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DUAL-BIMODULES AND FINITELY COGENERATED MODULES

In memory of Professor Hisao Tominaga

YOSHIKI KURATA and KAZUTOSHI KOIKE

Let R and S be rings with identity and ${}_R Q_S$ an (R, S) -bimodule. We shall call Q a left dual-bimodule provided that $\ell_{Rr_Q}(A) = A$ for every left ideal A of R and $r_Q \ell_R(Q') = Q'$ for every S -submodule Q' of Q (see [5]).

In this note, first we shall show that a left dual-bimodule ${}_R Q_S$ defines a duality between the finitely generated left ideals of R and the finitely cogenerated factor modules of Q_S . Then, as an application of this duality, we shall give necessary and sufficient conditions for R to be left semihereditary or left coherent.

For notations and definitions we shall follow [1] and [5].

1. Let R and S be rings with identity and ${}_R Q_S$ an (R, S) -bimodule. Suppose that Q_S is quasi-injective and the natural homomorphism $\lambda: R \rightarrow \text{End}(Q_S)$ is an isomorphism. Then by [7, Theorem 2.1], for each S -module N_S , there is a bijection between the finitely generated submodules of the Q -dual ${}_R N^*$ of N and the finitely closed submodules of N_S given by

$$L \longrightarrow r_N(L)$$

with the inverse $K \rightarrow \ell_{N^*}(K)$. Here, a submodule K of N_S is said to be finitely closed (with respect to Q_S) if there exists an integer $m > 0$ such that

$$0 \longrightarrow N/K \longrightarrow Q^m$$

is exact, or equivalently, there exist f_1, f_2, \dots, f_m in N^* such that

$$\bigcap_{j=1}^m \text{Ker } f_j = K.$$

In case Q_S is finitely cogenerated, K finitely closed means that N/K is finitely cogenerated Q -torsionless.

Using this theorem, Miller and Turnidge pointed out that, under the same assumption as above, R is left Noetherian (right perfect) if and only if Q_S has DCC (ACC) on finitely closed submodules.

If, in particular, ${}_R Q_S$ is a left dual-bimodule with Q_S quasi-injective and λ surjective, then the bijection yields one between the finitely generated left ideals of R and the finitely closed submodules of Q_S given by

$$A \longrightarrow r_Q(A)$$

with the inverse $Q' \rightarrow \ell_R(Q')$. Hence, in this case, R is left Noetherian (right perfect) if and only if Q_S has DCC (ACC) on the submodules $r_Q(A)$ of Q_S with A a finitely generated left ideal of R and R is regular if and only if every submodule of Q_S of the above form is a direct summand of Q_S (cf. [4, Proposition 4.2 and Theorem 4.3]). On the other hand, since the mapping $Ra \rightarrow r_Q(a)$ is a bijection between the principal left ideals of R and the submodules $r_Q(a)$ of Q_S with a in R , it follows that R is right perfect if and only if Q_S has ACC on the submodules $r_Q(a)$ of Q_S with a in R and that R is regular if and only if every submodule of Q_S of the last form is a direct summand of Q_S (cf. [4, Theorem 3.1 and Proposition 4.1]).

2. For an (R, S) -bimodule ${}_R Q_S$, as was shown in [5, Theorem 3.3], if Q_S is quasi-injective and λ is surjective, then the pair (H', H'') of functors

$$H' = \text{Hom}_R(-, Q) : {}_R \underline{M} \longrightarrow \underline{N}_S,$$

$$H'' = \text{Hom}_S(-, Q) : \underline{N}_S \longrightarrow {}_R \underline{M}$$

defines a duality between the full subcategory ${}_R \underline{M}$ of R -mod of finitely generated Q -torsionless R -modules and the full subcategory \underline{N}_S of mod- S whose objects are all the S -modules N_S such that

$$0 \longrightarrow N \longrightarrow Q^n \longrightarrow Q^I$$

is exact for some integer $n > 0$ and a set I . Assume further that Q_S is finitely cogenerated, then by [5, Proposition 3.4]

$${}_R \underline{M} = \{ {}_R M \mid M \text{ is finitely generated and } Q\text{-reflexive} \}$$

and

$$\underline{N}_S = \{ N_S \mid N \text{ is finitely cogenerated and } Q\text{-reflexive} \}.$$

