Proper Resolutions and Gorenstein Categories

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Abstract

Let \( \mathcal{A} \) be an abelian category and \( \mathcal{C} \) an additive full subcategory of \( \mathcal{A} \). We provide a method to construct a proper \( \mathcal{C} \)-resolution (resp. coproper \( \mathcal{C} \)-coresolution) of one term in a short exact sequence in \( \mathcal{A} \) from that of the other two terms. By using these constructions, we answer affirmatively an open question on the stability of the Gorenstein category \( \mathcal{G}(\mathcal{C}) \) posed by Sather-Wagstaff, Sharif and White; and also prove that \( \mathcal{G}(\mathcal{C}) \) is closed under direct summands. In addition, we obtain some criteria for computing the \( \mathcal{C} \)-dimension and the \( \mathcal{G}(\mathcal{C}) \)-dimension of an object in \( \mathcal{A} \).

1. Introduction

Auslander and Bridger generalized in [AB] finitely generated projective modules to finitely generated modules of G-dimension zero over (commutative) Noetherian rings. Furthermore, Enochs and Jenda introduced in [EJ1] Gorenstein projective modules for arbitrary modules over a general ring, which is a generalization of finitely generated modules of G-dimension zero. Also in [EJ1], Gorenstein injective modules were introduced as the dual of Gorenstein projective modules. It is well known that the class of modules of G-dimension zero and that of Gorenstein projective modules coincide for finitely generated modules over a left and right Noetherian ring, and that Gorenstein projective modules and Gorenstein injective modules share many nice properties of projective modules and injective modules, respectively (cf. [EJ1, EJ2, H]). The homological properties of Gorenstein projective and injective modules and some related generalized versions have been studied by many authors, see [AB, AM, CFH, CFrH, CI, EJ1, EJ2, EJL, GD, H, HI, HW, LHX, SSW1, SSW2, TW, W], and the literatures listed in them.

Let \( \mathcal{A} \) be an abelian category and \( \mathcal{C} \) an additive full subcategory of \( \mathcal{A} \). Sather-Wagstaff, Sharif and White introduce the Gorenstein category \( \mathcal{G}(\mathcal{C}) \), which unifies the following notions: modules of Gorenstein dimension zero ([AB]), Gorenstein projective modules, Gorenstein
stein injective modules ([EJ1]), V-Gorenstein projective modules, V-Gorenstein injective modules ([EJL]), and so on. The Gorenstein subcategory \( \mathcal{G}(\mathcal{C}) \) of \( \mathcal{A} \) is defined as \( \mathcal{G}(\mathcal{C}) = \{ M \text{ is an object in } \mathcal{A} \mid \text{there exists an exact sequence } \cdots \rightarrow C_1 \rightarrow C_0 \rightarrow C^0 \rightarrow C^1 \rightarrow \cdots \text{ in } \mathcal{C}, \) which is both \( \text{Hom}_{\mathcal{A}}(\mathcal{C}, -) \)-exact and \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact, such that \( M \cong \text{Im}(C_0 \rightarrow C^0) \}. \) Set \( \mathcal{G}^0(\mathcal{C}) = \mathcal{C}, \mathcal{G}^1(\mathcal{C}) = \mathcal{G}(\mathcal{C}), \) and inductively set \( \mathcal{G}^{n+1}(\mathcal{C}) = \mathcal{G}(\mathcal{G}^n(\mathcal{C})) \) for any \( n \geq 1. \) They proved that when \( \mathcal{C} \) is self-orthogonal, \( \mathcal{G}(\mathcal{C}) \) possesses many nice properties. For example, in this case, \( \mathcal{G}(\mathcal{C}) \) is closed under extensions and \( \mathcal{C} \) is a projective generator and an injective cogenerator for \( \mathcal{G}(\mathcal{C}), \) which induce that \( \mathcal{G}^n(\mathcal{C}) = \mathcal{G}(\mathcal{C}) \) for any \( n \geq 1. \) Also in this case, they proved that \( \mathcal{G}(\mathcal{C}) \) is closed under direct summands. In particular, they posed the following open question:

**Question 1.1.** (see [SSW1, Question 5.8]) Must there be an equality \( \mathcal{G}^n(\mathcal{C}) = \mathcal{G}(\mathcal{C}) \) for any \( n \geq 1? \)

In this paper, we will prove that the answer to this question is affirmative. The used methods are to construct a certain proper resolution (resp. coproper coresolution) of one term in a short exact sequence from that of the other two terms. This paper is organized as follows.

In Section 2, we give some terminology and some preliminary results.

In Section 3, we provide a method to construct a proper resolution (resp. coproper coresolution) of the first or last term in a short exact sequence from that of the other two terms. We will prove the following two theorems and their dual results.

**Theorem 1.2.** Let \( \mathcal{C} \) be a full subcategory of an abelian category \( \mathcal{A} \) and \( 0 \rightarrow X \rightarrow X^0 \rightarrow X^1 \rightarrow 0 \) an exact sequence in \( \mathcal{A}. \) Let

\[
\cdots \rightarrow C^j_i \rightarrow \cdots \rightarrow C^j_1 \rightarrow C^j_0 \rightarrow X^j \rightarrow 0 \quad (1.1(j))
\]

be a proper \( \mathcal{C} \)-resolution of \( X^j \) for \( j = 0, 1. \) Then

1. We get the following exact sequences:

\[
\cdots \rightarrow C^j_{i+1} \bigoplus C^0_i \rightarrow \cdots \rightarrow C^j_2 \bigoplus C^0_1 \rightarrow C \rightarrow X \rightarrow 0 \quad (1.2)
\]

and

\[
0 \rightarrow C \rightarrow C^j_1 \bigoplus C^0_0 \rightarrow C^j_0 \rightarrow 0
\]

2. If the exact sequence (1.1(j)) is \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact for \( j = 0, 1, \) then so is the exact sequence (1.2).

3. If \( \mathcal{C} \) is closed under finite direct sums and kernels of epimorphisms, then the exact sequence (1.2) is a proper \( \mathcal{C} \)-resolution of \( X. \)
Theorem 1.3. Let $C$ be a full subcategory of an abelian category $\mathcal{A}$ and
\[ 0 \to X_1 \to X_0 \to X \to 0 \quad (1.3) \]
an exact sequence in $\mathcal{A}$. Let
\[ C^n_j \to \cdots \to C^1_j \to C^0_j \to X_j \to 0 \quad (1.4(j)) \]
be a proper $C$-resolution of $X_j$ for $j = 0, 1$. Then

(1) We get the following exact sequence:
\[ C^n_0 \bigoplus C^{n-1}_1 \to \cdots \to C^2_0 \bigoplus C^1_1 \to C^1_0 \bigoplus C^0_1 \to C^0_0 \to X \to 0 \quad (1.5) \]

(2) If all the exact sequences (1.3) and (1.4(j)) are $\text{Hom}_\mathcal{A}(-, C)$-exact for $j = 1, 2$, then so is the exact sequence (1.5).

(3) If the exact sequence (1.3) is $\text{Hom}_\mathcal{A}(C, -)$-exact, then the exact sequence (1.5) is a proper $C$-resolution of $X$.

As applications of these constructions, in Section 4 we prove the following result, in which the first assertion answers Question 1.1 affirmatively.

Theorem 1.4. Let $\mathcal{A}$ be an abelian category and $C$ an additive full subcategory of $\mathcal{A}$. Then we have

(1) $G^n(C) = G(C)$ for any $n \geq 1$.

(2) $G(C)$ is closed under direct summands.

Let $\mathcal{A}$ be an abelian category and $C$ a full subcategory of $\mathcal{A}$. For a positive integer $n$, an object $A$ in $\mathcal{A}$ is called an $n$-$C$-syzygy object (of an object $M$) if there exists an exact sequence $0 \to A \to C_{n-1} \to \cdots \to C_1 \to C_0 \to M \to 0$ in $\mathcal{A}$ with all $C_i$ objects in $C$. For an object $M$ in $\mathcal{A}$, $C$-dim $M$ is defined as $\inf \{ n \geq 0 \mid \text{there exists an exact sequence } 0 \to C_n \to \cdots \to C_1 \to C_0 \to M \to 0 \text{ in } \mathcal{A} \text{ with all } C_i \text{ objects in } C \}$. We set $C$-dim $M$ infinity if no such integer exists.

In Section 5, assume that $C$ is closed under extensions. We first prove that for a positive integer $n$, an object $A$ in $\mathcal{A}$ is an $n$-$C$-syzygy if and only if it is $n$-cogen $C$-syzygy, where cogen $C$ is a cogenerator for $C$. Next we prove that if $\mathcal{X}$ is a generator-cogenerator for $C$, then for any object $M$ in $\mathcal{A}$ and $n \geq 0$, $C$-dim $M \leq n$ if and only if for every non-negative integer $t$ such that $0 \leq t \leq n$, there exists an exact sequence: $0 \to X_n \to \cdots \to X_1 \to X_0 \to M \to 0$ in $\mathcal{A}$ such that $X_t$ is an object in $C$ and all $X_i$ are objects in $\mathcal{X}$ for $i \neq t$. As a consequence, when $C$ is self-orthogonal, we obtain some criteria for computing $G(C)$-dim $M$ if it is finite.
2. Preliminaries

Throughout this paper, \( \mathcal{A} \) is an abelian category, all subcategories are full subcategories of \( \mathcal{A} \) closed under isomorphisms. We fix a subcategory \( \mathcal{C} \) of \( \mathcal{A} \).

In this section, we give some terminology and some preliminary results.

**Definition 2.1.** ([E]) Let \( \mathcal{C} \subseteq \mathcal{D} \) be subcategories of \( \mathcal{A} \). The morphism \( f : C \to D \) in \( \mathcal{A} \) with \( C \) an object in \( \mathcal{C} \) and \( D \) an object in \( \mathcal{D} \) is called a \( \mathcal{C} \)-precover of \( D \) if for any morphism \( g : C' \to D \) in \( \mathcal{A} \) with \( C' \) an object in \( \mathcal{C} \), there exists a morphism \( h : C' \to C \) such that the following diagram commutes:

\[
\begin{array}{ccc}
C' & \xrightarrow{h} & C \\
\downarrow{g} & & \downarrow{f} \\
D & \xleftarrow{f} & D
\end{array}
\]

The morphism \( f : C \to D \) is called right minimal if a morphism \( h : C \to C \) is an automorphism whenever \( f = fh \). A \( \mathcal{C} \)-precover \( f : C \to D \) is called a \( \mathcal{C} \)-cover if \( f \) is right minimal. Dually, the notions of a \( \mathcal{C} \)-preenvelope, a left minimal morphism and a \( \mathcal{C} \)-envelope are defined. Following Auslander and Reiten’s terminology in [AR1], a \( \mathcal{C} \)-(pre)cover and a \( \mathcal{C} \)-(pre)envelope are called a (minimal) right \( \mathcal{C} \)-approximation and a (minimal) left \( \mathcal{C} \)-approximation, respectively.

Recall that an exact sequence in \( \mathcal{A} \) is called \( \text{Hom}_{\mathcal{A}}(\mathcal{C},-) \)-exact if it remains still exact after applying the functor \( \text{Hom}_{\mathcal{A}}(\mathcal{C},-) \). Let \( M \) be an object in \( \mathcal{A} \). An exact sequence:

\[
\cdots \to C_i \xrightarrow{f_i} \cdots \to C_1 \xrightarrow{f_1} C_0 \xrightarrow{f_0} M \to 0
\]

in \( \mathcal{A} \) with all \( C_i \) objects in \( \mathcal{C} \) is called a \( \mathcal{C} \)-resolution of \( M \). Recall from [AM] that the above exact sequence is called a proper \( \mathcal{C} \)-resolution of \( M \) if it is a \( \mathcal{C} \)-resolution of \( M \) and is \( \text{Hom}_{\mathcal{A}}(\mathcal{C},-) \)-exact, that is, each \( f_i \) is an epic \( \mathcal{C} \)-precover of \( \text{Im} f_i \); and it is called a minimal proper \( \mathcal{C} \)-resolution of \( M \) if each \( f_i \) is an epic \( \mathcal{C} \)-cover of \( \text{Im} f_i \). Dually, the notions of a \( \text{Hom}_{\mathcal{A}}(-,\mathcal{C}) \)-exact exact sequence, a \( \mathcal{C} \)-coresolution and a (minimal) coproper \( \mathcal{C} \)-coresolution of \( M \) are defined.

