Note on quasi-injective modules

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Let $R$ be a ring with identity element and $M$ be a unitary left $R$-module. $M$ is called quasi-injective if every element in $\text{Hom}_R(N, M)$ for any $R$-module $N$ in $M$ is extended to an element in $\text{Hom}_R(M, M)$. $M$ is an essential extension of $N$ if $M' \cap N = (0)$ for any non-zero $R$-submodule $M'$ of $M$ and we call in this case that $N$ is an essential submodule in $M$.

In Goldie [2] and Johnson, Wong [4] they have defined an $R$-submodule in $M$ for $R$-submodule $N$ as follows: $\text{cl}N = \{m \in M | (N; m)\}$ is an essential left ideal in $R\}$. If $\text{cl}N = N$, then $N$ is called closed. We call $\text{cl}(0)$ the singular submodule of $M$.

Johnson and Wong studied structures of closed submodules of a quasi-injective $R$-module with zero singular submodule and Goldie has also considered rings with zero singular ideal in [3], [4] and [2], respectively.

In this short note we shall prove the following theorem:

Let $M$ be a quasi-injective $R$-module. Then $M$ is a direct-sum of $Z_2(M) = \text{cl}(0)$ and any maximal submodule $M_0$ with zero singular submodule: $M = M_0 \oplus Z_2(M)$. Furthermore, every closed submodule in $M$ corresponds uniquely to a direct summand of $M_0$, which is closed in $M_0$.

From this result we know some results in [3], [4] are valid without assumption $\text{cl}(0) = (0)$.

In § 2 we shall study all types of quasi-injective modules in a case where either $R$ is a Dedekind domain or an algebra over a field with finite dimension.

We always assume that $R$ is a ring with identity and $M$ a unitary left $R$-module.

1. Closed submodules.

We shall denote the singular submodule $\text{cl}(0)$ of $M$ by $Z(M)$ and $\text{cl}(0)$ by $Z_2(M)$ following to [2]. We also call $Z_2(M)$ the torsion submodule of $M$ and $M$ is torsion free if $Z_2(M) = (0)$. If $R$ is a commutative integral domain, then they coincide with the usual torsion submodules.
and torsion-free modules.

We note that if \( M \) is an essential extension of \( N \), then the left ideal \( (N : m) \) is essential in \( R \) for any element \( m \) in \( M \).

From [2], Lemma 2, we have

**Lemma 1.1.** \( Z_2(M) \) is a closed submodule in \( M \).

From the definition of closed module we have

**Lemma 1.2.** Every closed submodule of \( M \) contains \( Z_2(M) \).

**Lemma 1.3.** For submodules \( N_1, N_2 \) of \( M \) we have

\[
\text{cl}(N_1 \cap N_2) = \text{cl}N_1 \cap \text{cl}N_2.
\]

Let \( N \) be a submodule of \( M \). If a submodule \( B \) of \( M \) is a maximal one with property \( N \cap B = (0) \), then we call \( B \) a complement of \( N \) in \( M \). We denote it by \( N^c \).

**Lemma 1.4.** Let \( N \) be a submodule of \( M \) and \( B \) a complement of \( N \). Then \( M \) is an essential extension of \( B \oplus N \). Hence, \( \text{cl}(B \oplus N) = M \).

**Proposition 1.5.** Let \( M \) be a quasi-injective \( R \)-module. Then every closed submodule \( N \) is a direct summand of \( M \), namely \( M = N \oplus N^c \) (cf. [4], Proposition 1.5).

