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THE HOMOLOGICAL THEORY
OF
MAXIMAL COHEN-MACAULAY APPROXIMATIONS

by

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Summary: Let R be a commutative noetherian Cohen-Macaulay ring which admits a dualizing module. We show that for any finitely generated R-module N there exists a maximal Cohen-Macaulay R-module M which surjects onto N and such that any other surjection from a maximal Cohen-Macaulay module onto N factors over it. Dually, there is a finitely generated R-module I of finite injective dimension into which N embeds, universal for such embeddings. We prove and investigate these results in the broader context of abelian categories with a suitable subcategory of "maximal Cohen-Macaulay objects" extracting for this purpose those ingredients of Grothendieck-Serre duality theory which are needed.


§0. A Commutative Introduction

The aim of this work is to analyze the framework in which the theory of maximal Cohen-Macaulay approximations can be developed. Instead of outlining right away the abstract results, we want to start by describing the situation in the classical case of a commutative local noetherian ring R with maximal ideal m and residue class field k = R/m.

Assume that R admits a dualizing module ω. Then R is Cohen-Macaulay, and the finitely generated R-modules M which are maximal Cohen-Macaulay in the sense that depth\,_{m}M = \dim R can be characterized homologically as those modules for which Ext^{1}_{R}(M, ω) = 0 for i ≠ 0.

Our main result can then be paraphrased as saying that R-mod, the category of finitely generated R-modules, is obtained by gluing together the orthogonal subcategories...
of modules of finite injective dimension over $R$ and the category of maximal Cohen-Macaulay modules along their common intersection which is spanned by $\omega$.

More precisely, let us recall that $\omega$ is dualizing for the local ring $(R,m,k)$ if and only if it satisfies the following three conditions:

(i) $\omega$ is finitely generated and of finite injective dimension over $R$.

(ii) The natural ring homomorphism which is given by multiplication with scalars from $R$ on $\omega$, $R \rightarrow \text{Hom}_R(\omega, \omega)$ is an isomorphism.

(iii) For any integer $i \neq 0$, one has $\text{Ext}_R^i(\omega, \omega) = 0$.

Now our main results in this context are

**Theorem A: (Existence of the decomposition).** Let $(R,m,k)$ be a commutative, local noetherian ring with dualizing module $\omega$. For any finitely generated $R$-module $N$ there exist finitely generated $R$-modules $M_N$ and $I_N$ together with an $R$-linear map $d_N : M_N \rightarrow I_N$

such that

(a) The image of $d_N$ is isomorphic to $N$.

(b) $M_N$ is maximal Cohen-Macaulay and $I_N = \ker d_N$ is an $R$-module of finite injective dimension.

(c) $I_N$ is of finite injective dimension and $M_N = \text{Cok} d_N$ is maximal Cohen-Macaulay.

(d) There exists an integer $n \geq 0$ such that $d_N$ can be factored into an injection $j : M_N \rightarrow \omega^\otimes n$ and a surjection $p : \omega^\otimes n \rightarrow I_N$.

If $d_N = \iota^N \pi_N$ denotes the factorization of $d_N$ over its image $N$, we can arrange the data given in the theorem into the following exact commutative diagram of $R$-modules:

```
O \rightarrow N \rightarrow I_N \rightarrow M_N \rightarrow O
\pi_N \quad d_N \quad p
O \rightarrow M_N \rightarrow \omega^\otimes n \rightarrow M_N \rightarrow O
j
I_N \rightarrow \omega^\otimes n \rightarrow M_N \rightarrow O
\iota_N
```

```
O \rightarrow O
```

O \rightarrow O
Theorem B: (Essential Uniqueness)

(a) Assume given a second homomorphism \( d'_N: M'_N \to \mathcal{H}^N \) satisfying Theorem A for the same module \( N \). If the image factorization of \( d'_N \) is given as

\[
M'_N \xrightarrow{\pi'_N} N \xrightarrow{i'_N} \mathcal{H}^N,
\]

there exist modules \( P, P' \) and \( Q, Q' \) which are each finite direct sums of copies of \( \omega \), and \( R \)-module isomorphisms \( \mu, \kappa \) so that the following diagram commutes:

\[
\begin{array}{ccc}
M'_N \otimes P & \xrightarrow{\pi'_N \otimes \varnothing} & N \xrightarrow{\varnothing \otimes Q} \mathcal{H}^N \otimes Q \\
\mu \downarrow & & \kappa \\
M_N \otimes P' & \xrightarrow{\pi_N \otimes \varnothing} & N \xrightarrow{\varnothing \otimes Q'} \mathcal{H}^N \otimes Q'
\end{array}
\]

(b) If \( f:M \to N \) is any homomorphism from a maximal Cohen-Macaulay \( R \)-module \( M \) into \( N \), it factors over \( \pi_N \). If \( g: N \to J \) is any homomorphism from \( N \) into an \( R \)-module \( J \) of finite injective dimension, it factors over \( \mathcal{H}^N \).

These results suggest to call \( 0 \to \mathcal{H}^N \to N \to 0 \) a maximal Cohen-Macaulay approximation of \( N \) and \( 0 \to N \xrightarrow{i^N} \mathcal{H}^N \to M^N \to 0 \) a hull of finite injective dimension for \( N \).

To give a simple illustration, consider the case where \( N \) itself is a Cohen-Macaulay \( R \)-module, hence satisfying depth_{\mathfrak{m}} N = \dim N.

Set \( n = \mathrm{codepth}_{\mathfrak{m}} N = \dim R - \dim N \). Then local duality theory implies:

(i) \( \operatorname{Ext}^i_R(N, \omega) = 0 \) for \( i \neq n \).

(ii) \( N^\vee = \operatorname{Ext}^n_R(N, \omega) \) is again Cohen-Macaulay of codepth \( n \).

(iii) \( N = \operatorname{Ext}^n_R(N^\vee, \omega) = N^{\vee \vee} \).

Using this information, let

\[
0 \to \Omega_n(N) \xrightarrow{d_n} R^{\oplus n-1} \xrightarrow{d_n-2} \cdots \xrightarrow{d_0} R^{\oplus 1} \xrightarrow{d_0} N^\vee \to 0
\]

be an exact sequence obtained by truncating a free resolution of \( N^\vee \). It follows that \( \Omega_n(N) \) is maximal Cohen-Macaulay and that dualizing with respect to \( \omega \) results in an exact sequence

\[
0 \to \omega^{\oplus n} \to \cdots \xrightarrow{d_n-2} \omega^{\oplus n-1} \xrightarrow{d_n} \operatorname{Hom}_R(\Omega_n(N), \omega) \xrightarrow{\pi} N^{\vee \vee} = N \to 0.
\]

Then \( M_n = \operatorname{Hom}_R(\Omega_n(N), \omega) \xrightarrow{\pi} N \) is a desired maximal Cohen-Macaulay approximation of \( N \), and \( I_N = \operatorname{Cok} d_n-2 \) admits a finite resolution "by \( \omega \), which shows that \( I_N \) is of finite injective dimension. The hull of finite injective dimension \( I^N \) is then simply the cokernel of the \( \omega \)-dual of the next differential in the resolution of \( N^{\vee} \), namely \( I^N = \operatorname{Cok} \operatorname{Hom}_R(d_n-1, \omega) \).
If $R$ is a domain, for example, we get even more precise information:

(i) The rank of $M_N$ equals the alternating sum 
$$\sum_{i=1}^{n} (-1)^{i+1} b_{n-i} + (-1)^n \text{rk} N,$$

(ii) $M_N^\sim = \text{Hom}_R(M_N, \omega) = \Omega_n(N)$ embeds into $R^{\mathbb{G}b_{n-1}}$,

(iii) $M_N$ contains no copy of $\omega$ as a direct summand if and only if $\Omega_n(N)$, the $n$-th syzygy module of $N$, contains no free summand.

It follows that one can attach new numerical invariants to an $R$-module $N$ in this way. The minimum number of copies of $\omega$ necessarily contained in $M_N$ or $I^n$, the rank of the $\omega$-free summand of either $M_N$ or $I^n$, their minimum number of generators and so forth.

Here, we are not concerned with these more detailed consequences of the theory but rather with its general framework.

The first author first proved an essentially equivalent version of Theorem A but for the category of additive functors on $R\text{-mod}$, see [Ausl], where the result was phrased by saying that the category of maximal Cohen-Macaulay modules is "coherently (co-)finite". The essential step then was to establish the representability of the functors involved.

This background illuminates our approach here. Although the primary applications of the theory might be within the classical theory of rings and algebras, to a large extent it can be developed in any abelian category $C$ which admits a suitable subcategory $X$ of "maximal Cohen-Macaulay objects".

Here we establish sufficient conditions on $X$ to guarantee the categorical analogues of Theorems A and B. Section 1 deals with the decomposition theorem and section 2 addresses the uniqueness question. Sections 3 and 4 investigate the circumstances under which - in the terminology of the above example - the category of modules with "finite $\omega$-resolution" are all the modules of finite injective dimension. Section 5 assembles a few remarks on finiteness conditions and section 6 contains more examples, among other purposes highlighting the differences in the theory when applied to either commutative or non-commutative rings.

§1. The Basic Decomposition Theorem

In this section we prove the basic decomposition theorem on which this paper rests. Before stating the result, we give some definitions and notations.

Throughout, $C$ will be an abelian category. By a subcategory $A$ of $C$ we will always mean a full, additive and essential subcategory of $C$, so that $A$ is closed under finite direct sums in $C$ and such that any object $C$ in $C$ which is isomorphic to an object in $A$ is already an object in $A$.

A subcategory of $C$ is said to be additively closed (or karoubian in the
terminology of [SGA IV] or [Qu]), if it is closed under direct summands in $\mathbf{C}$, or, equivalently, if any projector ($p = p^2$) in the subcategory admits an image in that subcategory. Any subcategory $\mathbf{A}$ of $\mathbf{C}$ admits an additive closure $\text{add } \mathbf{A}$ in $\mathbf{C}$, consisting of all those objects $\mathbf{C}$ in $\mathbf{C}$ which are isomorphic to a direct summand (in $\mathbf{C}$) of an object in $\mathbf{A}$. Clearly $\mathbf{A}$ is additively closed in $\mathbf{C}$ if and only if $\mathbf{A} = \text{add } \mathbf{A}$.

More generally, given any collection $\{\mathbf{C}_i\}_{i \in I}$ of objects in $\mathbf{C}$, there is a unique smallest additively closed subcategory $\text{add } \{\mathbf{C}_i\}_{i \in I}$ containing each object $\mathbf{C}_i$, $i \in I$. It can be described by the following "universal mapping property": If $F: \mathbf{C} \to \mathbf{D}$ is any additive functor from $\mathbf{C}$ into another additive category $\mathbf{D}$ such that $F(\mathbf{C}_i)$ is a zero-object in $\mathbf{D}$ for each $i \in I$, then $F(\text{add } \{\mathbf{C}_i\}_{i \in I})$ consists entirely of zero-objects.

In particular, (cf. also [He]), there exists the additive quotient category $\pi: \mathbf{C} \to \mathbf{C}/\text{add } \{\mathbf{C}_i\}_{i \in I}$, where $\mathbf{C}/\text{add } \{\mathbf{C}_i\}_{i \in I}$ has the same objects as $\mathbf{C}$ and $\pi$ is a full, additive functor which is the identity on objects.

The projection functor $\pi$ is characterized by the property that any additive functor $F$ as before factors uniquely over $\pi$. Of course, even if $\mathbf{C}$ is assumed to be abelian, as here, $\mathbf{C}/\text{add } \{\mathbf{C}_i\}_{i \in I}$ need not to be so.

If $\mathbf{A}$ is an additively closed subcategory of $\mathbf{C}$, the morphism groups in $\mathbf{C}/\mathbf{A}$ are given by

$$\text{Hom}_{\mathbf{C}/\mathbf{A}}(\mathbf{C}_1, \mathbf{C}_2) = \frac{\text{Hom}_{\mathbf{C}}(\mathbf{C}_1, \mathbf{C}_2)}{\{\phi: \mathbf{C}_1 \to \mathbf{C}_2 | \phi \text{ factors over an object in } \mathbf{A}\}}$$

Now suppose again that $\mathbf{A}$ is any subcategory of $\mathbf{C}$ in the sense fixed above. We say that a sequence of morphisms $\cdots \to \mathbf{A}_{i+1} \to \mathbf{A}_i \to \mathbf{A}_{i-1} \to \cdots$ in $\mathbf{A}$ is exact, if when viewed as a sequence in $\mathbf{C}$ it is exact.

Suppose $\mathbf{C}$ is an object in $\mathbf{C}$. We define $\mathbf{A}$–resol.dim$\mathbf{C}$, the $\mathbf{A}$-resolution dimension of $\mathbf{C}$, to be the smallest nonnegative integer $n$ such that there exists an exact sequence $0 \to \mathbf{A}_n \to \mathbf{A}_{n-1} \to \cdots \to \mathbf{A}_0 \to \mathbf{C} \to 0$, with each $\mathbf{A}_i$ in $\mathbf{A}$, if such an integer exists. We say that $\mathbf{A}$–resol.dim$\mathbf{C} < \infty$ if $\mathbf{A}$–resol.dim$\mathbf{C} = n$ for some non-negative integer $n$. The subcategory of $\mathbf{C}$ consisting of all $\mathbf{C}$ in $\mathbf{C}$ such that $\mathbf{A}$–resol.dim$\mathbf{C} < \infty$ will be denoted $\mathbf{A}$.