We now introduce the notion of strongly (co)proper (co)resolutions as follows.

**Definition 2.2.** Let \( M \) be an object in \( \mathcal{A} \).

(1) A sequence:

\[
\cdots \to X_i \to \cdots \to X_1 \to X_0 \to M \to 0
\]
in \mathcal{A} is called \textit{strongly Hom}_{\mathcal{A}}(\mathcal{C}, -)-exact exact if it is exact and \text{Ext}^1_{\mathcal{A}}(\mathcal{C}, K_i) = 0 for any \(i \geq 1\), where \(K_i = \text{Im}(X_i \to X_{i-1})\). Dually, the notion of a \textit{strongly Hom}_{\mathcal{A}}(-, \mathcal{C})\)-exact exact sequence is defined.

(2) An exact sequence:

\[
\cdots \to C_i \to \cdots \to C_1 \to C_0 \to M \to 0
\]

in \mathcal{A} is called a \textit{strongly proper \mathcal{C}-resolution} of \(M\) if it is a \(\mathcal{C}\)-resolution of \(M\) and is strongly Hom_{\mathcal{A}}(\mathcal{C}, -)-exact. Dually, the notion of a \textit{strongly coproper \mathcal{C}-coresolution} of \(M\) is defined.

\textbf{Remark 2.3.} (1) It is easy to see that a strongly (co)proper \mathcal{C}-(co)resolution is a (co)proper \mathcal{C}-(co)resolution. But the converse does not hold true in general. For example, let \mathcal{C} be a full subcategory of \mathcal{A} closed under finite direct sums such that there exists an object \(M\) in \mathcal{C} with \text{Ext}^1_{\mathcal{A}}(M, M) \neq 0. Then the exact sequence:

\[
0 \to M \xrightarrow{(1,0)} M \bigoplus M \xrightarrow{(0,1)} M \to 0
\]

is both a proper \mathcal{C}-resolution and a coproper \mathcal{C}-coresolution of \(M\), but it neither a strongly proper \mathcal{C}-resolution nor a strongly coproper \mathcal{C}-coresolution of \(M\).

(2) For a ring \(R\), we use Mod \(R\) to denote the category of left \(R\)-modules. We have that any projective resolution (resp. injective coresolution) of a left \(R\)-module \(M\) is just a strongly proper \(\mathcal{P}(\text{Mod } R)\)-resolution (resp. strongly coproper \(\mathcal{I}(\text{Mod } R)\)-coresolution) of \(M\), where \(\mathcal{P}(\text{Mod } R)\) (resp. \(\mathcal{I}(\text{Mod } R)\)) is the subcategory of Mod \(R\) consisting of projective (resp. injective) modules.

(3) By the Wakamatsu’s lemma (see [X, Lemma 2.1.1]), if \mathcal{C} is closed under extensions, then a minimal (co)proper \mathcal{C}-resolution of an object \(M\) is a strongly (co)proper \mathcal{C}-resolution of \(M\).

The following two observations are useful in next section.

\textbf{Lemma 2.4.} Let

\[
\begin{array}{ccc}
M & \xrightarrow{f_1} & N \\
\downarrow{g_1} & & \downarrow{g} \\
X & \xrightarrow{f} & Y
\end{array}
\]

be a commutative diagram in \mathcal{A} and \(C\) an object in \mathcal{A}.

(1) If this diagram is a pull-back diagram of \(f\) and \(g\) and \text{Hom}_{\mathcal{A}}(C, g)\) is epic, then \text{Hom}_{\mathcal{A}}(C, g_1)\) is also epic.

(2) If this diagram is a push-out diagram of \(f_1\) and \(g_1\) and \text{Hom}_{\mathcal{A}}(g_1, C)\) is epic, then \text{Hom}_{\mathcal{A}}(g, C)\) is also epic.
Proof. Assume that the given diagram is a pull-back diagram of $f$ and $g$ and $\text{Hom}_\mathcal{A}(C,g)$ is epic. Let $\alpha \in \text{Hom}_\mathcal{A}(C,X)$. Then there exists $\beta \in \text{Hom}_\mathcal{A}(C,N)$ such that $f\alpha = \text{Hom}_\mathcal{A}(C,g)(\beta) = g\beta$. By the universal property of a pull-back diagram, there exists $\gamma \in \text{Hom}_\mathcal{A}(C,M)$ such that $\alpha = g_1 \gamma = \text{Hom}_\mathcal{A}(C,g_1)(\gamma)$. So $\text{Hom}_\mathcal{A}(C,g_1)$ is epic and the assertion (1) follows.

Dually, we get the assertion (2). \qed

Lemma 2.5. (1) Let

\[
\begin{array}{c}
K_1 \xrightarrow{h} K_0 \\
\downarrow \quad \quad \downarrow \alpha_0 \\
W_1 \xrightarrow{g} W_0 \\
\downarrow \quad \quad \downarrow \\
X_1 \xrightarrow{f} X_0 \\
0 \quad \quad 0
\end{array}
\]

be a commutative diagram in $\mathcal{A}$ with exact columns and $C$ an object in $\mathcal{A}$. If all of $\text{Hom}_\mathcal{A}(h,C)$, $\text{Hom}_\mathcal{A}(f,C)$ and $\text{Hom}_\mathcal{A}(\alpha_0,C)$ are epic, then so is $\text{Hom}_\mathcal{A}(g,C)$.

(2) Let

\[
\begin{array}{c}
0 \quad \quad 0 \\
\uparrow \quad \quad \uparrow \\
K_1 \xrightarrow{h} K_0 \\
\downarrow \quad \quad \downarrow \beta_1 \\
W_1 \xrightarrow{g} W_0 \\
\downarrow \quad \quad \downarrow \\
X_1 \xrightarrow{f} X_0
\end{array}
\]

be a commutative diagram in $\mathcal{A}$ with exact columns and $C$ an object in $\mathcal{A}$. If all of $\text{Hom}_\mathcal{A}(C,h)$, $\text{Hom}_\mathcal{A}(C,f)$ and $\text{Hom}_\mathcal{A}(C,\beta_1)$ are epic, then so is $\text{Hom}_\mathcal{A}(C,g)$.

Proof. (1) By assumption, we get the following commutative diagram with exact columns
By the snake lemma, $\text{Hom}_A(g, C)$ is epic.

(2) It is dual to (1). □

**Definition 2.6.** ([SSW1]) The Gorenstein subcategory $G(C)$ of $A$ is defined as $G(C) = \{M$ is an object in $A |$ there exists an exact sequence:

$$\cdots \to C_1 \to C_0 \to C^0 \to C^1 \to \cdots$$

in $C$, which is both $\text{Hom}_A(\mathcal{E}, -)$-exact and $\text{Hom}_A(-, \mathcal{E})$-exact, such that $M \cong \text{Im}(C_0 \to C^0))$; in this case, (2.1) is called a complete $\mathcal{E}$-resolution of $M$.

**Remark 2.7.** (1) Let $R$ be a left and right Noetherian ring and mod $R$ the category of finitely generated left $R$-modules. Put $\mathcal{P}(\text{mod}R)$ the subcategory of mod $R$ consisting of projective modules. Then $G(\mathcal{P}(\text{mod}R))$ coincides with the subcategory of mod $R$ consisting of modules with Gorenstein dimension zero ([AB]).

(2) For any ring $R$, $G(\mathcal{P}$(Mod $R$))) (resp. $G(\mathcal{I}$(Mod $R$)))) coincides with the subcategory of Mod $R$ consisting of Gorenstein projective (resp. injective) modules ([EJ1]).

(3) Let $R$ be a left Noetherian ring, $S$ a right Noetherian ring and $_RS$ a dualizing bimodule. Put $\mathcal{V} = \{V \otimes_S P | P$ is projective in Mod $S\}$ and $\mathcal{W} = \{\text{Hom}_S(V, E) | E$ is injective in Mod $S^{op}\}$. Then $G(\mathcal{V})$ (resp. $G(\mathcal{W})$) coincides with the subcategory of Mod $R$ consisting of $V$-Gorenstein projective (resp. injective) modules ([EJL]).

3. The constructions of (strongly) proper resolutions and coproper coresolutions

In this section, we introduce the notion of strongly (co)proper (co)resolutions of modules. Then we give a method to construct a (strongly) proper resolution (resp. coproper coresolution).
olution) of the first (resp. last) term in a short exact sequence from that of the other two terms, as well as give a method to construct a (strongly) proper resolution (resp. coproper coresolution) of the last (resp. first) term in a short exact sequence from that of the other two terms.

We first give the following easy observation, which is a generalization of the horseshoe lemma.

**Lemma 3.1.** Let \( 0 \to A \xrightarrow{f} A' \xrightarrow{g} A'' \to 0 \) be an exact sequence in \( \mathcal{A} \).

1. If there exist morphisms \( \alpha \in \text{Hom}_\mathcal{A}(C, A) \), \( \alpha'' \in \text{Hom}_\mathcal{A}(C'', A'') \) and \( h \in \text{Hom}_\mathcal{A}(C'', A') \) such that \( \alpha'' = gh \), then we have the following commutative diagram with exact rows:

\[
\begin{array}{ccccccccc}
0 & \to & C & \xrightarrow{(1_{C})} & C \oplus C' & \xrightarrow{(0,1_{C''})} & C'' & \to & 0 \\
\alpha & & \downarrow & & \alpha' & \downarrow & \alpha'' & & \\
0 & \to & A & \xrightarrow{f} & A' & \xrightarrow{g} & A'' & \to & 0
\end{array}
\]

where \( \alpha' = (f, h)(\in \text{Hom}_\mathcal{A}(C \oplus C'', A')) \).

2. If there exist morphisms \( \beta \in \text{Hom}_\mathcal{A}(A, D) \), \( \beta'' \in \text{Hom}_\mathcal{A}(A'', D'') \) and \( k \in \text{Hom}_\mathcal{A}(A', D) \) such that \( \beta = kf \), then we have the following commutative diagram with exact rows:

\[
\begin{array}{ccccccccc}
0 & \to & A & \xrightarrow{f} & A' & \xrightarrow{g} & A'' & \to & 0 \\
\beta & & \downarrow & & \beta' & \downarrow & \beta'' & & \\
0 & \to & D & \xrightarrow{(1_{D})} & D \oplus D' & \xrightarrow{(0,1_{D''})} & D'' & \to & 0
\end{array}
\]

where \( \beta' = (\beta, g)(\in \text{Hom}_\mathcal{A}(A', D \oplus D'')) \).

The following result contains Theorem 1.2, which provides a method to construct a (strongly) proper resolution of the first term in a short exact sequence from that of the last two terms.

**Theorem 3.2.** Let \( 0 \to X \to X^0 \to X^1 \to 0 \) be an exact sequence in \( \mathcal{A} \). Let

\[
\cdots \to C_i^0 \to \cdots \to C_1^0 \to C_0^0 \to X^0 \to 0 \quad (3.1)
\]

be a \( \mathcal{C} \)-resolution of \( X^0 \), and let

\[
\cdots \to C_i^1 \to \cdots \to C_1^1 \to C_0^1 \to X^1 \to 0 \quad (3.2)
\]

be a \( \text{Hom}_\mathcal{A}(\mathcal{C}, -) \)-exact exact sequence in \( \mathcal{A} \). Then

1. We get the following exact sequences:

\[
\cdots \to C_{i+1}^1 \bigoplus C_i^0 \to \cdots \to C_2^1 \bigoplus C_1^0 \to C \to X \to 0 \quad (3.3)
\]
and

\[ 0 \to C \to C_1^1 \bigoplus C_0^0 \to C_0^1 \to 0 \quad (3.4) \]

(2) If both the exact sequences (3.1) and (3.2) are \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact, then so is the exact sequence (3.3).

