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GORENSTEIN DERIVED FUNCTORS

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Abstract. Over any associative ring \( R \) it is standard to derive \( \text{Hom}_R(\cdot, \cdot) \) using projective resolutions in the first variable, or injective resolutions in the second variable, and doing this, one obtains \( \text{Ext}_R^n(\cdot, \cdot) \) in both cases. We examine the situation where projective and injective modules are replaced by Gorenstein projective and Gorenstein injective ones, respectively. Furthermore, we derive the tensor product \( \otimes_R \) using Gorenstein flat modules.

1. Introduction

When \( R \) is a two-sided Noetherian ring, Auslander and Bridger [2] introduced in 1969 the G-dimension, \( \text{G-dim}_R M \), for every finite (that is, finitely generated) \( R \)-module \( M \). They proved the inequality \( \text{G-dim}_R M \leq \text{pd}_R M \), with equality \( \text{G-dim}_R M = \text{pd}_R M \) when \( \text{pd}_R M < \infty \), along with a generalized Auslander-Buchsbaum formula (sometimes known as the Auslander-Bridger formula) for the G-dimension.

The (finite) modules with G-dimension zero are called Gorenstein projectives. Over a general ring \( R \), Enochs and Jenda in [6] defined Gorenstein projective modules. Avramov, Buchweitz, Martsinkovsky and Reiten proved that if \( R \) is two-sided Noetherian, and \( G \) is a finite Gorenstein projective module, then the new definition agrees with that of Auslander and Bridger; see the remark following [4, Theorem (4.2.6)]. Using Gorenstein projective modules, one can introduce the Gorenstein projective dimension for arbitrary \( R \)-modules. At this point we need to introduce:

1.1 (Notation). Throughout this paper, we use the following notation:

- \( R \) is an associative ring. All modules are—if not specified otherwise—left \( R \)-modules, and the category of all \( R \)-modules is denoted \( \mathcal{M} \). We use \( \mathcal{A} \) for the category of abelian groups (that is, \( \mathbb{Z} \)-modules).
- We use \( \mathcal{GP}, \mathcal{GI} \) and \( \mathcal{GF} \) for the categories of Gorenstein projective, Gorenstein injective and Gorenstein flat \( R \)-modules; please see [6] and [8], or Definition 2.7 below.
- Furthermore, for each \( R \)-module \( M \) we write \( \text{Gpd}_R M \), \( \text{Gid}_R M \) and \( \text{Gfd}_R M \) for the Gorenstein projective, Gorenstein injective, and Gorenstein flat dimension of \( M \), respectively.
Now, given our base ring $R$, the usual right derived functors $\text{Ext}^n_R(-,-)$ of $\text{Hom}_R(-,-)$ are important in homological studies of $R$. The material presented here deals with the Gorenstein right derived functors $\text{Ext}^n_{GP}(-,-)$ and $\text{Ext}^n_{GI}(-,-)$ of $\text{Hom}_R(-,-)$.

More precisely, let $N$ be a fixed $R$-module. For an $R$-module $M$ that has a proper left $GP$-resolution $G = \cdots \to G_1 \to G_0 \to 0$ (please see [2,1] below for the definition of proper resolutions), we define

$$\text{Ext}^n_{GP}(M,N) := \mathbb{H}^n(\text{Hom}_R(G,N)).$$

From [2,4] it will follow that $\text{Ext}^n_{GP}(-,-)$ is a well-defined contravariant functor, defined on the full subcategory $\text{LeftRes}_M(GP)$, of $M$, consisting of all $R$-modules that have a proper left $GP$-resolution.

For a fixed $R$-module $M'$ there is a similar definition of the functor $\text{Ext}^n_{GP}(M',-)$, which is defined on the full subcategory $\text{RightRes}_M(GI)$, of $M$, consisting of all $R$-modules that which have a proper right $GI$-resolution. Now, the best one could hope for is the existence of isomorphisms,

$$\text{Ext}^n_{GP}(M,N) \cong \text{Ext}^n_{GI}(M,N),$$

which are functorial in each variable $M \in \text{LeftRes}_M(GP)$ and $N \in \text{RightRes}_M(GI)$. The aim of this paper is to show a slightly weaker result.

When $R$ is $n$-Gorenstein (meaning that $R$ is both left and right Noetherian, with self-injective dimension $\leq n$ from both sides), Enochs and Jenda [9, Theorem 12.1.4] have proved the existence of such functorial isomorphisms $\text{Ext}^n_{GP}(M,N) \cong \text{Ext}^n_{GI}(M,N)$ for all $R$-modules $M$ and $N$.

