Tilting modules over an algebra by Igusa, Smalø and Todorov

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Abstract

The finiteness of the little finitistic dimension of an artin algebra \( R \) is known to be equivalent to the existence of a tilting \( R \)-module \( T \) such that \( \{ T \} \perp = (\mathcal{P}^{<\infty}) \perp \) where \( \mathcal{P}^{<\infty} \) is the category of all finitely presented \( R \)-modules of finite projective dimension. Moreover, \( T \) can be taken finitely generated if and only if \( \mathcal{P}^{<\infty} \) is contravariantly finite.

In this paper, we describe explicitly the structure of \( T \) for the IST-algebra, a finite dimensional algebra with \( \mathcal{P}^{<\infty} \) not contravariantly finite. We also characterize the indecomposable modules in \( \mathcal{P}^{<\infty} \), and all tilting classes over this algebra.

Key words: tilting modules, cotorsion pairs, representations of quivers

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Infinite dimensional tilting modules naturally occur in the approximation theory of modules over general rings. Surprisingly, they also play an important role in the classical setting of artin algebras.

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The point is that the little finitistic dimension of an artin algebra $R$ equals $n < \infty$ if and only if there is an $n$-tilting $R$-module $T$ such that $\{ T \}^\perp = (P^{<\infty})^\perp$ where $P^{<\infty}$ is the category of all finitely presented $R$-modules of finite projective dimension, and $C^\perp = \bigcap_{1 \leq i < \omega} \text{Ker Ext}_R^i(C, -)$ for a class of $R$-modules $C$. Moreover, $T$ can be taken finitely generated if and only if $P^{<\infty}$ is contravariantly finite, [3].

Though in principle $T$ can be computed by an iteration of $(P^{<\infty})^\perp$-approximations of the regular module $R$, the structure of $T$ remains unknown in general.

The main goal of this paper is to give an explicit description of $T$ in an important case where $P^{<\infty}$ is not contravariantly finite, namely for the IST-algebra $A$ – the particular path algebra over a field with relations introduced by Igusa, Smalø and Todorov in [13]. $A$ is known to have infinite global dimension, but the little and the big finitistic dimensions of $A$ equal 1, so $T$ is an infinite dimensional $A$-module of projective dimension 1. Besides describing $T$, we also characterize all indecomposable $A$-modules in $P^{<\infty}$, and all tilting classes over $A$.

The paper is organized as follows. After recalling necessary definitions and preliminary results (Section 1), we concentrate on the IST-algebra $A$, giving an overview of basic facts (Section 2), characterizing all indecomposable $A$-modules in $P^{<\infty}$ up to isomorphism (Proposition 16) and computing their $\tau$-translates. Next, we characterize the lattice of all tilting classes in $A$-Mod (Section 4) and compute corresponding tilting modules for some of these classes (Section 5), among them our tilting module $T$.

We also give examples of particular infinite dimensional $A$-modules that are in the tilting class $T = (P^{<\infty})^\perp$, but are not isomorphic to a direct limit of finite dimensional $A$-modules in $T$ (Section 4.2).

## 1 Preliminaries

Let $R$ be a ring (associative and unital) and let us denote by $R$-$\text{Mod}$ ($\text{Mod}$-$R$) the category of left (right) $R$-modules, respectively. Let $R$-$\text{mod}$ and $\text{mod}$-$R$ be the corresponding full subcategories of all modules possessing a projective resolution with all projective modules finitely generated. Note that in case when $R$ is noetherian, $R$-$\text{mod}$ and $\text{mod}$-$R$ coincide with the class of finitely generated left and right modules, respectively. For convenience, all modules from now on will be left $R$-modules if not stated otherwise. Further, let us denote by $P_n^{<\infty}$ the full subcategory of $R$-$\text{mod}$ consisting of the modules with proj. dim $\leq n$ and by $P^{<\infty}$ the full subcategory of $R$-$\text{mod}$ consisting of the modules of finite projective dimension.

A pair $(A, B)$ of classes of modules is called a (hereditary) cotorsion pair if $A = ^\perp B$ and $B = A^\perp$, where $^\perp B = \{ X \in R$-$\text{Mod} | \text{Ext}_R^i(X, B) = 0 \text{ for all } B \in B \text{ and } i \geq 1 \}$ and $A^\perp = \{ X \in R$-$\text{Mod} | \text{Ext}_R^i(A, X) = 0 \text{ for all } A \in A \text{ and } i \geq 1 \}$. A cotorsion pair $(A, B)$ is said to be cogenerated by a class of modules $C$ if the class $A$ is the
smallest possible containing $C$, that is $\mathcal{A} = \perp(C^\perp)$ and $\mathcal{B} = C^\perp$. In case $C$ contains just one module $C$, we will write $C^\perp$ instead of $\{C\}^\perp$.

A module $T$ (not necessarily finitely generated) is said to be $n$-tilting for $n < \omega$ if it satisfies the following conditions:

1. $\text{proj. dim } T \leq n$,
2. $\text{Ext}^i_R(T, T^{(\kappa)}) = 0$ for each $i \geq 1$ and cardinal $\kappa$,
3. there is an exact sequence $0 \to R \to T_0 \to T_1 \to \cdots \to T_m \to 0$, where $m < \omega$ and $T_j \in \text{Add} T$ for $0 \leq j \leq m$.

Here, $\text{Add} T$ stands for the class of all modules isomorphic to direct summands of direct sums of copies of $T$.

A class of modules $T$ is said to be $n$-tilting if there is an $n$-tilting module $T$ such that $T = T^\perp$. A cotorsion pair $(\mathcal{A}, \mathcal{B})$ is said to be $n$-tilting if $\mathcal{B}$ is an $n$-tilting class, or equivalently if it is cogenerated by some $n$-tilting module. A $(n)$-tilting class is of finite type in the sense of [2] if its corresponding cotorsion pair is cogenerated by some set of modules of $R$-mod. Note that $n$-tilting classes of finite type are exactly the classes $\mathcal{S}^\perp$ for $\mathcal{S} \subseteq \mathcal{P}^{<\infty}$, [19, 2.9].

The tilting theory is closely related to the second finitistic dimension conjecture. Let us denote by $\text{Fdim } R$ and $\text{fdim } R$ the big and the little finitistic dimension of $R$ respectively; that is, the supremum of the projective dimensions of all modules with proj. dim $< \infty$ or all finitely generated modules with proj. dim $< \infty$, respectively. The first finitistic dimension conjecture stated that $\text{Fdim } R$ and $\text{fdim } R$ coincide whenever $R$ is a finite dimensional algebra over a field, and it was proved to be false (cf. [18], [21]). The second conjecture states that $\text{fdim } R < \infty$ for finite dimensional algebras and it is still an open problem in general, even though it turned out to be true for several special cases, [20]. In particular, a sufficient but not necessary condition is the contravariant finiteness of $\mathcal{P}^{<\infty}$. The following theorem relating the second conjecture to tilting theory is shown in [3]:

**Theorem 1** Let $R$ be a left noetherian ring and $(\mathcal{A}, \mathcal{B})$ be the cotorsion pair cogenerated by $\mathcal{P}^{<\infty}$. Then $\text{fdim } R < \infty$ if and only if $\mathcal{B}$ is a tilting class. Moreover, if $T$ is a tilting module such that $T^\perp = \mathcal{B}$, then $\text{fdim } R = \text{proj. dim } T$.

In the rest of this section, we recall some results concerning modules over artin algebras. A ring $R$ is called an artin algebra if its centre $C$ is artinian and $R$ is finitely generated as a $C$-module. We will use the following notation: $D$ will stand for the canonical duality between left and right $R$-modules. For a finitely generated $R$-module $X$, we denote by $Tr X$ its transpose, by $\tau X = DTr X$ its Auslander-Reiten translation, and by $\tau^- = Tr D$ “inverse” of the translation. For unexplained terminology see [6].

For $R$-modules $X, Y$, denote by $\overline{\text{Hom}}_R(X, Y)$ the quotient group of $\text{Hom}_R(X, Y)$ by the subgroup of homomorphisms from $X$ to $Y$ which factor through an injective
module. Similarly, let $\text{Hom}_R(X, Y)$ be the quotient of $\text{Hom}_R(X, Y)$ by the homomorphisms which factor through projective modules. We will need the following important result:

**Theorem 2 (Auslander-Reiten formulas) [5], [14]** Let $R$ be an artin algebra and let $X, Y \in R\text{-Mod}$, $X$ finitely generated. Then there are following isomorphisms functorial in both $X$ and $Y$:

1. $D\text{Ext}_R^1(X, Y) \cong \text{Hom}_R(Y, \tau X)$
2. $\text{Ext}_R^1(Y, X) \cong D\text{Hom}_R(\tau^- X, Y)$

We also need a characterisation of the finitely generated modules of projective or injective dimensions at most 1, which immediately follows from [6, IV.1.16]:

**Proposition 3** Let $R$ be an artin algebra and $X \in R\text{-mod}$. Then:

1. proj. dim $X \leq 1$ if and only if $\text{Hom}_R(I, \tau X) = 0$ for every injective module $I$.
2. inj. dim $X \leq 1$ if and only if $\text{Hom}_R(\tau^- X, P) = 0$ for every projective module $P$. □

As a straightforward corollary, we get:

**Corollary 4** Let $X \in R\text{-mod}$. Then:

1. If proj. dim $X \leq 1$, then $X \perp = \text{Ker} \text{Hom}_R(-, \tau X)$.
2. If inj. dim $X \leq 1$, then $\perp X = \text{Ker} \text{Hom}_R(\tau^- X, -)$.

