Theorem 5.3.5

Let $\mathcal{A}$ be an abelian category. Let $(C_\bullet,d_\bullet)\in\text{Ch}(\mathcal{A})$ be a chain complex. Let F_pC be a filtered chain complex that is exhaustive. Then the map $d:E_p^r\to E_{p-r}^r$ determines an isomorphism
$$\frac{Z_p^r}{Z_p^{r+1}}\cong\frac{B_{p-r}^{r+1}}{B_{p-r}^r}$$
Moreover, this concludes that $(E_{p,q}^r,d)$ is a spectral sequence.

5.4 Convergence

Definition 5.4.1: Weakly Convergent

Let $(E_{\bullet,\bullet}^r,d^r)$ be a spectral sequence. We say that it is weakly convergent if there is a graded object $H_\bullet$ together with a filtration $F_\bullet H_n$ for every $n\in\mathbb{N}$, together with isomorphisms
$$\beta_{p,q}:E_{p,q}^\infty\xrightarrow{\cong}\frac{F_pH_{p+q}}{F_{p-1}H_{p+q}}$$

Definition 5.4.2: Convergent Spectral Sequences

Let $(E^r_{\bullet,\bullet}, d^r)$ be a spectral sequence. We say that it is convergent if the following are true.

- It is weakly convergent with filtrations $F_\bullet H_n$ for each $n \in \mathbb{N}$
- $\bigcap_{k=0}^\infty F_k H_\bullet = 0$

5.5 The Spectral Sequence of Double Complexes

5.6 Hyperhomology and Hypercohomology

Definition 5.6.1: Cartan-Eilenberg Resolution

Let $\mathcal{A}$ be an abelian category with enough projectives. Let $A_\bullet \in \text{Ch}(\mathcal{A})$ be a chain complex as follows:

$$\cdots \longrightarrow A_{p-1} \longrightarrow A_p \longrightarrow A_{p+1} \longrightarrow \cdots$$

A Cartan-Eilenberg resolution of $A_\bullet$ is an upper half double complex $P_{\bullet,\bullet}$ together with augmentation maps $\varepsilon : P_{P,\bullet} \to A_p$ as follows:

$$\begin{tikzcd}
 & \vdots \arrow[d] & \vdots \arrow[d] & \vdots \arrow[d] & \\
\cdots & P_{p-1,1} \arrow[l] \arrow[d] & P_{p,1} \arrow[l] \arrow[d] & P_{p+1,1} \arrow[l] \arrow[d] & \cdots \arrow[l] \\
\cdots & P_{p-1,0} \arrow[l] \arrow[d, "\varepsilon"] & P_{p,0} \arrow[l] \arrow[d, "\varepsilon"] & P_{p+1,0} \arrow[l] \arrow[d, "\varepsilon"] & \cdots \arrow[l] \\
\cdots & A_{p-1} \arrow[l] & A_p \arrow[l] & A_{p+1} \arrow[l] & \cdots \arrow[l]
\end{tikzcd}$$

such that the following are true.

- If $A_p = 0$ then $P_{p,\bullet} = 0$
- For each $p \in \mathbb{Z}$, the chain complex $(B_\bullet, d^v)$ of boundaries where $B_q = d^h(P_{p+1,q})$ form a projective resolution of A_p. This means that the vertical chain complexes

$$\begin{tikzcd}
\vdots \arrow[d] \\
d^h(P_{p,0}) \subseteq P_{p,1} \arrow[d] \\
d^h(P_{p+1,0}) \subseteq P_{p,0} \arrow[d, "\varepsilon"] \\
A_p
\end{tikzcd}$$

  are projective resolutions.

- For each $p \in \mathbb{Z}$, the chain complex $(H_\bullet, d^v)$ of the homology groups where

$$H_q = H_p(P_{\bullet,q}, d^h)$$

  form a projective resolution of $H_p(A_\bullet)$. This means that the vertical chain complexes

$$\begin{tikzcd} \vdots \arrow[d] \\ H_p(P_{\bullet,1}, d^h) \arrow[d, "d^v"] \\ H_p(P_{\bullet,0}, d^h) \arrow[d, "\varepsilon"] \\ H_p(A_\bullet) \end{tikzcd}$$

are projective resolutions.

Theorem 5.6.2

Let $\mathcal{A}$ be an abelian category. Then every chain complex $A_\bullet \in \text{Ch}(\mathcal{A})$ has a Cartan-Eilenberg resolution $P_{\bullet,\bullet} \to A_\bullet$.

