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PRIME AND PRIMARY SUBMODULES OF CERTAIN MODULES

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Abstract. In this paper we characterize all prime and primary submodules of the free R-module R^n for a principal ideal domain R and find the minimal primary decomposition of any submodule of R^n. In the case $n = 2$, we also determine the height of prime submodules.

Keywords: prime submodules, primary submodules, primary decomposition

MSC 2000: 13C13, 13C99

1. Introduction

Throughout this note all rings are commutative with identity and all modules are unitary.

Let S be a ring and M an S-module. A proper submodule N of M is called a prime submodule if $sm \in N$ for $s \in S$ and $m \in M$ implies that $m \in N$ or $s \in (N\colon M)$, where

$$(N\colon M) = \{t \in S\colon tM \subseteq N\}.$$

The following lemma is well-known (see for example [2]).

1.1 Lemma. *Let N be a submodule of an S-module M. Then*

i) *N is a prime submodule of M if and only if $P = (N\colon M)$ is a prime ideal of S and the S/P-module M/N is torsion-free.*

ii) *If $(N\colon M)$ is a maximal ideal of S, then N is a prime submodule of M.*

iii) *If N is a maximal submodule of M, then N is a prime submodule of M.*

Let K be a prime submodule of an S-module M. It is said that K has height n for some non-negative integer n, if there exists a chain

$$K_n \subset K_{n-1} \subset \ldots \subset K_1 \subset K_0 = K$$

of prime submodules K_i $(0 \leqslant i \leqslant n)$ of M, but no longer such chain.

Let M be a module over a ring S. Recall that a proper submodule Q of M is a primary submodule provided that for any $s \in S$ and $m \in M$, $sm \in Q$ implies that $m \in Q$ or $s^n \in (Q\colon M)$ for some positive integer n.

Let Q be a primary submodule of M, then the radical of the ideal $(Q\colon M)$ is a prime ideal of S, [4]. If $P = \sqrt{(Q\colon M)}$, then Q is called a P-primary submodule of M.

A submodule N of M has a primary decomposition if $N = Q_1 \cap \ldots \cap Q_t$ with each Q_i a P_i-primary submodule of M for some prime ideal P_i. If no Q_i contains $Q_1 \cap \ldots \cap Q_{i-1} \cap Q_{i+1} \cap \ldots \cap Q_t$ and if the ideals $P_1, \ldots, P_t$ are all distinct, then the primary decomposition is said to be minimal.

It is known that every prime ideal of the ring $S_1 \times S_2 \times \ldots \times S_n$, where S_i is a ring $(1 \leqslant i \leqslant n)$, is of the form $S_1 \times \ldots \times S_{i-1} \times P_i \times S_{i+1} \times \ldots \times S_n$ for some prime ideal P_i of S_i, [3]. Now it is natural to ask about the prime submodules of the S-module S^n for an arbitrary ring S.

Tiras and Harmanci in [5] studied prime submodules of the R-module $R \times R$ for a principal ideal domain (PID) R and investigated the primary decomposition of any submodule of $R \times R$. In Section 2 we will characterize all prime submodules of R^n where R is a PID and $n \geqslant 2$ is a positive integer. In Section 3 we find the height of prime submodules of $R \times R$ for a PID R. Finally, the primary decomposition of any submodule of R^n is discussed in Section 4.

2. Prime submodules of R^n

In this section R denotes a principal ideal domain and M the free R-module R^n for some positive integer $n \geqslant 2$.

Let N be a non-zero submodule of M. There exist a basis $\{x_1, \ldots, x_n\}$ of M and non-zero elements $d_1, \ldots, d_r$ $(r \leqslant n)$ of R such that $N = Rd_1x_1 + \ldots + Rd_rx_r$, [4]. Therefore any submodule of M can be generated by n elements.

Let $N = Ra_1 + \ldots + Ra_n$ be a submodule of M. Suppose that $a_i = (a_{i1}, \ldots, a_{in})$ $(1 \leqslant i \leqslant n)$. Put $A = (a_{ij}) \in M_{n\times n}(R)$ and $\Delta = \det A$. Let $A' = (a'_{ij})$ be the adjoint matrix of A. Then $AA' = A'A = \Delta I_n$, where I_n is the identity of the ring $M_{n\times n}(R)$. By considering all possible choices of Δ, we will characterize prime submodules of M. First we show that Δ is unique up to multiplication by a unit.