Finally, we deduce the following lemma for artin algebras, which is useful in Section 4.2. It was introduced in [4] with a different proof:

**Lemma 5** A finitely generated module $M$ belongs to $(P_1^{<\infty})\perp$ if and only if it is filtered by factors of the injective cogenerator $D(R)$.

**PROOF.** The if part is obvious, since $(P_1^{<\infty})\perp \cap R\text{-mod}$ is closed under factors and extensions. For the only if part, it is enough to prove that $\text{Hom}_R(D(R), M) \neq 0$ for each non-zero $M \in (P_1^{<\infty})\perp \cap R\text{-mod}$. Moreover, it is sufficient to prove this only for $M$ indecomposable non-injective. Assume to the contrary that $\text{Hom}_R(D(R), M)$ is trivial. Then proj. dim $\tau^- M \leq 1$ by Proposition 3. Thus $\text{Ext}_R^1(D(R), M) = 0$, a contradiction to the existence of an almost split sequence, [6, V.1.15].
2 An example by Igusa, Smalø and Todorov

Let us fix an algebraically closed field $k$ and let $A$ be the algebra introduced by Igusa, Smalø and Todorov in [13], shortly IST-algebra. It is a path algebra over $k$ over the quiver

$$
\Gamma : 1 \rightarrow 2
$$

with relations $\alpha \gamma = \beta \gamma = \gamma \alpha = 0$. In our notation, paths are composed as maps from right to left. From now on, all modules will be considered as modules over this algebra if not stated otherwise. Basic properties of $A$-modules are summarized in [1, Section 5].

Let us denote $\Lambda = A/\langle \gamma \rangle$; then $\Lambda$ is isomorphic to Kronecker algebra, the hereditary algebra $k\Gamma'$ over the following quiver:

$$
\Gamma' : 1 \rightarrow 2
$$

Modules $M$ with $\gamma M = 0$ will be called Kronecker modules, since they are also $\Lambda$-modules. Let us denote by $P_i$, $I_i$ and $S_i$ the indecomposable projective, injective and simple $A$-module corresponding to the vertex $i$ ($i = 1, 2$), respectively. Then $\dim_k P_i = 2$, $\dim_k P_2 = 4$ and $\dim_k I_1 = \dim_k I_2 = 3$. Let $\mathcal{P}^{<\infty}$ be the full subcategory of all finitely generated $A$-modules of finite projective dimension as before, and let $K\mathcal{P}^{<\infty}$ be the full subcategory of $\mathcal{P}^{<\infty}$ having exactly the Kronecker modules in $\mathcal{P}^{<\infty}$ as objects.

We will briefly recall basic facts about the Kronecker modules. A detailed description of the finite dimensional $\Lambda$-modules is done in [6]. More properties of infinite dimensional $\Lambda$-modules can be found in [16], [15] or [11].

The finite dimensional indecomposable $A$-modules are divided into three families, preprojective, preinjective and regular modules:

(1) The preprojectives $Q_n$, $n \geq 1$, are the modules with the representation $V_1 = k^n$, $V_2 = k^{n-1}$, $f_\beta = (E, 0)^T$ and $f_\alpha = (0, E)^T$, where $E$ is the unit matrix $(n-1) \times (n-1)$.

(2) The preinjectives $J_n$, $n \geq 1$, are the modules with the representation $V_1 = k^{n-1}$, $V_2 = k^n$, $f_\beta = (E, 0)$ and $f_\alpha = (0, E)$.

(3) For the quasi-simple regulars $R_\lambda$, $\lambda \in k \cup \{\infty\}$, the vector spaces of the representation are $V_1 = V_2 = k$. For $\lambda \in k$, $f_\beta$ is the multiplication by $\lambda$ and $f_\alpha$ is the identity map. For $\lambda = \infty$, $f_\beta$ the identity map and $f_\alpha = 0$.

(4) Every quasi-simple regular module $R_\lambda$, $\lambda \in k \cup \{\infty\}$, defines a tube; that is, a chain of indecomposable modules

$$
R_\lambda = R_{\lambda, 1} \subseteq R_{\lambda, 2} \subseteq R_{\lambda, 3} \subseteq \ldots
$$
connected by the almost split sequences $0 \to R_{\lambda,n} \to R_{\lambda,n-1} \oplus R_{\lambda,n+1} \to R_{\lambda,n} \to 0$ in $A$-mod. Any finite dimensional indecomposable regular module occurs in this way.

Note, that there are no non-zero homomorphisms from preinjectives to preprojectives or regulars, and no non-zero homomorphisms from regulars to preprojectives. Moreover, $\dim_k \text{Hom}_A(R_{\lambda,n},R_{\mu}) = \delta_{\lambda,\mu}$ for any $\lambda, \mu \in k \cup \{\infty\}$.

Prüfer modules $R_{\lambda,\infty}$ are defined as the direct limits of the ascending chains:

$$R_{\lambda,1} \subseteq R_{\lambda,2} \subseteq R_{\lambda,3} \subseteq \ldots$$

Then $\text{Hom}_A(R_{\lambda,\infty},R_{\mu}) = 0$ and $\dim_k \text{Hom}_A(R_{\mu},R_{\lambda,\infty}) = \delta_{\lambda,\mu}$ for any $\lambda, \mu \in k \cup \{\infty\}$.

3 Finitely generated modules of finite projective dimension

3.1 Simple modules and composition series in $\mathcal{P}^{<\infty}$

In fact, $\mathcal{P}^{<\infty}$ is not an abelian category, but it is closed under extensions, kernels of epimorphisms and cokernels of monomorphisms. We will call an object $X$ of $\mathcal{P}^{<\infty}$ simple in $\mathcal{P}^{<\infty}$, if it has no proper submodule that is again an object of $\mathcal{P}^{<\infty}$, or equivalently if it has no proper factor again in $\mathcal{P}^{<\infty}$.

For every finitely generated $A$-module $M$, there is an exact sequence

$$0 \to P_1^n \to M \to \overline{M} \to 0$$

where $n < \omega$ and $\overline{M}$ is a Kronecker module. As a consequence, we get:

**Lemma 6** [1, Proposition 5.1] A module $M$ is an object of $\mathcal{P}^{<\infty}$ if and only if it has a finite filtration

$$0 = M_0 \subset M_1 \subset \ldots \subset M_l = M$$

with the factors $M_j/M_{j-1}$ isomorphic either to $P_1$ or to $R_{\lambda}$ for some $\lambda \in k$.

Note also that the modules $P_1$ and $R_{\lambda}$, $\lambda \in k$, are then precisely the simples in $\mathcal{P}^{<\infty}$ in our sense.

3.2 The (non-)uniqueness of the composition series

In general, there is no result analogous to the Jordan-Hölder Theorem in $\mathcal{P}^{<\infty}$. Take for example the short exact sequences $0 \to P_1 \xrightarrow{\iota} P_2 \to R_{\lambda} \to 0$. These exist for all $\lambda \in k$.  

6
But the number of the factors isomorphic to $P_1$ is unique. Consider a function $f : \mathcal{P}^< \to \omega$ defined by the formula:

$$f(U) = \dim_k \text{Hom}_A(U, R_\infty)$$

Since $P_1$ is projective, we have $\text{Ext}^1_A(P_1, R_\infty) = 0$. The module $R_\infty$ has no submodule isomorphic to $S_2$, so $\text{Ext}^1_A(R_\lambda, R_\infty) = \text{Ext}^1_A(R_\lambda, R_\infty) = 0$ for each $\lambda \in k$ by [1, 5.3]. Thus, $\text{Ext}^1_A(U, R_\infty) = 0$ for each exact sequence $0 \to U \to V \to W \to 0$ of modules from $\mathcal{P}^<$. Further, $f(P_1) = 1$ and $f(R_\lambda) = 0$ for each $\lambda \in k$. The function $f$ “counts” the number of factors isomorphic to $P_1$ in composition series of modules $U \in \mathcal{P}^<$, and its definition is independent of the particular composition series.

If we are only concerned with the modules in $\mathcal{K}\mathcal{P}^<$, then composition series are unique in the sense of Jordan-Hölder. This can be seen by a similar reasoning as for $P_1$, this time using the functions:

$$g_\mu(U) = \dim_k \text{Hom}_A(U, R_\mu, \infty), \quad \mu \in k$$

Again, $\text{Ext}^1_A(R_\lambda, R_\mu, \infty) = 0$ for every $\lambda, \mu \in k$ and $g_\mu(R_\lambda) = \delta_{\lambda, \mu}$. The function $g_\mu$ “counts” the factors isomorphic to $R_\mu$ and its definition is independent of the particular composition series.