Finally, we say a subcategory $\mathbf{B}$ of $\mathbf{A}$ is a cogenerator for $\mathbf{A}$ if for each object $\mathbf{A}$ in $\mathbf{A}$ there is an exact sequence $0 \to \mathbf{A} \to \mathbf{B} \to \mathbf{A}' \to 0$ in $\mathbf{A}$ with $\mathbf{B}$ in $\mathbf{B}$.

With these notations, we fix throughout the rest of this paper an additively closed subcategory $\mathbf{X}$ of $\mathbf{C}$ which is furthermore closed under extensions, i.e. if $0 \to \mathbf{C}_1 \to \mathbf{C}_2 \to \mathbf{C}_3 \to 0$ is exact in $\mathbf{C}$ with $\mathbf{C}_1$ and $\mathbf{C}_3$ in $\mathbf{X}$, then also $\mathbf{C}_2$ is in $\mathbf{X}$. (In the terminology of [Qu], for example, $\mathbf{X}$ is a karoubian exact subcategory of $\mathbf{C}$.) Also we assume given an additively closed subcategory $\omega$ of $\mathbf{X}$ which is a cogenerator of $\mathbf{X}$.

The paper is now devoted to studying how the categories $\mathbf{X}$, $\omega$, $\mathbf{X}$ and $\omega$ are related.
All of our results depend on the following

**Theorem 1.1.** For each $C$ in $\hat{X}$ there are exact sequences

$$0 \to Y_C \to X_C \to C \to 0$$

and

$$0 \to C \to Y^C \to X^C \to 0$$

with $Y_C$ and $Y^C$ in $\hat{\omega}$ and $X_C$ and $X^C$ in $X$.

**Proof:** The proof proceeds by induction on $X$-resol.dim$C$ and is based on the following two easily proven observations.

**Lemma 1.2.** Suppose given exact sequences

$$0 \to K \to X \to C \to 0$$

and

$$0 \to K \to Y^1 \to X^1 \to 0$$

with $X$ and $X^1$ in $X$ and $Y$ in $\hat{\omega}$. Then in the pushout diagram

\[
\begin{array}{c}
0 \\
\downarrow \\
0 \longrightarrow K \longrightarrow X \longrightarrow C \longrightarrow 0 \\
\downarrow \\
0 \longrightarrow Y^1 \longrightarrow U \longrightarrow C \longrightarrow 0 \\
\downarrow \\
0 \\
\end{array}
\]

the exact sequence

$$0 \to Y^1 \to U \to C \to 0$$

has the property that $Y^1$ is in $\hat{\omega}$ and $U$ is in $X$.

**Proof:** As $Y^1$ is in $\hat{\omega}$ by assumption, it remains to be seen that $U$ is in $X$. This follows from the fact that both $X$ and $X^1$ are in $X$ and $X$ is closed under extensions.

The other observation we need is the following.

**Lemma 1.3.** Suppose that we have an exact sequence

$$0 \to Y_C \to X_C \to C \to 0$$

with $Y_C$ in $\hat{\omega}$ and $X_C$ in $X$. Let

$$0 \to X_C \to W \to X \to 0$$

be exact with $X$ in $X$ and $W$ in $\omega$. Then in the pushout diagram

\[
\begin{array}{c}
0 \\
\downarrow \\
0 \longrightarrow Y_C \longrightarrow X_C \longrightarrow C \longrightarrow 0 \\
\downarrow \\
0 \\
\end{array}
\]
the exact sequence
\[ 0 \to C \to Z \to X \to 0 \]
has the property that \( Z \) is in \( \hat{\omega} \) and \( X \) is in \( \mathfrak{X} \).

**Proof:** As again \( X \) is in \( \mathfrak{X} \) by assumption, it is only required to prove that \( Z \) is in \( \hat{\omega} \). But in the exact sequence \( 0 \to Y_C \to W \to Z \to 0 \), we have \( Y_C \) in \( \hat{\omega} \) and \( W \) in \( \omega \), so that \( Z \) is in \( \hat{\omega} \) by definition of that category. \[ \blacksquare \]

The proof of Theorem 1.1 follows now easily from these lemmas.

Suppose \( \mathfrak{X} \)-resol.dim\( C = n \) and let \( 0 \to X_n \to \ldots \to X_1 \overset{d_0}{\to} X_0 \to C \to 0 \) be exact with each \( X_i \) in \( \mathfrak{X} \). If \( n = 0 \), we have that \( C \) is already in \( \mathfrak{X} \). Since \( \omega \) is a cogenerator for \( \mathfrak{X} \), there is an exact sequence \( 0 \to C \to W \to X \to 0 \) in \( \mathfrak{X} \) with \( W \) in \( \omega \) which is one of our desired exact sequences. The other one is \( 0 \to 0 \to C \to C \to 0 \).

Now suppose that \( n > 0 \) and set \( K = \text{Im}d_0 \), so that we have exact sequences \( 0 \to K \to X_0 \to C \to 0 \) and \( 0 \to X_n \to \ldots \to X_1 \to K \to 0 \) with each \( X_i \) in \( \mathfrak{X} \). By the inductive hypothesis we know there is an exact sequence \( 0 \to K \to Y^K \to X^K \to 0 \) with \( Y^K \) in \( \hat{\omega} \) and \( X^K \) in \( \mathfrak{X} \). Therefore, by Lemma 1.2, the pushout diagram

\[
\begin{array}{ccccccccc}
0 & \to & K & \to & X_0 & \to & C & \to & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \\
0 & \to & Y^K & \to & U & \to & C & \to & 0
\end{array}
\]

has the property that \( U \) is in \( \mathfrak{X} \). Hence we may choose \( 0 \to Y^K \to U \to C \to 0 \) as one of our desired sequences for \( C \). From the existence of this exact sequence, it follows by Lemma 1.3 that we also have an exact sequence \( 0 \to C \to Y^C \to X^C \to 0 \) with \( Y^C \) in \( \hat{\omega} \) and \( X^C \) in \( \mathfrak{X} \). This finishes the proof of Theorem 1.1. \[ \blacksquare \]

For ease of reference, we call an exact sequence \( 0 \to Y_C \to X_C \overset{\pi_C}{\to} C \to 0 \) with \( X_C \) in \( \mathfrak{X} \) and \( Y_C \) in \( \hat{\omega} \) an \( \mathfrak{X} \)-approximation of \( C \). Dually, we call an exact sequence \( 0 \to C \overset{\iota_C}{\to} Y^C \to X^C \to 0 \) with \( Y^C \) in \( \hat{\omega} \) and \( X^C \) in \( \mathfrak{X} \) an \( \hat{\omega} \)-hull of \( C \).

From now on, we assume that \( \mathfrak{X} \) has the property that if \( 0 \to X_0 \to X_1 \to X_2 \to 0 \) is an exact sequence with \( X_1 \) and \( X_2 \) in \( \mathfrak{X} \), then \( X_0 \) is also in \( \mathfrak{X} \).
\( \mathbf{X} \), in addition to \( \mathbf{X} \) being an additively closed subcategory of \( \mathbf{C} \) which is closed under extensions. (In D. Quillen’s terminology, (loc. cit.), all epimorphisms from \( \mathbf{C} \) in \( \mathbf{X} \) are \textit{admissible}.)

It should be noted that in all our examples the categories \( \mathbf{X} \) satisfy this additional condition. As a consequence of this further hypothesis on \( \mathbf{X} \), we get the following

\textbf{Lemma 1.4.} Suppose \( \mathbf{C} \) in \( \mathbf{C} \) has an \( \hat{\omega} \)-hull \( 0 \rightarrow \mathbf{C} \rightarrow \mathbf{Y} \rightarrow \mathbf{X} \rightarrow 0 \). Then it also admits an \( \mathbf{X} \)-approximation \( 0 \rightarrow \mathbf{Y}_\mathbf{C} \rightarrow \mathbf{X}_\mathbf{C} \rightarrow \mathbf{C} \rightarrow 0 \). Furthermore, \( \mathbf{Y}_\mathbf{C} \) can be chosen such that \( \omega\text{-resol.dim}\mathbf{Y}_\mathbf{C} < \omega\text{-resol.dim} \mathbf{Y} \) if \( \mathbf{Y} \) is not already in \( \omega \).

\textbf{Proof.} Let \( 0 \rightarrow \mathbf{W}_n \rightarrow \mathbf{W}_{n-1} \rightarrow \cdots \stackrel{d_0}{\rightarrow} \mathbf{W}_0 \rightarrow \mathbf{Y}_\mathbf{C} \rightarrow 0 \) be exact with the \( \mathbf{W}_i \) in \( \omega \). Then we obtain the following pullback diagram

\[
\begin{array}{c}
\vdots \\
O \\
\downarrow \\
K \\
\downarrow \\
O \\
\rightarrow L \\
\downarrow \\
\rightarrow W_0 \\
\downarrow \\
\rightarrow X_\mathbf{C} \\
\downarrow \\
\rightarrow O \\
\end{array}
\end{equation}

where \( K = \text{Im} d_0 \). Since \( X_\mathbf{C} \) and \( W_0 \) are in \( \mathbf{X} \), the additional assumption yields that \( L \) is in \( \mathbf{X} \) too. By definition, \( K \) is in \( \hat{\omega} \) and so \( 0 \rightarrow K \rightarrow L \rightarrow C \rightarrow 0 \) is an \( \mathbf{X} \)-approximation of \( C \). Now set \( Y_\mathbf{C} = K \) and \( X_\mathbf{C} = L \).

As a consequence of this lemma, we obtain the following characterization of the objects in \( \hat{\mathbf{X}} \).

\textbf{Proposition 1.5.} Let \( \mathbf{X} \) be an additively closed and exact subcategory of \( \mathbf{C} \) in which every epimorphism is admissible. If \( \omega \) is a cogenerator of \( \mathbf{X} \), the following are equivalent for an object \( C \) in \( \mathbf{C} \):

(a) \( C \) is in \( \hat{\mathbf{X}} \).

(b) There exists an \( \mathbf{X} \)-approximation \( 0 \rightarrow \mathbf{Y}_\mathbf{C} \rightarrow \mathbf{X}_\mathbf{C} \rightarrow C \rightarrow 0 \) of \( C \).

(c) There is an \( \hat{\omega} \)-hull \( 0 \rightarrow C \rightarrow Y_\mathbf{C} \rightarrow X_\mathbf{C} \rightarrow 0 \) of \( C \).

\textbf{Proof.} Since (a) implies (b) and (c) by theorem 1.1, it is only required to show that (b) implies (a) and (c) implies (b).

(b) \Rightarrow (a): Since \( \mathbf{Y}_\mathbf{C} \) is in \( \hat{\omega} \) by assumption, there is an exact sequence

\( 0 \rightarrow \mathbf{W}_n \rightarrow \cdots \rightarrow \mathbf{W}_0 \rightarrow \mathbf{Y}_\mathbf{C} \rightarrow 0 \) with each \( \mathbf{W}_i \) in \( \omega \). Since \( \omega \) is a subcategory of \( \mathbf{X} \), it follows from the exact sequence \( 0 \rightarrow \mathbf{W}_n \rightarrow \cdots \rightarrow \mathbf{W}_0 \rightarrow \mathbf{X}_\mathbf{C} \rightarrow C \rightarrow 0 \) that \( C \) is in \( \hat{\mathbf{X}} \).
(c) ⇒ (b): This is just a restatement of Lemma 1.4.

We end this section with three examples, illustrating the theory developed so far.

**Example 1.** Let $X \to \text{Spec } k$ be a scheme of finite type over a field $k$. Assume that $X$ is equidimensional of dimension $d$ and locally Cohen-Macaulay in the sense that $\mathcal{O}_{X,x}$ is a local Cohen-Macaulay ring for each $x$ in $X$. Let $\mathcal{C}$ be the category of coherent sheaves of $\mathcal{O}_X$-modules and define $\mathcal{X}$ to be the subcategory of maximal Cohen-Macaulay coherent sheaves, where a coherent $\mathcal{O}_X$-module $\mathcal{M}$ is said to be maximal Cohen-Macaulay if for every $x \in X$ one has $\text{depth}_{\mathcal{O}_{X,x}} \mathcal{M}_x = \dim \mathcal{O}_{X,x} ; \mathfrak{m}_x$ the unique maximal ideal of $\mathcal{O}_{X,x}$.

It is then clear that if $0 \to \mathcal{M}_1 \to \mathcal{M}_2 \to \mathcal{M}_3 \to 0$ is an exact sequence in $\mathcal{C}$, then
(a) $\mathcal{M}_2$ is in $\mathcal{X}$ if $\mathcal{M}_1$ and $\mathcal{M}_3$ are in $\mathcal{X}$, and
(b) $\mathcal{M}_1$ is in $\mathcal{X}$ if $\mathcal{M}_2$ and $\mathcal{M}_3$ are in $\mathcal{X}$.

