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PAOLO ZANARDO

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On *-Modules Over Valuation Rings.

Paolo Zanardo (*)

The problem of investigating *-modules over valuation rings was proposed to the author by C. Menini. We recall the definition of *-module, given by D'Este in [3]. Let R be a ring, ${}_RM$ a left R-module and ${}_RE$ an injective cogenerator of the category of all R-modules; let $S = \mathrm{End}_R(M)$ and $H = \mathrm{Hom}_R({}_RM, {}_RE)$ and denote by $\mathrm{Gen}({}_RM)$ the category of all left R-modules generated by ${}_RM$ and by $\mathrm{Cog}({}_SH)$ the category of all left S-modules cogenerated by H. In this situation, ${}_RM$ is said to be a **-module* if there exists an equivalence of categories

$$\mathrm{Gen}({}_RM) \underset{G}{\overset{F}{\rightleftarrows}} \mathrm{Cog}({}_SH)$$

such that the functor F is naturally isomorphic to $\mathrm{Hom}_R({}_RM, -)$ and the functor G is naturally isomorphic to $M_S \otimes -$ (we shall write $F \approx \mathrm{Hom}_R({}_RM, -)$, $G \approx M_S \otimes -$).

The main motivation for the study of *-modules is the following result by Menini and Orsatti ([8], Theorem 3.1): let R, S be rings; if $\mathcal{G}$ is a full subcategory of R-Mod closed under direct sums and factor modules, $\mathcal{D}$ is a full subcategory of S-Mod containing ${}_SS$ and closed under submodules, and $\mathcal{G} \underset{G}{\overset{F}{\rightleftarrows}} \mathcal{D}$ is any equivalence with F and G additive functors, then there exists a module ${}_RM$ such that: $S = \mathrm{End}_R({}_RM)$, $\mathcal{G} = \mathrm{Gen}({}_RM)$, $\mathcal{D} = \mathrm{Cog}({}_SH)$ (where ${}_SH$ is as above), $F \approx \mathrm{Hom}_R({}_RM, -)$ and $G \approx M_S \otimes -$.

Recent results on *-modules have been obtained by D'Este [3], D'Este and Happel [4], Colpi [1], Colpi and Menini [2].

(*) Lavoro eseguito con il contributo del M.P.I.

Indirizzo dell'A.: Dipartimento di Matematica Pura e Applicata, Università dell'Aquila, 67100 L'Aquila, Italy.

In the present paper we characterize *finitely generated *-modules over a valuation ring R*. Using a theorem by Colpi ([1], Prop. 4.3) and some results in [9] (see also [5], Ch. IX), we prove that a finitely generated module X over a valuation ring R is a *-module if and only if $X \cong (R/A)^n$, for suitable $n \geqslant 0$ and A ideal of R (Theorem 3). Note that a module of the form $(R/A)^n$ is a *-module for any ring R, as a consequence of the above mentioned result by Colpi. Hence our Theorems 3 shows that the class of finitely generated *-modules over a valuation ring is, in a certain sense, as small as possible.

Note that, at present, there are no examples of rings which admit *-modules not finitely generated; Colpi and Menini in [2] proved that *-modules over artinian rings or noetherian domains with Krull dimension one are necessarily finitely generated. The author feels that the same is true for *-modules over valuation rings. Our final Remark 4 gives a contribution in this direction.

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1. – In the sequel, R will always denote a *valuation ring*, i.e. a commutative ring, not necessarily a domain, whose ideals are linearly ordered by inclusion; the maximal ideal of R is denoted by P. For general terminology and results on modules over valuation rings we refer to the book by Fuchs and Salce [5]; the results we need on finitely generated modules can be found in [9] or in Ch. IX of [5].