### 3.3 Determining regular Kronecker modules by matrices

Let $M \in \mathcal{K}\mathcal{P}^<$. Then we can write

$$M \cong R_{\lambda_1, i_1} \oplus \cdots \oplus R_{\lambda_m, i_m}$$

for some Kronecker regular modules $R_{\lambda_1, i_1}, \ldots, R_{\lambda_m, i_m}$ with $\lambda_1, \ldots, \lambda_m \in k$. In particular, the linear map $x \mapsto \alpha x$ is a bijective map $e_2M \to e_1M$, since this is true for every $R_{\lambda, i}$. Let us denote by $\alpha_M^{-1}$ the inverse map for a given module $M$ and define the map $\chi_M \in \text{End}_k(e_1M)$ by the formula $\chi_M(x) = \beta \cdot \alpha_M^{-1}(x)$.

Let us focus on the matrix $J_M$ of the linear map $\chi_M$ in the Jordan canonical form, with respect to some suitable $k$-basis of the vector space $e_1M$. When $M \cong R_{\lambda, i}$, then $J_M$ is the Jordan cell of size $i \times i$ corresponding to the eigenvalue $\lambda$, that is:

$$J_M = \begin{pmatrix} \lambda & 1 \\ \lambda & \ddots \\ \vdots & \ddots & \ddots & 1 \\ \lambda & \end{pmatrix}$$

In general, $J_M$ is block-diagonal, built of the Jordan cells corresponding to the direct summands $R_{\lambda_1, i_1}, \ldots, R_{\lambda_m, i_m}$ of $M$. That is, $J_M = \text{diag}(J_{R_{\lambda_1, i_1}}, \ldots, J_{R_{\lambda_m, i_m}})$.}

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Let $N$ be another module from $KP^{<\infty}$. It is easy to see that if the vector spaces $e_1M$ and $e_1N$ have the same dimension and the linear maps $\chi_M$ and $\chi_N$ are similar, then the modules $M$ and $N$ are isomorphic. Thus we can state:

**Lemma 7** Two modules $M$, $N$ from $KP^{<\infty}$ are isomorphic if and only if the Jordan canonical forms of matrices of the linear maps $\chi_M$ and $\chi_N$ are the same up to the order of Jordan cells.

### 3.4 Special modules of finite projective dimension

**Definition 8** A module $M \in P^{<\infty}$ will be called special if its composition series in $P^{<\infty}$ admits exactly one factor isomorphic to $P_1$ and if it has no submodule isomorphic to any $R_\lambda$, $\lambda \in k$. Let us denote by $SP^{<\infty}$ the full subcategory of $P^{<\infty}$ consisting of the special modules.

For example, the modules $P_1$ and $P_2$ are special. It is easy to see that special modules are indecomposable. Clearly, if $M \in SP^{<\infty}$ and $M'$ is a non-zero submodule of $M$ belonging to $P^{<\infty}$, then $M' \in SP^{<\infty}$ too. All modules in $SP^{<\infty}$ have even dimension, since by [13] the same is true for all modules in $P^{<\infty}$. In the next few paragraphs we will show that for each non-zero even $n < \omega$ there is exactly one isomorphism class of modules of dimension $n$ in $SP^{<\infty}$. We will start by proving the existence.

**Lemma 9** Let $\lambda \in k$, and let $\delta : 0 \to P_1 \to M \to R_\lambda \to 0$ be an exact sequence. Then either $\delta$ splits or $M \cong P_2$. Moreover, $\delta$ splits if and only if $M$ has a submodule isomorphic to $R_\lambda$.

**PROOF.** There is always an exact sequence $0 \to P_1 \overset{\iota_1}{\to} P_2 \to R_\lambda \to 0$, and since $P_2$ is projective, we have the following commutative diagram:

\[
\begin{array}{ccccccccc}
0 & \longrightarrow & P_1 & \overset{\iota_1}{\longrightarrow} & P_2 & \longrightarrow & R_\lambda & \longrightarrow & 0 \\
\downarrow f & & \downarrow & & \downarrow & & \downarrow & & \\
0 & \longrightarrow & P_1 & \longrightarrow & M & \longrightarrow & R_\lambda & \longrightarrow & 0 \\
\delta & \circ & & & & & & & \\
\end{array}
\]

Since $\dim_k \text{End}_A(P_1) = \dim_k e_1P_1 = 1$, $f$ is either the zero map or an isomorphism. In the first case $\delta$ splits, in the second case $M \cong P_2$. The second assertion holds, because $P_2$ has no submodule isomorphic to $R_\lambda$.

**Proposition 10** Take $n < \omega$ non-zero even. Then there is a module $M \in SP^{<\infty}$ of dimension $n$.

**PROOF.** We have the module $P_1$ for $n = 2$. So let $n > 2$. Put $m = \frac{n}{2} - 1$ and choose $m$ distinct elements $\lambda_1, \ldots, \lambda_m$ of the field $k$. For each $\lambda_j$, consider the exact
sequence $0 \to P_1 \xrightarrow{i_j} P_2 \to R_{\lambda_j} \to 0$. We will construct the desired module $M$ by the following push-out, where $\sigma : P_1^{m} \to P_1$ is the summation map:

$$
\begin{array}{ccccccccc}
0 & \to & P_1^{m} & \xrightarrow{\oplus i_j} & P_2^{m} & \to & \bigoplus_j R_{\lambda_j} & \to & 0 \\
\downarrow {\sigma} & & \downarrow & & \downarrow & & \| & & \\
0 & \to & P_1 & \xrightarrow{i} & M & \xrightarrow{\pi} & \bigoplus_j R_{\lambda_j} & \to & 0
\end{array}
$$

Suppose that there is a submodule $N \subseteq M$ isomorphic to $R_{\lambda}$ for some $\lambda \in k$. But $\text{soc} \ N \cong S_1$ and $\text{soc} \ i(P_1) \cong S_2$, so $i(P_1) \cap N = 0$ and $\pi \mid N$ is monic. The module $\pi(N)$ being a submodule of $\bigoplus_j R_{\lambda_j}$ and $\pi(N) \cong R_{\lambda}$, there must be an index $j$ such that $\lambda = \lambda_j$ and $\pi(N) = R_{\lambda_j}$. Then we have the commutative diagram

$$
\begin{array}{cccccc}
0 & \to & P_1 & \xrightarrow{i_j} & P_2 & \to & R_{\lambda_j} & \to & 0 \\
\downarrow {\sigma|P_1} & & \downarrow & & \downarrow & & \| & & \\
0 & \to & P_1 & \xrightarrow{i} & i(P_1) + N & \xrightarrow{\pi|\ i(P_1) + N} & R_{\lambda_j} & \to & 0
\end{array}
$$

The map in the left column, and therefore also the map in the middle column, is an isomorphism. But the first row does not split and the second row does, a contradiction. Thus $M \in \mathcal{SP}^{<\infty}$.

Next, we would like to prove that every two modules in $\mathcal{SP}^{<\infty}$ of the same dimension are isomorphic. This is obvious for the dimension 2. First, we will prove a lemma which places a restriction on possible forms of cokernels of inclusions of the module $P_1$ into a chosen module from $\mathcal{SP}^{<\infty}$.

**Lemma 11** Let $M \in \mathcal{SP}^{<\infty}$ and $0 \to P_1 \xrightarrow{i} M \xrightarrow{\pi} \bigoplus_{j=1}^{m} R_{\lambda_{j,i_j}} \to 0$ be an exact sequence. Then the elements $\lambda_1, \ldots, \lambda_m$ are pairwise distinct.

**PROOF.** Assume for a contradiction that the converse is true. Without loss of generality, put $\lambda = \lambda_1 = \lambda_2$. Then the module $\bigoplus_{j=1}^m R_{\lambda,j_i}$ has a submodule isomorphic to $R_{\lambda} \oplus R_{\lambda}$, and this gives rise to the exact sequence $0 \to P_1 \xrightarrow{i} M' \xrightarrow{\pi|M'} R_{\lambda} \oplus R_{\lambda} \to 0$. Denote $M'_v = \pi^{-1}(R_{\lambda})$ where $R_{\lambda}$ is the $v$-th component of $R_{\lambda} \oplus R_{\lambda}$, $v = 1, 2$. Since

$$
0 \to P_1 \to M'_v \to R_{\lambda} \to 0
$$

(1)
does not split, we have $M'_v \cong P_2$ by Lemma 9. Take a generator $h$ of $i(P_1)$ corresponding to $e_1$ in the presentation of $P_1$ as $Ae_1$. Let $g_1, g_2$ be generators of $M'_1, M'_2$, respectively, corresponding to the element $e_2 \in P_2 = Ae_2$. We see immediately from the non-split exact sequence (1) that $\beta g_v - \lambda\alpha g_v \in i(P_1) \setminus \{0\}$ for $v = 1, 2$. Hence

$$
h, \ (\beta g_1 - \lambda \alpha g_1), \ (\beta g_2 - \lambda \alpha g_2) \in i(e_1 P_1)
$$
And since \(\iota(e_1 P_1)\) is a 1-dimensional \(k\)-vector space, we can assume by possibly multiplying \(g_1\) or \(g_2\) by a scalar that
\[
\beta g_v - \lambda_1 g_v = h, \quad v = 1, 2
\]
Finally, denote \(g = g_1 - g_2\). It is straightforward to check that the submodule of \(M\) generated by \(g\) is isomorphic to \(R_\lambda\), a contradiction.