It is important to note that for an $n$-Gorenstein ring $R$, we have $\text{Gpd}_R M < \infty$, $\text{Gid}_R M < \infty$, and also $\text{Gfd}_R M < \infty$ for all $R$-modules $M$; please see [9, Theorems 11.2.1, 11.5.1, 11.7.6]. For any ring $R$, [12, Proposition 2.18] (which is restated in this paper as Proposition 3.1) implies that the category $\text{LeftRes}_M(GP)$ contains all $R$-modules $M$ with $\text{Gpd}_R M < \infty$; that is, every $R$-module with finite $G$-projective dimension has a proper left $GP$-resolution. Also, every $R$-module with finite $G$-injective dimension has a proper right $GI$-resolution. So $\text{RightRes}_M(GI)$ contains all $R$-modules $N$ with $\text{Gid}_R N < \infty$.

Theorem 3.6 in this text proves that the functorial isomorphisms $\text{Ext}^n_{GP}(M,N) \cong \text{Ext}^n_{GI}(M,N)$ hold over arbitrary rings $R$, provided that $\text{Gpd}_R M < \infty$ and $\text{Gid}_R N < \infty$. By the remarks above, this result generalizes that of Enochs and Jenda.

Furthermore, Theorems 4.8 and 4.10 give similar results about the Gorenstein left derived of the tensor product $- \otimes_R -$, using proper left $GP$-resolutions and proper left $GF$-resolutions. This has also been proved by Enochs and Jenda [9, Theorem 12.2.2] in the case when $R$ is $n$-Gorenstein.

2. Preliminaries

Let $T : \mathcal{C} \to \mathcal{E}$ be any additive functor between abelian categories. One usually derives $T$ using resolutions consisting of projective or injective objects (if the category $\mathcal{C}$ has enough projectives or injectives). This section is a very brief note on how to derive functors $T$ with resolutions consisting of objects in some subcategory $\mathcal{X} \subseteq \mathcal{C}$. The general discussion presented here will enable us to give very short proofs of the main theorems in the next section.
2.1 (Proper Resolutions). Let \( \mathcal{X} \subseteq \mathcal{C} \) be a full subcategory. A proper left \( \mathcal{X} \)-resolution of \( M \in \mathcal{C} \) is a complex \( X = \cdots \to X_1 \to X_0 \to M \to 0 \) where \( X_i \in \mathcal{X} \), together with a morphism \( X_0 \to M \), such that \( X^+ := \cdots \to X_1 \to X_0 \to M \to 0 \) is also a complex, and such that the sequence

\[
\text{Hom}_{\mathcal{C}}(X, X^+) = \cdots \to \text{Hom}_{\mathcal{C}}(X, X_1) \to \text{Hom}_{\mathcal{C}}(X, X_0) \to \text{Hom}_{\mathcal{C}}(X, M) \to 0
\]

is exact for every \( X \in \mathcal{X} \). We sometimes refer to \( X^+ = \cdots \to X_1 \to X_0 \to M \to 0 \) as an augmented proper left \( \mathcal{X} \)-resolution. We do not require that \( X^+ \) itself is exact. Furthermore, we use \( \text{LeftRes}_\mathcal{C}(\mathcal{X}) \) to denote the full subcategory of \( \mathcal{C} \) consisting of those objects that have a proper left \( \mathcal{X} \)-resolution. Note that \( \mathcal{X} \) is a subcategory of \( \text{LeftRes}_\mathcal{C}(\mathcal{X}) \).

Proper right \( \mathcal{X} \)-resolutions are defined dually, and the full subcategory of \( \mathcal{C} \) consisting of those objects that have a proper right \( \mathcal{X} \)-resolution is \( \text{RightRes}_\mathcal{C}(\mathcal{X}) \).

The importance of working with proper resolutions comes from the following:

**Proposition 2.2.** Let \( f: M \to M' \) be a morphism in \( \mathcal{C} \), and consider the diagram

\[
\begin{array}{ccccccccc}
\cdots & \to & X_2 & \to & X_1 & \to & X_0 & \to & M & \to & 0 \\
\downarrow f_2 & & \downarrow f_1 & & \downarrow f_0 & & \downarrow f & & \\
\cdots & \to & X'_2 & \to & X'_1 & \to & X'_0 & \to & M' & \to & 0
\end{array}
\]

where the upper row is a complex with \( X_n \in \mathcal{X} \) for all \( n \geq 0 \), and the lower row is an augmented proper left \( \mathcal{X} \)-resolution of \( M' \). Then the following conclusions hold:

(i) There exist morphisms \( f_n: X_n \to X'_n \) for all \( n \geq 0 \), making the diagram above commutative. The chain map \( \{f_n\}_{n \geq 0} \) is called a lift of \( f \).

(ii) If \( \{f'_n\}_{n \geq 0} \) is another lift of \( f \), then the chain maps \( \{f_n\}_{n \geq 0} \) and \( \{f'_n\}_{n \geq 0} \) are homotopic.

