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ON ALGEBRAS OF SECOND LOCAL TYPE, III

HIDETO ASASHIBA

Dedicated to Professor Hisao Tominaga on his 60th birthday

(Received November 5, 1985)

Throughout this paper, $A$ denotes a (left and right) artinian ring with identity 1, $J$ the Jacobson radical of $A$, and all modules are assumed to be (unitary) finitely generated one-sided $A$-modules unless otherwise stated. Further $k$ denotes an algebraically closed field and by the word algebra we mean a finite dimensional algebra over $k$.

As defined in [I], we say that $A$ is a ring of right 2nd local type in case the top$_2^2 M := M/MJ^2$ of every indecomposable right $A$-module $M$ is indecomposable. In [II, sections 3 and 4], we have determined all possible structures of indecomposable projective right and left modules over an algebra of right 2nd local type; and proved that conversely this classification condition on indecomposable projectives is sufficient for left serial algebras to be of right 2nd local type. Here we will generalize these results. Namely in section 1, corresponding to the first result above, we give a complete classification of local left and right modules over an arbitrary artinian ring of right 2nd local type (Theorem I). And in section 2, we prove the same statement as the second result above is still true for left serial rings with selfduality (Theorem II). In the last section, as examples of algebras of right 2nd local type, we give all the sincere simply connected (representation-finite) algebras of right 2nd local type using the method outlined in Ringel [10], and then characterize such algebras in terms of their ordinary quivers which include interpretations of lemmas used in the proof of the classification theorem above (Theorem III). This characterization leads us to necessary and sufficient conditions for representation-finite algebras to be of right 2nd local type (Theorem IV), by making use of the covering technique developed in [5], [7] and [6].

Since the property to be of right 2nd local type is Morita invariant, we may and will assume throughout that $A$ is a basic ring. We keep the notation and terminology used in [I] or [II].

1. Classification of local modules

We prove the following theorem.
Theorem I. Assume that \( A \) is a ring of right 2nd local type. Then

\((R)\) Every local right \( A \)-module \( P \) has one of the following structures:

\((R_1)\) \( P \) is uniserial.
\((R_2)\) \( P \) is of height 2 with the socle of length \( \geq 2 \).
\((R_3)\) \( P \) is non-uniserial of height 3 and colocal.
\((R_4)\) \( P \) is a direct sum of a simple right module and a non-uniserial colocal right module of height 2.
\((R_5)\) \( P \) is a direct sum of two non-zero uniserial right modules.

\((L)\) Every local left \( A \)-module \( P \) has one of the following structures:

\((L_1)\) \( P \) is uniserial.
\((L_2)\) \( P \) is non-uniserial of height 2.
\((L_3)\) \( P \) is non-uniserial of height 3 and colocal.
\((L_4)\) \( P \) is non-uniserial of height 4 with \( f^*P \) a uniserial waist in \( P \).

If, in addition, \( A \) is a ring with selfduality, the case of \((L_4)\) does not occur.

At present we have no example of a ring of right 2nd local type having a local left module of type \((L_4)\). To prove the theorem we assume up to the end of this section that \( A \) is a ring of right 2nd local type. We quote the following as a special case of [II, Theorem 2.5 (1R)\( \Rightarrow \)(2R)].

Lemma 1.0. Let \( L_1 \) and \( L_2 \) be local right modules and \( S_i \) a simple submodule of \( L_i \) for each \( i \) such that \( S_1 \leq L_1 f \) and \( S_2 \leq L_2 f \). Then for every isomorphism \( \alpha : S_1 \to S_2 \), \( \alpha \) is extendable to a homomorphism \( L_1 \to L_2 \) or \( \alpha^{-1} \) is extendable to a homomorphism \( L_2 \to L_1 \).

Lemma 1.1. Let \( P_A \) be a local module of height 3, \( L_A \) a local module of height 2 and \( S_A \) a simple submodule of \( L_A f \). Then every homomorphism \( \alpha : S \to Pf \) is extendable to a homomorphism \( L \to P \).

Proof. We may assume that \( \alpha \) is not zero, whence is a monomorphism. By Lemma 1.0, we have only to show that \( \alpha^{-1} : \text{Im} \alpha \to S \) is not extendable to any homomorphism \( \varphi : P \to L \). But otherwise, \( 3 = h(\text{Coim} \varphi) = h(\text{Im} \varphi) \leq h(L) = 2 \), a contradiction.

Lemma 1.2. Let \( P_A \) be a local module of height 3 and \( L_A \) a local submodule of \( Pf \) and put \( \text{soc} L = S_1 \oplus \cdots \oplus S_n \) with each \( S_i \) simple. Then there is a uniserial module \( L_i \) with \( \text{soc} L_i = S_i \) for each \( i \in \{1, \cdots, n\} \) such that \( L + L_1 + \cdots + L_{n-1} = L_1 \oplus L_2 \oplus \cdots \oplus L_n \). In particular, \( L \) is contained in a sum of uniserial modules.

Proof. By induction on \( n \). If \( n = 1 \), then the assertion holds for \( L_n := L \). So assume \( n > 1 \). Then \( h(L) = 2 \). Put \( M := L/(S_2 \oplus \cdots \oplus S_n) \) and \( S := \text{soc} M \) (\( \cong S_1 \)). Then by Lemma 1.1, the canonical injection \( \alpha : S \to S_1 \leq Pf \) is extendable to a homomorphism \( \varphi : M \to P \). Put \( L_1 := \text{Im} \varphi \). Then \( L_1 \) is uniserial
of length 2 and \( \text{soc} L_i = S_i \). Since \( \varphi \pi : L \to L_1 \) is an extension of the identity map of \( S_1 = L \cap L_1 \) (where \( \pi : L \to M \) is the canonical projection), we have \( L + L_1 = L_1 \oplus L' \) where \( L' \) is the image of the map \( 1_L - \varphi \pi : L \to L + L_1 \) (whence \( L' \) is a local submodule of \( PJ \)). In addition, as easily verified we have \( \text{soc} L' = S_2 \oplus \cdots \oplus S_n \). Applying the induction hypothesis to \( L' \), we have uniserial modules \( L_2, \ldots, L_n \) such that \( \text{soc} L_i = S_i \) for all \( i \in \{2, \ldots, n\} \) and \( L + L_2 + \cdots + L_{n-1} = L_2 \oplus \cdots \oplus L_{n-1} \oplus L_n \). Hence \( L + L_1 + \cdots + L_{n-1} = L_1 + L_2 + \cdots + L_{n-1} = L_1 + (L_2 \oplus \cdots \oplus L_{n-1} \oplus L_n) \) and the last sum is direct since \( \text{soc} L_i = S_i \) for all \( i \in \{1, \ldots, n\} \).