The core of the proof of uniqueness is the following proposition, which states that there is no other restriction for the form of a cokernel of the inclusion \(\iota\), apart from the one in Lemma 11.

**Proposition 12** Let \(M \in SP^{<\infty}, M \not\in P_1\). Put \(n = (\dim_k M)/2 - 1\). Then for arbitrary pairwise distinct elements \(\lambda_1, \ldots, \lambda_m \in k\) and positive integers \(i_1, \ldots, i_m\), there is no other restriction for the form of a cokernel of the inclusion \(\iota\), apart from the one in Lemma 11.

**PROOF.** Start by considering an arbitrary inclusion \(\iota' : P_1 \rightarrow M\) and denote \(C = \text{Coker } \iota' \cong \bigoplus_{j=1}^q R_{\mu_j, \iota_j'}\). Then by Lemma 7, the module \(C\) is determined up to isomorphism by the Jordan canonical form of a matrix of the linear map \(\chi_C\). But there is only one Jordan cell for each eigenvalue of \(\chi_C\) in the Jordan canonical form by Lemma 11. Thus, the cokernel \(C\) is in fact determined only by the multiplicities of the eigenvalues of \(\chi_C\). Using the following construction, we can increase by 1 a multiplicity of a chosen \(\iota \in k\) as an eigenvalue, or \(\lambda \in k\) will become an eigenvalue if it has not been before. And we can do this at the cost of decreasing the multiplicity of the eigenvalue \(\mu_1\) by 1. After applying this method a finite number of times, we can “change” the eigenvalues, and thus also the cokernel of an inclusion \(P_1 \rightarrow M\), to any prescribed form.

Take an exact sequence \(0 \rightarrow P_1 \rightarrow M \rightarrow \bigoplus_{j=1}^q R_{\mu_j, \iota_j'} \rightarrow 0\). Let us denote \(M_j = \pi^{-1}(R_{\mu_j, \iota_j'})\). Further, take the “canonical” generators \(\bar{g}_{j,v}\) of \(R_{\mu_j, \iota_j'}\) satisfying
\[
\begin{align*}
\beta \bar{g}_{j,1} &= \mu_j \alpha \bar{g}_{j,1} \\
\beta \bar{g}_{j,v} &= \mu_j \alpha \bar{g}_{j,v} + \alpha \bar{g}_{j,v-1}, & 1 < v \leq \iota_j' 
\end{align*}
\]
Let us denote by \(g_{j,v}\) some fixed preimages of \(\bar{g}_{j,v}\) under \(\pi\); that is, \(\bar{g}_{j,v} = \pi(g_{j,v})\).

Since all \(\bar{g}_{j,v}\) could have been chosen to lie in \(e_2 R_{\mu_j, \iota_j'}\), we can w.l.o.g. assume that all \(g_{j,v}\) are in \(e_2 M\). Moreover, equations (2) yields that \(\beta g_{j,1} - \mu_j \alpha g_{j,1} \in \iota'(e_1 P_1)\). Since the vector space \(\iota'(e_1 P_1)\) is only 1-dimensional, we can assume, possibly by multiplying some of the \(g_{j,v}\)’s by a scalar, that there is a non-zero element \(h \in \iota'(e_1 P_1)\) such that \(h = \beta g_{j,1} - \mu_j \alpha g_{j,1}\) for each \(j \leq q\). And it is easy to see from the representation of \(P_1\) that \(h\) generates \(\iota'(P_1)\).

Take the module \(L \subseteq M_1\) generated by \(g_{1,1}\). Then \(L \cong P_2\) by Lemma 9 and for any fixed \(\lambda \in k\), there is an exact sequence \(0 \rightarrow P_1 \rightarrow L \rightarrow R_\lambda \rightarrow 0\). In fact, we have
also the following exact sequence for some regular Kronecker module $Y$:

$$0 \to P_1 \xrightarrow{\vartheta} M \xrightarrow{\sigma} Y \to 0$$

Denote $f_{j,v} = \sigma(g_{j,v})$ and let $h'$ be a generator of $\vartheta(P_1)$ such that $h' = \beta g_{1,1} - \lambda \alpha g_{1,1}$. Then

$$\beta \bar{f}_{j,v} = \sigma(\beta g_{j,v}) = \sigma(\mu_j \alpha g_{j,v} + \alpha g_{j,v-1} + c_{j,v}h) = \mu_j \alpha \bar{f}_{j,v} + \alpha \bar{f}_{j,v-1} + c_{j,v} \sigma(h)$$

where $c_{j,v} \in k$ are suitable constants, and for convenience we assume $g_{j,0} = 0$ and $\bar{f}_{j,0} = 0$. This comes from the fact that $\beta g_{j,v} - \mu_j \alpha g_{j,v} - \alpha g_{j,v-1} \in \iota'(e_1 P_1)$ by equations (2) and (3) and $\iota'(e_1 P_1)$ is a 1-dimensional $k$-vector space generated by $h$. Further:

$$h = \beta g_{1,1} - \mu_1 \alpha g_{1,1} = h' + (\lambda - \mu_1) \alpha g_{1,1}$$

So we have:

$$c_{j,v} \sigma(h) = c_{j,v}(\lambda - \mu_1) \alpha \sigma(g_{1,1}) = c_{j,v}(\lambda - \mu_1) \alpha \bar{f}_{1,1}$$

and together:

$$\beta \bar{f}_{j,v} = \mu_j \alpha \bar{f}_{j,v} + \alpha \bar{f}_{j,v-1} + c_{j,v}(\lambda - \mu_1) \alpha \bar{f}_{1,1}$$

The matrix of the linear endomorphism $\chi_Y$ of the vector space $e_1 Y$, with respect to the basis $\alpha \bar{f}_{j,v}$, $j \leq q$, $v \leq \iota'_j$ and the pairs $(j, v)$ being ordered lexicographically, is of the form

$$\begin{pmatrix}
\lambda & * & * & * & \cdots \\
\mu_1 & \ddots & & & \\
& \ddots & 1 & & \\
& & \mu_1 & \ddots & \\
& & & \mu_2 & 1 \\
& & & & \ddots & \cdots
\end{pmatrix}$$

where the symbols * in the first row are to be substituted by some suitably chosen elements of $k$. Comparing the eigenvalues of $\chi_Y$ with the eigenvalues of $\chi_C$, we see that we have exactly changed one occurrence of $\mu_1$ for one occurrence of $\lambda$.

**Proposition 13** Let $n < \omega$. Then any two modules in $SP^{<\infty}$ of dimension $n$ are isomorphic.

**PROOF.** It is enough to carry out the proof only for $n > 2$ even. Choose an arbitrary $M \in SP^{<\infty}$ of dimension $n$. Put $m = \frac{n}{2} - 1$ and choose $m$ pairwise distinct elements $\lambda_1, \ldots, \lambda_m$ of the field $k$. Then, by the former proposition, there is an exact sequence

$$0 \to P_1 \xrightarrow{\vartheta} M \xrightarrow{\pi} \bigoplus_{j=1}^m R_{\lambda_j} \to 0$$

11
Let $N$ be the factor of the module $P^n_2$, with generators of the individual components of $P^n_2$ denoted $g_1, \ldots, g_m$, determined by the relations $\beta g_i - \lambda_i \alpha g_i = \beta g_{i+1} - \lambda_{i+1} \alpha g_{i+1}$. Then the dimension of $N$ is at most $n = 2m + 2$, since $\dim_k e_1 P^n_2 = \dim_k e_2 P^n_2 = 2m$, and for both these vector spaces we have $m - 1$ $k$-independent relations. Further, considering the proof of the preceding proposition, there is an epimorphism $N \rightarrow M$ which maps every element $g_i$ to some suitably chosen generator of $\pi^{-1}(R_\lambda)$. Thus, $\dim_k M = \dim_k N = 2m + 2 = n$ and $N \cong M$. And since the module $N$ is independent of the choice of the module $M$, we have at most one isomorphism class of $A$-modules in $\mathcal{SP}^{<\infty}$ for each dimension.

For every $n \geq 1$, let us denote by $P_n$ one fixed representative of the objects of $\mathcal{SP}^{<\infty}$ of dimension $2n$. This notation is consistent with the former notation of the indecomposable projectives $P_1$ a $P_2$, since these two modules are representatives of the modules in $\mathcal{SP}^{<\infty}$ of dimensions $2$ and $4$, respectively.

### 3.5 Auslander-Reiten translation of modules from $\mathcal{P}^{<\infty}$

In view of Corollary 4, it is convenient to determine the Auslander-Reiten translations of the modules in $\mathcal{P}^{<\infty}$. In this subsection, we will prove that the modules $R_\lambda$, $\lambda \in k$, are invariant with respect to the translation, while the modules from $\mathcal{SP}^{<\infty}$ are mapped to the Kronecker preprojective modules.

