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PROJECTIVE QUASI-COHERENT SHEAVES OF MODULES

RICHARD ARTHUR LEVARO

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Let R be a commutative ring and \tilde{R} the structure sheaf over the prime spectrum of R .

THEOREM: Suppose R has only finitely many minimal primes. Then \tilde{R} is a projective \tilde{R} -Module if and only if R is a finite direct product of local rings.

Let R be a nonzero commutative ring with identity, and let $x = \text{Spec}(R)$, the prime spectrum of R endowed with the Zariski topology. Let \tilde{R} be the structure sheaf of R on X . We shall use the terminology and notation of [5] in describing the category of \tilde{R} -Modules, $\text{Mod}(\tilde{R})$.

There is a functor $T: \text{mod}(R) \rightarrow \text{Mod}(\tilde{R})$ given $T(M) = \tilde{M}$ and $T(f) = \tilde{f}$, where \tilde{M} is the \tilde{R} -Module associated to M , and \tilde{f} is defined at each stalk of \tilde{M} to be the localization of f . The functor T is full, faithful and exact; moreover T preserves direct sums [5, Corollaire I.1.3.8 and I.1.3.9.]. In addition, T determines an equivalence between $\text{mod}(R)$ and the category of quasi-coherent \tilde{R} -Modules. In §1, we shall show that if \tilde{R} is a generator, then $\text{Mod}(\tilde{R})$ is equivalent to $\text{mod}(R)$. In §2 necessary and sufficient conditions are given for \tilde{R} to be a projective \tilde{R} -Module.

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1. The equivalence of $\text{Mod}(\tilde{R})$ and $\text{mod}(R)$. C. J. Mulvey [8] has given a necessary and sufficient condition for \tilde{R} to be a generator in $\text{Mod}(\tilde{R})$. For the case of the affine scheme ($X = \text{Spec}(R)$, \tilde{R}), we can state Mulvey's condition as follows:

PROPOSITION 1.1 (Mulvey, [8]). *A necessary and sufficient condition that \tilde{R} be a generator in $\text{Mod}(\tilde{R})$ is that the stalks of \tilde{R} may be generated by global sections of \tilde{R} of arbitrarily small support. If this condition holds, then $X = \text{Spec}(R)$ is necessarily a regular topological space.*

THEOREM 1.2. *The following are equivalent:*

- (i) $T: \text{mod}(R) \rightarrow \text{Mod}(\tilde{R})$ is an equivalence of categories, i.e., every \tilde{R} -Module is quasi-coherent;
- (ii) \tilde{R} is a generator for the category $\text{Mod}(\tilde{R})$;
- (iii) $X = \text{Spec}(R)$ is T_1 ;
- (iv) $R/N(R)$ is von Neumann regular, where $N(R)$ is the nil-

radical of R . If \tilde{R} is a flabby (flasque) \tilde{R} -Module, then the equivalent conditions (i)-(iv) are satisfied.

Proof. (i) implies (ii). Since R is a generator of $\text{mod}(R)$, this implication is clear.

(ii) implies (i). Since \tilde{R} is a generator, it is immediate that every \tilde{R} -Module is of the form \tilde{M} .

(ii) implies (iii). Because \tilde{R} is a generator, by Proposition 1.1, $X = \text{Spec}(R)$ is a regular topological space. But X is always T_0 , so it is also T_1 .

(iii) implies (iv). This is well-known and appears as an exercise in [2, page 143].

(iv) implies (ii). Since $R/N(R)$ is von Neumann regular and $X = \text{Spec}(R)$ is homeomorphic to $\text{Spec}(R/N(R))$, X has a basis of closed and open sets. We shall use the criterion of Proposition 1.1 to show \tilde{R} is a generator. Let $x \in X$, and let U be an open set in X with $x \in U$. Let V be an open and closed (basic) set such that $x \in V \subseteq U$. Define sections $s_1 \in \tilde{R}(V)$ and $s_0 \in \tilde{R}(X - V)$ by $s_1(z) = 1_z \in R_{p_z}$ for all $z \in V$, and $s_0(z) = 0_z \in R_{p_z}$ for all $z \in X - V$. Since V partitions X , we can collate s_1 and s_0 to obtain a global section s of \tilde{R} with $s(z) = 1_z$ if $z \in V$ and $s(z) = 0_z$ if $z \notin V$. Clearly s generates \tilde{R}_x , and the support of s is $V \subseteq U$. Therefore, by the Proposition, \tilde{R} is a generator.