**Proposition 1.3.** If \( PA \) is a local module of height 3, then \( PJ \) is expressed as an irredundant sum of uniserial modules.

**Proof.** Clear from Lemma 1.2. 

**Lemma 1.4.** Let \( L \) be a right module. Then the following are equivalent:

1. \( L \) is uniserial.
2. \( \text{top}^2 L \) is uniserial.
3. \( \text{soc}^2 L \) is uniserial.

**Proof.** The implications (1) \( \Rightarrow \) (2) and (1) \( \Rightarrow \) (3) are clear.

(2) \( \Rightarrow \) (1). Assume that \( \text{top}^2 L \) is uniserial but \( L \) is not. Let \( t \) be the smallest natural number such that \( |LJ^t|/|LJ^{t+1}| > 1 \). Then by assumption \( t > 1 \). Put \( P := L^t J^{t+1} \). Then \( P \) is a local module of height 3 and \( PJ \) is also local. Hence \( PJ \) is uniserial by Proposition 1.3. This implies \( 1 = |PJ| = |LJ^t|/|LJ^{t+1}| > 1 \), a contradiction.

(3) \( \Rightarrow \) (1). Assume that \( \text{soc}^2 L \) is uniserial but \( L \) is not. Let \( t \) be the smallest natural number such that \( |\text{soc}^t L|/|\text{soc}^t L| > 1 \). Then by assumption \( t > 1 \). Put \( P := \text{soc}^t L/\text{soc}^{t+1} L \). Then \( P \) is of height 3 and \( \text{soc}^2 P = \text{soc}^t L/\text{soc}^{t+1} L \) is uniserial. Again by assumption \( |\text{top} P| > 1 \). Hence \( P \) is expressed as an irredundant sum of at least two local modules \( L_i \). Put \( M := L_1 + L_2 \). Then \( \text{soc}^2 M = \text{soc}^t P \) and \( L_1 J = \text{soc}^t M = L_2 J \). Hence, in particular, \( L_1 \) and \( L_2 \) are uniserial of length 3. By Lemma 1.1 \( 1_{\text{soc}^t M} \) is extendable to a homomorphism \( \varphi : L_1 \to L_2 \). Putting \( L' := (L_1 - \varphi)(L) \) (\( \neq 0 \)), we have \( M = L' + L_2 \) and \( |L' \cap L_2| < |L_1 \cap L_2| = |\text{soc}^t M| = 2 \). Since \( M \) is indecomposable, \( L' \cap L_2 \neq 0 \) whence \( L' \cap L_2 = \text{soc} M \). Then \( 1 = |\text{soc}^2 M/\text{soc} M| = |\text{soc}(M/\text{soc} M)| = |\text{soc}(L' + L_2)|/|L' \cap L_2| = 2 \), a contradiction.

**Lemma 1.5 ([2]).** Let \( L \) be a non-zero proper submodule of a right module \( M \). Then \( L \) is a waist in \( M \) iff \( L/LJ \) is a waist in \( M/LJ \).

**Corollary 1.6.** Let \( L \) be a right module of height \( > 2 \) such that \( \text{top}^2 L \) is colocal. Then \( L \) is uniserial.
Proof. Since \( \text{top}^2 L = L/L^2 \) is colocal, we have \( L^2/L^2 = \text{soc}(L/L^2) \) is a waist in \( L/L^2 \). Hence by Lemma 1.5, \( L^2 \) is a waist in \( L \). We first show that \( L^2 \) is uniserial. Let \( x \) be any element in \( L \setminus L^2 \). Then \( xe \in L^2 \) for some \( e \in \pi(A) \). Putting \( N \equiv xeA \), \( N \) is a local submodule of \( L \) with \( N \not\leq L^2 \). By the above, \( L^2 < N \). Then since \( NJ \leq L^2 < N \) and \( N \) is local, we have \( NJ = L^2 \) and \( NJ/N^2 = L^2/L^2 \) is simple. Thus \( \text{top}^2 N \) is uniserial. Hence by Lemma 1.4, \( N \) is uniserial. So \( L^2 \) is uniserial. We now put \( L = h(L) \). Since \( L^2 = \text{soc}^2 L \) is uniserial and \( h < 1 \), \( \text{soc}^2 L \) is uniserial, whence so is \( L \) by Lemma 1.4. 

Lemma 1.7. Let \( L \) be a local right module. If \( L^2 \) is simple, then \( |\text{soc} L| \leq 2 \); more precisely \( L \) is colocal or \( L^2 \) is a direct sum of a simple right module and a colocal right module of height 2.

Proof. Since \( L^2 = 0 \) and \( A/J^3 \) is also a ring of right 2nd local type, we may assume that \( J^3 = 0 \). Consider the following exact sequence

\[
0 \to I \to eA \to L \to 0
\]

where \( e \in \pi(A) \) and \( eA \) is the projective cover of \( L \). Put \( T = eJ^3 \cap I \), \( M = eA/T \) and \( S = MJ^3 \). Then \( M \) is local and \( S = eJ^3/T \approx L^2 \) is simple.

We first show that \( |\text{soc} M| \leq 2 \). Assume \( |\text{soc} M| \geq 3 \). Then there are simple right modules \( S_1 \) and \( S_2 \) such that \( S_1 \oplus S_2 \supseteq \text{soc} M \). Define an isomorphism \( \alpha \) by the following commutative diagram

\[
\begin{array}{ccc}
S & \xrightarrow{\alpha} & S \\
\downarrow & & \downarrow \\
(S \oplus S_1)/S_1 & \longrightarrow & (S \oplus S_2)/S_2
\end{array}
\]

where the vertical maps are the canonical isomorphisms. Then it follows from \( (S \oplus S_1)/S_1 = (M/S_1)J^3 \) for each \( i \) that \( \alpha \) is extendable to a homomorphism \( \beta : M/S_1 \to M/S_2 \) or \( \alpha^{-1} \) is extendable to a homomorphism \( \beta : M/S_2 \to M/S_1 \). In either case \( \beta \) is an isomorphism. In fact, \( (M/S_1)J^3 \subseteq \ker \beta \) implies \( h(\text{Im} \beta) = 3 \), thus \( \beta \) is an epimorphism, whence an isomorphism since \( |M/S_1| = |M/S_2| \).