**Proof.** The proof is an exercise; please see [9, Exercise 8.1.2].

**Remark 2.3.** A few comments are in order:

- In our applications, the class \( \mathcal{X} \) contains all projectives. Consequently, all the augmented proper left \( \mathcal{X} \)-resolutions occurring in this paper will be exact. Also, all augmented proper right \( \mathcal{Y} \)-resolutions will be exact, when \( \mathcal{Y} \) is a class of \( R \)-modules containing all injectives.

- Recall (see [15, Definition 1.2.2]) that an \( \mathcal{X} \)-precover of \( M \in \mathcal{C} \) is a morphism \( \varphi: X \to M \), where \( X \in \mathcal{X} \), such that the sequence

\[
\text{Hom}_{\mathcal{C}}(X', X) \to \text{Hom}_{\mathcal{C}}(X', \varphi) \to \text{Hom}_{\mathcal{C}}(X', M) \to 0
\]

is exact for every \( X' \in \mathcal{X} \). Hence, in an augmented proper left \( \mathcal{X} \)-resolution \( X^+ \) of \( M \), the morphisms \( X_{i+1} \to \text{Ker}(X_i \to X_{i-1}) \), \( i > 0 \), and \( X_0 \to M \) are \( \mathcal{X} \)-precovers.

- What we have called proper \( \mathcal{X} \)-resolutions, Enochs and Jenda [9, Definition 8.1.2] simply call \( \mathcal{X} \)-resolutions. We have adopted the terminology proper from [3, Section 4].

2.4 (Derived Functors). Consider an additive functor \( T: \mathcal{C} \to \mathcal{E} \) between abelian categories. Let us assume that \( T \) is covariant, say. Then (as usual) we can define the \( n \)th left derived functor

\[
L_n^\mathcal{X}T: \text{LeftRes}_\mathcal{C}(\mathcal{X}) \to \mathcal{E}
\]
of $T$, with respect to the class $\mathcal{X}$, by setting $L_n^\mathcal{X}T(M) = H_n(T(X))$, where $X$ is any proper left $\mathcal{X}$-resolution of $M \in \text{LeftRes}(\mathcal{X})$. Similarly, the $n$th right derived functor
\[
R_n^\mathcal{X}T : \text{RightRes}(\mathcal{X}) \to \mathcal{E}
\]
of $T$ with respect to $\mathcal{X}$ is defined by $R_n^\mathcal{X}T(N) = H_n(T(Y))$, where $Y$ is any proper right $\mathcal{X}$-resolution of $N \in \text{RightRes}(\mathcal{X})$. These constructions are well-defined and functorial in the arguments $M$ and $N$ by Proposition 2.2.

The situation where $T$ is contravariant is handled similarly. We refer to [9, Section 8.2] for a more detailed discussion on this matter.

2.5 (Balanced Functors). Next we consider yet another abelian category $\mathcal{D}$, together with a full subcategory $\mathcal{Y} \subseteq \mathcal{D}$ and an additive functor $F : \mathcal{C} \times \mathcal{D} \to \mathcal{E}$ in two variables. We will assume that $F$ is contravariant in the first variable, and covariant in the second variable.

Actually, the variance of the variables of $F$ is not important, and the definitions and results below can easily be modified to fit the situation where $F$ is covariant in both variables, say.

For fixed $M \in \mathcal{C}$ and $N \in \mathcal{D}$ we can then consider the two right derived functors as in 2.4:
\[
R^n_\mathcal{X}F(-, N) : \text{LeftRes}(\mathcal{X}) \to \mathcal{E} \quad \text{and} \quad R^n_\mathcal{Y}F(M, -) : \text{RightRes}(\mathcal{Y}) \to \mathcal{E}.
\]
If furthermore $M \in \text{LeftRes}(\mathcal{X})$ and $N \in \text{RightRes}(\mathcal{Y})$, we can ask for a sufficient condition to ensure that
\[
R^n_\mathcal{X}F(M, N) \cong R^n_\mathcal{Y}F(N, M),
\]
functorial in $M$ and $N$. Here we wrote $R^n_\mathcal{X}F(M, N)$ for the functor $R^n_\mathcal{X}F(-, N)$ applied to $M$. Another, and perhaps better, notation could be
\[
R^n_\mathcal{X}F(-, N)[M].
\]

Enochs and Jenda have in [5] developed a machinery for answering such questions. They operate with the term left/right balanced functor (hence the headline), which we will not define here (but the reader might consult [5, Definition 2.1]). Instead we shall focus on the following result:

Theorem 2.6. Consider the functor $F : \mathcal{C} \times \mathcal{D} \to \mathcal{E}$ which is contravariant in the first variable and covariant in the second variable, together with the full subcategories $\mathcal{X} \subseteq \mathcal{C}$ and $\mathcal{Y} \subseteq \mathcal{D}$. Assume that we have full subcategories $\mathcal{X}$ and $\mathcal{Y}$ of $\text{LeftRes}(\mathcal{X})$ and $\text{RightRes}(\mathcal{Y})$, respectively, satisfying:

