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RINGS WITH FINITE GORENSTEIN INJECTIVE DIMENSION

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Abstract. In this paper we prove that for any associative ring \( R \), and for any left \( R \)-module \( M \) with finite projective dimension, the Gorenstein injective dimension \( \text{Gid}_R M \) equals the usual injective dimension \( \text{id}_R M \). In particular, if \( \text{Gid}_R R \) is finite, then also \( \text{id}_R R \) is finite, and thus \( R \) is Gorenstein (provided that \( R \) is commutative and Noetherian).

1. Introduction

It is well known that among the commutative local Noetherian rings \((R, \mathfrak{m}, k)\), the Gorenstein rings are characterized by the condition \( \text{id}_R R < \infty \). From the dual of [10] Proposition (2.27) \((10) \) Proposition 10.2.3\) is a special case\) it follows that the Gorenstein injective dimension \( \text{Gid}_R (\cdot) \) is a refinement of the usual injective dimension \( \text{id}_R (\cdot) \) in the following sense:

For any \( R \)-module \( M \) there is an inequality \( \text{Gid}_R M \leq \text{id}_R M \), and if \( \text{id}_R M < \infty \), then there is an equality \( \text{Gid}_R M = \text{id}_R M \).

Now, since the injective dimension \( \text{id}_R R \) of \( R \) measures Gorensteinness, it is only natural to ask what does the Gorenstein injective dimension \( \text{Gid}_R R \) of \( R \) measure? As a consequence of Theorem (2.1) below, it turns out that:

An associative ring \( R \) with \( \text{Gid}_R R < \infty \) also has \( \text{id}_R R < \infty \) (and hence \( R \) is Gorenstein, provided that \( R \) is commutative and Noetherian).

This result is proved by Christensen [2] Theorem (6.3.2) in the case where \((R, \mathfrak{m}, k)\) is a commutative local Noetherian Cohen-Macaulay ring with a dualizing module. The aim of this paper is to prove Theorem (2.1), together with a series of related results. Among these results is Theorem (3.2), which has the nice, and easily stated, Corollary (3.3):

Assume that \((R, \mathfrak{m}, k)\) is a commutative local Noetherian ring, and let \( M \) be an \( R \)-module of finite depth, that is, \( \text{Ext}^m_R(k, M) \neq 0 \) for some \( m \in \mathbb{N}_0 \) (this happens for example if \( M \neq 0 \) is finitely generated). If either

(i) \( \text{Gid}_R M < \infty \) and \( \text{id}_R M < \infty \) or (ii) \( \text{fd}_R M < \infty \) and \( \text{Gid}_R M < \infty \),

then \( R \) is Gorenstein.
This corollary is also proved by Christensen [2, Theorem (6.3.2)] in the case where \((R, m, k)\) is Cohen-Macaulay with a dualizing module. However, Theorem [3.2] itself (dealing not only with local rings) is a generalization of [8, Proposition 2.10] (in the module case) by Foxby from 1979.

We should briefly mention the history of Gorenstein injective, projective and flat modules: Gorenstein injective modules over an arbitrary associative ring, and the related Gorenstein injective dimension, was introduced and studied by Enochs and Jenda in [3]. The dual concept, Gorenstein projective modules, was already introduced by Auslander and Bridger [1] in 1969, but only for finitely generated modules over a two-sided Noetherian ring. Gorenstein flat modules were also introduced by Enochs and Jenda; please see [5].

1.1. Setup and notation. Let \(R\) be any associative ring with a nonzero multiplicative identity. All modules are—if not specified otherwise—left \(R\)-modules. If \(M\) is any \(R\)-module, we use pd\(_R\)\(M\), fd\(_R\)\(M\), and id\(_R\)\(M\) to denote the usual projective, flat, and injective dimension of \(M\), respectively. Furthermore, we write Gpd\(_R\)\(M\), Gfd\(_R\)\(M\), and Gid\(_R\)\(M\) for the Gorenstein projective, Gorenstein flat, and Gorenstein injective dimension of \(M\), respectively.

2. Rings with finite Gorenstein injective dimension

**Theorem 2.1.** If \(M\) is an \(R\)-module with pd\(_R\)\(M\) < \(\infty\), then Gid\(_R\)\(M\) = id\(_R\)\(M\).

In particular, if Gid\(_R\)\(R\) < \(\infty\), then also id\(_R\)\(R\) < \(\infty\) (and hence \(R\) is Gorenstein, provided that \(R\) is commutative and Noetherian).