Assume that \( \mathcal{C} \) is closed under finite direct sums and kernels of epimorphisms. Then we have

(3) If the exact sequence (3.2) is a \( \mathcal{C} \)-resolution of \( X^1 \), then the exact sequence (3.3) is a \( \mathcal{C} \)-resolution of \( X \).

(4) If both the exact sequences (3.1) and (3.2) are proper \( \mathcal{C} \)-resolutions of \( X^0 \) and \( X^1 \) respectively, then the exact sequence (3.3) is a proper \( \mathcal{C} \)-resolution of \( X \).

(5) If both the exact sequences (3.1) and (3.2) are strongly proper \( \mathcal{C} \)-resolutions of \( X^0 \) and \( X^1 \) respectively, then the exact sequence (3.3) is a strongly proper \( \mathcal{C} \)-resolution of \( X \).

Proof. (1) Put \( K_i^0 = \text{Im}(C_i^0 \to C_{i-1}^0) \) and \( K_i^1 = \text{Im}(C_i^1 \to C_{i-1}^1) \) for any \( i \geq 1 \). Consider the following pull-back diagram:

\[
\begin{array}{cccc}
0 & 0 & K_1^1 & K_1^1 \\
& & & \\
0 & X & M & C_0^1 & 0 \\
& & & \\
0 & X & X^0 & X^1 & 0 \\
& & & \\
0 & 0 & & \\
\end{array}
\]

Because the third column in the above diagram is \( \text{Hom}_{\mathcal{A}}(\mathcal{C}, -) \)-exact, so is the middle column by Lemma 2.4(1). Thus by Lemma 3.1(1) we get the following commutative diagram
with exact columns and rows and the middle row splitting:

\[
\begin{array}{ccc}
0 & 0 & 0 \\
\downarrow & \downarrow & \downarrow \\
0 \rightarrow K_2 & \rightarrow W_1 & \rightarrow K_1^0 \rightarrow 0 \\
\downarrow & \downarrow & \downarrow \\
0 \rightarrow C_1^1 & \rightarrow C_1^1 \oplus C_0^0 & \rightarrow C_0^0 \rightarrow 0 \\
\downarrow & \downarrow & \downarrow \\
0 \rightarrow K_1^1 & \rightarrow M & \rightarrow X^0 \rightarrow 0 \\
\downarrow & \downarrow & \downarrow \\
0 & 0 & 0 \\
\end{array}
\]

where \( W_1 = \text{Ker}(C_1^1 \oplus C_0^0 \rightarrow M) \). It is easy to verify the upper row in the above diagram is \( \text{Hom}_{\mathcal{A}}(\mathcal{C}, -) \)-exact.

On the one hand, we have the following pull-back diagram:

\[
\begin{array}{ccc}
0 & 0 & 0 \\
\downarrow & \downarrow & \downarrow \\
W_1 & \rightarrow W_1 \\
\downarrow & \downarrow & \downarrow \\
0 \rightarrow C & \rightarrow C_1^1 \oplus C_0^0 & \rightarrow C_0^1 \rightarrow 0 \\
\downarrow & \downarrow & \downarrow \\
0 \rightarrow X & \rightarrow M & \rightarrow C_0^1 \rightarrow 0 \\
\downarrow & \downarrow & \downarrow \\
0 & 0 & 0 \\
\end{array}
\]

On the other hand, again by Lemma 3.1(1) we get the following commutative diagram with exact columns and rows and the middle row splitting:
where $W_2 = \text{Ker}(C^i_2 \oplus C^0_1 \rightarrow W_1)$ and the upper row in the above diagram is $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact exact. Continuing this process, we get the desired exact sequences (3.3) and (3.4) with $W_i = \text{Im}(C^i_{i+1} \oplus C^0_i \rightarrow C^i_i \oplus C^0_{i-1})$ for any $i \geq 2$ and $W_1 = \text{Im}(C^1_2 \oplus C^0_1 \rightarrow C)$.

(2) By assumption, both the first and third columns in the second diagram are $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact. Then it is easy to see that both the first row and the middle column in this diagram are also $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact. It follows that the first column in the third diagram is $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact. Also by assumption, the first and third columns in the last diagram are $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact. So the middle column in this diagram is also $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact. Finally, we deduce that the exact sequence (3.3) is $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact.

(3) It follows from the assumption and the assertion (1).

(4) Assume that both the exact sequences (3.1) and (3.2) are proper $\mathcal{C}$-resolutions of $X^0$ and $X^1$ respectively. Then by the proof of (1) and [EJ2, Lemma 8.2.1], we have that both the middle column in the second diagram and the first column in the third diagram are $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact exact; and in particular we have a $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact exact sequence:

\[ \cdots \rightarrow C^i_{i+1} \oplus C^0_i \rightarrow \cdots \rightarrow C^j_2 \oplus C^0_1 \rightarrow W_1 \rightarrow 0. \]

Thus we get the desired proper $\mathcal{C}$-resolution of $X$.

(5) If both the exact sequences (3.1) and (3.2) are strongly proper $\mathcal{C}$-resolutions of $X^0$ and $X^1$ respectively, then $\text{Ext}^1_{\mathcal{A}}(\mathcal{C}, K^j_i) = 0$ for any $i \geq 1$ and $j = 0, 1$. By the proof of (1), we have an exact sequence:

\[ 0 \rightarrow K^1_{i+1} \rightarrow W_i \rightarrow K^0_i \rightarrow 0 \]

for any $i \geq 1$. So $\text{Ext}^1_{\mathcal{A}}(\mathcal{C}, W_i) = 0$ for any $i \geq 1$, and hence the exact sequence (3.3) is a strongly proper $\mathcal{C}$-resolution of $X$. □
Based on Theorem 3.2, by using induction on \( n \) it is not difficult to get the following

**Corollary 3.3.** Let \( \mathcal{C} \) be closed under finite direct sums and kernels of epimorphisms, and let \( 0 \to X \to X^0 \to X^1 \to \cdots \to X^n \to 0 \) be an exact sequence in \( \mathcal{A} \). Assume that

\[
\cdots \to C_i^j \to \cdots \to C_1^j \to C_0^j \to X^j \to 0 \quad (3.5(j))
\]

is a (strongly) proper \( \mathcal{C} \)-resolution of \( X^j \) for any \( 0 \leq j \leq n \). Then we have

(1)

\[
\cdots \to \bigoplus_{i=0}^n C_i^{i+3} \to \bigoplus_{i=0}^n C_i^{i+2} \to \bigoplus_{i=0}^n C_i^{i+1} \to C \to X \to 0 \quad (3.6)
\]

is a (strongly) proper \( \mathcal{C} \)-resolution of \( X \), and there exists an exact sequence:

\[
0 \to C \to \bigoplus_{i=0}^n C_i^i \to \bigoplus_{i=1}^n C_i^{i-1} \to \bigoplus_{i=2}^n C_i^{i-2} \to \cdots \to C_0^{n-1} \bigoplus_{i=1}^n C_1^n \to C_0^n \to 0.
\]

(2) If all \((3.5(j))\) are \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact, then so is \((3.6)\).

The next two results are dual to Theorem 3.2 and Corollary 3.3 respectively. The following result provides a method to construct a (strongly) coproper coresolution of the last term in a short exact sequence from that of the first two terms.

**Theorem 3.4.** Let \( 0 \to Y_1 \to Y_0 \to Y \to 0 \) be an exact sequence in \( \mathcal{A} \). Let

\[
0 \to Y_0 \to C_0^0 \to C_0^1 \to \cdots \to C_0^i \to \cdots \quad (3.7)
\]

be a \( \mathcal{C} \)-coresolution of \( Y_0 \), and let

\[
0 \to Y_1 \to C_1^0 \to C_1^1 \to \cdots \to C_1^i \to \cdots \quad (3.8)
\]

be a \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact exact sequence in \( \mathcal{A} \).

(1) We get the following exact sequences:

\[
0 \to Y \to C \to C_0^{i+2} \to \bigoplus_{i=0} C_0^{i+1} \to C_0^i \bigoplus_{i=0} C_1^{i+1} \to \cdots \quad (3.9)
\]

and

\[
0 \to C_0^i \to C_0^0 \bigoplus_{C_1^i} C_1^i \to C \to 0 \quad (3.10)
\]

(2) If both the exact sequences \((3.7)\) and \((3.8)\) are \( \text{Hom}_{\mathcal{A}}(\mathcal{C}, -) \)-exact, then so is the exact sequence \((3.9)\).

Assume that \( \mathcal{C} \) is closed under finite direct sums and cokernels of monomorphisms. Then we have
(3) If the exact sequence (3.8) is a $C$-coresolution of $Y_1$, then the exact sequence (3.9) is a $C$-coresolution of $Y$.

(4) If both the exact sequences (3.7) and (3.8) are coproper $C$-coresolutions of $Y_0$ and $Y_1$ respectively, then the exact sequence (3.9) is a coproper $C$-coresolution of $Y$.

(5) If both the exact sequences (3.7) and (3.8) are strongly coproper $C$-coresolutions of $Y_0$ and $Y_1$ respectively, then the exact sequence (3.9) is a strongly coproper $C$-coresolution of $Y$.

Proof. It is dual to the proof of Theorem 3.2, we give the proof here for the sake of completeness.

(1) Put $K^i_0 = \text{Im}(C^{i-1}_0 \rightarrow C^i_0)$ and $K^i_1 = \text{Im}(C^{i-1}_1 \rightarrow C^i_1)$ for any $i \geq 1$. Consider the following push-out diagram:

Because the first column in the above diagram is $\text{Hom}_{\mathcal{A}}(-, C)$-exact exact, so is the middle column by Lemma 2.4(2). Then by Lemma 3.1(2) we get the following commutative diagram with exact columns and rows and the middle row splitting:
where $W^1 = \text{Coker}(N \to C_0^0 \oplus C_1^1)$. It is easy to verify that the bottom row in the above diagram is $\text{Hom}_{\mathcal{A}}(-, \mathcal{E})$-exact exact.

On the one hand, we have the following push-out diagram:

![Diagram](image)

On the other hand, again by Lemma 3.1(2) we get the following commutative diagram with exact columns and rows and the middle row splitting:

![Diagram](image)

where $W^2 = \text{Coker}(W^1 \to C_0^1 \oplus C_1^2)$ and the bottom row in the above diagram is $\text{Hom}_{\mathcal{A}}(-, \mathcal{E})$-exact exact. Continuing this process, we get the desired exact sequences (3.9) and (3.10) with $W^i = \text{Im}(C_{i-1}^0 \oplus C_i^1 \to C_i^0 \oplus C_{i+1}^1)$ for any $i \geq 2$ and $W^1 = \text{Im}(C \to C_0^1 \oplus C_1^2)$.

(2) By assumption, both the first and third columns in the second diagram are $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact. Then it is easy to see that both the first row and the middle column in this diagram are also $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact. It follows that the first column in the third diagram is $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact. Also by assumption, the first and third columns in the last diagram are $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact. So the middle column in this diagram is also $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact. Finally, we deduce that the exact sequence (3.9) is $\text{Hom}_{\mathcal{A}}(\mathcal{E}, -)$-exact.
(3) It follows from the assumption and the assertion (1).

(4) Assume that both the exact sequences (3.7) and (3.8) are coproper \( \mathcal{C} \)-coresolutions of \( X_0 \) and \( X_1 \) respectively. Then by the proof of (1) and the dual version of [EJ2, Lemma 8.2.1], we have that both the middle column in the second diagram and the first column in the third diagram are \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact; and in particular we have a \( \text{Hom}_{\mathcal{A}}(-, \mathcal{C}) \)-exact exact sequence:

\[
0 \to W^1 \to C_0^1 \bigoplus C_1^2 \to \cdots \to C_0^i \bigoplus C_1^{i+1} \to \cdots .
\]

Thus we get the desired coproper \( \mathcal{C} \)-coresolution of \( X \).