(i) $\mathcal{X} \subseteq \mathcal{X}$ and $\mathcal{Y} \subseteq \mathcal{Y}$.
(ii) Every $M \in \mathcal{X}$ has an augmented proper left $\mathcal{X}$-resolution $\cdots \to X_1 \to X_0 \to M \to 0$, such that $0 \to F(M, Y) \to F(X_0, Y) \to F(X_1, Y) \to \cdots$ is exact for all $Y \in \mathcal{Y}$.
(iii) Every $N \in \mathcal{Y}$ has an augmented proper right $\mathcal{Y}$-resolution $0 \to N \to Y^0 \to Y^1 \to \cdots$, such that $0 \to F(X, N) \to F(X, Y^0) \to F(X, Y^1) \to \cdots$ is exact for all $X \in \mathcal{X}$.

Then we have functorial isomorphisms
\[
R^n_\mathcal{X}F(M, N) \cong R^n_\mathcal{Y}F(M, N),
\]
for all $M \in \mathcal{X}$ and $N \in \mathcal{Y}$.
Proof. Please see [5, Proposition 2.3]. That the isomorphisms are functorial follows from the construction. The functoriality becomes more clear if one consults the proof of [5, Proposition 8.2.14], or the proofs of [14] Theorems 2.7.2 and 2.7.6. □

In the next paragraphs we apply the results above to special categories $X$, $\tilde{X}$, $C$ and $Y$, $\tilde{Y}$, $D$, including the categories mentioned in 1.1. For completeness we include a definition of Gorenstein projective, Gorenstein injective and Gorenstein flat modules:

Definition 2.7. A complete projective resolution is an exact sequence of projective modules,

$P = \cdots \to P_1 \to P_0 \to P_{-1} \to \cdots$,

such that $\text{Hom}_R(P, Q)$ is exact for every projective $R$-module $Q$. An $R$-module $M$ is called Gorenstein projective ($G$-projective for short), if there exists a complete projective resolution $P$ with $M \cong \text{Im}(P_0 \to P_{-1})$. Gorenstein injective ($G$-injective for short) modules are defined dually.

A complete flat resolution is an exact sequence of flat (left) $R$-modules,

$F = \cdots \to F_1 \to F_0 \to F_{-1} \to \cdots$,

such that $I \otimes_R F$ is exact for every injective right $R$-module $I$. An $R$-module $M$ is called Gorenstein flat ($G$-flat for short), if there exists a complete flat resolution $F$ with $M \cong \text{Im}(F_0 \to F_{-1})$.

3. Gorenstein deriving $\text{Hom}_R(-, -)$

We now return to categories of modules. We use $\widehat{GP}$, $\widehat{GI}$ and $\widehat{GF}$ to denote the class of $R$-modules with finite Gorenstein projective dimension, finite Gorenstein injective dimension, and finite Gorenstein flat dimension, respectively.

Recall that every projective module is Gorenstein projective. Consequently, $GP$-precovers are always surjective, and $\widehat{GP}$ contains all modules with finite projective dimension.

We now consider the functor $\text{Hom}_R(-, -): \mathcal{M} \times \mathcal{M} \to \mathcal{A}$, together with the categories

$\mathcal{X} = \mathcal{GP}$, $\tilde{\mathcal{X}} = \widehat{\mathcal{GP}}$ and $\mathcal{Y} = \mathcal{GI}$, $\tilde{\mathcal{Y}} = \widehat{\mathcal{GI}}$.

In this case we define, in the sense of section 2.4

$\text{Ext}^n_{\mathcal{GP}}(-, N) = R^n_{\mathcal{GP}}\text{Hom}_R(-, N)$ and $\text{Ext}^n_{\mathcal{GI}}(M, -) = R^n_{\mathcal{GI}}\text{Hom}_R(M, -)$,

for fixed $R$-modules $M$ and $N$. We wish, of course, to apply Theorem 2.3 to this situation. Note that by [12, Proposition 2.18], we have:

Proposition 3.1. If $M$ is an $R$-module with $\text{Gpd}_RM < \infty$, then there exists a short exact sequence $0 \to K \to G \to M \to 0$, where $G \to M$ is a $GP$-precover of $M$ (please see Remark 2.3), and $\text{pd}_RK = \text{Gpd}_RM - 1$ (in the case where $M$ is Gorenstein projective, this should be interpreted as $K = 0$).

Consequently, every $R$-module with finite Gorenstein projective dimension has a proper left $GP$-resolution (that is, there is an inclusion $\widehat{GP} \subseteq \text{LeftRes}_\mathcal{M}(\mathcal{GP})$).