In the proof of Theorem 2 we shall need the following facts (see [9] or [5], Ch. IX): let X be a finitely generated R-module; then there exists a submodule B of X such that:

i) B is a direct sum of cyclic submodules;

ii) B is pure in X;

iii) B is essential in X;

such a B is said to be *basic* in X; the basic submodules of X are all isomorphic. Moreover, given a basic submodule B of X, there exists a *minimal* set of generators $\boldsymbol{x} = \{x_1, \ldots, x_k, x_{k+1}, \ldots, x_n\}$ of X such that:

a) $B = \langle x_1, \ldots, x_k \rangle = \bigoplus_{i=1}^{k} \langle x_i \rangle$;

b) if $A_j = \operatorname{Ann}(x_j + \langle x_1, \ldots, x_{j-1}\rangle)$ for all $j > k$, we have $A_{k+1} \leqslant \leqslant A_{k+2} \leqslant \ldots \leqslant A_n$;

c) for all $r \in A_{k+1}$ we have the relation

$$(1) \qquad rx_{k+1} = r\sum_{i=1}^{k} a_i^r x_i\,, \qquad \text{for suitable } \textit{units } a_i^r \in R\,.$$

The construction of $\boldsymbol{x}$ needs some explanation: we start with $B = \bigoplus_{i=1}^{k} \langle x_i\rangle$ basic in X and consider X/B; if $\{x_{k+1} + B, \ldots, x_n + B\}$ is a minimal set of generators of X/B, from the purity of B it follows that $\boldsymbol{x} = \{x_1, \ldots, x_k, x_{k+1}, \ldots, x_n\}$ is a minimal set of generators of X; in view of Lemma 1.1 of [9], we can permute the indexes $k+1, \ldots, n$ to obtain property b). Since B is pure in X, certainly, for all $r \in A_{k+1}$, the relation (1) holds for suitable elements $a_i^r \in R$, not necessarily units. However, if $r \in \operatorname{Ann} x_i$ for some $i \leqslant k$, obviously we can replace a_i^r with 1; moreover, if there exist $i \leqslant k$ and $s \in A_{k+1} \setminus \operatorname{Ann} x_i$ such that $a_i^s \in P$, then for all $r \in A_{k+1} \setminus \operatorname{Ann} x_i$ we have $a_i^r \in P$: in fact, if r divides s, from (1) we get $s(a_i^r - a_i^s)x_i = 0$, hence $a_i^s \in P$ implies $a_i^r \in P$; analogously, if s divides r, $r(a_i^r - a_i^s)x_i = 0$ implies $a_i^r \in P$. Let now $F = \{i \leqslant k\colon a_i^r \in P \text{ for all } r \in A_{k+1} \setminus \operatorname{Ann} x_i\}$; if we replace x_{k+1} with $x'_{k+1} = x_{k+1} + \sum_{i\in F} x_i$, we obtain that

$$\operatorname{Ann}(x'_{k+1} + B) = \operatorname{Ann}(x_{k+1} + B) = A_{k+1}\,,$$

$$\boldsymbol{x}' = \{x_1, \ldots, x_k, x'_{k+1}, \ldots, x_n\}$$

is a minimal set of generators of X, and (1) becomes

$$(1') \qquad rx'_{k+1} = r\sum_{i=1}^{k} b_i^r x_i \qquad \text{for all } r \in A_{k+1}$$

where $b_i^r = a_i^r$ if $i \notin F$ and $b_i^r = 1 + a_i^r$ if $i \in F$, so that b_i^r is a unit for all $i \leqslant k$ and for all $r \in A_{k+1}$. We conclude that there exists a minimal set of generators $\boldsymbol{x}$ of X which satisfies properties a), b), c), as desired.

Let us now recall Colpi's result (Prop. 4.3 of [1]).

THEOREM 1 (Colpi). *Let R be a ring, ${}_RM$ a left R-module. Then ${}_RM$ is a *-module if and only if the following conditions are satisfied:*

i) *${}_RM$ is self-small;*

ii) *for each exact sequence*

$$0 \to L \to N \to N/L \to 0$$

where N is an object of Gen $({}_RM)$, *the sequence*

$$0 \to \mathrm{Hom}_R(M, L) \to \mathrm{Hom}_R(M, N) \to \mathrm{Hom}_R(M, N/L) \to 0$$

is exact if and only if $L \in \mathrm{Gen}({}_RM)$. ///

We can now prove our main result.