Proof. Let \( N \) be a closed submodule and \( B \) a complement of \( N \) in \( M \). Put \( M_0 = B \oplus N \). Let \( p \) be a projection of \( M_0 \) to \( N \). Then there exists an element \( g \in \text{Hom}_R(M, M) \) such that \( g|_{M_0} = p \). Since \( g^{-1}(0) \supseteq B \) and \( g^{-1}(0) \cap N = (0) \), \( g^{-1}(0) = B \). Furthermore, since \( \text{cl}M_0 = M \) by Lemma 1.4, there exists an essential left ideal \( L \) for any element \( m \) in \( M \) such that \( Lm \subseteq M \). Therefore, \( Lg(m) = g(Lm) \subseteq N \). Since \( \text{cl}N = N \), \( g(m) \in N \). Hence, \( g(M) = N \). Therefore, \( M = g^{-1}(0) + g(M) = B \oplus N \).

**Corollary.** Let \( M \) be a quasi-injective. If \( N \) is closed, then \( N \) is quasi-injective (cf. [3], Theorem 1.6).

Proof. Since it is clear that a direct summand of a quasi-injective module is quasi-injective, we have the corollary from Proposition 1.5.

If we consider \( R \) as a left \( R \)-module, we have from the definition

**Lemma 1.6.** Let \( M \supseteq N \) be \( R \)-modules. Then 1) \( Z(R)M \subseteq Z(M) \), 2) \( Z_2(R)M \subseteq Z_2(M) \), 3) \( Z(N) = N \cap Z(M) \) and 4) \( Z_2(N) = N \cap Z_2(M) \).

**Theorem 1.7.** Let \( M \) be a quasi-injective \( R \)-module and \( M_0 \) a submodule which is a maximal one with \( Z(M_0) = (0) \). Then \( M = M_0 \oplus Z_2(M) \).

A submodule \( N \) of \( M \) is closed if and only if \( N \) contains \( Z_2(M) \) and \( M_0 \cap N \) is a direct summand of \( M_0 \).
Proof. From Lemma 1.6 we obtain that $M_0 \cap Z_2(M) = (0)$ and $M_0$ is a complement of $Z_2(M)$. Hence, $M = M_0 \oplus Z_2(M)$ by Proposition 1.5, since $Z_2(M)$ is closed. If $N$ is a closed submodule of $M$, then $N \supseteq Z_2(M)$ by Lemma 1.1 and $N = M_0 \cap N \oplus Z_2(M)$. Since $N \cap M_0$ is closed in $M_0$, $N \cap M_0$ is a direct summand of $M_0$ by Proposition 1.5. Conversely, we assume that $N \supseteq Z_2(M)$ and $N \cap M_0$ is a direct summand of $M_0$; $M_0 = N \cap M_0 \oplus N_1$. Considering in $M_0$, $M_0 = \text{cl}(M_0) = \text{cl}(M_0 \cap N) \oplus Z_2(M)$. Since $N_1 \cap M_0$ is closed in $M_0$, $N_1 \cap M_0$ is a direct summand of $M_0$. Hence, $M_0 \cap N = \text{cl}(N) \oplus Z_2(M)$.

Corollary. Let $M$ be a quasi-injective. If $N_1$, $N_2$ are closed in $M$, then $N_1 \cap N_2$ is closed. Hence, $\text{cl}(N_1 \cap N_2) = \text{cl}(N_1) \oplus \text{cl}(N_2)$ for any submodules $S_1$ and $S_2$ (cf. [3], Theorem 1.4 and [4], Theorem 1.2).

Proof. Since $N_1$ is closed, $N_1$ contains $Z_2(M)$. Hence, it is sufficient to show that $N_1 \cap M_0 \cap M_0$ is a direct summand of $M_0$ by Theorem 1.7, where $M = M_0 \oplus Z_2(M)$. Thus, we may assume $Z(M) = (0)$. $N_1 \cap M_0$ is closed by Lemma 1.2. Hence, $M = N_1 \oplus N_1' \oplus (N_1 \cap M')$. Since $N_1 \cap (N_1 \cap M') = (0)$, there exists a submodule $N_1'$ such that $N_1' \supseteq N_1 \cap M'$ and $M = N_1 \oplus N_1'$. Furthermore, $N_2' = (N_1 \cap M') \oplus N_1'$. Therefore, $M = N_1 \oplus (N_1 \cap M') \oplus N_1'$. On the other hand $N_1 = (N_1 \cap N_2) \oplus N_1 \cap M'$. Hence, $N_1 + N_2 = N_1 + N_1 = N_2 + (N_1 \cap M')$. Therefore, $M = (N_1 + N_2) \oplus N_1'$. The second half is clear from the first.