If, in addition, Q_S is a self-cogenerator, then by [6, Proposition 4]

$$\underline{N}_S = \{ N_S \mid 0 \rightarrow N \rightarrow Q^n \text{ is exact for some } n > 0 \}.$$

Using the bijection in Section 1, we shall now show that (H', H'') defines a duality between more restricted subcategories of ${}_{R}\underline{M}$ and \underline{N}_S .

Theorem 1. *Let ${}_{R}Q_S$ be a left dual-bimodule with Q_S quasi-injective and λ surjective. Then (H', H'') defines a duality between the finitely generated left ideals of R and the finitely cogenerated factor modules of Q_S .*

Proof. Let A be a finitely generated left ideal of R . Then A belongs to ${}_{R}\underline{M}$ and A^* is isomorphic to a finitely cogenerated factor module $Q/r_Q(A)$ of Q_S by [5, Lemma 1.13]. On the other hand, for each finitely cogenerated factor module Q/Q' of Q_S , Q' is finitely closed and hence $\ell_R(Q')$ is finitely generated and is Q -reflexive. Again by [5, Lemma 1.13], $Q/Q' \cong \ell_R(Q')^*$. Thus, Q/Q' is in \underline{N}_S and $(Q/Q')^*$ is isomorphic to $\ell_R(Q')$.

Corollary 2. *Let ${}_{R}Q_S$ be a left dual-bimodule with Q_S quasi-injective and λ surjective. If R is left Noetherian, then (H', H'') defines a duality between the left ideals of R and the factor modules of Q_S .*

In contrast with Corollary 2, (H', H'') always defines a duality between the factor modules of ${}_{R}R$ and the submodules of Q_S under the same assumption of Corollary 2. Indeed, for each left ideal A of R , R/A is Q -reflexive by [5, Theorem 3.2] and $(R/A)^* \cong r_Q(A)$. On the other hand, for each submodule Q' of Q_S , $Q' = r_Q(\ell_R(Q')) \cong (R/\ell_R(Q'))^*$. Hence, Q' is Q -reflexive by [1, Proposition 20.14] and $Q'^* \cong R/\ell_R(Q')$.

If ${}_{R}Q_S$ is a dual-bimodule with both ${}_{R}Q$ and Q_S injective, then using [1, Exercise 23.7] (H', H'') defines a duality between the left R -modules of finite length and the right S -modules of finite length by [5, Theorem 2.1]. However, we have

Theorem 3. *Let ${}_{R}Q_S$ be a left dual-bimodule with Q_S quasi-injective and λ surjective. Then (H', H'') defines a duality between the Q -torsionless left R -modules of finite length and the Q -torsionless right S -modules of finite length.*

Proof. Let ${}_{R}M$ be a Q -torsionless R -module of finite length and let

$$M = M_0 > M_1 > \cdots > M_n = 0$$

be a composition series of M . Then

$$0 = r_{M^\bullet}(M_0) \leq r_{M^\bullet}(M_1) \leq \cdots \leq r_{M^\bullet}(M_n) = M^*$$

is a series of S -submodules of M^* , where $r_{M^*}(M_i) = \{f: M \rightarrow Q \mid M_i \leq \text{Ker } f\}$ (see [1, p.281]). For each i , each element of $r_{M^*}(M_{i+1})$ induces an R -homomorphism from M_i/M_{i+1} to Q and hence $r_{M^*}(M_{i+1})/r_{M^*}(M_i)$ can be seen as an S -submodule of $(M_i/M_{i+1})^*$. Since M_i/M_{i+1} is simple, $(M_i/M_{i+1})^*$ is isomorphic to a simple submodule of Q_S , as is seen from the proof of [5, Theorem 2.1]. Hence, $r_{M^*}(M_{i+1})/r_{M^*}(M_i)$ is zero or simple. Thus, M_S^* is a module of finite length and $c(M^*) \leq c(M)$, where $c(-)$ denotes the composition length. Furthermore, by [1, Proposition 20.14], M_S^* is Q -torsionless.