**Proof.** Since Gid\(_R\)\(M\) ≤ id\(_R\)\(M\) always, it suffices to prove that id\(_R\)\(M\) ≤ Gid\(_R\)\(M\). Naturally, we may assume that Gid\(_R\)\(M\) < \(\infty\).

First consider the case where \(M\) is Gorenstein injective, that is, Gid\(_R\)\(M\) = 0. By definition, \(M\) is a kernel in a complete injective resolution. This means that there exists an exact sequence \(E = \cdots \rightarrow E_1 \rightarrow E_0 \rightarrow E_{-1} \rightarrow \cdots\) of injective \(R\)-modules, such that Hom\(_R\)\((I, E)\) is exact for every injective \(R\)-module \(I\), and such that \(M \cong \ker(E_1 \rightarrow E_0)\). In particular, there exists a short exact sequence \(0 \rightarrow M' \rightarrow E \rightarrow M \rightarrow 0\), where \(E\) is injective, and \(M'\) is Gorenstein injective. Since \(M'\) is Gorenstein injective and pd\(_R\)\(M\) < \(\infty\), it follows by [4, Lemma 1.3] that Ext\(_R^1(M, M') = 0\). Thus \(0 \rightarrow M' \rightarrow E \rightarrow M \rightarrow 0\) is split-exact; so \(M\) is a direct summand of the injective module \(E\). Therefore, \(M\) itself is injective.

Next consider the case where Gid\(_R\)\(M\) > 0. By [10, Theorem (2.15)] there exists an exact sequence \(0 \rightarrow M \rightarrow H \rightarrow C \rightarrow 0\) where \(H\) is Gorenstein injective and id\(_R\)\(C\) = Gid\(_R\)\(M\) - 1. As in the previous case, since \(H\) is Gorenstein injective, there exists a short exact sequence \(0 \rightarrow H' \rightarrow I \rightarrow H \rightarrow 0\) where \(I\) is injective and \(H'\) is Gorenstein injective. Now consider the pull-back diagram with exact rows and
Since $I$ is injective and $\text{id}_R M = 1$ we get $\text{id}_R P \leq \text{Gid}_R M$ by the second row. Since $H'$ is Gorenstein injective and $\text{pd}_R M < \infty$, it follows (as before) by 
Lemma 1.3] that $\text{Ext}^1_R(M, H') = 0$. Consequently, the first column $0 \to H' \to P \to M \to 0$ splits. Therefore $P \cong M \oplus H'$, and hence $\text{id}_R M \leq \text{id}_R P \leq \text{Gid}_R M$. \hfill $\square$

The theorem above has, of course, a dual counterpart:

**Theorem 2.2.** If $M$ is an $R$-module with $\text{id}_R M < \infty$, then $\text{Gpd}_R M = \text{pd}_R M$. \hfill $\square$

Theorem (2.6) below is a “flat version” of the two previous theorems. First recall the following.

**Definition 2.3.** The left finitistic projective dimension $\text{LeftFPD}(R)$ of $R$ is defined as

$$\text{LeftFPD}(R) = \sup \{ \text{pd}_R M \mid M \text{ is a left } R\text{-module with } \text{pd}_R M < \infty \}.$$ 

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

**Remark 2.4.** When $R$ is commutative and Noetherian, we have that $\text{LeftFPD}(R)$ and $\text{RightFPD}(R)$ equals the Krull dimension of $R$, by [9, Théorème (3.2.6) (Seconde partie)].

Furthermore, we will need the following result from [10, Proposition (3.11)]:

**Proposition 2.5.** For any (left) $R$-module $M$ the inequality

$$\text{Gid}_R \text{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}) \leq \text{Gfd}_R M$$

holds. If $R$ is right coherent, then we have $\text{Gid}_R \text{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}) = \text{Gfd}_R M$. \hfill $\square$

We are now ready to state:

**Theorem 2.6.** For any $R$-module $M$, the following conclusions hold:

(i) Assume that $\text{LeftFPD}(R)$ is finite. If $\text{fd}_R M < \infty$, then $\text{Gid}_R M = \text{id}_R M$.

(ii) Assume that $R$ is left and right coherent with finite $\text{RightFPD}(R)$. If $\text{id}_R M < \infty$, then $\text{Gfd}_R M = \text{fd}_R M$.