THEOREM 2. *Let R be a valuation ring, let X be a finitely generated R-module and let $\pi\colon X \to X/PX$ be the canonical homomorphism. If the map $\varphi\colon \mathrm{End}\, X \to \mathrm{Hom}_R(X, X/XP)$, $\varphi\colon f \mapsto \pi\circ f$ is surjective, then $X \cong (R/A)^n$ for suitable $n \geq 0$ and A ideal of R.*

PROOF. In the following we assume $X \neq (R/A)^0 = \{0\}$, otherwise all is trivial. First of all, let us prove that X is a direct sum of cyclic submodules. Let B be a basic submodule of X; it is enough to verify that $B = X$. By contradiction, suppose that $B < X$; let

$$\boldsymbol{x} = \{x_1, \ldots, x_k, x_{k+1}, \ldots, x_n\}$$

be a minimal set of generators of X which satisfies conditions *a*), *b*), *c*) above. Note that, since $B < X$, we have $k < n$, hence condition *c*) and the relation (1) are not trivially satisfied. For all $j \leq n$, let $\bar{x}_j = x_j + PX$; we have $X/PX = \bigoplus_{j=1}^{n} \langle \bar{x}_j \rangle$. Let us now consider the homomorphism $g\colon X \to X/PX$ defined extending by linearity the assignments

$$g\colon x_j \mapsto 0 \quad \text{if } j \neq k+1; \qquad g\colon x_{k+1} \mapsto \bar{x}_{k+1}\,.$$

By hypothesis, there exists $f \in \mathrm{End}\, X$ such that $g = \pi\circ f$. Hence, for $j \neq k+1$, we will have

$$f(x_j) = p \sum_{h=1}^{n} a_{hj} x_h\,, \quad \text{with } p \in P\,, \quad a_{hj} \in R \tag{2}$$

and

$$f(x_{k+1}) = x_{k+1} + q\sum_{h=1}^{n} b_h x_h\,, \qquad \text{with } q \in P\,, \quad b_h \in R\,. \tag{3}$$

From (1), (2), (3), and the linearity of f, it follows, for all $r \in A_{k+1}$

$$r\Big(x_{k+1} + q\sum_{h=1}^{n} b_h x_h\Big) = rp\sum_{i=1}^{k} a_i^r\Big(\sum_{h=1}^{n} a_{hi}x_h\Big)\,. \tag{4}$$

Since $A_{k+1} \leqslant A_t$ for all $t > k+1$, and B is pure, we deduce that, for all $r \in A_{k+1}$

$$rq\sum_{h=1}^{n} b_h x_h \in rqB \qquad \text{and } rp\sum_{i=1}^{k} a_i^r\Big(\sum_{h=1}^{n} a_{hi}x_h\Big) \in rpB\,. \tag{5}$$

Let $\bar{p} \in P$ be a common divisor of p and q; from (4) and (5) we get $rx_{k+1} \in r\bar{p}B$ for all $r \in A_{k+1}$, i.e.

$$rx_{k+1} = r\bar{p}\sum_{i=1}^{k} c_i^r x_i\,, \qquad \text{with } c_i^r \in R\,. \tag{6}$$

From (1), (6), and the linear independence of $x_1, \ldots, x_k$ we obtain

$$r(a_i^r - \bar{p}c_i^r)x_i = 0 \qquad \text{for } i = 1, \ldots, k; \tag{7}$$

since a_i^r is a unit for all i and r, we have that $a_i^r - \bar{p}c_i^r$ is a unit, too, hence (7) implies $r \in \operatorname{Ann} x_i$ for all $r \in A_{k+1}$. But this means that $rx_{k+1} \in B$ implies $rx_{k+1} = 0$, from which $\langle x_{k+1}\rangle \cap B = 0$, and B is not essential, against the definition of basic submodule. We conclude that, necessarily, $X = B$, as desired. It remains to prove that, if $A = \operatorname{Ann} X$, then $X \simeq (R/A)^n$. By contradiction, let us suppose that $X = \bigoplus_{i=1}^{n} \langle x_i\rangle$, where, for a suitable $j \leqslant n$, $\operatorname{Ann} x_j > A$. Let us assume, without loss of generality, that $\operatorname{Ann} x_1 = A$. Let $\eta\colon X \to X/PX$ be the homomorphism which extends by linearity the assignments

$$\eta\colon x_i \mapsto 0 \quad \text{if } i \neq j; \qquad \eta\colon x_j \mapsto \bar{x}_1 = x_1 + PX\,.$$