(5) If both the exact sequences (3.7) and (3.8) are strongly coproper \( \mathcal{C} \)-coresolutions of \( Y_0 \) and \( Y_1 \) respectively, then \( \text{Ext}_{\mathcal{A}}^1(K^i_j, \mathcal{C}) = 0 \) for any \( i \geq 1 \) and \( j = 0, 1 \). By the proof of (1), we have an exact sequence:

\[
0 \to K_0^i \to W^i \to K_1^{i+1} \to 0
\]

for any \( i \geq 1 \). So \( \text{Ext}_{\mathcal{A}}^1(W^i, \mathcal{C}) = 0 \) for any \( i \geq 1 \), and hence the exact sequence (3.9) is a strongly coproper \( \mathcal{C} \)-coresolution of \( Y \). \( \square \)

Based on Theorem 3.4, by using induction on \( n \) it is not difficult to get the following

**Corollary 3.5.** Let \( \mathcal{C} \) be closed under finite direct sums and cokernels of monomorphisms and let \( 0 \to Y_n \to \cdots \to Y_1 \to Y_0 \to Y \to 0 \) be an exact sequence in \( \mathcal{A} \). Assume that

\[
0 \to Y_j \to C_j^0 \to C_j^1 \to \cdots \to C_j^i \to \cdots \tag{3.11(j)}
\]

is a (strongly) coproper \( \mathcal{C} \)-coresolution of \( Y_j \) for any \( 0 \leq j \leq n \). Then we have

(1)

\[
0 \to Y \to C \to C_{i+1} \bigoplus C_i^{i+2} \to \bigoplus C_i^{i+3} \to \cdots \tag{3.12}
\]

is a (strongly) coproper \( \mathcal{C} \)-coresolution of \( Y \), and there exists an exact sequence:

\[
0 \to C_n^0 \to C_{n-1}^0 \bigoplus C_n^1 \to \cdots \to C_i^i \bigoplus C_i^{i+2} \to \bigoplus C_i^{i+3} \to \cdots .
\]

(2) If all (3.11(j)) are \( \text{Hom}_{\mathcal{A}}(\mathcal{C}, -) \)-exact, then so is (3.12).

The following result contains Theorem 1.3, which provides a method to construct a (strongly) proper resolution of the last term in a short exact sequence from that of the first two terms.

**Theorem 3.6.** Let

\[
0 \to X_1 \to X_0 \to X \to 0 \tag{3.13}
\]
be an exact sequence in $\mathcal{A}$. Let

$$C_0^n \to \cdots \to C_0^1 \to C_0^0 \to X_0 \to 0 \quad (3.14)$$

be a Hom$_\mathcal{A}$(C, −)-exact exact sequence and

$$C_1^{n-1} \to \cdots \to C_1^1 \to C_1^0 \to X_1 \to 0 \quad (3.15)$$

a C-resolution of $X_1$ in $\mathcal{A}$.

(1) We get the following exact sequence:

$$C_0^n \bigoplus C_1^{n-1} \to \cdots \to C_0^1 \bigoplus C_1^0 \to C_0^0 \to X \to 0 \quad (3.16)$$

(2) If all the exact sequences (3.13)–(3.15) are Hom$\mathcal{A}$(-, C)-exact, then so is the exact sequence (3.16).

Assume that C is closed under finite direct sums. Then we have

(3) If the exact sequence (3.14) is a C-resolution of $X_0$, then the exact sequence (3.16) is a C-resolution of $X$.

(4) If the exact sequence (3.13) is Hom$\mathcal{A}$(C, −)-exact and both the exact sequences (3.14) and (3.15) are proper C-resolutions of $X_0$ and $X_1$ respectively, then the exact sequence (3.16) is a proper C-resolution of $X$.

(5) If the exact sequence (3.13) is strongly Hom$\mathcal{A}$(C, −)-exact and both the exact sequences (3.14) and (3.15) are strongly proper C-resolutions of $X_0$ and $X_1$ respectively, then the exact sequence (3.16) is a strongly proper C-resolution of $X$.

Proof. (1) Put $K_i^j = \text{Im}(C_i^j \to C_{i-1}^j)$ for any $1 \leq i \leq n - j$ and $j = 0, 1$. Consider the following pull-back diagram:

![Diagram](image-url)
Note that the middle column in the above diagram is $\text{Hom}_A(\mathcal{C}, -)$-exact exact. So by Lemma 2.4(1), the first column is also $\text{Hom}_A(\mathcal{C}, -)$-exact exact. Then by Lemma 3.1(1) we get the following commutative diagram with exact columns and rows and the middle row splitting:

\[
\begin{array}{ccccccccc}
0 & & 0 & & 0 \\
\downarrow & & \downarrow & & \downarrow & & & & \\
0 & \to & K_0^2 & \to & W_2 & \to & K_1^1 & \to & 0 \\
\downarrow & & \downarrow & & \ downarrow & & \downarrow & & \downarrow & \\
0 & \to & C_0^1 & \to & C_0^1 \oplus C_1^0 & \to & C_1^0 & \to & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow & \\
0 & \to & K_1^1 & \to & W_1 & \to & X_1 & \to & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow & \\
0 & & 0 & & 0 & & 0 & & 0 \\
\end{array}
\]

where $W_2 = \text{Ker}(C_0^1 \oplus C_1^0 \to W_1)$. It is easy to check that the upper row in the above diagram is $\text{Hom}_A(\mathcal{C}, -)$-exact exact. Then by using Lemma 3.1(1) iteratively we get the exact sequence (3.16) with $W_i = \text{Im}(C_0^i \oplus C_1^i \to C_0^{i-1} \oplus C_1^{i-2})$ for any $2 \leq i \leq n$ and $W_1 = \text{Im}(C_0^1 \oplus C_1^0 \to C_0^0)$.

(2) By assumption, both the third row and the middle column in the first diagram are $\text{Hom}_A(\mathcal{C}, -)$-exact. Then the middle row in this diagram is $\text{Hom}_A(\mathcal{C}, -)$-exact by Lemma 2.5(1). It is easy to see that the first column in this diagram is also $\text{Hom}_A(\mathcal{C}, -)$-exact. Both the first and third columns in the second diagram are $\text{Hom}_A(\mathcal{C}, -)$-exact also by assumption, so the middle column in this diagram is also $\text{Hom}_A(\mathcal{C}, -)$-exact. Finally, we deduce that the exact sequence (3.16) is $\text{Hom}_A(\mathcal{C}, -)$-exact.

(3) It follows from the assumption and the assertion (1).

(4) If the exact sequence (3.13) is $\text{Hom}_A(\mathcal{C}, -)$-exact and both the exact sequences (3.14) and (3.15) are proper $\mathcal{C}$-resolutions of $X_0$ and $X_1$ respectively, then the middle row in the first diagram is $\text{Hom}_A(\mathcal{C}, -)$-exact exact by Lemma 2.4(1). Thus by [EJ2, Lemma 8.2.1], the exact sequence (3.16) is a proper $\mathcal{C}$-resolution of $X$.

(5) If the exact sequence (3.13) is strongly $\text{Hom}_A(\mathcal{C}, -)$-exact and both the exact sequences (3.14) and (3.15) are strongly proper $\mathcal{C}$-resolutions of $X_0$ and $X_1$ respectively, then $\text{Ext}_A^1(\mathcal{C}, K_i^j) = 0$ for any $1 \leq i \leq n - j$ and $j = 0, 1$. By the proof of (1), we have an exact
sequence:
\[ 0 \to K_0^i \to W_i \to K_{i-1}^i \to 0 \]
for any \(1 \leq i \leq n\) (where \(K_0^0 = X_1\)). So \(\text{Ext}^1_\mathcal{A}(\mathcal{C}, W_i) = 0\) for any \(1 \leq i \leq n\), and hence the exact sequence (3.16) is a strongly proper \(\mathcal{C}\)-resolution of \(X\). \(\square\)

Based on Theorem 3.6, by using induction on \(n\) it is not difficult to get the following

**Corollary 3.7.** Let \(\mathcal{C}\) be closed under finite direct sums, and let
\[ X_n \to \cdots \to X_1 \to X_0 \to X \to 0 \]
and
\[ C_{n-j}^0 \to \cdots \to C_j^1 \to C_j^0 \to X_j \to 0 \]
be exact sequences in \(\mathcal{A}\) for any \(0 \leq j \leq n\).

(1) Let the exact sequence (3.17) be \(\text{Hom}_\mathcal{A}(\mathcal{C}, -)\)-exact and (3.18(j)) a proper \(\mathcal{C}\)-resolution of \(X_j\) for any \(0 \leq j \leq n\). Then
\[ \bigoplus_{i=0}^{n} C_i^{n-i} \to \bigoplus_{i=0}^{n-1} C_i^{(n-1)-i} \to \cdots \to C_0^0 \bigoplus C_1^0 \to C_0^0 \to X \to 0 \]
(3.19)
is a proper \(\mathcal{C}\)-resolution of \(X\); furthermore, if (3.17) and all (3.18(j)) are \(\text{Hom}_\mathcal{A}(-, \mathcal{C})\)-exact, then so is (3.19).

(2) Let the exact sequence (3.17) be strongly \(\text{Hom}_\mathcal{A}(\mathcal{C}, -)\)-exact and (3.18(j)) a strongly proper \(\mathcal{C}\)-resolution of \(X_j\) for any \(0 \leq j \leq n\). Then (3.19) is a strongly proper \(\mathcal{C}\)-resolution of \(X\).

The next two results are dual to Theorem 3.6 and Corollary 3.7 respectively. The following result provides a method to construct a (strongly) coproper coresolution of the first term in a short exact sequence from that of the last two terms.

**Theorem 3.8.** Let
\[ 0 \to Y \to Y^0 \to Y^1 \to 0 \]
be an exact sequence in \(\mathcal{A}\). Let
\[ 0 \to Y^0 \to C_0^0 \to C_1^0 \to \cdots \to C_n^0 \]
be a \(\text{Hom}_\mathcal{A}(-, \mathcal{C})\)-exact exact sequence and
\[ 0 \to Y^1 \to C_0^1 \to C_1^1 \to \cdots \to C_{n-1}^1 \]
be an exact sequence in \(\mathcal{A}\). Let
\[ 0 \to Y^0 \to C_0^0 \to C_1^0 \to \cdots \to C_n^0 \]
(3.21)
a $\mathcal{C}$-coresolution of $Y^1$ in $\mathcal{A}$.

(1) We get the following exact sequence:

$$0 \rightarrow Y \rightarrow C^0_0 \rightarrow C^0_0 \bigoplus C^0_1 \rightarrow C^1_1 \bigoplus C^0_2 \rightarrow \cdots \rightarrow C^1_{n-1} \bigoplus C^0_n$$ (3.23)

(2) If all the exact sequences (3.20)–(3.22) are $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact, then so is the exact sequence (3.23).

Assume that $\mathcal{C}$ is closed under finite direct sums. Then we have

(3) If the exact sequence (3.21) is a $\mathcal{C}$-coresolution of $Y^0$, then the exact sequence (3.23) is a $\mathcal{C}$-coresolution of $X$.

(4) If the exact sequence (3.20) is $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact and both the exact sequences (3.21) and (3.22) are coproper $\mathcal{C}$-coresolutions of $Y^0$ and $Y^1$ respectively, then the exact sequence (3.23) is a coproper $\mathcal{C}$-coresolution of $Y$.

(5) If the exact sequence (3.20) is strongly $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact and both the exact sequences (3.21) and (3.22) are strongly coproper $\mathcal{C}$-coresolutions of $Y^0$ and $Y^1$ respectively, then the exact sequence (3.23) is a strongly coproper $\mathcal{C}$-coresolution of $Y$.

Proof. It is dual to the proof of Theorem 3.6, we give the proof here for the sake of completeness.