Using [1, Exercise 16.18], for a Q -torsionless S -module N_S of finite length, ${}_R N^*$ is a Q -torsionless R -module of finite length and $c(N^*) \leq c(N)$ holds.

Clearly each Q -torsionless R -module ${}_R M$ of finite length is Q -reflexive and we have $c(M) = c(M^*)$. On the other hand, each Q -torsionless S -module N_S of finite length is finitely cogenerated. Hence it is Q -reflexive. Thus, we have $c(N) = c(N^*)$.

Corollary 4. *Let ${}_R Q_S$ be a left dual-bimodule with Q_S quasi-injective and λ surjective. Then (H', H'') defines a duality between the simple left R -modules and the Q -torsionless simple right S -modules.*

In case ${}_R Q_S$ is a dual-bimodule, however, (H', H'') defines a duality between the simple left R -modules and the simple right S -modules, as is seen from [5, Theorem 2.1].

3. It is shown by [5, Proposition 1.12] that for a left dual-bimodule ${}_R Q_S$, R is semisimple if and only if Q_S is semisimple. On the other hand, we have

Theorem 5. *Let ${}_R Q_S$ be a left dual-bimodule with λ surjective. Then R is simple Artinian if and only if $Q_S \cong Q_1^n$ for some integer $n > 0$ and some simple right S -module Q_1 .*

Proof. Suppose that R is simple Artinian. Then Q_S is semisimple and is finitely generated by [5, Proposition 1.8]. Let Q_1 be a simple submodule of Q_S . Then $\ell_R(RQ_1)$ is a proper ideal of R and hence it must be zero by assumption. Therefore, $RQ_1 = r_Q \ell_R(RQ_1) = Q$. However, $RQ_1 = \sum_{a \in R} aQ_1$ and each aQ_1 is either zero or isomorphic to Q_1 . Thus we have $Q \cong Q_1^n$ for some integer $n > 0$.

Conversely, suppose that $Q_S \cong Q_1^n$ for some integer $n > 0$ and some simple right S -module Q_1 . Then since $R \cong^\lambda \text{End}(Q_S)$, R is isomorphic to the ring of all $n \times n$ matrices over the division ring $\text{End}(Q_1)$. Thus, R is simple Artinian.

Now, using Theorem 1, we shall give a necessary and sufficient condition for R to be left semihereditary (cf. [2, Corollary 2.4] and [8, Proposition 2.1]).

Theorem 6. *Let ${}_R Q_S$ be a left dual-bimodule with Q_S quasi-injective and λ surjective. Then the following conditions are equivalent:*

- (1) R is left semihereditary.
- (2) Every finitely cogenerated factor module of Q_S is Q -injective.
- (3) For every finitely generated left ideal A of R , A^* is Q -injective.

Proof. Let A be a finitely generated left ideal of R and let $R^n \rightarrow A \rightarrow 0$ be exact for some integer $n > 0$. Then the sequence

$$0 \longrightarrow A^* \longrightarrow Q^n \tag{*}$$

is also exact. Since A is Q -reflexive and $R \cong^\lambda \text{End}(Q_S)$, A is projective if and only if (*) is split exact and this is so if and only if A^* is Q -injective. Thus, (1) and (3) are equivalent. By Theorem 1, (2) and (3) are also equivalent.

Theorem 7. *For a dual ring R the following conditions are equivalent:*

- (1) R is left semihereditary.
- (2) R is semisimple.

Proof. (1) \implies (2). Suppose that R is left semihereditary. Since $R/\text{rad}(R)$ is semisimple by [5, Theorem 1.10], $0 \rightarrow R/\text{rad}(R) \rightarrow \text{soc}(R)^n$ is split exact for some integer $n > 0$. By [5, Proposition 1.8] $\text{soc}(R)$ is projective. Hence, $R/\text{rad}(R)$ is also projective. Thus, $\text{rad}(R)$ must be a direct summand of R , from which it follows that $\text{rad}(R) = 0$ and R is semisimple. (2) \implies (1) is trivial.

