Rings with finite Gorenstein injective dimension

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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, \( \text{Ext}_R^m(k, M) \neq 0 \) 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 \(\text{pd}_{R}M\), \(\text{fd}_{R}M\), 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 \(M \cong \ker(E_{1} \to E_{0})\). 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
columns:

\[
\begin{array}{c c c c c c c c c c c c c c c c c c}
0 & 0 & \rightarrow M & \rightarrow H & \rightarrow C & \rightarrow 0 \\
0 & \rightarrow P & \rightarrow I & \rightarrow C & \rightarrow 0 \\
\end{array}
\]

Since \( I \) is injective and \( \text{id}_{R}C = \text{Gid}_{R}M - 1 \) 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 \( 0 \rightarrow H' \rightarrow P \rightarrow M \rightarrow 0 \) splits. Therefore \( P \cong M \oplus H' \), and hence \( \text{id}_{R}M \leq \text{id}_{R}P \leq \text{Gid}_{R}M \).

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 \( \text{Gpd}_{R}M = \text{pd}_{R}M \).

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 [8] 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

\[ \text{Gid}_{R}\text{Hom}_{Z}(M, \mathbb{Q}/\mathbb{Z}) \leq \text{Gfd}_{R}M \]

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

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 \( \text{fd}_{R}\text{Hom}_{Z}(M, \mathbb{Q}/\mathbb{Z}) \leq \text{id}_{R}M < \infty \), by [12] Lemma 3.1.4]. By assumption, \( \text{RightFPD}(R) < \infty \), and therefore also...
pd_R Hom_Z(M, Q/Z) < ∞, by [11, Proposition 6]. Now Theorem 2.4 gives that 
Gid_R Hom_Z(M, Q/Z) = id_R Hom_Z(M, Q/Z). It is well known that 
fd_R M = id_R Hom_Z(M, Q/Z) (without assumptions on R), and by Proposition 2.5 above, we also get Gfd_R M = 
Gid_R Hom_Z(M, Q/Z), since R is right coherent. The proof is done.

3. 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:

3.1. 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 β^n_R(p, M), respectively, μ^n_R(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 

supp_R M = { p ∈ Spec R | ∃n ∈ N_0 : β^n_R(p, M) ≠ 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:

(a) The small support, supp_R M, is contained in the usual (large) support, Supp_R M, and supp_R M = Supp_R M if M is finitely generated. Also, if M ≠ 0, then supp_R M ≠ 0.

(b) supp_R M = { p ∈ Spec R | ∃n ∈ N_0 : μ^n_R(p, M) ≠ 0 }.

(c) Assume that (R, m, k) is local. If M is an R-module with finite depth, that is, 

depth_R M := inf{ m ∈ N_0 | Ext_R^m(k, M) ≠ 0 } < ∞

(this happens for example if M ≠ 0 is finitely generated), then m ∈ 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:

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) Gpd_R M < ∞ and id_R M < ∞,
(ii) pd_R M < ∞ and Gid_R M < ∞,
(iii) R has finite Krull dimension, and Gfd_R M < ∞ and id_R M < ∞,
(iv) R has finite Krull dimension, and fd_R M < ∞ and Gid_R M < ∞.

Then R_p is a Gorenstein local ring for all p ∈ supp_R M.

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, 

depth_R M := inf{ m ∈ N_0 | Ext_R^m(k, M) ≠ 0 } < ∞,

and which satisfies either

(i) Gfd_R M < ∞ and id_R M < ∞, or
(ii) fd_R M < ∞ and Gid_R M < ∞,

then R is Gorenstein.
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References


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