Therefore we may suppose that \( \alpha \) is extendable to some \( \beta : M/S_1 \to M/S_2 \). Let \( S'_i \) be the unique submodule of \( eA \) containing \( T \) such that \( S'_i/T = S_i \) for each \( i \). Then \( M/S_i \approx eA/S'_i \) for each \( i \). The homomorphism \( \beta \) induces an isomorphism \( \beta' : eA/S'_i \to eA/S_i \) which is clearly given by the left multiplication by an element \( t \) in \( eAe \setminus eJ^3 \). Thus \( tS'_i/S_i = S'_i \). Taking \( S = eJ^3/T \) into account it follows from \( S'_i \cap S = 0 \) that \( S'_i \cap eJ^3 = T \) for each \( i \). Hence \( tT = t(S'_i \cap eJ^3) = tS'_i \cap teJ^3 = S_i \cap eJ^3 = T \). Thus the left multiplication by \( t \) induces an automorphism \( \gamma \) of \( M \). As easily checked \( \gamma \) is a lift of \( \beta \), i.e. the diagram
is commutative where the vertical maps are the canonical epimorphisms. Then since \( \gamma(S) = \gamma(MJ^2) = MJ^2 = S \), the diagram above induces the following commutative diagram

\[
\begin{array}{ccc}
M & \xrightarrow{\gamma} & M \\
\downarrow & & \downarrow \\
M/S_1 & \xrightarrow{\beta} & M/S_2
\end{array}
\]

Thus \( \gamma|S = 1_S \). This means that \( t-e \in eJe \), whence \( t = e+j \) for some \( j \in eJe \).

Then \( S'_2 = tS'_1 = (e+j)S'_1 \leq eS'_1 + jS'_1 \leq S'_1 + eJ^2 \) since \( jS'_1 \leq jeJ \leq eJ^2 \). Thus \( S_2 \leq S_1 \oplus S \), a contradiction. Accordingly we must have \( |\text{soc} M| \leq 2 \).

Since \( T \leq I \), (1) induces an exact sequence \( 0 \to K \to M \to L \to 0 \).

\( LJ^2 \neq 0 \) implies \( MJ^2 \leq K \). Hence \( K \cap MJ^2 = 0 \) since \( MJ^2 \) is simple. By [II, Lemma 3.2.2] \( MJ = K \oplus H \) for some \( H \leq MJ \). Hence \( |\text{soc} L| = |\text{soc} LJ| = |\text{soc} (MJ/K)| = |\text{soc} H| \leq |\text{soc} MJ| = |\text{soc} M| \leq 2 \). This completes the proof of the first part of the statement. Now suppose that \( L \) is not colocal. Then by the above \( |\text{soc} L| = 2 \). Since \( LJ^2 \) is simple, \( L = X \oplus LJ^2 \) for some simple \( X \leq L \). In particular \( X \cap LJ^2 = 0 \). It follows from \( X \leq LJ \) that \( LJ = X \oplus Y \) for some \( Y \leq LJ \) by [II, Lemma 3.2.2]. Since \( LJ^2 = YJ \) is simple, \( h(Y) = 2 \).

Further \( Y \) is colocal since \( 2 = |\text{soc} LJ| = |\text{soc} LJ| = |X| + |\text{soc} Y| \). Hence \( L \) is a direct sum of a simple \( X \) and a colocal \( Y \) of height 2. //

**Proposition 1.8.** If \( P_A \) is a local module, then \( |PJ^2/PJ^3| \leq 2 \).

Proof. We may assume that \( h(P) = 3 \). Suppose that \( |PJ^2| \geq 3 \). Then by Proposition 1.3 we have an irredundant sum \( PJ = \sum_{i=1}^{3} L_i \) of \( PJ \) for some uniserial modules \( L_i \). So \( PJ^2 = \sum_{i=1}^{3} L_iJ \) where \( L_iJ \) is simple or zero, whence we may assume that \( PJ^2 = \bigoplus_{i=1}^{m} L_iJ \) for some \( m \geq 3 \). Put \( L := P/(\bigoplus_{i=1}^{m} L_iJ) \) and \( \pi: P \to L \) to be the canonical epimorphism. Then \( L \) is local and \( LJ^2 \approx L_0J \) is simple. Hence by Lemma 1.7 \( |\text{soc} L| \leq 2 \). But by construction \( 3 = |\pi L_1J \oplus \pi L_2 \oplus \pi L_3| \leq |\text{soc} L| \), a contradiction. //

**Proposition 1.9.** Let \( P_A \) be a local module. If \( |PJ^2/PJ^3| = 1 \), then \( P \) has
one of the following structures:

(1) \( P \) is colocal of height 3.

(2) \( PJ \) is a direct sum of a simple right module and a colocal right module of height 2.

(3) \( P \) is uniserial.

(4) \( PJ \) is a direct sum of a simple module and a nonzero uniserial module.

Proof. If \( h(P)=3 \), then by Lemma 1.7 \( P \) is of type (1) or (2). So we may assume that \( h(P)>3 \). By Lemma 1.7 \( P/P^3 \) is of type (1) or (2).

(a) In case \( P/P^3 \) is of type (1). Since \( \text{top}^3(P)=P/P^3 \) is colocal and \( h(P)>3 \), \( PJ \) is uniserial by Corollary 1.6. Thus \( P \) is of type (3).

(b) In case \( P/P^3 \) is of type (2). Put \( PJ=J\xi \oplus Y \) where \( \xi \) is simple and \( Y \) is colocal of height 2. Then since \( \text{top}^3(PJ)=P/P^3 \) is decomposable, so is \( PJ \). Let \( PJ=X'\oplus Y' \) where \( X' \) and \( Y' \) are non-zero. Then \( X\oplus Y\cong \text{top}^3X'\oplus \text{top}^3Y' \). By Krull-Schmidt's theorem we may assume that \( X\cong \text{top}^3X' \) and \( Y\cong \text{top}^3Y' \). Since \( X \) is simple, so is \( X' \) by Nakayama's lemma. Thus \( h(Y')\geq 3 \) since \( 0\neq PJ^2=Y'J^2 \). Then since \( \text{top}^3Y'\cong Y \) is colocal, \( Y' \) is uniserial by Corollary 1.6. Hence \( P \) is of type (4). //

Lemma 1.10. Let \( P_A \) be a local module of height 3. If \( |PJ^3|=2 \), then

(1) Every colocal submodule of \( PJ \) is uniserial; and

(2) \( \text{soc} P=PJ^3 \) (i.e. \( PJ \) has no simple direct summand).

