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ON DOMINANT DIMENSION OF NOETHERIAN RINGS

Dedicated to Professor Hiroyuki Tachikawa on his 60th birthday

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Throughout this note, R stands for a ring with identity and all modules are unital modules. In this note, for a given module M, we say that M has *dominant dimension* at least n, written dom dim $M \geqq n$, if each of the first n terms of the minimal injective resolution of M is flat. Following Morita [5], we call R left (resp. right) QF-3 if dom dim ${}_RR \geqq 1$ (resp. dom dim $R_R \geqq 1$). He showed that if R is left noetherian and left QF-3 then it is also right QF-3. Thus, if R is left and right noetherian, R is left QF-3 if and only if it is right QF-3. Generalizing this, we will prove the following

Theorem. *Let R be left and right noetherian. For any $n \geqq 1$,* dom dim ${}_RR \geqq n$ *if and only if* dom dim $R_R \geqq n$.

In case R is artinian, our dominant dimension coincides with Tachikawa's one [8], and the above theorem has been established (see Tachikawa [9] for details).

In what follows, for a given left or right R-module M, we denote by M^* the R-dual of M, by $\varepsilon_M\colon M \to M^{**}$ the usual evaluation map and by $E(M)$ the injective hull of M. We denote by mod R (resp. mod R^{op}) the category of all finitely generated left (resp. right) R-modules, where R^{op} stands for the opposite ring of R and right R-modules are considered as left R^{op}-modules.

1. Preliminaries. In this section, we recall several known facts which we need in later sections.

Lemma 1.1. *Let R be right noetherian. For any $N \in$ mod R^{op} and for any injective left R-module E,* $\mathrm{Hom}_R(\mathrm{Ext}^i_R(N, R), E) \simeq \mathrm{Tor}^R_i(N, E)$ *for $i \geqq 1$.*

Proof. See Cartan and Eilenberg [1, Chap. VI, Proposition 5.3].

Lemma 1.2. *Every finitely presented submodule of a flat module is torsionless.*

Proof. See Lazard [4, Théorème 1.2].

Lemma 1.3. *Let R be right noetherian. Let E be an injective left R-module* *and suppose that every finitely generated submodule of E is torsionless. Then E is flat.*

Proof. See Sato [6, Lemma 1.4]. His argument remains valid in our setting.

Lemma 1.4. *Let R be left and right noetherian. Suppose that R is left QF-3. An injective left R-module E is flat if and only if it is cogenerated by $E({}_RR)$.*

Proof. Immediate by Lemmas 1.2 and 1.3.

Lemma 1.5. *Let R be left noetherian. Suppose that* inj dim $R_R=n<\infty$. *For a minimal injective resolution $O\to{}_RR\to E_0\to E_1\to\cdots$, $E=\bigoplus_{i=0}^{n} E_i$ is an injective cogenerator.*

Proof. See Iwanaga [3, Theorem 2]. His argument remains valid in our setting.

2. Proof of Theorem. In order to prove the theorem, we need two more lemmas.

Lemma 2.1. *Let R be left noetherian and $n\geqq 1$. For any $M\in\operatorname{mod} R$ with $\operatorname{Ext}_R^i(M, R)=0$ for $1\leqq i\leqq n$ and for any $L\in\operatorname{mod} R$ with* proj dim $L=m<n$, *$\operatorname{Ext}_R^i(M, L)=0$ for $1\leqq i\leqq n-m$.*

Proof. By induction on $m\geqq 0$. The case $m=0$ is clear. Let $m\geqq 1$ and let $0\to K\to P\to L\to 0$ be an exact sequence in mod R with P projective. Since proj dim $K=m-1$, by induction hypothesis $\operatorname{Ext}_R^i(M, K)=0$ for $1\leqq i\leqq n-m+1$. Applying the functor $\operatorname{Hom}_R(M, -)$ to the above exact sequence, we get $\operatorname{Ext}_R^i(M, L)\simeq\operatorname{Ext}_R^{i+1}(M, K)=0$ for $1\leqq i\leqq n-m$.