Proposition 1.8. Let $M$ be quasi-injective. Then the set of closed submodules coincides with the set of complement submodules containing $Z(M)$. Especially, if we assume $Z(M) = (0)$, then every complement of a submodule $N$ is isomorphic to each other and $N^c$ containing $N$ coincides with $\text{cl}(N)$.

Proof. Let $N = N_1 \supseteq Z(M)$. For any element $n \in N_1 \cap \text{cl}(N)$ we have $Ln \subseteq N_1 \cap N = (0)$, where $L$ is an essential left ideal. Hence, $n \in Z(M) \cap N_1 = (0)$. Therefore, $\text{cl}(N) = N$. The converse is clear from Proposition 1.5. We assume $Z(M) = (0)$. In this case we note that $\text{cl}(N) = \text{cl}(N)$. By Lemmas 1.3 and 1.4 and Corollary to Theorem 1.7 we have $M = \text{cl}(N \oplus N^c) = \text{cl}(N) \oplus N^c$ for any submodule $N$. Hence, $N^c \approx M / \text{cl}(N)$. Furthermore, we obtain $N = N \oplus N^c = \text{cl}(N) \oplus N^c$ by Proposition 1.5. If $N^c \supseteq N$, then $N^c \supseteq \text{cl}(N)$. Hence, $N^c \approx \text{cl}(N)$.

2. Special cases.

First we consider some relations between a quasi-injective module $M$ and its injective envelope $E(M)$.
Proposition 2.1. Let $M$ be an $R$-module. Then $E(M) = E(Z(M)) \oplus E(B)$ and $Z_+(E(M)) = E(Z_+(M))$, where $B$ is a maximal torsion-free submodule in $M$.

Proof. We assume $Z_+(M) = (0)$ and $E = E(M)$. Then $E = E_0 \oplus Z_+(E)$ by Theorem 1.7. Let $p$ be a projection of $E$ to $E_0$. If $p(m) = 0$ for $m \in M$, then $m \in M \cap Z_+(E) = Z_+(M) = (0)$ by Lemma 1.6. Hence, $M$ is monomorphic to $E_0$. Therefore, $Z_+(E) = (0)$. If $Z_+(M) = M$, then $M \subseteq E(M) \subseteq Z_+(E)$. Hence, $Z_+(E) = E$. Since $M$ is an essential extension of $B \oplus Z_+(M)$, $E = E(B) \oplus E(Z_+(M))$.

Lemma 2.2. Let $M$ be an $R$-module and $K = \text{Hom}_R(E(M), E(M))$. $M$ is quasi-injective if and only if $M$ is a $K$-module. (See [3], Theorem 1.1.)

Proposition 2.3. Let $M$ be quasi-injective. If $E(M) = N_1 \oplus N_2$, then $M = M \cap N_1 \oplus M \cap N_2$, and $N_i = E(M \cap N_i)$.

Proof. Let $p$ be a projection of $E(M)$ to $N$. Since $p \in K$, $p(M) \subseteq M$ by Lemma 2.2. Hence, $M = M \cap N_1 \oplus M \cap N_2$.

Corollary. Let $R$ be a commutative integral domain. Then every injective module is a direct sum of the torsion submodule and a maximal torsion-free submodule. An injective envelope of torsion (resp. torsion-free) module is torsion (resp. torsion-free).