It is well-known that the functor $(-)^* = \text{Hom}_A(-, A)$ maps the indecomposable projective (left) $A$-module $P_i = Ae_i$ to an indecomposable projective right $A$-module isomorphic to $e_i A$, $i = 1, 2$. And the latter isomorphism assigns to the path $p \in e_i A$ ending at the vertex $i$ the following homomorphism from $A e_i$ to $A$:

$$p^* : \ A e_i \rightarrow A$$

$$e_i \mapsto p \ (\in A)$$

From now on, we will identify the modules $e_i A$ and $P_i^*$. In particular, we will denote the homomorphism in $P_i^*$ corresponding to a path $p \in e_i A$ as $p^*$ to distinguish elements of $A$ considered as left or right $A$-module. Note that the right $A$-module structure of $P_i^*$ is given by $p^* \cdot q = (pq)^*$ for a path $q \in A$. It is also clear that a homomorphism $f \in P_i^*$ is determined by its value on $e_i$. Thus, if $f(e_i) = \sum_{j=1}^m a_j p_j$ for some paths $p_1, \ldots, p_m \in A$ and elements $a_1, \ldots, a_m \in k$, then $f = \sum_{j=1}^m a_j p_j^*$.

**Lemma 14** Let $\lambda \in k$. Then $\tau R_\lambda \cong R_\lambda$.

**PROOF.** The minimal projective presentation of the module $R_\lambda$ is $0 \rightarrow P_i \xrightarrow{i^*_\lambda} P_2 \rightarrow R_\lambda \rightarrow 0$, where $i_\lambda(e_1) = \beta - \lambda \alpha$. Considering the map $i^*_\lambda : P_2^* \rightarrow P_i^*$, we see:

$$\left(\iota^*_\lambda(e_2^*)\right)(e_1) = e_2^* i_\lambda(e_1) = e_2^* (\beta - \lambda \alpha) = \beta - \lambda \alpha$$

Thus, $\iota^*_\lambda(e_1^*) = \beta^* - \lambda \alpha^*$. The module $P_i^*$ has a $k$-basis $e_1^*, \alpha^*, \beta^*$. For $M = P_1^*/\text{Im} \ i^*_\lambda$, we have $\dim_k M e_1 = \dim_k M e_2 = 1$ and $M \gamma = 0$. Therefore, $DM$ must
be a Kronecker quasi-simple regular module. Because $M(\beta - \lambda \alpha) = 0$, it is also $(\beta - \lambda \alpha)DM = 0$, and thus $DM = DTR\lambda \cong R\lambda$.

Recall that $Q_j$ denotes the $j$-th indecomposable Kronecker preprojective module; that is dim$_k e_1 Q_j = j$ and dim$_k e_2 Q_j = j - 1$. For $P_1$ and $P_2$, obviously $\tau P_1 = \tau P_2 = 0$.

**Lemma 15** Let $3 \leq n < \omega$. Then $\tau P_n \cong Q_{n-2}$.

**PROOF.** Looking at the first (push-out) diagram in the proof of Proposition 10, we see that there is a projective presentation of $P_n$ of the form

$$0 \rightarrow P_1^{n-2} \xrightarrow{b_2} P_2^{n-1} \rightarrow P_n \rightarrow 0$$

(4)

Next, fix $n - 1$ pairwise distinct elements $\lambda_1, \ldots, \lambda_{n-1}$ of the field $k$. Let us denote by $f_j$ the residue of the trivial path $e_1$ in the $j$-th copy of $P_1$ and by $g_l$ the residue of the path $e_2$ in the $l$-th copy of $P_2$. Examining the proof of Proposition 13 (namely, the construction of the module $N$ there which turns out to be isomorphic to $P_n$), we can assume that $\vartheta$ acts as follows:

$$\vartheta(f_j) = (\beta g_j - \lambda_j \alpha g_j) - (\beta g_{j+1} - \lambda_{j+1} \alpha g_{j+1}), \quad 1 \leq j \leq n - 2$$

Consequently, it is straightforward to see that the presentation (4) is minimal.

For arbitrary $A$-modules $M, N$ and non-zero natural numbers $m, v$, there is a canonical bijection between the elements of $\text{Hom}_A(M^m, N^v)$ and the matrices $v \times m$ over $\text{Hom}_A(M, N)$. Let us denote by $i_j : M \rightarrow M^m$ the $j$-th inclusion and by $p_l : N^v \rightarrow N$ the $l$-th projection. Then this bijection assigns to an homomorphism $h \in \text{Hom}_A(M^m, N^v)$ the matrix $(p_l h i_j)_{l \leq v, j \leq m}$. Moreover, $i_j^* : (M^*)^m \rightarrow M^*$ is the $j$-th projection, $p_l^* : N^* \rightarrow (N^*)^v$ is the $l$-th inclusion, and by the similar canonical bijection for right $A$-module homomorphisms, the element $h^* \in \text{Hom}_A((N^*)^v, (M^*)^m)$ corresponds to the matrix $(i_{j}^* p_l^*)_{l \leq m, j \leq v}$.

Now put $M = P_1, N = P_2, m = n - 2$ and $v = n - 1$. Then the map $\vartheta$ corresponds to the matrix $(\vartheta_{ij})$, where $\vartheta_{ij} = p_l \vartheta i_j$. It holds:

$$\vartheta_{ij}(e_1) = p_l \vartheta(f_j) = \begin{cases} 
\beta - \lambda_l \alpha & \text{for } l = j \\
-(\beta - \lambda_l \alpha) & \text{for } l = j + 1 \\
0 & \text{otherwise}
\end{cases}$$

It follows that:

$$\begin{align*}
(\vartheta_{jj}^*(e_j^*)) & (e_1) = e_j^* \vartheta_{jj}(e_1) = e_j^*(\beta - \lambda_j \alpha) = \beta - \lambda_j \alpha \\
(\vartheta_{j+1,j}^*(e_{j+1}^*)) & (e_1) = e_{j+1}^* \vartheta_{j+1,j}(e_1) = e_{j+1}^*(-(\beta - \lambda_{j+1} \alpha)) = -(\beta - \lambda_{j+1} \alpha)
\end{align*}$$

Thus:

$$\vartheta_{jj}^*(e_j^*) = \begin{cases} 
\beta^* - \lambda_l \alpha^* = e_j^* \cdot (\beta - \lambda_l \alpha) & \text{for } l = j \\
-(\beta^* - \lambda_l \alpha^*) = -e_j^* \cdot (\beta - \lambda_l \alpha) & \text{for } l = j + 1 \\
0 & \text{otherwise}
\end{cases}$$
For the map $\vartheta^*: (P_2^*)^{n-1} \to (P_1^*)^{n-2}$, let us denote by $g'_l$ the residue of the element $e^*_2$ in the $l$-th copy of $P_2^*$, and by $f'_j$ the residue of the element $e^*_1$ in the $j$-th copy of $P_1^*$. We attain the following formulas by composing the results of the former computations:

$$\vartheta^*(g'_l) = \begin{cases} 
   f'_1 (\beta - \lambda_1 \alpha) & \text{for } l = 1 \\
   f'_1 (\beta - \lambda_1 \alpha) - f'_{l-1}(\beta - \lambda_l \alpha) & \text{for } 1 < l < n - 1 \\
   -f'_{l-1}(\beta - \lambda_l \alpha) & \text{for } l = n - 1 
\end{cases}$$

Since $\lambda_1, \ldots, \lambda_{n-1}$ are pairwise distinct, we have $\dim_k(\text{Im } \vartheta^*)e_2 = n - 1$. Clearly $(\text{Im } \vartheta^*)e_1 = 0$. And we have $\dim_k P_1^*e_1 = 1$, $\dim_k P_1^*e_2 = 2$. Thus for the module $L = (P_1^*)^{n-2}/ \text{Im } \vartheta^*$ we have $\dim_k Le_1 = n - 2$ and $\dim_k Le_2 = 2(n - 2) - (n - 1) = n - 3$. Then $\dim_k e_1 DL = n - 2$ and $\dim_k e_2 DL = n - 3$. Moreover, $DL = DTnP_n$ must be an indecomposable Kronecker module, and by the characterisation of such modules we have $DL \cong Q_{n-2}$.

### 3.6 Indecomposable modules in $\mathcal{P}^{<\infty}$

We will use the results of the preceding section to characterize the indecomposable modules of $\mathcal{P}^{<\infty}$ up to isomorphism.

**Proposition 16** Let $0 \neq M \in \mathcal{P}^{<\infty}$ be indecomposable. Then one of the following cases holds true:

1. $M \cong R_{\lambda,i}$ for some $\lambda \in k$ and $i \geq 1$,
2. $M \cong P_n$ for some $n \geq 1$.

Before we prove the proposition itself, we need some auxiliary lemmas.

**Lemma 17** Let $M \in \mathcal{P}^{<\infty}$ such that $M$ has no submodule isomorphic to $R_{\lambda}$ for any $\lambda \in k$. Then $M$ is $\mathcal{SP}^{<\infty}$-filtered.