Lemma 2.2. *Let R be left and right noetherian. Suppose that R is left QF-3. For any $n\geqq 2$,* dom dim ${}_RR\geqq n$ *if and only if for an $M\in\operatorname{mod} R$, $M^*=0$ implies $\operatorname{Ext}_R^i(M, R)=0$ for $1\leqq i\leqq n-1$.*

Proof. Let $0\to{}_RR\xrightarrow{f_0}E_0\xrightarrow{f_1}E_1\to\cdots$ be a minimal injective resolution. For any $i\geqq 1$ we have an exact sequence of functors

$$\operatorname{Hom}_R(-, E_{i-1})\to\operatorname{Hom}_R(-, \operatorname{Im} f_i)\to\operatorname{Ext}_R^i(-, R)\to 0\,.$$

"Only if" part. For a given $M\in\operatorname{mod} R$ with $M^*=0$, by Lemma 1.2 $\operatorname{Hom}_R(M, E_i)=0$ for $1\leqq i\leqq n-1$. Thus $\operatorname{Hom}_R(M, \operatorname{Im} f_i)=0$, and by the above exact sequence $\operatorname{Ext}_R^i(M, R)=0$ for $1\leqq i\leqq n-1$.

"If" part. By induction on $i\geqq 0$, we show that E_i is flat for $0\leqq i\leqq n-1$. By assumption, E_0 is flat. Let $1\leqq i\leqq n-1$ and suppose that E_{i-1} is flat. For a given $M\in\operatorname{mod} R$ with $M^*=0$, we claim $\operatorname{Hom}_R(M, \operatorname{Im} f_i)=0$. We have

$\operatorname{Ext}_R^i(M, R)=0$. Also, by Lemma 1.2 $\operatorname{Hom}_R(M, E_{i-1})=0$. Thus by the above exact sequence $\operatorname{Hom}_R(M, \operatorname{Im} f_i)=0$. Hence $\operatorname{Im} f_i$ is cogenerated by $E({}_R R)$, and by Lemma 1.4 E_i is flat.

We are now in a position to prove the theorem. It suffices to prove the "only if" part.

"Only if" part of Theorem. The case $n=1$ is due to Morita [5, Theorem 1]. Let $n \geqq 2$. Note that R is left and right QF-3. Replacing R with R^{op} in Lemma 2.2, it suffices to show that for any $N \in \operatorname{mod} R^{op}$ with $N^*=0$ we have $\operatorname{Ext}_R^i(N, R)=0$ for $1 \leqq i \leqq n-1$. For a given $N \in \operatorname{mod} R^{op}$ with $N^*=0$, we claim first that $\operatorname{Ext}_R^i(N, R)^*=0$ for $i \geqq 1$. For any $i \geqq 1$, by Lemma 1.1 $\operatorname{Hom}_R(\operatorname{Ext}_R^i(N, R), E({}_R R)) \simeq \operatorname{Tor}_i^R(N, E({}_R R))=0$, thus $\operatorname{Ext}_R^i(N, R)^*=0$. Hence by Lemma 2.2 $\operatorname{Ext}_R^j(\operatorname{Ext}_R^i(N, R), R)=0$ for $i \geqq 1$ and $1 \leqq j \leqq n-1$. Now, by induction on $i \geqq 1$, we show that $\operatorname{Ext}_R^i(N, R)=0$ for $1 \leqq i \leqq n-1$. Let $\cdots \to P_1 \xrightarrow{f_1} P_0 \xrightarrow{f_0} N \to 0$ be an exact sequence in mod R^{op} with the P_i projective and put $N_i=\operatorname{Im} f_i$. Since $N^*=0$, we have an exact sequence

$$0 \to P_0^* \xrightarrow{\beta_1} N_1^* \xrightarrow{\alpha_1} \operatorname{Ext}_R^1(N, R) \to 0 .$$