Remark also that, by hypothesis, the structure sheaf $\mathcal{O}_X$ is in $\mathcal{X}$ and that consequently $\mathcal{X}$ contains all locally free sheaves of $\mathcal{O}_X$-modules. Conversely, a maximal Cohen-Macaulay $\mathcal{O}_X$-module is locally free on the regular locus $X_{\text{reg}} \subseteq X$. Moreover, $\mathcal{C} = \hat{\mathcal{X}}$, and if $\mathcal{C} \neq 0$ is in $\mathcal{C}$, then $\mathcal{X}$-resol.$\dim \mathcal{C} = n$ if and only if $n$ is the largest integer such that $\mathcal{E}xt^n_{\mathcal{O}_X}(\mathcal{C}, \omega_X) \neq 0$, where $\omega_X$ is a dualizing sheaf for $X$.

Now assume that either $X$ admits a very ample invertible sheaf $L$ or that $X$ is affine (in which case $L = \mathcal{O}_X$ in the following). Then $X$ can be embedded into a projective space over $k$, say $i : X \to \mathbb{P}^N_k$, with $L = i^* \mathcal{O}_{\mathbb{P}^N}(1)$.

Denoting by $\omega_L$ the smallest additively closed subcategory which contains the family of objects $\{ \omega_X \otimes (\mathcal{O}^{\otimes n})_{\text{sec}} \}_{n \in \mathbb{Z}}$, it follows easily from Grothendieck-Serre duality theory that $\omega_L$ is a cogenerator for $\hat{\mathcal{X}}$.

**Proposition 1.6.** For each coherent sheaf $\mathcal{C}$ of $\mathcal{O}_X$-modules we have both an $\mathcal{X}$-approximation with respect to $\omega_L$ of the form $0 \to Y_C \to X_C \to \mathcal{C} \to 0$ and an $\hat{\omega}_L$-hull $0 \to \mathcal{C} \to Y^C \to X^C \to 0$.

Remark that in this example the category $\mathcal{X}$ depends only on the scheme $X$ whereas its cogenerator depends on the choice of both a dualizing module $\omega_X$ and a very ample sheaf $L$. Also the $\mathcal{X}$-approximations and $\hat{\omega}_L$-hulls will vary with these choices.

Next consider the following modified version of Example 1.

**Example 2.** As in Example 1, we let $X \to \text{Spec } k$ be an equidimensional Cohen-Macaulay scheme over a field $k$. Let $X' \subseteq X$ be the Gorenstein locus of $X$, which is the set of all points $x$ in $X$ for which $\mathcal{O}_{X,x}$ is a Gorenstein local ring. Let $\mathcal{X'}$ be the subcategory of $\mathcal{C}$, the category of coherent sheaves of $\mathcal{O}_X$-modules, consisting of those Cohen-Macaulay sheaves $\mathcal{M}$ such that $\mathcal{M}_x$ is $\mathcal{O}_{X,x}$-free for all $x$ in $X'$. It is clear again that $\mathcal{X'}$ is an exact subcategory of $\mathcal{C}$ in which every epimorphism is admissible. Also $\hat{\mathcal{X}}'$ consists of all those
\( M \) in \( C \) for which \( M_x \) is of finite projective dimension over \( O_{X,x} \) for each \( x \) in \( X' \). This implies that an exact sequence \( 0 \to A \to B \to C \to O \) in \( C \) is in \( \mathcal{X}' \) if any two of \( A, B \) or \( C \) are in \( \mathcal{X}' \).

Again, any invertible sheaf of \( O_X \)-modules is in \( \mathcal{X}' \), and in particular for any dualizing sheaf \( \omega_L \) and each very ample invertible sheaf \( L \) on \( X \), the category \( \omega_L \) defined above is a cogenerator of \( \mathcal{X}' \). We leave it to the reader to give in this case the analogue of Proposition 1.6.

Our final example in this section treats a not necessarily commutative version of Gorenstein rings of finite Krull dimension.

Example 3. Let \( R \) be a ring with unit which is noetherian on both sides and such that the injective dimension of \( R \) as a right module over itself is finite, say equal to \( d \).

Take \( C = R\text{-mod} \), the category of finitely generated left \( R \)-modules, and let \( \mathcal{X} \) be the subcategory consisting of all modules \( M \) in \( R\text{-mod} \) which satisfy \( \text{Ext}_R^i(M,R) = 0 \) for \( i \neq 0 \).

Then \( \mathcal{X} \) is certainly additively closed and has the property that an exact sequence \( 0 \to M_1 \to M_2 \to M_3 \to 0 \) is in \( \mathcal{X} \) as soon as either \( M_1 \) and \( M_3 \) or \( M_2 \) and \( M_3 \) are in \( \mathcal{X} \). Hence \( \mathcal{X} \) satisfies our general assumptions.

For \( \omega \), take the subcategory of all finitely generated projective left \( R \)-modules. Then \( \omega \) is by definition a subcategory of \( \mathcal{X} \) which is additively closed.

For our theory to apply, we have hence to show that \( \omega \) constitutes a cogenerator for \( \mathcal{X} \). To obtain this result we need our assumption on \( R \). Namely, let

\[
\cdots \to P_j \to \cdots \to P_0 \to M \to 0
\]

be a projective resolution of a module \( M \) in \( \mathcal{X} \). By definition of \( \mathcal{X} \), the dualized complex

\[
0 \to M^* \to P_0^* \xrightarrow{d_0^*} P_1^* \to \cdots \to P_j^* \xrightarrow{d_j^*} \cdots
\]

is acyclic. But then our hypothesis furnishes the following more precise information.

Lemma 1.7. With notations and assumptions as above, for every module \( M \) in \( \mathcal{X} \) one has

(a) For all integers \( j \geq 0 \), the right \( R \)-modules \( K_j = \ker d_j^* \) satisfy \( \text{Ext}_R^i(K_j,R) = 0 \) for \( i \neq 0 \).

(b) \( M \) is reflexive, that is, the natural morphism of left \( R \)-modules \( M \to M^{**} \) is an isomorphism.

(c) If \( 0 \to L \to Q \xrightarrow{p} M^* \to 0 \) is an exact sequence of right \( R \)-modules with \( Q \) finitely generated projective, then \( L^* \) satisfies \( \text{Ext}_R^i(L^*,R) = 0 \) for \( i \neq 0 \).

Proof. (a) As all the modules \( P_j^* \) are finitely generated projective right \( R \)-modules, they satisfy necessarily \( \text{Ext}_R^i(P_j^*,R) = 0 \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to C \to B \to A \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by

\[
\cdots \to M_1 \to M_2 \to M_3 \to 0
\]

This is an exact sequence, so for each integer \( n \geq 0 \), we have natural isomorphisms \( \text{Ext}_R^i(M_x,R) = \text{Ext}_R^i(M_x,R) \) for \( i \neq 0 \). But this implies that for any integer \( n \geq 0 \) one has natural isomorphisms \( \text{Ext}_R^i(K_{j-n},R) \to \text{Ext}_R^{i+n}(K_j,R) \) for any \( i > 0 \). Since by
assumption $\Ext^k_R(-, R) = 0$ as soon as $k > d$, it suffices to take $n \geq d$ above to conclude $\Ext^1_R(K_j, R) = 0$ for all $i > 0$ and $j \geq 0$.

(b) This is a consequence of (a). By [A-B; 2.1.], for any left $R$-module $M$ the natural morphism $M \to M^{**}$ fits into an exact sequence

$$0 \to \Ext^1_R(D(M), R) \to M \to M^{**} \to \Ext^2_R(D(M), R) \to 0,$$

where $D(M) = \text{Cok } d^*_0$. But if $M$ is in $X$, we have $\text{Cok } d^*_0 = \text{Ker } d^*_2$ and (a) shows that the extreme terms of this exact sequence vanish, establishing (b).

(c) As $M^* = K_0$, part (a) implies that the sequence

$$(*) \quad 0 \to M^{**} \to Q^* \to L^* \to 0$$

is exact. From (b) we have $M \cong M^{**}$ and as $M$ is in $X$, it follows already that $\Ext^1_R(L^*, R) = 0$ for $i > 1$. It hence only remains to be seen that $\Ext^1_R(L^*, R) = 0$, or, equivalently, that the dual sequence of $(*)$:

$$0 \to L^{**} \to Q^{**} \to M^{***} \to 0$$

is again exact. But this is obvious as both $Q$ and $M^*$ are reflexive right $R$-modules and $p^{**} = p$.

Combining (b) and (c) of this lemma, we have now that any module $M$ in $X$ embeds into the finitely generated projective module $\text{Hom}_R(Q, R)$ and that the cokernel, isomorphic to $L^*$, is again in $X$. This shows that $\omega$ is indeed a cogenerator for $X$.

Finally observe that $\hat{X}$ consists of all left $R$-modules $N$ in $C$ satisfying $\Ext^1_R(N, R) = 0$ for all sufficiently large $i$, and that $\hat{\omega}$ is the category of all finitely generated left $R$-modules of finite projective dimension.

Now Theorem 1.1 yields in this context the following.

Theorem 1.8. Let $R$ be a ring which is noetherian on both sides and of finite injective dimension as a right module over itself. Then for any finitely generated left $R$-module $N$ satisfying $\Ext^1_R(N, R) = 0$ for all sufficiently large $i$, there are modules $Y_N$ and $Y^N$ in $R$-mod of finite projective dimension and modules $X_N$ and $X^N$ in $R$-mod with $\Ext^1_R(X_N, R) = \Ext^1_R(X^N, R) = 0$ for $i \neq 0$ which fit into exact sequences

$$0 \to Y_N \to X_N \to N \to 0$$

and

$$0 \to N \to Y^N \to X^N \to 0.$$
their uniqueness.

To see which conditions ought to be imposed, assume given two $X$-approximations for the same object $C$ in $\mathcal{X}$, say $0 \to Y_C \to X_C \to C \to 0$ and $0 \to Y'_C \to X'_C \to C \to 0$. Then the least one should ask for is that these $X$-approximations can be compared in the sense that there exists a morphism $\phi : X_C \to X'_C$ making the following diagram commutative

\[
\begin{array}{ccccccccc}
0 & \to & Y_C & \longrightarrow & X_C & \longrightarrow & C & \longrightarrow & O \\
\downarrow & & \downarrow & & \phi & & \downarrow & & \\
0 & \to & Y'_C & \longrightarrow & X'_C & \longrightarrow & C & \longrightarrow & O
\end{array}
\]

Apparently, the existence of such a comparison morphism is guaranteed as soon as $\text{Ext}_X^1(X_C,Y'_C) = 0$.

Hence, for comparisons to exist and to yield an equivalence relation, it certainly suffices to have that $\text{Ext}_X^1(X,Y) = 0$ for all $X$ in $\mathcal{X}$ and $Y$ in $\mathcal{Y}$. This section is devoted to a study of this condition and its consequences. First, once again, some general remarks and notations.

Let $A$ and $C$ be objects in $\mathcal{C}$. As $\mathcal{C}$ is supposed to be abelian, the groups $\text{Ext}_C^i(A,C)$ are defined for all $i \geq 0$. If there is an integer $n$ such that $\text{Ext}_C^i(A,C) = 0$ for all $i > n$, then the smallest nonnegative such integer $n$ is called the $A$-injective dimension of $C$, (notation: $A$-inj.dim$C$), or the $C$-projective dimension of $A$, (notation: $C$-proj.dim$A$).

Otherwise we set $A$-inj.dim$C = \infty = C$-proj.dim$A$. If $B$ is a subcategory of $\mathcal{C}$, for each $A$ in $\mathcal{C}$ we define $A$-inj.dim$B$ to be the maximum (in $\mathbb{Z} \cup \{\infty\}$) of $A$-inj.dim$B$ for all $B$ in $B$. Dually, for each $C$ in $\mathcal{C}$, we define $C$-proj.dim$B$ to be the maximum of $C$-proj.dim$B$ for all $B$ in $B$.

Clearly $A$-inj.dim$B = B$-proj.dim$A$.

Suppose now that $A$ and $B$ are subcategories of $\mathcal{C}$. Then define $A$-proj.dim$B$ to be the maximum of $A$-proj.dim$B$ for all $A$ in $A$ and $B$ in $B$. We define dually $A$-inj.dim$B$ to be the maximum of $A$-inj.dim$B$ for all $A$ in $A$ and $B$ in $B$. Again, one has clearly $A$-inj.dim$B = B$-proj.dim$A$.

If for two such subcategories $A$-inj.dim$B = 0 = B$-proj.dim$A$, we follow J.L. Verdier, [SGA 4½, C.D.; I.2.6.1.], and say that $A$ is left orthogonal to $B$ and $B$ is right orthogonal to $A$ - with respect to the "augmented" bilinear $\mathbb{Z}$-graded pairing induced by $(\text{Ext}_C^i(\cdot,\cdot))_{i \geq 0}$ on the monoid of isomorphism classes of objects of $\mathcal{C}$.

Consequently, if $A$ consists precisely of those objects $A$ in $C$ for which $A$-inj.dim$B = 0$, we call $A$ the left orthogonal complement of $B$ in $\mathcal{C}$, denoted $A = ^\perp B$. Dually again, $A^\perp$, the right orthogonal complement of $A$ in $\mathcal{C}$, is the subcategory of $\mathcal{C}$ consisting of all objects $B$ in $\mathcal{C}$ for which $A$-inj.dim$B = 0$.