2.1 Lemma. *Let N be a submodule of M. Suppose that $N = Ra_1 + \ldots + Ra_n$ and also $N = Rb_1 + \ldots + Rb_n$ for some $a_i, b_i \in M$ $(1 \leqslant i \leqslant n)$. Let $A = (a_{ij})$ and*

$B = (b_{ij})$ *be as above. Then*

$$\det A = u(\det B)$$

for some unit u of R.

Proof. For each $1 \leqslant i \leqslant n$, there are $c_{ij} \in R$ $(1 \leqslant j \leqslant n)$ such that $a_i = \sum_{j=1}^{n} c_{ij} b_j$. Let $C = (c_{ij}) \in M_{n\times n}(R)$. Then $A = CB$. Therefore

$$\det A = \det(CB) = (\det C)(\det B)$$

and hence $\det B$ divides $\det A$. By symmetry $\det A$ divides $\det B$. Thus $\det A = u(\det B)$ for some unit $u \in R$, as required. □

Now we consider the submodules of M with non-zero Δ. For our purpose we need the following result.

2.2 Proposition. *Let $N = Ra_1 + \ldots + Ra_n$ be a submodule of M and let $A = (a_{ij})$ be as above. If $\Delta = \det A \neq 0$, then*

$$N = \left\{(x_1, \ldots, x_n) \in M \colon \ \Delta \textit{ divides } \sum_{i=1}^{n} x_i a'_{ij} \ (1 \leqslant j \leqslant n)\right\},$$

where $A' = (a'_{ij})$ is the adjoint matrix of A. Moreover, $\Delta M \subseteq N$.

Proof. Let

$$K = \left\{(x_1, \ldots, x_n) \in M \colon \ \Delta \text{ divides } \sum_{i=1}^{n} x_i a'_{ij} \ (1 \leqslant j \leqslant n)\right\}.$$

Then K is a submodule of M. Since $AA' = \Delta I_n$, we have $a_i \in K$ $(1 \leqslant i \leqslant n)$ and hence $N \subseteq K$. On the other hand, suppose that $(x_1, \ldots, x_n) \in K$. There is $(y_1, \ldots, y_n) \in M$ such that

$$(x_1, \ldots, x_n)(a'_{ij}) = \Delta(y_1, \ldots, y_n).$$

Therefore

$$\Delta(x_1, \ldots, x_n) = (x_1, \ldots, x_n)(a'_{ij})(a_{ij}) = \Delta(y_1, \ldots, y_n)(a_{ij}).$$

Since $\Delta \neq 0$, we have $(x_1, \ldots, x_n) = (y_1, \ldots, y_n)(a_{ij})$. Thus $(x_1, \ldots, x_n) = y_1 a_1 + \ldots + y_n a_n \in N$. Consequently, $K = N$. Now the last assertion follows immediately from the equality. □

2.3 Corollary. *Let $N = Ra_1 + \ldots + Ra_n$ be a submodule of M and let $A = (a_{ij})$. Then $N = M$ if and only if $\Delta = \det A$ is a unit of R.*

Proof. If Δ is a unit of R, then by Proposition 2.2, $M = \Delta M \subseteq N$.

Conversely, suppose that $N = M$. Then

$$N = R(1, 0, \ldots, 0) + R(0, 1, 0, \ldots, 0) + \ldots + R(0, \ldots, 0, 1).$$

Now Lemma 2.1 implies that Δ is a unit of R. $\square$

Let $C \in M_{n\times n}(R)$ and let C' be the adjoint matrix of C. If $d = \det C \neq 0$, then $CC' = dI_n$ implies that

$$d(\det C') = (\det C)(\det C') = \det(CC') = \det(dI_n) = d^n.$$

Therefore, $\det C' = d^{n-1} = (\det C)^{n-1}$.

Now we are ready to characterize prime submodules of M with non-zero Δ.

2.4 Theorem. *Let $N = Ra_1 + \ldots + Ra_n$ be a submodule of M and let $A = (a_{ij})$. If $\Delta = \det A \neq 0$, then N is a prime submodule if and only if $\Delta = up^r$ for some unit $u \in R$, a prime element $p \in R$, and a positive integer $r \leqslant n$ and moreover, p^{r-1} divides a'_{ij} $(1 \leqslant i \leqslant n, 1 \leqslant j \leqslant n)$ where $A' = (a'_{ij})$ is the adjoint matrix of A.*