Definition 5.6.3: Left Hyperderived Functors

Let $\mathcal{A}, \mathcal{B}$ be abelian categories. Let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. Define the left hyperderived functors

$$\mathbb{L}_i F : \mathbf{Ch}(\mathcal{A}) \to \mathcal{B}$$

by the following.

- For $A_\bullet$ a chain complex in $\mathcal{A}$, choose a Cartan-Eilenberg resolution $P_{\bullet,\bullet} \to A_\bullet$ of $A_\bullet$. Then
$$\mathbb{L}_i F(A_\bullet) = H_i(\text{Tot}^{\oplus}(F(P_{\bullet,\bullet})))$$
- For $f : A_\bullet \to B_\bullet$ a chain map, choose Cartan-Eilenberg resolutions for both complexes and consider the induced map $\overline{f} : P_{\bullet,\bullet} \to Q_{\bullet,\bullet}$. Define
$$\mathbb{L}_i F(f) = H_i(\text{Tot}^{\oplus}(\overline{f})) : \mathbb{L}_i F(A_\bullet) \to \mathbb{L}_i F(B_\bullet)$$

Definition 5.6.4: Right Hyperderived Functors

Let $\mathcal{A}, \mathcal{B}$ be abelian categories. Let $F : \mathcal{A} \to \mathcal{B}$ be a left exact functor. Define the right hyperderived functors

$$\mathbb{R}^i F : \mathbf{CCh}(\mathcal{A}) \to \mathcal{B}$$

by the following.

- For $A_\bullet$ a cochain complex in $\mathcal{A}$, choose a Cartan-Eilenberg resolution $A_\bullet \to I_{\bullet,\bullet}$ of $A_\bullet$. Then
$$\mathbb{R}^i F(A_\bullet) = H^i(\text{Tot}^{\oplus}(F(I_{\bullet,\bullet})))$$
- For $f : A_\bullet \to B_\bullet$ a chain map, choose Cartan-Eilenberg resolutions for both complexes and consider the induced map $\overline{f} : I_{\bullet,\bullet} \to J_{\bullet,\bullet}$. Define
$$\mathbb{R}^i F(f) = H^i(\text{Tot}^{\oplus}(\overline{f})) : \mathbb{R}^i F(A_\bullet) \to \mathbb{R}^i F(B_\bullet)$$

Lemma 5.6.5

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. Let $X \in \mathcal{A}$ be an object. Then the following are true.

- Let $F : \mathcal{A} \to \mathcal{B}$ be right exact. By considering X as a chain complex with only non-zero term in degree 0, the hyperderived left functor $\mathbb{L}_i F(X) = L_i F(X)$ is the same as the usual left derived functor.

- Let $F : \mathcal{A} \to \mathcal{B}$ be left exact. By considering X as a cochain complex with only non-zero term in degree 0, the hyperderived right functor $\mathbb{R}^i F(X) = R^i F(X)$ is the same as the usual right derived functor.

Lemma 5.6.6

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. Then the following are true.

- Let $F : \mathcal{A} \to \mathcal{B}$ be right exact. Then the restriction of $\mathbb{L}_i F : \mathbf{Ch}(\mathcal{A}) \to \mathcal{B}$ to $\mathbf{Ch}^+(\mathcal{A})$ are precisely the left derived functor $L_i(H_0 F) : \mathbf{Ch}^+(\mathcal{A}) \to \mathcal{B}$ of the functor $H_0 F : \mathbf{Ch}(\mathcal{A})^+ \to \mathcal{B}$.
- Let $F : \mathcal{A} \to \mathcal{B}$ be left exact. Then the restriction of $\mathbb{R}^i F : \mathbf{CCh}(\mathcal{A}) \to \mathcal{B}$ to $\mathbf{CCh}^+(\mathcal{A})$ are precisely the left derived functor $R^i(H^0 F) : \mathbf{CCh}^+(\mathcal{A}) \to \mathcal{B}$ of the functor $H^0 F : \mathbf{CCh}(\mathcal{A})^+ \to \mathcal{B}$.