Proposition 2.4. Let $M_1$, $M_2$ be quasi-injective such that $E(M_1) \supseteq E(M_2)$. Then $M_1 \oplus M_2$ is quasi-injective if and only if $M_i \simeq M_2$.

Proof. $E(M_1 \oplus M_2) = E(M_1) \oplus E(M_2)$. If $M_i \simeq M_2$, $M = M_1 \oplus M_2$ is a $\text{Hom}_R(E(M), E(M))$-module, and hence $M$ is quasi-injective by Lemma 2.2. Conversely, we assume that $M$ is quasi-injective. Let $f$ be an element in $K = \text{Hom}_R(E(M), E(M))$ such that $f|E(M_2) \equiv 0$, $f|E(M_1)$ induces the isomorphism $\varphi$. Then $f(M) = f(M_1) \subseteq M \cap E(M_2) = M_2$ by Proposition 2.3. If we consider the same argument on $M_2$ for $\varphi^{-1}$, we can find $g \in K$ such that $gf|E(M_1) \equiv \text{identity}|E(M_1)$. Hence, $M_1 = gf(M_1) \subseteq g(M_2) \subseteq M$. Therefore, $M_i \simeq M_2$.

Proposition 2.5. Let $R$ be a left noetherian ring and $M$ a quasi-injective $R$-module. Then $M$ is a direct-sum of indecomposable quasi-injective $R$-modules. Furthermore, this decomposition is unique up to isomorphism, ([10], Theorem 4.5).

Proof. $E(M) = \sum \oplus M_a$ by [6], Theorem 2.5, where $M_a$ is an indecomposable injective $R$-module. Put $M_a = M \cap \overline{M}_a$. Then $M = \sum \oplus M_a$ by Lemma 2.2. Since $M_a$ is a direct summand of $M$, $M_a$ is quasi-injective. It is clear that $M_a$ is indecomposable. We assume $M = \sum \oplus M_a'$.
is a second decomposition. Since $R$ is left noetherian, $E(M) = \bigoplus E(M_{\alpha})$ and $E(M_{\alpha})$ is indecomposable by Proposition 2.3. Then there exists an automorphism $\varphi$ in $K$ such that $\varphi : M_{\alpha} \cong E(M_{\rho(\alpha)})$ for all $\alpha$ by [5], Proposition 2.7, where $\rho$ is a permutation of indices $\alpha$. Since $\varphi(M) \subseteq M$, $\varphi(M_{\alpha}) = \varphi(M \cap M_{\alpha}) \subseteq M \cap E(M_{\rho(\alpha)}) = M_{\rho(\alpha)}$. Taking $\varphi^{-1}$, we obtain $M_{\alpha} \cong M_{\rho(\alpha)}$.

Now we assume that $R$ is a commutative noetherian ring. Then we know by [6], Proposition 3.1 that every indecomposable injective $R$-module is isomorphic to $E(R/P)$, where $P$ is a prime ideal in $R$.

**Proposition 2.6.** Let $M$ be an indecomposable quasi-injective $R$-module. If $M$ is torsion-free, then $M$ is injective.

Proof. Since $E(M) = E(R/P)$ is torsion-free by Proposition 2.1, $Z(R/P) = (0)$. Hence, $P$ is not essential in $R$. There exists a non-zero ideal $Q$ such that $P \cap Q = (0)$. Therefore, $P$ is minimal prime and $(0)_P = PR_P$. From [6], Theorem 3.6 $E(R/P)$ is $R_P$-injective. Since $R_P$ is the quotient field $K$ of $R/P$, $E(M) = Km$. Furthermore, $K \cong \text{Hom}_R(E(R/P), E(R/P))$. Hence, $M = KM = E(M)$.

**Corollary.** Let $R$ be a Dedekind domain and $M$ a quasi-injective $R$-module. Then $M$ is either injective or a direct-sum of $R$-modules $E(R/P_i)$ and $R/S_i$. Conversely, such a module is quasi-injective, where $\{P_i, S_i\}$ is a set of non-zero distinct primes in $R$.

