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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), \([6]\) 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.

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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 \(\text{pd}_{R}M\), \(\text{id}_{R}M\), and \(\text{id}_{R}M\) to denote the usual projective, flat, and injective dimension of \(M\), respectively. Furthermore, we write \(\text{Gpd}_{R}M\), \(\text{Gfd}_{R}M\), and \(\text{Gid}_{R}M\) 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 \(\text{pd}_{R}M < \infty\), then \(\text{Gid}_{R}M = \text{id}_{R}M\). In particular, if \(\text{Gid}_{R}R < \infty\), then also \(\text{id}_{R}R < \infty\) (and hence \(R\) is Gorenstein, provided that \(R\) is commutative and Noetherian).

**Proof.** Since \(\text{Gid}_{R}M \leq \text{id}_{R}M\) always, it suffices to prove that \(\text{id}_{R}M \leq \text{Gid}_{R}M\). Naturally, we may assume that \(\text{Gid}_{R}M < \infty\).

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

Next consider the case where \(\text{Gid}_{R}M > 0\). By [10, Theorem (2.15)] there exists an exact sequence \(0 \to M \to H \to C \to 0\) where \(H\) is Gorenstein injective and \(\text{id}_{R}C = \text{Gid}_{R}M - 1\). As in the previous case, since \(H\) is Gorenstein injective, there exists a short exact sequence \(0 \to H' \to I \to H \to 0\) 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 [4, Lemma 1.3] that $\text{Ext}_{R}^1(M, H') = 0$. Consequently, the first column $0 \to H' \to P$ splits. Therefore $P \cong M \oplus H'$, and hence $\text{id}_R M \leq \text{id}_R P \leq \text{Gid}_R M$.

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

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 [3, 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

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

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

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 $\text{fd}_R \text{Hom}_R(M, \mathbb{Q}/\mathbb{Z}) \leq \text{id}_R M < \infty$, by [12, Lemma 3.1.4]. By assumption, $\text{RightFPD}(R) < \infty$, and therefore also
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) \( \text{Gpd}_R M < \infty \) and \( \text{id}_R M < \infty \),
(ii) \( \text{pd}_R M < \infty \) and \( \text{Gid}_R M < \infty \),
(iii) \( R \) has finite Krull dimension, and \( \text{Gfd}_R M < \infty \) and \( \text{id}_R M < \infty \),
(iv) \( R \) has finite Krull dimension, and \( \text{fd}_R M < \infty \) and \( \text{Gid}_R M < \infty \).

Then \( R_p \) is a Gorenstein local ring for all \( p \in \text{supp}_R M \). \( \square \)

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, \( \text{depth}_R M := \inf \{ m \in \mathbb{N}_0 \mid \text{Ext}^m_R(k, M) \neq 0 \} < \infty \),

and which satisfies either

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

then \( R \) is Gorenstein. \( \square \)
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References


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