One has obviously $A \subseteq ^\perp (A^\perp)$ and $A \subseteq (A^\perp)^\perp$, but not necessarily $^\perp (A^\perp) = (A^\perp)^\perp$. If $B'$ is a subcategory of $B$ in $\mathcal{C}$, then $^\perp B$ is contained in $^\perp B'$ and similiar for right orthogonal complements. Remark also that by definition $^\perp \mathcal{C}$, the left radical of $\mathcal{C}$ with respect to the pairing $(\text{Ext}_C^i(\cdot,\cdot))_{i \geq 0}$, consists precisely of all projective objects of $\mathcal{C}$.
whereas $C^\perp$, the right radical of $C$, is given by all injective objects of $C$.

Furthermore, it is obvious that orthogonal complements are additively closed and exact subcategories of $C$ and that in a left orthogonal complement $\mathcal{B}$ all epimorphisms are admissible, whereas in a right orthogonal complement $\mathcal{A}^\perp$ all monomorphisms are admissible.

Returning to our subcategories $\mathcal{X}$ and $\omega$ of $C$ from the previous section, we say that $\omega$ is a injective cogenerator for $\mathcal{X}$ if $\mathcal{X}$-inj.dim $\omega = 0$, that is, $\omega \subseteq \mathcal{X}^\perp$. If there is a cogenerator for $\mathcal{X}$ in $\mathcal{X} \cap \mathcal{X}^\perp$, we say also that the exact category $\mathcal{X}$ has enough relatively injective objects.

Unless stated to the contrary, we assume from now on that $\omega$ is an injective cogenerator for $\mathcal{X}$. Our next aim is to explore some important properties of $\mathcal{X}$-approximations and $\omega$-hulls implied by this additional assumption.

We begin with the following relations between some of the dimensions we have just introduced for an object $C$ in $\mathcal{X}$. These relations do not require that any epimorphism in $\mathcal{X}$ is admissible.

**Proposition 2.1.** Given an object $C$ in $\mathcal{X}$, where $\mathcal{X}$ is an additively closed exact subcategory of $C$ and $\omega$ is an injective cogenerator for $\mathcal{X}$, the following are equivalent for any integer $n \geq 0$.

(a) $\mathcal{X}$-resol.dim $C = n$,
(b) $C$-inj.dim $\omega = n$,
(c) $\mathcal{X}$-inj.dim $\omega = n$,
(d) $\text{Ext}^n_C(Y, C) = 0$ for all $Y$ in $\omega$.

**Proof:** Proceed by induction on $n = \mathcal{X}$-resol.dim $C$, the case $n = 0$ being settled as follows.
(a) $\Rightarrow$ (b) is true because $\omega$ is contained in $\mathcal{X}^\perp$ by assumption.
(b) $\Rightarrow$ (c) follows from the usual dimension shift argument.
(c) $\Rightarrow$ (d) is the definition of $\mathcal{X}$-inj.dim $\omega$.
(d) $\Rightarrow$ (a): Since $C$ is in $\mathcal{X}$ by the general hypothesis, there is an $\mathcal{X}$-approximation $0 \to Y_C \to X_C \to C \to 0$ which splits by (d). Hence $C$ is a direct summand of $X_C$ in $\mathcal{X}$ and so $C$ is in $\mathcal{X}$.

The proof of the inductive step follows easily from what we have just shown and is left to the reader. $\blacksquare$

As an obvious consequence of this proposition we have

**Corollary 2.2.** $\mathcal{X}$-inj.dim $\omega = 0$. $\blacksquare$

This corollary yields the following important properties of $\mathcal{X}$-approximations and $\omega$-hulls.
Theorem 2.3. Let \(0 \rightarrow Y \rightarrow X \rightarrow C \rightarrow 0\) be an \(X\)-approximation for \(C\) in \(\hat{X}\). Then for each \(X\) in \(\hat{X}\) we have

(a) \(0 \rightarrow \text{Hom}_{\hat{X}}(X,Y) \rightarrow \text{Hom}_{\hat{X}}(X,X) \rightarrow \text{Hom}_{\hat{X}}(X,C) \rightarrow 0\) is exact,
(b) \(\rho\) induces isomorphisms \(\text{Ext}_{\hat{X}}^i(X,Y) \rightarrow \text{Ext}_{\hat{X}}^i(X,C)\) for all \(i > 0\).

Proof: As \(X\)-inj.dim\(\otimes\) = 0, one has \(\text{Ext}_{\hat{X}}^i(X,Y) = 0\) for all \(i > 0\).

The exact sequence \(0 \rightarrow Y \rightarrow X \rightarrow C \rightarrow 0\) is called an \(X\)-approximation precisely because \(\text{Hom}_{\hat{X}}(X,X) \rightarrow \text{Hom}_{\hat{X}}(X,C) \rightarrow 0\) is exact for all \(X\) in \(\hat{X}\). This property of \(X\)-approximations of \(C\) gives rise to a weak sort of uniqueness for such approximations as we now explain.

Let us call two morphisms \(f:B \rightarrow C\) and \(f':B' \rightarrow C\) in \(C\) equivalent if there are morphisms \(g:B \rightarrow B'\) and \(h:B' \rightarrow B\) such that \(f = f'g\) and \(f = fh\). Also, we say that two exact sequences \(0 \rightarrow A \rightarrow B \rightarrow C\) and \(0 \rightarrow A' \rightarrow B' \rightarrow C\) are (right) equivalent, if \(f\) and \(f'\) are equivalent, which amounts to the same as saying that there is a commutative diagram

\[
\begin{array}{ccc}
0 & \rightarrow & A' \\
\downarrow & & \downarrow h \\
0 & \rightarrow & B' \\
& & \downarrow f \\
0 & \rightarrow & C
\end{array}
\]

In particular, \(\text{id}_A - hg\) factors over \(A\) and \(\text{id}_{A'} - gh\) factors over \(A'\), so that \(h,g\) become inverse isomorphisms in \(\text{C/\text{add}[A,A']}\).

As an immediate consequence of theorem 2.3 we obtain the following uniqueness result.

Corollary 2.4. \(X\)-approximations for an object \(C\) in \(\hat{X}\) are unique up to equivalence, that is, any two \(X\)-approximations for \(C\) are (right) equivalent exact sequences.

There are also similar results for \(\omega\)-hulls of an object \(C\) in \(\hat{X}\) as we now point out.

Theorem 2.5. Let \(0 \rightarrow C \rightarrow \gamma\rightarrow X \rightarrow 0\) be an \(\omega\)-hull for \(C\) in \(\hat{X}\). Then for each \(Y\) in \(\omega\) we have the following

(a) \(0 \rightarrow \text{Hom}_{\hat{X}}(\gamma,C) \rightarrow \text{Hom}_{\hat{X}}(Y,C) \rightarrow \text{Hom}_{\hat{X}}(C,Y) \rightarrow 0\) is exact,
(b) \(\rho\) induces isomorphisms \(\text{Ext}_{\hat{X}}^i(\gamma,C) \rightarrow \text{Ext}_{\hat{X}}^i(C,Y)\) for all \(i > 0\).

Proof: This follows again from the fact that \(X\)-inj.dim\(\otimes\) = 0.
gives rise to a weak sort of uniqueness for \( \hat{\omega} \)-hulls, similar to that already discussed for \( X \)-approximations, as we now explain.

Dually to the above, we say two morphisms \( f:C \to D \) and \( f':C \to D' \) are equivalent if there are morphisms \( g:D \to D' \) and \( h:D' \to D \) such that \( f' = gf \) and \( f = hf' \). Also, we say that two exact sequences \( C \to D \to E \to 0 \) and \( C \to D' \to E' \to 0 \) are (left) equivalent if \( f \) and \( f' \) are equivalent, which is the same thing as saying that there is a commutative diagram

\[
\begin{array}{ccc}
C & \xrightarrow{f} & D & \xrightarrow{g} & E & \to 0 \\
\downarrow & & \downarrow & & \downarrow & \\
C & \xrightarrow{f'} & D' & \xrightarrow{h} & E' & \to 0 \\
\downarrow & & \downarrow & & \downarrow & \\
C & \xrightarrow{f} & D & \xrightarrow{g} & E & \to 0
\end{array}
\]

In particular, \( \text{id}_D \circ g \) factors over \( E \) and \( \text{id}_{D'} \circ h \) factors over \( E' \), so that \( h \) and \( g \) become inverse isomorphisms in \( C/\text{add}\{E,E'\} \).

As an immediate consequence of theorem 2.5 we have the following uniqueness theorem.

**Corollary 2.6.** \( \hat{\omega} \)-hulls for an object \( C \) in \( \hat{X} \) are unique up to equivalence, that is, any two \( \hat{\omega} \)-hulls are (left) equivalent exact sequences.

We may reformulate and sharpen these uniqueness results slightly by considering the situation "modulo \( \omega \)". This depends on the following simple observation.

**Lemma 2.7.** Let \( f:X \to C \) be a morphism in \( C \) with \( X \) in \( X \) and \( C \) in \( \hat{X} \). Then the following conditions on \( f \) are equivalent.

(a) \( f \) factors through an object in \( \hat{\omega} \).

(b) \( f \) factors through an object in \( \omega \).

**Proof:** As (b) is a priori a special case of (a), we need only to show that in fact (a) implies (b). Hence assume that \( f = gh \) where \( h:X \to Y \) and \( g:Y \to C \) are morphisms in \( C \) and \( Y \) is in \( \hat{\omega} \). By definition of \( \hat{\omega} \), there is an exact sequence \( 0 \to K \to W \to Y \to 0 \) with \( W \) in \( \omega \) and \( K \) again in \( \hat{\omega} \). By corollary 2.2, \( X \)-inj.dim \( \hat{\omega} \) = 0 and so \( \text{Ext}^2_C(X,K) = 0 \). This shows that \( h \), and then also \( f \), factor over \( W \) in \( \omega \).

Now choose for any object \( C \) in \( \hat{X} \) an \( X \)-approximation

\[
0 \to Y_C \to X_C \xrightarrow{\pi_C} C \to 0 \text{ and an } \hat{\omega} \text{-hull } 0 \to C \xrightarrow{f_C} Y_C \to X_C \to 0,
\]

as well as for any morphism \( f:C \to D \) in \( \hat{X} \) liftings \( f:X_C \to X_0 \) and \( f':Y_C \to Y_0 \) which exist by the above.

By the uniqueness results just established, it follows that given a second morphism \( g:D \to E \) in \( \hat{X} \), the differences \( g^*f' - (gf)^* \) and \( g_*f. - (gf)_* \) factor over objects in \( \omega \), hence become zero-morphisms in \( \hat{X}/\omega \), the full subcategory spanned by \( \hat{X} \) in \( C/\omega \).
From this we obtain immediately the following

**Theorem 2.8.** Denote $i: \hat{\omega} \to \hat{X}$ and $j X \to \hat{X}$ the natural inclusion functors. Then

(a) The induced functor $j_1; \hat{\omega}/\omega \to \hat{X}/\omega$ is fully faithful and admits a *right adjoint* $j_1^1; \hat{X}/\omega \to X/\omega$ which associates to an object $C$ in $\hat{X}$ the chosen $X$-approximation $X_C$.

The adjunction morphism $j_1 j_1 C \to C$ is given by the class of $\pi_C; X_C \to C$ in $\text{Hom}_{\hat{X}/\omega}(X_C, C)$.

(b) The induced functor $i^1; \hat{\omega}/\omega \to \hat{X}/\omega$ is fully faithful and admits a *left adjoint* $i^1; \hat{X}/\omega \to \hat{\omega}/\omega$ which associates to an object $C$ in $\hat{X}$ the chosen $\omega$-hull $Y_C$. The adjunction morphism $C \to i^1 i^1 C$ is given by the class of $i^1; C \to Y_C$ in $\text{Hom}_{\hat{X}/\omega}(C, Y_C)$.

(c) One has $j_1^1 i^1 = 0$ and $i^1 j_1 = 0$.

(d) The composition of the adjunction morphisms

$$j_1 i^1 \longrightarrow \text{id}_{\hat{\omega}/\omega} \longrightarrow i^1 i^1$$

is zero in $\hat{X}/\omega$.

**Proof:** The remarks preceding the theorem show that $X_-$ and $Y_-$ define functors from $\hat{X}$ into $X/\omega$ and $\hat{\omega}/\omega$ respectively. By the universal property of quotient categories these functors factor over $X/\omega$, yielding $j_1$ and $i^1$. To prove that $j_1$ is indeed right adjoint to the inclusion functor $j_1; \hat{X}/\omega \to \hat{X}/\omega$, it suffices to give the natural isomorphisms $\phi_{X,C}: \text{Hom}_{\hat{X}/\omega}(X_j C) \cong \text{Hom}_{\hat{X}/\omega}(j_1 X, C)$. Now composition with $\pi_C; X_C \to C$ defines the natural map $\text{Hom}_{\hat{X}}(X, X_C) \to \text{Hom}_{\hat{X}}(X, C)$ which is surjective by theorem 2.3.(a). Let $\phi_{X,C}$ be the induced map on the quotient groups, which is hence still surjective. To prove that it is injective, let $f$ in $\text{Hom}_{\hat{X}}(X, X_C)$ be a morphism such that $\pi_C; X_C \to C$ factors over some object $W$ in $\omega$. This means that there is a commutative diagram in $C$

$$
\begin{array}{ccc}
O & \longrightarrow & Y_C \\
\downarrow f & & \downarrow g \\
X & \longrightarrow & W
\end{array}
$$

As $W$ is a priori in $X$ and $Y_C$ is in $\hat{\omega}$, corollary 2.2 applies once again to yield $\text{Ext}_C^1(W, Y_C) = 0$ and hence to establish the existence of a morphism $g'; W \to X_C$ such that $\pi_C g' = g$. But then $f-g'h$ satisfies $\pi_C(f-g'h) = \pi_C f-\pi_C g' h = gh = gh = 0$, so that $f-g'h$ factors over $Y_C$. Then lemma 2.7 shows that $f-g'h$ factors already over some object $W'$ in $\omega$ and hence the class of $f-g'h$ in $\text{Hom}_{\hat{X}/\omega}(X, X_C)$ is the zero-morphism. As $g'h$ factors over $W$ in $\omega$, its class is zero as well, which shows that $f$ and $f-g'h$ define the same morphism in $\text{Hom}_{\hat{X}/\omega}(X, X_C) = \text{Hom}_{\hat{X}/\omega}(X, j_1 C)$. Hence already the class of $f$ is the zero-morphism and $\phi_{X,C}$ is injective as claimed.