Furthermore, we will need the following from [12, Theorem 2.13]:

Theorem 3.2. Let $M$ be any $R$-module with $\text{Gpd}_RM < \infty$. Then

$\text{Gpd}_RM = \sup\{n \geq 0 \mid \text{Ext}^n(R, L) \neq 0 \text{ for some } R\text{-module } L \text{ with } \text{pd}_RL < \infty\}$. 

Remark 3.3. It may be useful to compare Theorem 3.2 to the classical projective dimension, which for an $R$-module $M$ is given by
\[ \text{pd}_R M = \{ n \geq 0 \mid \text{Ext}^n_R(M, L) \neq 0 \text{ for some } R\text{-module } L \}. \]

It also follows that if $\text{pd}_R M < \infty$, then every projective resolution of $M$ is actually a proper left $\mathcal{GP}$-resolution of $M$.

**Lemma 3.4.** Assume that $M$ is an $R$-module with finite Gorenstein projective dimension, and let $G^+ = \cdots \to G_1 \to G_0 \to M \to 0$ be an augmented proper left $\mathcal{GP}$-resolution of $M$ (which exists by Proposition 3.1). Then $\text{Hom}_R(G^+, H)$ is exact for all Gorenstein injective modules $H$.

**Proof.** We split the proper resolution $G^+$ into short exact sequences. Hence it suffices to show exactness of $\text{Hom}_R(S, H)$ for all Gorenstein injective modules $H$ and all short exact sequences
\[ S = 0 \to K \to G \to M \to 0, \]
where $G \to M$ is a $\mathcal{GP}$-precover of some module $M$ with $\text{Gpd}_R M < \infty$ (recall that $\mathcal{GP}$-precovers are always surjective). By Proposition 3.1 there is a special short exact sequence,
\[ S' = 0 \to K' \xrightarrow{\iota} G' \xrightarrow{\pi} M \to 0, \]
where $\pi: G' \to M$ is a $\mathcal{GP}$-precover and $\text{pd}_R K' < \infty$.

It is easy to see (as in Proposition 2.2) that the complexes $S$ and $S'$ are homotopy equivalent, and thus so are the complexes $\text{Hom}_R(S, H)$ and $\text{Hom}_R(S', H)$ for every (Gorenstein injective) module $H$. Hence it suffices to show the exactness of $\text{Hom}_R(S', H)$ whenever $H$ is Gorenstein injective.

Now let $H$ be any Gorenstein injective module. We need to prove the exactness of
\[ \text{Hom}_R(G', H) \to \text{Hom}_R(K', H) \to 0. \]
To see this, let $\alpha: K' \to H$ be any homomorphism. We wish to find $\varrho: G' \to H$ such that $\varrho \iota = \alpha$. Now pick an exact sequence
\[ 0 \to \tilde{H} \xrightarrow{\tilde{g}} E \xrightarrow{g} H \to 0, \]
where $E$ is injective, and $\tilde{H}$ is Gorenstein injective (the sequence in question is just a part of the complete injective resolution that defines $H$). Since $\tilde{H}$ is Gorenstein injective and $\text{pd}_R K' < \infty$, we get $\text{Ext}^1_R(K', \tilde{H}) = 0$ by [7, Lemma 1.3], and thus a lifting $\varepsilon: K' \to E$ with $g \varepsilon = \alpha$:

\[ \begin{array}{c}
\varepsilon \\
\Downarrow \varepsilon \\
E
\end{array} \quad \begin{array}{c}
\Downarrow \tilde{g} \\
\Downarrow \tilde{H} \\
K'
\end{array} \quad \begin{array}{c}
\Downarrow \alpha \\
\Downarrow \varrho \\
G'
\end{array} \]

Next, injectivity of $E$ gives $\tilde{\varepsilon}: G' \to E$ with $\tilde{\varepsilon} \iota = \varepsilon$. Now $\varrho = g \tilde{\varepsilon}: G' \to H$ is the desired map.

With a similar proof we get:
Lemma 3.5. Assume that $N$ is an $R$-module with finite Gorenstein injective dimension, and let $H^+ = 0 \to N \to H^0 \to H^1 \to \cdots$ be an augmented proper right $\mathcal{G}_I$-resolution of $N$ (which exists by the dual of Proposition 3.4). Then $\text{Hom}_R(G, H^+)$ is exact for all Gorenstein projective modules $G$.

Comparing Lemmas 3.4 and 3.5 with Theorem 2.6, we obtain:

Theorem 3.6. For all $R$-modules $M$ and $N$ with $\text{Gpd}_R M < \infty$ and $\text{Gid}_R N < \infty$, we have isomorphisms

$$\text{Ext}^n_{\mathcal{G}_P}(M, N) \cong \text{Ext}^n_{\mathcal{G}_I}(M, N),$$

which are functorial in $M$ and $N$. □

3.7 (Definition of GExt). Let $M$ and $N$ be $R$-modules with $\text{Gpd}_R M < \infty$ and $\text{Gid}_R N < \infty$. Then we write

$$\text{GExt}_R^n(M, N) := \text{Ext}^n_{\mathcal{G}_P}(M, N) \cong \text{Ext}^n_{\mathcal{G}_I}(M, N)$$

for the isomorphic abelian groups in Theorem 3.6 above.