Proof. (1) Let \( C \) be a colocal submodule of \( PJ \). If \( h(C)=1 \), then the assertion is trivial. So we may assume that \( h(C)=2 \). Since \( CJ=\text{soc} C \) is simple and \( |PJ^3|=2 \), \( PJ^3=CJ\oplus S \) for some simple \( S\leq PJ^3 \). Put \( L:=P/CJ \). Then \( L \) is local and \( LJ^3\simeq S \) is simple. Hence by Lemma 1.7 \( |\text{soc} L|\leq 2 \). Then since \( C/CJ\cap LJ^3=0 \), \( CJCJ\oplus LJ^3\leq \text{soc} L \), whence \( |C/CJ|=1 \). Thus \( C \) is uniserial.

(2) Assume that \( \text{soc} P\neq PJ^3 \). Then \( P \) has a simple direct summand \( S \). By Proposition 1.3 there are uniserial modules \( L_i \) such that \( PJ=\sum_{i=1}^n L_i \) is an irredundant sum. Since \( |PJ^3|=2 \), we may assume that \( PJ^3=L_nJ\oplus L_nJ \). Put \( L:=P/L_nJ \) and \( \pi: P\to L \) to be the canonical epimorphism. Then \( L \) is local and \( LJ^3\cong L_nJ \) is simple. So by Lemma 1.7 \( |\text{soc} L|\leq 2 \). But \( 3\leq |\pi L_nJ\oplus \pi L_nJ\oplus \pi S|\leq |\text{soc} L| \), a contradiction. //

Lemma 1.11. Let \( P_A \) be a local module of height 3 with \( |PJ^3|=2 \) and \( PJ=\sum_{i=1}^n L_i \) be an irredundant sum of uniserial modules. Then \( \text{soc} L_i\neq \text{soc} L_j \) for each \( i\neq j \in \{1, \ldots, n\} \).

Proof. Assume \( \text{soc} L_i=\text{soc} L_j=S \). If the identity map \( 1_s \) of \( S \) is ex-
tendable to a homomorphism \( \varphi : L_j \rightarrow L_j \), then \( L_i + L_j = L \oplus L_j \) where \( L := (1_{L_j} - \varphi)(L_j) \) is simple. So since \( PJ = \sum_{i \neq j} L_i + L_j \) is an irredundant sum of local modules, \( PJ \) has a simple direct summand \( L \). This contradicts Lemma 1.10 (2). Hence \( L_i \) is not extendable to any homomorphism \( L_i \rightarrow L_j \). Therefore \( L_i + L_j \) is colocal by [12, Lemma 1.2 (2)]. Hence \( L_i + L_j \) is uniserial by Lemma 1.10 (1). Thus \( L_i = L_j \), i.e. \( i = j \). //

**Proposition 1.12.** Let \( P_A \) be a local module. If \( |PJ| = 2 \), then \( PJ \) is a direct sum of two non-zero uniserial modules.

Proof. First we prove the assertion in the case of \( h(P) = 3 \). By Proposition 1.3 \( PJ = \sum L_i \) is an irredundant sum of some uniserial modules \( L_i \). Put \( S_i := L_i \) for each \( i \). By Lemma 1.10 (2) \( |L_i| = h(L_i) = 2 \) for each \( i \). Since \( |PJ| = 2 \), we may assume that \( \text{soc} PJ = PJ = S_1 \oplus S_2 \). We show that \( n = 2 \). Assume \( n \geq 3 \). Define \( \alpha_i : S_3 \rightarrow S_i \) by \( \alpha_i := \pi_i | S_3 \) where \( \pi_i : S_1 \oplus S_2 \rightarrow S_i \) is the canonical projection for each \( i = 1, 2 \). Then \( \alpha_1 \neq 0 \) and \( \alpha_2 \neq 0 \). For, otherwise, say \( \alpha_1 = 0 \), we would have \( S_2 = S_2 \) contradicting Lemma 1.11. By Lemma 1.1 \( \alpha_1 \) is extendable to a monomorphism \( \varphi : L_3 \rightarrow P \). If \( \varphi(L_3) + L_1 \) is colocal, then \( \varphi(L_3) = L_1 \) by Lemma 1.10 (1). In this case we put \( \lambda := 1_{L_1} \). If \( \varphi(L_3) + L_1 \) is not colocal, then \( 1_{S_2} \) is extendable to an isomorphism \( \varphi(L_3) \rightarrow L_1 \). In this case we put \( \lambda \) to be this isomorphism. In either case we have a commutative diagram

\[
\begin{array}{ccc}
L_3 & \xrightarrow{\varphi} & L_3 \\
\downarrow & & \downarrow \\
S_3 & \xrightarrow{\alpha_1} & S_1 = S_1
\end{array}
\]

Then \( L_1 + L_2 = L_1 + L_3 \) where \( L_3 := (1_{L_3} - \lambda \varphi)(L_3) \). Since \( (1_{L_3} - \lambda \varphi)|_{S_3} = 1_{S_3} - \alpha_1 = \alpha_2 \neq 0 \), \( 1_{L_3} - \lambda \varphi : L_3 \rightarrow L_3 \) is an isomorphism. Hence \( \text{soc} L_i = \alpha_i S_i = S_2 = \text{soc} L_2 \). But the sum \( PJ = \sum_{i=3} L_i + L_3 \) is also an irredundant sum of uniserial modules. This contradicts Lemma 1.11. As a consequence \( n \leq 2 \). If \( n = 1 \), then \( |PJ| = 1 \), a contradiction. Hence \( n = 2 \). Thus \( PJ = L_1 \oplus L_2 \).

In the general case, since \( h(PJP) = 3 \), we have \( \text{top}^2 PJ = PJ/PJP = L_1 \oplus L_2 \) for some uniserial modules \( L_i \) of length 2 by the special case above. Then \( PJ \) is decomposable. Put \( PJ = X_1 \oplus X_2 \) with \( X_i \neq 0 \) for each \( i \). Then \( L_1 \oplus L_2 = \text{top}^2 X_1 \oplus \text{top}^2 X_2 \). By Krull-Schmidt's theorem each \( \text{top}^2 X_i \) is uniserial. Hence each \( X_i \) is uniserial by Lemma 1.4. //

The following statement holds without the assumption that \( A \) is a ring of right 2nd local type.
Lemma 1.13. Let \( e \) be in \( \pi(A) \) such that \( eJ = U \oplus V \) for some uniserial right modules \( U \) and \( V \) which are of length 2, and \( f \) and \( g \) be in \( \pi(A) \) with \( \text{top } U \cong fA[fJ \text{ and } \text{soc } U \cong gA[gJ. \) Assume that \( Af \) and \( Ag \) are uniserial left modules. Then every local submodule \( L \) of \( ej \) with top \( L \cong fA[fJ \text{ is uniserial.} \)