The definition of $\phi_{X,C}$ is natural in both arguments, so that the adjointness of $j_1$ and $j_1^1$ is established. Furthermore, the construction of $\phi_{X,C}$ shows that $\pi_C$ induces the adjunction morphism $j_1^1 j_1 C \to C$. 


This proves (a).
As the proof of (b) is completely analogous, it is left to the reader.
For (c), just remark again that by definition of \( \hat{\omega} \), any object \( Y \) in \( \hat{\omega} \) appears in an exact sequence \( 0 \to K \to W \to Y \to 0 \) with \( W \) in \( \omega \) and \( K \) in \( \hat{\omega} \). But this sequence serves as an \( X \)-approximation for \( Y \) whence \( j^! \mathcal{I} Y \), the chosen \( X \)-approximation of \( Y \), is isomorphic to \( W \) in \( X/\omega \), i.e. it is a zero object. This shows \( j^! \mathcal{I} \mathcal{I} = 0 \) and \( i^* j_! = 0 \) follows then by adjunction.
(d) follows now from (c), as one has by naturality the commutative diagram of morphisms of functors

\[
\begin{array}{ccc}
Jj^! & \xrightarrow{\pi} & \text{Id}_{X/\omega} \\
\downarrow \quad \iota^*(j^!j_!) & & \downarrow \iota \\
I_i^*j_i^!j_i^! & \xrightarrow{\pi_c} & \iota_i^* \\
\end{array}
\]

in which the lower left corner is zero by (c). (In more concrete terms, (d) says that for any object \( C \) in \( \hat{\mathfrak{X} \mathfrak{X}} \) there is a commutative diagram

\[
\begin{array}{ccc}
X_C & \xrightarrow{\pi_c} & C \\
\downarrow J & & \downarrow j^c \\
W & \longrightarrow & Y^c
\end{array}
\]

with \( W \) in \( \omega \), and we have seen indeed in lemma 1.3 and the proof of theorem 1.1 that \( j^c \) can be obtained as the push-out of such a morphism \( j \) along \( \pi_c \).) This finishes the proof of theorem 2.8. □

The reader puzzled by the notations used in the preceding theorem should compare it with the treatment of the "glueing of categories" in [BBD; 1.4]. It shows that in our situation one should think of \( \hat{\mathfrak{X} \mathfrak{X}} \) as being obtained by "glueing together the open subcategory \( X \) and the closed subcategory \( \hat{\omega} \) along \( \omega \)". What is missing for a complete glueing in the sense of (loc. cit.) is the existence of the other adjoints \( j^* \) and \( i^! \).

The statements (c) and (d) in theorem 2.8 also explain why we think of theorem 1.1 as a "decomposition theorem": an object \( C \) in \( \hat{\mathfrak{X} \mathfrak{X}} \) is decomposed - at least in \( \hat{\mathfrak{X} \mathfrak{X}}/\omega \) - into its \( X \)-approximation \( X_C \) and its \( \hat{\omega} \)-hull \( Y^c \), which belong to "orthogonal" subcategories of \( \hat{\mathfrak{X} \mathfrak{X}}/\omega \).

The property which is desirable but missing yet is that \( X \) and \( \hat{\omega} \) should have \( \omega \) as their common intersection. This will be addressed later on in Proposition 3.6.

For now, we return to the examples 1 and 2 of the previous section. As soon as \( X \to \text{Spec } k \) is projective, \( \omega_X \) is not an injective generator in either \( X \) or \( X' \), as \( \text{Ext}_X^d(\omega_X, \omega_X \otimes L^\otimes n) = H^d(X, \omega_X \otimes L^\otimes n) \) does not vanish for all integers \( n \). None the less, the following analogues of the results for injective cogenerators are valid for these examples if one substitutes \( \mathcal{E} \text{xt}_{\mathcal{O}_X}^d(A, B) \) for \( \text{Ext}_{\mathcal{O}_X}^d(A, B) \).
Lemma 2.9. With notations as in examples 1 and 2, the following are equivalent for a sheaf \( M \) in \( C \).

(a) \( M \) is in \( X \).

(b) \( \operatorname{Ext}^i_{O_X}(M, \omega_X) = 0 \) for all \( i > 0 \).

(c) \( \operatorname{Ext}^i_{O_X}(M, \omega_X \otimes \mathcal{O}_X^n) = 0 \) for all \( i > 0 \) and all \( n \) in \( \mathbb{Z} \).

(d) \( \operatorname{Ext}^i_{O_X}(M, Y) = 0 \) for all \( i > 0 \) and \( Y \) in \( \omega_X \).

Proof: Easy consequence of the fact that the corresponding statements hold for Cohen-Macaulay local rings with a dualizing module.

Proposition 2.10. With the same assumptions and notations as above, let

\[
0 \to Y \to X \to C \to 0
\]

be an \( X \)-approximation for \( C \) in \( C \).

Then we have for any \( M \) in \( X \):

(a) \( 0 \to \operatorname{Hom}_{O_X}(M, Y) \to \operatorname{Hom}_{O_X}(M, X) \to \operatorname{Hom}_{O_X}(M, C) \to 0 \) is exact.

(b) The induced morphisms \( \operatorname{Ext}^i_{O_X}(M, Y) \to \operatorname{Ext}^i_{O_X}(M, X) \) are isomorphisms for \( i > 0 \).

Proof: Immediate consequence of lemma 2.7.

Remark that in Example 3 the category \( \omega \) is in fact an injective cogenerator as by definition there \( X = \omega \). Furthermore, in that example \( X/\omega \) is the category of left maximal Cohen-Macaulay \( R \)-modules - in the sense that \( \operatorname{Ext}^i_{\mathfrak{m}}(M, R) = 0 \) for \( i \neq 0 \) - modulo stable equivalence: two modules \( M \) and \( M' \) from \( X \) become isomorphic in \( X/\omega \) if and only if there are finitely generated projective left \( R \)-modules \( P \) and \( P' \) such that \( M \oplus P = M' \oplus P' \) is isomorphic to \( M' \oplus P \) in \( R\text{-mod} \).

We end this section with two more illustrations of situations where \( \omega \) is an injective cogenerator for \( X \).

Example 4. Suppose \( R \) is a commutative noetherian Cohen-Macaulay ring in the sense that all its localizations \( R_\mathfrak{p} \) at primes \( \mathfrak{p} \) are local Cohen-Macaulay rings. We say that a finitely generated \( R \)-module \( M \) is maximal Cohen-Macaulay (MCM for short), if \( M_\mathfrak{p} \) satisfies depth \( \dim R_\mathfrak{p} = \dim R \) for all primes \( \mathfrak{p} \).

Now suppose that \( R \) is a Gorenstein ring and that \( S \) is a commutative \( R \)-algebra which is MCM as an \( R \)-module. Let \( C = S\text{-mod} \) be the category of finitely generated \( S \)-modules and let \( X \) be the subcategory of \( C \) consisting of those \( S \)-modules \( M \) which are maximal Cohen-Macaulay as \( R \)-modules. Then \( X \) satisfies the usual properties. Set \( \omega_{S/R} = \operatorname{Hom}_R(S, R) \), which is a relative dualizing module for the algebra \( R \to S \). Then \( \omega = \operatorname{add}(\omega_{S/R}) \) consists of all \( S \)-modules of the form \( \operatorname{Hom}_R(P, R) \) with \( P \) finitely generated projective over \( S \). It is easily seen - and well-known - that \( \omega \) is an injective cogenerator for \( X \).

To acknowledge the scope of this example and to emphasize its relevance for Grothendieck duality theory, we quote the following from [FGR; Cor. 5.9].
Theorem. Suppose $S$ is a commutative ring with finite Krull dimension and with connected prime spectrum. Then $S$ admits a canonical module if and only if $S$ is a homomorphic image of a Gorenstein ring $R$ such that $S$ is maximal Cohen-Macaulay as an $R$-module.

Our final illustration of this section is the following variant of Examples 4 and 2.

Example 5. Maintain the hypotheses on $S$ and $R$ from Example 4. Let $X \subset \text{Spec } R$ have the property that if $p$ is in $X$, then $S_p$ is a Gorenstein ring, or equivalently, $(\omega_{S/R})_p$ is $S_p$-free.

Set again $C = S\text{-mod}$ and let $X'$ consist of those $S$-modules $M$ which are MCM over $R$ and satisfy furthermore that $M_p$ is $S_p$-projective for all $p$ in $X$. Then $X'$ satisfies the usual properties and contains $\omega = \text{add}(\omega_{S/R})$. Again, $\omega$ is an injective cogenerator for $X'$ and $\tilde{X}'$ consists of all $S$-modules $C$ such that $\text{proj.dim}_{S_p} C_p < \infty$ for all $p$ in $X$.

§3. Exactness properties of $X$ and $\omega$.

We maintain our general assumption that $X$ is an additively closed and exact subcategory of $C$ in which every epimorphism is admissible, and that $\omega$ is an injective cogenerator for $X$.

In this situation, we show that $\tilde{X}$ is an additively closed subcategory of $C$ which has the property that an exact sequence $0 \to A \to B \to C \to 0$ is in $\tilde{X}$ whenever two of $A$, $B$ and $C$ are in $\tilde{X}$. This result is then used to prove that $\hat{\omega}$ is an additively closed subcategory of $C$ having the property that an exact sequence $0 \to A \to B \to C \to 0$ in $C$ is already in $\hat{\omega}$ if either $A$ and $C$ are in $\hat{\omega}$ or $A$ and $B$ are in $\hat{\omega}$. Hence $\hat{\omega}$ is seen to be an additively closed exact subcategory of $C$ in which every monomorphism is admissible.

We begin with the following

Lemma 3.1. The category $\tilde{X}$ is closed under extensions.

Proof: Suppose $0 \to A \to B \to C \to 0$ is an exact sequence in $C$ with $A$ and $C$ in $\tilde{X}$. Proceed by induction on $n = \text{resol dim}_C$. Suppose $n = 0$, which means that $C$ is in $\tilde{X}$. As $A$ is in $\tilde{X}$, there is an $\tilde{X}$-approximation $0 \to Y_A \to X_A \to A \to 0$ of $A$. Since $C$ is in $\tilde{X}$, we know by theorem 2.3, that the induced map $\text{Ext}_C^1(C,X_A) \to \text{Ext}_C^1(C,A)$ is an isomorphism. Hence there exists an exact commutative diagram
Since $X_A$ and $C$ are in $X$, the object $Z$ is also in $X$, as that category is closed under extensions. Now $Y_A$ is in $\hat{\mathcal{F}}$, hence in $\check{\mathcal{F}}$, and it follows that $B$ is in $\check{\mathcal{F}}$ as required.

Suppose now that $n > 0$ and let $0 \to L \to X_0 \to C \to 0$ be exact with $X$-resol.dim$L = n-1$. Since $X_0$ is in $X$, we have that $\text{Ext}_C^1(X_0, X_A) \to \text{Ext}_C^1(X_0, A)$ is an isomorphism by theorem 2.3, and so there exists an exact commutative diagram in $C$

\[
\begin{array}{ccccccccc}
& & & & & & & & & \\
& & & & & & & & & \\
& & & & & & & & & \\
& & & & & & & & & \\
& & & & & & & & & \\
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& & & & & & & & & \\
& & & & & & & & & \\
& & & & & & & & & \\
\end{array}
\]

This shows that $B$ is in $\check{\mathcal{F}}$ since $V$ is necessarily in $X$ and $U$ is in $\check{\mathcal{F}}$ by the inductive hypothesis.

We now use the fact that $\check{\mathcal{F}}$ is closed under extensions to prove the following

**Lemma 3.2.** Let $0 \to K \to X \to C \to 0$ be an exact sequence in $C$ with $X$ in $\mathcal{X}$. Then $C$ is in $\check{\mathcal{F}}$ if and only if $K$ is in $\check{\mathcal{F}}$.