Naturally we want to compare GExt with the classical Ext. This is done in:

Theorem 3.8. Let $M$ and $N$ be any $R$-modules. Then the following conclusions hold:

(i) There are natural isomorphisms $\text{Ext}^n_{\mathcal{G}_P}(M, N) \cong \text{Ext}^n_R(M, N)$ under each of the conditions

\begin{enumerate}
  \item[(i)] $\text{pd}_R M < \infty$ or $M \in \text{LeftRes}_M(\mathcal{G}_P)$ and $\text{id}_R N < \infty$.
  \item[(ii)] There are natural isomorphisms $\text{Ext}^n_{\mathcal{G}_I}(M, N) \cong \text{Ext}^n_R(M, N)$ under each of the conditions
  \begin{enumerate}
    \item [(i)] $\text{id}_R N < \infty$ or $N \in \text{RightRes}_M(\mathcal{G}_I)$ and $\text{pd}_R M < \infty$.
    \item [(ii)] Assume that $\text{Gpd}_R M < \infty$ and $\text{Gid}_R N < \infty$. If either $\text{pd}_R M < \infty$ or $\text{id}_R N < \infty$, then
      \begin{align*}
      \text{GExt}^n_R(M, N) & \cong \text{Ext}^n_R(M, N)
      \end{align*}
  \end{enumerate}

is functorial in $M$ and $N$.

Proof. (i) Assume that $\text{pd}_R M < \infty$, and pick any projective resolution $P$ of $M$. By Remark 3.3, $P$ is also a proper left $\mathcal{G}_P$-resolution of $M$, and thus

$$\text{Ext}^n_{\mathcal{G}_P}(M, N) = \text{H}^n(\text{Hom}_R(P, N)) = \text{Ext}^n_R(M, N).$$

In the case where $M \in \text{LeftRes}_M(\mathcal{G}_P)$ and $\text{id}_R N = m < \infty$, we see that Gorenstein projective modules are acyclic for the functor $\text{Hom}_R(-, N)$, that is, $\text{Ext}^i_R(G, N) = 0$ (the usual Ext) for every Gorenstein projective module $G$, and every integer $i > 0$.

This is because, if $G$ is a Gorenstein projective module, and $i > 0$ is an integer, then there exists an exact sequence $0 \to G \to Q^0 \to \cdots \to Q^{m-1} \to C \to 0$, where $Q^0, \ldots, Q^{m-1}$ are projective modules. Breaking this exact sequence into short exact ones, and applying $\text{Hom}_R(-, N)$, we get $\text{Ext}^i_R(G, N) \cong \text{Ext}^{m+i}_R(C, N) = 0$, as claimed.

Therefore [11, Chapter III, Proposition 1.2A] implies that $\text{Ext}^n_R(-, N)$ can be computed using (proper) left Gorenstein projective resolutions of the argument in the first variable, as desired.

The proof of (ii) is similar. The claim (iii) is a direct consequence of (i) and (ii), together with the Definition 3.7 of GExt $^n_R(-,-)$. □
4. Gorenstein deriving $- \otimes_R -$ 

In dealing with the tensor product we need, of course, both left and right $R$-modules. Thus the following addition to Notation 1.1 is needed:

If $\mathcal{C}$ is any of the categories in Notation 1.1 ($\mathcal{M}$, $\mathcal{GP}$, etc.), we write $\mathcal{R}\mathcal{C}$, respectively, $\mathcal{C}R$, for the category of left, respectively, right, $R$-modules with the property describing the modules in $\mathcal{C}$.

Now we consider the functor $- \otimes_R -$ : $\mathcal{M} \times R\mathcal{M} \to \mathcal{A}$. For fixed $M \in \mathcal{M}R$ and $N \in R\mathcal{M}$ we define, in the sense of section 2.4:

\[ \text{Tor}^G_{GP}(\cdot, N) := L^G_{GP}(\cdot \otimes R N) \text{ and } \text{Tor}^R_{GP}(M, \cdot) := L^R_{GP}(M \otimes_R \cdot), \]

and

\[ \text{Tor}^G_{GF}(\cdot, N) := L^G_{GF}(\cdot \otimes R N) \text{ and } \text{Tor}^R_{GF}(M, \cdot) := L^R_{GF}(M \otimes_R \cdot). \]

The first two $\text{Tor}$s use proper left Gorenstein projective resolutions, and the last two $\text{Tor}$s use proper left Gorenstein flat resolutions. In order to compare these different $\text{Tor}$s, we wish, of course, to apply (a version of) Theorem 2.6 to different combinations of $(X, X) = (GP_R, \widehat{GP}_R)$ or $(GF_R, \widehat{GF}_R)$, and

\[ (Y, Y) = (rGP, \widehat{rGP}) \text{ or } (rGF, \widehat{rGF}), \]

namely, the covariant-covariant version of Theorem 2.6, instead of the stated contravariant-covariant version. We will need the classical notion:

**Definition 4.1.** The left finitistic projective dimension $\text{LeftFPD}(R)$ of $R$ is defined as

\[ \text{LeftFPD}(R) = \sup\{pd_R M \mid M \text{ is a left } R\text{-module with } pd_R M < \infty\}. \]

The right finitistic projective dimension $\text{RightFPD}(R)$ of $R$ is defined similarly.