(1) Put $K^j_i = \text{Im}(C^j_{i-1} \rightarrow C^j_i)$ for any $1 \leq i \leq n - j$ and $j = 0, 1$. Consider the following push-out diagram:

```
\[ \begin{array}{ccccccccc}
0 & \rightarrow & Y & \rightarrow & Y^0 & \rightarrow & Y^1 & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
0 & \rightarrow & Y & \rightarrow & C^0_0 & \rightarrow & W^1 & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
K^0_1 & \rightarrow & K^0_1 & & & & & & \rightarrow & 0 \\
\downarrow & & \downarrow & & & & & & \downarrow & & \downarrow \\
0 & \rightarrow & 0 & & & & & & 0 & \rightarrow & 0
\end{array} \]
```

Note that the middle column in the above diagram is $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact exact by assumption. So the third column is also $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact exact by Lemma 2.4(2). Then by Lemma 3.1(2) we get the following commutative diagram with exact columns and rows and
the middle row splitting:

\[
\begin{array}{c}
0 & 0 & 0 \\
\downarrow & \downarrow & \downarrow \\
0 & \longrightarrow Y^1 & \longrightarrow W^1 & \longrightarrow K^0 & \longrightarrow 0 \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
0 & \longrightarrow C_0^1 & \longrightarrow C_0^1 \oplus C_0^0 & \longrightarrow C_0^0 & \longrightarrow 0 \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
0 & \longrightarrow K_1^1 & \longrightarrow W^2 & \longrightarrow K_2^0 & \longrightarrow 0 \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
0 & 0 & 0 & 0 & 0
\end{array}
\]

where \( W^2 = \text{Coker}(W^1 \rightarrow C_0^1 \oplus C_0^0) \). It is easy to verify that the bottom row in the above diagram is Hom\(_A(-, C)\)-exact. Then by using Lemma 3.1(2) iteratively we get the exact sequence (3.23) with \( W^i = \text{Im}(C_i^{i-2} \oplus C_i^{i-1} \rightarrow C_i^{i-1} \oplus C_i^0) \) for any \( 2 \leq i \leq n \) and \( W^1 = \text{Im}(C_0^0 \rightarrow C_0^1 \oplus C_0^0) \).

(2) By assumption, both the first row and the middle column in the first diagram are Hom\(_A(C, -)\)-exact. Then the middle row in this diagram is Hom\(_A(C, -)\)-exact by Lemma 2.5(2). It is easy to see that the third column in this diagram is also Hom\(_A(C, -)\)-exact. Both the first and third columns in the second diagram are Hom\(_A(C, -)\)-exact also by assumption, so the middle column in this diagram is also Hom\(_A(C, -)\)-exact. Finally, we deduce that the exact sequence (3.23) is Hom\(_A(C, -)\)-exact.

(3) It follows from the assumption and the assertion (1).

(4) If the exact sequence (3.20) is Hom\(_A(-, C)\)-exact and both the exact sequences (3.21) and (3.22) are coproper \( C \)-coresolutions of \( Y^0 \) and \( Y^1 \) respectively, then the middle row in the first diagram is Hom\(_A(-, C)\)-exact exact by Lemma 2.4(2). Thus by the dual version of [EJ2, Lemma 8.2.1], the exact sequence (3.23) is a coproper \( C \)-coresolution of \( Y \).

(5) If the exact sequence (3.20) is strongly Hom\(_A(-, C)\)-exact and both the exact sequences (3.21) and (3.22) are strongly coproper \( C \)-coresolutions of \( Y^0 \) and \( Y^1 \) respectively, then \( \text{Ext}^1_A(K_i^j, C) = 0 \) for any \( 1 \leq i \leq n - j \) and \( j = 0, 1 \). By the proof of (1), we have an exact sequence:

\[
0 \rightarrow K_{i-1}^j \rightarrow W^i \rightarrow K_i^0 \rightarrow 0
\]

for any \( 1 \leq i \leq n \) (where \( K_0^1 = Y^1 \)). So \( \text{Ext}^1_A(W^i, C) = 0 \) for any \( 1 \leq i \leq n \), and hence the exact sequence (3.23) is a strongly coproper \( C \)-coresolution of \( Y \). \( \Box \)
Based on Theorem 3.8, by using induction on $n$ it is not difficult to get the following

**Corollary 3.9.** Let $\mathcal{C}$ be closed under finite direct sums, and let

$$0 \to Y \to Y^0 \to Y^1 \to \cdots \to Y^n \quad (3.24)$$

and

$$0 \to Y^j \to C^j_0 \to C^j_1 \to \cdots \to C^j_{n-j} \quad (3.25(j))$$

be exact sequences in $\mathcal{A}$ for any $0 \leq j \leq n$.

1. Let the exact sequence (3.24) be $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact and (3.25(j)) a coproper $\mathcal{C}$-coresolution of $Y^j$ for any $0 \leq j \leq n$. Then

$$0 \to Y \to C^0_0 \to C^1_0 \to \cdots \to \bigoplus_{i=0}^{n-1} C^i_{(n-1)-i} \to \bigoplus_{i=0}^n C^i_{n-i} \quad (3.26)$$

is a coproper $\mathcal{C}$-coresolution of $Y$; furthermore, if (3.24) and all (3.25(j)) are $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact, then so is (3.26).

2. Let the exact sequence (3.24) be strongly $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact and (3.25(j)) a strongly coproper $\mathcal{C}$-coresolution of $Y^j$ for any $0 \leq j \leq n$. Then (3.26) is a strongly coproper $\mathcal{C}$-coresolution of $Y$.

### 4. Gorenstein categories

In the rest of this paper, all subcategories are additive subcategories of $\mathcal{A}$, that is, all subcategories are closed under finite direct sums. Set $\mathcal{G}^0(\mathcal{C}) = \mathcal{C}$, $\mathcal{G}^1(\mathcal{C}) = \mathcal{G}(\mathcal{C})$, and inductively set $\mathcal{G}^{n+1}(\mathcal{C}) = \mathcal{G}(\mathcal{G}^n(\mathcal{C}))$ for any $n \geq 1$. As an application of the results in the above section, we get the the following result, which answers Question 1.1 affirmatively.

**Theorem 4.1.** $\mathcal{G}^n(\mathcal{C}) = \mathcal{G}(\mathcal{C})$ for any $n \geq 1$.

**Proof.** It is easy to see that $\mathcal{C} \subseteq \mathcal{G}(\mathcal{C}) \subseteq \mathcal{G}^2(\mathcal{C}) \subseteq \mathcal{G}^3(\mathcal{C}) \subseteq \cdots$ is an ascending chain of additive subcategories of $\mathcal{A}$.

Let $M$ be an object in $\mathcal{G}^2(\mathcal{C})$ and

$$\cdots \to G_1 \to G_0 \to G^0 \to G^1 \to \cdots$$

a complete $\mathcal{G}(\mathcal{C})$-resolution of $M$ with $M \cong \text{Im}(G_0 \to G^0)$. Then for any $j \geq 0$, there exist exact sequences:

$$\cdots \to C^i_j \to \cdots \to C^1_j \to C^0_j \to G_j \to 0$$

and

$$0 \to G^j \to B^0_j \to B^1_j \to \cdots \to B^i_j \to \cdots$$
in $\mathcal{A}$ with all $C^i_j$ and $B^i_j$ objects in $\mathcal{C}$, which are both $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact and $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact. By Corollaries 3.7 and 3.9, we get exact sequences:

$$\cdots \to \bigoplus_{i=0}^{n} C_{i}^{n-i} \to \cdots \to C_{1}^{1} \bigoplus C_{0}^{0} \to C_{0}^{0} \to M \to 0$$

and

$$0 \to M \to B_{0}^{0} \to B_{1}^{0} \bigoplus B_{1}^{1} \to \cdots \to \bigoplus_{i=0}^{n} B_{n-i}^{i} \to \cdots$$

which are both $\text{Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact and $\text{Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact. So

$$\cdots \to \bigoplus_{i=0}^{n} C_{i}^{n-i} \to \cdots \to C_{1}^{1} \bigoplus C_{0}^{0} \to B_{0}^{0} \to B_{1}^{0} \bigoplus B_{1}^{1} \to \cdots \to \bigoplus_{i=0}^{n} B_{n-i}^{i} \to \cdots$$

is a complete $\mathcal{C}$-resolution of $M$ with $M \cong \text{Im}(C_{0}^{0} \to B_{0}^{0})$, and hence $M$ is an object in $\mathcal{G}(\mathcal{C})$ and $\mathcal{G}^{2}(\mathcal{C}) \subseteq \mathcal{G}(\mathcal{C})$. Thus we have that $\mathcal{G}^{2}(\mathcal{C}) = \mathcal{G}(\mathcal{C})$. By using induction on $n$ we get easily the assertion. □

Definition 4.2. (cf. [SSW1]) A subcategory $\mathcal{X}$ of $\mathcal{C}$ is called a generator (resp. cogenerator) for $\mathcal{C}$ if for any object $C$ in $\mathcal{C}$, there exists an exact sequence $0 \to C' \to X \to C \to 0$ (resp. $0 \to C \to X \to C' \to 0$) in $\mathcal{C}$ with $X$ an object in $\mathcal{X}$; and $\mathcal{X}$ is called a projective generator (resp. an injective cogenerator) for $\mathcal{C}$ if $\mathcal{X}$ is a generator (resp. cogenerator) for $\mathcal{C}$ and $\text{Ext}^i_{\mathcal{A}}(X, C) = 0$ (resp. $\text{Ext}^i_{\mathcal{A}}(C, X) = 0$) for any object $X$ in $\mathcal{X}$, any object $C$ in $\mathcal{C}$ and $i \geq 1$.

As an immediate consequence of Theorem 4.1, we get the following three corollaries. The first one generalizes [SSW1, Proposition 4.6] and answers positively a question in [SSW1, p.492].

Corollary 4.3. (1) If $\mathcal{X}$ is a (projective) generator for $\mathcal{C}$, then $\mathcal{X}$ is a (projective) generator for $\mathcal{G}^n(\mathcal{C})$.

(2) If $\mathcal{X}$ is an (injective) cogenerator for $\mathcal{C}$, then $\mathcal{X}$ is an (injective) cogenerator for $\mathcal{G}^n(\mathcal{C})$.

We define $\text{res}\mathcal{C} = \{M \in \mathcal{A} \mid \text{there exists a Hom}_{\mathcal{A}}(\mathcal{C}, -)$-exact exact sequence $\cdots \to C_{i} \to \cdots \to C_{1} \to C_{0} \to M \to 0 \text{ in } \mathcal{A} \text{ with all } C_{i} \text{ objects in } \mathcal{C} \}$. Dually, we define $\text{cores}\mathcal{C} = \{M \in \mathcal{A} \mid \text{there exists a Hom}_{\mathcal{A}}(-, \mathcal{C})$-exact exact sequence $0 \to C_{0} \to C_{1} \to \cdots \to C^{i} \to \cdots \text{ in } \mathcal{A} \text{ with all } C^{i} \text{ objects in } \mathcal{C} \}$. (see [SSW1]).

The next corollary generalizes [SSW1, Theorem 4.8].

Corollary 4.4. Let $\mathcal{X}$ be a subcategory of $\mathcal{C}$. Then we have
(1) If \( C \subseteq \text{res} \tilde{\mathcal{X}} \), then \( \mathcal{G}^n(C) \subseteq \text{res} \tilde{\mathcal{X}} \) for any \( n \geq 0 \).

(2) If \( C \subseteq \text{cores} \tilde{\mathcal{X}} \), then \( \mathcal{G}^n(C) \subseteq \text{cores} \tilde{\mathcal{X}} \) for any \( n \geq 0 \).

Proof. (1) Let \( C \subseteq \text{res} \tilde{\mathcal{X}} \). Because \( \mathcal{X} \) is closed under finite sums, \( \mathcal{G}(C) \subseteq \text{res} \tilde{\mathcal{X}} \) by Corollary 3.7. Then the assertion follows from Theorem 4.1.

(2) It is dual to (1). □

We also have the following corollary, which generalizes [SSW1, Theorem 4.9].

**Corollary 4.5.** Let \( \mathcal{X} \) be a subcategory of \( \mathcal{C} \). If \( C \subseteq \text{res} \tilde{\mathcal{X}} \cap \text{cores} \tilde{\mathcal{X}} \), then \( \mathcal{G}^n(C) \subseteq \mathcal{G}(\mathcal{X}) \) for any \( n \geq 1 \).

Proof. By using an argument similar to that in the proof of Theorem 4.1, we get \( \mathcal{G}(C) \subseteq \mathcal{G}(\mathcal{X}) \). Then the assertion follows from Theorem 4.1. □

As another application of the results in the above section, we get the following result, in which the second assertion shows that the assumption of the self-orthogonality of \( C \) in [SSW1, Proposition 4.11] is superfluous.