For the last statement, suppose \tilde{R} is flabby and $s \in R$. Then the restriction map $\tilde{R}(X) \rightarrow \tilde{R}(D(s))$ is onto, and hence the localization map $R \rightarrow R_s$ is onto. Now $D(s) \approx \text{Spec}(R_s)$, and because $R \rightarrow R_s$ is onto, $\text{Spec}(R_s)$ is homeomorphic to a closed set of X . Hence the usual basis is both open and closed; therefore points in X are closed and X is T_1 .

R. Wiegand has shown, using different techniques, that a reduced prescheme (X, \mathcal{A}) is regular (i.e., X can be covered by open sets U_i such that $(U_i, \mathcal{A}|_{U_i})$ is the affine scheme of a von Neumann regular ring) if and only if every \tilde{R} -Module is quasi-coherent [9].

The Theorem provides examples of rings for which there are projectives in $\text{Mod}(\tilde{R})$.

COROLLARY 1.3. *Suppose $R/N(R)$ is von Neumann regular where $N(R)$ is the nilradical of R . The \tilde{R} -Module F is projective if and only if $F(X)$ is a projective R -module. In particular, P is a projective R -module if and only if \tilde{P} is a projective \tilde{R} -Module.*

2. Projective quasi-coherent \tilde{R} -Modules. Suppose \tilde{R} is a projective \tilde{R} -Module. If P is a projective R -module, then there is an R -module Q such that $P \oplus Q \cong \sum R$; hence $\tilde{P} \oplus \tilde{Q} \cong \sum \tilde{R}$ since T

preserves direct sums. Therefore, \tilde{P} is a projective \tilde{R} -Module. Thus, to discover when projective R -module yield projective \tilde{R} -Modules, it is enough to determine when \tilde{R} is projective.

PROPOSITION 2.1. *If R is a local (not necessarily Noetherian) ring, then \tilde{R} is a projective \tilde{R} -Module.*

Proof. Since $\text{Hom}_{\tilde{R}}(\tilde{R}, F)$ is naturally isomorphic to $F(X)$ for every \tilde{R} -Module F , we need only show the global section functor is exact. Let p_x be the unique maximal ideal of R . For any \tilde{R} -Module F , $F_x = \lim_{\rightarrow} F(U)$ where the direct limit is taken over all open sets containing x . Because $X = \text{Spec}(R)$ is the only open set containing x , $F_x = F(X)$. Now, the formation of stalks is exact, so $\text{Hom}_{\tilde{R}}(\tilde{R},)$ is exact, i.e., \tilde{R} is projective.

R. Bkouche [1] introduced the notion of soft rings.

DEFINITION. The ring R is *soft* (mou) if $\text{Max}(R)$, the maximal spectrum of R , is Hausdorff and $J(R) = 0$, where $J(R)$ is the Jacobson radical of R .

For our purposes, we need a notion a bit more general.

DEFINITION. The ring R is *quasi-soft* if for every $x \in \text{Max}(R)$, the localization map $\alpha_x: R \rightarrow R_{p_x}$ is onto.

Every local ring is quasi-soft, but not necessarily soft. Every von Neumann regular ring is quasi-soft. The relation between soft and quasi-soft rings is given by the following.

PROPOSITION 2.2. *If R is quasi-soft, then $R/J(R)$ is soft, where $J(R)$ is the Jacobson radical of R . Every soft ring is quasi-soft.*

Proof. If R is quasi-soft, then $\text{Max}(R)$ is regular as can be seen by imitating the proof for soft rings [1, Proposition 1.6.1 and 1.6.2]. But $\text{Max}(R)$ is always T_1 ; hence $\text{Max}(R)$ is Hausdorff. Since $\text{Max}(R) \approx \text{Max}(R/J(R))$ and $J(R/J(R)) = 0$, $R/J(R)$ is soft.