Lemma 5.6.7

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

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

be a short exact sequence of chain complexes in $\mathbf{Ch}^+(\mathcal{A})$. Let $F : \mathcal{A} \to \mathcal{B}$ be right exact. Then there exists a long exact sequence

$$\cdots \longrightarrow \mathbb{L}_{i+1} F(C) \xrightarrow{\delta} \mathbb{L}_i F(A) \longrightarrow \mathbb{L}_i F(B) \longrightarrow \mathbb{L}_i F(C) \xrightarrow{\delta} \mathbb{L}_{i-1} F(A) \longrightarrow \cdots$$

Proposition 5.6.8

There is always a convergent spectral sequence

$$E^2_{pq} = (L_p F)(H_q(A)) \Rightarrow \mathbb{L}_{p+q} F(A)$$

Corollary 5.6.9

Let $\mathcal{A}, \mathcal{B}$ be abelian categories. Let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. Then the following are true.

- If A is exact, then $\mathbb{L}_i F(A) = 0$ for all i.
- If $f : A \to B$ is a quasi-isomorphism, then it induces isomorphisms $\mathbb{L}_i F(A) \cong \mathbb{L}_i F(B)$

Next: dual versions of the above propositions.

6 Triangulated Categories

6.1 Axioms of a Triangulated Category

Definition 6.1.1: Triangles

Let $\mathcal{C}$ be a category and $T : \mathcal{C} \to \mathcal{C}$ an automorphism functor. Let $A, B, C \in \mathcal{C}$. A triangle on (A, B, C) is a triple (u, v, w) of morphisms in $\mathcal{C}$ where $u : A \to B$, $v : B \to C$, $w : C \to T(A)$.

Define similarly the homotopy categories $K^+(\mathcal{A})$, $K^-(\mathcal{A})$ and $K^b(\mathcal{A})$ for $\mathbf{CCh}^+(\mathcal{A})$, $\mathbf{CCh}^-(\mathcal{A})$ and $\mathbf{CCh}^b(\mathcal{A})$ respectively.

Definition 6.1.2: Morphisms of Triangles

Let $\mathcal{C}$ be a category and $T : \mathcal{C} \to \mathcal{C}$ an automorphism functor. Let (u, v, w) and (u', v', w') be triangles in $\mathcal{C}$. A morphism of triangles is a triple (f, g, h) such that the following diagram commutes:

$$\begin{tikzcd} A \arrow[r, "u"] \arrow[d, "f"'] & B \arrow[r, "v"] \arrow[d, "g"'] & C \arrow[r, "w"] \arrow[d, "h"'] & T(A) \arrow[d, "T(f)"] \\ A' \arrow[r, "u'"'] & B' \arrow[r, "v'"'] & C' \arrow[r, "w'"'] & T(A') \end{tikzcd}$$

Definition 6.1.3: Triangulated Categories

Let $\mathcal{C}$ be an additive category. We say that $\mathcal{C}$ is a triangulated category if there is a functor $T : \mathcal{C} \to \mathcal{C}$ and a family $\{(u, v, w) \mid u, v, w \in \text{Mor}(\mathcal{C})\}$ of triangles called exact triangles such that the following hold.

- For any morphism $u : A \to B$, there exists an exact triangle (u, v, w):

$$\begin{tikzcd} A \arrow[r, "u"] & B \arrow[r, "v"] & C \arrow[r, dashed, "\exists w"] & T(A) \end{tikzcd}$$

  If (u, v, w) is a triangle on (A, B, C) isomorphic to an exact triangle (u', v', w') on (A', B', C'), then (u, v, w) is also exact:

$$\begin{tikzcd} A \arrow[r, "u"] \arrow[d, "\cong"'] & B \arrow[r, "v"] \arrow[d, "\cong"'] & C \arrow[r, "w"] \arrow[d, "\cong"'] & T(A) \arrow[d, "\cong"] \\ A' \arrow[r, "u'"'] & B' \arrow[r, "v'"'] & C' \arrow[r, "w'"'] & T(A') \end{tikzcd}$$

  Finally, $(\text{id}_A, 0, 0)$ is exact:

$$\begin{tikzcd} A \arrow[r, "\text{id}_A"] & A \arrow[r] & 0 \arrow[r] & T(A) \end{tikzcd}$$

- Rotations: If (u, v, w) is an exact triangle on (A, B, C), then both rotations $(v, w, -T(u))$ and $(-T^{-1}(w), u, v)$ are exact triangles on $(B, C, T(A))$ and $(T^{-1}(C), A, B)$ respectively.
- Morphisms: Let the following be exact triangles:

$$\begin{tikzcd} A \arrow[r, "u"] & B \arrow[r, "v"] & C \arrow[r, "w"] & T(A) \\ A' \arrow[r, "u'"] & B' \arrow[r, "v'"] & C' \arrow[r, "w'"] & T(A') \end{tikzcd}$$