**Proof:** By definition, if $K$ is in $\check{\mathcal{F}}$ then also $C$ is in $\check{\mathcal{F}}$. Hence assume that $C$ is in $\check{\mathcal{F}}$ and let $0 \to Y_C \to X_C \to C \to 0$ be an $X$-approximation of $C$. Since $X$ is in $\mathcal{X}$, we have by theorem 2.3 that $\text{Hom}_C(X, X_C) \to \text{Hom}_C(X, C)$ is surjective. Therefore we obtain a commutative exact diagram
Since $Y_C$ is in $\hat{\omega}$, we know there is an epimorphism $W \to Y_C$ with $W$ in $\omega$. Adding this epimorphism to the foregoing diagram, we obtain the following commutative exact diagram

$$
\begin{array}{c}
\text{O} \quad \text{O} \\
\downarrow \quad \downarrow \\
\text{Y} \quad \text{V} \\
\downarrow \quad \downarrow \\
\text{K} \otimes W \quad \text{X} \otimes W \\
\downarrow \quad \downarrow \\
\text{Y}_C \quad \text{X}_C \\
\downarrow \quad \downarrow \\
\text{O} \quad \text{O}
\end{array}
$$

where $K \otimes W \to X \otimes W$ is the sum of $K \to X$ and the identity on $W$. Since $W$ and $X$ are both in $\hat{\mathbf{X}}$, we have that $V$ is in $\mathbf{X}$, as any epimorphism of $C$ in $\mathbf{X}$ is admissible by assumption. Therefore $K \otimes W$ is in $\hat{\mathbf{X}}$, since $Y_C$ and $V$ are in $\hat{\mathbf{X}}$ and $\hat{\mathbf{X}}$ is closed under extensions. We now show that this implies that $K$ is in $\hat{\mathbf{X}}$. Since $K \otimes W$ is in $\hat{\mathbf{X}}$, we obtain the following exact commutative diagram from an $\mathbf{X}$-approximation of $K \otimes W$

$$
\begin{array}{c}
\text{O} \quad \text{O} \\
\downarrow \quad \downarrow \\
\text{O} \quad \text{Y}_{K \otimes W} \\
\downarrow \quad \downarrow \\
\text{W} \quad \text{K} \otimes W \\
\downarrow \quad \downarrow \\
\text{O} \quad \text{O}
\end{array}
$$

Hence we have the exact sequence $0 \to Y_{K \otimes W} \to Z \to W \to 0$. Since $W$ and $Y_{K \otimes W}$ are in $\hat{\mathbf{X}}$, (in fact already in $\hat{\omega}$, and $\hat{\mathbf{X}}$ is closed under extensions, we have that $Z$ is in $\hat{\mathbf{X}}$ as well. This implies that $K$ is in $\hat{\mathbf{X}}$ since $X_{K \otimes W}$ is in $\mathbf{X}$. This completes the proof of the lemma.
We now apply the foregoing lemma to prove

**Proposition 3.3.** Suppose $C$ is an object in $\mathbf{X}$. Then the following are equivalent for any integer $n \geq 0$:

(a) $\mathbf{X}$-resol.dim$C \leq n$,

(b) If $0 \to U \to X_{n-1} \to \ldots \to X_0 \to C \to 0$ is exact with $X_i$ in $\mathbf{X}$ for $i = 0, \ldots, n-1$, then $U$ is in $\mathbf{X}$.

**Proof:** For $n = 0$ there is nothing to prove. So suppose $n > 0$. Assuming (a), repeated application of lemma 3.2 shows that $U$ is in $\mathbf{X}$. Also we have $\operatorname{Ext}^1_C(U, W) = \operatorname{Ext}^n_C(C, W) = 0$ for all $W$ in $\omega$ since $\mathbf{X}$-inj.dim$\omega = 0$ and $\mathbf{X}$-resol.dim$C \leq n$. Therefore by proposition 2.1, it follows that $U$ is in $\mathbf{X}$ proving that (a) implies (b). As (a) follows from (b) by definition of $\mathbf{X}$-resol.dim$C$, we are done. $\blacksquare$

As a first application of this proposition we prove the following

**Proposition 3.4.** $\mathbf{X}$ is an additively closed subcategory of $\mathbf{C}$, that is $\mathbf{X} = \operatorname{add} \mathbf{X}$.

**Proof:** Suppose $C_1 \oplus C_2$ is in $\mathbf{X}$ for two objects $C_1$ and $C_2$ in $\mathbf{C}$. Proceed by induction on $n = \mathbf{X}$-resol.dim$(C_1 \oplus C_2)$. If $n = 0$, the summands $C_1$ and $C_2$ are in $\mathbf{X}$ as $\mathbf{X}$ is an additively closed subcategory of $\mathbf{C}$. Suppose $n > 0$. Since $C_1 \oplus C_2$ is in $\mathbf{X}$, there is an epimorphism $X \to C_1 \oplus C_2 \to 0$ with $X$ in $\mathbf{X}$. Therefore we obtain exact sequences $0 \to L_i \to X \to C_i \to 0$ for $i = 1, 2$ which yield the exact sequence $0 \to L_1 \oplus L_2 \to X \oplus X \to C_1 \oplus C_2 \to 0$. Now by Lemma 3.2, we know that $L_1 \oplus L_2$ is in $\mathbf{X}$ and proposition 3.3 shows that $\mathbf{X}$-resol.dim$(L_1 \oplus L_2) \leq n-1$. By the inductive hypothesis $L_1$ and $L_2$ are in $\mathbf{X}$ and another application of lemma 3.2 shows that then also $C_1$ and $C_2$ are in $\mathbf{X}$. $\blacksquare$

We are now in position to establish one of the results promised in the beginning of this section.

**Proposition 3.5.** An exact sequence $0 \to A \to B \to C \to 0$ from $\mathbf{C}$ is in $\mathbf{X}$ if any two of $A$, $B$ and $C$ are in $\mathbf{X}$.

**Proof:** Since we already know that $\mathbf{X}$ is closed under extensions by lemma 3.1, it suffices to show that if $B$ is in $\mathbf{X}$ then $A$ is in $\mathbf{X}$ if and only if $C$ is in $\mathbf{X}$. We first show that if $A$ and $B$ are in $\mathbf{X}$ then $C$ is in $\mathbf{X}$. Choose an $\mathbf{X}$-approximation $0 \to Y_b \to X_b \to B \to 0$ for $B$. It gives rise to an exact commutative diagram
from which we get an exact sequence \( 0 \rightarrow Y_B \rightarrow L \rightarrow A \rightarrow 0 \). It follows that \( L \) is in \( \hat{X} \) since \( Y_B \) and \( A \) are in \( \hat{X} \) and \( \hat{X} \) is closed under extensions. Therefore \( C \) is in \( \hat{X} \) since \( X_B \) is in \( X \).

Suppose now that \( B \) and \( C \) are in \( \hat{X} \). Using lemma 3.2, the exact sequence \( 0 \rightarrow L \rightarrow X_B \rightarrow C \rightarrow 0 \) from (*) shows that \( L \) is in \( \hat{X} \). Applying the just established result to the exact sequence \( 0 \rightarrow Y_B \rightarrow L \rightarrow A \rightarrow 0 \), it follows that \( A \) is in \( \hat{X} \). This completes the proof of the proposition.

We now turn our attention to \( \omega \). We begin with the characterization of \( \omega \) as a subcategory of \( \hat{X} \), proving that \( \omega = X \bot \cap \hat{X} \) in \( C \).

**Proposition 3.6.** The following statements are equivalent for an object \( C \) in \( \hat{X} \).

(a) \( C \) is in \( \omega \).
(b) \( X\text{-inj.dim } C = 0 \), that is: \( C \) is in \( X \bot \cap \hat{X} \).
(c) If \( 0 \rightarrow Y_C \rightarrow X_C \rightarrow C \rightarrow 0 \) is any \( X \)-approximation of \( C \), then \( X_C \) is in \( \omega \).

**Proof:** That (a) implies (b) was seen in corollary 2.2, and it is obvious that (c) implies (a). Hence we only need to show that (b) implies (c).

Since \( X\text{-inj.dim } C = 0 = X\text{-inj.dim } Y_C \), it follows that \( X\text{-inj.dim } X_C = 0 \). Our desired result is therefore a trivial consequence of the following, which proves \( \omega = X \cap \omega \).

**Lemma 3.7.** The following are equivalent for an object \( X \) in \( X \).

(a) \( X \) is in \( \omega \).
(b) \( X \) is in \( \hat{\omega} \).
(c) \( X\text{-inj.dim } X = 0 \).

**Proof:** Again it is obvious that (a) implies (b), and Corollary 2.2 shows that (b) implies (c). It remains to prove

(c) \( \Rightarrow \) (a): Let \( 0 \rightarrow X \rightarrow W \rightarrow X' \rightarrow 0 \) be an exact sequence in \( X \) with \( W \) in \( \omega \) which exists as \( \omega \) is a cogenerator for \( X \). Then by (c) this sequence splits. Therefore \( X \) is a direct summand of \( W \) which implies that \( X \) is in \( \omega \) as that category is assumed to be additively closed.

This establishes lemma 3.7 and finishes the proof of proposition 3.6.
These results prove the following fact, already announced in the introduction to this section.

**Proposition 3.8.** $\mathcal{U}$ is an additively closed and exact subcategory of $C$ in which any monomorphism is admissible. In more detail, let $0 \to A \to B \to C \to 0$ be an exact sequence in $C$. Then

(a) $B$ is in $\mathcal{U}$ if $A$ and $C$ are in $\mathcal{U}$, and

(b) $C$ is in $\mathcal{U}$ if $A$ and $B$ are in $\mathcal{U}$.

**Proof:** We know by now that $\mathcal{U} = X^\perp \cap \hat{X}$ in $C$. But the statements hold for $\hat{X}$ by propositions 3.4 and 3.5, and as $X^\perp$ is a right orthogonal complement, it also is an additively closed and exact subcategory of $C$ in which every monomorphism is admissible. As all these properties are stable under intersection in $C$, the result for $\mathcal{U}$ follows. 

We sum up the foregoing results as

**Theorem 3.9.** Let $X$ be an additively closed and exact subcategory of an abelian category $C$. Assume that

(i) all epimorphisms from $C$ in $X$ are admissible, and

(ii) $X$ has enough relatively injective objects.

Let $\omega$ be an injective cogenerator for $X$. Then there results a diagram of additively closed and exact subcategories of $C$

\[
\begin{array}{ccc}
X & \longrightarrow & \hat{X} & \longrightarrow & C \\
\uparrow & & \uparrow & & \uparrow \\
\omega & \longrightarrow & \hat{\omega} & \longrightarrow & X^\perp
\end{array}
\]

such that

(a) each square is cartesian, i.e.: $\hat{\omega} = \hat{X} \cap X^\perp$ and $\omega = X \cap X^\perp$,

(b) in $\hat{X}$ all mono- or epimorphisms from $C$ are admissible,

(c) in $X^\perp$ and $\hat{\omega}$ all monomorphisms from $C$ are admissible.

In particular, there is a unique injective cogenerator $\omega$ for $X$ in $C$, namely $\omega = X \cap X^\perp$.

To reformulate it once again modulo $\omega = X \cap X^\perp$, let us say that a sequence $0 \to A \to B \xrightarrow{p} C \to 0$ of additive functors between additive categories is exact if and only if $A$ is a full, essential and additively closed subcategory of $B$ and $p$ is equivalent to the projection functor $\pi : B \to B/A$.

With the notations of theorem 2.8 we have then the following
Corollary 3.10. The adjoint pairs of functors \((i^*, i_*)\) and \((j_!, j^!)\) fit into the commutative diagram of exact sequences of additive categories

\[
\begin{array}{ccccccccc}
0 & \rightarrow & \hat{\omega}/\omega & \rightarrow & \hat{X}/\omega & \rightarrow & X/\omega & \rightarrow & 0 \\
& & \downarrow & & \downarrow & & \downarrow & & \\
0 & \rightarrow & \hat{\omega}/\omega & \rightarrow & \hat{X}/\omega & \rightarrow & X/\omega & \rightarrow & 0
\end{array}
\]

§4. The category \(\hat{\omega}\).

Our aim in this section is to describe under which assumptions \(\hat{\omega}\) has the further property that an exact sequence \(0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0\) is in \(\hat{\omega}\) if \(B\) and \(C\) are in \(\hat{\omega}\).

To investigate this problem, we first define \(\hat{\omega}\) to be the subcategory of \(C\) consisting of all objects \(C\) in \(C\) which appear in an exact sequence

\(0 \rightarrow C \rightarrow Y_0 \rightarrow \ldots \rightarrow Y_n \rightarrow 0\)

with each \(Y_i\) in \(\hat{\omega}\). Clearly such an object \(C\) is in \(\hat{\omega}\) since the \(Y_i\) are in \(\hat{\omega} \subseteq \hat{\omega}\) and the kernel of an epimorphism in \(\hat{\omega}\) is again in \(\hat{\omega}\) by proposition 3.5. Also it is obvious that \(\hat{\omega}\) is a subcategory of \(\hat{\omega}\).

Lemma 4.1. The following statements are equivalent:
(a) An exact sequence \(0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0\) is in \(\hat{\omega}\) if \(B\) and \(C\) are in \(\hat{\omega}\).
(b) \(\hat{\omega} = \omega\).

The proof is trivial. \(\blacksquare\)

This simple observation explains the relevance of the category \(\hat{\omega}\) to our problem about \(\hat{\omega}\). The following description of \(\hat{\omega}\) is basic to the results in this paragraph.