**Proof.** (i) If $\text{fd}_R M < \infty$, then also $\text{pd}_R M < \infty$, by [11] Proposition 6] (since $\text{LeftFPD}(R) < \infty$). Hence the desired conclusion follows from Theorem (2.1) above.

(ii) Since $R$ is left coherent, we have that $\text{fd}_R \text{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}) \leq \text{id}_R M < \infty$, by [12, Lemma 3.1.4]. By assumption, $\text{RightFPD}(R) < \infty$, and therefore also
pd_R\text{Hom}_Z(M, \mathbb{Q}/\mathbb{Z}) < \infty$, by [11, Proposition 6]. Now Theorem 2.1 gives that 
\text{Gid}_R\text{Hom}_Z(M, \mathbb{Q}/\mathbb{Z}) = \text{id}_R\text{Hom}_Z(M, \mathbb{Q}/\mathbb{Z}). It is well known that 
\text{fd}_RM = \text{id}_R\text{Hom}_Z(M, \mathbb{Q}/\mathbb{Z})
(without assumptions on R), and by Proposition 2.5 above, we also get \text{Gfd}_RM = \text{Gid}_R\text{Hom}_Z(M, \mathbb{Q}/\mathbb{Z}), since R is right coherent. The proof is done. 

\section{A theorem on Gorenstein rings by Foxby}

We end this paper by generalizing a theorem [8, Proposition 2.10] on Gorenstein rings by Foxby from 1979. For completeness, we briefly recall:

\subsection{The small support.}
Assume that R is commutative and Noetherian. For an R-module M, an integer n, and a prime ideal p in R, we write \beta^R_n(p, M), respectively, \mu^R_n(p, M), for the nth Betti number, respectively, nth Bass number, of M at p.

Foxby [8, Definition p. 157] or [7, (14.8)] defines the small (or homological) support of an R-module M to be the set 
\text{supp}_R M = \{ \ p \in \text{Spec} \ R \ | \ \exists n \in \mathbb{N}_0 : \beta^R_n(p, M) \neq 0 \}.

Let us mention the most basic results about the small support, all of which can be found in [8, pp. 157–159] and [7, Chapter 14]:

(i) The small support, \text{supp}_R M, is contained in the usual (large) support, \text{Supp}_R M, and \text{supp}_R M = \text{Supp}_R M if M is finitely generated. Also, if M \neq 0, then \text{supp}_R M \neq 0.

(ii) \text{supp}_R M = \{ \ p \in \text{Spec} \ R \ | \ \exists n \in \mathbb{N}_0 : \mu^R_n(p, M) \neq 0 \}.

(iii) Assume that (R, m, k) is local. If M is an R-module with finite depth, that is, 
\text{depth}_R M := \inf \{ \ m \in \mathbb{N}_0 \ | \ \text{Ext}^m_R(k, M) \neq 0 \} < \infty
(this happens for example if M \neq 0 is finitely generated), then m \in \text{supp}_R M, by (b) above.

Now, given these facts about the small support, and the results in the previous section, the following generalization of [8, Proposition 2.10] is immediate:

\textbf{Theorem 3.2.} Assume that R is commutative and Noetherian. Let M be any R-module, and assume that any of the following four conditions is satisfied:

(i) \text{Gpd}_RM < \infty and \text{id}_RM < \infty,

(ii) \text{pd}_RM < \infty and \text{Gid}_RM < \infty,

(iii) R has finite Krull dimension, and \text{Gfd}_RM < \infty and \text{id}_RM < \infty,

(iv) R has finite Krull dimension, and \text{fd}_RM < \infty and \text{Gid}_RM < \infty.

Then \text{R}_p is a Gorenstein local ring for all \ p \in \text{supp}_R M. \quad \square

\textbf{Corollary 3.3.} Assume that (R, m, k) is a commutative local Noetherian ring. If there exists an R-module M of finite depth, that is, 
\text{depth}_R M := \inf \{ \ m \in \mathbb{N}_0 \ | \ \text{Ext}^m_R(k, M) \neq 0 \} < \infty,
and which satisfies either

(i) \text{Gfd}_RM < \infty and \text{id}_RM < \infty, or

(ii) \text{fd}_RM < \infty and \text{Gid}_RM < \infty,

then R is Gorenstein. \quad \square
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References


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