Since $\operatorname{Ext}_R^1(\operatorname{Ext}_R^1(N, R), R)=0$, α_1 splits. On the other hand, since $\operatorname{Ext}_R^1(N, R)^* =0$, $\operatorname{Hom}_R(\operatorname{Ext}_R^1(N, R), N_1^*)=0$. Thus $\operatorname{Ext}_R^1(N, R)=0$. Next, let $1<i \leqq n-1$ and suppose that $\operatorname{Ext}_R^j(N, R)=0$ for $1 \leqq j \leqq i-1$. We have an exact swquence

$$0 \to P_0^* \to \cdots \to P_{i-1}^* \xrightarrow{\beta_i} N_i^* \xrightarrow{\alpha_i} \operatorname{Ext}_R^i(N, R) \to 0 .$$

Since $\operatorname{Ext}_R^j(\operatorname{Ext}_R^i(N, R), R)=0$ for $1 \leqq j \leqq n-1$, and since proj dim $\operatorname{Im} \beta_i \leqq i-1 <n-1$, by Lemma 2.1 $\operatorname{Ext}_R^1(\operatorname{Ext}_R^i(N, R), \operatorname{Im} \beta_i)=0$. Thus α_i splits. On the other hand, $\operatorname{Ext}_R^i(N, R)^*=0$ implies $\operatorname{Hom}_R(\operatorname{Ext}_R^i(N, R), N_i^*)=0$. Hence $\operatorname{Ext}_R^i(N, R)=0$.

3. Left exactness of the double dual.

In this section, we establish the relation between the dominant dimension of a left and right noetherian ring R and the behavior of the functor $(\ )^{**}$: mod $R \to$ mod R. Compare our results with Colby and Fuller [2, Theorems 1 and 2].

Proposition 3.1. *Let R be left and right noetherian. Then R is left QF-3 if and only if the functor* $(\ )^{**}$: mod $R \to$ mod R *preserves monomorphisms.*

This is an immediate consequence of Morita [5, Theorem 1] and the following lemmas.

Lemma 3.2. *Let R be left noetherian and right QF-3. For any monomorphism $\alpha: M \to L$ with $M, L \in \operatorname{mod} R$, α^{**} is monic.*

Proof. For a given exact sequence $0\to M\xrightarrow{\alpha}L\to K\to 0$ in mod R, we claim $(\operatorname{Cok}\alpha^*)^*=0$. By Lemma 1.1 $\operatorname{Hom}_R(\operatorname{Ext}_R^1(K,R), E(R_R))\simeq\operatorname{Tor}_1^R(E(R_R),K)=0$. Since $\operatorname{Cok}\alpha^*$ is imbedded into $\operatorname{Ext}_R^1(K,R)$, we get $\operatorname{Hom}_R(\operatorname{Cok}\alpha^*, E(R_R))=0$. Thus $(\operatorname{Cok}\alpha^*)^*=0$, and α^{**} is monic.

Lemma 3.3. *Let R be right noetherian. Suppose that for any monomorphism $\alpha\colon M\to L$ with $M, L\in\operatorname{mod} R$ α^{**} is monic. Then R is left QF-3.*

Proof. For a given $M\in\operatorname{mod} R$ with $M\subset E({}_RR)$, we claim that M is torsionless. Replacing M with $M+R$ if necessary, we may assume $R\subset M$. Denote by ι the inclusion $R\hookrightarrow M$. Since ι^{**} is monic, so is $\iota^{**}\circ\varepsilon_R=\varepsilon_M\circ\iota$. Thus $R\cap\operatorname{Ker}\varepsilon_M=0$, which implies $\operatorname{Ker}\varepsilon_M=0$. Hence by Lemma 1.3 $E({}_RR)$ is flat.