Proof. First suppose that N is a prime submodule of M. Since $N \neq M$, by Corollary 2.3, Δ is not a unit of R. Assume that $\Delta = st$ for some relatively prime elements $s, t \in R$. Proposition 2.2 implies that $st \in (N \colon M)$, which is a prime ideal of R. Thus $s \in (N \colon M)$ or $t \in (N \colon M)$. Suppose that $s \in (N \colon M)$. Thus for any $1 \leqslant i \leqslant n$, $(0, \ldots, 0, s, 0, \ldots, 0) \in sM \subseteq N$ with s as the ith component. Therefore by Proposition 2.2, $st = \Delta$ divides sa'_{ij} $(1 \leqslant j \leqslant n)$ and so t divides a'_{ij} $(1 \leqslant j \leqslant n)$. Hence t^n divides $\det(a'_{ij}) = (\det A)^{n-1} = s^{n-1}t^{n-1}$. Thus t divides s^{n-1}. Since s and t are relatively prime, t divides 1, i.e., t is a unit. Consequently, $\Delta = up^r$ for some unit $u \in R$, a prime element $p \in R$ and a positive integer r. Since $\Delta \in (N \colon M)$ and $(N \colon M)$ is a prime ideal of R, $p \in (N \colon M)$. As in the above case, up^r divides pa'_{ij} $(1 \leqslant i \leqslant n,\ 1 \leqslant j \leqslant n)$ and so p^{r-1} divides a'_{ij} $(1 \leqslant i \leqslant n,\ 1 \leqslant j \leqslant n)$. Hence $p^{n(r-1)}$ divides $\det(a'_{ij}) = (\det A)^{n-1} = u^{n-1}p^{r(n-1)}$. Therefore, $n(r-1) \leqslant r(n-1)$ and so $r \leqslant n$.

Conversely, since Δ is not a unit, N is a proper submodule of M. We shall show that $(N \colon M)$ is a maximal ideal of R and hence by Lemma 1.1, N is a prime submodule of M. Let $(x_1, \ldots, x_n) \in pM$. Since p^{r-1} divides a'_{ij} $(1 \leqslant i \leqslant n$, $1 \leqslant j \leqslant n)$, $\Delta = up^r$ divides $\sum\limits_{i=1}^{n} x_i a'_{ij}$ $(1 \leqslant j \leqslant n)$. Thus $(x_1, \ldots, x_n) \in N$ and so $pM \subseteq N$. Therefore, $p \in (N \colon M)$ and hence $Rp \subseteq (N \colon M) \subset R$. Consequently, $(N \colon M) = Rp$ is a maximal ideal of R, as required. $\square$

Remark. Note that in the above theorem, if $\Delta = up$ for some unit $u \in R$ and a prime element $p \in R$, then N is a prime submodule of M (because the second condition holds trivially).

Now we consider the submodules of M with zero Δ.

2.5 Theorem. *Let $N = Ra_1 + \ldots + Ra_n$ be a submodule of M and let $\Delta = \det(a_{ij}) = 0$. Then N is a prime submodule of M if and only if N is a direct summand of M.*

Proof. Suppose that $M = N \oplus K$ for some submodule K of M. Since $\Delta = 0$, we have $N \neq M$. Let $r \in R$ and $m \in M$ be such that $rm \in N$. There are $m_1 \in N$ and $m_2 \in K$ with $m = m_1 + m_2$. If $r \neq 0$, then $rm_2 = rm - rm_1 \in N \cap K = 0$. Hence $m_2 = 0$ and so $m = m_1 \in N$. It follows that N is a prime submodule of M.

Conversely, suppose that N is a prime submodule of M. There exist a basis $\{x_1, \ldots, x_n\}$ of M and non-zero elements $d_1, \ldots, d_r$ of R ($r \leqslant n$) such that $N = Rd_1x_1 + \ldots + Rd_rx_r$. Suppose that $x_i = (x_{i1}, \ldots, x_{in})$ ($1 \leqslant i \leqslant n$), then $\det(x_{ij}) = u$ is a unit of R. If $r = n$, then $\det(d_ix_{ij}) = d_1 \ldots d_n u \neq 0$, which is impossible (because $N = Ra_1 + \ldots + Ra_n = Rd_1x_1 + \ldots + Rd_nx_n$ implies that $0 = \det(a_{ij}) = \det(d_ix_{ij})$, by Lemma 2.1). Therefore $r < n$. Note that $d_ix_i \in N$ and $d_iM \nsubseteq N$, thus $x_i \in N$ ($1 \leqslant i \leqslant r$). Hence $N = Rx_1 + \ldots + Rx_r$. Let $K = Rx_{r+1} + \ldots + Rx_n$. Then $M = N \oplus K$. □

3. Some special cases

In this section we consider the module $M = R \times R$ over a principal ideal domain R.