As is easily seen, a ring R is left coherent if and only if for every integer $n > 0$ and every R -homomorphism $f: {}_R R^n \rightarrow {}_R R$ there exist an integer $m > 0$ and an R -homomorphism $g: {}_R R^m \rightarrow {}_R R^n$ such that

$$R^m \xrightarrow{g} R^n \xrightarrow{f} R$$

is exact. For a left dual-bimodule ${}_R Q_S$, using Q_S instead of R , a similar characterization for R to be left coherent can be obtained (cf. [2, Theorem 2.6 and Corollary 2.7]).

Theorem 8. *For a left dual-bimodule ${}_R Q_S$ with Q_S quasi-injective and λ surjective, the following conditions are equivalent:*

(1) *R is left coherent.*

(2) *For every finitely cogenerated factor module Q/Q' of Q_S , there exist integers $n, m > 0$ such that*

$$0 \longrightarrow Q/Q' \longrightarrow Q^n \longrightarrow Q^m$$

is exact.

(3) *For every finitely generated left ideal A of R , there exist integers $n, m > 0$ such that*

$$0 \longrightarrow A^* \longrightarrow Q^n \longrightarrow Q^m$$

is exact.

(4) *For every integer $n > 0$ and every S -homomorphism $f: Q \rightarrow Q^n$ there exist an integer $m > 0$ and an S -homomorphism $g: Q^n \rightarrow Q^m$ such that*

$$Q \xrightarrow{f} Q^n \xrightarrow{g} Q^m$$

is exact.

Proof. It is easy to see that (1), (2) and (3) are equivalent.

(1) \implies (4). Assume (1) and let $f: Q \rightarrow Q^n$ be an S -homomorphism. Then $0 \rightarrow Q/K \xrightarrow{\bar{f}} Q^n$ is exact, where $K = \text{Ker } f$ and \bar{f} is the homomorphism induced by f . Hence Q/K is finitely cogenerated Q -reflexive. By Theorem 1, $(Q/K)^*$ is a finitely generated left ideal of R and $R^n \rightarrow (Q/K)^* \rightarrow 0$ is exact. Since R is left coherent, there exists an integer $m > 0$ such that $R^m \rightarrow R^n \rightarrow (Q/K)^* \rightarrow 0$ is exact. Thus, $0 \rightarrow Q/K \xrightarrow{\bar{f}} Q^n \xrightarrow{g} Q^m$ is exact for some S -homomorphism g , which shows that

$$Q \xrightarrow{f} Q^n \xrightarrow{g} Q^m$$

is exact.

(4) \implies (2). Assume (4) and let Q/Q' be any finitely cogenerated factor module of Q_S . Then Q' is finitely closed and hence there exists an integer $n > 0$ such that $0 \rightarrow Q/Q' \xrightarrow{f} Q^n$ is exact for some S -homomorphism f . Let $\pi: Q \rightarrow Q/Q'$ be the canonical epimorphism. Then by (4) there exist

an integer $m > 0$ and an S -homomorphism g such that $Q \xrightarrow{f\pi} Q^n \xrightarrow{g} Q^m$ is exact and thus so is $0 \rightarrow Q/Q' \xrightarrow{f} Q^n \xrightarrow{g} Q^m$.

It is to be noted that if R is a dual ring with R_R injective, then the bimodule ${}_R R_R$ defines a Morita duality by [1, Exercise 24.10] and [6, Corollary 6]. However, this is not the case for a left dual-bimodule in general. For example, let $R = Q = \mathbb{Z}/(p)$, p a prime number, and $S = \mathbb{Z}$. Then the bimodule ${}_R Q_S$ is a left dual-bimodule with Q_S quasi-injective and λ surjective, but does not define any Morita duality.

For this left dual-bimodule, R is left Noetherian, right perfect and is also regular. Furthermore, it is left semihereditary and left coherent, too.

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