**Proof.** We will prove the lemma by an induction on the number $n$ of composition factors isomorphic to $P_1$ in a composition series of $M$ in $\mathcal{P}^{<\infty}$. There is nothing to prove for $n = 1$. Let $n > 1$. Take a composition series

$$0 = M_0 \subset M_1 \subset \cdots \subset M_l = M$$

of $M$ such that the last index $j$ for which $M_{j+1}/M_j \cong P_1$ is the greatest possible. Then $M/M_j \in \mathcal{SP}^{<\infty}$ by the assumption and $M_j$ is $\mathcal{SP}^{<\infty}$-filtered by the induction hypothesis. Thus, $M$ is $\mathcal{SP}^{<\infty}$-filtered too.

**Lemma 18** Let $M$ be a finitely generated $\mathcal{SP}^{<\infty}$-filtered module. Then $M$ is a direct sum of modules from $\mathcal{SP}^{<\infty}$.
The modules $P_1$ and $P_2$ are projective and every module $P_n$, $n \geq 3$ has a minimal projective presentation of the form $0 \to P^{n-2}_1 \to P^{n-1}_2 \to P_n \to 0$. Thus, a minimal projective presentation of the module $M$ must be of the form:

$$
0 \to P^m_1 \to P^n_1 \oplus P^n_2 \to M \to 0
$$

The module $TrM$ is a factor of $(P^*_1)^m$ by definition. Therefore, the module $DTrM$ is a submodule of $D(P^*_1)^m = I^m_1$. Since $I^m_1$ is a Kronecker module, so is $\tau M$.

Let us choose an arbitrary $\lambda \in k \cup \{\infty\}$. Then

$$
D\text{Ext}^1_A(P_n, R_\lambda) \cong \text{Hom}_A(R_\lambda, \tau P_n) \cong \text{Hom}_A(R_\lambda, Q_{n-2}) = 0
$$

for all $n \geq 3$. The first isomorphism follows by Theorem 2 and Proposition 3 and the second by Lemma 15. In particular, $\text{Ext}^1_A(M, R_\lambda) = 0$, and so $\text{Hom}_A(R_\lambda, \tau M) = 0$. Thus, the module $\tau M$ is preprojective, that is $\tau M \cong \bigoplus_{j=1}^m Q_{i_j}$ for some $i_1, \ldots, i_m$. Then

$$
M \cong P \oplus \tau^-(\tau M) \cong P \oplus \bigoplus_{j=1}^m P_{i_j+2}
$$

for some finitely generated projective module $P$.

\textbf{PROOF.} [Proposition 16] Let $M \in P^{<\infty}$ be indecomposable. If $M$ is a Kronecker module, we are in the case number 1.

Suppose $M$ is not a Kronecker module and $L$ is a maximal $KP^{<\infty}$-submodule of $M$. Since the subcategory $KP^{<\infty}$ is closed under extensions, $M/L$ has no submodule isomorphic to $R_\lambda$, $\lambda \in k$. Then $M/L$ is $SP^{<\infty}$-filtered by Lemma 17. Further, we have

$$
D\text{Ext}^1_A(P_n, R_\lambda) \cong \text{Hom}_A(R_\lambda, \tau P_n) \cong \text{Hom}_A(R_\lambda, Q_{n-2}) = 0
$$

for all $\lambda \in k$ and $n \geq 3$ — the first isomorphism by Theorem 2 and Proposition 3 and the second by Lemma 15. In particular, $\text{Ext}^1_A(M/L, L) = 0$ and $M \cong L \oplus M/L$. Thus, $L = 0$ and $M \in SP^{<\infty}$ by Lemma 18.

\section{4 Tilting classes}

\subsection{The lattice of tilting classes}

Since $\text{Fdim} A = 1$ by [13], every tilting $A$-module is 1-tilting. By [9], all 1-tilting classes over any associative unital ring are of finite type. Thus, every tilting class in $A$-Mod can be obtained as $S^\perp$, where $S$ is some subset of objects of $P^{<\infty}$. Let us denote by $\text{ind} P^{<\infty}$ a representative subset of the indecomposable modules in $P^{<\infty}$. Obviously, it is always possible to choose $S$ as a subset of $\text{ind} P^{<\infty}$.
Proposition 19  The class \( T \subseteq A\text{-Mod} \) is a tilting class if and only if there is a subset \( S \subseteq \text{ind} \mathcal{P}^{<\infty} \) such that \( S^\perp = T \). \( \square \)

Let \( S \subseteq \text{ind} \mathcal{P}^{<\infty} \). Let us denote \( \bar{S} = \perp(S^\perp) \cap \text{ind} \mathcal{P}^{<\infty} \). It is easy to see that \( S^\perp = \bar{S}^\perp \). We will call a subset \( S \) of \( \text{ind} \mathcal{P}^{<\infty} \) closed if \( S = \bar{S} \). Clearly, the lattice of 1-tilting classes is anti-isomorphic to the lattice of closed subsets of \( \text{ind} \mathcal{P}^{<\infty} \). A description of the closed subsets follows.

Theorem 20  A subset \( S \subseteq \text{ind} \mathcal{P}^{<\infty} \) is closed if and only if it satisfies the following conditions:

1. \( P_1 \in S, P_2 \in S \).
2. If \( R_{\lambda,i} \in S \) for some \( \lambda \in k \) and \( i \geq 1 \), then \( R_{\lambda,j} \in S \) for every \( j \geq 1 \).
3. If \( R_{\lambda,i} \in S \) for some \( \lambda \in k \) and \( i \geq 1 \), then \( P_j \in S \) for every \( j \geq 1 \).
4. If \( P_n \in S \) for some \( n \geq 3 \), then \( P_j \in S \) for every \( j \leq n \).

PROOF. First, assume \( S \subseteq \text{ind} \mathcal{P}^{<\infty} \) is closed. The necessity of the condition 1 is obvious. For Kronecker regular modules, we have the exact sequences:

\[
0 \to R_{\lambda,i} \to R_{\lambda,i-1} \oplus R_{\lambda,i+1} \to R_{\lambda,i} \to 0
\]

Thus, if \( R_{\lambda,i} \in S \), then also \( R_{\lambda,i-1}, R_{\lambda,i+1} \in S \). The condition 2 follows by induction. Further, by Proposition 12 we have

\[
0 \to P_1 \to P_j \to R_{\lambda,j-1} \to 0,
\]

for each \( j \geq 3 \). This implies the condition 3. Let \( n \geq 3 \) and \( M \in P^\perp_n \). Then \( \text{Hom}_A(M, Q_{n-2}) = 0 \) by Corollary 4 and Lemma 15. Thus, \( \text{Hom}_A(M, Q_{j-2}) = 0 \) for each \( 3 \leq j \leq n \), since \( Q_{n-2} \) has submodules isomorphic to \( Q_{j-2} \). This means that \( M \in P^\perp_j \), and \( P_j \in \perp(P^\perp_n) \) for each \( 3 \leq j \leq n \). This yields condition 4.

Conversely, let \( S \subseteq \text{ind} \mathcal{P}^{<\infty} \) satisfy the conditions 1–4. Assume that there is some \( M \in \bar{S} \setminus S \). If \( M = R_{\lambda,i} \) for some \( \lambda \) and \( i \), then \( R_{\lambda,j} \notin S \) for each \( j \geq 1 \) by the condition 2. But this implies \( R_{\lambda} \in S^\perp \) using the characterization of \( \text{ind} \mathcal{P}^{<\infty} \) in Proposition 16. Then also \( R_{\lambda} \in \bar{S}^\perp \), which is a contradiction. Thus, it remains only the case \( M = P_n \) for some \( n \geq 3 \). But then \( R_{\lambda,i} \notin S \) for each \( \lambda \in k, i \geq 1 \) and \( P_j \notin S \) for each \( j \geq n \) by the conditions 3 and 4. So \( S \) consists only of some of the modules \( P_1, \ldots, P_{n-1} \), again by Proposition 16. But then Corollary 4 and Lemma 15 yield \( Q_{n-2} \in S^\perp = \bar{S}^\perp \) and \( D \text{Ext}^1_A(P_n, Q_{n-2}) \cong \text{Hom}_A(Q_{n-2}, Q_{n-2}) \neq 0 \), a contradiction to the assumption \( P_n \in \bar{S} \).

Corollary 21  \((\mathcal{P}^{<\infty})^\perp = \{R_{\lambda}| \lambda \in k\}^\perp = \bigcap_{\lambda \in k} \text{Ker} \text{Hom}_A(-, R_{\lambda})\).

PROOF. For the first equality, see [1, 5.4]. Or alternatively, if we take \( S = \{R_{\lambda}| \lambda \in k\} \), then \( \bar{S} = \text{ind} \mathcal{P}^{<\infty} \) by the former theorem. Thus \( S^\perp = (\text{ind} \mathcal{P}^{<\infty})^\perp = (\mathcal{P}^{<\infty})^\perp \).

The second equality follows from Corollary 4 and Lemma 14.
### 4.2 Impossibility of reconstructing a tilting class from finitely generated modules by direct limits

This section is inspired by the dual case, where every 1-cotilting class \( C \) over a noetherian ring could be reconstructed from its finitely generated modules by direct limits. That is \( C = \lim \bigcap R \text{-mod} \), \( C \) being closed under direct limits, since every 1-cotilting module is pure-injective by [7]. So there is a bijective correspondence between the 1-cotilting classes and the torsion-free classes of finitely generated modules containing \( R \), [19].