Now we can prove the following

Proposition 3.4. *Let R be left and right noetherian. Then* dom dim ${}_RR\geqq 2$ *if and only if the functor $(\ \ )^{**}$:* mod $R\to$ mod R *is left exact.*

Proof. "Only if" part. For a given exact sequence $0\to M\xrightarrow{\alpha}L\xrightarrow{\beta}K\to 0$ in mod R, we claim $(\operatorname{Cok}\alpha^*)^*=0=\operatorname{Ext}_R^1(\operatorname{Cok}\alpha^*, R)$. Note that dom dim $R_R\geqq 2$. By Lemma 3.2, α^{**} is monic. Thus $(\operatorname{Cok}\alpha^*)^*=0$, and by Lemma 2.2 $\operatorname{Ext}_R^1(\operatorname{Cok}\alpha^*, R)=0$. Hence the following sequence is exact:

$$0\to M^{**}\xrightarrow{\alpha^{**}}L^{**}\xrightarrow{\beta^{**}}K^{**}\,.$$

"If" part. By Lemma 3.3, $E({}_RR)$ is flat. For a given $M\in\operatorname{mod} R$ with $M\subset E({}_RR)/R$, we claim that M is torsionless. There is some $L\in\operatorname{mod} R$ such that $L\subset E({}_RR)$ and $M=L/R$. By Lemma 1.2, L is torsionless. We have the following commutative diagram with exact rows:

$$\begin{array}{ccccccc} 0\to & R & \longrightarrow & L & \longrightarrow & M & \longrightarrow 0\\ & \downarrow\wr & & \downarrow\varepsilon_L & & \downarrow\varepsilon_M & \\ 0\to & R^{**} & \to & L^{**} & \to & M^{**}\,. & \end{array}$$

Since ε_L is monic, so is ε_M. Thus by Lemma 1.4 $E(E({}_RR)/R)$ is flat.

4. Remarks.

In this final section, we make some remarks on noetherian rings of finite self-injective dimension.

The following proposition is essentially due to Iwanaga [3].

Proposition 4.1. *Let R be left noetherian. Suppose that* inj dim ${}_RR<\infty$ *and that the last non-zero term of the minimal injective resolution of ${}_RR$ is flat. Then R is quasi-Frobenius.*

Proof. Suppose to the contrary that ${}_RR$ is not injective. Put $n=$inj dim ${}_RR$

and let $0 \to {}_R R \to E_0 \to E_1 \to \cdots \to E_n \to 0$ be a minimal injective resolution. There is a torsion theory $(\mathcal{T}, \mathcal{F})$ in mod R such that $\mathcal{F}$ consists of the modules $M \in \text{mod}\, R$ with $\text{Ext}_R^n(M, R) = 0$. Note that $\mathcal{T}$ contains a simple module L. Since E_n is flat, and since $\text{Hom}_R(L, E_n) \simeq \text{Ext}_R^n(L, R) \neq 0$, by Lemma 1.2 L is torsionless, which implies $L \in \mathcal{F}$, a contradiction.

Proposition 4.2. *Let R be left noetherian. Suppose that* inj dim $R_R <$ dom dim ${}_R R$. *Then $E({}_R R)$ is an injective cogenerator.*

Proof. Let $0 \to {}_R R \to E_0 \to E_1 \to \cdots$ be a minimal injective resolution and put $E = \bigoplus_{i=0}^{n} E_i$, where $n =$ inj dim R_R. By Lemma 1.5 E is an injective cogenerator. Thus, since E is flat, by Lemma 1.2 every $M \in \text{mod}\, R$ is torsionless, namely $E({}_R R)$ is an injective cogenerator.

The next proposition generalizes Sumioka [7, Theorem 5].

Proposition 4.3. *Let R be left and right noetherian and $n \geqq 1$. Suppose that* inj dim ${}_R R \leqq n \leqq$ dom dim ${}_R R$. *For a minimal injective resolution $0 \to {}_R R \to E_0 \to E_1 \to \cdots$, $E = \bigoplus_{i=0}^{n} E_i$ is an injective cogenerator if and only if* inj dim $R_R \leqq n$.

Proof. "Only if" part. Since E_i is flat for $0 \leqq i \leqq n-1$, and since $E_i = 0$ for $i > n$, E_n and thus E have weak dimension at most n. Thus by Lemma 1.1 $\text{Hom}_R(\text{Ext}_R^{n+1}(N, R), E) \simeq \text{Tor}_{n+1}^R(N, E) = 0$ for all $N \in \text{mod}\, R^{op}$. Hence, since E is an injective cogenerator, inj dim $R_R \leqq n$.

"If" part. By Lemma 1.5.

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