Proof. If \( h(L)=1 \), then the statement is trivial. So we may assume that \( h(L)=2 \). Assume that \( L \) is not uniserial. Then \( LJ = eJ \). Put \( L = u_iA \) and \( U = u_2A \) where \( u_i \in \text{eff} \setminus \text{eff}^2 \) for each \( i \). Since \( L \cap U = \text{soc } U \cong gA[gJ \), we have \( 0 \neq u_ia_i = u_2a_2 \) for some \( a_i \in \text{eff} \setminus \text{eff}^2 \). Since \( Ag \) is uniserial, \( Jg \) is simple, whence there is some \( t \in fAf \setminus \text{eff} \) such that \( a_2 \in a_1t + fJg. \) Thus \( u_2a_2 = u_2a_1 \) since \( u_2Jg \leq eJ^2 = 0. \) Hence \( (u_1 - u_2)a_1 = 0. \) Consider the homomorphism \( \alpha : Af \to Ag \) defined by the right multiplication by \( a_1. \) Since \( Af \) is uniserial and \( \alpha(J) \ni u_ia_i \neq 0, \) \( \text{Ker } \alpha \cong JfJ. \) As a consequence \( u_1 - u_2 \in JfJ. \) Thus \( L = u_1A \leq u_2A + eJfA \leq U + eJ = U \oplus VJ. \) Comparing the composition lengths, we see that \( L = U \oplus VJ \text{ which contradicts that } L \text{ is local.} \)

Remark. In the above it is necessary that \( Af \) is uniserial as the following example says. Let \( A^{op} \) be an algebra defined by the bounden quiver

\[
\begin{array}{ccc}
1 & \alpha & 3 \\
\beta & 2 & \gamma \\
\delta & 4 \\
\end{array}
\]

Then \( e_1J = \alpha A \oplus \beta A \) with \( \alpha A \) and \( \beta A \) uniserial, and top \( \alpha A \cong e_2A[e_2J \) and \( \text{soc } \alpha A \cong e_2A[e_2J. \) But \( e_1J \) has a non-uniserial local module \( L := (\alpha + \beta)A \) with top \( L \cong e_2A[e_2J \). In this case \( Ae_3 \) is uniserial but \( Ae_2 \) is not.

Proof of Theorem I. The statement (R) immediately follows from Propositions 1.8, 1.9 and 1.12. We show the statement (L). By [II, Theorem 2.5 (1R) \( \Rightarrow (3-iL)] \) \( J^e \) is a uniserial waist in \( Ae \) if \( J^e = 0 \) for each \( e \in \pi(A). \) Hence we have only to show that every local left module \( P \) of height 5 is uniserial. Further since \( A/J^3 \) is also a ring of right 2nd local type, we may assume that \( J^3 = 0 \) and \( P = Ah \) for some \( h \in \pi(A). \) Then \( \text{eff}^2 \cong \bigoplus_{i=1}^n A_{g_i}J_{g_i}, \) \( Jh^2 \cong JfA[J^2h \cong \bigoplus_{i=1}^n A_{g_i}J_{g_i} \) and \( J^2hJ^2h \cong \bigoplus_{i=1}^n A_{g_i}J_{g_i} \) where \( e, f \) and \( g_i \) are in \( \pi(A). \) Then all \( A_{g_i} \) and \( Af \) are uniserial by the argument used in the proof of [I, Proposition 2.4.1]. It is enough to show that \( n = 1. \) Suppose that \( n > 1. \) Then there are some \( x_i \in g_i Jh \setminus g_i J^2h \text{ for } i = 1, 2 \) such that the sum \( Y := Ax_1 + Ax_2 \) is irredundant and \( Ax_1 \cap Ax_2 = Ax_1 = Jh = JY. \) Hence we have \( y_i x_i = y_i x_2 \text{ and } Ay_i x_i = J^2h \text{ for some } y_i \in \text{eff} \setminus \text{eff}^2 \) such that \( Ax_1 x_2 = J. \) Consider a homomorphism
\[ \alpha := (\cdot y_1, \cdot y_2): \text{A}eJf \rightarrow \text{Ag}_1Jg_1 \oplus \text{Ag}_2Jg_2 \]

where for each \( t \in \text{A}, \cdot t \) is the map defined by the right multiplication by \( t \).

By the argument similar to that used in the proof of the implication (3)\( \Rightarrow \) (1) in Lemma 1.4, it follows from the structure of \( Y/JY \) that \( \alpha \) is infusible. Therefore by [I, Corollary 1.4.2] the map

\[ \alpha^* := (\cdot y_1^*, \cdot y_2^*) : \text{g}_1A/g_1Jg_2A/g_2J \rightarrow eJ/eJ \]

is a monomorphism where for each \( t \in \text{A}, t^* \) is the map defined by the left multiplication by \( t \). Thus \([\cdot y_1]A \oplus [\cdot y_2]A \leq eJ/eJ \) where \([\cdot y_i] := \cdot y_i + eJ \) for each \( i \). By the statement \( (\text{R}) \), we have \( eJ/eJ = U_1 \oplus U_2 \) for some uniserial modules \( U_i \) of length 2. Hence \( eJ/eJ = [\cdot y_1]A \oplus [\cdot y_2]A \leq \langle \cdot \rangle A \) where \( \langle \cdot \rangle := x + eJ \). On the other hand, since \( eJ/eJ = eJ/eJ \) for some \( i \), say \( i = 1 \). Further since \( \text{soc} U_1 \) is a direct summand of \([\cdot y_1]A \oplus [\cdot y_2]A \), \( \text{soc} U_1 \cong \text{g}_1A/g_1J \) for some \( j \). Hence by Lemma 1.13, \( \langle \cdot \rangle A \) must be a uniserial module, a contradiction. This completes the proof of \( (\text{L}) \). Finally assume that \( A \) is a ring with selfduality. Then by Lemma 1.4, the following holds.

(a) Let \( L \) be a left module. If \( \text{soc}^2L \) is uniserial, then so is \( L \).

As easily seen this implies that every local left module of height \( \geq 4 \) is uniserial. Hence in this case \( (\text{L}_4) \) does not occur. //

2. Left serial rings with selfduality

Theorem II. Assume that \( A \) is a left serial ring with selfduality. Then the following are equivalent:

1. \( A \) is of right 2nd local type.
2. For every \( e \in \text{p}(A) \), if \( h(eA) > 2 \), then \( eJ \) is a direct sum of two uniserial modules.
3. Every indecomposable right module of height \( > 2 \) is local.