  Suppose that there exists morphisms $f : A \to A'$ and $g : B \to B'$ such that $g \circ u = u' \circ f$. Then there exists $h : C \to C'$ such that (f, g, h) is a morphism of triangles:

$$\begin{tikzcd}
A \arrow[r, "u"] \arrow[d, "f"'] & B \arrow[r, "v"] \arrow[d, "g"'] & C \arrow[r, "w"] \arrow[d, dashed, "\exists h"'] & T(A) \arrow[d, "T(f)"] \\
A' \arrow[r, "u'"'] & B' \arrow[r, "v'"'] & C' \arrow[r, "w'"'] & T(A')
\end{tikzcd}$$

- The Octahedral Axiom: Let the following be exact triangles:

$$A \xrightarrow{u} B \xrightarrow{j} C' \xrightarrow{k} T(A)$$

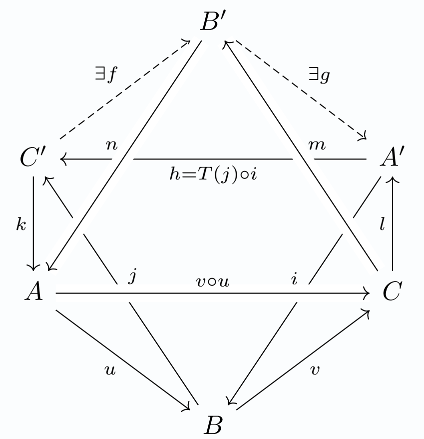
$$B \xrightarrow{v} C \xrightarrow{l} A' \xrightarrow{i} T(B)$$

$$A \xrightarrow{v \circ u} C \xrightarrow{m} B' \xrightarrow{n} T(A)$$

  Then there exists an exact triangle:

$$C' \xrightarrow{f} B' \xrightarrow{g} A' \xrightarrow{h} T(C')$$

  such that $l = g \circ m$, $k = n \circ f$, $h = T(j) \circ i$, $i \circ g = T(u) \circ n$ and $f \circ j = m \circ v$. In other words, the following diagram commutes:



  Where we abused notation by drawing $k : C' \to T(A)$ as a morphism $C' \to A$ etc so that the drawing becomes compact.

Lemma 6.1.4

Let $(\mathcal{C}, T)$ be a triangulated category. Let (u, v, w) be an exact triangle. Then $v \circ u$, $w \circ v$ and $T(u) \circ w$ are 0 in $\mathcal{C}$.

Lemma 6.1.5

Let $(\mathcal{C}, T)$ be a triangulated category. Let (f, g, h) be a morphism of exact triangles. If both f and g are isomorphisms, then h is an isomorphism.

6.2 Morphisms of Triangulated Categories

Definition 6.2.1: Morphisms of Triangulated Categories

Let $\mathcal{C}$ and $\mathcal{D}$ be triangulated categories. A morphism from $\mathcal{C}$ to $\mathcal{D}$ is a functor $F : \mathcal{C} \to \mathcal{D}$ such that the following are true.

- F is an additive functor
- F commutes with the translation functor. If T is the automorphism of $\mathcal{C}$ and S is the automorphism of $\mathcal{D}$, then
$$F \circ T = S \circ F$$
- F sends exact triangles to exact triangles

7 Derived Categories

7.1 The Homotopy Category of Cochain Complexes

Definition 7.1.1: Homotopy Category of Cochain Complexes

Let $\mathcal{A}$ be an abelian category. Let $\mathbf{CCh}(\mathcal{A})$ be the category of cochain complexes of $\mathcal{A}$. Define the homotopy category of chain complexes $K(\mathcal{A})$ to be the category defined as follows.

- The objects are the objects of $\mathbf{CCh}(\mathcal{A})$
- The morphisms are homotopy classes of chain maps
- Composition is given by composition of chain maps

Lemma 7.1.2

Let $\mathcal{A}$ be an abelian category. Then the cohomology functors $H^\bullet : \mathbf{CCh}(\mathcal{A}) \to \mathcal{A}$ induces a well defined functor from $K(\mathcal{A})$ to $\mathcal{A}$.

Proposition 7.1.3

Let $\mathcal{A}$ be an abelian category. The homotopy category of cochain complexes satisfy the following universal property.