**Theorem 4.6.** (1) Both \( \text{res} \tilde{\mathcal{C}} \) and \( \text{cores} \tilde{\mathcal{C}} \) are closed under direct summands.

(2) \( \mathcal{G}(\mathcal{C}) \) is closed under direct summands.

Proof. Assume that \( M = X \bigoplus Y \) and

\[
0 \to Y \xrightarrow{(0, 1_Y)} M \xrightarrow{(1_X, 0)} X \to 0
\]

is an exact and split sequence.

(1) We only prove \( \text{res} \tilde{\mathcal{C}} \) is closed under direct summands. Dually, we get that \( \text{cores} \tilde{\mathcal{C}} \) is also closed under direct summands.

Let \( M \) be an object in \( \text{res} \tilde{\mathcal{C}} \) and

\[
\cdots \xrightarrow{f_{i+1}} C_i \xrightarrow{f_i} \cdots \xrightarrow{f_3} C_2 \xrightarrow{f_2} C_1 \xrightarrow{f_1} C_0 \xrightarrow{f_0} M \to 0
\]

a \( \text{Hom}_\mathcal{A}(\mathcal{C}, -) \)-exact exact sequence in \( \mathcal{A} \) with all \( C^i \) objects in \( \mathcal{C} \). Then

\[
C_0 \xrightarrow{(1_X, 0) f_0} X \to 0
\]

is a \( \text{Hom}_\mathcal{A}(\mathcal{C}, -) \)-exact exact sequence. Similarly,

\[
C_0 \xrightarrow{(1_Y, 0) f_0} Y \to 0
\]

is a \( \text{Hom}_\mathcal{A}(\mathcal{C}, -) \)-exact exact sequence. By Theorem 3.6, we get the following \( \text{Hom}_\mathcal{A}(\mathcal{C}, -) \)-exact exact sequences:

\[
C_0 \bigoplus C_1 \to C_0 \to X \to 0
\]
and
\[ C_0 \bigoplus C_1 \to C_0 \to Y \to 0. \]
Again by Theorem 3.6, we get the following Hom$_\mathcal{A}_0(\mathcal{C}, -)$-exact exact sequences:
\[ C_0 \bigoplus C_1 \bigoplus C_2 \to C_0 \bigoplus C_1 \to C_0 \to X \to 0 \]
and
\[ C_0 \bigoplus C_1 \bigoplus C_2 \to C_0 \to Y \to 0. \]
Continuing this procedure, we finally get the following Hom$_\mathcal{A}_0(\mathcal{C}, -)$-exact exact sequences:
\[ \cdots \to \bigoplus_{i=0}^{n-1} C_i \to \cdots \to C_0 \bigoplus C_1 \bigoplus C_2 \to C_0 \bigoplus C_1 \to C_0 \to X \to 0 \]
and
\[ \cdots \to \bigoplus_{i=0}^{n-1} C_i \to \cdots \to C_0 \bigoplus C_1 \bigoplus C_2 \to C_0 \bigoplus C_1 \to C_0 \to Y \to 0, \]
which implies that both $X$ and $Y$ are objects in res $\widetilde{\mathcal{C}}$.

(2) Let $M$ be an object in $\mathcal{G}(\mathcal{C})$ and
\[ \cdots \to C_1 \to C_0 \to C^0 \to C^1 \to \cdots \]
a complete $\mathcal{C}$-resolution of $M$ with $M \cong \text{Im}(C_0 \to C^0)$. By (1) and Theorem 3.6, we get the following exact sequence:
\[ \cdots \to \bigoplus_{i=0}^{n-1} C_i \to \cdots \to C_0 \bigoplus C_1 \bigoplus C_2 \to C_0 \bigoplus C_1 \to C_0 \to X \to 0 \quad (4.1) \]
which is both Hom$_\mathcal{A}_0(\mathcal{C}, -)$-exact and Hom$_\mathcal{A}_0(-, \mathcal{C})$-exact. Dually, we get the following exact sequence:
\[ 0 \to X \to C^0 \to C^0 \bigoplus C^1 \to C^0 \bigoplus C^1 \bigoplus C^2 \to \bigoplus_{i=0}^{n-1} C^i \to \cdots \quad (4.2) \]
which is also both Hom$_\mathcal{A}_0(\mathcal{C}, -)$-exact and Hom$_\mathcal{A}_0(-, \mathcal{C})$-exact. Combining the sequences (4.1) and (4.2), we conclude that $X$ is an object in $\mathcal{G}(\mathcal{C})$.

We also have the following two out of three property.

**Proposition 4.7.** (1) If $\mathcal{C}$ is closed under kernels of epimorphisms, then so is res $\widetilde{\mathcal{C}}$.
(2) If $\mathcal{C}$ is closed under cokernels of monomorphisms, then so is cores $\widetilde{\mathcal{C}}$.

Let
\[ 0 \to X \to Y \to Z \to 0 \quad (4.3) \]
(1) If the exact sequence (4.3) is Hom$_{\mathcal{A}}(\mathcal{C}, -)$-exact and X, Y are objects in res\(\mathcal{C}\), then Z is also an object in res\(\mathcal{C}\).

(4) If the exact sequence (4.3) is Hom$_{\mathcal{A}}(-, \mathcal{C})$-exact and Y, Z are objects in cores\(\mathcal{C}\), then X is also an object in cores\(\mathcal{C}\).  

(5) If the exact sequence (4.3) is both Hom$_{\mathcal{A}}(\mathcal{C}, -)$-exact and Hom$_{\mathcal{A}}(-, \mathcal{C})$-exact, and if any two of X, Y and Z are objects in \(\mathcal{G}(\mathcal{C})\), then the third term is also an object in \(\mathcal{G}(\mathcal{C})\).

Proof. We get (1) and (2) by Theorems 3.2 and 3.4 respectively. Dually, we get (3) and (4) by Theorems 3.6 and 3.8 respectively.  

(5) If X, Z are objects in \(\mathcal{G}(\mathcal{C})\), then so is Y by [SSW1, Proposition 4.4]. By the above arguments, we get the other two assertions.  

5. Gorenstein syzygies and dimension

In this section, we fix subcategories \(\mathcal{C}\) and \(\mathcal{D}\) of \(\mathcal{A}\). We use gen\(\mathcal{C}\) (resp. cogen\(\mathcal{C}\)) to denote a generator (resp. cogenerator) for \(\mathcal{C}\). The following result plays a crucial role in this section.

**Proposition 5.1.** Let \(\mathcal{C}\) be closed under extensions and

\[
0 \to A \to C_1 \xrightarrow{f} C_0 \to M \to 0
\]  

an exact sequence in \(\mathcal{A}\) with \(C_0\) and \(C_1\) objects in \(\mathcal{C}\).

(1) Then we have the following exact sequences:

\[
0 \to A \to C_1' \to P_0 \to M \to 0
\]  

and

\[
0 \to A \to I_1 \to C_0' \to M \to 0
\]

in \(\mathcal{A}\) with \(C_1', C_0'\) objects in \(\mathcal{C}\), \(P_0\) an object in gen\(\mathcal{C}\) and \(I_1\) an object in cogen\(\mathcal{C}\).

(2) For an object D in \(\mathcal{A}\), if (5.1) is Hom$_{\mathcal{A}}(D, -)$-exact (resp. Hom$_{\mathcal{A}}(-, D)$-exact), then so is (5.2) (resp. (5.3)).

Proof. (1) There exists an exact sequence:

\[
0 \to C_0' \to P_0 \to C_0 \to 0
\]

in \(\mathcal{A}\) with \(P_0\) an object in gen\(\mathcal{C}\) and \(C_0'\) an object in \(\mathcal{C}\). Then we have the following pull-back
Consider the following pull-back diagram:

\[
\begin{array}{c}
\text{0} & \text{0} \\
\downarrow & \downarrow \\
C'_0 & C'_0 \\
\downarrow & \downarrow \\
N & P_0 \\
\downarrow & \downarrow \\
\text{Im } f & C_0 \\
\downarrow & \downarrow \\
0 & 0
\end{array}
\]

Because \( \mathcal{C} \) is closed under extensions and both \( C'_0 \) and \( C_1 \) are objects in \( \mathcal{C} \), \( C'_1 \) is also an object in \( \mathcal{C} \). Connecting the middle rows in the above two diagrams, then we get the first desired exact sequence. Dually, taking push-out, we get the second desired sequence.

(2) If (5.1) is \( \text{Hom}_\mathcal{A}(D, -) \)-exact, then so are the middle rows in the above two diagrams by Lemma 2.4. Thus (5.2) is also \( \text{Hom}_\mathcal{A}(D, -) \)-exact. Dually, one gets the other assertion. \( \square \)

**Definition 5.2.** Let \( n \) be a positive integer. If there exists an exact sequence \( 0 \to A \to C_{n-1} \to C_{n-2} \to \cdots \to C_0 \to M \to 0 \) in \( \mathcal{A} \) with all \( C_i \) objects in \( \mathcal{C} \), then \( A \) is called an \( n\)-\( \mathcal{C} \)-syzygy object (of \( M \)), and \( M \) is called an \( n\)-\( \mathcal{C} \)-cosyzygy object (of \( A \)).

The following theorem is one of main results in this section.
Theorem 5.3. Let \( \mathcal{C} \) be closed under extensions, and let \( n \geq 1 \) and

\[
0 \to A \to C_{n-1} \to C_{n-2} \to \cdots \to C_0 \to M \to 0
\]  
be an exact sequence in \( \mathcal{A} \) with all \( C_i \) objects in \( \mathcal{C} \). Then we have the following

1. There exist exact sequences:

\[
0 \to A \to I_{n-1} \to I_{n-2} \to \cdots \to I_0 \to N \to 0
\]

and

\[
0 \to M \to N \to X \to 0
\]
in \( \mathcal{A} \) with all \( I_i \) objects in cogen \( \mathcal{C} \) and \( X \) an object in \( \mathcal{C} \). In particular, an object in \( \mathcal{A} \) is an \( n \)-\( \mathcal{C} \)-syzygy if and only if it is an \( n \)-cogen \( \mathcal{C} \)-syzygy.

2. There exist exact sequences:

\[
0 \to B \to P_{n-1} \to P_{n-2} \to \cdots \to P_0 \to M \to 0
\]

and

\[
0 \to Y \to B \to A \to 0
\]
in \( \mathcal{A} \) with all \( P_i \) objects in gen \( \mathcal{C} \) and \( Y \) an object in \( \mathcal{C} \). In particular, an object in \( \mathcal{A} \) is an \( n \)-\( \mathcal{C} \)-cosyzygy if and only if it is an \( n \)-gen \( \mathcal{C} \)-cosyzygy.

3. For an object \( D \) in \( \mathcal{A} \), if \((5.4) = \text{Hom}_\mathcal{A}(D, -)\)-exact (resp. \( \text{Hom}_\mathcal{A}(-, D)\)-exact), then so are \((5.5) \) (resp. \((5.6)\)).

Proof. (1) We proceed by induction on \( n \).

Let \( n = 1 \) and

\[
0 \to A \to C_0 \to M \to 0
\]
be an exact sequence in \( \mathcal{A} \) with \( C_0 \in \mathcal{C} \). Then there exists an exact sequence:

\[
0 \to C_0 \to I_0 \to X \to 0
\]
in \( \mathcal{A} \) with \( I_0 \) an object in cogen \( \mathcal{C} \) and \( X \) an object in \( \mathcal{C} \).
Consider the following push-out diagram:

\[
\begin{array}{ccc}
0 & \rightarrow & A \\
\downarrow & & \downarrow \\
0 & \rightarrow & I_0 \\
\downarrow & & \downarrow \\
X & = & X \\
\downarrow & & \downarrow \\
0 & \rightarrow & 0
\end{array}
\]

Then the middle row and the third column in the above diagram are the desired exact sequences.