Let N be a submodule of M. There are elements a, b, c, and d of R such that $N = R(a,b) + R(c,d)$. Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ and $\Delta = \det A = ad - bc$. Then the adjoint matrix of A has the simple form $\begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$. Therefore we have the following result.

3.1 Proposition. *Let $N = R(a,b) + R(c,d)$ be a submodule of M and $\Delta = ad - bc \neq 0$. Then*

$$N = \{(x,y) \in M \colon \ \Delta \textit{ divides both } ay - bx \textit{ and } cy - \mathrm{d}x\}.$$

Let $N = R(a,b) + R(c,d)$ be a submodule of M and let $\Delta = ad - bc \neq 0$. If N is a prime submodule of M, then Theorem 2.4 implies that $\Delta = up$ or $\Delta = up^2$ for some unit $u \in R$ and a prime element $p \in R$. In the case $\Delta = up^2$, $p = p^{2-1}$ must divide the entries of the adjoint matrix of $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$. Therefore p divides a, b, c and d and hence $N \subseteq pM$. On the other hand, $up^2 \in (N\colon M)$, which is a prime ideal of R. Thus $p \in (N\colon M)$ so that $pM \subseteq N$. Hence $N = pM$ and by [5, Proposition 2.4], N is of height one. The height of prime submodules of M with $\Delta = up$ will be discussed later.

3.2 Lemma. *Let $N = R(a,b) + R(c,d)$ be a submodule of M. Then N is cyclic if and only if $\Delta = 0$.*

P r o o f. Suppose that N is cyclic. Then $N = R(x,y)$ for some $(x,y) \in M$. There are $r, s \in R$ such that $(a,b) = r(x,y)$ and $(c,d) = s(x,y)$ and so $\Delta = ad - bc = rxsy - rysx = 0$.

Conversely, suppose that $\Delta = 0$. If one of the elements a, b, c or d is zero, then the result is clear. (Indeed, if $a = 0$, then $0 = ad - bc = -bc$. Therefore $b = 0$ or $c = 0$. If $b = 0$, then $N = R(c,d)$ and we are done. Now if $c = 0$, then $N = R(0,b) + R(0,d) = R(0,e)$, where $Re = Rb + Rd$.) Now suppose that a, b, c and d are all non-zero. Let f be the greatest common divisor (gcd) of the elements a and c and let g be the gcd of the elements b and d, so that $a = a'f$, $c = c'f$, $b = b'g$ and $d = d'g$ for some $a', b', c', d' \in R$. Since $ad = bc$, we have $a'd'fg = b'c'fg$ and so $a'd' = b'c'$. As a' and c' are coprime, a' divides b' and b' divides a'. Hence $a' = b'u$ for some unit $u \in R$. Therefore, $c' = d'u$. Now it is easy to show that $N = R(uf, g)$. $\square$

The proof of the following result can be found in [1] and [5].

3.3 Proposition. *Let $N = R(a,b)$ be a cyclic submodule of M. Then N is prime if and only if either $a = b = 0$ or a and b are coprime.*

Suppose that $N = R(a,b)$ is a non-zero prime submodule of M. Since $N \cong R$, every submodule of N is of the form $R(ta, tb)$ for some $t \in R$ and by the above proposition N is of height one.

3.4 Corollary. *Let $N = R(a,b) + R(c,d)$ be a submodule of M and $\Delta = ad - bc = up$ for some unit $u \in R$ and a prime element $p \in R$. Then N is a prime submodule of height two.*

P r o o f. By the remark after Theorem 2.4, N is a prime submodule of M. Let K be a non-zero prime submodule of M contained in N. Then $K = R(x,y) + R(z,w)$ for some (x,y) and $(z,w) \in M$. There are q, r, s, and $t \in R$ such that $(x,y) =$

$q(a,b)+r(c,d)$ and $(z,w)=s(a,b)+t(c,d)$. Hence

$$xw-yz=(qt-rs)(ad-bc)=up(qt-rs).$$

Since K is a prime submodule of M, there are three choices for $qt-rs$.

i) If $qt-rs=0$, then $xw-yz=0$ and so K is a cyclic prime submodule of M. Therefore, K is of height one.

ii) If $qt-rs=u'p$ for some unit $u'\in R$, then $xw-yz=uu^rp^2$ and so $K=pM$. Therefore, K is of height one.

iii) If $qt-rs=v$ is a unit of R, then it is easy to check that $N=K$.