**Remark 4.2.** When $R$ is commutative and Noetherian, the dimensions $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ coincide and are equal to the Krull dimension of $R$, by [10 Théorème (3.2.6) (Seconde partie)].

We will need the following three results, [12 Proposition 3.3], [12 Theorem 3.5] and [12 Proposition 3.18], respectively:

**Proposition 4.3.** If $R$ is right coherent with finite $\text{LeftFPD}(R)$, then every Gorenstein projective left $R$-module is also Gorenstein flat. That is, there is an inclusion $rGP \subseteq rGF$.

**Theorem 4.4.** For any left $R$-module $M$, we consider the following three conditions:

(i) The left $R$-module $M$ is $G$-flat.

(ii) The Pontryagin dual $\text{Hom}_\mathbb{Z}(M, \mathbb{Q}/\mathbb{Z})$ (which is a right $R$-module) is $G$-injective.

(iii) $M$ has an augmented proper right resolution $0 \to M \to F^0 \to F^1 \to \cdots$ consisting of flat left $R$-modules, and $\text{Tor}_i^R(I, M) = 0$ for all injective right $R$-modules $I$, and all $i > 0$.

The implication (i) $\Rightarrow$ (ii) always holds. If $R$ is right coherent, then also (ii) $\Rightarrow$ (iii) $\Rightarrow$ (i), and hence all three conditions are equivalent.
Proposition 4.5. Assume that $R$ is right coherent. If $M$ is a left $R$-module with $\text{Gfd}_R M < \infty$, then there exists a short exact sequence $0 \to K \to G \to M \to 0$, where $G \to M$ is an $\text{RGF}$-precover of $M$, and $\text{fd}_R K = \text{Gfd}_R M - 1$ (in the case where $M$ is Gorenstein flat, this should be interpreted as $K = 0$).

In particular, every left $R$-module with finite Gorenstein flat dimension has a proper left $\text{RGF}$-resolution (that is, there is an inclusion $\text{RGF} \subseteq \text{LeftRes}_{R,M}(\text{RGF})$).

Our first result is:

Lemma 4.6. Let $M$ be a left $R$-module with $\text{Gpd}_R M < \infty$, and let $G^+ = \cdots \to G_1 \to G_0 \to M \to 0$ be an augmented proper left $\text{RGP}$-resolution of $M$ (which exists by Proposition 3.4). Then the following conclusions hold:

(i) $T \otimes_R G^+$ is exact for all Gorenstein flat right $R$-modules $T$.

(ii) If $R$ is left coherent with finite $\text{RightFPD}(R)$, then $T \otimes_R G^+$ is exact for all Gorenstein projective right $R$-modules $T$.

Proof. (i) By Theorem 3.4 above, the Pontryagin dual $H = \text{Hom}_Z(T, \mathbb{Q}/\mathbb{Z})$ is a Gorenstein injective left $R$-module. Hence $\text{Hom}_R(G^+, H) \cong \text{Hom}_Z(T \otimes_R G^+, \mathbb{Q}/\mathbb{Z})$ is exact by Proposition 3.4. Since $\mathbb{Q}/\mathbb{Z}$ is a faithfully injective $\mathbb{Z}$-module, $T \otimes_R G^+$ is exact too.

(ii) With the given assumptions on $R$, the dual of Proposition 3.4 implies that every Gorenstein projective right $R$-module also is Gorenstein flat.

Lemma 4.7. Assume that $R$ is right coherent with finite $\text{LeftFPD}(R)$. Let $M$ be a left $R$-module with $\text{Gfd}_R M < \infty$, and let $G^+ = \cdots \to G_1 \to G_0 \to M \to 0$ be an augmented proper left $\text{RGF}$-resolution of $M$ (which exists by Proposition 3.4 since $R$ is right coherent). Then the following conclusions hold:

(i) $\text{Hom}_R(G^+, H)$ is exact for all Gorenstein injective left $R$-modules $H$.

(ii) $T \otimes_R G^+$ is exact for all Gorenstein flat right $R$-modules $T$.

(iii) If $R$ is also left coherent with finite $\text{RightFPD}(R)$, then $T \otimes_R G^+$ is exact for all Gorenstein projective right $R$-modules $T$.