Now suppose that \( n \geq 2 \) and

\[
0 \rightarrow A \rightarrow C_{n-1} \rightarrow C_{n-2} \rightarrow \cdots \rightarrow C_0 \rightarrow M \rightarrow 0
\]

is an exact sequence in \( \mathcal{A} \) with all \( C_i \) objects in \( \mathcal{C} \). Put \( K = \text{Coker}(C_{n-1} \rightarrow C_{n-2}) \). By Proposition 5.1(1), we get an exact sequence:

\[
0 \rightarrow A \rightarrow I_{n-1} \rightarrow C'_{n-2} \rightarrow K \rightarrow 0
\]

in \( \mathcal{A} \) with \( I_{n-1} \) an object in cogen \( \mathcal{C} \) and \( C'_{n-2} \) an object in \( \mathcal{C} \). Put \( A' = \text{Im}(I_{n-1} \rightarrow C'_{n-2}) \). Then we get an exact sequence:

\[
0 \rightarrow A' \rightarrow C'_{n-2} \rightarrow C_{n-3} \rightarrow \cdots \rightarrow C_0 \rightarrow M \rightarrow 0
\]

in \( \mathcal{A} \). Now we get the assertion by the induction hypothesis.

(2) The proof is dual to that of (1).

(3) It follows from Lemma 2.4 and Proposition 5.1 □

For any \( n \geq 1 \), we denote by \( \Omega^n_\mathcal{C}(\mathcal{A}) \) (resp. \( \Omega^{-n}_\mathcal{C}(\mathcal{A}) \)) the subcategory of \( \mathcal{A} \) consisting of \( n \)-\( \mathcal{C} \)-syzygy (resp. \( n \)-\( \mathcal{C} \)-cosyzygy) objects.

**Corollary 5.4.** Let \( \mathcal{C} \) be closed under extensions. Then for any \( n \geq 1 \) we have

(1) If \( \mathcal{X} \) is a cogenerator for \( \mathcal{C} \), then \( \Omega^n_\mathcal{C}(\mathcal{A}) = \Omega^n_\mathcal{X}(\mathcal{A}) \).

(2) If \( \mathcal{X} \) is a generator for \( \mathcal{C} \), then \( \Omega^{-n}_\mathcal{C}(\mathcal{A}) = \Omega^{-n}_\mathcal{X}(\mathcal{A}) \).

For an object \( M \) in \( \mathcal{A} \), the \( \mathcal{C} \)-dimension of \( M \), denoted by \( \mathcal{C} \text{-dim} M \), is defined as \( \inf\{n \geq 0 \mid \text{there exists an exact sequence } 0 \rightarrow C_n \rightarrow \cdots \rightarrow C_1 \rightarrow C_0 \rightarrow M \rightarrow 0 \text{ in } \mathcal{A} \} \) with
all $C_i$ objects in $\mathcal{C}$. We set $\mathcal{C}$-$\text{dim} \ M$ infinity if no such integer exists. A subcategory $\mathcal{X}$ of $\mathcal{C}$ is called a generator-cogenerator for $\mathcal{C}$ if it is both a generator and a cogenerator for $\mathcal{C}$.

Another main result in this section is the following

**Theorem 5.5.** Let $\mathcal{C}$ be closed under extensions and $\mathcal{X}$ a generator-cogenerator for $\mathcal{C}$. Then the following statements are equivalent for any object $M$ in $\mathcal{A}$ and $n \geq 0$.

1. $\mathcal{C}$-$\text{dim} \ M \leq n$.
2. There exists an exact sequence:
   
   $$0 \to C_n \to X_{n-1} \to \cdots \to X_1 \to X_0 \to M \to 0$$
   
   in $\mathcal{A}$ with $C_n$ an object in $\mathcal{C}$ and all $X_i$ objects in $\mathcal{X}$.
3. There exists an exact sequence:
   
   $$0 \to X_n \to X_{n-1} \to \cdots \to X_1 \to C_0 \to M \to 0$$
   
   in $\mathcal{A}$ with $C_0$ an object in $\mathcal{C}$ and all $X_i$ objects in $\mathcal{X}$.
4. For every non-negative integer $t$ such that $0 \leq t \leq n$, there exists an exact sequence:
   
   $$0 \to X_n \to \cdots \to X_1 \to X_0 \to M \to 0$$
   
   in $\mathcal{A}$ such that $X_t$ is an object in $\mathcal{C}$ and all $X_i$ are objects in $\mathcal{X}$ for $i \neq t$.

**Proof.** (4) $\Rightarrow$ (2) $\Rightarrow$ (1) and (4) $\Rightarrow$ (3) $\Rightarrow$ (1) are trivial.

(1) $\Rightarrow$ (4) We proceed by induction on $n$.

Let $\mathcal{C}$-$\text{dim} \ M \leq 1$ and

$$0 \to C_1 \to C_0 \to M \to 0$$

be an exact sequence in $\mathcal{A}$ with $C_0, C_1$ objects in $\mathcal{C}$. By Proposition 5.1 with $A = 0$, we get the exact sequences

$$0 \to C_1' \to X_0 \to M \to 0$$

and

$$0 \to X_1 \to C_0' \to M \to 0$$

in $\mathcal{A}$ with $X_0, X_1$ objects in $\mathcal{X}$ and $C_0', C_1'$ objects in $\mathcal{C}$.

Now suppose $\mathcal{C}$-$\text{dim} \ M = n \geq 2$ and

$$0 \to C_n \to \cdots \to C_1 \to C_0 \to M \to 0$$

be an exact sequence in $\mathcal{A}$ with $C_0, C_1, \ldots, C_n$ objects in $\mathcal{C}$. By Proposition 5.1 with $A = 0$, we get the exact sequences

$$0 \to C_1' \to X_0 \to M \to 0$$

and

$$0 \to X_1 \to C_0' \to M \to 0$$

in $\mathcal{A}$ with $X_0, X_1$ objects in $\mathcal{X}$ and $C_0', C_1'$ objects in $\mathcal{C}$.

Now suppose $\mathcal{C}$-$\text{dim} \ M = n \geq 2$ and

$$0 \to C_n \to \cdots \to C_1 \to C_0 \to M \to 0$$

be an exact sequence in $\mathcal{A}$ with $C_0, C_1, \ldots, C_n$ objects in $\mathcal{C}$. By Proposition 5.1 with $A = 0$, we get the exact sequences

$$0 \to C_1' \to X_0 \to M \to 0$$

and

$$0 \to X_1 \to C_0' \to M \to 0$$

in $\mathcal{A}$ with $X_0, X_1$ objects in $\mathcal{X}$ and $C_0', C_1'$ objects in $\mathcal{C}$.

Now suppose $\mathcal{C}$-$\text{dim} \ M = n \geq 2$ and

$$0 \to C_n \to \cdots \to C_1 \to C_0 \to M \to 0$$

be an exact sequence in $\mathcal{A}$ with $C_0, C_1, \ldots, C_n$ objects in $\mathcal{C}$. By Proposition 5.1 with $A = 0$, we get the exact sequences

$$0 \to C_1' \to X_0 \to M \to 0$$

and

$$0 \to X_1 \to C_0' \to M \to 0$$

in $\mathcal{A}$ with $X_0, X_1$ objects in $\mathcal{X}$ and $C_0', C_1'$ objects in $\mathcal{C}$.
is an exact sequence in $\mathcal{A}$ with all $C_i$ objects in $\mathcal{C}$. Set $A = \text{Coker}(C_3 \to C_2)$. By applying Proposition 5.1 to the exact sequence:

$$0 \to A \to C_1 \to C_0 \to M \to 0,$$

we get the following exact sequences:

$$0 \to A \to C'_1 \to X_0 \to M \to 0$$

and

$$0 \to C_n \to \cdots \to C_2 \to C'_1 \to X_0 \to M \to 0$$

in $\mathcal{A}$ with $C'_1$ an object in $\mathcal{C}$ and $X_0$ an object in $\mathcal{X}$. Set $N = \text{Coker}(C_2 \to C_1)$. Then we have $\mathcal{C}$-dim $M \leq n - 1$. By the induction hypothesis, there exists an exact sequence:

$$0 \to X_n \to \cdots \to X_t \to \cdots \to X_1 \to X_0 \to M \to 0$$

in $\mathcal{A}$ such that $X_t$ is an object in $\mathcal{C}$ and $X_i$ is an object in $\mathcal{X}$ for $i \neq t$ and $1 \leq t \leq n$.

In the following we only need to prove (4) for the case $t = 0$. Set $B = \text{Coker}(C_2 \to C_1)$. By the induction hypothesis, we get an exact sequence:

$$0 \to X_n \to \cdots \to X_3 \to X_2 \to C'_1 \to B \to 0$$

in $\mathcal{A}$ with $C'_1$ an object in $\mathcal{C}$ and all $X_i$ objects in $\mathcal{X}$. Set $K = \text{Coker}(X_3 \to X_2)$. Then by applying Proposition 5.1 to the exact sequence:

$$0 \to K \to C'_1 \to C_0 \to M \to 0,$$

we get an exact sequence:

$$0 \to K \to X_1 \to C'_0 \to M \to 0$$

in $\mathcal{A}$ with $X_1$ an object in $\mathcal{X}$ and $C'_0$ an object in $\mathcal{C}$. Thus we obtain the desired exact sequence:

$$0 \to X_n \to \cdots \to X_2 \to X_1 \to C'_0 \to M \to 0.$$

Let $R$ be a ring. For a module $M$ in Mod $R$ (resp. mod $R$), we use $\text{Add}_R M$ (resp. $\text{add}_R M$) to denote the subcategory of Mod $R$ (resp. mod $R$) consisting of all modules isomorphic to direct summands of (finite) direct sums of copies of $R M$. Recall that a subcategory $\mathcal{D}$ of Mod $R$ (resp. mod $R$) is called projectively resolving if $\mathcal{D}$ contains (finitely generated)
projective left \( R \)-modules, and \( \mathcal{D} \) is closed under extensions and kernels of epimorphisms in \( \text{Mod} \ R \) (resp. \( \text{mod} \ R \)).

**Remark 5.6.** Let \( R \) and \( S \) be rings. Then we have

(1) Let \( R C S \) be a semiflat bimodule, that is, the following conditions are satisfied:
   (c1) \( R C \) admits a degreewise finite \( R \)-projective resolution, and \( C S \) admits a degreewise finite \( S^{op} \)-projective resolution; (c2) both the homothety maps \( R R \rightarrow \text{Hom}_{S^{op}}(C, C) \) and \( SS \rightarrow \text{Hom}_{R}(C, C) \) are isomorphisms; and (c3) \( \text{Ext}^i_{R}(C, C) = 0 = \text{Ext}^i_{S^{op}}(C, C) \) for any \( i \geq 1 \). Then \( \mathcal{P}(\text{Mod} \ R) \cup \text{Add}_R C \) is a generator-cogenerator for the subcategory of \( \text{Mod} \ R \) consisting of \( G_{C} \)-projective modules (see [W] and [LHX, Corollary 2.10]).

(2) \( \mathcal{P}(\text{Mod} \ R) \) is a projective generator and an injective cogenerator for the subcategory \( G(\text{Mod} \ R) \) of Gorenstein projective left \( R \)-modules. In particular, \( G(\text{Mod} \ R) \) is projectively resolving by [H, Theorem 2.5].

(3) If \( R \) is an Artinian algebra and \( T \in \text{mod} \ R \) is cotilting, then \( \text{add}_R (T \bigoplus R) \) is a generator-cogenerator for \( \perp T \) by [AR1, Theorem 5.4(b)], and clearly \( \perp T \) is projectively resolving, where \( \perp T = \{ M \in \text{mod} \ R \mid \text{Ext}^i_{R}(M, T) = 0 \text{ for any } i \geq 1 \} \).