Proposition 4.2. For an object \(C\) in \(\hat{\omega}\) the following are equivalent:
(a) \(C\) is in \(\hat{\omega}\),
(b) \(X\)-inj.dim \(C < \infty\).

Proof: (a) \(\Rightarrow\) (b). Let \(0 \rightarrow C \rightarrow Y_0 \rightarrow \ldots \rightarrow Y_n \rightarrow 0\) be exact with each \(Y_i\) in \(\hat{\omega}\). Since \(X\)-inj.dim \(\hat{\omega} = 0\), it follows by induction on \(n\) that \(X\)-inj.dim \(C \leq n < \infty\).

(b) \(\Rightarrow\) (a): Since \(C\) is in \(\hat{\omega}\), it admits an \(\hat{\omega}\)-hull \(0 \rightarrow C \rightarrow Y^C \rightarrow X^C \rightarrow 0\). The assumption that \(X\)-inj.dim \(C < \infty\) and the fact that \(X\)-inj.dim \(Y^C = 0\) imply that \(X\)-inj.dim \(X^C < \infty\). Therefore if we show that an object \(X\) from \(X\) which satisfies \(X\)-inj.dim \(X < \infty\) is necessarily in \(\hat{\omega}\), we will be done. Indeed we have the following more specific result.

Lemma 4.3. Let \(X\) be an object in \(X\), \(n\) a nonnegative integer. Then \(X\)-inj.dim \(X \leq n\) if and only if there is an exact sequence \(0 \rightarrow X \rightarrow W_0 \rightarrow W_1 \rightarrow \ldots \rightarrow W_n \rightarrow 0\) with \(W_i\) in \(\omega\) for \(i = 0, \ldots, n\).
Proof: The if-part follows as before from $\mathbf{X}\text{-inj.dim } \omega = 0$. Hence suppose that $\mathbf{X}\text{-inj.dim } X = n$. Since $\omega$ is a cogenerator for $\mathbf{X}$, we can construct an exact sequence

$$0 \to X \to W_0 \to \cdots \to W_{n-1} \to X' \to 0$$

in $\mathbf{X}$ such that each $W_i$ is in $\omega$ for $i = 0, \ldots, n-1$. As $\mathbf{X}\text{-inj.dim } \omega = 0$ and $\mathbf{X}\text{-inj.dim } X \leq n$ by assumption, it follows that for any integer $i > 0$ and all objects $Z$ in $\mathbf{X}$ one has $\text{Ext}^i_C(Z,X') \cong \text{Ext}^i_C(Z,X) = 0$. But by lemma 3.7 this shows that $X'$ is already in $\omega$ as desired.

This concludes the proof of lemma 4.3 and proposition 4.2.

As a first application we get the following.

**Corollary 4.4.** $\tilde{\omega}$ is an additively closed subcategory of $\mathbf{C}$ with the property that an exact sequence $0 \to A \to B \to C \to 0$ is in $\tilde{\omega}$ if any two of $A$, $B$ and $C$ are in $\tilde{\omega}$.

**Proof:** Since $\mathbf{X}$ is additively closed, it contains with $\omega$ also $\text{add } \omega$. It then follows from proposition 4.2 that $\omega = \text{add } \omega$. Also if $0 \to A \to B \to C \to 0$ is an exact sequence in $\mathbf{C}$ with two of $A$, $B$ and $C$ in $\tilde{\omega}$, then all of $A$, $B$ and $C$ are in $\mathbf{X}$ by Proposition 3.5. It then follows from proposition 4.2 that they are all in $\tilde{\omega}$.

As another immediate consequence of proposition 4.2 we get the following.

**Corollary 4.5.** The following are equivalent:

(a) $\tilde{\omega} = \omega$.

(b) If $C$ is an object in $\mathbf{X}$ with $\mathbf{X}\text{-inj.dim } C < \infty$, then $\mathbf{X}\text{-inj.dim } C = 0$.

**Proof:** Let $C$ be in $\mathbf{X}$. By proposition 4.2 we have that $C$ is in $\tilde{\omega}$ if and only if $\mathbf{X}\text{-inj.dim } C < \infty$. By Proposition 3.6 we have that $C$ is in $\tilde{\omega}$ if and only if $\mathbf{X}\text{-inj.dim } C = 0$.

Hence the equivalence of (a) and (b).

We now give criteria for the property $\tilde{\omega} = \omega$ in terms of the categories $\omega$ and $\mathbf{X}$ themselves.

**Proposition 4.6.** The following are equivalent:

(a) $\tilde{\omega} = \omega$.

(b) If $0 \to C \to W_0 \to W_1 \to 0$ is exact in $\mathbf{C}$ with $W_0$ and $W_1$ in $\omega$, then $C$ is in $\omega$.

(c) If $0 \to C \to W_0 \to W_1 \to \cdots \to W_n \to 0$ is exact with each $W_i$ in $\omega$ for $i = 0, \ldots, n$, then $C$ is in $\omega$.

(d) If $X$ is in $\mathbf{X}$ and $\mathbf{X}\text{-inj.dim } X < \infty$, then $X$ is in $\omega$.

**Proof:** (a) $\Rightarrow$ (b). Since $W_0$ and $W_1$ are objects in $\omega$, they are in $\mathbf{X}$, so $C$ is in $\mathbf{X}$. Clearly $C$ is in $\tilde{\omega}$ which means by the assumption that it is in $\tilde{\omega}$. Therefore $C$ is in $\mathbf{X} \cap \tilde{\omega}$ which category equals $\omega$ by Lemma 3.7.

(b) $\Rightarrow$ (c) by induction on $n$.

(c) $\Rightarrow$ (d). Suppose $X$ is in $\mathbf{X}$ with $\mathbf{X}\text{-inj.dim } X < \infty$. Then by Lemma 4.3, we know there
is an exact sequence $0 \twoheadrightarrow X \rightarrow W_0 \rightarrow \ldots \rightarrow W_n \rightarrow 0$ with $W_i$ in $\omega$ for $i = 0, \ldots, n$.

Therefore by (c) we have that $X$ is in $\omega$.

(d) $\Rightarrow$ (a). Let $C$ be an object in $\omega$. Then we can choose an $X$-approximation $0 \twoheadrightarrow Y_C \rightarrow X_C \rightarrow C \rightarrow 0$ for $C$ and proposition 4.2 shows that $X$-inj.dim $C < \infty$. But $X$-inj.dim $Y_C = 0$ so that $X$-inj.dim $X_C < \infty$. Therefore $X_C$ is in $\omega$ by the hypothesis (d), which shows that $C$ is in $\omega$.

Now we establish the following.

**Proposition 4.7.** Let $C$ be an object in $\omega$. Then $\omega$-inj.dim $C = X$-inj.dim $C$.

**Proof:** Since $\omega$ is a subcategory of $X$, we have that always $\omega$-inj.dim $C \leq X$-inj.dim $C$. So it suffices to show that $\omega$-inj.dim $C \geq X$-inj.dim $C$. As $C$ is in $\omega$ by assumption, we also know from proposition 4.2 that $X$-inj.dim $C$ is finite.

To begin with, we prove the proposition when $C = X$ is an object in $X \cap \omega$. By lemma 4.3, we have that then there is an exact sequence $0 \twoheadrightarrow X \rightarrow W_0 \rightarrow \ldots \rightarrow W_n \rightarrow 0$ with each $W_i$ in $\omega$ for $i = 0, \ldots, n$. Assume that $\omega$-inj.dim $X = 0$. Since $\omega$-inj.dim $\omega = 0$, it follows by induction on $n$ that the exact sequence $0 \twoheadrightarrow X \rightarrow W_0 \rightarrow \ldots \rightarrow W_n \rightarrow 0$ splits. Hence $X$ is already in $\omega$ which implies $X$-inj.dim $X = 0$. This result shows furthermore that $\omega$-inj.dim $X \leq n$ if and only if there is an exact sequence $0 \twoheadrightarrow X \rightarrow W_0 \rightarrow \ldots \rightarrow W_n \rightarrow 0$ with each $W_i$ in $\omega$. But we have seen in lemma 4.3 that the existence of such an exact sequence is equivalent to $X$-inj.dim $X \leq n$. Hence we have shown that $\omega$-inj.dim $C = X$-inj.dim $C$ when $C$ is in $X \cap \omega$.

Assume now that $C$ is an arbitrary object in $\omega$. Let $0 \twoheadrightarrow C \rightarrow Y^C \rightarrow X^C \rightarrow 0$ be an $\omega$-hull of $C$. Since $C$ and $Y^C$ are in $\omega$ by assumption, we get that $X^C$ is in $\omega$ by corollary 4.4. Suppose now $\omega$-inj.dim $C = 0$. Then also $\omega$-inj.dim $X^C = 0$ which implies that $X^C$ is in $\omega$ by our previous result. But our current hypothesis then implies that Ext$_{X^C}(X^C, C) = 0$, which means that the chosen $\omega$-hull of $C$ splits. So $C$ is a direct summand of $X^C$ in $\omega$ and is hence itself in $\omega$, as $\omega$ is additively closed by proposition 3.8. Therefore $X$-inj.dim $C = 0$ by corollary 2.2 and we are done in this case.

Finally suppose $\omega$-inj.dim $C = n > 0$. Since $\omega$-inj.dim $Y^C = 0$, it follows that $\omega$-inj.dim $X^C = n - 1$. Therefore $X$-inj.dim $X^C = n - 1$ by our first result, which implies that $X$-inj.dim $C \leq n$. Hence $\omega$-inj.dim $C \geq X$-inj.dim $C$ for all $C$ in $\omega$, which completes the proof of the proposition.

The following is an immediate consequence of our earlier results and summarizes sufficient conditions for $\omega = \omega$ to hold.

**Corollary 4.8.** Consider the following conditions:
(a) $\omega$-inj.dim $X = 0$,
(b) $\omega$-inj.dim $X = 0$,
(c) $\omega$-inj.dim $\omega = 0$,
(d) Every epimorphism $W' \rightarrow W \rightarrow 0$ in $C$ with $W$ and $W'$ in $\omega$ admits a section.
(e) $\omega = \omega$. 

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is an exact sequence $0 \twoheadrightarrow X \rightarrow W_0 \rightarrow \ldots \rightarrow W_n \rightarrow 0$ with $W_i$ in $\omega$ for $i = 0, \ldots, n$.
Then one has (a) \iff (b) \implies (c) \implies (d) \implies (e).

**Proof.** As \( X \) and \( \hat{\omega} \) are subcategories of \( \hat{X} \), the implications (b) \implies (a) and (b) \implies (c) are trivial. That (a) \implies (b) follows from the existence of an \( X \)-approximation \( 0 \to Y_C \to X_C \to C \to 0 \) for any object \( C \) in \( X \) and the fact that \( \omega \)-inj.dim \( \hat{\omega} = X \)-inj.dim \( \hat{\omega} = 0 \). That (c) \implies (d) follows from the fact that the kernel \( K \) of any epimorphism \( W' \to W \to 0 \) between objects from \( \omega \) is by definition an object in \( \hat{\omega} \). But (c) implies \( \text{Ext}_{X}^1(W,K) = 0 \), whence the exact sequence \( 0 \to K \to W' \to W \to 0 \) splits. The remaining implication (d) \implies (e) is a special case of proposition 4.2. \qed

**Example 6.** A special case in which \( \hat{\omega} = \omega \) holds, has been investigated already by A.Heller [He]. Following him let us say that \( X \) in \( C \) is a \textit{Frobenius category} if it satisfies our usual assumptions of being additively closed and exact in \( C \) with every epimorphism from \( C \) in \( X \) being admissible and if furthermore \( \omega = X \cap X^\perp \) is also a \textit{projective generator} for \( X \), which is equivalent to \( \omega^{op} \) being an injective cogenerator of \( X^{op} \).

This means hence that

(i) \( X \)-inj.dim \( \omega = X \)-proj.dim \( \omega = 0 \) and

(ii) for every object \( X \) in \( X \) there exists both a monomorphism \( i : X \to W \) as well as an epimorphism \( p : W' \to X \) with \( W, W' \) in \( \omega \) such that the objects \( \text{Kerp} \) and \( \text{Cokl} \), calculated in \( C \), are again objects in \( X \).

A.Heller himself gave already some examples of such categories and further such categories are discussed in [Ha]. Also, it is clear from the definitions that in Example 3 the category \( X \) of maximal Cohen-Macaulay \( R \)-modules is Frobenius.

### §5. Some remarks on the \( X \)-resolution dimension of \( \hat{X} \).

We define \( X \)-resol.dim \( \hat{X} \) to be the maximum (including \( \infty \)) of \( X \)-resol.dim \( C \) for all objects \( C \) in \( \hat{X} \). This paragraph is devoted to interpreting some of our previous results when \( X \)-resol.dim \( \hat{X} \) is \textit{finite}. So for the remainder of this section we assume \( X \)-resol.dim \( \hat{X} = d < \infty \).

Our remarks are based on the following observation.

**Lemma 5.1.** The following statements are equivalent for an object \( C \) in \( C \).

(a) \( X \)-inj.dim \( C \) < \( \infty \),

(b) \( \hat{X} \)-inj.dim \( C \) < \( \infty \).

Moreover, if \( X \)-inj.dim \( C \) = \( m \) < \( \infty \), then \( \hat{X} \)-inj.dim \( C \) \leq d+m \).