Proof. (i) Since $\text{Gfd}_R M < \infty$ and $R$ is right coherent, Proposition 3.4 gives a special short exact sequence $0 \to K' \to G' \to M \to 0$, where $G' \to M$ is an $\text{RGF}$-precover of $M$, and $\text{fd}_R K' < \infty$. Since $R$ has $\text{LeftFPD}(R) < \infty$, Proposition 6] implies that also $\text{pd}_R K' < \infty$. Now the proof of Lemma 3.4 applies.

(ii) If $T$ is a Gorenstein flat right $R$-module, then the left $R$-module $H = \text{Hom}_Z(T, \mathbb{Q}/\mathbb{Z})$ is Gorenstein injective, by (the dual of) Theorem 3.4 above. By the result (i), just proved, we have exactness of

$$\text{Hom}_R(G^+, H) \cong \text{Hom}_Z(T \otimes_R G^+, \mathbb{Q}/\mathbb{Z}).$$

Since $\mathbb{Q}/\mathbb{Z}$ is a faithfully injective $\mathbb{Z}$-module, we also have exactness of $T \otimes_R G^+$, as desired.

(iii) Under the extra assumptions on $R$, the dual of Proposition 3.4 implies that every Gorenstein projective right $R$-module is also Gorenstein flat. Thus (iii) follows from (ii).

Theorem 4.8. Assume that $R$ is both left and right coherent, and that both $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ are finite. For every right $R$-module $M$, and every left $R$-module $N$, the following conclusions hold:
(i) If $\text{Gfd}_R M < \infty$ and $\text{Gfd}_R N < \infty$, then
$$\text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N).$$

(ii) If $\text{Gpd}_R M < \infty$ and $\text{Gfd}_R N < \infty$, then
$$\text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N).$$

(iii) If $\text{Gfd}_R M < \infty$ and $\text{Gpd}_R N < \infty$, then
$$\text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N).$$

(iv) If $\text{Gpd}_R M < \infty$ and $\text{Gpd}_R N < \infty$, then
$$\text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N).$$

All the isomorphisms are functorial in $M$ and $N$.

Proof. Use Lemmas 4.6 and 4.7 as input in the covariant-covariant version of Theorem 2.6.

4.9 (Definition of $g\text{Tor}$ and $\text{GTor}$). Assume that $R$ is both left and right coherent, and that both $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ are finite. Furthermore, let $M$ be a right $R$-module, and let $N$ be a left $R$-module. If $\text{Gfd}_R M < \infty$ and $\text{Gfd}_R N < \infty$, then we write
$$g\text{Tor}^R_{n}(M, N) := \text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N)$$
for the isomorphic abelian groups in Theorem 4.8(i). If $\text{Gpd}_R M < \infty$ and $\text{Gpd}_R N < \infty$, then we write
$$\text{GTor}^R_{n}(M, N) := \text{Tor}^{GF}_{n}(M, N) \cong \text{Tor}^{GF}_{n}(M, N)$$
for the isomorphic abelian groups in Theorem 4.8(iv).

We can now reformulate some of the content of Theorem 4.8.

Theorem 4.10. Assume that $R$ is both left and right coherent, and that both $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ are finite. For every right $R$-module $M$ with finite $\text{Gpd}_R M$, and for every left $R$-module $N$ with $\text{Gpd}_R N < \infty$, we have isomorphisms:
$$g\text{Tor}^R_{n}(M, N) \cong \text{GTor}^R_{n}(M, N)$$
that are functorial in $M$ and $N$.

Finally we compare $g\text{Tor}$ (and hence $\text{GTor}$) with the usual $\text{Tor}$.

Theorem 4.11. Assume that $R$ is both left and right coherent, and that both $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ are finite. Furthermore, let $M$ be a right $R$-module with $\text{Gfd}_R M < \infty$, and let $N$ be a left $R$-module with $\text{Gfd}_R N < \infty$. If either $\text{fd}_R M < \infty$ or $\text{fd}_R N < \infty$, then there are isomorphisms
$$g\text{Tor}^R_{n}(M, N) \cong \text{Tor}^R_{n}(M, N)$$
that are functorial in $M$ and $N$.

Proof. If $\text{fd}_R M < \infty$, then we also have $\text{pd}_R M < \infty$ by [13, Proposition 6] (since $\text{RightFPD}(R) < \infty$). Let $P$ be any projective resolution of $M$. As noted in Remark 3.3, $P$ is also a proper left $\mathcal{GP}_R$-resolution of $M$. Hence, Theorem 4.8(ii) and the definitions give:
$$g\text{Tor}^R_{n}(M, N) = \text{Tor}^{\mathcal{GP}}_{n}(M, N) = H_n(P \otimes_R N) = \text{Tor}^R_{n}(M, N),$$
as desired. \qed
GORENSTEIN DERIVED FUNCTORS

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