If $F : \mathbf{CCh}(\mathcal{A}) \to \mathcal{D}$ is a functor that sends chain homotopy equivalences to isomorphisms, then F factors uniquely through $K(\mathcal{A})$:

$$\begin{tikzcd} \mathbf{CCh}(\mathcal{A}) \arrow[r] \arrow[dr, "F"'] & K(\mathcal{A}) \arrow[d, dashed, "\exists!"] \\ & \mathcal{D} \end{tikzcd}$$

Definition 7.1.4: Distinguished Triangles in K$(\mathcal{A})$

Let $\mathcal{A}$ be an abelian category. We say that a triangle

$$A \longrightarrow B \longrightarrow C \longrightarrow T(A)$$

is distinguished in $K(\mathcal{A})$ if it is isomorphic to a triangle of the form

$$X \xrightarrow{f} Y \longrightarrow C(f) \longrightarrow T(X)$$

Lemma 7.1.5

Let $\mathcal{A}$ be an abelian category. Then $K(\mathcal{A})$, $K^+(\mathcal{A})$, $K^-(\mathcal{A})$ and $K^b(\mathcal{A})$ are all triangulated categories with distinguished triangles given by the above definition.

7.2 Localization of Categories

Definition 7.2.1: Localization of a Category

Let $\mathcal{C}$ be a category and let S be a collection of morphisms in $\mathcal{C}$. A localization of $\mathcal{C}$ with respect to S is a category $S^{-1}\mathcal{C}$ together with a functor $q : \mathcal{C} \to S^{-1}\mathcal{C}$ such that the following are true.

- For all $s \in S$, $q(s)$ is an isomorphism in $S^{-1}\mathcal{C}$
- If $F : \mathcal{C} \to \mathcal{D}$ is a functor such that $F(s)$ is an isomorphism for all $s \in S^{-1}\mathcal{C}$, then there exists a unique functor $G : S^{-1}\mathcal{C} \to \mathcal{D}$ such that the following diagram commute:

$$\begin{tikzcd} \mathcal{C} \arrow[r, "q"] \arrow[dr, "F"'] & S^{-1}\mathcal{C} \arrow[d, dashed, "\exists! G"] \\ & \mathcal{D} \end{tikzcd}$$

Lemma 7.2.2

Let $\mathcal{A}$ be an abelian category. Then $K(\mathcal{A})$ is a localization of $\mathcal{A}$ with respect to all homotopy equivalences.

Not all localizations are well defined by set-theoretic issues. Morphisms that one wants to invert may not form a set or even a collection. We will give a way of explicitly constructing the localization of some specific categories below.

Definition 7.2.3: Multiplicative System

Definition 7.2.4: Locally Small Multiplicative System

Theorem 7.2.5: Gabriel-Zisman Theorem

Corollary 7.2.6

Let $\mathcal{C}$ be a category containing the zero object 0 and let $q : \mathcal{C} \to S^{-1}\mathcal{C}$ be a localization of $\mathcal{C}$. Then $q(X) \cong 0$ if and only if the S contains the 0 map $0 : X \to X$.

Corollary 7.2.7

Let $\mathcal{C}$ be a category and let $q : \mathcal{C} \to S^{-1}\mathcal{C}$ be a localization of $\mathcal{C}$. If $\mathcal{C}$ is additive, then $S^{-1}\mathcal{C}$ and q are both additive.

7.3 Derived Categories

Definition 7.3.1: Derived Categories

Let $\mathcal{A}$ be an abelian category and let $\mathbf{CCh}(\mathcal{A})$ be any category of chain complexes of $\mathcal{A}$. Define the derived category

$$D(\mathcal{A}) = \mathbf{CCh}(\mathcal{A})[\mathcal{W}^{-1}]$$

of $\mathcal{A}$ where $\mathcal{W}$ is all the quasi-isomorphisms in $\mathbf{CCh}(\mathcal{A})$.

Respectively, for $\mathbf{CCh}^+(\mathcal{A})$ and $\mathbf{CCh}^b(\mathcal{A})$ define their derived categories to be the localization of the categories with respect to quasi-isomorphisms, denoted by $D^+(\mathcal{A})$ and $D^b(\mathcal{A})$ respectively.