Consequently, N is of height two. □

4. Primary decomposition in R^n

As in Section 2, let M be the free module R^n over a principal ideal domain R for some integer $n\geqslant 2$.

We know that every submodule of a Noetherian module has a primary decomposition, [4], and also that M is a Noetherian R-module.

We begin our investigation by the following result.

4.1 Theorem. *Let $N=Ra_1+\ldots+Ra_n$ be a proper submodule of M. Let $A=(a_{ij})$ and $\Delta=up_1^{\alpha_1}\ldots p_s^{\alpha_s}$ for some distinct prime elements $p_k\in R$, positive integers α_k, and unit $u\in R$. Then N has a minimal primary decomposition $N=Q_1\cap\ldots\cap Q_s$ where $Q_k=\{(x_1,\ldots,x_n)\in M\colon\ p_k^{\alpha_k}$ divides $\sum\limits_{i=1}^{n}x_ia'_{ij}$ $(1\leqslant j\leqslant n)\}$. Note that $A'=(a'_{ij})$ is the adjoint matrix of A.*

Proof. It is easy to check that Q_k is a primary submodule of M with $\sqrt{(Q_k\colon M)}=Rp_{_k}$ $(1\leqslant k\leqslant s)$. By Proposition 2.2, $N\subseteq Q_1\cap\ldots\cap Q_s$. Now let $x=(x_1,\ldots,x_n)\in Q_1\cap\ldots\cap Q_3$. Then for each $1\leqslant k\leqslant s$, $p_k^{\alpha_k}$ divides $\sum\limits_{i=1}^{n}x_ia'_{ij}$ $(1\leqslant j\leqslant n)$. Consequently, Δ divides $\sum\limits_{i=1}^{n}x_ia'_{ij}$ $(1\leqslant j\leqslant n)$. Again by Proposition 2.2, $x\in N$. □

4.2 Corollary. *Let N be a proper submodule of M with $\Delta\neq 0$. Then N is a primary submodule of M if and only if $\Delta=up^\alpha$ for some unit $u\in R$, a prime element $p\in R$, and a positive integer α.*

Suppose that $N\neq 0$ is a submodule of M with $\Delta=0$. There exist a basis $\{x_1,\ldots,x_n\}$ of M and non-zero elements $d_1,\ldots,d_r$ $(r\leqslant n)$ of R such that $N=$

$Rd_1x_1 + \ldots + Rd_rx_r$. Let $x_i = (x_{i1}, \ldots, x_{in})$, then by Corollary 2.3, $\det(x_{ij}) = u$ for some unit u of R. Since $\Delta = 0$, $r < n$. Suppose that $d_i = u_i p_1^{\alpha_{i1}} \ldots p_s^{\alpha_{is}}$ $(1 \leqslant i \leqslant r)$, where u_i is a unit of R, p_k is a prime element of R and $\alpha_{ik} \geqslant 0$ $(1 \leqslant k \leqslant s)$. Let $Q = Rx_1 + \ldots + Rx_r$. Theorem 2.5 implies that Q is a prime and hence a primary submodule of M. Now set $Q_k = Rp_k^{\alpha_{1k}}x_1 + \ldots + Rp_k^{\alpha_{rk}}x_r + Rx_{r+1} + \ldots + Rx_n$ $(1 \leqslant k \leqslant s)$. Then by Corollary 4.2, Q_k is a primary submodule of M. It is clear that $N \subseteq Q \cap Q_1 \cap \ldots \cap Q_s$. Now let $y \in Q \cap Q_1 \cap \ldots \cap Q_s$ and suppose that $y = a_1x_1 + \ldots + a_nx_n$ for some $a_i \in R$. Since $y \in Q$, we have $a_{r+1} = \ldots = a_n = 0$. Also since $y \in Q_k$ $(1 \leqslant k \leqslant s)$, we conclude that for each $1 \leqslant i \leqslant r$, $p_k^{\alpha_{ik}}$ divides a_i and hence d_i divides a_i. Therefore $y \in N$. Thus we have proved:

4.3 Theorem. *Let $N \neq 0$ be a submodule of M with $\Delta = 0$. Then $N = Q \cap Q_1 \cap \ldots \cap Q_s$ is a minimal primary decomposition of N, where $Q, Q_1, \ldots, Q_s$ are as above.*

4.4 Corollary. *Let N be a submodule of M with $\Delta = 0$. Then N is a primary submodule if and only if N is a prime submodule.*

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