Proof. The proof is quite similar to that of [II, Theorem 4.1]. The implication (3)\( \Rightarrow \) (1) is trivial, and (1)\( \Rightarrow \) (2) follows from Theorem I and the selfduality of \( A \). By the selfduality of \( A \) the condition (3) is equivalent to the following.

(3') Every indecomposable left module of height \( > 2 \) is colocal.

The implication (2)\( \Rightarrow \) (3') also follows as in [II], with the following (necessary) changes and additions.

First the definition of a simple left module being of \( V \)-type is changed.

Definition. Let \( S \) be a simple left module. Then \( S \) is said to be of \( V \)-type in case \( E(S)/S \) is a direct sum of two uniserial left modules and \( eJ \) is a direct sum of two uniserial right modules where \( E(\cdot) \) denotes the injective
hull of \((-\)) and \(e\) is an element in \(\pi(A)\) such that \(Ae/Je=S\).

Then the following lemma (quite similar to [II, Lemma 4.3]) holds.

**Lemma 2.1.** Assume that \(A\) is a left serial ring with selfduality which satisfies the condition (2) of Theorem II. Let \(S\) be a simple left module. If \(S=\soc L\) for some left module \(L\) of height >2, then \(S\) is of \(V\)-type.

Proof. Let \(D\) be a selfduality of \(A\). Since \(h(E(S))=h(L)>2\), \(D(E(S)))J\) is a direct sum of two uniserial modules by the condition (2) of Theorem II, whence so is \(E(S)/S\cong D(D(E(S)))J\). Let \(e\) be in \(\pi(A)\) such that \(S=Ae\). There is some local submodule \(M\) of \(L\) such that \(h(M)>2\). Since \(A\) is left serial, \(M=Af/Jf\) for some \(f\) in \(\pi(A)\) where \(h:=h(M)>2\). Since \(Ae/Je=S=\soc L=\soc M=M=Jf/Jf, ef=0\). Thus \(ef=0\), i.e. \(h(eA)>h>2\). Hence \(e\) is a direct sum of two uniserial right modules by the condition (2) of Theorem II. //

**Lemma 2.2.** Let \(L\) be a quasi-projective uniserial left module of length 2 such that \(\soc L\) is of \(V\)-type. Then \(\dim_{D(L)}D_1(L)\leq 2\) ([II, 4.2]).

Proof. Assume that \(\dim_{D(L)}D_1(L)\geq 3\). Then there exist \(\alpha_2\) and \(\alpha_3\) in \(D_1(L)\) such that \(\{1, \alpha_2, \alpha_3\}\) is a linearly independent set in \(D_1(L)\). Put \(S:=\soc L\) and \(\alpha:=\begin{pmatrix} \alpha_2 & -1 & 0 \\ \alpha_3 & 0 & -1 \end{pmatrix}: S^0\to L^0\). Since \(L\) is quasi-projective, \(M:=\Coker \alpha\) is a colocal left module of height 2 and \(|M/S|=3\) by the argument used in [12, Lemma 5.3] (or the dual version of [1, Theorem]). This contradicts that \(S\) is of \(V\)-type, since \(M\leq E(S)\). //

Completion of the proof of Theorem II. The above lemma enables us to prove [II, Lemma 4.8] in the selfdual artinian case by the argument used in [12, Lemma 3.7]. Now the proof of the implication (2) \(\Rightarrow\) (3') of Theorem II proceeds along the same way of that of [II, Theorem 4.1 (2) \(\Rightarrow\) (3')] //

3. Examples: representation-finite algebras of right 2nd local type

In this section we give necessary and sufficient conditions for representation-finite algebras to be of right 2nd local type, using the method outlined in Ringel [10]. This gives many examples of algebras of right 2nd type, and helps further considerations. Throughout this section, we assume that our algebra \(A\) is (basic) representation-finite and, in addition, (without loss of generality) is connected. Following Ringel [11], we say that a left \(A\)-module \(M\) is sincere in case \(eM=0\) for every \(e\) in \(\pi(A)\), and that an algebra is sincere if it has a sincere indecomposable left module. First we give the result for sincere, simply connected (in the sense of Bongartz-Gabriel [5]) algebras, and
then reduce the general case to this special one. We identify algebras with their isomorphism classes and with their bounden quivers below.

**Example 3.1.** (1) Consider the following list $\mathcal{L}$ of sincere simply connected algebras:

- *(A*) Quiver algebras of (Dynkin) type $A_n$ with the following orientation.

- *(D*) Quiver algebras of type $D_n$ of height 2 ($n \geq 4$).

- *(E*) Quiver algebras of type $E_n$ of height 2 ($n = 6, 7, 8$).

- *(X*) A bounden quiver algebra

\[
\begin{array}{c}
\alpha \\
\beta \\
\gamma \\
\delta
\end{array} ; \beta \alpha = \delta \gamma.
\]

- *(X*) Bounden quiver algebras ($n \geq 5$)

\[
\begin{array}{c}
\alpha \\
\beta \\
\gamma \\
\delta
\end{array} ; \beta \alpha = \delta \gamma.
\]

- *(Y*) An algebra defined by the quiver

\[
\begin{array}{c}
\alpha \\
\beta \\
\gamma
\end{array}
\]

with full commutativity relations.

Then it is easy to see that all algebras in $\mathcal{L}$ are of right 2nd local type.

(2) The quiver algebras in the following list $\mathcal{S}$ are not of right 2nd local type:

- *(A*)

- *(D*)

- *(D*) ($n \geq 5$)
where each edge represents an arrow with an arbitrary orientation.

The two lists in Example 3.1 determines the right 2nd local type for sincere simply connected algebras as the following theorem says.

**Theorem III.** Assume that \( A \) is a sincere simply connected algebra. Then the following are equivalent:

1. \( A \) is of right 2nd local type.
2. \( e_E A e_E \in S \) for any \( E \subseteq \pi(A) \).
3. \( A \subseteq \mathcal{L} \).

where we put \( e_E := \sum_{e \in E} e \).

Proof of (3)\( \Rightarrow \) (1) and (1)\( \Rightarrow \) (2). Example 3.1 (1) says the implication (3)\( \Rightarrow \) (1). By Example 3.1 (2), the implication (1)\( \Rightarrow \) (2) follows from the next statement for an arbitrary artinian ring \( A \).

**Proposition 3.2.** If \( A \) is a ring of right 2nd local type, then so is \( e A e \) for every idempotent \( e \) in \( A \).