(4) Put \( \Omega^n(\text{Mod} \ R) = \{ M \in \text{Mod} \ R \mid \text{there exists an exact sequence } 0 \rightarrow M \rightarrow P_{n-1} \rightarrow P_{n-2} \rightarrow \cdots \rightarrow P_0 \text{ in } \text{Mod} \ R \text{ with all } P_i \text{ projective} \} \) for any \( n \geq 1 \), and put \( \Omega^\infty(\text{Mod} \ R) = \bigcap_{n \geq 1} \Omega^n(\text{Mod} \ R) \). Then \( \mathcal{P}(\text{Mod} \ R) \) is a generator-cogenerator for \( \Omega^\infty(\text{Mod} \ R) \). Put \( \Omega^n(\text{mod} \ R) = \Omega^n(\text{Mod} \ R) \cap \text{mod} \ R \) for any \( n \geq 1 \), and put \( \Omega^\infty(\text{mod} \ R) = \bigcap_{n \geq 1} \Omega^n(\text{mod} \ R) \). Then \( \mathcal{P}(\text{mod} \ R) \) is a generator-cogenerator for \( \Omega^\infty(\text{mod} \ R) \) over a left Noetherian ring \( R \). By [AR2, Theorem 1.7 and Proposition 2.2], we have that for a left and right Noetherian ring \( R \), if the right flat dimension of the \( i \)-th term in a minimal injective coresolution of \( R_R \) is at most \( i + 1 \) for any \( i \geq 0 \), especially if \( R \) is a commutative Gorenstein ring (cf. [B, Fundamental Theorem]), then all \( \Omega^n(\text{mod} \ R) \) and \( \Omega^\infty(\text{mod} \ R) \) are closed under extensions.

(5) A subcategory \( \mathcal{X} \) of \( \mathcal{A} \) is called self-orthogonal, denoted by \( \mathcal{X} \perp \mathcal{A} \), if \( \text{Ext}^i_{\mathcal{A}}(X, X') = 0 \) for any objects \( X \) and \( X' \) in \( \mathcal{X} \) and \( i \geq 1 \). If \( \mathcal{X} \perp \mathcal{X} \), then \( \mathcal{G}(\mathcal{X}) \) is closed under extensions and \( \mathcal{X} \) is a projective generator and an injective cogenerator for \( \mathcal{G}(\mathcal{X}) \) by [SSW1, Corollaries 4.5 and 4.7]. In the rest of this section, we will focus on the self-orthogonal subcategories of \( \mathcal{A} \).

**Lemma 5.7.** Let \( \mathcal{X} \perp \mathcal{A} \). Then \( \mathcal{G}(\mathcal{X}) = (\perp \mathcal{X} \cap \mathcal{X}^\perp) \cap (\text{res} \mathcal{X} \cap \text{cores} \mathcal{X}) \).

**Proof.** It is easy to get the assertion by the definition of \( \mathcal{G}(\mathcal{X}) \). \( \square \)

As an application of Theorem 5.5, we have the following

**Theorem 5.8.** Let \( \mathcal{X} \perp \mathcal{A} \) and \( M \) be an object in \( \mathcal{A} \) with \( \mathcal{G}(\mathcal{X}) \)-dim \( M < \infty \). Then the
following statements are equivalent for any \( n \geq 0 \).

(1) \( \mathcal{G}(\mathcal{X}) \)-dim \( M \leq n \).

(2) There exists an exact sequence:

\[
0 \to C_n \to X_{n-1} \to \cdots \to X_1 \to X_0 \to M \to 0
\]

in \( \mathcal{A} \) with \( C_n \) an object in \( \mathcal{G}(\mathcal{X}) \) and all \( X_i \) objects in \( \mathcal{X} \).

(3) There exists an exact sequence:

\[
0 \to X_n \to X_{n-1} \to \cdots \to X_1 \to C_0 \to M \to 0
\]

in \( \mathcal{A} \) with \( C_0 \) an object in \( \mathcal{G}(\mathcal{X}) \) and all \( X_i \) objects in \( \mathcal{X} \).

(4) For every non-negative integer \( t \) such that \( 0 \leq t \leq n \), there exists an exact sequence:

\[
0 \to X_n \to \cdots \to X_1 \to X_0 \to M \to 0
\]

in \( \mathcal{A} \) such that \( X_t \) is an object in \( \mathcal{G}(\mathcal{X}) \) and all \( X_i \) are objects in \( \mathcal{X} \) for \( i \neq t \).

(5) \( \text{Ext}^{n+1}_{\mathcal{A}}(M, X) = 0 \) for any object \( X \) in \( \mathcal{X} \) and \( i \geq 1 \).

(6) \( \text{Ext}^{n+1}_{\mathcal{A}}(M, Y) = 0 \) for any object \( Y \) in \( \mathcal{A} \) with \( \mathcal{X} \)-dim \( Y < \infty \).

(7) \( \text{Ext}^{n+1}_{\mathcal{A}}(M, Y) = 0 \) for any object \( Y \) in \( \mathcal{A} \) with \( \mathcal{X} \)-dim \( Y < \infty \) and \( i \geq 1 \).

**Proof.** Because \( \mathcal{X} \perp \mathcal{X} \) by assumption, \( \mathcal{G}(\mathcal{X}) \) is closed under extensions and \( \mathcal{X} \) is a projective generator and an injective cogenerator for \( \mathcal{G}(\mathcal{X}) \) by [SSW1, Corollaries 4.5 and 4.7]. So by Theorem 5.5, we have (1) \( \iff \) (2) \( \iff \) (3) \( \iff \) (4).

(7) \( \Rightarrow \) (6) and (7) \( \Rightarrow \) (5) are trivial.

It is easy to get (1) \( \Rightarrow \) (5) \( \Rightarrow \) (7) by Lemma 5.7 and the dimension shifting, respectively.

(6) \( \Rightarrow \) (1) Let \( \mathcal{G}(\mathcal{X}) \)-dim \( M = m(< \infty) \). Then by Theorem 5.5, there exists an exact sequence:

\[
0 \to X_m \to X_{m-1} \to \cdots \to X_1 \to C_0 \to M \to 0
\]

in \( \mathcal{A} \) with all \( X_i \) objects in \( \mathcal{X} \) and \( C_0 \) an object in \( \mathcal{G}(\mathcal{X}) \). We claim that \( m \leq n \). Otherwise, let \( m > n \). Note that \( \mathcal{X} \)-dim \( \text{Im}(X_{n+1} \to X_n) \leq m - n - 1 < \infty \). So \( \text{Ext}^1_{\mathcal{A}}(\text{Im}(X_n \to X_{n-1}), \text{Im}(X_{n+1} \to X_n)) \cong \text{Ext}^{n+1}_{\mathcal{A}}(M, \text{Im}(X_{n+1} \to X_n)) = 0 \) (note: \( X_0 = C_0 \)) by assumption and Lemma 5.7. Hence the exact sequence \( 0 \to \text{Im}(X_{n+1} \to X_n) \to X_n \to \text{Im}(X_n \to X_{n-1}) \to 0 \) splits and \( \text{Im}(X_n \to X_{n-1}) \) is isomorphic to a direct summand of \( X_n \). By Theorem 4.6(2), \( \text{Im}(X_n \to X_{n-1}) \) is an object in \( \mathcal{G}(\mathcal{X}) \) and \( \mathcal{G}(\mathcal{X}) \)-dim \( M \leq n \), which is a contradiction. \( \square \)

As an immediate consequence of Theorem 5.8, we get the following
Corollary 5.9. Let $\mathcal{X} \perp \mathcal{X}$ and $M$ an object in $\mathcal{A}$ with $\mathcal{G}(\mathcal{X})$-$\dim M < \infty$. Then $\mathcal{G}(\mathcal{X})$-$\dim M = \sup\{n \geq 0 \mid \text{Ext}^n_{\mathcal{G}}(M, X) \neq 0 \text{ for some object } X \text{ in } \mathcal{X}\} = \sup\{n \geq 0 \mid \text{Ext}^n_{\mathcal{G}}(M, Y) \neq 0 \text{ for some object } Y \text{ in } \mathcal{A} \text{ with } \mathcal{X}$-$\dim Y < \infty\}.

By Lemma 5.7 and Corollary 5.9, we get the following

Corollary 5.10. Let $\mathcal{X} \perp \mathcal{X}$ and $0 \to M_3 \to M_2 \to M_1 \to 0$ be an exact sequence in $\mathcal{A}$ with $M_3 \neq 0$ and $M_1$ an object in $\mathcal{G}(\mathcal{X})$. Then $\mathcal{G}(\mathcal{X})$-$\dim M_3 = \mathcal{G}(\mathcal{X})$-$\dim M_2$.

In general, we have $\mathcal{G}(\mathcal{X})$-$\dim M \leq \mathcal{X}$-$\dim$ for any object $M$ in $\mathcal{A}$. By Corollary 5.9 we get the following

Corollary 5.11. Let $\mathcal{X} \perp \mathcal{X}$ and $M$ an object in $\mathcal{A}$ with $\mathcal{X}$-$\dim M < \infty$. Then $\mathcal{G}(\mathcal{X})$-$\dim M = \mathcal{X}$-$\dim M$.

Proof. Let $\mathcal{X}$-$\dim M = n < \infty$. It suffices to prove $\mathcal{G}(\mathcal{X})$-$\dim M \geq \mathcal{X}$-$\dim M = n$. It is easy to get that $\text{Ext}^n_{\mathcal{G}}(M, X) \neq 0$ some object $X$ in $\mathcal{X}$, so $\mathcal{G}(\mathcal{X})$-$\dim M \geq n$ by Corollary 5.9. \hfill $\square$

By the definition of $\mathcal{G}(\mathcal{X})$, we have that each object in $\mathcal{G}(\mathcal{X})$ can be embedded into an object in $\mathcal{X}$ with the cokernel still in $\mathcal{G}(\mathcal{X})$. The first assertion in the following result generalizes this fact and [CrH, Lemma 2.17].

Corollary 5.12. Let $\mathcal{X} \perp \mathcal{X}$ and $M$ be an object in $\mathcal{A}$ and $n \geq 0$, and let $\mathcal{G}(\mathcal{X})$-$\dim M = n < \infty$. Then we have

1. There exists an exact sequence $0 \to M \to N \to G \to 0$ in $\mathcal{A}$ with $\mathcal{X}$-$\dim N = n$ and $G$ an object in $\mathcal{G}(\mathcal{X})$.
2. There exists an exact sequence $0 \to N \to G \to M \to 0$ in $\mathcal{A}$ with $\mathcal{X}$-$\dim N \leq n - 1$ and $G$ an object in $\mathcal{G}(\mathcal{X})$. This exact sequence is an epic $\mathcal{G}(\mathcal{X})$-precover of $M$.

Proof. Let $M$ be an object in $\mathcal{A}$ with $\mathcal{G}(\mathcal{X})$-$\dim M = n < \infty$.

1. We apply Theorem 5.3(1) with $A = 0$ to get an exact sequence $0 \to M \to N \to G \to 0$ in $\mathcal{A}$ with $\mathcal{X}$-$\dim N \leq n$ and $G$ an object in $\mathcal{G}(\mathcal{X})$. By Corollary 5.10, we have $\mathcal{G}(\mathcal{X})$-$\dim N = n$. Then it follows from Corollary 5.11 that $\mathcal{X}$-$\dim N = n$.

2. By Theorem 5.8, there exists an exact sequence $0 \to N \to G \to M \to 0$ in $\mathcal{A}$ with $\mathcal{X}$-$\dim N \leq n - 1$ and $G$ an object in $\mathcal{G}(\mathcal{X})$. Also by Theorem 5.8, $\text{Ext}^1_{\mathcal{G}}(G', N) = 0$ for any object $G'$ in $\mathcal{G}(\mathcal{X})$. So the above exact sequence is an epic $\mathcal{G}(\mathcal{X})$-precover of $M$. \hfill $\square$

Remark 5.13. For an object $M$ in $\mathcal{A}$, we may define dually the $\mathcal{C}$-codimension of $M$, denoted by $\mathcal{C}$-codim $M$, as $\inf\{n \geq 0 \mid$ there exists an exact sequence $0 \to M \to C^0 \to C^1 \to \cdots \to C^n \to 0$ in $\mathcal{A}$ with all $C^i$ objects in $\mathcal{C}\}$. We set $\mathcal{C}$-codim $M$ infinity if no such integer
exists. We point out the dual versions on the \( c \)-codimension of all the above results (5.5 and 5.8–5.12) also hold true by using a completely dual arguments.

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