Theorem 7.3.2

Let $\mathcal{A}$ be an abelian category. Let $K(\mathcal{A})$ be the homotopy category of chain complexes of $\mathcal{A}$. Let $\mathcal{W}$ be all the quasi-isomorphisms in $\mathbf{CCh}(\mathcal{A})$. Then there is an equivalence of categories

$$D(\mathcal{A}) = K(\mathcal{A})[\mathcal{W}^{-1}]$$

Definition 7.3.3: Distinguished Triangles in D($\mathcal{A}$)

Let $\mathcal{A}$ be an abelian category. We say that a triangle

$$A \longrightarrow B \longrightarrow C \longrightarrow T(A)$$

is distinguished in $D(\mathcal{A})$ if it is isomorphic to a triangle of the form

$$X \xrightarrow{f} Y \longrightarrow C(f) \longrightarrow T(X)$$

Theorem 7.3.4

Let $\mathcal{A}$ be an abelian category. Then $D(\mathcal{A})$ is a triangulated triangles with distinguished triangles given by the above definition.

Definition 7.3.5: Full Subcategory of Complexes

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories such that $\mathcal{A}$ is a subcategory of $\mathcal{B}$. Define

$$D^{(}_{\mathcal{A}}\mathcal{B})$$

to be the full triangulated subcategory of complexes with cohomology in $\mathcal{A}$.

7.4 Derived Functors of Derived Categories

Definition 7.4.1: Total Right Derived Functors

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. Let $F : K(\mathcal{A}) \to K(\mathcal{B})$ be a morphism of triangulated categories. A total right derived functor of F is a morphism

$$RF : D(\mathcal{A}) \to D(\mathcal{B})$$

together with a natural transformation $\xi : (K(\mathcal{A}) \to K(\mathcal{B}) \to D(\mathcal{B})) \Rightarrow (K(\mathcal{A}) \to D(\mathcal{A}) \to D(\mathcal{B}))$ using the following diagram:

$$\begin{tikzcd} K(\mathcal{A}) \arrow[r, "F"] \arrow[d, "\exists!"'] & K(\mathcal{B}) \arrow[d, "\exists!"] \\ D(\mathcal{A}) \arrow[r, "RF"'] & D(\mathcal{B}) \end{tikzcd}$$

from the top-right path to the lower-left path which is universal in the following sense. If $G : D(\mathcal{A}) \to D(\mathcal{B})$ is another morphism equipped with the same natural transformation χ, then there exists a unique natural transformation

$$\eta : RF \Rightarrow G$$

such that $\chi = \eta \circ \xi$.

Definition 7.4.2: Total Left Derived Functors

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. Let $F : K(\mathcal{A}) \to K(\mathcal{B})$ be a morphism of triangulated categories. A total right derived functor of F is a morphism

$$LF : D(\mathcal{A}) \to D(\mathcal{B})$$

together with a natural transformation $\xi : (K(\mathcal{A}) \to D(\mathcal{A}) \to D(\mathcal{B})) \Rightarrow (K(\mathcal{A}) \to K(\mathcal{B}) \to D(\mathcal{B}))$ using the following diagram:

$$\begin{tikzcd} K(\mathcal{A}) \arrow[r, "F"] \arrow[d, "\exists!"'] & K(\mathcal{B}) \arrow[d, "\exists!"] \\ D(\mathcal{A}) \arrow[r, "RF"'] & D(\mathcal{B}) \end{tikzcd}$$

from the lower-left path to the top-right path which is universal in the following sense. If $G : D(\mathcal{A}) \to D(\mathcal{B})$ is another morphism equipped with the same natural transformation χ, then there exists a unique natural transformation

$$\eta : G \Rightarrow LF$$

such that $\chi = \eta \circ \xi$.

Lemma 7.4.3

Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. Let $F : K(\mathcal{A}) \to K(\mathcal{B})$ be a morphism of triangulated categories. If F is exact, then F is its own left and right total derived functor.

Theorem 7.4.4

Let $\mathcal{A}, \mathcal{B}$ be abelian categories. Let $F : \mathcal{A} \to \mathcal{B}$ be a functor. Then the following are true.

- If F is left exact and $\mathcal{A}$ has enough injectives, then
$$\mathbb{R}^i F = H^i(RF) : \mathbf{CCh}(\mathcal{A}) \to \mathcal{B}$$
- If F is right exact and $\mathcal{A}$ has enough projectives, then
$$\mathbb{L}_i F = H_i(LF) : \mathbf{Ch}(\mathcal{A}) \to \mathcal{B}$$

Notice that in particular, if $X \in \mathcal{A}$ is an object considered as a chain complex in degree 0, we have seen that $\mathbb{L}_i F = L_i F : \mathcal{A} \to \mathcal{B}$ hence $L_i F = H_i(LF) : \mathcal{A} \to \mathcal{B}$. This is similar for the dual version.