Proof. Obviously we may assume that \( e \neq 0 \). Put \( B := e A e \) and denote by \( T \) and by \( H \) the functors \(- \otimes_B e A : \text{mod } B \to \text{mod } A\) and \( \text{Hom}_A(e A, -) : \text{mod } A \to \text{mod } B\), respectively where \( \text{mod } C \) denotes the category of finitely generated right \( C \)-modules for \( C = A \) and \( B \). Then \( T \) is a left adjoint of \( H \) and \( HT \cong 1_{\text{mod } B} \), the identity functor of \( \text{mod } B \). We first claim

1. \( T \) preserves indecomposables.

In fact, let \( M \) be an indecomposable module in \( \text{mod } B \) and assume that \( TM \) is decomposable, say \( TM = X \oplus Y \) with \( X, Y \neq 0 \). Then \( M \cong HT M = HX \oplus HY \). Since \( M \) is indecomposable, we may assume that \( HX = 0 \). But then \( 0 \neq \text{Hom}_A(TM, X) \cong \text{Hom}_B(M, HX) = 0 \), a contradiction.

Next putting \( j := eje \), direct calculation shows

2. Let \( M \) be in \( \text{mod } B \) and \( \alpha : M j \to M \) the inclusion map. Then \( \alpha_*(T(M j)) \leq (TM) j^2 \) where \( \alpha_* := T(\alpha) : T(M j) \to T(M) \).

Now since \( T \) is right exact, \( T(\top^2 M) \cong TM/\alpha_*(T(M j^3)) \). Assume that \( B \) is not of right 2nd local type, thus \( \top^2 M = X \oplus Y \) with \( X, Y \neq 0 \) for some indecomposable \( M \) in \( \text{mod } B \). Then by (i), \( TM \) is indecomposable in \( \text{mod } A \) but \( \top^2(TM) \) is decomposable as follows.

\[
\top^2(TM) = TM/[(TM)j^2] \cong \frac{TM/\alpha_*(T(M j^3))}{(TM)j^2/\alpha_*(T(M j^3))} = \frac{TM/\alpha_*(T(M j^3))}{[TM/\alpha_*(T(M j^3))]j^2} 
\]

\[
\cong \frac{T(\top^2 M)}{[T(\top^2 M)]j^2} \cong \top^2(TX) \oplus \top^2(TY) \).
We denote by $n(A)$ the number of isomorphism classes of simple right $A$-modules, i.e. $n(A)$ is equal to the cardinality of $\pi(A)$. The following result in [11] makes it possible to prove the implication (2)$\Rightarrow$(3) in Theorem III by induction on $n(A)$. We put $D:=\text{Hom}_k(-, k)$ to be the usual self-duality of $A$.

**Proposition 3.3** ([11, Proposition 6.5 (2)]). Assume that $A$ is a sincere simply connected algebra with $n(A)>1$. Then $A$ is a one-point extension \[
\begin{pmatrix}
B & R \\
0 & k
\end{pmatrix}
\] or a one-point coextension \[
\begin{pmatrix}
B & 0 \\
DR & k
\end{pmatrix}
\] of a sincere simply connected algebra $B$ by an indecomposable left $B$-module $R$ such that $\text{Hom}_B(R, N)\neq 0$ or $\text{Hom}_B(N, R)\neq 0$ for some sincere indecomposable left $B$-module $N$, respectively.

Proof of (2)$\Rightarrow$(3) of Theorem III. First note that this assertion is easily verified for quiver algebras and for bounden quiver algebras whose relation ideal is generated by a single commutativity relation. The proof proceeds by induction on $n(A)$. If $n(A)=1$, then $A=k$, and so there is nothing to show. Assume $n(A)>1$. Then by Proposition 3.3 $A$ is a one-point extension or a one-point coextension of a sincere simply connected algebra $B$ by an indecomposable left $B$-module $R$ such that $\text{Hom}_B(R, N)\neq 0$ or $\text{Hom}_B(N, R)\neq 0$ for some sincere indecomposable left $B$-module $N$, respectively. Assume that $A$ satisfies the condition (2) of Theorem III. Then so does $B$ since $B\cong eAe$ where $e:=\begin{pmatrix}1_B & 0 \\ 0 & 0\end{pmatrix}$. By the induction hypothesis it follows from $n(B)=n(A)-1$ that $B$ is in $\mathcal{L}$. Hence it suffices to check that the algebras obtained by the above type of one-point extension and one-point coextension from some $B$ in $\mathcal{L}$ are again in $\mathcal{L}$ if they are representation-finite and satisfy the condition (2) of Theorem III. In doing so, as noted above, we can remove the quiver algebras and the bounden quiver algebras whose relation ideal is generated by a single commutativity relation. Further the condition that $A$ is representation-finite requires that (i) $|\text{top } R|\leq 3$ (resp. $|\text{soc } R|\leq 3$) in the one-point extension (resp. coextension) case, and (ii) $\dim R(a)\leq 1$ for the vertex $a$ of $(D_a)$ or $(E_a)$ in $\mathcal{L}$ which has three neighbours. In particular, the second condition yields that $\dim R(a)\leq 1$ for all vertices $a$ of $(D_a)$ or $(E_a)$ in $\mathcal{L}$. This makes the verification easy, and details are left to the reader. Above all, since the condition $\text{Hom}_B(R, N)\neq 0$ (resp. $\text{Hom}_B(N, R)\neq 0$) in the extension (resp. coextension) case guarantees that the obtained algebras are sincere, we can ignore non-sincere algebras from the start. //

**Remark.** (a) In Theorem III, the condition (2) is equivalent to the following condition which is easier to check.
(2') \( e_\leq A e_\leq \in \mathcal{S} \) for any set of vertices \( E \subseteq \pi(A) \) of any connected subquiver of the ordinary quiver of \( A \).

For the verification of (2)\( \Rightarrow \) (3) is, in fact, done by that of (2')\( \Rightarrow \) (3).

(b) In case \( n(A) > 13 \), the implication (2)\( \Rightarrow \) (3) of Theorem III is easily verified by Bongartz' theorem [4, Klassifikationssatz] (see also [11, Theorem 6.3 (1)]).