If $\theta \in \operatorname{End} X$ is such that $\eta = \pi \circ \theta$, then we have

$$(8) \qquad \theta(x_j) = x_1 + p \sum_{i=1}^{n} a_i x_i\,, \qquad \text{with } p \in P\,, \quad a_i \in R\,.$$

Choose now $r \in \operatorname{Ann} x_j \setminus A$; from (8) we obtain

$$(9) \qquad 0 = \theta(rx_j) = r(1 + pa_1)x_1 + rp \sum_{i=2}^{n} a_i x_i\,,$$

from which $r(1 + pa_1)x_1 = 0$, which is impossible, because $r \notin A = \operatorname{Ann} x_i$. This concludes the proof. ////

As an easy consequence of the preceding result we obtain the following

THEOREM 3. *Let R be a valuation ring. A finitely generated R-module X is a *-module if and only if $X \simeq (R/A)^n$ for suitable $n \geqslant 0$ and A ideal of R.*

PROOF. For any ring R, modules of the form $(R/A)^n$ are *-modules as a consequence of Theorem 1, observing that $\operatorname{Gen}((R/A)^n) = R/A - \operatorname{Mod}$, and $\operatorname{Hom}_R((R/A)^n, -) \approx \operatorname{Hom}_{R/A}((R/A)^n, -)$, if $n \geqslant 1$.

Conversely, let us note that $PX \in \operatorname{Gen}(X)$, as it is easy to check. Therefore, if X is a finitely generated *-module, then, by Theorem 1, X must satisfy the condition in the hypothesis of Theorem 2, hence X has the desired form. ///

The problem of finding *-modules which are not finitely generated remains open. We actually think that a *-module over a valuation ring must be finitely generated; this opinion is mainly based on the following remark, derived from discussions with L. Salce.

REMARK 4. The simplest non finitely generated R-modules are the *uniserial* ones, i.e. those R-modules whose lattice of submodules is linearly ordered. Fuchs and Salce proved that, if U is a *divisible* uniserial module over a valuation *domain* R, whose elements have nonzero principal annihilators, then there is an equivalence of categories

$$\operatorname{Gen}(U) \underset{G}{\overset{F}{\rightleftarrows}} \mathcal{C}$$

where $\mathcal{C}$ *is the class of complete torsion-free reduced R-modules*, $F \approx \mathrm{Hom}_R(U, -)$ and $G \approx U \otimes_R -$ (see [6]; this equivalence was inspired by Matlis equivalence in [7]; see also [5], p. 99). Moreover, U is small if and only if it is not countably generated. Nevertheless, for any choice of R we notice that U is not a *-module. This is clear if U is countably generated (see Theorem 1). If U is not countably generated, then also Q, the field of fractions of R, is not countably generated as an R-module; in this case we get that $\mathcal{C}$ *is not closed for submodules*, hence $\mathcal{C}$ cannot be cogenerated by any module. It is worth giving a check of this last fact: let us suppose, by contradiction, that $\mathcal{C}$ is closed for submodules, for a convenient R, with Q not countably generated as an R-module; with these assumptions, R must be complete, and each *free* R-module F is complete, too, in view of Cor. 2.2 of [6]. Let us consider a short exact sequence

$$0 \to K \to F \to Q \to 0$$

with F free; then $F \in \mathcal{C}$ implies $K \in \mathcal{C}$, hence K is closed in F and $Q \cong F/K$ must be Hausdorff in the natural topology, i.e. $\{0\} = \bigcap_{r \in R^*} rQ = Q$, a contradiction.

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