Now suppose R is soft, $x \in \text{Max}(R)$, and let $\alpha_x: R \rightarrow R_{p_x}$ be the localization map. Because $J(R) = 0$ and $\text{Max}(R)$ is Hausdorff, $V_{\mathcal{M}}(\ker(\alpha_x)) = \{x\}$, where $V_{\mathcal{M}}(I) = \text{Max}(R) \cap V(I)$ for an ideal I of R . Therefore, $R/\ker(\alpha_x)$ is a local ring with maximal ideal p_x , and so every element outside p_x is invertible. By the universal mapping property of localization, $R/\ker(\alpha_x) \cong R_{p_x}$; hence R is quasi-soft.

Quasi-softness is the condition we must investigate to find necessary conditions for \tilde{R} to be a projective \tilde{R} -Module in view of the following result.

PROPOSITION 2.3. *If \tilde{R} is a projective \tilde{R} -Module, then R is quasi-soft.*

Proof. Let $x \in \text{Max}(R)$ and set $A = \{x\}$. Then $A \subseteq X$ is closed, and we have the exact sequence

$$0 \longrightarrow \tilde{R}_{x-A} \longrightarrow \tilde{R} \xrightarrow{\alpha} \tilde{R}_A \longrightarrow 0$$

of \tilde{R} -Modules [4, Théorème 2.9.3.]. Since \tilde{R} is projective, $\text{Hom}_{\tilde{R}}(\tilde{R}, _)$ is exact, and hence $\text{Hom}_{\tilde{R}}(\tilde{R}, \tilde{R}) \xrightarrow{\alpha_*} \text{Hom}_{\tilde{R}}(\tilde{R}, \tilde{R}_A)$ is onto. Now $\text{Hom}_{\tilde{R}}(\tilde{R}, \tilde{R}) \cong R$ and $\text{Hom}_{\tilde{R}}(\tilde{R}, \tilde{R}_A) \cong R_{p_x}$, and it is routine to check that α_* may be identified with the localization map $\alpha_x: R \rightarrow R_{p_x}$ (i.e., the obvious diagram commutes). Therefore R is quasi-soft.

We can now state and prove the

MAIN THEOREM. *Suppose R has only finitely many minimal primes. Then \tilde{R} is a projective \tilde{R} -Module if and only if R is finite direct product of local rings.*

Proof. Since R has only finitely many minimal primes, R is the finite direct product of connected rings, say $R = R_1 \times R_2 \times \cdots \times R_n$ each having only finitely many minimal primes. If \tilde{R} is a projective \tilde{R} -Module, \tilde{R}_i is a projective \tilde{R}_i -module for each i . By Proposition 2.3 R_i is quasi-soft. Hence $\text{Max}(R_i)$ is finite, since each prime ideal of a quasi-soft, ring is contained in a unique maximal ideal [1, Proposition 1.6.1]. Also, since R_i is quasi-soft, $\text{Max}(R_i)$ is the continuous image of $\text{Spec}(R_i)$ [1, Proposition 1.6.2]. (See also [3]). Thus, $\text{Max}(R_i)$ is finite and discrete, but also connected being the continuous image of $\text{Spec}(R_i)$. Therefore $\text{Max}(R_i)$ consists of a single point, and hence R_i is local.

Conversely, if $R = R_1 \times \cdots \times R_n$ where each R_i is local, then \tilde{R}_i is a projective \tilde{R}_i -Module by Proposition 2.1. Hence, \tilde{R} is a projective \tilde{R} -Module.

The Main Theorem resolves the problem of determining the projectivity of \tilde{R} for rings with only finitely many minimal primes; in particular, for Noetherian rings and integral domains.

Let R be a discrete valuation domain. In this case; $X = \text{Spec}(R) = \{(0), p\}$, where p is the unique maximal ideal of R . Since R is local,

\tilde{R} is a projective \tilde{R} -Module. Since $U = \{(0)\}$ is smallest open set containing (0) , \tilde{R}_U is also a projective \tilde{R} -Module. Thus, there are examples of projective \tilde{R} -Modules which are not quasi-coherent. Furthermore, since $\tilde{R} \oplus \tilde{R}_U$ is a generator for $\text{Mod}(\tilde{R})$ [6, Proposition 3.1.1], in this case $\text{Mod}(\tilde{R})$ has a small projective generator. Hence $\text{Mod}(\tilde{R})$ is equivalent to a category of modules [7, Theorem 4.1, page 104], but the functor T is not the equivalence since $X = \text{Spec}(R)$ is not T_1 .

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