We go on to the general case. This is done as usual by the covering technique developed in [5], [7] and [6]. Put \( \Gamma \) to be the Auslander-Reiten quiver of \( A \) and \( \tilde{\Gamma} \) the universal cover of \( \Gamma \) (see [5]). By \( \text{mod} \ A \) and by \( \text{ind} \ A \) we denote the category of finite dimensional right \( A \)-modules and the full subcategory of \( \text{mod} \ A \) consisting of the chosen representatives of isomorphism classes of indecomposable right \( A \)-modules where projective indecomposables are canonical ones, respectively. Then as well known, there exists a well-behaved ([9]), covering functor \( E: k(\tilde{\Gamma}) \to \text{ind} \ A \) where \( k(\tilde{\Gamma}) \) is the mesh category of \( \tilde{\Gamma} \). Let \( \bar{A} \) be the full subcategory of \( k(\tilde{\Gamma}) \) consisting of projective vertices of \( \tilde{\Gamma} \). Then it is well known that \( k(\tilde{\Gamma}) \approx \text{ind} \ A \) by which we identify these categories. We have a commutative diagram

\[
\begin{array}{ccc}
A & \rightarrow & \text{ind} \ A \\
\downarrow F & & \downarrow E \\
\text{ind} \ A & \rightarrow & \text{ind} \ A
\end{array}
\]

where the horizontal functors are Yoneda embeddings, and \( E \) and \( F \) are covering functors. Since \( \text{ind} \ A \) is locally bounded and \( \text{ind} \ A \) is basic, \( \text{ind} \ A \) is locally bounded by [7, Proposition 1.2 a]), i.e. \( \bar{A} \) is locally representation-finite. Hence by [7, Proposition 2.7], the push down \( F_\lambda: \text{mod} \ A \to \text{mod} \bar{A} \) preserves Auslander-Reiten sequences and \( E \approx F_\lambda|_{\text{ind} \bar{A}} \). In particular, for every \( M \in \text{mod} \ A \), \( M \) is indecomposable iff so is \( F_\lambda(M) \in \text{mod} \bar{A} \).

**Proposition 3.4.** \( A \) is of right 2nd local type iff so is \( \bar{A} \).

Proof. Note that for every \( M \in \text{ind} \ A \), \( M = F_\lambda(\tilde{M}) \) for some \( \tilde{M} \in \text{ind} \bar{A} \) by [7, Proposition 1.2 b)]. Now let \( M \) be in \( \text{ind} \ A \) and \( \tilde{M} \) in \( \text{ind} \bar{A} \) such that \( M = F_\lambda(\tilde{M}) \). Since \( F_\lambda \) is an exact functor and preserves the radical by [5, Proposition 3.2], \( F_\lambda(\text{top}^2 \tilde{M}) \approx \text{top}^2 M \). Hence by the above \( \text{top}^2 \tilde{M} \) is indecomposable iff so is \( \text{top}^2 M \). //

Note that by [6, Remark 3.3 (a)] \( \bar{A} \) is directly constructed from \( A \). Since \( A \) is representation-finite, there exists a connected subquiver \( Q \) of \( Q_A \) with the set \( Q_o \) of vertices finite such that for every \( M \in \text{ind} \ A \), there exists an \( \tilde{M} \in \text{ind} \bar{A} \) such that \( F_\lambda(\tilde{M}) = M \) and \( \text{sp} M \subseteq Q_o \), where \( \text{sp} \tilde{M} \) is the support of \( \tilde{M} \), i.e. the set of vertices \( v \) of \( Q_A \) such that \( \tilde{M}(v) \neq 0 \). By \( \bar{A} \) we denote the factor category of \( A \) by the ideal generated by all the vertices \( v \) of \( Q_A \) such that
Since $\mathcal{A}$ has only a finite number of objects, $\mathcal{A}$ can be regarded as a representation-finite algebra. Further the Auslander-Reiten quiver $\Gamma$ of $\mathcal{A}$ has no oriented cycle since so does $\Gamma$.

**Theorem IV.** Assume that $\mathcal{A}$ is a (basic, connected) representation-finite algebra (of finite dimension over $k$). Then the following are equivalent.

1. $\mathcal{A}$ is of right 2nd local type.
2. $e_\nu \mathcal{A}e_\nu \in \mathcal{S}$ for every $E \subseteq \text{pi}(\mathcal{A})$.
3. $\text{Sp}(\mathcal{M}) \subseteq \mathcal{L}$ for every indecomposable right $\mathcal{A}$-module $\mathcal{M}$.

In the above, $\text{Sp}(\mathcal{M})$ denotes the *support algebra* of $\mathcal{M}$, i.e. $\text{Sp}(\mathcal{M}) := e_\nu \mathcal{A}e_\nu$ where $\mathcal{S} := \text{sp}(\mathcal{M})$.

Proof. (1)$\Rightarrow$(2). Assume that $\mathcal{A}$ is of right 2nd local type. Then so is $\mathcal{A}$ by Proposition 3.4, and so is $\mathcal{A}$ since $\mathcal{A}$ is a factor of $\mathcal{A}$. Hence $e_\nu \mathcal{A}e_\nu \in \mathcal{S}$ for every $E \subseteq \text{pi}(\mathcal{A})$ by Proposition 3.2.

(2)$\Rightarrow$(3). Assume that (2) holds, and let $\mathcal{M} \in \text{ind} \mathcal{A}$. Then $e_\nu \text{Sp}(\mathcal{M})e_\nu \in \mathcal{S}$ for every $E \subseteq \text{sp}(\mathcal{M})$, and $\text{Sp}(\mathcal{M})$ is a sincere representation-finite algebra. Further the Auslander-Reiten quiver of $\text{Sp}(\mathcal{M})$ has no oriented cycle since so does $\Gamma$. Hence $\text{Sp}(\mathcal{M})$ is a sincere tilted algebra by [8, Corollary 8.3]. Thus $\text{Sp}(\mathcal{M})$ is a sincere simply connected algebra by [3, Theorem 3.1]. Hence by Theorem III, $\text{Sp}(\mathcal{M}) \subseteq \mathcal{L}$.

(3)$\Rightarrow$(1). Let $\mathcal{M} \in \text{ind} \mathcal{A}$. Then $\mathcal{M} = F_\nu(\mathcal{M})$ for some $\mathcal{M} \in \text{ind} \mathcal{A}$. Clearly we can regard $\mathcal{M} \in \text{ind} \text{Sp}(\mathcal{M})$. Since $\text{Sp}(\mathcal{M}) \subseteq \mathcal{L}$ is of right 2nd local type, $\text{top}^2 \mathcal{M}$ is indecomposable, whence so is $\text{top}^2 \mathcal{M}$. //

**Remark.** The list $\mathcal{S}$ is closely related to Lemmas 1.4 and 1.7 and to the conditions (R) and (L) in Theorem I. In fact, it is possible to describe the condition (2) in Theorems III and IV by certain conditions on local $\mathcal{A}$-modules.

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**References**


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