**Proof:** Usual dimension shift argument. \qed

This lemma implies immediately the following.
Proposition 5.2. Suppose $C$ is an object in $\hat{X}$.
(a) $\hat{X}$-inj.dim$C < \infty$ if and only if $C$ is in $\hat{\omega}$.
(b) If $C$ is an object in $\hat{\omega}$, then $\hat{X}$-inj.dim$C \leq d$.

Proof: (a): By lemma 5.1, we know that $\hat{X}$-inj.dim$C < \infty$ if and only if $X$-inj.dim$C < \infty$. But by proposition 4.2, we know that $X$-inj.dim$C < \infty$ if and only if $C$ is in $\hat{\omega}$.
(b): Since $X$-inj.dim$\hat{\omega} = 0$ by corollary 2.2, the result follows from lemma 5.1.

As a special case we obtain the following consequence.

Corollary 5.3. If $\hat{X} = C$, then we have:
(a) $C$ is in $\hat{\omega}$ if and only if inj.dim$C < \infty$.
(b) If $C$ is in $\hat{\omega}$, then inj.dim$C \leq d$.

Remark that the injective dimension of an object $C$ in $\mathcal{C}$ is defined here in terms of vanishing of the functors $\text{Ext}^*(\cdot, C)$. As soon as $C$ itself has enough injective objects it coincides with the notion obtained from the length of a shortest injective resolution.

Applying the foregoing result to our decomposition into $X$-approximations and $\hat{\omega}$-hulls we have the following.

Corollary 5.4. Suppose again $\hat{X} = C$ and let $0 \rightarrow Y_C \rightarrow X_C \rightarrow C \rightarrow 0$ and $0 \rightarrow C \rightarrow Y^C \rightarrow X^C \rightarrow 0$ be an $X$-approximation and an $\hat{\omega}$-hull of an object $C$ in $\mathcal{C}$ respectively. Then inj.dim$Y_C < \text{inj.dim} Y^C \leq d$ or both $Y_C$ and $Y^C$ are already injective.

Finally, consider the case where $\hat{\omega} = \tilde{\omega}$. Then we have first the following consequence of lemma 5.1.

Proposition 5.5. Suppose $\hat{\omega} = \tilde{\omega}$. Then the following statements are equivalent for an object $C$ in $\hat{X}$.
(a) $C$ is in $\hat{\omega}$.
(b) $\hat{X}$-inj.dim$C \leq d$.
(c) $\hat{X}$-inj.dim$C < \infty$.

Proof: (a) $\Rightarrow$ (b) by proposition 5.2.
(b) $\Rightarrow$ (c) is trivial.
(c) $\Rightarrow$ (a): Since $\hat{X}$-inj.dim$C < \infty$, we have that $X$-inj.dim$C < \infty$.
Therefore $C$ is in $\hat{\omega}$ by proposition 4.2. Hence $C$ is in $\hat{\omega}$ since $\hat{\omega} = \tilde{\omega}$ by assumption.

As an obvious consequence of this proposition we have the following.
Corollary 5.6. Suppose \( \tilde{X} = C \) and \( \tilde{\omega} = \hat{\omega} \). Then the following conditions are equivalent for an object \( C \) in \( C \).
(a) \( C \) is in \( \tilde{\omega} \).
(b) \( \text{inj.dim} \ C \leq d \).
(c) \( \text{inj.dim} \ C < \infty \). 

\[ \square \]

§6. More Examples

In this section we describe various situations where the theory we have developed is applicable.

First we consider a generalization of Example 4.

Example 7. Let \( R \) be a commutative noetherian Gorenstein ring of finite dimension \( d \). Let \( \Lambda \) be an \( R \)-algebra, not necessarily commutative, which is a \textit{maximal Cohen-Macaulay \( R \)-module}. Set \( C = \text{mod}-\Lambda \), the category of finitely generated right \( \Lambda \)-modules, and let \( X \) be the full subcategory of \( C \) whose objects are the \( \Lambda \)-modules which are MCM if considered as \( R \)-modules. Then \( X \) is again additively closed, exact and has all its epimorphisms admissible. Also we have that \( \tilde{X} = \text{mod}-\Lambda \) and that \( X \)-resol.dim \( \tilde{X} = d < \infty \).

As in Example 4, we let \( \omega \) consist of all \( \Lambda \)-modules isomorphic to \( \text{Hom}_R(P,R) \) for some finitely generated projective \( \Lambda^{\text{op}} \)-module \( P \). Again, \( \omega \) is just the additive closure of \( \omega_{\Lambda,R} = \text{Hom}_R(\Lambda,R) \), and it is an injective cogenerator for \( X \).

Applying the results in section 5, we have the following.

Proposition 6.1. Let \( C \) be in \( \text{mod}-\Lambda \).
(a) \( \text{inj.dim} \ C < \infty \) if and only if \( C \) is in \( \tilde{\omega} \).
(b) If \( C \) is in \( \tilde{\omega} \) then \( \text{inj.dim} \ C \leq d \).

\textbf{Proof:} See Corollary 5.3. \[ \square \]

As a consequence of this we obtain hence the following.

Corollary 6.2. Let \( C \) be in \( \text{mod}-\Lambda \). Then \( 0 \rightarrow Y_C \rightarrow X_C \rightarrow C \rightarrow 0 \), the \( X \)-approximation of \( C \), and \( 0 \rightarrow C \rightarrow Y^C \rightarrow X^C \rightarrow 0 \), the \( \tilde{\omega} \)-hull of \( C \), have the property that \( X_C \) and \( X^C \) are maximal Cohen-Macaulay \( R \)-modules and that \( \text{inj.dim} \ Y_C \leq d-1 \) and \( \text{inj.dim} \ Y^C \leq d \). \[ \square \]

We now turn our attention to the question of when \( \hat{\omega} = \hat{\omega} \) in this context.

Proposition 6.3. The following statements are equivalent for \( \Lambda \).
(a) \( \hat{\omega} = \hat{\omega} \).
(b) If \( X \) is a \( \Lambda^{\text{op}} \)-module which is MCM as an \( R \)-module and such that \( \text{proj.dim}_{\Lambda^{\text{op}}} X < \infty \) then \( X \) is a projective \( \Lambda^{\text{op}} \)-module.
Proof: We know by Proposition 4.6 that \( \omega = \hat{\omega} \) if and only if an exact sequence
\[
0 \to C \to W_0 \to \ldots \to W_n \to 0
\]
is in \( \omega \) as soon as each \( W_i \) is in \( \omega \) for \( i = 0, \ldots, n \).

(a) \( \Rightarrow \) (b): Suppose \( 0 \to P_m \to \ldots \to P_0 \to X \to 0 \) is a projective resolution for a given \( \Lambda^{op} \)-module \( X \) which is MCM over \( R \). Then
\[
0 \to \text{Hom}_R(X, R) \to \text{Hom}_R(P_0, R) \to \ldots \to \text{Hom}_R(P_m, R) \to 0
\]
is exact in \( \text{mod-} \Lambda \) with each \( \text{Hom}_R(P_i, R) \) in \( \omega \) for \( i = 0, \ldots, m \). By (a) we have that \( \text{Hom}_R(X, R) \) is necessarily in \( \omega \). Therefore \( \text{Hom}_R(X, R) \cong \text{Hom}_R(P, R) \) for some projective \( \Lambda^{op} \)-module \( P \), which then yields \( X \cong P \).

(b) \( \Rightarrow \) (a): Suppose that \( X \) in \( \text{mod-} \Lambda \) is MCM over \( R \) and that
\[
0 \to X \to W_0 \to \ldots \to W_m \to 0
\]
is an exact sequence with \( W_i \) in \( \omega \) for all \( i = 0, \ldots, m \). Then
\[
0 \to \text{Hom}_R(W_m, R) \to \ldots \to \text{Hom}_R(W_0, R) \to \text{Hom}_R(X, R) \to 0
\]
is exact and \( \text{Hom}_R(W_i, R) \) is a projective \( \Lambda^{op} \)-module for each \( i \). The \( \Lambda^{op} \)-module \( \text{Hom}_R(X, R) \) is still MCM as an \( R \)-module and hence \( \text{Hom}_R(X, R) \cong P \) for some projective \( \Lambda^{op} \)-module by our assumption. As MCM's are reflexive, \( X \cong \text{Hom}_R(P, R) \) and \( X \) is therefore in \( \omega \).

This proposition gives the following generalization of a result of R. Sharp [Sh].

**Corollary 6.4.** Suppose \( \Lambda \) is a commutative ring. Then the following are equivalent for a finitely generated \( \Lambda \)-module \( M \).

(a) \( \text{inj.dim}_\Lambda M < \infty \).

(b) There is an exact sequence
\[
0 \to W_m \to \ldots \to W_0 \to M \to 0
\]
with \( W_i \) in \( \omega \) for all \( i = 0, \ldots, m \).

**Proof:** The equivalence of (a) and (b) is nothing more than the statement that \( \omega = \hat{\omega} \).

But this follows from Proposition 6.3 since it is well-known for commutative rings, that a maximal Cohen-Macaulay module of finite projective dimension is projective.

However, if \( \Lambda \) is not commutative, it is not necessarily true that a \( \Lambda^{op} \)-module which is MCM over \( R \) and of finite projective dimension over \( \Lambda^{op} \) is necessarily projective. For example, let \( R \) be a regular local ring of dimension \( d > 0 \) and let \( \Lambda \) be the algebra of lower triangular \( n \times n \) matrices over \( R \) with \( n \geq 2 \). Then \( \Lambda \) is a free and finitely generated \( R \)-module and \( \text{gl.dim } \Lambda^{op} = d+1 \). Let
\[
0 \to P_{d+1} \to P_d \to \ldots \to P_0 \to M \to 0
\]
be a projective \( \Lambda^{op} \)-resolution of a \( \Lambda^{op} \)-module \( M \) with \( \text{proj.dim}_{\Lambda^{op}} M = d+1 \). Then \( \text{Im}(P_d \to P_{d-1}) \) is an MCM over \( R \) which is of projective dimension one over \( \Lambda^{op} \) and is hence not \( \Lambda^{op} \)-projective.

**Example 8.** Let \( k \) be a field and \( P = k[x_0, \ldots, x_n] \) a polynomial ring over \( k \) in \( n+1 \) variables which we grade by assigning arbitrary positive integral weights to the variables. Let \( I \) be a homogeneous ideal in \( P \) and set \( S = P/I \) which is hence a positively graded \( k \)-algebra.
We assume that $S$ is a Cohen-Macaulay ring. It is known then that there exists a sequence $y_1, \ldots, y_m$ of homogeneous elements of strictly positive degrees in $I$ which is a regular $k[x_0, \ldots, x_n]$-sequence, and such that $R = P/(y_1, \ldots, y_m)$ has the same dimension as $S$. As $R$ is a complete intersection, it is a Gorenstein ring and by construction the natural surjection $R \rightarrow S \rightarrow 0$ is a degree-preserving homomorphism of rings. Let $\mathcal{C} = S\text{-grmod}$ be the category of finitely generated graded $S$-modules with degree zero graded maps as morphisms. Also let $\mathcal{X}$ be the subcategory of $\mathcal{C}$ consisting of all maximal Cohen-Macaulay modules. In addition to the usual properties, $\mathcal{X}$ also satisfies $\mathcal{X} = \mathcal{C}$ and $\mathcal{X}\text{-resol.dim } \mathcal{X} = n+1-m = d$, the dimension of $S$.

Set $\omega_{S/R} = \text{Hom}_R(S,R)$, which is a dualizing module of $S$ over $R$, and define $\omega$ to be the subcategory of $\mathcal{C}$ consisting of all $\omega_{S/R}(n)$ for $n \in \mathbb{Z}$. Then $\omega$ is an injective cogenerator for $\mathcal{X}$. Moreover we know that $X$ in $\mathcal{X}$ is of finite projective dimension if and only if it is isomorphic to a direct sum $\oplus S(a_i)$.

As in the previous example, this implies $\hat{\omega} = \omega$. We leave it to the reader to write down in detail what this means for $\mathcal{X}$-approximations, $\hat{\omega}$-hulls and modules of finite injective dimension.

We now give our last example.

**Example 9.** Let $\Lambda \rightarrow \Gamma$ be a ring homomorphism with $\Lambda$ both left and right noetherian and $\Gamma$ a finitely generated projective $\Lambda$-module on both left and right. Let $\mathcal{C} = \Gamma\text{-mod}$ be the category of all finitely generated left $\Gamma$-modules and let $\mathcal{X}$ consist of all $M$ in $\mathcal{C}$ such that $M$ is a projective $\Lambda$-module. In addition to the usual properties, we have that $\mathcal{X}$ consists of all $N$ in $\mathcal{C}$ such that $\text{proj.dim}_\Lambda N < \infty$.

Define $\omega$ to be the category of all modules isomorphic to $\text{Hom}_\Lambda(P,\Lambda)$ for some finitely generated projective $\Gamma^\text{op}$-module $P$. Then $\omega$ is an injective cogenerator for $\mathcal{X}$. In general $\hat{\omega} \neq \omega$, but if all the modules in $\omega$ are projective $\Gamma$-modules, then we do have $\hat{\omega} = \omega$ by Corollary 4.8 and in fact $\mathcal{X}$ becomes a Frobenius category, see Example 6.

**References**