But an analogous proposition with direct limits is not true for 1-tilting classes over IST-algebra. Take \( T = (P^\infty)^\perp \) and \( T^\infty = T \cap A \text{-mod} \). Then \( T = \lim T^\infty \) implies that \( \lim T^\infty \) is closed under direct products. This is equivalent to the covariant finiteness of \( T^\infty \) in \( A \text{-mod} \) by [1], and thus to the contravariant finiteness of \( P^\infty \) in \( A \text{-mod} \) by [17]. But this is not true for IST-algebra. The aim of this subsection is to give particular examples of modules from \( T \setminus \lim T^\infty \).

**Proposition 22** Let \( T = (P^\infty)^\perp \) and \( T^\infty = T \cap A \text{-mod} \). Then the Prüfer module \( R_{\lambda,\infty} \) is a member of \( T \) for each \( \lambda \in k \), but \( \text{Hom}_A(M, R_{\lambda,\infty}) = 0 \) for all \( M \in T^\infty \).

**PROOF.** It is well-known that \( \text{Hom}_A(R_{\lambda,\infty}, R_{\mu}) = 0 \) for each \( \mu \in k \). Therefore, \( R_{\lambda,\infty} \in T \) by Corollary 21.

We have \( \text{Hom}_A(I, R_{\lambda}) = 0 \) for an injective cogenerator \( I = I_1 \oplus I_2 \) by Proposition 3 and Lemma 14. Then also \( \text{Hom}_A(I, R_{\lambda,\infty}) = 0 \) and \( \text{Hom}_A(M, R_{\lambda,\infty}) = 0 \) for every factor \( M \) of \( I \). Thus, \( \text{Hom}_A(M, R_{\lambda,\infty}) = 0 \) for each \( M \in T^\infty \) by Lemma 5.

**Corollary 23** \( R_{\lambda,\infty} \in T \setminus \lim T^\infty \) for each \( \lambda \in k \).

### 5 Tilting modules

#### 5.1 Constructing more complex preenvelopes

Now we are close to show an explicit structure of a tilting module for the class \( (P^\infty)^\perp \). First, we need the following general proposition which is valid for any ring \( R \). Let us recall that a module \( X \) over an arbitrary ring is said to be \( FP_2 \), if it possesses an exact sequence \( W_2 \to W_1 \to W_0 \to X \to 0 \) with \( W_0, W_1, W_2 \) finitely generated projective \( R \)-modules. Then whenever \( X \) is an \( FP_2 \) module, \( X^{\perp_1} = \ker \text{Ext}_R^1(X, -) \) is closed under direct limits, thus also under filtrations and arbitrary direct sums (see eg. [1]).

**Proposition 24** Let \( R \) be an arbitrary ring and \( S \) be a set of \( FP_2 \) modules such that \( \text{Ext}_R^1(X, Y) = 0 \) for any pair of distinct modules \( X, Y \in S \). Further, let \( M \in R \text{-Mod} \).
be any module and assume that

\[ 0 \to M \to J_X \to C_X \to 0 \]

is a special \( X^{\perp 1} \)-preenvelope with an \( \{X\} \)-filtered cokernel \( C_X \) for each \( X \in S \). Then the second row of the following push-out diagram (the map \( \sigma \) just adding up the components of the direct sum) is a special \( S^{\perp 1} \)-preenvelope of \( M \):

\[
\begin{array}{cccccc}
0 & \longrightarrow & M(S) & \longrightarrow & \bigoplus_{X \in S} J_X & \longrightarrow & \bigoplus_{X \in S} C_X & \longrightarrow & 0 \\
& & \sigma \downarrow & & \downarrow & & \| & & \\
0 & \longrightarrow & M & \longrightarrow & J & \longrightarrow & \bigoplus_{X \in S} C_X & \longrightarrow & 0
\end{array}
\]

**Proof.** It is sufficient to prove that \( J \in S^{\perp 1} \) and \( C = \bigoplus_{X \in S} C_X \in ^{\perp 1}(S^{\perp 1}) = \text{Ker Ext}^1_R(-, S^{\perp 1}) \). But the latter is clear, since the module \( C \) is a direct sum of \( S \)-filtered modules and \( ^{\perp 1}C \) is closed under direct sums and filtrations for an arbitrary class of modules \( C \).

Choose an arbitrary \( Y \in S \). If we take only the component corresponding to the module \( Y \) in the first row of the commutative diagram above, and if we denote by \( \sigma' \) the restriction of the map \( \sigma \) to that component, we will get an induced diagram:

\[
\begin{array}{cccccc}
0 & \longrightarrow & 0 & & \\
& & \downarrow & & \\
0 & \longrightarrow & M & \longrightarrow & J_Y & \longrightarrow & C_Y & \longrightarrow & 0 \\
& & \sigma' \downarrow & & \downarrow & & \downarrow & & \\
0 & \longrightarrow & M & \longrightarrow & J & \longrightarrow & \bigoplus_{X \in S} C_X & \longrightarrow & 0 \\
& & \downarrow & & \downarrow & & \downarrow & & \\
& & \bigoplus_{X \in S \setminus \{Y\}} C_X & \longrightarrow & \bigoplus_{X \in S \setminus \{Y\}} C_X & & & & \\
& & \downarrow & & \downarrow & & \\
& & 0 & \longrightarrow & 0 & & & &
\end{array}
\]

By assumption, \( X \in Y^{\perp 1} \) for each \( X \in S \setminus \{Y\} \) and \( Y^{\perp 1} \) is closed under filtrations and direct sums, thus \( \bigoplus_{X \in S \setminus \{Y\}} C_X \in Y^{\perp 1} \). But also \( J_Y \in Y^{\perp 1} \), therefore \( J \in Y^{\perp 1} \).

And this is true for any \( Y \in S \), so \( J \in S^{\perp 1} \).

### 5.2 Structure of tilting modules for \( R^1_\lambda \)

**Construction 25** (\( R^1_\lambda \)-preenvelopes of \( P_1 \) and \( P_2 \)) Let \( \lambda \in k \). By Proposition 12, there is an exact sequence \( 0 \to P_1 \to P_{n+1} \to R_{\lambda,n} \to 0 \) for each \( n \geq 1 \). If we take an inclusion \( j : R_{\lambda,n-1} \to R_{\lambda,n} \) for any \( n \geq 2 \), then the module \( M = \sigma^{-1}(\text{Im } j) \) is
clearly an object of $\mathcal{SP}^{<\infty}$ (cf. the remark after Def. 8), thus $M \cong P_n$ by Proposition 13. Moreover, $P_{n+1}/M \cong R_{\lambda,n}/\text{Im} j \cong R_{\lambda}$. So we have the following exact sequence for any $n \geq 1$:

$$0 \longrightarrow P_n \xrightarrow{\iota_{n+1,n}} P_{n+1} \longrightarrow R_{\lambda} \longrightarrow 0$$

Let us denote $\iota_{m,n} = \iota_{m,m-1} \ldots \iota_{n+2,n+1} \iota_{n+1,n}$ and $\iota_{n,n} = 1_{P_n}$ for every $m > n \geq 1$.

The following squares are obviously commutative for $n \geq 2$:

\[
\begin{array}{ccc}
P_1 & \xrightarrow{\iota_{n,1}} & P_n \\
& \| & \\
& \iota_{n+1,n} \downarrow & \\
P_1 & \xrightarrow{\iota_{n+1,1}} & P_{n+1}
\end{array}
\]

Further, $\text{Coker} \iota_{n,1}$ is $R_{\lambda}$-filtered, thus $\text{Coker} \iota_{n,1} \cong R_{\lambda,n-1}$ by Lemma 11. Therefore, we have the exact commutative diagrams with monomorphisms in columns:

$$0 \longrightarrow P_1 \xrightarrow{\iota_{n,1}} P_n \xrightarrow{\pi_n} R_{\lambda,n-1} \longrightarrow 0$$

$$0 \longrightarrow P_1 \xrightarrow{\iota_{n+1,1}} P_{n+1} \xrightarrow{\pi_{n+1}} R_{\lambda,n} \longrightarrow 0$$

Let us denote by $T_{\lambda}$ the direct limit of the modules $P_n$, $n \geq 1$, with the inclusions $\iota_{m,n}$, $m \geq n \geq 1$. We obtain the exact sequence:

$$\delta_1: 0 \longrightarrow P_1 \xrightarrow{\iota} T_{\lambda} \xrightarrow{\pi} R_{\lambda,\infty} \longrightarrow 0$$

Next, take the commutative diagram with the canonical inclusions in columns:

$$0 \longrightarrow P_1 \xrightarrow{\iota_{2,1}} P_2 \xrightarrow{\pi_2} R_{\lambda} \longrightarrow 0$$

$$0 \longrightarrow P_1 \xrightarrow{\iota'} T_{\lambda} \xrightarrow{\pi'} R_{\lambda,\infty} \longrightarrow 0$$

Then $\text{Coker} \iota' \cong \text{Coker} \iota' \cong R_{\lambda,\infty}$, thus we have the exact sequence:

$$\delta_2: 0 \longrightarrow P_2 \xrightarrow{\iota'} T_{\lambda} \xrightarrow{\pi'} R_{\lambda,\infty} \longrightarrow 0$$

Using this notation, we get:

**Proposition 26** The short exact sequences $\delta_1$ and $\delta_2$ are special $R_{\lambda}^\perp$-preenvelopes of the indecomposable projective modules $P_1$ and $P_2$, respectively.
PROOF. It is sufficient to prove that \( T_\lambda \in R_\lambda^\perp \) and \( R_{\lambda,\infty} \in \perp(R_\lambda^\perp) \). The latter is clear, since the Prüfer module \( R_{\lambda,\infty} \) is \( R_\lambda \)-filtered.