Proof. $M = M_0 \oplus Z(M)$. If $M_0 \neq (0)$, then $M_0 \cong \sum \oplus Q$ by Propositions 2.5 and 2.6, where $Q$ is the quotient field of $R$. Since $Z(M)$ is torsion, $Z(M) = \sum \oplus (E(R/P_i))^{*} \oplus \sum \oplus (R/(S^*)^{*})^{*}$ by Proposition 2.5 and [5], Theorem 10. However if $M_0 \neq (0)$ then there exist natural epimorphisms of $M_0$ to $E(R/S_i)$. Hence, $J = \phi$ by Lemma 2.2, which means $M$ is injective. If $M_0 = (0)$, then $M \cong \sum \oplus E(R/P_i) \oplus \sum \oplus (R/(S^*))^{*}$ and $\{P_i, S_i\}$ is a set of non-zero distinct primes by Proposition 2.4. The converse is clear.

Next, we consider a case of algebra $A$ over a field $K$ with finite dimension. Then we know from [7] that every indecomposable $A$-injective module $M$ is isomorphic to $(eA)^* = \text{Hom}_K(eA, K)$, where $e$ is a primitive idempotent in $A$. Hence, there exists a non-degenerated bilinear mapping $(,)_{eA \otimes K}$ of $eA \otimes M$ to $K$ with respect to $A$. It is clear that the adjoint elements of $\text{Hom}_A(M, M) = B$ is equal to $eAe$. Hence for an $A$-submodule $N$ of $M$, ann $N = \{x \in eA, (x, N) = 0\}$ is an $eAe$-module if and only if $N$ is a $B$-module. Thus from Lemma 2.2 we have

\[ 1) \ M^\alpha \text{ means a direcsum of } \alpha\text{-copies of } M. \]
Proposition 2.7. Let \( A \) be an algebra over a field \( K \) such that \( [A:K]<\infty \). Then every quasi-injective \( A \)-module is a direct-sum of modules \( (e_i A/e_iR_i)^* \), where \( e_i \) is a primitive idempotents and \( R_i \) is a right ideal in \( A \) such that \( e_i A e_i \subseteq R_i \).

Corollary. Let \( A \) be as above. If \( A \) is a generalized uniserial ring, then every sub-module of indecomposable injective module is quasi-injective.

Remark. The converse of Proposition 2.7 is, in general, not true. Finally, we consider the singular ideal of quasi-Frobenius ring.

Proposition 2.8. Let \( R \) be quasi-Frobenius. Then \( Z(R) \) is equal to the radical \( N \) of \( R \) and \( R \) is a direct sum of semi-simple subring and a quasi-Frobenius ring \( R_1 \) such that \( Z_2(R_1) = R_1 \).

Proof. Let \( S \) be a left socle of \( R \), namely the sum of minimal left ideals in \( R \). Then \( S \) is a unique minimal essential left ideal of \( R \). Hence, \( Z(R) = \) the right annihilator \( S_r \) of \( S \) in \( R \). Since \( N_r = N_i \) by [8] and \( S = N_r, Z(R) = S = N_r = N \) by [8]. Furthermore, \( R \) is left \( R \)-injective by [1]. Hence, \( R = L \oplus Z_2(R) \) as a left \( R \)-module by Theorem 1.7. Since \( Z_2(R) \subseteq N, NL \subseteq N \cap L = (0) \). Hence, \( L \subseteq S. S = S \cap N \oplus L' \), where \( L' \oplus L \) is a direct-sum of non-nilpotent minimal left ideals. Since \( SN = (0), S' = L' \). It is clear that \( Z_2(R) = (S')_r \). Therefore, \( L'Z_2(R) = (0) \), which means that \( L \) is a two-sided ideal. Since \( L \) is completely reducible, \( L \) is semi-simple.

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References