It is enough to show that \( \text{Hom}_A(T_\lambda, R_\lambda) = 0 \) by Corollary 4 and Lemma 14. Take an arbitrary \( f \in \text{Hom}_A(T_\lambda, R_\lambda) \). If we apply the functor \( \text{Hom}_A(-, R_\lambda) \) to the exact sequence \( 0 \rightarrow P_1 \xrightarrow{\iota_{2,1}} P_2 \rightarrow R_\lambda \rightarrow 0 \), we obtain

\[
0 \longrightarrow \text{Hom}_A(R_\lambda, R_\lambda) \longrightarrow \text{Hom}_A(P_2, R_\lambda) \xrightarrow{\text{Hom}_A(\iota_{2,1}, R_\lambda)} \text{Hom}_A(P_1, R_\lambda)
\]

But \( \dim_k \text{Hom}_A(R_\lambda, R_\lambda) = 1 \), and also \( \dim_k \text{Hom}_A(P_i, R_\lambda) = \dim_k e_i R_\lambda = 1 \) for \( i = 1, 2 \). This implies \( \text{Hom}_A(\iota_{2,1}, R_\lambda) = 0 \). So \( f = f \iota_{2,1} = 0 \). Therefore, there is a map \( \bar{f} \) such that \( f = \bar{f} \pi \). But now \( \bar{f} \in \text{Hom}_A(R_{\lambda,\infty}, R_\lambda) \), and thus \( f = 0 \).

Theorem 27 Let \( \lambda \in k \) and \( T_\lambda \) be as in Construction 25. Then \( T_\lambda \oplus R_{\lambda,\infty} \) is a tilting module corresponding to the tilting class \( R_\lambda^\perp \).

PROOF. By the proof of [19, Theorem 29], once we have a tilting class \( T \), we can construct a corresponding tilting module by iterating special \( T \)-preenvelopes starting with the regular module \( _A A \). Since \( R_\lambda^\perp \) is a 1-tilting class, we need to construct only the first iteration. We have \( _A A \cong P_1 \oplus P_2 \), and by the former proposition, there is a special \( R_\lambda^\perp \)-preenvelope of \( A \) of the form

\[
0 \rightarrow A \rightarrow T_\lambda \oplus T_\lambda \rightarrow R_{\lambda,\infty} \oplus R_{\lambda,\infty} \rightarrow 0
\]

The corresponding tilting module is then \( T = (T_\lambda \oplus T_\lambda) \oplus (R_{\lambda,\infty} \oplus R_{\lambda,\infty}) \). Note that if \( T' \) is a module such that \( T' \in \text{Add}T \) and \( T \in \text{Add}T' \), then \( T' \) is tilting too, and \( T^\perp = (T')^\perp \). Putting \( T' = T_\lambda \oplus R_{\lambda,\infty} \) gives us the desired result.

Remark 28 Let us write down a linear representation corresponding to the module \( T_\lambda \). It is of the shape

\[
\begin{array}{ccc}
V_1 & \xleftarrow{f_\alpha} & V_2 \\
\xlink{f_\beta} & \xlink{f_\gamma} & \xlink{f_\delta}
\end{array}
\]

with the linear maps satisfying equations \( f_\alpha f_\gamma = f_\beta f_\gamma = f_\gamma f_\alpha = 0 \).

Since \( T_\lambda \) is countable dimensional, we put \( V_1 = V_2 = k^{(\omega)} \). Then the linear maps for \( T_\lambda \) are given by the following column-finite matrices:

\[
f_\alpha = \begin{pmatrix}
0 & 0 & 0 & \ldots \\
0 & 1 & 0 & \ldots \\
0 & 1 & 0 & \ldots \\
\vdots & \ddots & \ddots & \ddots
\end{pmatrix}, \quad f_\beta = \begin{pmatrix}
0 & 1 & 0 & \ldots \\
0 & \lambda & 1 & \ldots \\
0 & \lambda & \ddots & \ddots \\
\vdots & \ddots & \ddots & \ddots
\end{pmatrix}, \quad f_\gamma = \begin{pmatrix}
1 & 0 & 0 & \ldots \\
0 & 0 & 0 & \ldots \\
0 & 0 & 0 & \ldots \\
\vdots & \ddots & \ddots & \ddots
\end{pmatrix}
\]
For the sake of completeness, we also write down a representation of the corresponding Prüfer module $R_{\lambda,\infty}$:

$$f_\alpha = \begin{pmatrix} 1 & 0 & 0 & \ldots \\ 0 & 1 \\ 0 & 1 \\ \vdots & \ddots \end{pmatrix}, \quad f_\beta = \begin{pmatrix} \lambda & 1 \\ 0 & \lambda & 1 \\ 0 & \lambda & \ddots \\ \vdots & \ddots \end{pmatrix}, \quad f_\gamma = \begin{pmatrix} 0 & 0 & 0 & \ldots \\ \end{pmatrix}.$$

Note also that in contrast to Proposition 13, the modules $T_\lambda$ and $T_\mu$ are non-isomorphic for $\lambda \neq \mu$. Otherwise, there would be an inclusion $i : P_1 \to T_\mu$ with the cokernel isomorphic to $R_{\lambda,\infty}$. But this is not possible, since a cokernel of any inclusion $i : P_1 \to T_\mu$ is isomorphic to $R_{\mu,\infty} \oplus M$, where $M$ is a suitable finitely generated Kronecker regular module.

5.3 Structure of a tilting module for $(\mathcal{P}^{<\infty})^\perp$

**Theorem 29** Let $X \subseteq k$ be a non-empty subset and put $S = \{R_\lambda \mid \lambda \in X\}$. For each $\lambda \in X$ take the special preenvelope $0 \to P_1 \xrightarrow{i_\lambda} T_\lambda \to R_{\lambda,\infty} \to 0$ from Construction 25, and take the following push-out diagram with the summation map $\sigma$:

$$
\begin{array}{cccccccc}
0 & \to & P_1^{(X)} & \to & \bigoplus_{\lambda \in X} T_\lambda & \to & \bigoplus_{\lambda \in X} R_{\lambda,\infty} & \to & 0 \\
\sigma \downarrow & & \downarrow & & \downarrow & & \downarrow \\
0 & \to & P_1 & \to & T_X & \to & \bigoplus_{\lambda \in X} R_{\lambda,\infty} & \to & 0
\end{array}
$$

Then $T = T_X \oplus \bigoplus_{\lambda \in X} R_{\lambda,\infty}$ is a tilting module corresponding to the tilting class $S^\perp$.

**PROOF.** The set $S$ fulfills the assumptions of Proposition 24. Thus, the exact sequence $0 \to P_1 \to T_X \to \bigoplus_{\lambda \in X} R_{\lambda,\infty} \to 0$ is a special $S^\perp$-preenvelope of the projective $P_1$.

Take an arbitrary $\mu \in X$. Then we have the following commutative diagram with isomorphisms in the first and monomorphisms in the other columns:

$$
\begin{array}{cccccccc}
0 & \to & P_1 & \to & P_2 & \to & R_\mu & \to & 0 \\
\parallel & & \downarrow i' & & \downarrow j' & & \downarrow \\
0 & \to & P_1 & \xrightarrow{i_\mu} & T_\mu & \to & R_{\mu,\infty} & \to & 0 \\
\sigma' \parallel & & \downarrow \parallel & & \downarrow \parallel & & \downarrow \\
0 & \to & P_1 & \to & T_X & \to & \bigoplus_{\lambda \in X} R_{\lambda,\infty} & \to & 0
\end{array}
$$

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Thus $T_X/\text{Im }i''i' \cong \bigoplus_{\lambda \in X} R_{\lambda, \infty}/\text{Im }j''j' \cong \bigoplus_{\lambda \in X} R_{\lambda, \infty}$, and we have the following short exact sequence, which is necessarily a special $S^\perp$-preenvelope of the module $P_2$:

$$0 \longrightarrow P_2 \xrightarrow{i''i'} T_X \longrightarrow \bigoplus_{\lambda \in X} R_{\lambda, \infty} \longrightarrow 0$$

Since $A \cong P_1 \oplus P_2$, the module $T \oplus T$ is tilting corresponding to the tilting class $S^\perp$ [19, Proof of Theorem 2.9], and so is $T$ itself.

With the notation of Theorem 29, we get for $X = k$:

**Corollary 30** $T_k \oplus \bigoplus_{\lambda \in k} R_{\lambda, \infty}$ is a tilting module corresponding to $(P^{<\infty})^\perp$.

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**References**


